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On microjets in sunspot penumbrae

Thesis submitted for the degree of Philosophiae Doctor

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To Marianne.
Preface

In popular imagination, natural science is often exemplified by its most revolutionary, inspiring or even terrifying achievements. These achievements are plentiful and take equally many forms. There are those that not only grant us knowledge of the natural world, but also change how we perceive our collective self. The theory of evolution by natural selection reframes our understanding of humans as an animal among many. The big bang theory and astrophysics at large similarly reframe our standing in the cosmos - reveals it as infinitesimal compared to both the scales of time and space over which the universe evolves. Biology, chemistry and physics have eradicated diseases, allowed us to not just subsist but thrive, and have brought us ever so slightly closer to the stars. Defying gravity, we have just begun to pull ourselves out of the dark well in which we have sat trapped since our primordial origins. Nuclear physics first unravelled the atom in our minds, then in actuality. Perhaps more viscerally than any theoretical knowledge, the crack of its rending taught us the fragility of humankind’s existence. By the same laws of the atom, we can predict our Sun’s eventual demise. Red, baleful, bloated, Sol will devour Earth as it experiences a drawn-out death.

Still, none of the many discoveries made in the name of science, in whatever form it takes, were achieved in isolation. For each great discovery, each leap forward, a multitude of little steps had to come before. As has been oft-repeated, Isaac Newton wrote, “If I have seen further it is by standing on the shoulders of Giants.” I prefer to think of our collective effort to expand our horizon, both physical and metaphorical, as a process in which we build, together, a great edifice from which we can observe the world and ourselves from ever greater heights. The continued contribution of many is necessary for this great endeavour to continue. Assuredly, most of us will not be remembered as giants. Parts of the great edifice will crumble or will have to be replaced when we find that we have built on unsteady ground. Other parts will stand fast through the ages. Sometimes, a great momentous block of stone is added, hoisted up by many - the theory of evolution by natural selection, the big bang theory, the standard model. Sometimes a giant will help with the final push. Each stone is supported by others, great and small, some as small as to be easily missed. I have no pretences about my contributions so far. Nonetheless, here it is - my pebble, to be added to the great edifice.

Meanderings aside, what follows is my doctoral thesis in the field of solar physics. The focus of my work has been the observational study of objects called penumbral microjets. These are found in the murky twilight zone of sunspots, the penumbra. They are on the smallest physical scale that is currently observable on the Sun, on the order of measly hundreds of kilometres. Penumbral microjets, or PMJs, are primarily observed as brief flashes of light, jet-like in their appearance. With their home, relative size, and looks hinted at, their name hopefully becomes less mysterious. PMJs are interesting in and of themselves, but they may also serve as tell-tale clues in the endeavour to unravel the detailed conditions found in sunspots. Since they are thought to be caused
by the violent reordering of stressed magnetic field lines, or magnetic reconnection, PMJs may also teach us about this complicated process in particular. My work has been largely observational, with various numerical, theoretical and diagnostic techniques employed to study the appearance, behaviour and origin of PMJs in various wavelengths of light. In this doctoral thesis, I will first delve into the context necessary to understand my original research; we will examine the Sun and its atmosphere, the techniques and instruments used to study it and the general state of research concerning PMJs. At last, we will turn to the original research itself. I will allow to let the thesis speak for itself at greater lengths below.

The completion of this thesis has taken longer than both planned or expected. I am glad to have completed it at last, since sometimes the horizon seemed very far-off indeed. However, I am more than happy to be able to add my little contribution to solar physics and I am very grateful for the lessons learned along the journey travelled. Hopefully, my contribution will allow someone to see just a little bit further, who in turn will add their own pebble to the great pile on which I have just tossed mine.

This thesis is submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor at the University of Oslo. The work of this thesis was carried out at the Institute of Theoretical Astrophysics, under the guidance of Luc Rouppe van der Voort and Mats Carlsson who had roles as primary and secondary supervisors respectively. The research of this thesis was partially funded by the Norwegian Research Council and by the European Research Council.
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First, I would like to thank Luc Rouppe van der Voort, my primary supervisor, and Mats Carlsson, my secondary supervisor. I must thank them both for their advice and guidance, but also for their continued patience with me and my work throughout lengthy delays. I owe them both a great debt of gratitude for the opportunities that they gave me, and for the fact that they helped me pull through to the end. I would also like thank them for all the good conversations and coffees shared throughout my time at the institute.

Throughout my work, I have had the privilege of encouragement and support from both family and friends. I’d like to thank my parents, Doris and Hartwig, both for their support throughout my work on this doctoral thesis, but also for their encouragement throughout my childhood that eventually led me to the natural sciences in the first place. Without them, I would not have been able to take the path that I did. Both my big brother, Haakon, and my little sister, Sirkka, were there for me growing up, and during my work in particular - especially during my slumps and woes. They were there to listen and nod along to my complaints. For this, I thank them greatly. There are many others to whom I wish to extend my thanks, whether for advice on work or life in general, for a sympathetic ear, or simply for good company. Here, I’d first like to thank my long-time friends Tom Erik, Mats, Magnus and Remi for all our times shared over many years. From my time at ITA, I particularly want to thank Clara, Robert W. and Marie for their advice and encouragement and also for the adventures we shared, both during and after our time together at the institute. I also wish to extend my thanks for the coffees, chats, discussions and everything else we had to Benedikte, Lluis, Robert H., Charalambos and Max. To name everyone I have had the fortune of sharing time with at ITA and the University of Oslo over the years would take far too long, and I apologize for not being able to do so - here I wish to extend my gratitude for every coffee, joke, conversation and Christmas party shared over the years.

Last, I wish to thank my dear Marianne. I will not embarrass her at length, but I will say that I would not have been able to complete this thesis without her, not to speak of everything else that she has done for me. I am forever grateful to her, both for being there with me through it all, but also for all that she is.

Ainar Drews
Oslo, July 2021
List of publications

Publications included in this thesis

The following refereed publications constitute the original research of this thesis. They are reproduced in full in the latter part of this thesis.

**Paper I: “Microjets in the penumbra of a sunspot”**

Authors: A. Drews and L. Rouppe van der Voort
DOI: [10.1051/0004-6361/201630312](https://doi.org/10.1051/0004-6361/201630312).

**Paper II: “Penumbral microjets at high spatial and temporal resolution”**

Authors: L. Rouppe van der Voort and A. Drews
DOI: [10.1051/0004-6361/201935343](https://doi.org/10.1051/0004-6361/201935343).

**Paper III: “A multi-diagnostic spectral analysis of penumbral microjets”**

Authors: A. Drews and L. Rouppe van der Voort
DOI: [10.1051/0004-6361/202037911](https://doi.org/10.1051/0004-6361/202037911).
List of publications

Publications not included in this thesis

I was involved as a co-author in the following refereed publications during the course of my studies. However, they are not a part of this thesis.

“Observationally Based Models of Penumbral Microjets”

Authors: Esteban Pozuelo, S.; de la Cruz Rodríguez, J.; Drews, A.; Rouppe van der Voort, L.; Scharmer, G. B.; Carlsson, M.

“High-resolution observations of the solar photosphere, chromosphere, and transition region. A database of coordinated IRIS and SST observations”

DOI: 10.1051/0004-6361/202038732.
Introduction

As its title has hopefully already conveyed, this thesis is on the topic of microjets found in sunspot penumbrae. For the sake of both distinction and brevity, these are most commonly referred to as penumbral microjets, and for the sake of even greater brevity, as PMJs. As their name implies, penumbral microjets are found in the penumbrae of sunspots, and they constitute a rather small jet-like phenomenon. With lengths typically ranging from a few hundred to some thousand kilometres, PMJs are indeed a rather small-scale affair in comparison to the Sun’s overall size. They are also humbled by comparisons to many of the more famous solar phenomenons, such as solar flares and sunspots, the latter of which are also the home of PMJs. PMJs are chiefly defined by the brief flashes of light they exhibit in the grey twilight zones of sunspots, or penumbrae. Most commonly, these flashes appear swiftly and typically fade on the order of less than a minute, or up to a few minutes. Much is to be said on the wavelengths of light with which we can observe PMJs, and the nuances of how PMJs appear in these different wavelengths, and I will do so at length below. Chiefly however, PMJs are most commonly associated with spectral lines that correspond to the middle layer of the solar atmosphere - the chromosphere. Among these, the wavelengths of the Ca II H line, in which PMJs were first observed, and that of the Ca II 8542 Å line, are those that PMJs are most usually observed in. However, PMJs have been observed both throughout the chromosphere, but also as far up as the transition region of the solar atmosphere. There are also some tantalizing signs of PMJs in the deepest layer of the solar atmosphere, the photosphere, but with less direct signatures than the clear flashes that we can see further up. One of the most interesting aspects of PMJs is their formation, which is not yet entirely understood or described to its fullest. However, it is both speculated and very likely that PMJs are at least triggered by magnetic reconnection events, a process in which stressed or tangled magnetic field lines release sudden outbursts of energy as they reorder themselves. Magnetic reconnection is a topic of great interest to solar physicists, and it is a complex topic both in terms of capturing its observational signatures, as well as its descriptions, here both in theoretical and numerical terms. Typically, magnetic reconnection is associated with solar flares and thus larger length-scales on the Sun; therefore, PMJs offer the potential of a unique glimpse at this process at much smaller scales, offering tantalizing new insights.

My own work, which will be presented at the end of this thesis, is primarily that of a solar observer characterizing penumbral microjets and their behaviour. Employing various techniques, ranging from an automated detection scheme for PMJs that employed a simple machine learning algorithm, to the detailed manual tracking of PMJs and their dynamics, and to detailed spectral analyses of PMJs - and much more besides - I have studied PMJs in order to constrain their properties and glean their secrets. All this work and its necessary context will be presented below. Much more could be said on the topic of penumbral microjets at this point, but for now this appetizer will have to suffice.
Introduction

lest I repeat myself unnecessarily. Before moving onto the thesis-proper, I will give a summary of what lies ahead for the reader.

Perhaps to little surprise, we will begin with that one thing that all our lives must by necessity revolve around, the Sun. In Chapter 1, I will attempt to provide a brief examination of our nearest star. Sol is our convenient laboratory of extremes, and it provides us with invaluable insight into physical processes we could not hope to reproduce in either scale of space or in magnitudes of energy down on Earth. In this chapter, I will first offer a general tour both into and across the nuclear furnace that we orbit, before I will then steer us on to specifics. In particular, I will focus on and examine in greater detail the atmosphere that envelopes our Sun. I will review both the different processes that take place there, and we will explore what different layers it can be divided into. I will then turn to the peculiarities of a large-scale solar phenomenon of special interest for this thesis; Active Regions are areas of particularly extreme conditions on the Sun and are hosts to sunspots. As we know, we also find the ultimate objects of our interests in sunspots, so they are of particular importance in the context of this thesis. As such, Active Regions and sunspots deserve some special attention before we move on.

Having satisfied our curiosity with regards to the venue of our drama, we will then turn to both the proverbial and the literal how of the observations that were utilized in this thesis. We will elucidate such questions in Chapter 2, where I will examine the practicalities of how we can observe our nearest star and its going-ons using telescopes and their various instruments. After some generalities, we will take a look at the two specific telescopes that were vital to this thesis’ work. We will first examine our most extensively utilized telescope, the Swedish 1-m Solar Telescope, or SST, situated on the sometimes-warm and sometimes-chilly mountain-top of Roque de los Muchachos, which is found on the subtropical island of La Palma. We then take a peek at the Interface Region Imaging Spectrograph, or IRIS, which resides in low Earth orbit, and which in contrast to Roque de los Muchachos has a more stable temperature of always-very-chilly.

At length, we will then squint and examine objects near the smallest of scales that we can observe on the Sun. Of course, these are our penumbral microjets, the protagonists of this work. In Chapter 3 we examine these brief flashes of heated plasma. In this chapter, I will review the history around their discovery and study, and I will attempt to present a rather comprehensive overview of our current understanding surrounding them.

In the last chapter-proper, armed and girded with the required background, we will finally turn to the original research that forms the backbone of this thesis. In Chapter 4, I will provide a detailed overview of this research by introducing each of the different publications in which it culminated. Furthermore, this chapter also provides some additional context for the motivations behind these papers and how they came about. After this, all that remains are the publications themselves, which are reproduced in full at the very end of this thesis.

With our roadmap laid out and with no further ado, let us continue onwards. There is much metaphorical ground to cover.
Chapter 1

The Sun

1.1 The Sun - a brief history and overview

The Sun began its life as a molecular cloud of dust approximately 4.6 billion years ago. Over time, the cloud began to coalesce around a clump in the gas caused by some lucky perturbation. Compacting over time, the cloud also began to swirl with a preferred horizontal plane because the system as a whole had to conserve its angular momentum. All the while, the central mass began to accrete and grow in earnest. Further out from the central mass, smaller perturbations in the gas allowed for lesser accretions of mass to occur. These eventually gave rise to the other large bodies of the solar system, Earth included. At long last, the Sun accumulated enough material to collapse into a spherical mass, and its temperature began to rise as potential gravitational energy was transformed into thermal energy; with the enormous pressure of the outer layers of the proto-Sun pressing down on the ones below, the core of the proto-Sun became severely compacted, forcing hydrogen nuclei into ever closer proximity while being heated more and more. Reaching a final threshold, the temperature and pressure finally reached such extremes that fusion of hydrogen began, halting the collapse of the proto-Sun as the radiation pressure of the fusion process began to counteract the force of gravity. At this point, the Sun turned into a star-proper at last.

Thus, the Sun is defined both at its proverbial and at its literal core by the nuclear fusion that it hosts. Due to the immense pressure of the outer layers of the Sun, the conditions at the core of the Sun are extreme enough for nuclear fusion to occur. The least massive element on the periodic table, hydrogen, is fused into the second least massive element, Helium. All energy released from the Sun can ultimately be traced back to this process; gravity compacts matter until its fusion releases energy as radiation. The nuclear fusion process in the Sun’s core takes place through one of three multi-tiered processes of elemental particle interaction (though one is by far the most common) that ultimately releases excess energy according to Einstein’s famous equation, \( E = mc^2 \). Here, the energy released, \( E \), is determined by the difference in the mass, \( m \), between the starting ingredients, the by-products, and ultimately, the end-products. The mass-energy conversion is mediated by the constant conversion factor, \( c \), the universal speed limit of the natural world, which is also the speed of light.

In simple terms and side-stepping the complex processes under which fusion happens in practice, the theoretical sum of four hydrogen atom masses comes out to more than the actual mass of one Helium atom, and thus fusion provides a surplus of mass that is converted and released as an equivalent amount of energy in the form of electromagnetic radiation and the emission of neutrinos (neutrinos however interact so weakly with ordinary matter that they promptly escape the core and then the star altogether). This, and the fact that this principle also holds true for other, heavier, elements makes star formation possible. Ultimately, by extension, fusion processes give rise to the universe.
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as we observe it today - a place that hosts a multitude of light-emitting stars.

In our own humble Sun, only the fusion of hydrogen is currently taking place, although it will turn to other fusion processes in the distant future. Due to the high temperature in the interior of the Sun, the atomic nuclei found there are not bound to their usual compatriots, electrons, and nuclei comprised of protons and neutrons intermingle with electrons in a fluid-like state, called plasma. Thus, the actual fusion taking place at the Sun’s core is more precisely that of hydrogen nuclei, consisting of lone protons, into Helium nuclei, consisting of two protons and two neutrons. As alluded to, the fusion of protons only takes place under extraordinary circumstances. This is in part due to the electrostatic repulsion that normally keeps protons apart, caused by the positive charge that the lone protons possess (since they are already stripped of their electron companions by the high temperature of the compressed solar core). When protons are crowded together in the core of the Sun in such great densities that their mutual electrostatic repulsion can be overcome, fusion can occur. These conditions are met in the Sun’s core due to the monumental pressure provided by the force of gravity; the Sun’s mass in the outer layers compress its central core, forcing the core’s hydrogen atoms together. However, the radiation emitted by the fusion processes in the Sun’s core provides a radiation pressure that counteracts the gravitational pressure. This radiation pressure pushes against the force of gravity that tries to further compact the Sun; these two forces are thus locked in an evenly matched struggle within the Sun, fought over billions of years, with gravity ever trying to compact the Sun to the smallest size possible, while the radiation pressure in turn tries to scatter the Sun’s mass across the void. This balancing of forces is expressed in the state of hydrostatic equilibrium which the Sun settled into once fusion began. This means that today, on human time-scales, the Sun neither contracts further, nor does it expel relatively large amounts of its mass across the solar system. At the moment, it is content with slowly emitting some excess mass as solar wind and excess electromagnetic radiation as light.

After the Sun’s internal equilibrium was reached, all other dynamics of the Sun such as we observe them today could begin to establish themselves. At this point in time, the Sun entered the main-sequence phase of its lifetime, much like other stars of the same kind. This is the Sun we study with our telescopes today by way of the light it emits; ultimately released at the Sun’s core, the Sun’s energy takes an adventurous journey through the interior of the Sun, where it scatters as light and interacts with the plasma through a myriad of physical processes. Energy released at the Sun’s core may take thousands of years to reach its surface. Ultimately, it passes the final gauntlet, the outer layers of the Sun; here, the Sun’s plasma becomes thin enough for light to pass through it unhindered, and here we find the solar atmosphere. Different wavelengths of light interact differently with plasma at different heights of the solar atmosphere because conditions differ with height. Thus, from the light emitted by the solar atmosphere we may learn many a thing about the solar atmosphere itself. By inference, we can also learn about deeper layers of the Sun by way of their effects on the layers above. Since the objects studied in this thesis, penumbral microjets, reside in the solar atmosphere, we will examine the solar atmosphere in more detail in the following sections, and this will be the primary focus of this chapter.
1.2 The solar atmosphere (and how to unravel it)

Akin to what we find for Earth and our own atmosphere, the atmosphere of the Sun constitutes its outermost part and it permits light to pass through it to varying degrees. Another commonality of the Earth’s and the Sun’s atmosphere is that neither are as simple as they may appear at first glance. A difference however is that not only is the intrepid solar physicist faced with the challenge of unravelling the solar atmosphere’s bewildering complexity, but that this is further complicated by the fact that we cannot observe the solar atmosphere from the inside. In this regard, climatologists studying the Earth’s atmosphere have an advantage that solar physicists do not when it comes to their place of work. Even though this state of affairs probably is for the best where the health of solar physicists is concerned, it is still something that must be contended with. More details on how the solar atmosphere is observed in practice and how this problem is mitigated will be explored in Chapter 2. There, I will examine how the sun is observed and present the telescopes most relevant to this thesis. Taking a more positive view, the study of the Sun luckily still provides us with a lot more readily available observations than what is available to stellar physicists, who have to make do with much less in their study of more distant stars. Due to the distances involved, other stars are not observable as objects with any physical extension and appear as mere point sources. In stark contrast, the Sun blots out all others stars with its glare and presents itself as an extended disk during daytime. As a consequence, the Sun’s atmosphere is the only stellar atmosphere for which we can observe any dynamics directly. The study of the solar atmosphere is thus not only a way to understand our own particular favourite star, but also provides us with a way to make inferences about the atmospheres of other stars in the universe for which we cannot make any such direct observations.

The complexity of the Sun’s atmosphere is traceable to the extreme processes that power the Sun, as I sketched out in very broad terms in the introductory section to this chapter. After all, the physics of the solar interior must ultimately dictate the formation and the behaviour of the atmosphere that envelopes it. This last point may seem trivial, but its implications are also vital in understanding the Sun and its atmosphere. The Sun itself is indifferent to the well-meaning scientist that carves it into different layers. This holds true for both the partitioning of the solar interior and the solar atmosphere. When compared to the present-day, earlier investigations of the formation and evolution of the solar atmosphere had to simplify whatever problems arose to a much greater degree than we are forced to today, even though approximations are still inescapable. Broad regimes of solar heights with somewhat uniform temperatures and other observables, or those regions dominated by specific physical processes, were simplified to semi-separate entities that only interact at discrete boundaries. Such simplifications are, of course, not in accordance with nature and its lacking obligation to adhere to any rigid nomenclature. These sort of assumptions and approximations were nonetheless vital stepping stones in the formation of our collective understanding of the Sun’s atmosphere. Of course, more often than not, they were also a simple necessity. This was due to a number of reasons. First, our ever-developing theoretical understanding of various physical processes has been steadily refined over the years, and second, the creation of more dynamic numerical models of the solar atmosphere was constrained by the past’s technical limitations on both observations, computing power and the limitations of numerical models. Limited
observations of the real dynamics taking place in the solar atmosphere were a requisite to create and evaluate the validity any numerical models and their outputs, and the computing power and the complexity of the simulations limited the ability to mimic and shed light on any actually observed dynamics.

Today, the solar atmosphere is increasingly understood to be both highly dynamic and to be a highly interacting system. Through advances in both observations and in 3D numerical modelling, distinctions between different atmospheric layers have become as fluid as the plasma that is being studied and modelled. In solar physics, the processes that are being studied are of such extreme character and operate over such large scales in both space and magnitudes that experiments designed to replicate such conditions in a laboratory on Earth are largely unfeasible. Experiments such as those performed on high-energy plasmas, such as in the study of hydrogen fusion for the development of Tokamak-reactors, which constrain physical theories are helpful. However, given both the energy and spatial scales of the solar atmosphere, the only physical “laboratory” we truly have at our disposal is the Sun and its atmosphere itself. Of course, numerical models and simulations of that same atmosphere are also available, but these must necessarily be constrained and tested against the real solar atmosphere. Given our predicament that we cannot reproduce a true miniature Sun in a laboratory, numerical models and simulations of the solar atmosphere provide us with invaluable opportunity to either formulate simplified models that match observations congruent with the real Sun in the sky, or indeed to create virtual simulacra which we can study at our leisure. Thus, we can establish a back-and-forth in which we compare actual observations of the solar atmosphere with artificial observations derived from our numerical models, and this provides us with an indirect approach through which we can study whether the physics we implement in simulations correspond to those in the real solar atmosphere. In turn, discrepancies between true and simulated observation of the solar atmosphere tell us that we are either limited by our algorithms or their technical implementation or, more interestingly, by our understanding of the relevant physics played out on the Sun. Because numerical models have been so influential and vital in our increasing understanding of the solar atmosphere, I will first outline some points about two of their classes in subsection 1.2.1 below. Discussing ways in which the solar atmosphere’s dynamics are studied before turning to how we actually divide the solar atmosphere into different layers may seem counter-intuitive, but in reviewing how a thing is studied before giving a summary of the inner workings of the thing itself, we may find a greater appreciation for the way we talk about it. Thus, in 1.3 we then discuss the criteria and motivations for dividing the solar atmosphere into different layers, and will also finally discuss the separate atmospheric layers themselves; we discuss the photosphere in Sect. 1.3.1, the chromosphere in Sect. 1.3.2 and discuss the transition region and the corona in tandem in Sect. 1.3.3.

Lastly before continuing onwards, I want to make a note of the literature that had the most influence in the writing of the following sections. In the writing of this chapter, general values and facts have been drawn from a variety of sources, with especially specific instances cited where appropriate. However, for further reading and deeper dives into the subject matter at hand, I direct the reader to these more general sources of information I will list here. For a general overview of stars in general and the Sun and its properties in particular, the relevant chapter(s) in An introduction to modern
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*astrophysics and cosmology* (Carroll and Ostlie 2006) are an excellent resource, and were also referenced for writing this chapter. For an overview of the solar atmosphere’s layers and their properties, especially from the viewpoint as how they are described in terms of 1D and 3D modeling, the excellent book *The Sun as a Guide to Stellar Physics* (Engvold, Vial, and Skumanich 2019) is a particularly informative read. This book was of particular use as a reference for the writing of Sect. 1.2.1. For a deep dive on the newest developments in the study of the solar chromosphere, the Annual Review publication “New View of the Solar Chromosphere” (Carlsson, De Pontieu, and Hansteen 2019) is also well-worth a read, and was of great help in untangling the solar chromosphere for Sect. 1.3. The solar atmosphere is described in the context of magneto hydrodynamics in all of its glorious complexity in *Magnetohydrodynamics of the Sun* (Priest 2014). It is a daunting read, but well worth the effort. Particularly Sect. 1.4 benefited much from its perusal.

### 1.2.1 Modelling and simulating the solar atmosphere

Although this thesis does not directly employ nor expand on the numerical modelling of the solar atmosphere, like all modern solar physics research, it tremendously benefited from and relied on both the early and the more recent results derived from such models. Solar atmospheric temperature profiles and information at which heights specific spectral lines are formed in the solar atmosphere were both established during the early days of numerical modelling (though refined in later times), and were vital for the work in this thesis. As observations obtained by the IRIS satellite feature heavily in parts of this thesis, the formation heights and the formation conditions of spectral lines observed by IRIS were of particular importance to this thesis as well; these were obtained through more recent and more advanced solar atmospheric modelling, and were absolutely crucial to the work in this thesis. It is thus fitting to briefly mention the two most influential types of solar atmospheric numerical-modelling developed over the years and to discuss some of their properties. Furthermore, an excursion into the story of how the solar atmosphere has been described and studied in terms of numerics is also illuminating in terms of the types of physics that are important in the solar atmosphere. After this, we will be more knowledgable in how results obtained from these efforts inform our understanding of the different layers of the solar atmosphere.

#### 1.2.1.1 1D Semi-empirical models

To this day, when discussing time and (horizontally) space averaged temperature profiles and the average depths from which specific spectral lines or wavelengths of radiation emerge from the solar atmosphere, their values are often based on 1D numerical models. These models assume that the solar atmosphere is plane-parallel and as the name implies, they only describe the variations of the solar atmosphere with height and not along the other spatial dimensions. For these models therefore, there is the implicit simplification that there is no variation along the solar horizontal plane in terms of physical processes or temperature, or this variation is baked-in by approximations. Of course, while this simplification is not actually the case in practice, on average the variability in physical parameters (such as temperature, pressure and the magnetic field strength) do in fact
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Figure 1.1: Average 1D temperature distribution for the quiet Sun, with approximate ranges for the formation heights of different continua and spectra lines indicated. First presented in and reproduced from Vernazza, Avrett, and Loeser 1981.

vary to a much greater degree with vertical height rather than on the horizontal plane. For this reason, these types of models can still provide us with very valuable insights into the solar atmosphere, in particular into the solar atmosphere averaged over time and (horizontal-) space.

The 1D models were very important in forming our current understanding of the solar atmosphere. Most prominent in the context of solar (as opposed to stellar) physics are the so-called semi-empirical (SE) 1D models. In SE 1D solar atmospheric models, a temperature profile of the solar atmosphere along its height is used to calculate a theoretical spectrum of electromagnetic radiation that would be emitted by an atmosphere with such an atmospheric profile. This synthetic emission spectrum is then compared against that derived from observations, and the degree of the match between the two is quantified. Then, the initial model atmosphere is adjusted, and the process is repeated. Each new synthetic solar spectrum corresponding to a new model atmosphere
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is then iteratively checked against the observed solar spectrum until the fit between the two no longer improves and a best fit is found. In these semi-empirical models, the theoretical spectra are calculated using Non-Local Thermodynamic Equilibrium (NLTE) radiative transfer equations. Since the temperature profiles in the 1D SE models are found in an iterative fashion, it is evident that no actual simulation of any of the heating processes that actually lead to the model temperature profile is actually undertaken. As such, such modelling provides a temperature stratification of the solar atmosphere that is consistent with the observed spectra, but it can not provide any direct insights into the dynamical physical processes that may actually produce such a temperature profile. However, the models can provide us with estimates for the amount of heating that is necessary to produce the resultant temperature profile, since the need heating is associated with the amount of radiation that is emitted by the synthetic solar atmosphere. The emitted spectrum can in turn be compared to the spectrum that we actually observe. The most widely used, and the most famous, 1D SE model is the VAL3C model, so called for Vernazza, Avrett and Loeser, who first introduced its first iteration in the series of papers, Vernazza, Avrett, and Loeser 1973, Vernazza, Avrett, and Loeser 1976 and Vernazza, Avrett, and Loeser 1981. It, along with its successors that improved upon it over the years is still of great importance in solar physics today. The radiation output from the VALC3C model corresponds very well with the relevant spectra from the quiet Sun when averaged over time an space. In Fig. 1.1, the original VALC temperature profile of the solar atmosphere is reproduced from Vernazza, Avrett, and Loeser 1981.

There are a few key limitations to 1D SE models however. Different temperature profiles can produce the same or similar spectra that match observations, and the explanatory power of semi-empirical 1D models is therefore limited because the problem of which temperature profiles match which type of spectra is degenerate, i.e. there is more than one mathematically valid temperature profile that matches a given spectrum. Without further observations or experiments, we therefore cannot tell which is the one found in the actual solar atmosphere, although there are ways to mitigate this. Another clear issue with the SE 1D models is that the actual solar atmosphere is dynamic over both short and long time scales and over large and small spatial scales, and the 1D SE time-averaged temperature profile derived from time and space averaged spectra only corresponds to a time- and space-averaged spectrum of the solar atmosphere. Furthermore, the real solar atmosphere hosts a bewildering array of transient phenomena that impact the properties of the time- and space-averaged “canonical solar atmosphere” that we study when interpreting simplified SE 1D models. Phenomena ranging from smaller scale events such as spicules (although ubiquitous) to larger scale phenomena such as prominences and the myriad of others that exist, all impact the solar atmosphere in a staggering amount of ways. Slow and fast events all contribute or have an impact on the various heating processes in the atmosphere, and also affect the magnetic setting of their surroundings. Thus, local and time-constrained events shape the time- and space- averaged solar atmosphere - even though these events cannot be distinguished or observed in time- and space-averaged spectra. Thus, because these processes and phenomena are not directly observable through time- or space- averaged parameters, yet still impact the actual average heating and behaviour of the solar atmosphere, it is important to go beyond the earlier models and attempt not only to model or parametrize the solar atmosphere, but to simulate it in earnest.
1. The Sun

1.2.1.2 Magnetohydrodynamic simulations

In more recent years, largely due to a steady increase in computational power and innovations in the algorithmic underpinnings of numerical modelling, it has become possible to mimic the nature of the solar atmosphere to a greater degree. Furthermore, due to results from improved models and the observations from next-generation telescopes both on the ground and in space, it has become ever-more evident that while it can be advantageous to focus on different aspects of the solar atmosphere in isolation, that the solar atmosphere is a strongly interacting and inter-dependent system. As such, we arrive at the currently most advanced attempts to describe the solar atmosphere as a whole: 3D magnetohydrodynamic (MHD) simulations. The most comprehensive simulations of the evolving solar atmosphere are currently provided by MHD simulations, and in contrast to the 1D semi-empirical models, not only do these models account for all 3 spatial dimensions, but they also simulate key aspects of the actual dynamics of the atmosphere through time.

MHD simulations operate on the basis of explicitly combining the physics of 1), electrodynamics by way of Maxwell’s equations and Ohm’s law which describe the motions and behaviour of charged particles, with 2), the physics of hydrodynamics which are needed to describe the motion of gases and fluids by way of a gas law, the principle of conservation of mass, and equations governing the plasma’s motion and energy exchange. Thus we get magnetohydrodynamics. A full treatment of MHD is far beyond the scope of this thesis, and I aim only to give a brief overview of it in order to illustrate the current trend towards finer granularity and more detailed descriptions of the solar atmosphere. In contrast to the 1D SE models outlined above, the actual simulation of physical processes in 3D MHD simulations means that they can in fact be used for **predictive** rather than only **descriptive** purposes, of which only the latter is true for the 1D SE models. Here, I will only point to the main building blocks that go into an MHD solver; in essence, an MHD simulator will describe the physical system at hand by way of a set of inter-dependent differential equations that describe the dynamics and energetics of the solar atmospheric plasma. A given simulation is performed in a 3D virtual box that aims to simulate a relatively speaking small part of the solar atmosphere. Much simplified, during a simulation run the set of aforementioned partial differential equations describing the plasma dynamics in the magnetohydrodynamic framework are evaluated at every point in the simulation box, and then advanced forward in time by a given time-step. Of course, the simulation is also initialized with given start-parameters, such as the plasma density with height and the magnetic field strength throughout the box. Boundary conditions must also be defined. The boundary conditions are dictated by the assumptions that are placed on the solar interior that lies under the solar atmosphere, how the upper boundary in space is treated, and how the in-flow and out-flow of plasma is treated at the sides of the simulation box. The specific form of the MHD equations used in a simulation depend on the specific MHD code-implementation at hand, and can take somewhat different forms depending on their formulation.

Following the same convention and layout as in **Gudiksen et al. 2011** (in which the advanced MHD code BIFROST was first described), these equations can be formulated
The solar atmosphere (and how to unravel it)

as:

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{u} \quad (1.1)
\]

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} = -\nabla \cdot (\rho \mathbf{u} \mathbf{u} - \tau) - \nabla P + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} \quad (1.2)
\]

\[
\mu \mathbf{J} = \nabla \times \mathbf{B} \quad (1.3)
\]

\[
\mathbf{E} = \eta \mathbf{J} - \mathbf{u} \times \mathbf{B} \quad (1.4)
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \quad (1.5)
\]

\[
\frac{\partial e}{\partial t} = -\nabla \cdot e \mathbf{u} - P \nabla \cdot \mathbf{u} + Q \quad (1.6)
\]

Here, \( \rho, \mathbf{u}, e \) and \( \mathbf{B} \) are the density, the velocity vector, the internal energy per unit volume and the magnetic flux density vector respectively, while \( \tau, P, \mathbf{J}, \mathbf{g}, \mu, \mathbf{E} \) and \( \eta \) are the stress tensor, the gas pressure, the electric current density vector, the gravitational acceleration, the vacuum permeability, the electric field vector and the magnetic diffusivity respectively. The last term, \( Q \), may contain different terms, corresponding to the specific equation of state (EOS) chosen for the experiment, or a term for the Spitzer thermal conductivity or a term for the radiative transfer, among others - depending on the experimental setup. This set of equations requires that one defines a specific equation of state, as alluded to. In the simplest case, this may correspond to the ideal gas law, but may be more complicated, and include more complex physical effects.

This set of equations, as given from top to bottom in the above, describe the following:

(2.1) The mass continuity equation, which expresses that the amount of mass is constant;

(2.2) The momentum equation, or alternatively the equation of motion, describing the motion of the plasma, and where the \( \mathbf{J} \times \mathbf{B} \) is the Lorentz force;

(2.3) Ampere’s Law, which describes the relationship between the current density and the magnetic field, and in this case it is formulated as the non-relativistic simplification;

(2.4) Derived from Ohm’s law, this equations describes the effect of the electric field on the plasma, detailing two types of interactions - when the plasma is at rest and when plasma is in motion;

(2.5) This is a formulation of Maxwell’s equation or alternatively Faraday’s Law, which describes the induction of electric fields by varying magnetic fields;

(2.6) The last equation describes the energy balance, meaning the energy flux and the mechanical work, as well as the extra heating or cooling terms that are contained in the term \( Q \).
1. The Sun

The listing of these equations is not meant to represent a rigorous explanation of the MHD simulation process, but aims only to demonstrate its explicit nature - MHD simulations aim to reproduce the physical processes that take place in the solar atmosphere, which in turn should spontaneously reproduce the behaviour we observe for the real atmosphere if the simulation is accurate. As mentioned above, and as known from the 1D SE models and observations, the solar atmosphere exhibits tremendous differences in the characteristic mass densities and temperatures at different heights. The plasma's mass density drops dramatically from the lower boundary of the solar atmosphere, where it has a value of about $10^{-4}$ kg/m$^3$ to the lower part of the Corona, where it is about $10^{-13}$ kg/m$^3$, a difference of nine orders of magnitudes. In inverse, the temperature rises dramatically from the lower atmosphere where it has a minimum of about 4000 K to the Corona where it reaches values in excess of 1 Million K, a difference of three orders of magnitude. The strength of the magnetic field in the solar atmosphere also varies strongly from specific locations, such as sunspots versus the less-active “quiet” parts of the Sun; at the bottom of the solar atmosphere, the strongest magnetic field strength ever recorded for the largest sunspots is a little above 6000 Gauss, although 2000 – 4000 Gauss is more typical, whereas the magnetic field strength in the quiet Sun reaches only values on the order of a 100 Gauss, with field concentrations appearing in a non-uniform patchwork pattern. Furthermore, the magnetic field attenuates and disperses with height, decreasing exponentially. Moreover, the solar atmosphere spans over several megameters in height, but we also observe dynamic behaviour in the solar atmosphere on length scales down to the resolution limits of our current telescopes, which is on the order of tens of kilometres, while other phenomena appear on the scales of megameters. All in all, this enumeration of the incredibly wide parameter space is meant to illustrate that the solar atmosphere when viewed as whole presents profound difficulties when trying to simulate it; computational precision becomes all the more difficult to achieve the wider the range of values that are being considered, and less simplifications and approximations in ones approach are valid the greater the range of physical regimes that is being considered. For this reason, the first MHD codes tended to focus on specific parts of the solar atmosphere, such as the photosphere, thus limiting the need to consider the numerically expensive calculations spanning such a wide range of values in parameters. Now, with increasingly more sophisticated numerical methods that adapt to the different scales being considered with regards to for example small-scale turbulence, energy dissipation and steep gradients at small spatial scales, as well as with advances in the descriptions of the physical processes being considered, MHD simulations that span the entirety of the solar atmosphere are becoming not only more feasible, but also increasingly more accurate in their descriptions.

With the two major ways of numerically simulating and describing the solar atmosphere in mind, let us now turn to an actual summary of the solar atmosphere’s properties next.

1.3 The layers of the solar atmosphere

The Sun’s atmosphere is host to a great variety of physical processes and extremes. Above all, it is characterized by a bewildering variety of both different types of dynamics
The layers of the solar atmosphere

(a) A proverbial textbook schematic of the solar atmospheric layers with discrete boundaries for the different atmospheric layers indicated. Approximate heights and approximate regions for different $\beta$ parameter values are also indicated ($\beta$ is the ratio of the gas pressure over the magnetic pressure in the plasma).

(b) A greyscale temperature map, depicting a slice through the $x$-$z$ plane of a snapshot of a BIFROST solar atmosphere simulation. Lighter values indicate higher temperatures, and $\beta$ parameter value-boundaries are indicated. Reproduced from Fig. 3 in Carlsson, De Pontieu, and Hansteen 2019.

Figure 1.2: Two depictions of the solar atmosphere.

and statistical regimes in terms of its thermodynamics and radiative properties, which all determine its evolution and its appearance. Viewing the disk of the Sun “from above”,

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we can observe distinct dynamics and large-scale physical processes vary substantially.

However, while we find great variability in conditions at different heights of the solar atmosphere, they are also more predictable with regards to height. This is due to the fact that different regions of height in the atmosphere correlate to distinct regimes in which different physical processes and dynamics dominate. Here, I will paint a few pictures depicting the different layers of the solar atmosphere. For the most part, I will do so with a broad brush. I will call out specific points of interest, but otherwise these summaries will be of a rather general nature.

As mentioned previously, the solar atmosphere consists of three to four layers, depending a little on one’s tastes. These layers are the photosphere, the chromosphere, the transition region, and the corona. The latter two may be hard to disentangle, and are at the very least often discussed in tandem, even though they are generally considered distinct layers. The different layers are primarily defined by the plasma density, the temperature, the plasma’s degree of ionization, and perhaps most important of all, what sort of physical processes, dynamics and what mode of energy transfer dominates in the layer. What sort of physical process dominates the motion of the plasma and the validity of certain statistical approximations for the radiative transfer and the thermodynamics of the plasma are key in how we view and constrain the different layers of the solar atmosphere. This sort of statistical view of the different layers also makes it obvious that the borders between them cannot be overly discrete - the transition between different statistical regimes can by its very nature not be determined down to an arbitrarily sharp boundary. Thus, neither can the atmospheric layers. In the subsections below, each of the solar atmospheric layers will be described with the help of both the time-averaged profiles with height as obtained through 1D SE models, and we will examine the average values of physical parameters such as the temperature, mass-densities and magnetic-field strengths as are typically found in the different layers. However, we will also discuss results from MHD simulations that shed light on the dynamics and how these inform our knowledge of the statistics of the solar atmosphere. Especially the way that the gas pressure and the magnetic pressure interact is important in descriptions of the solar atmosphere, as it determines much of the plasma dynamics, and we have gained invaluable insight into these processes from MHD simulations. Furthermore, both the question of which mode of energy transfer is dominant, as well as the interplay between different types of energy transfer in each layer is also of great interest, and this has been subject of intense focus through both observations and MHD simulations in recent years. Especially the mode of energy transfer from the photosphere and through the chromosphere and onwards to the corona has been of greater and greater interest, as all scenarios of energy transfer that seek to explain the infamous coronal heating problem must necessarily do so in a way that explains how this energy first moves through the chromosphere. With the discussion of the MHD simulations in mind, the descriptions below will once again underscore the importance of such advanced modelling efforts. This is especially so since the transitions between different kind of regimes in the solar atmosphere are highly complex, and can only be truly understood in a dynamic context.

With the above in mind, and in order to prime the reader for what lies ahead, I have included a schematic representation of the solar atmosphere in Fig. 1.2. The illustration depicts the solar atmosphere as consisting of discrete layers, and this textbook depiction is akin to what one would find in any introductory astrophysics textbook that includes a
chapter on the Sun. Here, the “textbook” moniker is not a slight, and this schematic, which clearly depicts the simplified stratification of the solar atmosphere, is very useful to ground any more detailed discussion of it. For the reader somewhat unaccustomed to the solar atmosphere, I advise to refer back to it when perusing the following subsections on the individual atmospheric layers when our descriptions become more nuanced. In the schematic, we see first the solar interior that underlies the solar atmosphere as a whole, with the photosphere, chromosphere, the transition region, and finally the corona layered above, in that order. The approximate thicknesses indicated are also useful to ground the reader in the relative sizes of the layers. Also shown in the image are value-boundaries of the parameter $\beta$, which is the ratio of the plasma gas-pressure over the magnetic pressure, giving us a measure for which pressure dominates the other. This interplay will be discussed for the different layers below.

With this basic overview in mind, I will begin the description of the individual solar atmospheric layers with the photosphere, the lowest layer of the solar atmosphere, in Sect. 1.3.1. In Sect. 1.3.2 we examine the chromosphere that lies immediately above the photosphere, and in Sect. 1.3.3 we discuss both the transition region and the corona that lie atop the chromosphere.

### 1.3.1 The photosphere

One must first define the nebulous solar “surface” in order to speak of the solar atmosphere above it. This is necessary since there is no neat phase boundary between the atmosphere of the sun and its “surface” as there is for the Earth; on Earth, we find a rather clear distinction between its gaseous atmosphere and its earthen or watery surface. Colloquially, the solar surface is instead defined to lie at a height below which none or very little of the light that is emitted actually escapes into space. Reciprocally, this also gives us a definition for the beginning of the solar atmosphere, where most radiation does escape into space. In quantifiable terms, the solar surface is usually determined in relation to the reference height at which the optical depth at a wavelength of 500 nm takes the value of unity, or $\tau_{500\text{nm}} = 1$. With optical depth being a measure for the amount of radiation that is absorbed or scattered along the unit-less length $\tau$. An optical depth of $\tau_{500\text{nm}} = 1$ implies that the ratio of surviving photons at a wavelength of 500 nm is about $e^{-1} \approx 37\%$. This is still a rather significant amount, and it may therefore be more reasonable to define the border to the solar interior to lie a little deeper than this, in order to ensure that almost no radiation escapes from below the boundary. At $\tau_{500\text{nm}} = 10$ only $\approx 0.005\%$ of emitted radiation will escape the Sun, and such a depth may thus be a better boundary if the measure of opacity is used for a definition. However, given the rapid fall of the plasma density at these heights, the height difference between $\tau_{500\text{nm}} = 1$ and $\tau_{500\text{nm}} = 10$ is only about 100 km anyway. See Fig. 1.2 for the schematic depiction of the lower photospheric boundary.

Thus, we define the first layer of the solar atmosphere to begin above the solar surface: the photosphere. Its name is derived from “photos” and “sphaira”, greek for light and sphere respectively, giving us the poetic sphere of light. Above, we defined the solar surface to lie at about 100 km below the height at which the optical depth at a wavelength of 500 nm is $\tau_{500\text{nm}} = 1$. This is a convenient definition in terms of the plasma’s opacity - but what are the photosphere’s defining, intrinsic, characteristics?
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The photosphere is the source of the majority of the Sun’s light that reaches the Earth, and thus unsurprisingly, it shines mostly in the visible part of the spectrum, to which our eyes are adapted. The lower boundary of the photosphere also marks the sharp boundary that we see by-eye when viewing the Sun (which is ill-advised without proper eye-protection), which of course corresponds well to our definition of the boundary between the solar surface and the atmosphere above. From the Sun’s core and outwards through its interior, the temperature decreases the further out one gets from the nuclear fusion that provides the Sun’s heat. Spatially averaged (across the x-y plane) and in terms of its 1D temperature profile with height, the photosphere continues this trend and its temperature continues to fall with increasing height. This trend is observable all along the photosphere’s height of approximately 500 km. Near its lower boundary, at around $\tau_{500\text{nm}} = 1$, the photosphere is at a temperature of about 6000 – 7000 K, and the temperature decreases to about 4000 – 5000 K at its upper boundary. The effective temperature of the Sun is approximately 5777 K, and consequently most of the solar flux originates from within the photosphere. This continued temperature decrease with height is in good accordance with the naive expectation one would have for an idealized solid sphere that is heated at its core - on average, the temperature at any given distance from the Sun’s core ought to be lower than at points below it, simply due to the volumetric dilution of heat as it is dispersed outward through the plasma. However, counter to intuition, this is not the case for the atmospheric layers above the photosphere, as was already discernible to the astute reader when inspecting the 1D SE VALC temperature model, shown in Fig. 1.1. In the figure, the steady decrease of the temperature in the photosphere is clearly visible, with the more complicated rise of the temperature in the layers above also evident. Before discussing the why behind this puzzling behaviour, this does at least provide us with a rather simple definition for the upper boundary of the photosphere. As such, before even having to discuss the various dynamics that dominate the photosphere, we can define the photosphere’s upper boundary by the temperature minimum we find at its apex. Above this height, the spatially averaged temperature begins to increase with height, rather than decrease.

Why however, does the photosphere follow our intuitive expectation that the temperature should fall as we move outwards in the Sun, while the layers above do not? The answer lies in the mode of energy transfer that takes place in the plasma of the different layers. In the deep parts of the photosphere, the primary mode of energy transfer is that of convective motions, or movement of hot plasma. In its upper parts, energy is mostly transported by radiation. Most importantly, the photosphere is in statistical local thermodynamic equilibrium (LTE) and in radiative equilibrium (RE); this implies that any given volume of plasma radiates as much energy as it receives, and that emitted radiation does not affect the plasma far from the point of its emission before interacting with matter again. If one imagines infinitesimally thin spherical shells at increasing heights in the solar atmosphere, each imaginary “shell” thus receives and radiates less energy per area, because the area of each shell increases with height. Thus, also the temperature must decrease with increasing height. At heights above the photosphere, the validity of RE breaks down because the plasma density falls rapidly with height, and radiation is carried farther and farther before it interacts with plasma, or just escapes the Sun entirely. This also means that at heights above the photosphere, processes other than radiative energy transfer must dominate in the exchange of energy.
The layers of the solar atmosphere

in order to explain the *increase* in temperature at these heights. This will be discussed for the layers higher up in the atmosphere in the subsections below.

Another feature of the photosphere that is both interesting and important for its behaviour, is the fact that it is the region in the solar atmosphere where the amount of hydrogen that is ionized is at a minimum. This happens due to the reversal in the temperature profile discussed above. In the lower parts of the photosphere, hydrogen ionization increases downwards into the hotter interior of the Sun, since electrons are less likely to remain attached to their hydrogen protons with the increasing temperature. Upwards in the photosphere however, the ionization of hydrogen decreases, since the temperature drops towards the atmospheric temperature minimum that marks the photosphere’s upper bound. At the top of the photosphere and around the region of the temperature minimum, the hydrogen ionization is at its lowest with an ionization ratio of around $10^{-5}$. After the temperature minimum, the degree of ionization increases again, and this becomes very important in the chromosphere and for its dynamics, which will be discussed in the next section. The fact that the ratio of ionization is low in the photosphere (and that it is higher in the chromosphere) also has strong implications for accurate MHD simulations of the layer; the greater the ionization in a plasma, the less accurate the plasma can be described as a single fluid, because there is a significant amount of both neutral particles and charged ones, the dynamics of which differ. If the plasma’s gas-pressure is high enough, neutral and charged particles will still largely act as a single fluid however, because they interact strongly through collisions, and “drag” each other along. Since hydrogen in the photosphere is largely non-ionized, and because the pressure is sufficiently large, a single-fluid description typically works well in the photosphere for MHD simulations. In atmospheric layers higher up, due to the degree of ionization or the lower gas-pressure, such a straight-forward description may not always be accurate.

When speaking of the plasma dynamics in the solar atmosphere, there is a relation between two particular properties of the solar plasma that is of great significance, and it determines many of the plasma’s important behaviours. Furthermore, it also serves us well in further delineating between different layers of the atmosphere. This interplay takes place between the plasma’s pressure, or alternatively its density, and secondly, the magnetic field strength that permeates the plasma, or alternatively, the plasma’s magnetic pressure. To which degree one or the other affects the plasma, or how balanced their influence is, plays a vital role in its behaviour. This interplay is conveniently described by the parameter,

$$\beta = \frac{p}{B^2/(2\mu)}.$$  

The parameter $\beta$ is the ratio of the plasma gas pressure, $p$, and the magnetic pressure force, $B^2/(2\mu)$. The latter is itself comprised of the magnetic field strength, $B$ and the magnetic permeability in vacuum, $\mu$. As such, when $\beta > 1$ the gas pressure dominates the magnetic pressure, whereas reciprocally when, $\beta < 1$, the magnetic pressure dominates. For the photosphere, the gas density is generally high enough and in turn the magnetic pressure low enough, such that $\beta \gg 1$, and thus the gas motions dominate the magnetic field. The exception to this is in areas of particularly strong magnetic fields, such as they are found in so-called active regions, including pores and sunspots (active regions
1. The Sun

will be discussed separately in sect. 1.4). However, what does this interplay entail? The fact that the plasma gas pressure dominates the magnetic pressure is often colloquially described as “the magnetic field follows the plasma”. This, much simplified, generally means that any magnetic field lines emerging from the solar interior will follow the bulk movement of the plasma. This in turn heavily determines the structure and appearance of the photosphere. As mentioned, the lower part of the photosphere is dominated by convective energy transport. This is due to the convection flows from the solar interior that “bubble” up into the photosphere, such that hot plasma flows up to the solar surface, cools due to radiative energy losses, and flows back down again in channels between the hot up-flows. This creates the ubiquitous granules that characterize the vast majority of the Sun’s photospheric surface outside of active regions. Thus their granular pattern visually defines the lower photosphere. Granules have cross sections on the order of 700 km, with bright interiors corresponding to hot up-flows and darker intergranular lanes corresponding to the down-flows. Individual granules have lifetimes on the order of 10-20 minutes and exhibit flows with velocities of about 0.4 km s$^{-1}$. Since $\beta \gg 1$ in the photosphere, the magnetic field lines that appear from the solar interior are thus moved about by the solar granular pattern in the quiet Sun. The origin of the magnetic field that emerges into the solar atmosphere is created by the global solar dynamo. The global solar dynamo has its origin in the differing rotational speeds that the plasma moves at for differing distances from the solar poles, with velocities being the highest at the equator. The difference in speed of the large bulks of charged particles creates a global magnetic field. There may also exist a local dynamo that has its origin in the bulk movement of material in the convection zone of the Sun. In any case, the resulting magnetic field emerges at a granular scale in the quiet Sun with a field strength on the order of 100 Gauss, while it emerges in much greater concentrations in active regions, with typical field strengths of about 2000 – 4000 Gauss. In the quiet Sun of the photosphere these magnetic fields are then at the mercy of the plasma movements, as the gas pressure exceeds that of the magnetic pressure. Thus, magnetic fields in the quiet Sun typically concentrate in the intergranular lanes, leading to “bright points” at these concentrations. Here, the increase in magnetic field strength lowers the opacity somewhat (it is possible to see further through the plasma), and the observed bright points are the signatures of radiation originating from deeper in the atmosphere, where the plasma is hotter, and thus brighter.

The upper panel of Fig. 1.3 shows a snapshot of the quiet Sun at photospheric heights as it appears in the wide-band wavelength region of the Ca ii K spectral line. Both images in the figure were captured by the Swedish 1-m Solar Telescope (SST), located at the observatory of Roque de los Muchachos on the canary island of La Palma, during an observing campaign that I participated in. The SST is described in some detail in Chapter 2, Sect. 2.2.1, for the reason that it provided the majority of the observations employed in the original research of this thesis. For the present moment, it suffices to say that the SST is capable of observing the Sun at impressive spatial, spectral and temporal resolution. Since the amount of emission in different spectral lines is dependent on the temperature of the emitting plasma, the emission in different wavelength regions broadly originates from specific height-regimes of the solar atmosphere. This was already indicated for some spectral lines in Fig. 1.1, but this principle will also be discussed in Chapter 2. For our illustrative purposes and the inspection of Fig. 1.3, we
The layers of the solar atmosphere

Figure 1.3: The same region of the quiet Sun is shown in the top and bottom panels. The field of view covers approximately $59'' \times 37''$. The tick-mark separation is 1''. The scene was observed by the Swedish 1-m Solar Telescope on May 25, 2017. The top panel shows the FOV in the Ca $\Pi$ K wide-band, while the bottom was observed in the Ca $\Pi$ K line at a line-core offset of $-20$ km s$^{-1}$. The Ca $\Pi$ K line was observed by the CHROMIS instrument (for details, see Chapter 2; Sect. 2.2.1.4 in particular). The amount of emission at the two wavelengths is dependent on the temperature, and therefore the emitted light at these wavelengths originates from different heights in the solar atmosphere. The top panel thus highlights the appearance of the quiet Sun in the photosphere, while the bottom panel shows its appearance in the chromosphere. See the main text for further discussion.
1. The Sun

limit ourselves to two observations; the wide-band region of the Ca\,\textsc{ii} K line broadly corresponds to photospheric heights, and the wavelength in the wing of the Ca\,\textsc{ii} K line, at an offset of $-20\,\text{km}\,\text{s}^{-1}$ from the line core, corresponds broadly to the chromosphere, which is shown for the same field of view in the bottom panel. We will discuss the appearance of the chromosphere in the next section. For the upper panel of Fig. 1.3, we see many of the previously mentioned features of the photosphere; the granular pattern of the photosphere is obvious, appearing as bright cells with the dark intergranular lanes delineating them. Inside the intergranular lanes, the aforementioned bright points also clearly stand out in many places.

Now, with this parting glimpse of the actual photosphere behind us, we will turn to loftier heights, lest we linger too long in one place. Chronicling our continuing travel upwards in the solar atmosphere largely entails the study of how the different properties of the solar plasma that were just sketched out for the photosphere will evolve as we travel further up. Changes in the plasma density and thus the gas pressure, and in turn its changing relation to the magnetic pressure force, the increasing temperature upwards in the atmosphere, the changing degree of ionization and finally the modes of energy transfer all change with height. We thus move on to the chromosphere, perhaps the most dynamic of the solar atmospheric layers, and see how these properties evolve there.

1.3.2 The chromosphere

Defining the chromosphere could be as simple as stating that it is the layer that lies above the photosphere. However, this is tells us nothing new and is somewhat tautological; so, rather, let us pose the question - what chiefly characterizes the chromosphere? First, we may note that the chromosphere derives its name from the Greek “\textit{chroma}”, here meaning colour, and “\textit{sphaira}”, again for sphere, and thus we have our \textit{coloured sphere}. Normally, the chromosphere is not visible due to the photosphere’s much greater luminosity, and the chromosphere received its name because it is observable during solar eclipses as a red ring that lies above the photosphere. The red or pinkish colour of the chromosphere arises because the chromosphere’s output is dominated by emission in the H\ae line, which radiates in the red at a wavelength of $6563\,\text{Å}$. There is an observable characteristic of the chromosphere that is already known to us from the discussion on the modelling of the solar atmosphere and the 1D temperature profiles of the solar atmosphere in Fig. 1.1, and also touched upon the subsequent discussion of the photosphere; we know that the chromosphere has a temperature profile for which the temperature rises from a minimum of about $5000\,\text{K}$ at the boundary to the photosphere, to a maximum of about $10,000\,\text{K}$ at the boundary to the transition region. The chromosphere on average spans about $1500\,\text{km}$ or so, but again, any such measures of thickness will represent an average, and the actual solar atmosphere, and the chromosphere in particular, is very dynamic and has shifting boundaries. Due to the rise in temperature, the plasma continues to become increasingly ionized in the chromosphere. However, the energy input required for the ionization of the plasma also acts as a sort of heat sink, and a lot of energy transported from the photosphere into the chromosphere goes into this process rather than raising the temperature. Thus, the temperature rise in the chromosphere is not as dramatic as it would be without this effect, and a simplistic horizontally-averaged temperature profile rises at first quickly from the roughly $5000\,\text{K}$ temperature found
at the boundary between photosphere and chromosphere to about 7000 K or so. The temperature increase then only continues slowly, until it reaches around 10,000 K before it begins to increase dramatically as we enter the transition region layer and leave the chromosphere behind. The sudden increase of temperature also marks the point at which the ionization degree of the plasma increases to more significant levels, and this is no accident; in the upper chromosphere, the ionization of hydrogen reaches a sufficient amount that this process no longer absorbs as much heat as at lower heights, and the kinetic energy begins to rise instead, and consequently, the temperature shoots up dramatically.

However, why does the temperature of the chromosphere increase at all, and where does the energy that leads to this temperature increase come from? Ultimately of course, all energy in the chromosphere must come from the photosphere below it, which in turn is heated by the hot solar interior, which finally is heated by the Sun’s core. The main mechanisms that explain the rise in temperature above the photosphere are grounded in the fact that in the chromosphere the validity of the statistical measure of radiative equilibrium breaks down, and the chromosphere can no longer be assumed to be in local thermodynamic equilibrium (LTE); in the chromosphere the plasma density falls to such a degree that emitted photons and the gas are no longer strongly coupled through inelastic collisions, and thus photons reach further on average before they go through another interaction. Thus, photons effect the plasma properties in (statistically significantly) more distant parts of the atmosphere than under conditions of RE and LTE. Usually, the plasma in the chromosphere is still assumed to be in statistical equilibrium, which is typically approximately valid, even as the more restrictive measure of local thermodynamic equilibrium is no longer valid. This approach leads to the approximation of non-local thermodynamic equilibrium (non-LTE) descriptions of the chromosphere, which is especially useful in the context of MHD simulations. Without delving into specifics, while an assumption of LTE allows the explicit computation of population densities for different species of ions by way of the explicit Saha and Boltzmann equations, and for predictions of both the degree of ionization and the typical time scales for ionization/recombination (which LTE descriptions underestimate), non-LTE descriptions allow for the calculation of ionization rates that align more closely with observations, even though they are more computationally expensive and require a careful approach. In the quiet Sun, the energy that heats the chromosphere is thought to be primarily provided through acoustic waves that originate in the solar convection layers. These waves travel upwards, and as the density of the plasma falls, can form shocks. The shocks may then deposit kinetic energy in the surrounding chromosphere, heating the plasma and increasing the temperature at last. The specifics of this heating are under intense scrutiny and many different specific ways in which the heating takes place have been proposed and are under investigation.

Due to the basic hydrostatic equilibrium of the Sun, the density of the solar atmosphere continues to fall approximately exponentially as we travel through the heights of the chromosphere. Over the height of the chromosphere, the plasma’s mass density falls by around seven orders of magnitude, from about $10^{-4}\text{kg/m}^3$ to about $10^{-11}\text{kg/m}^3$. The attentive reader will note that this fall in mass density will affect the balance of power between the plasma’s gas pressure and the magnetic pressure force, measured by the previously introduced parameter $\beta$. However, another effect must be
taken into account. The magnetic field lines that originate from below the chromosphere also become less densely packed as they fan out with height; however, the magnetic pressure turns out to fall at a slower rate than the plasma’s gas pressure, and hence there is a point at which the magnetic pressure becomes equal to the gas pressure, before it in turn becomes greater. Thus, at the bottom of the chromosphere we still have $\beta > 1$, before there is a tenuous interface region at which $\beta = 1$, before the trend continues and we find that $\beta < 1$ in the upper chromosphere. In terms of dynamics we thus find that the chromosphere represents a transition in dominance of the mass motions of the plasma and that of the magnetic field; this is one of the defining features of the chromosphere, and informs much of its behaviour but also presents challenges in its description. It is also at and around the boundary of $\beta = 1$, where the plasma goes from being dominated by the gas pressure to the magnetic pressure, that acoustic waves from lower in the atmosphere can go through various processes and interact with the magnetic field. At the $\beta = 1$ boundary, the Alfvén speed (the speed of a transversal wave in the magnetic field) and the sound speed of the plasma are equal, and the acoustic waves can therefore undergo mode conversion, and be refracted or reflected at this boundary-surface. Here it may therefore be decided whether the waves carry onward towards the upper chromosphere and consequently the TR and beyond, or whether they may be reflected, depending on the specific conditions of the atmosphere. These processes, and how the acoustic waves carry energy upwards into the atmosphere and how these waves interact with the magnetic field is an area of intense study, with many unknowns remaining.

Due to the increase in ionization of hydrogen in the chromosphere and the decrease in plasma density, the simulation of the chromosphere is further complicated; in MHD simulations, the plasma-as-a-fluid is usually assumed to be a fluid consisting of a single species of particles - no distinction is made between charged and non-charged particles, as the assumption is that they interact so strongly that they can be treated as a single fluid. However, when the density falls rapidly in the chromosphere, charged ions may no longer be strongly collisionally coupled - they no longer bump into each other enough - with the still mostly-neutral hydrogen in the chromosphere. Treating charged and non-charged particles in the plasma separately in a true multi-fluid approach would be the ideal solution to this problem, but this is necessarily very computationally expensive. Instead, an approximation that still employs a single-fluid approach, but that rewrites the electric field using Ohm’s generalized law such that includes ambipolar diffusion and the Hall term, can be employed to save computation costs.

If one has poetic inclinations, the chromosphere’s appearance can be described as structured chaos; less visually ordered than the quiet-Sun photosphere with its more regular granulation, the chromosphere appears more like the roiling ocean close to shore, with multitudes of frond-like structures of plasma anchored in its depths, forever moving with some order that seems just beyond comprehension (at least to the humble author). As the magnetic field extends into the chromosphere from the photosphere, it expands due to the falling density, filling space. Also, as the density falls and $\beta$ thus falls below unity, the magnetic field asserts its will over the plasma. The plasma then follows along the dispersing field lines, although not always, since the chromosphere is highly dynamic and the magnetic field varies locally. We see many phenomena such as fibrils in the quiet Sun, which exhibit dynamic motions. Fibrillar structures are ubiquitous,
mostly aligning with the magnetic field. Objects called spicules visually define the limb of the Sun when viewed in the H\(\alpha\) line; these jets can extend up to 15 Mm beyond the limb, and have speeds of 10 – 40 km s\(^{-1}\), although they come in two different types, and form through different dynamics.

As mentioned in the previous section, the bottom panel of Fig. 1.3 depicts the quiet Sun at chromospheric heights. Here, in stark contrast to the photospheric scene, we see only glimpses of any underlying granular pattern, as it is obscured by the overlying fibrilar structures. As mentioned, these fibrilar structures mostly align with the magnetic field, and this can be readily discerned from the image as well. The frond-like plasma follows along ordered directions, extending and connecting different regions of the field of view. Furthermore, even an untrained eye may catch tantalizing glimpses of connections between the photosphere and the chromosphere; intergranular lanes with particularly large concentrations of bright points also appear bright in the chromosphere, appearing as nexus-points where many fibrils extend outwards from concentrations of magnetic field lines.

Again however, we must travel onwards. To summarize, the chromosphere begins with a transition from a falling temperature profile to a rising one, is host to a transition between the domination of the plasma by the gas-motion to being dominated by the magnetic field, sees a a transition from low ionization to significant ionization of hydrogen, harbours a transition from LTE to non-LTE conditions and also hosts a transition from plasma densities in which particles are strongly collisionally coupled, to no longer being so. Thus, the chromosphere is very much a transitional layer in itself, even if the next layer, the transition region, took the name for itself. We will look at this transitional layer next, and see which transitions will usher us from there onwards and into the corona, which we will discuss in tandem with the transition region.

### 1.3.3 The transition region, the corona and into the wild yonder

As the name implies, the transition region is somewhat of an in-between layer. It is wedged between the chromosphere and the corona and can be viewed as an intermediary between the two. The transition region is also a more recent addition to our description of the solar atmosphere, since it was in the study of how the chromosphere and corona transition into each other that the peculiar processes that define the transition region were found to be deserving of their own atmospheric layer. Much to the author’s disappointment, the transition region therefore lacks the Greek flair that the other layers posses. It may be argued that the transition region should perhaps be viewed as a transitional process, rather than a region per se, even though of course this process happens at a given altitude in the solar atmosphere. However, not only is the typical length-scale of the transition region very short compared to the extent of the other layers, as it typically only spans about 100 km, but the height at which it may be found can vary substantially compared to its extent, depending on the local dynamics, which, as oft-repeated, can vary substantially across the Sun. For example, higher magnetic field strengths lead to a transition region that is lower in the atmosphere.

In what way then does the transition region, well, transition the atmosphere from the chromosphere into the corona? In the transition region the plasma density falls to ever lower values and the magnetic field dominates even further, and \(\beta \ll 1\). However,
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at first glance, its most striking feature is the transition in temperature that we find in this region. The dramatic temperature increase could already be seen in the VALC 1D temperature profile shown in Fig. 1.1, and is probably the profile’s most striking feature. Up until the transition region, the radiation emitted in the Lyman $\alpha$ lines provides a very effective cooling mechanism that counteracts the effects of heating in the chromosphere, whatever forms this heating may ultimately consist of. However, as mentioned in the previous section, due to the slow, but still-persistent temperature increase upwards in the chromosphere, hydrogen becomes more and more ionized, until it reaches full ionization at the top of the chromosphere - at this point, this important cooling mechanism begins to fail. The plasma’s hydrogen, with the majority of the nuclei stripped of their single electrons, can no longer emit radiation by de-excitation. At the bottom of the transition region, or alternatively at the upper reaches of the chromosphere, the temperature increases gradually from about 10,000 K to about 25,000 K and at this point hydrogen becomes fully ionized. Once this happens, the radiative cooling by way of the Lyman $\alpha$ lines fails, and the atmosphere no longer balances the chromospheric heating mechanism and the temperature shoots up dramatically up to about 100,000 K over a very short distance, then keeps increasing more slowly as it tends towards 1 MK. Helium also becomes fully ionized in the lower transition region, while other, heavier elements also become ionized to greater and greater degrees as the temperature rises with height. While the energy input required for the ionization of other elements, as well as the radiative cooling through emission in other lines also counteract the increase in temperature somewhat, it is the radiation from the hydrogen’s Lyman $\alpha$ lines that provides the most significant cooling, and once this cooling mechanism fails, we find ourselves in the transition region proper.

As mentioned, the temperature increase in the transition region eventually slows down, as we move further upwards and, at last, into the corona. But why does the temperature at the top of the transition region not simply continue to rise? As the temperature increases, another cooling mechanism eventually becomes more efficient and halts the runaway temperature increase. In a fully ionized plasma, as we find at the top of transition region, thermal heat conduction is given by

$$Q = -\kappa_0 T^{5/2} \nabla \parallel T,$$

where $Q$ is the heat conduction, $\kappa_0$ is the thermal conduction coefficient, $T$ is the temperature and $\nabla \parallel T$ is derivative of the temperature along the magnetic field. Here, the partial derivative is taken along the magnetic field lines because the heat conduction acts mostly along the magnetic field when the magnetic field is strong compared to the gas pressure - which is the case in the upper transition region. From the expression for $Q$, it is most important to note its qualitative behaviour; due to the $T^{5/2}$ term, $Q$’s absolute value increases strongly when the temperature is high. Also, due to the dependence on the temperature gradient through the term $\nabla \parallel T$, the absolute value of $Q$ increases with sudden increases in temperature - which is what we see up until the top of the transition region. At a temperature of about 1MK, the heat conduction becomes strong enough to slow the temperature increase at the top of the transition region.

We thus find ourselves in the corona, which takes its name from the Latin word for crown, although the Latin word itself is derived from the ancient Greek $k\acute{\text{o}}\rho\omega\nu\acute{\text{e}}$, so at
The layers of the solar atmosphere

Figure 1.4: A full view of the Sun, as observed by the Solar Dynamics Observer’s (SDO) Atmospheric Imaging Assembly (AIA) instrument on May 25, 2017. The image combines the AIA passbands at 211 Å, 193 Å, and 171 Å, coded to red, green and blue respectively. The 171 Å, 193 Å, and the 211 Å channels approximately correspond to the upper TR, the Corona and hot flare plasma, and the upper chromosphere or TR, respectively. The image highlights the appearance of the Sun in the higher reaches of the solar atmosphere. Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

least in a roundabout way, we continue with our Greek theme after the more mundane naming of the transition region. The corona’s name was chosen due to its appearance during solar eclipses when it is visible to the naked eye. It extends out into space with indistinct tendrils, tantalizing fine-structure hiding within their fuzzy appearance. As such, perhaps the older meaning of the ancient Greek, kōronē, which means garland or wreath, is more fitting than the Latin for crown, since the corona appears more like
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a living, dynamic thing, rather than an unchanging crown, cast out of out of precious metals.

The corona is characterized by a temperature range of $1 – 5$ MK and the density continues to fall, and in the lower corona the particle density is only $10^{15}$ particles/m$^3$. We still find that $\beta \ll 1$, and the magnetic field completely dominates the plasma motions. In the corona most elements are fully ionized due to the high temperature, and the plasma is optically thin. In the corona there exist both open and closed magnetic field lines. Strong closed field lines lead to the creation of coronal loops, which are one of the defining features of the corona. In coronal loops, much simplified and generalizing, magnetic field lines connect to points of opposite polarity, with one foot-point often rooted in an active region or a sunspot. The most common type of coronal loops tend to suck plasma up from lower atmospheric layers along strong magnetic field lines from one foot-point. The plasma is heated to coronal temperatures as it is transported upwards, and a lot of the material is usually transported back to lower layers and cooled as it descends towards the other foot-point of the coronal loop. Coronal loops span tens to hundreds of millions of meters, providing for stunning visuals when observed in x-rays and in the extreme ultraviolet (EUV). Coronal loops also provide the sites at which flares and coronal mass ejections take place: violent outbursts of plasma that feed into the solar wind, caused by stress in and the subsequent reconnection of magnetic field lines. Another visually defining feature of the corona are coronal holes. These exist in areas of open magnetic flux tubes and appear as darker areas. The open field lines leads to lower concentrations of plasma, lower temperatures and therefore less emission than in other parts of the corona, hence the appearance and the name. The corona has no sharp edge or convenient physical process that defines its outer edge, and it continues outwards and transitions smoothly into the solar wind, which is fed both by the violent solar flares and coronal mass-ejections, as well as by the fast solar wind that emanates from coronal holes along their open field lines.

Figure 1.4 shows the entirety of the Sun as imaged by the space-borne Solar Dynamics Observatory (SDO), which makes continuous observations of the Sun as it resides in geosynchronous orbit above Earth. The image shows the Sun in an amalgamation of different wavelengths, captured by the SDO’s Atmospheric Imaging Assembly (AIA) instrument. The image was captured on May 25, 2017, the same recording date as for the observations shown in Fig. 1.3. The AIA instrument observes in many wavelengths, but in Fig. 1.4 only the near-simultaneous observations in the 211 Å passband, the 193 Å, and the 171 Å passband are shown, coded to red, green and blue respectively. Again, as for our photospheric and chromospheric snapshots from the SST, different wavelength regimes correspond to different heights. All three pass-bands mentioned here correspond to higher parts of the solar atmosphere, with the 171 Å, 193 Å, and the 211 Å channels corresponding approximately to the upper TR, the Corona and hot flare plasma, and the upper chromosphere or TR, respectively. The combined image highlights many features of the solar atmosphere in the TR and the corona. We see long and far reaching coronal loops, and strong concentrations of magnetic fields where plasma loops originate or connect. We also see large dark features, which correspond to the aforementioned coronal holes. We also see the corona extending and reaching into the void beyond the Sun, transitioning into the solar wind.

Another topic concerning the corona must also be mentioned, since as is tradition,
when speaking the words “solar corona”, the phrase, “coronal heating problem” is usually not far behind. The coronal heating problem has vexed solar physicists since it was discovered that the corona has emission originating from highly ionized iron, Fe X and Fe XI, which confirmed that the corona has a temperature in excess of 1 MK. Since then, the puzzlement of how it comes to be that the outermost part of our Sun has a higher temperature than the photosphere has occupied solar physicists. Above, I already alluded to a part of this problem, as the chromosphere also has a temperature that is above that of the photosphere. Here, I mentioned that the reason for why this temperature increase is possible at all is due to the breakdown of RE and LTE, and that other processes than radiative heating are taking place. In fact, the coronal heating problem is not entirely separable from the chromospheric heating problem; any heating of the corona must in some form pass through both the chromosphere and the transition region. Strides have been made in the decades since the problem was first formulated, for many reasons that all come down to the increased ability to test or to falsify possible heating mechanisms. Different undertakings and improvements in methods have all contributed to our understanding so far: better simulations of the solar atmosphere, here MHD simulations in particular, and also great improvements in the simulation of specific plasma dynamics such as magnetic reconnection and Alfvén- and acoustic- waves. This has all been made possible by and been tested against high resolution observations that have greater wavelength coverages than ever before. There are still several heating candidates remaining today, and their finer details are beyond the scope of this summary. However, our current bests bets are that the corona is fed the necessary heat by two main contending mechanisms - waves, either of the Alfvénic/magnetic or acoustic variants, or through magnetic reconnection events. Already mentioned above, in the context of the chromosphere, waves that travel along the magnetic field may carry energy from the convection zone and up through the atmosphere. Challenges lie in identifying the specific processes in which these waves can cross into the corona without dissipating or being either reflected or refracted, and further, how the energy they transport is converted into thermal energy once they arrive further up in the atmosphere. In the context of magnetic reconnections, promising research into small-scale reconnection seem to indicate that nano-flare reconnections along coronal loops may be able to provide energy sufficient to heat the corona. In this scenario, stresses in the magnetic field caused by movements of their foot-points (in turn caused by the motions of the convective layer) are released in small-scale reconnection events throughout the length of coronal loops, heating them at their apex and thus the corona. With the upcoming next-generation telescopes that are currently being planned or constructed, coupled with steadily improving MHD simulations, both aided by improvements in hardware and more efficient numerical solvers, this turn of the century promises further great strides in the unravelling of the solar atmosphere, and in turn the coronal heating problem.

With the general layout and nature of the solar atmosphere hopefully somewhat clearer than before, we will now turn to more specific features on the sun - active regions and sunspots.
1.4 Active regions and sunspots

As the ultimate objects of our interest, penumbral microjets, reside in the penumbrae of sunspots, which themselves have their home in active regions, the questions of what constitutes an active region, why they host sunspots, and in turn what the penumbra and other parts of a sunspot are, are all in need of at least some answers in order to guide the reader. Here, I will only give broad descriptions, enough to ground our discussion, but without delving into too many specifics, as that would be beyond the scope of this thesis. I will begin at the largest scale of this topic, and proceed to smaller scales from there, only leaving the dramatis personae themselves, our PMJs, to be expanded upon in Chapter 3.

It is perhaps rather unsurprising that so-called active regions, or ARs, are places of particularly strong activity both on the surface of the Sun, as well as in the overlying atmosphere. Tautologies aside, what is particularly active, about ARs? Active regions are chiefly characterized by particularly strong magnetic field strengths emerging from the solar interior, distinguishing the area from the quiet Sun that displays weaker magnetic fields and more uniform conditions. An active region begins its life when the solar surface is breached by coherent magnetic flux-bundle loops. These are usually Ω-shaped, and will emerge with their roundish top-part first. Typically, an active region begins its life as a so-called “ephemeral active region” that is smaller in size than a true active region. However, most of the ephemeral active regions do not develop into proper active regions and fade over the scale of hours. Ephemeral active regions have sizes on the order of 10 Mm and show up as bright points in the corona and are visible in x-rays. Those that continue to grow become “true” active regions over the course of days, and these have typical scales of 100 megameters. A typical AR will grow into its own over 10 – 15 days at which point it will have developed one or more sunspots and may develop some of their smaller cousins, so-called pores. Both preceding the formation of sunspots and pores, as well as after their disappearance at the end of an AR’s life, AR’s also host “faculae” at photospheric heights and “plage” in the chromosphere. Faculae, so-named for the Latin facula, meaning little torch, are networks of bright patches. These patches are hosts to magnetic concentrations on the order of kilogauss and appear brighter because the opacity is somewhat lowered, making hotter material from further down visible, a mechanism we also see for quiet Sun bright points. In fact, at high resolution, faculae can be discerned as individual points with sizes on the order of 100 km, and can be observed in the intergranular lanes, akin to bright points. The patches cluster in active regions, and can be seen in visible light, in which they are most discernable when viewed at the limb. In the G-band, they can also be observed at disk-centre. Plage, French for beach, is visible in chromospheric channels, and correspond well to areas of faculae that lie below them. Areas of plage appear as bright inter-connected patches in Hα and are host to magnetic fields with mean strengths of around 100 G. From the chromosphere, fibrils extend into the corona, long dark loops of plasma that follow along the typically bipolar, emerging flux. Active regions as whole take much longer to disperse than to form, and may remain as magnetically enhanced regions on time-scales of weeks or months, even after any sunspots that developed there have disappeared.

Pores and sunspots will begin to form inside an AR when the large magnetic flux begins to emerge from the solar interior. Again, as for ARs in general, the most defining
Active regions and sunspots

feature of sunspots is the magnetic field and its configuration that governs them. At this point it is worth to point out something important to keep in mind when discussing sunspots in the following. Due to the strong magnetic fields, the actual structure and values of which will discuss below, the plasma motions inside sunspots are utterly at the mercy of the magnetic field. Calling back to the discussion in the previous sections on the different atmospheric layers, we find that $\beta \ll 1$ inside sunspots, even down in the photosphere, and this remains true further up. This means that the more general discussions of the different atmospheric layers are not as readily applicable when dealing with these fascinating objects. The inevitability of the falling plasma density with height still holds true in sunspots, albeit the generally higher magnetic field strengths alter the specifics somewhat, but the shared dynamics of sunspots truly make for a special edge-case in terms of their solar atmospheric behaviour. They are therefore best discussed as a separate beast, as we will do in the following.

Sunspots typically form in sunspot groups, with a leading and a trailing sunspot in the group, and possibly with some sunspots lying between them. The leading sunspot is defined by the rotational direction of the Sun, which is left to right when observed from the northern hemisphere of Earth. A group thus travels with the Sun’s rotation from left to right when observed from this vantage point. Typically, the leading and trailing sunspots have overall opposite polarity, existing in a bipolar magnetic field configuration. However, almost half of sunspot groups can be unipolar, while some few groups have more complex configurations than either. Particularly interesting is that the formation of sunspots, and active regions in general, follow a regular 11-year cycle, with the number of sunspots increasing and decreasing throughout the cycle. The cycle also influences the polarity of the sunspots that are formed. The leading sunspot of a sunspot group in one hemisphere will always have the opposite polarity of the sunspot leading a group in the opposite hemisphere. If this wasn’t peculiar enough, the polarity of the lead sunspots in either hemisphere will be switched from one cycle to the next and remain opposite to each other the next cycle. This behaviour is further correlated to the Sun’s global polarity reversal, which takes place during the minimum of the 11-year sunspot cycle. We thus see that the formation and magnetic configuration of individual sunspot groups and sunspots are not only intimately connected to each other, but also to the Sun’s magnetic configuration as a whole. The location of active regions and their sunspots is also dependent on the time within the 11-year cycle; sunspots generally form in a region of about 40° above and below the equator line, but will form at the highest and lowest latitudes at the beginning of the cycle but form near the equator when the cycle approaches its minimum, with sunspot formation migrating towards the equator throughout the cycle. Sunspot groups, once formed, typically remain at the same latitude throughout their lifetimes.

Individual sunspots have typical radii of 10 Mm – 20 Mm, but can range from only 1.75 Mm to 30 Mm in radius. Leading sunspots of a group tend to be bigger and last the longest. The smaller cousins of sunspots, pores, have sizes on scales of only a few thousand kilometres, but can range in radius from 0.3 Mm, and even up to 3.5 Mm. Both sunspots and pores are most obvious in the photosphere. They are both typically roughly circular, but can be significantly deformed from this ideal. A sunspot consists of a darker interior, called the umbra and an outer part that is called the penumbra. The penumbra is still darker than the surrounding quiet Sun, but brighter than the umbra,
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and completely or partially surrounds the umbra. Fittingly enough, “umbra” is Latin for *shadow* while correspondingly, “penumbra” comes from the Latin “peane”, or almost, and “umbra”, yielding *almost-shadow*, or perhaps more aptly, *half-shadow*. Pores can be described as lone umbras that lack a penumbra, although they sometimes exhibit partial ones. The dark interior of both sunspots and pores is caused by the strong magnetic field that inhibits the convective motions that ordinarily leads to the granular pattern in the quiet Sun. Since convective motions are inhibited, this means that the convective heating from the solar interior is also disrupted, which leads to a significant drop in temperature, and hence radiative emission, from the interior of sunspots, which is why they appear darker. Typically, sunspot umbras have temperatures that are 1000 K to 1900 K cooler than the surrounding quiet Sun, while penumbrae are 250 K to 400 K cooler on average.

The magnetic field configuration and the general dynamics of individual sunspots is remarkably similar across sunspots, hinting at an ordered process when it comes to the large-scale features of sunspots; however, many of the finer details remain unexplained. In the umbra, the magnetic field lines emerging from the solar interior are near-vertical and the field has a typical strength of 2.8 kG. Our “stand-alone umbras”, pores, have generally lower magnetic field strengths than umbras, with typical values of 1.8 kG – 2.3 kG at their centres. The magnetic field lines tend to open up and become more horizontal as they cross into the penumbrae of sunspots, and the field strength decreases gradually at the same time. Once we reach the boundary between the penumbra and its surroundings, the field is typically only about 10° above the horizontal and the field has weakened to about 0.7 kG – 0.9 kG.

Umbrae may seem rather uneventful at first glance, as the dynamics that take place there have much less contrast than in the brighter penumbrae that surround them. Nonetheless, umbrae are host to a variety of dynamical processes such as the notable umbral dots and umbral oscillations. Umbral dots are small bright patches that flow upwards in the umbra, and which are significantly hotter, by about 1000 K, than their umbral surroundings. They have sizes of 100 km to 450 km and flow upwards with velocities of about 1 km s\(^{-1}\) and have lifetimes on the scales of minutes to a couple of hours. At least the umbral dots commonly found in the centres of umbrae are likely caused by localized convective motions. Despite the name, umbral dots are present in both sunspot umbras but also in pores. Oscillations in umbrae range over a wide span of frequencies, and are present both in the photosphere and in the chromosphere. In the photosphere, we find oscillations with 3 minute and 5 minute periods and with velocities on the order of 40 m s\(^{-1}\) – 100 m s\(^{-1}\). So far, these are best explained by p-mode waves that are absorbed and partially mode-converted. In the chromosphere, so-called “3-min” oscillations give rise to compressive wave-fronts that are faster than those in the photosphere, reaching velocities of 40 km s\(^{-1}\) with periods of between 140 s – 190 s. These waves cause shock-fronts in the chromosphere, manifesting as a bright circular front that ripples outwards from the umbra before dissipating more slowly. This visually striking phenomenon is called an umbral flash, and it repeats over and over again. Umbral flashes can thus appear as the steady beats of a sunspot’s heart.

In the photosphere, sunspot penumbrae are visually characterized chiefly by dark and bright penumbral filaments that roughly alternate and that extend outward from the umbra-penumbra boundary. Individual penumbral filaments have typical lifetimes
on the scale of hours. Bright filaments extend from the umbra-penumbra boundary to the edge of the sunspot, becoming less defined as they reach their ends, and their brightness may decrease. Of particular interest to us in the context of this thesis is the more nuanced magnetic field configuration of the penumbra, since this is the setting in which penumbral microjets are formed. In the penumbra, the magnetic field consists of magnetic field lines that cross each other at an angle, with the magnetic field being more vertical in bright penumbral filaments, and more horizontal in the dark penumbral filaments. This is often described as an “interlocking comb” configuration, or alternatively, a “spine, inter-spine” pattern. The fields aligned with both bright and dark penumbral filaments both become more horizontal in the direction of the umbra to the outer edge of the penumbra; however, while both have inclinations of about 40° to the vertical at the inner border of the penumbra, the field along the bright filaments reaches a maximum inclination to the vertical of about 60°, while the field along dark filaments continues to decline until it reaches the horizontal before the edge of the penumbra is even reached. The field along the dark penumbral filaments are at this point still slightly above the photosphere, and thus dip down even below the horizontal until they connect back to the edge of the sunspot in the photosphere. Thus, in parts of this configuration, we find magnetic field lines with substantial angular shear, i.e. differences in inclination to the vertical, in the penumbra. The bright filaments in the penumbra thus extend further up into the atmosphere than those of the dark ones, and are clearly visible in the chromosphere as they reach beyond the photospheric boundary of the sunspot. Some of the dark filaments also extend outwards and beyond the sunspot, but at heights of only 300 km or so, while the rest of the dark filaments connect back to the sunspot approximately at the outer penumbral boundary. More nuanced descriptions of the interplay between what constitutes bright and dark filaments and the deduced magnetic field lines exist. However, for our purposes we note that whatever the precise details of this magnetic configuration, the locations at which the magnetic field lines in the penumbra have acute angles are the primary proposed location at which penumbral microjets are hypothesized to form. This is because we can clearly observe penumbral microjets as jet-like brightenings in chromospheric wavelength-channels inside penumbrae. Furthermore, since penumbral microjets are very sudden events that exhibit a significant increase in brightness compared to their penumbral surroundings, they are thought to form by a process sufficiently fast to create them - magnetic reconnection. Magnetic reconnection is the sudden and violent release of potential energy that was previously contained in a stressed magnetic field. This stress is usually caused by the tangling of magnetic field lines, or by significant inclinations between magnetic field lines. We just saw that the latter of these conditions is a state of affairs found throughout the penumbrae of sunspots. We will limit ourselves to this surface-level hypothesis for the creation of microjets here, and return to them in earnest in Chapter 3.

Sunspots also host both important and famous dynamic flows, which bear mentioning here. The Evershed flow is named after its discoverer John Evershed (and it has no relation to the term “watershed”, nor any similar word, as I may or may not have foolishly assumed upon first learning of the phenomenon and its name), and it was first described in Evershed 1909. The Evershed flow is observable at photospheric heights inside penumbrae, and is aligned with the overall magnetic field direction as it fans
1. The Sun

outswards, meaning that it is overall close to horizontal. It is an outflow with a velocity of about 6 km s\(^{-1}\) and runs along narrow channels inside both dark and bright penumbral filaments. At the umbra-penumbra boundary, it is directed slightly upwards, whereas it dips down below the horizontal at the edge of the penumbra. The Evershed flow evolves as we go up in height in the atmosphere; the flow’s velocity first decreases, until it reaches a theoretical boundary at which it ceases, before its direction reverses and it becomes an inflow, into the sunspot’s penumbra. At this point, the Evershed flow has become, rather intuitively, the inverse Evershed flow. The inverse Evershed flow has flow velocities of in-falling plasma between 20 km s\(^{-1}\) and 50 km s\(^{-1}\) at an atmospheric height of 5000 km. The inverse Evershed flow follows along long superpenumbral filaments, especially visible in H\(\alpha\), which are long filamentary structures that radiate outwards above sunspots. Further up, in the transition region, sunspots also host sunspot loops, long loops of plasma that follow the magnetic field lines as they extend upwards, and these also harbour downflows.

While far removed from the much smaller scales that we are interested in for the purposes of this thesis, the atmosphere above active regions and sunspots are also associated with the impressive and hugely energetic events called Coronal Mass Ejections (CMEs) and solar flares. As the name implies, CMEs involve the ejection of mass from the corona, which are at least facilitated, or are also likely directly caused by, magnetic reconnection of field lines at a much, much greater scale in terms of both energy and size, than for our much humbler penumbral microjets. A CME consists of a cool bubble of plasma at coronal heights that drags additional coronal plasma along with it, as it is catapulted into space when strong magnetic field lines release energy. The cool plasma that forms the nexus from which a CME erupts is also called a prominence. Prominences float at coronal heights, despite being both much more dense than the surrounding coronal material and only having temperatures of 7500 K – 9000 K, compared to the million-kelvin scale temperatures otherwise found in the corona. They are kept aloft by Lorentz-forces mediated by strong magnetic fields, and hence are common in ARs, but also occur elsewhere in the presence of strong fields. When viewed on-disk, rather than on the limb, a prominence is usually called a dark filament, as they appear as long, elongated loops in H\(\alpha\) when seen from above. A so-called quiescent prominence may remain in one piece on the time-scales of weeks or months. In contrast, an active prominence has a much shorter lifespan, on the scale of hours, and can either form quickly on its own, or may develop from a previously quiescent prominence. The active type of prominences are those that explosively release material, manifesting as CMEs. The mass ejected by a CME event can range from about 10\(^{11}\) kg to 4 \times 10\(^{13}\) kg, reaching speeds of 4000 km s\(^{-1}\) all the way to 1000 km s\(^{-1}\). The mass catapulted outwards by CMEs is a major source of space-weather, able to disrupt satellites but also Earth-based electronics. Solar flares also occur in ARs, and are also best explained by a process of magnetic reconnection of strong magnetic fields, which is why they are found in ARs. The total energy released in a solar flare can range from 10\(^{17}\) J to 10\(^{25}\) J, truly staggering amounts, even more impressive considering the typical timescales over which solar flares release this energy, which ranges from milliseconds to about an hour. Solar flares are also a major source of the solar x-rays that impact Earth, also able to disrupt electrical systems. Flares emit their energy through varied processes and in wavelengths from radio-waves to short-wave x-rays and down to gamma-ray
Figure 1.5: A sunspot hosted by Active Region 11785, observed on July 4, 2013 by the SST during a campaign that I had the fortune to participate in. Shown is the same field of view in different wavelengths, top: the Ca ii wide-band, which images the photosphere, bottom: the Ca ii H line-core, which images the chromosphere. The tick-mark separations are 1”. The sunspot had a full penumbra, as well as a light-bridge bisecting the umbra. There are several pores present, both with and without partial penumbrae.

wavelength emissions. The field of solar flare physics is both complex and deep, both in terms of terminology and its physics. There are a wide variety of different flare types. Unfortunately, how they interact with their host ARs and with CMEs, the latter of which often occur concurrently and in interact with flares in complex ways, are regrettably not areas of study we will dwell on here.
There are vastly more nuances to the dynamics and evolution of both active regions, sunspots and their associated phenomena. However, this introduction with its focus on the more relevant aspects that concern the locations and scales that this thesis deals with will have to suffice. Before continuing on to the next chapter entirely however, I offer Fig. 1.5 as a particularly striking example of a complex sunspot. The sunspot was imaged on July 4, 2013 by the Swedish 1-m Solar Telescope during the first observing campaign that I had the pleasure to participate in at the telescope. The sunspot is shown both at photospheric heights, as seen in the Ca ii wide-band, and at chromospheric heights, as seen in the Ca ii H line-core. We see that the sunspot is of irregular shape, sports both a full penumbra, but also exhibits a so-called light-bridge. Light bridges typically form in smaller sunspots. They usually do so towards the end of their lives, and they can lead to the breakup of the sunspot. They can be viewed as an intrusion of the regular convective solar surface into the umbra. We also see several smaller pores below the main sunspot, several with partial penumbrae. The appearance of the bright and dark penumbral filaments is well-exemplified both in the photosphere and the chromosphere; in the photosphere they appear regular and rather well-ordered, while in the chromosphere the penumbral filaments follow along the elevated magnetic field lines in a looser, frond-like configuration. Finally, with this beautiful example of an observation of the solar atmosphere to whet our appetites, we shall continue onwards to the next chapter, which deals with exactly this topic - observations of the Sun, and how we obtain them.
Chapter 2

Observing the Sun

2.1 An introduction to solar observations

Experiments with lenses and mirrors and the subsequent development of theoretical optics eventually led to the invention of the first telescopes at the beginning of the 17th century. Since then, they have been used not only to study the heavens at large, but more relevant to our interests, the Sun as well. To undertake observations of our nearest star poses problems that both share commonalities with, but also profoundly differ from the problems observers face when studying our neighbouring planets, more distant stars and their planets, and other objects visible in the night sky. Common to all Earth-bound astronomy is that from its very beginnings, the Earth’s atmosphere has put limits on our ability to observe celestial objects. In fact, this has only become of greater and greater importance the more precise our instruments have become; this is due to the fact that any adverse effects caused by the atmosphere become more noticeable the greater levels of precision are attempted. Today, entire areas of study and research are dedicated to mitigate the detrimental effects of so-called seeing. Seeing is the catch-all term applied to any distortions in the observations made by a telescope that are caused by the Earth’s atmosphere. Common and obvious reasons for seeing are clouds, rain and other such nuisances, and these are regrettably also nigh-insurmountable for the poor observer. These types of seeing typically make any worthwhile observations in visible light impossible. However, even skies that seem gloriously clear to the untrained eye may pose great difficulties when seeking observations of the heavens in ever-greater detail.

Before getting to more surmountable seeing-effects however, we must discuss a problem that the Earth’s atmosphere poses for astronomers that is more fundamental than even clouds and other such phenomena; the atmosphere is partially or completely opaque to some wavelengths of light, regardless of other fleeting conditions found in the atmosphere. Depending on its wavelength, light that enters the Earth’s atmosphere from space is blocked or scattered to varying degrees by molecular absorption and other processes. Without going into detail concerning specific absorption and scattering processes, a particular example is the absorption of light in the infrared by water vapour present in the atmosphere. It is no coincidence that human eye-sight is optimized for vision in the somewhat tautologically named visible spectrum of light. It is in this wavelength regime that the Sun emits most of its radiation. Furthermore, and perhaps of greater importance, the Earth’s atmosphere also permits light at these wavelengths to pass through largely unscathed. It is thus in this spectrum of light that the eyesight of humans and, with some variation towards bluer or redder wavelengths (the UV or infrared), that much of the other life on earth has evolved to perceive. Other wavelengths of light also pass through the atmosphere largely unhindered; a small part of the infrared band, parts of the microwave regime, as well as short to medium length
2. Observing the Sun

radio waves are all observable from the ground, the latter of which enables the entire field of radio-astronomy.

Other wavelengths of light are not as lucky in their travels through the atmosphere; high-energy wavelengths such as gamma-rays, x-rays and most of the ultra-violet wavelengths are blocked by the atmosphere, and the same goes for the low energy, long radio waves. All of these wavelength regimes can be of great use to astronomers, and in order to observe the cosmos in these wavelengths, the only feasible approach is to bypass the Earth’s atmosphere entirely. Therefore, observing platforms in outer space are of great utility to astronomers in general, but also for observers of the Sun in particular. One of several telescopes that observes the Sun from space is the Interface Region Imaging Spectrograph, or more poetically, IRIS. This telescope’s capabilities will be discussed in Sect. 2.2.2, as it was invaluable to some of the original research included in this thesis. Furthermore, IRIS also serves to illustrate the great importance and utility of space-borne telescopes at large, as well as in the context of solar physics.

Of course, while placing one’s telescope in space neatly bypasses all problems caused by the Earth’s atmosphere, it presents many other problems; these are in part associated with challenges of engineering, but limiting factors are also costs and logistics. Telescopes bound for the great void must be able to withstand both the vacuum of space but also harmful cosmic and solar radiation, which is capable of damaging unshielded electronics. Launching a telescope into space also puts constraints on both the size and complexity of its instruments; space-launches are very expensive, costs rise with weight, and additionally, instruments must be robust to survive the launch itself. Another large drawback is that once in space, the telescope is usually impossible to repair or upgrade. A notable exception was the costly and risky repair of the Hubble space telescope shortly after its initial launch. Due to its importance, it warranted a visit by NASA’s Space Shuttle and was repaired when its main mirror was discovered to have a critical flaw. Other space telescopes should not expect such luxury. Furthermore, space telescopes must also transmit data back to Earth and have enough local data storage available for observations until such transfers can be achieved. IRIS is no exception, and limited transmission bandwidth and local storage mean that observations must be planned meticulously. However, due to the enormous benefit of enabling the observation of otherwise inaccessible wavelength bands, space telescopes are well worth both the effort and cost - provided of course that they are conceived and planned properly and that they survive their perilous journey into the dark yonder. IRIS, of course, is an example of such a confluence of events, and it was conceived to perform hitherto unobtainable high-resolution observations of the Sun. We shall return to IRIS below.

First however, we shall return to solid ground. It must be stressed that even though particular wavelengths may pass through the Earth’s atmosphere, this does not mean that useful Earth-bound observations are always easy to obtain in these wavelengths. As alluded to above, any atmosphere will cause seeing effects, and this holds true even if it is generally transparent at a given wavelength. Turbulent air will refract light that passes through it at slightly different angles, mostly due to the mixing of air that has somewhat different temperatures; this is due to the fact that air has slightly different refractive indices at different temperatures. Seeing effects are typically categorized as large or small scale, and are usually also divided by whether they originate at high or low altitudes in the atmosphere. Large-scale seeing effects are typically easier to mitigate,
An introduction to solar observations

since their effect is more easily estimated for larger patches of the sky. These are often
due to high-altitude winds and currents. Small-scale fluctuations can be more difficult to
deal with, as they distort the captured image in many different ways across small parts
of the field of view. These small-scale variations in seeing are consequently often due to
local conditions found around the telescope in question and typically originate in the
lower atmosphere. Local temperature variations and turbulence caused by the heating or
cooling of the telescope’s environment are common sources for such seeing effects.

A general measure of seeing is the Fried parameter, typically signified by \( r_0 \), which
has the unit of length, and was first introduced in Fried and Cloud 1966. The parameter
measures the coherence length of optical transmissions through the atmosphere, or
alternatively, the typical length in the atmosphere over which a ray of light will remain
un-refracted due to seeing effects. It is thus also a measure for the size of isoplanar
patches in the atmosphere, meaning the spatial scale over which the atmosphere can
be considered uniform. Consequently, larger values for \( r_0 \) imply a more uniform
atmosphere, and therefore better seeing conditions. For convenience, \( r_0 \) is typically
given in centimetres, corresponding to the typical scale of isoplanar patches found for
good observing sites. As an example, at the Swedish 1-m Solar Telescope, or SST,
seeing conditions are typically considered good for values above \( r_0 = 20 \) cm. The
SST was of even greater importance to the original research of this thesis than IRIS.
The SST provided all observations for two out of the three papers included in this
thesis, and half of the third paper’s observations. Naturally, we will therefore explore its
particular capabilities and properties in more detail below, in Sect. 2.2.1. Before we do
so however, the world-class SST is also supremely illustrative in terms of the general
challenges faced by ground-based telescopes, as well as for telescopes observing the
Sun in particular, and it exemplifies how to overcome or mitigate many of these.

The SST is located at an altitude of 2360 meters near the top of the mountain Roque
de los Muchachos on the Canary island of La Palma. The mountain’s observatory is
home to a wide variety of telescopes, due to its excellent seeing conditions. These are
among the best on Earth, due to wind conditions that are both favourable and stable.
The best observatories are located at high altitudes, as this provides the great benefit that
any observed light does not have to pass through as thick an atmosphere as would be
the case at lower altitudes. Weather or wind conditions can often be more challenging
for observations during day-time. At day-time, local seeing may be caused by the
very object of our attention; the Sun’s radiation not only heats the Earth’s atmosphere
both directly and indirectly, but can also heat the observing platform and its immediate
surroundings as well. This in turn causes local air currents that rise upwards. This can of
course have serious adverse effects on observations. At the SST, heating of the telescope
itself and its surroundings is partly mitigated by the application of special white paint
that is especially reflective, and thus more readily reflects sunlight and therefore prevents
some of the heating altogether. In order to avoid some of the seeing effects created by
local air currents, the SST’s main aperture also sits atop a tower 17 meter above its
immediate surroundings.

The SST itself is also specifically designed to combat any possible sources of seeing
inside of it; any air inside the SST’s tower would itself be heated by the light that its
main lens focuses and transmits towards its base via a set of secondary mirrors. To
avoid rising and falling air currents inside the SST caused by heated air, the inside
of the tower is therefore kept at a near-vacuum, removing any “internal atmosphere” entirely. Remaining seeing effects are mitigated by the SST in two major ways that both exemplify the ever increasing advances in modern astronomy. The first of these is the use of an adaptive optics (AO) system. An AO system counteracts the effects of seeing in real-time. In the case of the SST, this consists of a wave-front sensor that estimates the seeing conditions in the atmosphere above the telescope across the field of view of the telescope. This information is then fed to a tip-tilt mirror that adjusts its angle to mitigate large-scale distortions across the field of view, and additional corrections are achieved by a deformable mirror that is capable of changing its shape at specific locations to counteract the effects of small-scale seeing. The second way is through post-facto corrections of seeing in already recorded observations. At the SST, this is achieved through an image-correction process called Multi-Object Multi-Frame Blind Deconvolution, or MOMFBD, that seeks to correct captured observations for seeing effects. In order to do so, the observations are compared in different wavelengths and over very short timescales in order to estimate and correct for remaining seeing effects. Both of these processes will be discussed further in the context of the SST below. Both AO systems and image correction processes akin to MOMFBD, such as its relative called Speckle Imaging, are vital in modern solar astronomy in order to achieve observations of sufficient quality from ground-based telescopes.

As discussed in Chapter 1, the solar atmosphere is strongly stratified by temperature with height, meaning different heights strongly correlate to rather specific temperature ranges. Since the likelihood of atomic transitions are in turn heavily dependent on temperature, different heights of the solar atmosphere are also strongly associated with the different wavelengths associated with the radiation emitted through de-excitation of particular atomic transitions. Particular spectral lines associated with specific atomic transitions are hence of special interest for solar physicists, especially if they wish to observe the entirety of the solar atmosphere. As mentioned, particularly high-energy wavelengths are blocked by the Earth’s atmosphere. Such high energy wavelengths are associated with greater heights of the solar atmosphere in which the temperature rises quickly, such as at the upper chromosphere, the TR and finally the corona. As such, to observe the higher reaches of the solar atmosphere, one must leave the Earth’s atmosphere behind, precisely as the Interface Region Imaging Spectrograph does in order to observe the region that gave it its name. The interface region is the region between the middle chromosphere and the corona and constitutes IRIS’ primary target. Bound by Earth’s gravity, the wavelength regions at which the SST observes means that the heights it images somewhat overlap with IRIS’ in the chromosphere. However, the SST’s main focus lies lower than for IRIS, and the SST observes from the photosphere to the upper chromosphere. Other telescopes, such as the Hinode satellite’s Solar Optical Telescope also observe in the chromosphere, but unhindered by atmospheric distortions. Also in space, the Solar Dynamics Observatory (SDO) is capable of delivering full-disk observations of the solar corona. We therefore see that a wide variety of approaches and telescopes are needed to truly unravel the solar atmosphere. Now however, we shall turn to the two telescopes of particular interest to this thesis, the SST and IRIS, and I will endeavour to present them in some more detail. This will also serve to illustrate some of the general topics just discussed in some more detail.
2.2 Exploring two solar telescopes: the SST and IRIS

Below, I will introduce the Swedish 1-m Solar Telescope (SST) and the Interface Region Imaging Spectrograph (IRIS) to the reader, both of which were vital to the work of this thesis. Both will also serve as examples of their respective kinds: Earth- and space-based telescopes. The SST may be the beneficiary of some favouritism in terms of the amount of detail with which it is described. I spent many a sunny day within the confines of its dark basement, staring at the Sun through screens rather than enjoying its shine outside. As a consequence, some latent Stockholm-Syndrome may bias me with a particular affection for it. Furthermore, because of my time at the telescope, I am generally also more familiar with it. With that said, I shall not neglect the eye-in-the-sky that is IRIS, as it too provided me with many hours spent counting grey-on-grey pixels in images of the Sun.

2.2.1 The Swedish 1-m Solar Telescope

The Swedish 1-m Solar Telescope (SST, Scharmer et al. 2003) is among the very best solar telescopes operating today, both on Earth and in space. This is largely thanks to continued upgrades that have allowed it to keep pace with advances in instrumentation and new observing techniques. As mentioned previously, it is situated on the Canary island of La Palma, atop the mountain of Roque de los Muchachos at a height of 2360 meters. The observing conditions at the top of the mountain are frequently excellent, as the wind conditions around the island and its dormant volcanic caldera make for uniform winds that are extremely favourable for atmospheric seeing conditions. The telescope can be said to have begun as an upgrade itself. It began observations in 2002, when it emerged from the remains of its predecessor, the Swedish Vacuum Solar Telescope (SVST). The main structure of the preceding SVST, such as the main building and its tower were repurposed when the SST was installed at the same site. Previously, the SVST had observed the Sun with a main doublet lens with a diameter of 47.5 cm, obtaining excellent observations of the Sun for its time. However, the SVST lacked the benefit of hindsight in its design; while the telescope was retro-fitted with technological advancements of newer generation telescopes, it was not initially conceived with these in mind. The SVST was one of the first solar telescopes to pioneer and employ adaptive optics for the correction of atmospheric seeing, and toward the end of its life it made use of both a correlation tracker, a tip-tilt mirror and a deformable mirror in its setup. Such a setup, which we will examine for the specific case of the SST below, enabled the SVST to deliver observations of higher quality than it had previously; however, the planning of its successor, the SST, provided the opportunity to fully realize the potential of such new technologies. In fact, the SST became the first solar telescope to have a fully integrated adaptive optics system included in its design. The planning and construction of the SST was further motivated by the fact that the plans for a large modern solar telescope, the Large Earth-based Solar Telescope (LEST), fell through, meaning that the LEST was never built. This made the need for a modern solar telescope with greater resolving power keenly felt indeed, and thus the SST was conceived and constructed shortly thereafter.

The SST has a main aperture of just under one meter; in actuality, its main singlet
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...lens measures a metre in diameter, but safety guards reduce the main opening by 3 cm, so that its effective main aperture is 97 cm. Since the diffraction limited resolution of any telescope is inversely proportional to the size of its main aperture, the SST thus doubled the theoretical resolving power compared to its forbearer when it doubled its main aperture size. For a given wavelength that the telescope observes at, $\lambda$ and the telescopes aperture size $D$, its diffraction-limited resolution $\theta_{D}$ is given by the Rayleigh criterion,

$$\theta_{D} = \frac{1.22 \lambda}{D}.$$

Observations from the SST in the Ca II 8542 Å line and the Ca II H line (located at 3968 Å) were vital for work included in this thesis, and are suitable as example wavelengths at both the blue and red ends of the SST’s wavelength window. For the two lines, the SST’s theoretical diffraction limit is about $\theta_{Ca\text{ II} \ 8542\text{ Å}} = 0.22\"$ and $\theta_{Ca\text{ II} \ H \ line} = 0.10\"$, respectively corresponding to resolvable distances of about $\approx 160$ km and $\approx 70$ km on the surface of the Sun (depending on the current distance to the Sun). Of course, limits imposed by other instruments, but above all the effects of seeing, will resist us in achieving these lower bounds. However, due to the adaptive optics system and post-facto seeing-removal by the MOMFBD image restoration process, the SST can often operate at, or very close to its theoretical limits. When it began its life in 2002, the SST was the highest resolving solar telescope in the world, and it continues to operate amongst the best to this day.

In the following, I will give a (somewhat) colloquial overview of the SST’s layout and its instrumentation at the time of writing, roughly following the Sun’s light as it is swallowed up for eventual informational digestion in its innards. The SST continues to undergo renewals and upgrades in frequent fits and spurts, and consequently I refer the reader to the newest publications on the SST’s continued improvements for any in-depth technical details for any given components and instruments.

Here, I will focus on the telescope’s main functions and parts, only referring to some general values when it comes to instrument specifications. The SST can be divided into four rough sections, though there is an interplay between components in the different parts. The different parts are described in separate sections. The tower and its turret through which sunlight enters and where it is initially focused are described in Sect. 2.2.1.1, the Adaptive Optics (AO) system is described in Sect. 2.2.1.2, here, the incoming light is corrected for effects of atmospheric seeing in real-time. Finally, we turn to the two parts of the light-beam along which the “true” instruments used for scientific analysis are located. These two are complimentary parts of the optical path and are set up in parallel, since the light coming from the AO system is split along two paths: the red beam, which is described in Sect. 2.2.1.3, and the blue beam, which is laid out in Sect. 2.2.1.4. We will discuss all of these below, after which we will briefly outline the MOMFBD image restoration process in Sect. 2.2.1.6. This process is used to correct for seeing effects in observations after they have been acquired.

However, there is one last aside that remains before we move on to the specifics of the SST’s design and its instrumentation as it exists today. I wish to direct the reader...
Exploring two solar telescopes: the SST and IRIS
to two figures that will hopefully keep us securely in the saddle as we piggyback on
the Sun’s ray of light as it traverses the insides of the SST. In Fig. 2.1, the SST’s turret,
tower and the last bit of the optical path before we reach the adaptive optics are outlined
schematically. The different parts depicted in the schematic are labelled in the figure
and named in the caption. I will describe the different components that are depicted in
the schematic in the next section (Sect. 2.2.1.1), and I invite the reader to follow along
in the figure as we trace the path of the light rays from where they enter the telescope
at the top of the schematic. The second figure that will aid us greatly going forward is
shown in Fig. 2.2. Here, the setup of the SST’s optical table is shown, which houses
the instrumentation beyond the telescope’s tower. Again, the different components
are labelled in the schematic and then named in the caption. This figure might seem
daunting at first glance, but its contents will hopefully become clearer as we turn to the
sections on the adaptive optics system (Sect. 2.2.1.2), subsequently to the section on the
red beam (Sect. 2.2.1.3) and finally the blue beam (Sect. 2.2.1.2). For all three sections,
I invite the reader to follow along the relevant parts on the schematic once more; quite a
few optical components will be mentioned in the following, but armed with these two
schematics, at least their spatial relationships along the optical path should be easier to
track.

2.2.1.1 Reach for the sky: the tower and the turret

The SST has an altitude-azimuth turret, rotating about two axes, and with it tracks the
Sun across the sky. The main optical components of the SST consist of its main singlet
lens with a clear aperture of 0.97 cm and two flat mirrors that are all housed in the
telecope’s turret. The main lens focuses at a distance of 20.3 meters at a wavelength of
460 nm. The tall 17 meter tower of the SST is thus also useful in that it covers a large
part of the main lens’ focal length, besides mitigating seeing. The main lens suffers from
chromatic aberration, which is corrected for later in the light-path, but its design already
corrects for coma. After the light passes the primary lens and the two flat mirrors, it
is transmitted into the vacuum-tower. The tower houses a 60 mm field mirror and a
Schupmann corrector. The latter corrects for the chromatic aberration of the main lens,
and consists of a 30.5 cm lens and a 30.0 cm mirror. The light is then transmitted out
of the vacuum-tower and towards the horizontal optical table beyond. Here, there is
normal atmospheric pressure, much to the delight of observers who service or initialize
the instruments located there.

2.2.1.2 Bending light: The adaptive optics system

The adaptive optics system at the SST assumes the seeing-scenario sketched out in the
chapter’s preamble; the Earth’s atmosphere distorts incoming light, at a scale measured
by Fried’s parameter, $r_0$, such that an image that spans lengths greater than $r_0$ in the
atmosphere will be distorted. To mitigate these effects, the SST has an integrated AO
system that incorporates both a tip-tilt mirror and a deformable mirror, which work
in tandem to actively correct the image originating from the tower. The information
necessary for these corrections is collected further down the light path, past the point
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Figure 2.1: A schematic of the SST’s turret, tower and vacuum system is shown in the centre. Light enters from the top of the schematic. First, the light passes through the turret’s opening and the main 1-m lens, before it is reflected by the two altitude-azimuth mirrors and into the interior of the tower. The light then passes through the different optical elements as shown in the main schematic and detailed in the separate inlets. The different inlets show setups of, A: the field mirror and the field lens, B: the Schupmann corrector and C: the reimaging optics that consist of the tip-tilt-mirror, the adaptive deformable mirror and a re-imaging lens, which all reside on the optical table. See the text for further details. The schematic first appeared and is reproduced from Fig. 1 in Scharmer et al. 2003.

at which the light is split into a red and a blue beam, by a wave-front sensor and a correlation tracker.
Figure 2.2: Schematic of the SST’s optical table. Sunlight enters from the top left and is coloured alternatingly red and blue prior to the dichroic beam splitter, and red and blue for the subsequent red- and blue- beams respectively. The meaning of the different abbreviations are as follows. FL: Field Lens, FS: Field Stop, TM: Tip-tilt-Mirror, DM: Deformable Mirror, RL: Reimaging Lens, DC: DiChroic beamsplitter, DBS: Double BeamSplitter, CT: Correlation Tracker, AO WFS: Adaptive-Optics WaveFront Sensor, WB BS: Wide-Band BeamSplitter, FPI: Fabry-Pérot Interferometer, LCs: Liquid Crystal modulators, P BS: Polarizing BeamSplitter, NB: NarrowBand, WB: WideBand, NBT: NarrowBand Transmitted, NBR: NarrowBand Reflected, PD: Phase Diversity. The schematic is not to scale nor are relative distances or angles accurate. The schematic is reproduced with the much appreciated permission from Mats Löfdahl from Fig. 2 in Löfdahl et al. 2018.

The tip-tilt mirror comes first, and it behaves as the name implies; it tips and tilts in its entirety and corrects for seeing-effects that effect the entire image coming from the tower. It aims to move in inverse lockstep with unwanted movements of the original image, correcting for them. The tip-tilt mirror not only corrects for atmospheric seeing effects, but also for unwanted movements of the turret. The deformable mirror that follows is also aptly named; it is deformed by 85 tiny actuators that push and pull on the mirror from its rear. These deformations seek to distort the reflected image in the inverse to small-scale distortions caused by seeing. The deformable mirror operates at a staggering rate of 2 kHz to achieve this. The AO system has also been updated over
the SST’s lifetime; the observations used in Paper I of this thesis were recorded when it possessed a deformable mirror that was controlled by only 37 actuators.

After the tip-tilt mirror and the deformable mirror follows a dichroic beam splitter that carves the light into a red and a blue beam. The light is split at 500 nm, such that the blue beam has light of wavelengths less than 500 nm, and the red beam above. The blue beam is split twice more; with the first fork sending most of the light towards a narrow-band beam, where further instruments lie, and towards a wide-band beam. In the wide-band beam, the second fork takes place, and here a correlation tracker receives some of the blue beam’s light. The correlation tracker is used to estimate the larger-scale movement of the incoming image, and it provides the corrections that the tip-tilt mirror must perform to correct these. The red beam is also split. After its first fork sits a Schack-Hartmann wavefront sensor which controls the deformable mirror. The sensor matches the deformable mirror in geometry (in terms of its 85 actuators), and it estimates the corrections the deformable mirror has to perform.

The adaptive optics system as a whole works as a closed-loop system; at any given time the sensors will detect changes in the incoming image and will instruct both the tip-tilt mirror and the deformable mirror to correct for these in real-time. If the corrections are possible in a sufficiently small time-frame, the system will continue to operate in its loop successfully. However, if atmospheric seeing is severe enough, distortions will exceed the ability of the mirrors to correct, and the sensors will also be unable to provide the necessary feedback to correct them. This means that the AO cannot keep up with the seeing, either because it varies on too short time scale, or over too small spatial scales. In either case, it means that the observers have the opportunity to sneak in a snack while they wait for seeing conditions to improve. If seeing is sufficiently good, the actual scientific instruments along the red and blue beam can be used, and we will detail each path past the 500 nm dichroic splitter below.

### 2.2.1.3 The Red Beam

The red beam of the SST is chiefly characterized by the CRisp Imaging SpectroPolarimeter, or CRISP, instrument. It was first installed in 2008 and has provided excellent observations since, going through both repairs and upgrades throughout this time, keeping it up-to-date with technical advances. The spectropolarimeter enables the detailed sampling of different spectral lines with full Stokes information available for a subset of them (dependent on calibration). The red beam setup with CRISP is very flexible in that it allows for a wide variety of choices in terms of optimizing between observation parameters, chiefly the time-resolution, the number of observed spectral lines, the spectral resolution of the scanned spectral lines and whether polarimetry is acquired. For example, by limiting the number of spectral lines that are observed as well as the number of wavelength sampling points for them, the time-resolution is much improved, allowing for the capture of extremely dynamic phenomena. On the other hand, densely sampling several spectral lines and capturing full polarimetry for one of them will cause the time-resolution to suffer, but this may be worth the cost if the phenomena under study is less dynamic but its magnetic setting is under investigation. Here, I will chart the red beam’s and CRISP’s layout as it exists at the time of writing.
Following the dichroic beam-splitter along the red beam, the light is split again, as mentioned above. Some of the light is diverted to the AO’s Schack-Hartmann wavefront sensor, as explained above. The rest is sent onwards to the what constitutes CRISP when considered in its entirety. A rotating shutter-wheel first blocks incoming light at specific time-frequencies; this is necessary to synchronize the image-recording of the CCD cameras further down the beam. These cameras do not have sufficiently accurate read-out times, and must therefore be synchronized mechanically to ensure that the level of synchronicity between the cameras is sufficient for the MOMFBD post-processing. Along the blue beam, such a mechanical shutter is not necessary because it uses newer cameras that can be synchronized electronically; the cameras along both light beams will be updated in the future, which will also remove the need for this setup on the red beam.

Next, a prefilter-wheel allows for a varied selection of prefilters that determines which wavelength band is permitted further down the red-beam, blocking the rest; the prefilter wavelengths can be changed by turns of the wheel in timespans of 250 ms – 600 ms, depending on the position of the prefilters on the wheel. This allows for observations in different spectral lines during the same observational run by switching between prefilters throughout. New prefilters were obtained for the SST for the observing season of 2018 because the old ones had some unwanted focusing power. Only the new and improved prefilters are therefore encouraged for use. The new prefilters allow observations in the spectral lines of Mg i 5172 Å, He i D3 5876 Å, Fe i 6173 Å, Fe i 6302 Å, H i 6563 Å and Ca ii 8542 Å, enabling the observation of a wide variety of solar temperatures and many diagnostic uses. Observations originating from along the red beam of the SST and that were used in the publications included in this thesis were obtained in the timeframe of 2010 – 2016. During this time period, there were few significant changes to the red beam’s setup, and the major differences in the red beam during the given timeframe and the current time of writing are the newly installed prefilters just mentioned. Today, the prefilters of the iron, the Ca ii 8542 Å, the Mg i 5172 Å and the He i D3 5876 Å lines are also pre-calibrated for polarimetry measurements later in the beam, especially useful for the study of magnetic fields on the Sun. Following the prefilter-wheel, a wide-beam beam-splitter diverts some of the light to a wide-band camera that records the raw wide-band spectral line observations. These wide-band observations are used as reference images for later MOMFBD processing, but can also be used for scientific purposes in their own right.

The rest of the light continues onwards towards a pair of ferroelectric liquid crystal modulators; these modulators replaced older nematic liquid crystal modulators before the observing season of 2015, and are faster than their predecessors. They are also especially suited for operation at different wavelengths. The modulators allow for the recording of the four different Stokes parameters, provided that the current prefilter is calibrated for it, enabling polarimetry in the line.

Next, the light is re-focused by reimaging optics, before we arrive at CRISP’s most vital components. CRISP’s primary feature is the scanning of specific spectral lines at excellent spectral resolution. The primary spectral line is selected by way of the prefilter discussed above. In order to sample the incoming light at more specific wavelength positions within the selected spectral line, CRISP employs a dual Fabry-Pérot Interferometer, or FPI. The FPI consists of two tunable interference etalons...
(IEs). Much simplified, each of the interference etalons consists of two parallel plates. The outer surface of the plates permits light to enter, while their inner surfaces are extremely reflective. Between the two plates, constructive interference of light that enters and is reflected many times produces infinitely many transmission peaks, though they are located at specific and quantized wavelength positions. This works akin to the constructive interference in a flute, in which specific wavelengths of sound are selected for instead. When playing the flute, one manipulates the distance available to the air-flow inside, producing specific notes. In much the same way, one can select the wavelength locations for the transmission peaks of an interference etalon by tuning the distance between its two reflective plates - and thus, light can be made to sing. The inner surfaces of the IE plates have a very low transmission rate. Therefore the light that eventually passes outside will have been tuned to the specific wavelength range of the IE by the many reflections between the two plates. As mentioned, a lone IE will produce infinitely many transmission peaks, whereas only one of these peaks is actually wanted in order to probe only one very narrow wavelength-region inside a spectral line. This problem is solved in two steps. First, the initial prefilter limits the incoming light to a relatively wide wavelength-band, limiting it to the spectral line in question. The second step is the combination of the two IEs that the dual FPI consists of. The first of the two IEs is a high-resolution (HR) IE, and it produces the very narrow transmission peak at the wanted wavelength position, but also unwanted secondary transmission peaks. The second IE is a low-resolution (LR) IE that is used to sufficiently suppress the unwanted secondary transmission peaks that are produced by the HR IE. Once the light exits the dual FPI it is therefore limited to a very narrow wavelength, determined by the tuning of the two IEs. The HR IE determines the final wavelength width that CRISP can be tuned to in order to sample a wavelength, and its spectral resolution ranges from 22.9 mÅ to 107.3 mÅ. The best resolution is achieved when probing the Mg I 5172 Å line at shorter wavelengths, while it has its greatest value in the Ca II 8542 Å line, at longer wavelengths. These limits are excellent, and allow for very detailed probing of spectral lines.

Following the heart of CRISP that is the dual FPI, we first come to another set of imaging optics. Then, we come to a polarizing beam splitter. It splits the light into its vertical and horizontal components, and each of the resulting beams is recorded by its own narrow-band camera. This polarizing beam splitter setup and the separate and simultaneous recording of the two polarized orthogonal components allows for the removal of polarization cross-talk caused by seeing.

At this point, all light branches in the red beam have reached their final destinations. Throughout observations, CRISP will run through its pre-selected set of prefilters. For each of the wide wavelength bands, the Fabry-Pérot interferometer then tunes to the specific wavelength positions that are desired, scanning the relevant spectral line. As the dual FPI scans the line, the cameras all record a frame for each of the narrow-band tunings. After one cycle is completed, all lines are scanned again. Once observations are complete, they are ready for post-processing. Before we turn to the latter, we will first examine the blue beam of the SST. However, we will save some time in its exploration because it shares many similarities in both its setup and components with the red beam.
2.2.1.4 The Blue Beam

On the other side of the dichroic beam splitter, nowadays the blue beam is as much defined by the CHROMospheric Imaging Spectrometer, or CHROMIS, as the red beam is by the CRISP instrument. However, CHROMIS is a much more recent addition to the SST and is the younger sibling of CRISP. Correspondingly, they share many similarities, but also some differences. In the context of this thesis, it is important to note that since the observations used for the thesis’ original work were originally obtained in the years 2010 – 2016, CHROMIS itself was not yet installed during this time. However, I have participated in work utilizing observations from CHROMIS (Esteban Pozuelo et al. 2019), and I find it would be remiss not to present the SST as it operates at the time of writing, while also providing the context of the observations actually employed for this thesis. I will therefore first outline the blue beam’s setup as it existed when the thesis’ observations were obtained and then move on to the current setup and CHROMIS as they exist at the time of writing.

Pre-CHROMIS

Before the installation of CHROMIS, the blue beam was more sparsely populated by instruments than the red beam. Following the dichroic beam splitter, the blue beam was split by a beam splitter with light diverted to the first instrument along the blue beam, namely the correlation tracker. At this time, the correlation tracker already functioned as described in Sect. 2.2.1.2. Following the correlation tracker, the blue beam continued onward, passing three consecutive beam splitters, with each beam splitter diverting 50% of the light to different components, and with the light arriving at four different cameras. Following along the main blue beam, I will enumerate the different secondary beams.

Forking off from the first beam splitter, light was diverted to the chief science-instruments on the beam. Here, a narrow-band filter was positioned after the split, with an imaging camera positioned behind it. This narrow-band filter was used to sample in and around a specific spectral line. This filter could not be changed during observations. The narrow-band filter used was typically one centred on the Ca\textsuperscript{ii} H line core. There was a limited possibility to scan the spectral line by tilting the narrow-band filter in relation to the incoming light, thereby slightly altering its transmission profile and shifting its central wavelength compared to when it was kept perpendicular to the beam. During this time of the SST, this tilt-able narrow-band filter was therefore the blue beam’s “poor man’s” counterpart to CRISP. At the time, the spectral resolution in the Ca\textsuperscript{ii} H line was given by a FWHM of 0.970 Å when there was no significant tilt of the filter (a value ascertained experimentally in Löfdahl, Henriques, and Kiselman 2011). The resolution of the old Ca\textsuperscript{ii} H line narrow-band filter was therefore eight times worse than CHROMIS’ current wavelength resolution in the Ca\textsuperscript{ii} H line, which today is characterized by a FWHM of 0.120 Å. Furthermore, with increasing tilt-angles during scans of the Ca\textsuperscript{ii} H line, the spectral resolution of the old narrow-band filter was further degraded as an inescapable by-product of the process. In practice, the tilt-able Ca\textsuperscript{ii} H line filter was rarely used to actually scan the line. This was mostly due to the fact that this process also degraded the cadence of the science data, and this trade-off was usually deemed more costly than beneficial. Thus, while scans in the blue beam using this setup
were sometimes useful, the need for an instrument akin to CRISP in the blue wing of
the SST was evident, given the process’ drawbacks and limitations.

Following the main science beam, the next beam splitter directed a beam towards
a Ca II H line-wing narrow-band filter centred at a wavelength of $\lambda = 3964.7$ Å and
with a FWHM of 1.2 Å. This beam was then recorded by a second camera. This
camera was housed in a “tower” setup, for which the light-beam was directed up in the
vertical direction before recording. The Ca II H line-wing filter of this branch imaged
wavelengths further out in the Ca II H wing than the previously described Ca II H line
narrow-band filter could image when tilted. Also, as previously mentioned, since the
Ca II H line-core narrow-band filter was usually not used to scan the line anyway, an
additional wavelength position in the Ca II H line region meant that solar features could
be tracked through different height regimes with this setup.

The main, “still raw”, blue beam (following the first two camera-forks) then passed
through a final wide-band filter centred at a wavelength of $\lambda = 3954$ Å, with a much
larger FWHM of 10 Å. This wide-band beam was then split one last time, with the
two beams recorded by one camera each. Both of these cameras were also housed
in the vertical, with the light directed upwards. These wide-band channels provided
both photospheric images as well as yielding an anchor channel for the MOMFBD
process. Furthermore, the two cameras formed a phase-diversity camera pair; one of
the cameras recorded the beam 1 wave out of focus, for special use in the MOMFBD
image-restoration process (the reasoning for which will be mentioned in Sect. 2.2.1.6).

After observations were performed, all the recorded images from all (running)
cameras were reduced as one dataset in the MOMFBD restoration process. In practice,
the old network and computing system at the SST was not capable of running all four
cameras at the same time however; this was due to the sheer amounts of data that could
be produced by the 2k × 2k pixel cameras when they ran at their maximum frame rate
of 10.8 frames per seconds. A greater number of frames per second usually yields the
best results when applying the MOMFBD image restoration process afterwards, rather
than using more wavelength channels instead. Therefore, in order to maximise the
total number of frames per seconds, rather than channels, this meant that in practice
some channels were not recorded when observing. As an example, for the blue beam
observations from June of 2010 that were utilized in Paper I and Paper II, only the two
cameras actually recorded data; only the narrow-band Ca II H line-core channel and
only the focused wide-band channel were actually recorded. However, since the seeing
conditions were excellent, this still provided for very high quality observations (despite
the reduced number of channels available for the MOMFBD restoration process; see
Sect. 2.2.1.6). With the old pre-CHROMIS setup sketched out, we will now turn to the
current setup of the blue beam, which includes the CHROMIS instrument.

**CHROMIS**

Turning to more recent times, in 2016 CHROMIS was installed, joining its elder
sibling, CRISP, at the SST. To date, CHROMIS is capable of performing detailed scans
of spectral lines, but unlike CRISP it does not yet posses the ability to record any
polarimetry. CHROMIS is specifically optimized for observations in the Ca II H and
Ca II K lines. Like CRISP, it also employs a dual Fabry-Pérot interferometer to scan
spectral lines in detail. Below, I will give an overview of the setup for the blue beam and CHROMIS as the setup exists at the time of writing. I refer again to Fig. 2.2 for this newer setup.

We begin again at the start of the blue beam, following the beam after the dichroic splitter divides the telescope’s light into the red and blue beams. First, the blue beam is split again by a double beamsplitter, where the main beam leads towards CHROMIS. We will first examine the secondary beam, before doubling back to the main beam and CHROMIS.

The secondary beam is split again, where the first half leads towards the correlation tracker of the AO system, which functions as discussed previously. The other half of the secondary beam is transmitted through a wide-band filter that is selected independently from CHROMIS’ observing configuration. After this wide-band filter, the beam is split yet again and recorded by two cameras. One camera records the wide-band beam both for the purposes of aligning observations between the blue and the red beam, and for use in the MOMFBD restoration process. Since the wavelength region of this wide-band beam can be selected separately from the wavelength that CHROMIS itself observes in, it allows for easier alignment by use of a 3950 Å wide-band filter, which yields images of the photosphere. Photospheric features can then be used for high-precision alignment of the red and blue beam observations. It is also possible to select an Hβ wide-band filter, that is offset by 1.5 nm, providing reference observations in the continuum. The other camera along this wide-band branch records the wide-band beam but 1 wave out of focus. These recordings are used in the phase diversity image restoration that is incorporated in the MOMFBD process, similar to the approach that was used for the old blue beam setup.

Returning to the main beam that splits off towards CHROMIS, the instrument’s first component is a prefilter wheel which determines which wavelength band that CHROMIS observes in, and which therefore determines which bandpass that the instrument can subsequently scan through. In the wavelength region of the Ca ii K and Ca ii H lines, the narrow-band prefilter-wheel offers five different narrow-band filters. These filters have narrow bandpasses with FWHM values of 0.41 nm to 0.42 nm, and they are centred on the Ca ii K blue wing, the Ca ii K core, the Ca ii H core, the Ca ii H red wing and the Ca ii continuum. The prefilter wheel offers an additional prefilter centered on the Hβ line, which has a FHWM of 0.48 nm. After the prefilter wheel follow focusing optics. We then come to CHROMIS’ own Fabry-Pérot interferometer, which scans through the pre-selected spectral-line regions by the same principle as for CRISP. For the Ca ii line wavelength-region, CHROMIS’ FPI is able to sample with a spectral resolution of 120 mÅ, while it has a resolution of 100 mÅ when scanning in the Hβ region. After the FPI system, there are again focusing optics before the beam is imaged and recorded on the narrow-band camera located at the end of the beam. As mentioned, the blue beam lacks a mechanical chopper that physically blocks light at a given time frequency in order to synchronize the cameras down along the beam branches. Instead, the blue-beam cameras are synchronized electronically.

During observations, CHROMIS operates simultaneously and independently of CRISP, and the two instruments provide detailed and concurrent line scans in the two disparate spectral regions. When CHROMIS became operational, the SST was finally able to provide detailed line scans in the Ca ii K, Ca ii H and Hβ lines, which enabled
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entirely new avenues of study with the telescope. In the future, CHROMIS will no doubt benefit from the same type of gradual upgrades as CRISP has benifited from over the years. In the future, we can therefore expect that CHROMIS will be able to observe in additional spectral bands and importantly, that it will also gain the capability to capture simultaneous polarimetric information. Both of these additions would once again open up new and exciting avenues for exploring the solar atmosphere, all thanks to the SST’s versatile design that enables continual improvements and upgrades. With our tours of the SST’s light paths complete, we will now turn to the topic of how observations are processed after their recording.

2.2.1.5 The data reduction pipeline at the SST

After the actual observations captured by the SST’s instruments are complete, they are not yet suitable for scientific analysis. Common to all modern telescopes, the data has to be made-science ready through use of both calibration data that is used to correct for noise that results from instrumentation and the optical system of the telescope. Such corrections include the somewhat straight-forward mitigation of dark current (mostly noise in camera equipment) and flat-field effects (variations in sensitivity across the FOV of cameras and the optical equipment), among others. Such corrections can be corrected for to very good precision by the use of calibration data. These are typically obtained by capturing data and running instruments while not actually observing any light source, or by the observation of a uniform and known light source that can be calibrated against. These are necessary for both ground- and space- based telescopes. Post-facto corrections for seeing are only necessary for ground-based telescopes, and are carried out through use of the MOMFBD image restoration process at the SST. At this point in time, the full data reduction pipeline for the SST is very involved and continues to grow in complexity. Especially since the installation of CHROMIS however, there has been an effort in consolidating miscellaneous data reduction processes and the MOMFBD restoration in one pipeline. This consolidation and the newest features and improvements of the SST’s data reduction pipeline are described in Löfdahl et al. 2018, and I direct the reader here for details. Previously, much of the reduction processes were undertaken both as disparate steps and in partial isolation between the red and blue beam setup. The new iteration of the SST pipeline was designed to be easier to use without requiring as much deep, intimate knowledge of the underlying methods and the inner workings of the pipeline as was previously the case. Such requirements always pose a barrier of entry for new users, and ease-of-use becomes a serious concern the less streamlined a complex data pipeline is. Furthermore, making the data reduction more efficient also frees up more time for experienced users, time that can now be spent on actual scientific analysis instead.

Until recently, the reduction pipeline used for observations from CRISP, called CRISPRED, and the one used for the blue beam were largely formulated and executed in isolation. With the installation of CHROMIS a new pipeline called CHROMISRED was created for the instrument. It began as a fork of CRISPRED, due to the similarity of the two instruments. Today, the newest versions of CRISPRED and CHROMISRED are incorporated as different run-modes of the new and consolidated reduction pipeline used for the reduction of all SST data, which is called SSTRED. The efforts in consolidating
the SST’s reduction pipeline also resulted in a new-and-improved MOMFBD reduction pipeline called REDUX, which is also incorporated into SSTRED. REDUX both added features and improved the use of computational resources and has less required runtime than previous iterations. As part of the new developments, an effort has also been made towards including relevant metadata in the SST’s science-ready observations, aiming for a standardized approach that is more in line with those used for other telescopes. Especially for space-based telescopes there has been a pioneering effort in which both raw data, the data reduction pipelines, as well as metadata is made widely available through online databases. The new SST pipeline is now also freely available online, and observations reduced with the new pipeline now also includes newly-standardized metadata for the output observations. The inclusion of standardized metadata means that observers not familiar with the SST and its data reduction process should encounter less problems working with the actual science-ready observations. The planning for the inclusion of metadata was done in conjunction with the SOLARNET project, which has made efforts to formulate a standard for metadata accompanying solar observations. This is meant to facilitate planned Solar Virtual Observatories that aim to incorporate observations from a variety of solar telescopes for easy dissemination of observations in the scientific community.

Some SST and IRIS co-observations are already made available to the community at large. Observations used in this thesis exemplify the ongoing improvements to the SST and upgrades to both its instrumentation and its data reduction pipeline; the SST observations used in Paper I for this thesis predate both CHROMIS and consequently large parts of the above developments, while co-observations by the SST and IRIS that were studied for Paper III are now freely available online. Through the upgrades of the SST’s reduction pipeline it is now part of an increasing push towards more streamlining, ease-of-use and the easy sharing of both code and solar observations between solar physicists. To anyone that has pored over arcane scripts that are distributed over many different files, all of which require careful application and tweaking depending on the specific observations being reduced, these are all welcome developments.

### 2.2.1.6 MOMFBD corrections and post-processing

Here, I will sketch out only a very brief description of the MOMFBD process that is used to correct for seeing in SST observations. In particular, I wish to grasp the opportunity to illustrate how the data reduction process of a telescope’s observations are most optimized when the design of the physical telescope and that of the reduction process of its observations are carried out in harmony. The core of the MOMFBD process used for SST observations is described in van Noort, Rouppe van der Voort, and Löfdahl 2005. The MOMFBD reduction process has seen incremental improvements and changes throughout the years. As a major example, it has been adjusted to accommodate CHROMIS. However, the actual underlying assumptions and principles have remained the same. It is only these basic principles that we are interested in here, and for details and further developments, I direct the reader to the literature once again. For the initial description of the MOMFBD system at the SST, see van Noort, Rouppe van der Voort, and Löfdahl 2005 and van Noort, Rouppe van der Voort, and Löfdahl 2006, and for a subsequent descriptions of it in use, see van Noort and Rouppe van der Voort 2008. For
the most recent changes to the MOMFBD REDUX pipeline at the SST see Löfdahl et al. 2018.

Multi-object multi-frame blind deconvolution image restoration operates under the basic assumption that a recorded image of an object is comprised of a “true” image that depicts the actual object that has been convolved with a space-invariant point spread function (PSF) and random noise, both of which distort the “true” image. The PSF encompasses both the seeing effects of the atmosphere, as well as any image distortions that are inherent to the telescope (and which have not been mitigated by previous, simpler, image corrections). The task of the MOMFBD process is then in essence to estimate the PSF and deconvolve it from the recorded image to find a closer approximation to the true image.

In a much-simplified way, the core of the MOMFBD process can be sketched out by describing the base assumptions underlying the first two parts of its name. In order to estimate the PSF that distorts the observed images, the algorithm can utilize different images that share the same PSF. To achieve this, simultaneous observations in different wavelengths are recorded, which yield images that show “multiple objects”, since the solar atmosphere appears different for different wavelength bands. For the SST, this is facilitated by the wide-band cameras that are included for both the red and the blue beam. These wide-band recordings are in the same wavelength band as either CRISP or CHROMIS are scanning, and thereby provide simultaneous reference images for this part of the process. Thus, for each time-frame in the recordings, multiple objects are imaged (although the field of view is the same, the scene differs in the different wavelengths). These images are affected by the same PSF, determined by the current seeing conditions, making its estimation more accurate. However, without being able to determine what aspects of the images differ because they capture different objects (or solar heights) or whether it is the PSF distorting the images, the determination of the PSF is still difficult. The multi-frame component of MOMFBD is the counterpart to the multi-object component. If one assumes that a given object being imaged is unchanging with time, but that the PSF that distorts the image does change with time, its estimation would become trivial given enough recorded frames to estimate the appearance of the unchanging object. Such a scenario can be approximated by assuming that the imaged solar surface does not change as fast as the PSF does. One can then record many images for which the PSF changes, but the imaged scene only changes very little. For images recorded in quick succession, this is approximately true, since the solar features typically change on slower timescales than the Earth’s atmospheric seeing-inducing effects. Therefore, for short bursts of images, the PSF’s change can be estimated from frame to frame, and by inference, the PSF itself. Combined with the multi-object step, the estimation of the PSF then becomes feasible to sufficient accuracy. The blind-deconvolution in MOMFBD refers to the fact that the process begins with a “blind” assumption on the PSF, because the problem is inherently ill-constrained when considering only a single image, where an infinite number of PSFs could in principle be distorting the image.

The aberrations of the incoming wavefront, caused by the atmospheric seeing-effects, are in practice approximated by a linear combination of basis functions in the MOMFBD implementation. In actuality, only a subspace of all theoretically possible aberrations are considered, and are found by use of Karhunen-Loève modes. In practice, the PSF is
estimated in small, overlapping patches across the recorded FOV for each wavelength, for each scan. The PSF of each sub-patch is de-convolved from the image separately and then combined. The PSF subpatches conceptually correspond to the isoplanar patches in the atmosphere over which the aberrations of the incoming wavefront are uniform. Appropriate PSF subpatch sizes are thus correlated to Fried’s $r_0$ parameter for the given observation’s seeing conditions. The patch sizes must therefore be tuned to the seeing conditions accordingly. This makes for easier and faster MOMFBD reduction for large values of $r_0$ and thus subpatch sizes, or for more difficult and slower MOMFBD reduction for smaller values of $r_0$. By use of a phase-diversity channel (now in use for both the red and the blue beam), the MOMFBD process can also correct for some static aberrations caused by the optical setup.

After MOMFBD, some post-processing of the observations remain before it is science-ready. These includes the de-rotation of observations. This is necessary because the SST’s turret rotates about its axis as it tracks the Sun across the sky, and therefore the solar surface also rotates in the field of view as it is recorded. Residual errors, dubbed “rubber-sheet” motions caused by atmospheric distortions smaller than the MOMFBD’s PSF sub-patch size are also mitigated, to the extent it is possible. This is done by removing detected differences in images recorded at the same wavelength but at adjacent time-steps. Images from the red and the blue beams also need to be aligned, using wide-band images from either beam. The actual time-resolution of the final, reduced observations is also lower than that of the actual recorded observations. This is because the MOMFBD process relies on a much greater time-resolution to estimate the atmospheric seeing than what is actually retained for the final observations. Neglecting all the glossed-over detail in the processes outlined above, the SST’s observations are then science-ready, and actual scientific analysis can begin. Without further ado, we therefore turn to loftier heights and our next telescope of particular interest - IRIS.

2.2.2 The Interface Region Imaging Spectrograph

The Interface Region Imaging Spectrograph is a space-based imaging telescope that was launched into space in June of 2013. The design and instruments of IRIS are well-described and documented in the great resource that is De Pontieu et al. 2014, from which the information in this section is largely drawn from. It is there that I direct the reader for detail that might be missing in this section, where I will limit myself to a briefer overview than for the SST. IRIS now circles us in a Sun-synchronous, low-Earth orbit. The Sun-synchronous orbit was chosen in order to maximize the amount of time that the satellite can observe the Sun without the Earth blocking the Sun. During a given year, from the start of February and almost through October, IRIS is able to view the Sun without any interruptions. In November and January, IRIS flies in the Earth’s shadow for parts of its orbit, and cannot observe during these periods. Naturally, the conception and eventual launch of IRIS was motivated by the desire to study that which inspired its name - the interface region of the solar atmosphere. In this context, the interface region encompasses both the chromosphere and the transition region, as outlined previously. At the time of its planning and launch, there were many open questions surrounding this highly dynamic region. And although much headway has been made since, in part precisely due to new observations that could only have been provided by IRIS,
many question also remain. The interface region holds the keys to understanding many unexplained processes on the Sun. Both the heat and material that fuel the corona must pass through this region, and the coronal heating problem is still not adequately explained. Furthermore, the heating of the chromosphere, in particular its upper reaches, is also not yet fully understood. The processes in the chromosphere and the TR are shaped by a confluence of different types of transitions. In the chromosphere lies the transitional region where the plasma goes from being dominated by mass-motions and from where the magnetic field follows the plasma motions, to larger heights, where the magnetic field dominations the motions of the plasma instead. This boundary is traced out by the \( \beta \) parameter (discussed in Chapter 1), which can be used to draw a tenuous surface somewhere in the chromosphere where the magnetic pressure and the gas pressure are equal, and \( \beta = 1 \). This interface determines many dynamics in the plasma and is the region where waves can undergo mode-conversions and where the main energy transfer can shift from being mediated by mass motions, to transfer by way of the magnetic field. The TR is home to the rapid rise in temperature of 10,000 K to the order of 1 MK that is observed in the atmosphere and that precedes the corona. IRIS was specifically designed to probe this interface region, although it is also capable to observe in wavelengths that originate from the photosphere and the corona. The interplay of flux emergence from deeper layers in the atmosphere with the onset of flares and mass ejections also pose interesting questions. IRIS provides observations in pass-bands corresponding to the wide variety of temperatures and solar heights that these phenomena correspond to. Since these wavelengths typically lie to the blue of visible light, these are largely inaccessible to ground-based telescopes (as we saw in the beginning of the chapter). Earlier observations in these passbands obtained by either rocket or balloon flights only provided a very limited volume of observations. Other space-based satellite missions provided more long-term observations, but observations from all these sources were at lesser resolutions than what IRIS is capable of of providing today.

The three general questions that the IRIS mission was motivated by are (chapter 3, De Pontieu et al. 2014),

1. “Which Types of Non-Thermal Energy dominate in the Chromosphere and Beyond?”
2. “How Does the Chromosphere Regulate the Mass and Energy Supply to the Corona and Heliosphere?”

To provide sufficient spatial-, spectral- and time- resolutions with its various instruments, the satellite’s scientific mission requirements were meticulously formulated; all the while, the stringent constraints imposed on its design by virtue of its space-based mission had to be weighed against its scientific goals and naturally, trade-offs had to be negotiated. In the end, IRIS has proved to be a rousing success, and has delivered many new insights. I will give a brief overview of its properties and its main instruments below.
2.2.2.1 IRIS’ scientific instruments

IRIS’ base is a Cassegrain telescope with a field of view that spans 3’ × 3’, and that employs a primary mirror with a diameter of 19 cm, and has a secondary mirror capable of changing its focus. It observes in the far ultraviolet (FUV) band, spanning from 1332 Å to 1407 Å and in the near ultraviolet (NUV) band, spanning from 2784 Å to 2835 Å, and sends the captured light onwards to different instruments inside its spectrograph box.

IRIS’s chief characteristic is that it can observe images in different pass-bands simultaneously as it collects spectra with a separate slit-spectrograph that intersects the FOV of the image(s). The slit-spectrograph can collect spectrograms along its entire length, which spans the height of the image-FOV, and more importantly it is designed so that it can scan through the image-plane at discretized raster-positions. In this way, spectra along the nominal y-axis can be collected at set positions along the nominal x-axis through time, as the spectrograph slit is exposed at the discrete raster-slit positions. The scanning with the raster-slit is in actuality performed by the scanning of the secondary mirror of the telescope perpendicular to the slit orientation, which in turn means that the slit is exposed to different parts of the Sun.

The basic setup of the telescope is such that light from the main telescope-tube is directed towards the spectrograph box, where it is first focused on a slit assembly. The slit assembly is comprised of a reflective outer surface that houses a slit-prism - this means that one part of the beam is reflected towards the imaging path that actually produces resolved images of the Sun, while part of the beam passes through the slit, which disperses the beam in two directions. The two directions of course correspond to the FUV and NUV passbands that IRIS is set up for. The two FUV and NUV beams are then directed towards their separate spectrograph units, with their own camera assemblies. The reflected beam is passed through or reflected off of selected broadband filters, producing images in the wide-band of corresponding spectral lines. The produced images are named “slit-jaw” images (SJ images or SJI), as they are the result of the light that is reflected off of the reflective surface that surrounds the slit-prism, or “slit-jaw”.

The slit-jaw imager

The slit-jaw imager provides wide-band observations in bandpasses each respectively dominated by the Mg η wing around 2830 Å, the Mg η k 2796 Å line, the C η 1334/1335 Å line-pair, and the Si iv 1394/1403 Å line-pair. These lines originate from throughout the solar atmosphere, covering the photosphere (Mg η wing), the chromosphere (Mg η h/k) and the transition-region (C η and Si iv). The slit-jaw images have FOVs of 175” × 175” and have a spatial-resolutions between 0.33” (in the FUV) and 0.4” (in the NUV).

The Spectrograph

IRIS’ two slit spectrographs cover each of the FUV and NUV passbands and are separately recorded on different CCD assemblies. The two passbands cover a variety of lines, formed throughout the solar atmosphere, of course also encompassing those
2. Observing the Sun

imaged by the slit-jaw imager. These bandpasses covered encompass the Mg ii wing, the O i 1335.6 Å line, the Mg ii h & k lines, the C ii 1334 Å & 1335 Å line-pair, the Si iv 1394 Å & 1403 Å line-pair, the two O iv 1401 Å lines and the two iron Fe xii and Fe xxi lines. Together, these cover the formidable log(T) temperature range of (3.7 – 7.0) [log(K)]. The spectrograph has an effective spectral resolution of 26 mÅ in the FUV and 53 mÅ in the NUV. The slit of the spectrograph, as described above, has an effective width of 0.33” and a length of 175”, which is equal to the height of the slit-jaw image FOV. Typically, for high-cadence observations, the brightest lines, namely the Mg ii h & k lines, the C ii 1334 Å & 1335 Å line-pair, and the Si iv 1394 Å & 1403 Å line-pair, are recorded.

Observing with the SJI and the IRIS spectrograph

Since the slit-jaw imager and the two slit spectrographs are intrinsically entwined in their design, the recording of SJ images and of spectral scans are likewise dependent on each other. IRIS has the possibility for a wide variety of observing setups, and the choices made determine both the different wavelengths and spectral lines observed by both the SJI and the spectrograph but also the cadences for the two instruments, as well as the area that is scanned by the spectrograph. There are about 50 different observing modes made available for observers, which are already pre-configured for ease of use, each with specific observation-ids. However, the different modes can also be further customized in terms of their specific parameters.

As previously mentioned, the IRIS spectrograph slit is capable of scanning across the image-plane of IRIS at discretized raster-positions; it can also be operated in a sit-and-stare mode however, in which the slit position is not altered and remains at the same position throughout. In any case, the exposure times are universal for both the slit-jaw imager and the spectrograph, meaning that this value sets the exposure time for both individual raster-slit scans and individual slit-jaw images. In turn, the individual exposure times thus determine the cadence for a series of raster-slit scans for a specific raster-position configuration; the exposure time for individual raster-slit scans and the time needed to move the raster-slit position, before a series is then repeated, determines the cadence of a raster-slit scan. Since the slit-jaw imager runs on the same exposure time as the dual spectrograph, this means that it can record slit-jaw images during the same time as individual raster-slit scans are performed. Therefore, slit-jaw images are recorded in different wavelength regions when the spectrograph is at specific raster-positions for a given observing program (provided that it is not in sit-and-stare mode). However, often-times slit-jaw images are not recorded for all raster-slit positions - either to save on local storage or to eliminate the need to transfer such data to Earth.

The shared exposure time can take values from 0.5 s – 30 s (or more, if going beyond typical observing programs). As mentioned, this limits the exposure time for individual raster-slit scans, and the exposure time for individual slit-jaw images; the cadence between a full spectrograph scan of all individual raster slit positions and the cadence of slit-jaw images at specific wavelengths can thus vary substantially. Generally, the so-called raster modes available for the spectrograph affect the overall scan-times through the number of individual raster-slit positions and by the spatial area covered by each series of scans. The basic raster modes consist of “dense rasters”, for which the step
size is the same as the slit-width of 0.33”, “sparse rasters” and “coarse rasters”, for both of which the step sizes are larger than the slit-width, “sit-and-stare” mode, for which the slit position does not change at all, and finally, “multi-point dense/sparse rasters”, for which a limited number of longer-duration raster-slit positions are selected. The different modes are of course suitable for the study of different phenomena - large-scale features require the scanning of larger areas, perhaps with only sparse coarse rasters, while fast-evolving small-scale features may require smaller scan-areas but with dense rasters, for example.

An illustrative example for a typical IRIS observing program is the one that was employed for Paper III of this thesis, and may illuminate the interplay between the available choices for IRIS raster modes and the possible choices for the recording of slit-jaw images in the different wavelength channels. For this paper, a predefined setup called a “medium sparse eight-step raster” was used, which is a variant of the about 50 pre-defined programs available to observers. This observing program covered a 7” wide region with the IRIS spectrograph and included 8 slit positions separated by 1” that the raster-scan cycled through for each scan, with each slit-scan having an exposure time of 4 seconds. The 0.33” wide spectrograph slit scanned along 60” of its length. This yielded an effective cadence of ≈ 40 seconds between each series of spectrograph scans across the 7” wide region. Slit-jaw images for this program were captured for the Si iv 1400 Å, the C ii 1330 Å and the Mg ii 2796 Å channels twice during each spectrograph series, such that the cadence for the slit-jaw images was ≈ 20 seconds. Lastly, the program also included the capture of slit-jaw images in the 2832 Å channel, but only for every third spectrograph scan-series, making for a cadence of ≈ 122 seconds. As is evident from this example, an incredible amount of different observation configurations are possible; trade-offs between the spatial scale covered by spectrograph scans, the number of spectrograph slit-positions for each scan, which in turn determine the coarseness of the scans, and the temporal resolution required for each spectrograph scan make for optimization problems that must be considered for each individual set of observations and its intended use. The size of the solar features under investigation, the wavelength that are of interest for their study, the temporal scales over which the features change, and more, must be taken into consideration.

Overall, we see that IRIS is a highly versatile instrument. As with any space-based telescope, there are challenges associated with data-retrieval, since all data must be transmitted back to Earth. This means that the volume of scientific data is limited by the available down-link bandwidth of the satellite and is contingent on base-stations that are within signal-range of the satellite for sufficient amounts of time to make transmissions possible. Furthermore, physical upgrades or repairs to IRIS are of course not possible, and instrument failure and degradation will become an inevitability given enough time. In the meantime however, IRIS will continue to provide us with unique observations, and has enabled us to investigate hitherto nigh-inaccessible parts of the solar atmosphere.
Chapter 3

Penumbral microjets

Penumbral microjets are one of many solar phenomena that have been discovered in recent years and are part of a veritable solar zoo that keeps on expanding as more and more species are added to the collection. This ongoing process of discovery is fuelled by the equally rapid advancement of solar physics that has taken place around and since the turn of the millennium. Armed with the treatments in previous sections concerning the Sun, its atmosphere, and some examples of the instruments used to observe it, we will now dive into an overview of penumbral microjets, PMJs, and the current state of knowledge concerning them. The study of PMJs is still a relatively young subfield of a subfield. However, following their initial description in 2007, there has been a steady increase in the number of works published on PMJs. Here, I will attempt to give a somewhat comprehensive overview on the current state of this little subfield. I will do so mostly from the point of view of a solar observer, with an emphasis on concrete observations, although broader theoretical considerations will be touched on. Of course, any such overview will inevitably be biased in subtle, or not so subtle, ways by the author’s own particular interests or specific areas of expertise (or by a lack of the latter). I therefore humbly submit that any glaring omissions or lack of appropriate emphasis, as judged by a particularly astute reader, are merely a result of ignorance and not of malice.

With that said, as we arrive at the crucial point where the main focus of this thesis is to be de-mystified, we may finally ask the question - what are penumbral microjets? I will attempt to answer this innocuous question by chopping PMJs into their metaphorical constituent parts, before hopefully putting them back together again into something more comprehensible than what we had at the start. First, I shall outline the origin story of our fiery protagonists in sect. 3.1. This will also serve as an introduction to PMJs and “the basics”, as it were. With the scene set with how PMJs first entered the stage and having outlined their basic appearance, I will then summarize some different avenues of inquiry into the nature of PMJs and different PMJ properties that have been uncovered so far. In sect. 3.2, we will first examine in which spectral lines and wavelength bandpasses PMJs have typically been observed, and how they appear in both images and what sort of general spectral profile shapes they exhibit in different lines. Subsequently, we will examine how PMJs relate spatially to their host penumbras in sect. 3.3. Armed with an idea of how PMJs appear and where, we will examine their dynamics in sect. 3.4, and what this tells about their nature. Since PMJs are found in sunspots, which host strong and complex magnetic fields, and additionally because PMJs are hypothesized to be caused by magnetic reconnection events, we will summarize what has been learned about the nuances of the magnetic setting of PMJs in sect. 3.5. Since it is the age of modern solar physics, I would be remiss if I did not summarize the efforts to unravel PMJs with the help of numerical modelling and simulations, which I endeavour to do in sect. 3.6. At the very last, I shall give a brief, somewhat personal account of what all
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the preceding sections may tell us about the formational process of PMJs in sect. 3.7.
The last section will also serve as a place for some final remarks before we move on to
the next and final chapter.

3.1 PMJs at first glance

In terms of their prototypical visual appearance, PMJs are chiefly defined as sudden,
elongated brightenings most readily observed at chromospheric heights in the penumbrae
of sunspots. Generally, they have lifetimes on the scale of minutes, lengths on the scale
of a several hundred to some thousand kilometres and some few hundred kilometres
in width. The specific values that are obtained for PMJ lifetimes depend on several
factors however. They depend on which lines that the PMJs are observed in, whether
slow brightening and fading phases are considered, and on whether newly-discovered
associated dark-features that appear in some lines are also considered when measuring
them. Especially the measured lengths are also dependent on whether PMJs are observed
in only one line, or if they are observed across different wavelengths and heights with
their lengths tracked across these. Individual PMJ lengths can also differ significantly,
ranging from a few hundred kilometres, up to about 10 000 km. The general scales
remain the same nonetheless, and we will return to these considerations in more detail
in the following sections.

The first tell-tale chromospheric brightenings corresponding to PMJs were observed
in the Ca\textsuperscript{ii} H line, and these brightenings were synonymous with PMJs until further
observations were made in other lines. Penumbral microjets were first discovered,
described, and named in Katsukawa et al. 2007, laying the ground-work for all
subsequent studies of PMJs. For the report that started it all, the Solar Optical Telescope
(SOT) aboard the Hinode satellite observed a sunspot with its 3 Å wide imaging filter
in the Ca\textsuperscript{ii} H line, which predominantly images the sub-chromosphere. PMJs were
observed as transient, highly dynamic objects in the penumbra of the observed sunspot,
and were most visible in running-difference images. They had lengths of 1000 km –
4000 km and widths of about 400 km, typical lifetimes of up to 1 minute and brightness
enhancements of 10% – 20% compared to their penumbral surroundings.

Figure 3.1 shows a few example PMJs observed in the Ca\textsuperscript{ii} H line in order to ground
the reader’s imagination. The figure shows a zoomed-in view of the penumbra of a
sunspot with the central dark umbra in the middle of the frame. The sunspot belongs to
active region AR11084, and the observation was obtained by the Swedish 1-m Solar
Telescope on June 28th, 2010 with a Ca\textsuperscript{ii} H line filter with a FWHM of 1.1 Å. Note
that this FWHM is just above a third of the wavelength width of the original SOT
Ca\textsuperscript{ii} H line observations, and so the observations by the Hinode’s SOT and the SST
in the Ca\textsuperscript{ii} H line are not wholly equivalent. The dataset to which this observation
belongs was utilized in Paper I of this thesis, although the main focus of the paper was
simultaneous Ca\textsuperscript{ii} 8542 Å line observations. The dataset was also utilized in Paper II,
where the Ca\textsuperscript{ii} H line observations were used to probe PMJs at high spatial and temporal
resolution.

In the figure, arrows point to six specific locations at which PMJs are currently
visible at differing parts of their lifetimes, with one particularly energetic event visible
PMJs at first glance

Upon their discovery, the newly-dubbed penumbral microjets were observed between adjacent dark filament structures in the penumbra and exhibited significant apparent rise-velocities of around 100 km s\(^{-1}\). This was a much greater value than what is found for acoustic velocities in chromospheric penumbrae which is about 10 km s\(^{-1}\). Since their discovery, the initially observed characteristics of PMJs have been refined, nuance has been added to their interpretations and of course, more typical commonalities have been uncovered. However, the generalities remain; PMJs appear as swift, jet-like brightening in the penumbrae of sunspots.

Upon their discovery, the specific process giving rise to PMJs was an open question. However, a prime suspect for the triggering event that gives rise to PMJs was identified upon their discovery, and this suspect has remained the same to this day: a magnetic reconnection event between inclined magnetic field lines with an associated release of energy, which is ultimately observable as a PMJ. Two distinct scenarios, both involving magnetic reconnection, were proposed. These two scenarios first described in Katsukawa et al. 2007, have since influenced much of the inquiries into the nature of PMJs in the years that have followed. The authors speculated that PMJs could be explained by a magnetic reconnection event taking place between the more horizontal magnetic field of dark penumbral filaments and the more vertical fields in the brighter penumbral regions, and that the PMJ-event may then evolve in one of two ways. In the first scenario, a true mass flow of hot plasma is caused by the reconnection event, which then propagates through the atmosphere. In the second scenario, the magnetic reconnection event gives
rise to a thermal conduction front that propagates upwards, visible as a brightening that traces out its path. Both of these scenarios would be able to explain the high apparent velocities that were initially observed; a true mass flow of sufficient velocity would constitute a true jet, while a propagating heat-front would also be able to propagate at high speeds, even though no significant mass-motions may occur.

While it is too early to make a truly authoritative statement just yet, observational evidence from recent years seems to point towards some variation of the second scenario to be the most likely to adequately explain the formation of PMJs; alternatively, perhaps it is more correct to claim that the first scenario is becoming less and less likely to be true. This is due to recent studies failing to find evidence supporting the presence of significant mass flows for PMJs through a variety of different diagnostic methods; these include Doppler shift measurements, spectral line diagnostic analyses and advanced numerical inversions of spectral lines. We will return to such inquiries and the formational process of PMJs in due time. First however, we will consider some more basic properties of PMJs that have been uncovered since their discovery.

3.2 PMJs at second glance: filtergrams and spectral profiles

Rather than upending our view of PMJs completely, more observations have mostly added to our understanding; over the years following their discovery, PMJs have been observed in more and more spectral lines corresponding to solar atmospheric heights that range from the chromosphere to the TR, with some secondary diagnostics providing signal in the photosphere. In this section, I will focus on the appearance of PMJs in spatially resolved images and their response in resolved spectral lines. The nuances of their dynamics and other properties, which are in part also inferred from less direct diagnostics, will be summarized later. Once we have detailed how PMJs appear, and in which wavelengths they do so, other such considerations should be much clearer.

Today, besides the distinct brightenings apparent in wide-band Ca H line images, PMJs are strongly associated with brightenings in the the inner line-wings of the Ca 8542 Å line. These were first observed with the Dunn Solar Telescope in the spectrally resolved Ca 8542 Å line using the Fabry-Pérot Interferometric Bidimensional Spectrometer (IBIS) instrument by Reardon, Tritschler, and Katsukawa 2013. This also marked the first time any resolved spectral profiles for PMJs were presented, and since then, their distinct Ca 8542 Å spectral profile shape has become one of the key defining features of PMJs. PMJs exhibit a lopsided moustache-shape in the Ca 8542 Å line with enhancements in the inner line wings, with enhanced emission at peaks in both wings, but with a blue peak that is typically stronger than its red counterpart. In Reardon, Tritschler, and Katsukawa 2013, the emission-peaks of two example-PMJs were situated in the “knees of the line”, at ±400 mÅ offsets around the line-core. An analysis of a very large sample of Ca 8542 Å PMJ line profiles in Paper I later placed the blue and red peaks, when clearly present, at average wavelength offsets of $\Delta\lambda_{\text{blue peak}} = -345$ mÅ and $\Delta\lambda_{\text{red peak}} = 341$ mÅ respectively, with the core at a negligible offset of $\Delta\lambda_{\text{core}} = -4.55$ mÅ. The equivalent average Doppler-velocity offsets given in the same order, are $\Delta v_{\text{blue peak}} = -12.12$ km s$^{-1}$, $\Delta v_{\text{red peak}} = 11.95$ km s$^{-1}$ and
PMJs at second glance: filtergrams and spectral profiles

\[ \Delta v_{\text{core}} = -0.160 \text{ km s}^{-1}. \]

Of course, as with any statistics for PMJs, values are expected to vary for individual events, but their averages may also vary from sunspot to sunspot and dataset to dataset.

The blue-over-red asymmetry observed in PMJ Ca \( \text{ii} \) 8542 Å profiles has since been proven to be the norm, although it has been found that Ca \( \text{ii} \) 8542 Å PMJ profiles can also exhibit peaks that have similar intensities, or in much rarer cases, they can exhibit a red peak that is stronger than the blue counterpart. These relative frequencies for the appearance of different Ca \( \text{ii} \) 8542 Å spectral profile shapes was also investigated in Paper I. The wings of the Ca \( \text{ii} \) 8542 Å line generally correspond to the mid-chromosphere, similar to the Ca \( \text{ii} \) H line, meaning that some sort of observations of PMJs in the line were to be expected. However, since the IBIS instrument, and later the SST’s CRISP instrument, were able to deliver actually resolved spectral line profiles in the Ca \( \text{ii} \) 8542 Å line, it meant that Ca \( \text{ii} \) 8542 Å observations were of particular interest. Also, as was already noted in Reardon, Tritschler, and Katsukawa 2013, PMJ Ca \( \text{ii} \) 8542 Å line profiles share obvious similarities with Ellerman bomb (EB) profiles in the same line. Ellerman bombs (first described in Ellerman 1917, and receiving their name in McMath, Mohler, and Dodson 1960; for more recent reviews on EBs see e.g. Georgoulis et al. 2002 and Rutten et al. 2013) also exhibit peaks in the Ca \( \text{ii} \) 8542 Å line wings, although they tend to be more symmetric. The Ca \( \text{ii} \) 8542 Å observations of PMJs therefore opened avenues for a comparison to another chromospheric phenomenon of similar scale that is also thought to be triggered by magnetic reconnection. In Reardon, Tritschler, and Katsukawa 2013, the PMJs were also observed to exhibit a more gradual brightening and fading phase in the wing of the Ca \( \text{ii} \) 8542 Å line. These took place before and after the rapid brightening typically viewed as the “true” PMJ event; these much more gradual brightenings and fadings preceded and followed the main PMJ event by about 2 minutes, thus extending the authors’ estimated PMJ lifetimes.

In order to guide the reader with regards to the appearance of the typical PMJ Ca \( \text{ii} \) 8542 Å line profile, I direct them to fig. 3.2. Here, I have reproduced an average PMJ Ca \( \text{ii} \) 8542 Å line profile generated from the individual line profiles found at 35 577 pixel positions associated with PMJs. This profile was computed following the automated detection of PMJs and their analysis carried out in Paper I (see chapter 4, sect. 4.1 or the paper itself for further details). The typical blue-over-red asymmetry is evident in the figure. The characteristic enhancement in the red wing is visible, but it is less pronounced than what is often the case for PMJs; the process of averaging many PMJ profiles means that any features that may be more pronounced in individual profiles will be smeared out in the total average profile. However, the profile represents a typical PMJ Ca \( \text{ii} \) 8542 Å line profile very well.

Observations that revealed that PMJs are associated with an entirely new temperature (or height) regime were presented by Vissers, Rouppe van der Voort, and Carlsson 2015.

\footnote{Particularly attentive readers may note that the Doppler-velocity offset(s) given here do not accurately match those given in Paper I. The value(s) given here are corrected for an error that happened in the conversion of line-offset values from units of m\(\text{Å}\) to units of km s\(^{-1}\) in the cited paper. This error unfortunately prevailed throughout the work for all these types of conversions (for both given values and in figure-axes) due to a rather embarrassingly pervasive erroneous bit of code. Values given or in figure axes not in units of km s\(^{-1}\) were not affected. I take this opportunity to present these corrected km s\(^{-1}\) line offsets and point out this error in Drews and Rouppe van der Voort 2017.}
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Figure 3.2: An average Ca ii 8542 Å PMJ profile generated from 35,577 individual PMJ pixel-positions (solid line) drawn from a dataset of 453 automatically detected PMJs. Also shown are average profiles for a quiet Sun region from the same observations (dotted line), and the average line profile of the penumbra of the host sunspot (dashed line). All intensities are normalized to the first wavelength position intensity of the quiet Sun average profile. These profiles were first derived in Paper I. Note that line-core offsets expressed in km s\(^{-1}\) in this figure’s axis are corrected for a calculation error in the km s\(^{-1}\)-offsets in the original paper.

This was achieved through use of observations in markedly different wavelengths than had been employed previously, and marked the first observations of PMJ signals associated with TR temperatures or heights, an important result that showed that PMJs are not merely chromospheric objects. For the study, the SST observed Ca ii H-core images for reference and provided the first PMJ Ca ii 8542 Å line profiles observed by the SST’s CRISP instrument (see also Chapter 2). Co-observations made by IRIS enabled both imaging and the capture of spectral profiles in IRIS lines. IRIS slit-jaw images centred on the Mg ii k line, the C ii lines and the Si iv 1400 Å all showed brightenings that aligned spatially with PMJs observed in the Ca ii 8542 Å line wing. Through use of the IRIS slit-spectrograph, the enhanced line profiles for a small number of PMJs could be established in the Mg ii k & h lines, the C ii 1334 Å & 1335 Å lines, and the Si iv 1394 Å & 1403 Å lines. While the Mg ii line pair corresponds mostly to chromospheric heights, the C ii 1334 Å & 1335 Å lines correspond to the upper chromosphere or TR, and the Si iv 1394 Å & 1403 Å lines correspond to the TR. Thus, a TR connection for PMJs had been established both through wide-band images but also through responses in resolved spectral lines. This was of note because speculation about
whether PMJs may contribute to heating the TR and beyond had been ongoing since their discovery by Katsukawa et al. 2007. This discovery therefore at least made such a process plausible. In Vissers, Rouppe van der Voort, and Carlsson 2015, it also became evident that the PMJs progressed radially outwards in the penumbra, such that going from the umbral-side outwards, PMJs progressed spatially from SST Ca ii H images to the IRIS Mg ii k slitjaw images, and finally to the IRIS C ii or Si iv slit-jaw images. However, the time resolutions were not sufficient to disentangle whether PMJs appeared in one channel before others. The spatial progression was strikingly demonstrated using so-called “rainbow images” in which the different channels were coded to different colours. In these, a given PMJ appeared as a bright object that begins as red at its foot-point in the Ca ii H line, progressing to green at its middle in the Mg ii k line and transitioning to blue in either the C ii or Si iv slitjaw images at its head.

In Samanta et al. 2017, the connection of PMJs to IRIS channels was further solidified. Here, the authors coupled PMJs to brightenings in IRIS Si iv 1400 Å and Mg ii k slit-jaw images. The brightenings in the IRIS Si iv 1400 Å slit-jaw images were identified as transition region bright dots (BDs, Alpert et al. 2014; Tian et al. 2014a). In fact, in the study the TR BDs were identified first, and where possible they were subsequently matched to associated chromospheric PMJs in Hinode SOT Ca ii H line and the IRIS Mg ii k slit-jaw images. In the study, half of the 180 initially identified TR BDs could be linked to chromospheric PMJ brightenings. Most interestingly, the study also produced evidence that the identified BDs preceded their PMJ counterparts in time in a majority of cases; this prompted the formulation of a new scenario for the formation of PMJs which posits that PMJs may form through a process of magnetic reconnection in the TR (rather than in the chromosphere or photosphere). They would therefore become visible as TR BDs first, with hot plasma subsequently descending along magnetic field-lines and later appearing as chromospheric PMJs. Here, I will allow myself the latitude to comment that despite these intriguing results, that the most likely scenario for the formation of PMJs still appears to involve a magnetic reconnection event at lower heights, presumably in the lower chromosphere or more likely in the photosphere. The reasons for this assertion will be discussed in the following sections.

Further investigations of chromospheric PMJ brightenings and corresponding signals in IRIS channels were carried out in Paper III. For the study we observed a large number of PMJs in simultaneous observations carried out by the SST and IRIS as part of a broader investigation of PMJ diagnostics. Here, PMJs were also observed as brightenings in the same SST and IRIS channels as in Vissers, Rouppe van der Voort, and Carlsson 2015. For Paper III, a larger collection of IRIS spectral line-profiles for PMJs was collected, though they were in general agreement with the results obtained from the smaller number of PMJ profiles collected by Vissers, Rouppe van der Voort, and Carlsson 2015. In the IRIS spectral lines, meaning the Mg ii k & h lines, the C ii 1334 Å & 1335 Å lines, and the Si iv 1394 Å & 1403 Å lines, PMJs did not exhibit pronounced asymmetries in their profiles or significant Doppler shifts of their line-cores. Usually PMJs caused only “simply” enhanced profiles when intensity enhancements were present. The Mg ii line pair exhibited only double peaks, the C ii line pair both double and single peaks (with double peaks more common), and the Si iv line pair only single peaks. Although a great wealth of secondary diagnostics was also made available from the study of these lines, it was shown that their responses were rather typical of
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Figure 3.3: The same field of view of a sunspot’s penumbra is shown in the four panels, taken from co-observations of AR12533 by the SST and IRIS on April 30, 2016. The images are drawn from the same dataset that was used in Paper III of this thesis. The same PMJ at peak-brightness is the focus of each of the panels. The top left panel corresponds to observations in the Ca \(\text{ii}\) 8542 Å line at an \(-350\) mÅ offset, while the top-right and bottom-left panels show frames from the near-simultaneous IRIS Mg \(\eta\) k and Si \(\text{iv}\) 1400 Å slit-jaw observations, respectively. Relative observation-times are indicated. The PMJ appears as a brightening in all three wavelength-channels, and is pointed out with an arrow in each of the panels. The “rainbow” image in the bottom right combines the different channels such that the Ca \(\text{ii}\) 8542 Å observations corresponds to red, while the Mg \(\eta\) k and Si \(\text{iv}\) 1400 Å slit-jaw images correspond to green and blue respectively. Note: the vertical shadow visible in the Mg \(\eta\) k slit-jaw image and the rainbow-image is due to the IRIS spectrograph slit. Tick mark separations are 1”.

an “ordinary” increase in intensity for these lines. This is in contrast to the typical PMJ Ca \(\text{ii}\) 8542 Å line profile shapes, of which their formation is still not satisfactorily explained. The blended Mg \(\eta\) triplet line adjacent to the Mg \(\eta\) k line was shown to be in
emission for a few PMJs (relative to the total number of PMJs) observed in Paper III, providing some indications of an upper-photospheric response to PMJs, congruent with a temperature increase at this height.

In Fig. 3.3 I have included a rainbow image, along with its constituent parts, similar to those first produced in Vissers, Rouppe van der Voort, and Carlsson 2015. The figure shows the appearance of a PMJ as it spans the different temperatures or heights of the solar atmosphere up to the TR. This example is produced from observations of a sunspot from April 30, 2016, co-observed by the SST and IRIS, and is part of the dataset that was studied in Paper III. The figure shows a PMJ as observed in the Ca ii 8542 Å line at an –350 mÅ offset, and IRIS slit-jaw observations centred on the Mg ii k line and Si iv 1400 Å lines. In the images, a PMJ is shown in the middle of the frames, at approximately peak-brightness in all channels. Going from the Ca ii 8542 Å line observations, to the Mg ii k SJI, and finally to Si iv 1400 Å SJI, we see that the position of the brightening in the different channels moves from the umbral-side of the images (the upper left) to the outer edge of the sunspot (the lower right). This is demonstrated in the rainbow-image that combines the three channels, with the PMJ visible as a brightening that goes from red, to green and to blue along its length.

The wavelength channels that PMJs can be observed in were further expanded by Tiwari et al. 2016, but important non-observations in specific channels were also reported. For the study, co-observations of PMJs with Hinode’s SOT and the Solar Dynamics Observatory’s (SDO) Atmospheric Imaging Assembly (AIA) were utilized. Additional, but much shorter, co-observations by the High-resolution Coronal Imager (HI-C), further constrained the atmospheric heights at which PMJs are typically found. The HI-C telescope was mounted on a sub-orbital sounding rocket and observed the Sun’s corona at an unprecedented spatial resolution of about 150 km - but only for a brief 5 minutes. Of these, 1.75 minutes were suitable for studying PMJs. Ten PMJs were identified in the Ca ii H line by Hinode’s SOT, in which PMJs were well-established, but none of these PMJs could be identified in HI-C’s 193 Å observations. This channel corresponds to coronal heights, providing the first indication that PMJs do not reach coronal temperatures. The authors went on to study a larger number of PMJs visible in the longer co-observations by Hinode’s SOT and the SDO’s AIA. Here, the larger PMJs proved to be visible in the AIA 1600 Å channel, in which they usually overlapped with the typical brightenings in the Ca ii H line. SDO’s AIA 1600 Å channel primarily captures continuum emission from the lower chromosphere; however, it also spans the wavelengths of the two C iv lines at about 1500 Å which form in the TR and at about $10^5$ K. The authors explained the PMJ-associated brightenings in the 1600 Å channel by emission in the C iv lines, originating in the lower TR. As such, these observations were further confirmation that many PMJs reach TR temperatures, as first shown in Vissers, Rouppe van der Voort, and Carlsson 2015. Moreover, Tiwari et al. 2016, also observed that the heads of larger PMJs appeared in SDO’s AIA image channels centred at 171 Å, 193 Å, and 304 Å, which usually correspond to the upper TR, the corona or hot flare plasma, and the chromosphere or TR respectively. Interestingly, in the last available bandpass, SDO AIA’s 93 Å channel, these PMJs were not discernable at all. This channel corresponds to coronal or flare temperatures in the 6 million Kelvin range. This non-observation thus again indicated that PMJs do not seem to reach high coronal temperatures or heights. In fact, so far it still appears that PMJs seem to be confined to
the upper TR, and no coronal signatures have been reported to date. With regards to speculations that PMJs may contribute to the heating of the solar corona, this implies that any direct heating probably only reaches the TR. Alternatively, some heating of the corona may occur through processes that are not discernable as simple brightenings, such as through waves and interactions with the magnetic field.

Returning from the loftier heights just discussed, more recently, PMJs have been shown to also exhibit signatures in the predominantly chromospheric Ca \textsc{ii} K line. In this line, PMJs appear both as typical jet-like brightenings in images, but also exhibit distinct line profiles. This was first shown by Esteban Pozuelo et al. 2019, enabled by the then newly-installed CHROMIS instrument at the SST. The study showed that the Ca \textsc{ii} K line exhibits similar PMJ profile shapes to those seen in the Ca \textsc{ii} 8542 Å line, such that the blue-over-red asymmetry typical of PMJs in the Ca \textsc{ii} 8542 Å line was also seen in the Ca \textsc{ii} K line. Likewise, PMJs were visible as brightenings in images of the Ca \textsc{ii} K inner line wings, very similar to those in Ca \textsc{ii} 8542 Å line-wing images. Also, the degree, or absence, of the asymmetry present in the Ca \textsc{ii} K line was shown to often correlate across the two lines for the same PMJs, suggesting a common mechanism for the formation of the two lines.

Recently, it has also been shown that PMJs have a darker side to them, as is only befitting a tale set in the more nuanced times of modern solar physics. After their descriptions as bright objects in the penumbra of sunspots in various lines corresponding to different heights, it was discovered that PMJs also appear as, or are at least strongly associated with, dark features in some lines. First came the observation that PMJs appear as dark features in the H\textalpha line, both in the line’s core and in its wings, albeit during different times of their evolution. The findings were first described by Buehler et al. 2019, in which observations by the SST of a sunspot in a variety of spectral lines including the H\textalpha line were analysed. In the blue wing of H\textalpha, dark features were spatially aligned with typical brightenings that were simultaneously observed in the inner wings of the Ca \textsc{ii} 8542 Å and Ca \textsc{ii} K lines. However, the blue-wing darkenings in H\textalpha outlived the brightenings in the wings of the two Ca \textsc{ii} lines and continued to evolve after the disappearance of the brightenings. This also extended the lifetimes of the observed PMJs. In the core of the H\textalpha line, darkenings appeared at the site of PMJs towards the end of their lifetimes. The latter darkenings were interpreted as resulting from the presence of line of sight (LOS) velocities. Lastly, the cores of the two Ca \textsc{ii} lines also exhibited dark features after the disappearance of the brightenings in their wings. This was explained by the presence of upwards plasma motions, shifting the cores blue-ward.

The PMJ-associated darkenings in the wings of the H\textalpha line were also confirmed in Paper III of this thesis, but additionally, we also observed similar darkenings for a large relative number of PMJs in the inner wing of the Ca \textsc{ii} 8542 Å line. The darkenings appeared at the same wavelength as the typical PMJ brightenings, and both preceded and followed the main PMJ brightenings, very similar to the darkenings in the wings of the H\textalpha line. However, the Ca \textsc{ii} 8542 Å line darkenings were usually partially obscured by the typical PMJ brightening when the PMJs reached peak-brightness. The darkenings in the Ca \textsc{ii} 8542 Å and H\textalpha line-wings were observed to align spatially to a large degree for most PMJs, and were also largely co-spatial with co-observed IRIS Mg \textsc{ii} k slit-jaw PMJ-brightenings. The spectral line profiles of the Ca \textsc{ii} 8542 Å and H\textalpha lines at the
Figure 3.4: A PMJ imaged by the SST in the Ca II 8542 Å line at an offset of −350 mÅ (left panel) and in the Hα line at an offset of −400 mÅ (right panel), drawn from co-observations of AR12533 by the SST and IRIS on April 30, 2016. The PMJ is visible as a brightening in the Ca II 8542 Å −350 mÅ observations, marked by a red arrow. The PMJ is also associated with spatially aligned darkenings in both the Ca II 8542 Å −350 mÅ and Hα −400 mÅ observations, marked with a yellow and a green arrow in the relevant panels respectively. The darkening in the Ca II 8542 Å −350 mÅ image is partially obscured by the main PMJ brightening. Tick mark separations are 1”.

positions of darkenings showed no distinct spectral line profiles, but were congruent with slight reductions of emission at the relevant wavelengths.

Figure 3.4 highlights the same PMJ as pictured in fig. 3.3, and is drawn from the same set of observations. The figure’s left panel highlights both the brightening in the blue wing of the Ca II 8542 Å line at an offset of −350 mÅ, but also the PMJ-associated darkening at the same wavelength. The second panel highlights the more apparent darkening in the inner blue wing of the Hα at an offset of −400 mÅ. The darkening in the Ca II 8542 Å line is partially obscured by the brightening.

In terms of an initial overview, hopefully this section sufficiently summarized the directly observable responses to PMJs at various wavelengths, both in terms of how they appear as spatially resolved objects, but also in terms of the distinct signatures they exhibit in resolved spectral lines. Of course, I have barely touched upon the wealth of additional diagnostics available through the actual analysis of these various responses. Both the morphological study of PMJs in resolved images and the detailed analysis of spectral line features has yielded many valuable insights into the properties of PMJs. Further intricate methods of analysis, such as through use of inversions of spectral lines and application of methods such as the weak-field-approximation have garnered insights into both the dynamics and the magnetic settings of PMJs. Armed with the summary of where we may find PMJs, both in terms of wavelengths and terms of atmospheric
temperatures or heights, I will summarize some more of these secondary results in the following.

3.3 The spatial setting and morphology of PMJs

Important for an overall understanding of PMJs are both how they relate to their host penumbrae and how their own morphology presents itself. We will consider both these topics in this section. I will touch upon the most well-established results concerning these two topics, without straying too far into speculations and keeping mostly to observationally confirmed results. First we will summarize how PMJs relate to their host penumbrae in sect. 3.3.1, after which we will examine the particulars of their morphology in sect. 3.3.2. Of course, both of these concepts are intrinsically linked; PMJs consist of hot plasma that is not truly separate from its surroundings, so how they relate to their surroundings is very much part of their morphology. For simplicity’s sake however, larger-scale and smaller-scale aspects of how PMJs appear are discussed a lot more readily by making such distinctions.

3.3.1 PMJs in relation to their host penumbrae

Other than the already well-established fact that PMJs are found in sunspot penumbrae, some more generalities have been observed in how they relate to their host sunspots. Three general observations are, first, how PMJs are oriented in the penumbra, second, that PMJs occur more frequently in specific penumbral areas, and third, that PMJs seem to originate in a specific relation compared to the photospheric spine-intraspine pattern of the penumbral magnetic field. We will discuss these in the enumerated order in the following.

One of the first and most important results in the investigation of how PMJs relate to their host sunspots was published in Jurčák and Katsukawa 2008 soon after their discovery. Here, the angular inclinations of PMJs relative to their penumbral environment was studied for a large sample of 209 PMJs in SOT Ca ii H line observations. It was found that PMJ inclinations tended to increase from the centre of the sunspot from about 35° towards the edges of the sunspot, to about 70°. This roughly matched the expected inclinations of magnetic field lines in the penumbra found in the high photosphere, but with an offset of about 10° in the vertical direction. The authors therefore speculated that this behaviour was due to the PMJs following the background magnetic field of the sunspot; hearkening back to Chapter 1, sect. 1.4, the magnetic field of the penumbra begins as near-vertical at lower heights and gradually opens up and becomes more horizontal at greater heights. Since there was an observed offset between the PMJ inclinations and the inclination expected of the magnetic field lines in the high photosphere, this further implied that the PMJs were, on average, found above the high photosphere. Their inclinations were thus more in line with those found at greater heights. In the study, some individual PMJs could also be observed in consecutive time-frames, which enabled some glimpses at how their inclinations evolved with time. For these PMJs, inclinations tended to become more horizontal as they evolved, congruent with the assumption that PMJs rise along the background field
which fans out with height. This general observation - that PMJs seem to follow the background field - is important both for the theoretical understanding of how PMJs evolve, but has also been an important feature when attempting to model PMJs. It is also intuitive of course, seeing as how sunspots are dominated by the magnetic field, it is perhaps no surprise that the directionality of PMJs is governed by the field as well. Since this revelation, no large-scale measurements of PMJ-inclinations compared to their penumbral background has have been undertaken. However, the PMJs observed in later studies seem to exhibit the same behaviour and no newer findings seem to contradict this behaviour. In particular, the numerical inversion of two sample PMJs by Esteban Pozuelo et al. 2019, using the Stockholm inversion code (de la Cruz Rodríguez et al. 2018; de la Cruz Rodríguez, Leenaarts, and Asensio Ramos 2016, STiC code) on the full Stokes profiles of the Fe $\text{i}$ 630 nm, Ca $\text{ii}$ 8542 Å and the Ca $\text{ii}$ K lines, observed by the SST, also indicated that the PMJs’ local magnetic field lines became more horizontal with height. In Siu-Tapia et al. 2020, the authors also observed that enhancements in the Ca $\text{ii}$ 8542 Å line-core were offset from the typical brightenings in the Ca $\text{ii}$ 8542 Å wings at distances matching the estimated projections along the magnetic field lines. Both of these results are in agreement with the general trend for the PMJ inclinations found by Jurčák and Katsukawa 2008. Furthermore, the observation that PMJs tend to follow the penumbral magnetic background field corresponds well with the numerical models and simulations of PMJs that we have available (see Sakai and Smith 2008, 2009, Magara 2010 and Nakamura, Shibata, and Isebe 2012). We will return to the particulars of these modelling efforts and other implications they may have in sect. 3.6. Here, the main takeaway can be summarized as: in observations, PMJs seem to follow the background magnetic field of the penumbra as they evolve, and modelling efforts seem to support such an interpretation.

It may therefore also not be surprising that PMJs seem to follow, or perhaps even consist of, pre-existing fibrils in the penumbra that brighten up along their length. This was observed in very fast, and highly resolved Ca $\text{ii}$ H line observations in Paper II of this thesis. The paper will also be mentioned when discussing the dynamics of PMJs, but here the observations that PMJs seemed to consist of fainter pre-existing fibrils that light up along their length may reinforce our perception of PMJs as objects that follow along the magnetic field lines in the penumbra as they evolve; if PMJs in fact originate along pre-existing fibrils that are already at the mercy of the penumbral magnetic field, it is no surprise that PMJs are too, no matter the particular process that causes their brightening.

The second major observation in how PMJs relate to their penumbrae is that PMJs tend to cluster in specific locations. These locations are often called “hot-spots”. Here, PMJs both occur more often, but also in closer proximity to each other than they do otherwise. This behaviour has been observed in several studies, first in Tiwari et al. 2016, followed by further confirmations in Paper I and Esteban Pozuelo et al. 2019. Especially in Paper I of this thesis this was one of the major results, since we demonstrated this behaviour conclusively by creating a density map of where many automatically detected and tracked PMJs occurred throughout the observations. In the paper, 453 PMJs were automatically detected and tracked through time, making for a very large sample of PMJ-detections (4253 PMJs if each tracked PMJ-area is considered independently from other time-frames).
3. Penumbral microjets

Figure 3.5: A density map of PMJs that were automatically detected and tracked over time. The map is drawn over a single example frame of observations in the Ca II 8542 Å at an offset of −275 m Å, showing the sunspot in active region AR11084, which hosted the tracked PMJs. The overdrawn density map only includes those areas for which PMJs were present for at least one time-frame at a given pixel. The maximum brightness in the density map corresponds to the maximum number of frames a pixel was observed to overlap with a PMJ, not the total number of frames in the observations. The total number of frames in the observations was 202, with a cadence of 12.4 s, making for a time-series of 41 minutes. The observations were made by the CRISP instrument at the Swedish 1-m Solar Telescope on 28 June 2010. The tick-mark separation is 1”. The observation and the PMJ-density data stems from Paper I of this thesis, see the paper itself and Sect. 4.1 for details.

For reference, fig. 3.5 shows a density map of PMJ-pixels through time for the PMJs studied in Paper I. The map is drawn over an example-frame of the SST Ca II 8542 Å −275 m Å observations in which the PMJs were identified. This density map is similar to the one shown in Fig. 11 of Paper I, and is produced from the same data. The density map was produced by counting the number of times a given pixel was located within any PMJ-area throughout the full lengths of the observations. Only pixel positions that were part of a PMJ for at least one frame are highlighted, and the maximum value in the density scale corresponds to the maximum number of frames that a pixel-position was found to be part of a PMJ (and not the total number of frames in the observations). Evident in Fig. 3.5 is that two locations in the upper right of the penumbra were host to
a near-continuous series of PMJ-events throughout most of the observations. A third location at the top of the penumbra exhibits another, but smaller, location where PMJs occurred repeatedly over long stretches of the observations.

The observation of PMJ hot-spots carries with it likely implications. First, it implies that the conditions favouring the formation of PMJs are not uniformly distributed in the penumbrae of sunspots. This is also congruent with the original description by Tiwari et al. 2016, in which the PMJs occurring at such locations were specifically described as “larger penumbral jets”, because they tended to be wider and brighter than their “normal” penumbral jet counterparts, found elsewhere in the penumbra. Indeed, the authors associated these hot-spots (although the term was coined later) to locations of the tails of penumbral filaments, setting them apart from other areas in the penumbra. The potential for larger and repeated production of PMJs was explained by a greater opposite polarity flux found at these locations, that in turn leads to stronger magnetic reconnection events between the “spine field” and the “tail field” in the area, rather than between the sides of penumbral filaments. The latter was proposed as the formation mechanism that may explain the formation of weaker, “normal”, penumbral jets that were observed elsewhere. When studying large penumbral jets again in Tiwari et al. 2018, a majority of the objects were associated with mixed-polarity flux at photospheric heights, observed in magnetogram-equivalent maps. PMJs occurring at hot-spot locations observed in Paper I were also often particularly energetic and large, bolstering an interpretation that hot spots not only produce many recurring PMJs, but also larger and more intensive ones.

A second implication arising naturally from the existence of PMJ hot-spots is that whatever abnormal conditions give rise to the repeated production of PMJs must persist over time-scales that exceed the typical lifetimes of individual PMJs. Any such physical conditions must therefore not be dissipated by the formation of the repeatedly-produced PMJs, or be restored to their former state on time-scales shorter than the life-times of PMJs. With regards to this implication, a priori, and before the observations of hot-spots and their behaviour, it would not have been unreasonable to assume that the process giving rise to PMJs may also inhibit the formation of future PMJs at the same site, at least for a short while. The likely culprit to cause PMJs, magnetic reconnection, is typically thought of as re-ordering magnetic field lines such that they end up in a lower energy state then before the reconnection process. Therefore, it would not be unreasonable to assume that following a PMJ-event, that the local conditions would not be favourable for another event to occur immediately following the first. However, as we will return to in a little more detail in sect. 3.6, the simulation of a PMJ-event by Magara 2010, has provided a possible scenario in which a particular magnetic-field configuration may facilitate recurring magnetic reconnections after-all. Observationally, there is also evidence that the occurrence of individual PMJs does not significantly impact the magnetic setting of their surroundings. This was shown in Siu-Tapia et al. 2020, in which the evolution and the magnetic setting of short-lived PMJs was studied. Here, the authors studied 36 short-lived PMJs through the application of the weak-field-approximation to observations in the \( \text{Ca} \, \ii \, 8542 \, \text{Å} \) line. This enabled the observation of the magnetic field configuration in time for both the photosphere and the chromosphere. In turn, this revealed that the magnetic field properties were very similar before and after the occurrence of PMJs, implying that the PMJs did not leave lasting imprints. Other
3. Penumbral microjets

than the observation that hot-spots may correlate to the locations of penumbral tails, other observations may point us to the particular conditions that may prevail there. In general, PMJs preferentially appear at locations of strong gradients in the magnetic field, as reported by Esteban Pozuelo et al. 2019, both between penumbral filaments, as we will discuss below, and as is also found at the outer boundary of the penumbra (as mentioned in Sect. 1.4). Thus, hot-spots are likely locations at which such strong gradients in the magnetic field inclinations persist over time. Furthermore, the “large PJs” that were first noted to appear repeatedly at specific locations by Tiwari et al. 2016, were found to occur at sites of opposite polarity patches. These were linked to the sites of filament-tails, but in aggregate this may just suggest that PMJ hot-spots are sites of strong magnetic-field inclination-gradients and locations where the difference in opposite polarities is more pronounced. This also neatly brings us to the last and smallest scale at which we will examine how PMJs relate to penumbrae.

At the smallest, PMJs appear to form above the photospheric borders between the so-called “spines” and “intraspines” of the penumbra. These spines and intraspines correspond to the magnetic field configuration of the photosphere, as discussed in sect. 1.4, which displays a variation in its inclination in a “combed” pattern. That PMJs form at such locations was first shown in Tiwari et al. 2016, in SOT/FG Ca \textsc{ii} H line filtergrams and SOT/FG Stokes-V images, where PMJs (or large penumbral jets) were observed to occur at the sites of opposite polarity patches, as mentioned above. However, also as mentioned, the authors specifically associated these patches to the tails of penumbral filaments. The latter were in turn surrounded by the spines, the heads of neighbouring filaments or both, which had the opposite polarity to the patches. The preference to appear at the spine-intraspine interface was also confirmed by Esteban Pozuelo et al. 2019, who employed both Milne-Eddington inversions of the Fe \textsc{i} 6300 Å pair and (numerical) spectropolarimetric inversions with the STiC code of the Fe \textsc{i} 6300 Å pair, and the Ca \textsc{ii} 8542 Å and Ca \textsc{ii} K lines to retrieve information on the magnetic configuration of PMJs. Here, maps of the magnetic field configuration showed the clear combed pattern of the spines and intraspines, with PMJs found at their borders. Most recently, in Siu-Tapia et al. 2020, it appears that this behaviour can also be seen for some PMJs in maps of their photospheric magnetic field configurations. These maps were derived from the weak-field-approximation applied to observations by the SST in the Ca \textsc{ii} 8542 Å line. Since the borders between spines and intraspines are the locations at which the photospheric magnetic field displays a discontinuity in both strength and angle, this intuitively fits neatly with a scenario in which the sheared magnetic field lines may reconnect in some fashion, producing PMJs. More details on the magnetic setting of PMJs and what we know of its evolution will be expanded upon in Sect. 3.5. Furthermore, a magnetic reconnection scenario between such field lines also fits with the various modelling efforts that we will review in Sect. 3.6.

Other than the observations of how PMJs relate to their sunspots we have just examined, other broad generalities have already been summarized by necessity in sections 3.1 and 3.2, which I will not belabour again at any length here. Particularly the heights at which PMJs are found was discussed in sect. 3.2, since the observation of PMJs at any particular wavelength is intrinsically tied to the formation height and temperature of whatever spectral line(s) a given wavelength corresponds to. PMJs appear as brightenings (and darkenings) in spectral lines associated with temperatures
and consequently heights associated throughout the chromosphere and into the TR.

However, signal that has not always been as visually striking, but signal nonetheless, has also been reported for photospheric heights; the best-established signals at or close to photospheric heights include the following. First, in Katsukawa and Jurčák 2010, and Jurčák and Katsukawa 2010, down flow patches with velocities of about 1 km s\(^{-1}\) at photospheric heights could be associated with PMJs in a subset of cases. These were found through use of Stokes V/I maps in the Fe\(\text{I} 6301.5\) Å line obtained with the Hinode SOT. Furthermore, in Ryutova et al. 2008, the authors linked all their observed PMJs (or “penumbral transients”) observed in the SOT Ca\(\text{II}\) H line to photospheric bright points observed in the 4305 Å G band. In Tiwari et al. 2018, the majority of the studied large penumbral jets were associated with mixed-polarity flux at photospheric heights; this was accomplished by way of magnetogram-equivalent maps from the narrow-band Stokes-V/I maps from the FG Na\(\text{I} 5896\) Å line and using Stokes-V images for the Fe\(\text{I} 6301.5\) Å and 6302.5 Å lines, all observed with Hinode’s SOT/SP. More indirect signal at photospheric heights were found in Esteban Pozuelo et al. 2019, where Milne-Eddington and numerical inversions of PMJs showed evidence for downflow channels at photospheric heights. The magnetic setting of short-lived PMJs was studied in Siu-Tapia et al. 2020, which revealed a clear evolution of the magnetic field at photospheric heights at the sites of PMJs. This was achieved through the application of the weak-field-approximation for SST Ca\(\text{II}\) 8542 Å line observations. We will return to the actual particulars of the magnetic settings of PMJs later, however. Also, in Paper III, we could link a small subset of PMJ-events to emission in the Mg\(\text{II}\) triplet blend near the Mg\(\text{II}\) k line, which is typically associated with a temperature increase of at least 1500 K at upper photospheric or lower chromospheric heights (Pereira et al. 2015). As mentioned previously, no coronal signals have been confirmed for PMJs so far. Collectively, these observations therefore imply that PMJs most likely extend from the upper photosphere, through the chromosphere and up to the TR. The signal seen at photospheric heights imply modest line-of-sight downflows, clear evolution of distinct magnetic field settings and some evidence that a temperature increase is taking place.

Now, with the qualitative overview of how PMJs relate to their penumbral surroundings behind us, let us turn to some further nuance in how PMJs themselves appear.

### 3.3.2 The morphology of PMJs

As touched upon in both the preceding sections, Sect. 3.1 and Sect. 3.2, the morphology of PMJs must be considered in the context of what wavelengths and hence temperatures or heights that they are observed at, whether multiple wavelengths are observed and considered simultaneously and whether all “secondary” PMJ features such as associated pre-brightening phases or associated dark features are considered. The nuance of all these considerations cannot be reproduced in this review without simply regurgitating what is best read in full in the relevant publications instead. Hence, I will give specific values when appropriate, but focus on broader considerations for the most part. Again, I will also focus on PMJ properties that are well-established or for which there is direct observational evidence.
3. Penumbral microjets

Table 3.1: Observed PMJ lengths and widths in the literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Lengths [km]</th>
<th>Widths [km]</th>
<th>Diagnostic(s)</th>
<th>Sample type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(1000, 4000)</td>
<td>400</td>
<td>SOT: Ca ii H</td>
<td>Est.</td>
</tr>
<tr>
<td>2</td>
<td>(2000, 10,000)</td>
<td>/</td>
<td>SOT: Ca ii H</td>
<td>Est.</td>
</tr>
<tr>
<td>2c</td>
<td>≤ 1000</td>
<td>/</td>
<td>SOT: Ca ii H</td>
<td>Est.</td>
</tr>
<tr>
<td>3</td>
<td>≤ 1500</td>
<td>/</td>
<td>DST: Ca ii 8542 Å</td>
<td>Est.</td>
</tr>
<tr>
<td>4</td>
<td>2100</td>
<td>/</td>
<td>(SST: Ca ii 8542 Å) + (IRIS SJI: Mg ii k + Si iv)</td>
<td>µ, N=180</td>
</tr>
<tr>
<td>5</td>
<td>10,000</td>
<td>500</td>
<td>SOT: Ca ii H</td>
<td>Est.</td>
</tr>
<tr>
<td>5a</td>
<td>≤ 4200</td>
<td>(150, 300)</td>
<td>SOT: Ca ii H</td>
<td>Est.</td>
</tr>
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<td>/</td>
<td>SOT: Ca ii H</td>
<td>µ, N=90</td>
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<tr>
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<td>(2010 ± 800)</td>
<td>/</td>
<td>IRIS SJI: Mg ii k</td>
<td>µ, N=90</td>
</tr>
<tr>
<td>6B</td>
<td>(2000 ± 820)</td>
<td>/</td>
<td>(SOT: Ca ii H) + (IRIS SJI: Si iv)</td>
<td>µ, N=90</td>
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<td>(1840 ± 750)</td>
<td>/</td>
<td>(IRIS SJI: Mg ii k + Si iv)</td>
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<td>802</td>
<td>179</td>
<td>SST: Ca ii H</td>
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<tr>
<td>12c</td>
<td>(2204 ± 195.0)</td>
<td>≈ (243, 729)</td>
<td>(SST: Ca ii 8542 Å) + (IRIS, Si iv pair)</td>
<td>µ(length), N=33</td>
</tr>
<tr>
<td>12g</td>
<td>(1940 ± 138.2)</td>
<td>≈ (243, 729)</td>
<td>——–—– ——–—–</td>
<td>µ(length), N=44</td>
</tr>
</tbody>
</table>


b Diagnostic/wavelength channel(s) used. The “+” denotes the combination of channels. SOT: Solar Optical Telescope, DST: Dunn Solar Telescope, IRIS: Interface Region Imaging Spectrograph, SJI: Slit-Jaw Imager, SST: Swedish 1-m Solar Telescope.

c Sample types are, “µ, N = X”: values are averages, µ (or medians, µ(1/2)), found for X number events, “Est.”: values given are a ranges/estimates for an unspecified nr. of events, sometimes case-studies.

d-e: Values are for objects here considered PMJs, though in the references they were described as, d: “bow-shock-type-transients”, e: “true microjets” (vs. d), f: “large penumbral jets”, g: “normal penumbral jets” (vs. f).

h Lengths of PMJs associated with TR BDs were measured for different combinations of channels.

i This average width was calculated for this table using indiviual values given in the original study.

j Values given for ref. 12 were derived from two datasets. The given widths are approximate ranges.

In whatever wavelength they are observed in, many publications have produced estimates for the simple spatial dimensions of length and width for the jet-like brightenings that PMJs are chiefly identified with. As mentioned at the very beginning of the chapter however, the general spatial scales of PMJs have remained the same throughout the time they have been studied. PMJ lengths and widths range from the initially observed lengths of 1000 km – 4000 km and widths of about 400 km in Katsukawa et al. 2007, to values both greater and smaller. However, the measurement of smaller values, especially for lengths, have become increasingly more common with time. This may simply be due to an increased effort to uncover the smallest scales of PMJs, an increase in the use of both high-resolution and high-cadence observations.
(making such detections easier), but also due to the analysis of larger samples that include a greater variety of PMJs. Measured widths have been somewhat more consistent, which is likely due to the fact that these will be less affected by observing in different wavelengths and by observing in simultaneous passbands.

For a full overview of the different spatial scales that have been measured for PMJs, I have collated a collection of length and width measurements from various publications, which is reproduced in Table 3.1. These lengths and widths were measured for characteristic PMJ brightenings in the relevant diagnostics indicated. I have included only directly observed values (rather than numerical, theoretical or speculated ones), and I have converted units to kilometres where necessary. Different studies have presented values in a variety of ways, ranging from rough estimates, ranges of values, to averages or medians for larger samples of PMJs and sometimes with our without uncertainties. I have attempted to present this variety of values as compactly as possible, whilst retaining legibility. The table also shows which telescopes and which diagnostics were used to obtain the different values and gives sample sizes where applicable and available. For some studies I have included multiple entries for values that were computed either through use of different diagnostics for the same sample of PMJs, or for PMJs from different datasets that were investigated in the same study; see the table’s footnote for more information. Where I have not included sample sizes, they were not given explicitly in the given study, or the values were estimates for only a few case-studies of PMJs. Of course, any omissions, misrepresentations or errors in the table are entirely my own. As a note of caution, and with more details provided in the table’s caption, several of the cited values were measured for objects that in the original publications were not strictly identified as penumbral microjets; however, these different jet-like events in the penumbrae of sunspots have typically not been distinguished from PMJs in other publications, and I have treated them simply as PMJs here. This will also be the case when we discuss the dynamics of PMJs in the next section.

First and foremost, the table is meant to serve as an illustration of the general spread of values reported in the literature. It is also meant to highlight that the values are congruent with each other in terms of scale. However, inspecting Table 3.1, it is also evident that value ranges or averages tend towards smaller values both when sample sizes are defined at all, and also tend to be smaller when sample sizes are larger. Speculating, this may be due to bias - analysing only a few case studies or small samples, the PMJs studied are naturally often those most visually striking and discernable. This in turn often translates into larger PMJs, since they are more easily identified. Overall, however, we see that PMJs range from about 600 km up to an impressive 10,000 km, although more modest lengths of a few thousand or several hundreds of kilometres are much more commonly found in the literature. Widths have been estimated less frequently, but are also more consistent in their values, typically on the order of a few hundred kilometres. I encourage the reader to inspect the publications corresponding to any particularly lengths or widths that are out of the norm or are eye-catching due to the wavelength channels they were estimated in. However, other than establishing the basic spatial scales of PMJs, the measurements of lengths and widths are useful for the estimation of energy released for an average PMJ, given basic assumptions on temperatures. This is best left for considerations when discussing PMJ dynamics however. For now, I will continue onwards with more qualitative aspects of PMJ morphology, rather than linger...
3. Penumbral microjets

Traditionally, “canonical” PMJs have been viewed as simple elongated structures, appearing as elongated brightenings in a variety of bandpasses, as previously described. Furthermore, and as already mentioned, PMJs are likely to propagate and progress along pre-existing fibril structures (Paper II), which perhaps would make such a simple morphology unsurprising. In some contrast to this simple view however, is that some PMJs have been observed to exhibit a two-part structure, which may also evolve throughout their lifetime. Such two-part structures were first observed by Ryutova et al. 2008 in Ca ii H line observations by Hinode’s SOT. In this study, the term “penumbral transients” was applied to what I will here consider PMJs. Furthermore, these PMJs, or penumbral transients, were divided into two groups on the basis of somewhat differing dynamics and properties. The first group was termed as “not true” PMJs, because they were speculated not to involve significant mass-motions because they had only modest apparent velocities. Significant mass-motions were thus considered an integral part of what defined “true” PMJs to the authors; this view is probably not as common now, particularly due to the fact that the detection of significant, verifiable, mass-motions for any PMJs has proven difficult in the decade since. We will return to this topic in the section on PMJ dynamics. The “not true” PMJs were speculated to be caused by bow-shocks that were triggered by magnetic-reconnection events, and they were observed to exhibit drifting motions perpendicular, rather than parallel to their long-axes, with speeds of $\leq 1.5 \text{ km s}^{-1}$ to $\approx 20 \text{ km s}^{-1}$. The second group of PMJs had faster velocities along their long axes, and were therefore speculated to be caused by mass motions. The aforementioned two part structure that some PMJs exhibit could be observed for only a subset of the “not true” PMJs. These PMJs could be discerned to consist of two parallel brightenings that seemed split along their length, and the two parts moved in tandem before dissipating. The authors speculated that all of the PMJs in this particular subset of PMJs may exhibit such double-structures, but that this may only be apparent at favourable viewing angles for which the two parts did not overlap. That some PMJs exhibit such two-part structures was confirmed in Paper II. Here, very fast and high resolution observations in the Ca ii H line by the SST revealed that 31% (14 out of a total of 45) of the studied PMJs displayed a two-part morphology. In this paper, we made no distinction between sub-types of PMJs. Interestingly, due to the high cadence, it was possible to directly observe some PMJs split into two parts sometime during their evolution after previously only appearing as one brightening. We too speculated that such double-structures may be even more common than evident from our observations, provided that the double-structures have no preferred orientation with regards to the observer. In such a scenario, we may simply not observe this phenomenon in all cases due to unfavourable viewing effects, poor resolution or obscuring features. The reason for why PMJs may exhibit such two-part structures is not settled, although a mechanism was proposed in Ryutova et al. 2008 upon the initial discovery of this property. As mentioned, here it was proposed that this particular group of “penumbral transients” was caused by a magnetic reconnection event that subsequently triggered bow-shocks. These bow-shocks were hypothesized to be triggered by an initial magnetic reconnection, causing two shock-fronts that propagate away from each other with an angle between them; depending on the angle, which may vary, one or both of the shocks may be visible by an observer. For a full theoretical treatment, I direct the reader to the study itself.
Whether PMJs are indeed the manifestations of bow shocks, which may explain the double-structures that some PMJs exhibit is unsettled. Numerical modelling has so far only produced PMJ-like events consisting of bi-directional outflows along the magnetic background field, rather than perpendicular to it. The reason for why some PMJs may exhibit two-part structures warrants both further observational studies, but may therefore also be particularly suited for study through further modelling efforts. The existence of these double-structures may also hint at further fine-structure of PMJs that is not yet fully resolved by the current generation of solar telescopes. The next generation of 4-meter aperture solar telescopes, such as the European Solar Telescope (Collados et al. 2013, EST) and the Daniel K. Inouye Solar Telescope (Rimmele 2019, DKIST) may resolve this problem and reveal other yet-unobserved fine structures associated with PMJs.

Other than the caveat that at least a subset of PMJs appear as twinned elongated brightenings, the broad morphology of PMJs has remained the same; elongated brightenings. Now that we have a general concept both of where to find PMJs and what their general morphology is, let us consider in some more detail how PMJs evolve through time in the next section.

3.4 The dynamics of PMJs

When discussing the dynamics of PMJs, once more I will not stray too far from firm observations. I have divided some particular aspects of PMJ evolution and dynamics into discrete topics, though as usual, all their different aspects are tightly related. I will examine the typical lifetimes of PMJs in sect. 3.4.1 before turning to how PMJs propagate through the penumbra in sect. 3.4.2. The latter topic is arguably the most interesting aspect concerning PMJs and their dynamics, and the measurement of seemingly incongruent line-of-sight and apparent velocities will be our main focus here. Lastly, I will present some basic considerations in what we can say about the energetics of PMJs in sect. 3.4.3.

3.4.1 PMJ lifetimes

Similar to PMJ lengths and widths, lifetimes are an oft-measured property when PMJs are studied in any capacity. Perhaps the typically measured lifetimes of PMJs have undergone some more significant revisions than their spatial scales since the discovery of PMJs, but the overall time-scales over which one can observe PMJs remains on the order of minutes. Upon their discovery, most PMJs were reported to have typical lifetimes of less than 1 minute by Katsukawa et al. 2007. Since then, observations have shown that many PMJs do indeed show their most striking evolution over time-scales of a minute or less, but that taking into consideration their onsets and their final faint signals can significantly increase their overall lifetimes. The first precursor brightenings and the fading phases that typically precede the main brightening event of PMJs were initially described by Reardon, Tritschler, and Katsukawa 2013, increasing their typical lifetimes in Ca ii 8542 Å line in observations from the DST. However, even in Ca ii H line wide-band observations by the SOT, PMJ lifetimes had already been revised to
the order of less than one minute to several minutes (Ryutova et al. 2008, Jurčák and Katsukawa 2010). In later years, PMJ lifetimes have been shown to last from less than a minute to many minutes. The analysis of 453 automatically detected and tracked PMJs observed in the SST Ca ii 8542 Å line in Paper I showed that the lifetimes of PMJ Ca ii 8542 Å line enhancements may exceed 8 minutes; however, this was dependent on the definition of PMJ-onsets and PMJ-ends. The automatic tracking revealed that sites of repeated PMJs, the hot-spots previously discussed, could lead to a scenario in which the onset of subsequent PMJs may overlap with the fading phase of previous PMJs at the same location, making the distinction between events unclear. In any case, even this study showed that typical PMJs had lifetimes of less than 2 min; when discarding PMJs with lifetimes over 8 min we found an average lifetime of only 90 s and a median of only 75 s.

As mentioned in sect. 3.2, PMJ lifetimes are also affected by whether they are considered in several wavelength channels simultaneously or only a single one. Typically, observing in several channels means that measured lifetimes will be longer, since PMJs will become visible, fade or become obscured earlier in some channels than in others. Here, some consideration is important with regards to the reason for why lifetimes may be extended when they are measured through use of several “simultaneous” observations in different wavelengths; the quotation marks serve to highlight the somewhat misleading moniker of “simultaneous observations”, since while such observations usually certainly capture signal from the same objects, and with observations overlapping in time as they do so, they are not truly simultaneous. Unless observations are captured by the same telescope with a setup that ensures recording in different wavelengths at very small time-scales (such as for some observation programs with the current red- and blue-beam setup at the SST), co-observations in different wavelengths will often have quite significant time-offsets. With objects such as PMJs, with dynamic time-scales down to tens of seconds, cadences of the same order will impact measured lifetimes to small or large degrees. Co-observations with different telescopes, such as with the SST and IRIS (as was undertaken in Paper III), will inevitably involve some time-offsets in the observations obtained by the different instruments and telescopes. As such, this must be considered when appraising differing onset and last-signal times in different wavelength channels when observing PMJs. However, typically, time-differences between wavelength channels can be constrained to the order of a few tens of seconds, or even less, which means that the average lifetimes of a sample of PMJs may be somewhat increased, but not to an extent that would revise our overall understanding of PMJs. The careful check of both observation cadences and the time-differences between multi-wavelength co-observations can in principle quantify any such possible confounders. As we will see however, the spread in PMJ lifetimes measured in different publications is of such a size that such differences will do little to confound our overall understanding of PMJ lifetimes, since they can vary significantly in any case. The true interest in measuring PMJ onset- and end-times at different wavelengths lies in whether there are systematic differences that are due to actual differences in appearance in different wavelengths.

Estimates for the lifetimes of PMJ-brightenings observed in both the chromosphere and the TR were found in Vissers, Rouppe van der Voort, and Carlsson 2015. Here, the maximum time of visibility across the the SST Ca ii H line and the IRIS slit-jaw images
in the Mg \(\text{II}\ k\) and Si \(\text{IV}\) channels was shown to be greater than when only considering the Ca \(\text{II}\ H\) line to determine lifetimes. The average lifetime of 180 PMJs was found to be \(\approx 30\) s, very much in line with the initial estimate by Katsukawa et al. 2007, even though this average lifetime was obtained by combining all the different available wavelength channels. Interestingly, no systematic time-offset between diagnostics could be observed. The different diagnostics had time-offsets of at most 10 s, implying that the propagation of the PMJs through the different heights associated with the different wavelength channels was sufficiently fast not to be evident at such time-scales.

Later, in Samanta et al. 2017, the authors identified and studied 180 transition region bright dots in the IRIS Si \(\text{IV}\) slit-jaw channel, which is sensitive to the transition region. They could link half of their detected TR bright dots (BDs), 90 events, to PMJ-brightenings found in the chromosphere, which were identified and observed in Hinode SOT Ca \(\text{II}\ H\) line observations. Here, contrary to the findings of Vissers, Rouppe van der Voort, and Carlsson 2015, the authors found a significant time-offset between signal associated with PMJs in the chromosphere and the TR. The average time-offsets between the appearance of TR BDs and their chromospheric PMJ counterparts averaged 15 – 16 s, but a significant number displayed time-offsets as large as 1 minute. The most significant part of this finding was that it was the TR BDs that preceded their chromospheric PMJ counterparts, rather than the other way around. This implied that the PMJs’ overall lifetimes were greater than if only the chromospheric signal had been considered (although only lifetimes of the TR bright dots were presented explicitly). Since the limiting IRIS cadence was only 10.5 s and the SOT and IRIS observations were synchronized to a level of sub-seconds, these findings were significant. However, more significantly, and as mentioned in Sect. 3.2, this observation also prompted the authors to propose a scenario in which PMJs are caused by magnetic reconnection events in the TR, rather than at lower layers. In this scenario hot plasma at TR heights subsequently cools and descends to chromospheric heights along the background magnetic field lines. To my best knowledge, other publications published since have not reported significant time-offsets in the first-appearances of PMJs in different wavelength channels corresponding to different atmospheric heights. Typically such observations have had poorer cadences than was the case for the observations employed in Samanta et al. 2017. Nonetheless, the time-offsets observed by Samanta et al. 2017 are in conflict with the results in Vissers, Rouppe van der Voort, and Carlsson 2015, where no significant time-offsets between signal in the chromosphere and the TR where found; the cadences were similar for both publications, making this discrepancy more puzzling. In Paper III, PMJs were observed using spectral signals originating from the chromosphere to the TR in the resolved SST Ca \(\text{II}\ 8542\) Å spectral line and in the resolved IRIS spectral Mg \(\text{II}\ k\ &\ h\) lines, the C \(\text{II}\ 1334\ &\ 1335\) Å lines, and the Si \(\text{IV}\ 1394\ &\ 1403\) Å lines. Here, we could not prove any time offsets between the appearance of PMJ-signals in any of the different spectral lines on the order of \(\approx 40\) s, which was the cadence of the IRIS spectrograph-slit observations. Further high cadence observations of PMJs spanning from the chromosphere to the TR, preferably filtergrams, would be of great interest to confirm or refute any such time offsets as found in Samanta et al. 2017. Any further confirmation of such time offsets would be increasingly puzzling, since there is mounting evidence of both temperature increases (Paper III) and an evolution of the magnetic field configuration at photospheric heights at the sites of PMJs (Esteban
3. Penumbral microjets

Pozuelo et al. 2019; Buehler et al. 2019; Siu-Tapia et al. 2020). We will also return to such considerations later.

Even more drastic difference in onset-times in different diagnostics corresponding to different atmospheric heights may be inferred from results presented in Jurčák and Katsukawa 2010. Here, the authors linked a subset of photospheric downflow-patches of sizes ≤ 0.5" detected in SOT Fe i Stokes V observations to SOT Ca ii H PMJ brightenings. The downflow patches exhibited a wide variety of lifetimes, with typical values between 2 and 3 minutes, but some lasted as long as 14 minutes. The longest-lasting photospheric down-flow patches associated with chromospheric PMJ brightenings had a lifetime of about 13 minutes, but for the most part, down-flows associated with chromospheric brightenings had more typical lifetimes of only a few minutes. These results may have significant implications; if the much more sudden chromospheric PMJ brightenings are generally preceded by photospheric-downflow patches that last several minutes longer, this would naturally impact our understandings for the evolution of PMJs. PMJs were also associated with photospheric downflows in Tiwari et al. 2016, at the tails of filaments as discussed previously. Whether photospheric downflows are merely indicative of sites favourable to produce PMJs (due to increased shears because of plasma motions) or whether they are resultant of the PMJ-events themselves would also have to be delineated. We will return to an explicit discussion of PMJ velocities below.

Moving on from differing measurements in different diagnostic channels, we turn to PMJ-associated features clearly distinct from the typical chromospheric brightenings. The inclusion of PMJ-associated dark features in the Hα line, which were already discussed in Sect. 3.2, also effects the lifetimes of PMJs. This was first shown by Buehler et al. 2019. Since the dark features in both the Hα line core and the wings continued to evolve after the disappearance of the main brightenings in the two Ca ii lines, this increased the measured lifetime for any given individual PMJ. However, again, the average lifetime of the studied PMJs was not categorically different from those of other studied PMJs, with a value of \((163 \pm 25)\) s.

Indeed, even when accounting for precursor brightenings, the gradual fading of the typical chromospheric brightenings and the combination of different wavelength channels, the values of measured PMJ lifetimes still vary and overlap between different studies. It is evident that PMJs in general can span over short and long time-scales, both dependent on nuances in how their lifetimes are measured, but also inherently, as PMJs simply seem to differ in how long they last. Considering the evolution of PMJs over very short time-scale, we studied PMJs at very fast cadences of \(\approx 1\) s and high spatial resolution in SST Ca ii H line observations in Paper II. While we did not present average lifetimes in the study, we showed that the estimation of PMJ lifetimes is quite dependent on both the time- and spatial- resolution of the observations. We also demonstrated that the primary brightenings of PMJs evolve significantly over very short time-scales, perhaps an order of an magnitude smaller than the typical cadences of \(\approx 10\) s or more that have been employed in previous observations. In the study, one example PMJ saw a rapid increase in brightness to 90% of maximum over a spatial scale of several hundreds of kilometres in only 1-3 seconds; it then faded to below 60% brightness in only 20 s. Observations at slower cadences may have overestimated the PMJs main brightening’s lifetime by several time-steps of tens of seconds, smearing it out in time. Thus, defining
Table 3.2: Lifetimes of PMJ (and of some associated features) in the literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Lifetime [s]</th>
<th>Main diagnostic(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≤ 60</td>
<td>SOT: Ca II H</td>
<td>Estimated</td>
</tr>
<tr>
<td>2&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(40, 360)</td>
<td>SOT: Ca II H</td>
<td>Estimated</td>
</tr>
<tr>
<td>2&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Typically ≤ 40</td>
<td>SOT: Ca II H</td>
<td>Estimated</td>
</tr>
<tr>
<td>3</td>
<td>≈ (120, 180) but ≤ 840</td>
<td>SOT: Fe i Stokes V</td>
<td>For 181 ≤ 0.5° downflow-patches, only ≈ 36 of these were linked to PMJs.</td>
</tr>
<tr>
<td>4</td>
<td>≈ 180</td>
<td>DST: Ca II 8542 Å</td>
<td>Estimated, includes precursor brightening and fading phases of ≈ 60 s each.</td>
</tr>
<tr>
<td>5</td>
<td>≈ 30</td>
<td>(SST: Ca II H) + (IRIS, SJI: Mg II k + Si IV)</td>
<td>µ, N = 180</td>
</tr>
<tr>
<td>6&lt;sup&gt;f&lt;/sup&gt;</td>
<td>≤ 60</td>
<td>SOT: Ca II H</td>
<td>Estimated</td>
</tr>
<tr>
<td>7&lt;sup&gt;g&lt;/sup&gt;</td>
<td>(36.9 ± 18)</td>
<td>IRIS, SJI: Si IV</td>
<td>µ, N = 90</td>
</tr>
<tr>
<td>8</td>
<td>117</td>
<td>SST: Ca II 8542 Å</td>
<td>µ, N = 453</td>
</tr>
<tr>
<td>8</td>
<td>90&lt;sup&gt;h&lt;/sup&gt;</td>
<td>SST: Ca II 8542 Å</td>
<td>µ, N = 437 (subset of the above entry’s PMJs, but with lifetimes &gt; 8 min. excluded)</td>
</tr>
<tr>
<td>9&lt;sup&gt;i&lt;/sup&gt;</td>
<td>82</td>
<td>IRIS, SJI: Mg II k</td>
<td>µ, N = 6</td>
</tr>
<tr>
<td>9</td>
<td>111&lt;sup&gt;h&lt;/sup&gt;</td>
<td>IRIS, SJI: Mg II k</td>
<td>µ, N = 11</td>
</tr>
<tr>
<td>10</td>
<td>(≈ 60, 390)</td>
<td>SST: Ca II 8542 Å</td>
<td>N=37</td>
</tr>
<tr>
<td>11</td>
<td>(163 ± 25)</td>
<td>SST: Ca II K + Ca II 8542 Å + Hα</td>
<td>µ, N = 10</td>
</tr>
<tr>
<td>12</td>
<td>71</td>
<td>SST: Ca II 8542 Å</td>
<td>µ, N = 36 (PMJs were pre-selected to have lifetimes &lt; 2 min.)</td>
</tr>
</tbody>
</table>


<sup>b</sup> Main Wavelength channel/diagnostic method used for the lifetime measurement, others may have been used in combination. The “+” denotes the combination of methods/channels. SOT: Solar Optical Telescope, DST: Dunn Solar Telescope, IRIS: Interface Region Imaging Spectrograph, SJI: Slit-Jaw Imager, SST: Swedish 1-m Solar Telescope.

<sup>c</sup> Comments on the origin of values, or abbreviated notes meaning: “µ, N = X”: values are averages, µ (or medians, µ<sub>1/2</sub>), found for X number events, “Estimated”: values given are ranges/estimates for an unspecified nr. of events, sometimes for case-studies.

<sup>d-f</sup> Values are for objects here considered PMJs, though in the references they were described as, d: “bow-shock-type-transients”, e: “true microjets” (vs. d), f: “large penumbral jets”.

<sup>g</sup> Values are for TR bright dots that were found to be associated with PMJs, not the chromospheric PMJ brightening they were associated to in SOT Ca II H and IRIS SJI Mg II k observations.

the lifetimes of PMJs to only include their main chromospheric brightening, this may reduce it to the order of seconds, rather than minutes. Further implications for the dynamics of PMJs with regards to such effects will be discussed below.

At last, with these words of nuance and caution, I will leave the reader with an opportunity to ground their perception of PMJ lifetimes with the help of Table 3.2.
3. Penumbral microjets

In the table I have reproduced various PMJ lifetime estimates and measurements, drawn from the literature. As for the table over PMJ lengths and widths, it is first and foremost meant as a guide to the reader and to prompt further study of the relevant publications and to highlight the observed spread in measurements. Again, any errors in the reproduction or selection of values are my own. The table also highlights the different main diagnostic channels used, alone or in combination, that were used to obtain the lifetime measurements - see the table’s caption for details.

The table reinforces what was mentioned earlier, PMJ lifetimes vary from less than a minute, to many minutes, depending on the study, the PMJ features considered, and the diagnostics employed. More detailed discussions would be out of scope at this point, and for more such considerations, I direct the reader to the literature, where Table 3.2 may be helpful in the selection of relevant publications. Now however, we will dive into more specific measures of PMJ dynamics - namely their propagation through their host penumbras.

3.4.2 The motions of PMJs and their velocities

Some context for PMJ velocity measurements

Velocity measurements of PMJs provide a vital clue as to what both their formational and their evolutionary processes may entail. There are two particular velocity scale-values that are useful to us in this discussion. Each is associated with a different mode of propagation through the solar atmosphere’s plasma. These two are, first, the value of the local Alfvén speed, which corresponds to the speed of a wave that propagates transverse to the magnetic field, and second, the local speed of sound of the plasma, associated with sound waves. How any observed values of PMJ velocities compare to the local values of the two can yield likely indications about how PMJs may propagate through the atmosphere themselves.

Much simplified, but hopefully sufficient for our current purposes, an Alfvén wave propagates along the direction of magnetic field lines and consists of oscillating ions in a plasma - however, both the oscillating displacement of the ions and the disturbance of the magnetic field are perpendicular to the magnetic field lines and thus the direction of propagation. Therefore, there is little actual mass motion, and no net mass motion along the wave’s direction of propagation. The speed at which such a wave propagates is given by the Alfvén speed, which is dependent on both the plasma density and the magnetic field strength. The local Alfvén speed is therefore strongly dependent on the height of the solar atmosphere because the atmosphere is strongly stratified. The Alfvén speed, \( v_a \), can generally be expressed by

\[
v_a = \frac{B}{\sqrt{\mu \rho}},
\]

where \( B \) is the magnetic field strength, \( \mu \) is the vacuum permeability and \( \rho \) is the mass density of the charged particles in the plasma. As the density increases strongly with height in the solar atmosphere, faster than the magnetic field strength decreases, the
Alfvén velocity increases strongly with height. In sunspot penumbrae specifically, it has values of about $6 - 8 \text{ km s}^{-1}$ at photospheric heights, but may reach values on the order of $200 \text{ km s}^{-1}$ at upper chromospheric heights. Consequently, at heights in-between, we find intermediate values for the local Alfvén speed.

A sound wave travelling through plasma, much like through air, consists of a compression-front that travels through the medium. Again, little mass motion is involved. The value of the sound speed in a plasma, $c_s$, is generally given by

$$c_s = \sqrt{\frac{\gamma R T_e}{\mu}},$$

where $\gamma$ is the adiabatic index, $R$ is the gas constant, $T_e$ is the plasma temperature and $\mu$ is the mean molecular weight. As such, the sound speed’s variation with height in the solar atmosphere depends most strongly on the temperature’s variation with height. It therefore varies more slowly than the typical Alfvén speed. In stark contrast to the Alfvén speeds, in the photosphere of penumbrae, the sound speed has a value of only about $6 \text{ km s}^{-1}$ and rises to only about $10 \text{ km s}^{-1}$ in the penumbral chromosphere.

How the velocities of PMJs relate to these scale-velocities can thus hint at their own mode of propagation; if PMJs propagate faster than the sound speed, they are unlikely to be acoustic waves, and may be due to either mass motions or faster, Alfvénic-type waves. In turn, if PMJs exhibit velocities close to the Alfvén speed, they may be due to a thermal conduction front that propagates through oscillations of the plasma’s ions, heating plasma as it passes and the wave propagates through the atmosphere. Lastly, PMJs may be the manifestations of significant mass-motions that carry with them heated plasma. Such mass motions can plausibly exhibit a wide range of velocities, depending on the amount of energy available to accelerate it in the first place; this might plausibly yield velocities on the order of only a few to hundreds of km s$^{-1}$. Complicating the matter, PMJs might conceivably also exhibit some mass motions, but could also be the source of simultaneous acoustic waves, or of much faster Alfvén waves.

As was already discussed in sect. 3.1, speculations pertaining to how PMJs actually propagate through the atmosphere were already put forth by Katsukawa et al. 2007, when PMJs were first discovered. At their discovery, PMJs appeared to exhibit apparent velocities in excess of $100 \text{ km s}^{-1}$ and it was evident that the observed PMJ velocities far exceeded the local chromospheric acoustic speed of about $10 \text{ km s}^{-1}$. The authors thus posited that the high velocities could be explained best either by fast true mass motions, or by the evolution of a thermal conduction front caused by the transient heating of plasma. It was posited that both of these scenarios could be caused by a magnetic reconnection event at photospheric heights, triggering either of these processes. As pointed out in this seminal work, the key to distinguish between the two scenarios, which either involves significant mass motions or a propagating heating front, is the measurement of Doppler shifts for PMJs. This is the case because the disentanglement of how PMJs primarily propagate comes down to the distinction between the measurement of apparent velocities and the measurement of actual mass motions by way of line-of-sight velocities.
The measurement of apparent velocities is achieved by measuring the plane-of-sky motions of PMJs through use of time-series of resolved images. This is typically done through the direct tracking of PMJ-brightenings in images or by the use of time-space diagrams by which velocity gradients of PMJs can be estimated. When measuring the apparent motions of PMJs it is implicitly assumed that the measured velocities are valid for the typical formation height of the wavelength region that is being observed. Here, some caution must be applied - specifically when observing heating events such as PMJs, the objects themselves may originate at somewhat lower atmospheric heights than the heights that their temperatures are usually associated with; this is of course due to the fact that emission in a particular wavelength bandpass corresponds to specific spectral-lines. These in turn emit most efficiently at specific temperatures, with the given temperature normally correlated to an average height in the solar atmosphere. However, hotter material at lower heights may emit in spectral lines typically associated with greater heights, because of the increased temperature. For this reason, phrasings such as “PMJs are observable at temperatures associated with the TR”, are typically preferable to ones such as, “PMJs are observed at TR heights”.

The measurement of LOS velocities is performed either by way of direct Doppler velocity measurements or through secondary methods, typically also sensitive to the Doppler effect; the latter methods encompass more nuanced spectral line diagnostics of specific spectral line features, as well as advanced numerical inversions of one or more spectral lines that aim to reproduce the velocity-profile (and other parameters) of the solar atmosphere with height. Since LOS velocities are indicative of actual shifts in spectral line features through the Doppler effect, they are indicative of true mass motions. As the name implies, the measured line of sight velocity corresponds to the mass-motions along the line of sight connecting the observer to the mass in motion. The moving mass of plasma emits radiation that can be blue or red shifted, depending whether it moves towards or away from the observer, respectively. Again, some caution must also be applied in the use of LOS velocities; measured LOS velocities may also be sensitive to material that lies between the observer and the object of interest in the atmosphere, rather than only the objects being studied. The values of LOS velocities are usually obtained from ascertaining the wavelength-shift of specific spectral lines and their different features, such as their line cores or any intensity peaks or minimums they may exhibit. Through both theoretical considerations and numerical modelling, it can be established at which temperatures in the solar atmosphere, and therefore typically associated heights, such spectral line features originate. Doppler shifts of these features can thus be associated to specific heights in the solar atmosphere. Here, the same caution must be applied as to observing heating events in filtergrams with regards to the origin-height and typical temperatures. In the case of numerical inversions, this method typically employs several spectral lines, and implicitly also all their spectral features. The inversion process is iterative; artificial parameter profiles of the solar atmosphere are produced, together with corresponding artificial spectral profiles for the same lines. The artificial profiles are compared to the observed ones and the mismatch is quantified and the process is repeated until the match is deemed sufficiently close. The artificial parameter profile of the solar atmosphere can then be inspected and analysed. Numerical inversions are however much more computationally costly than more direct spectral line profile diagnostics.
One last caveat that bears mentioning is that apparent and LOS velocities naturally only measure a projected component of the true three-dimensional velocity vector of whatever object is being observed. Designating the solar direction of gravity as the z-axis and the perpendicular horizontal direction as the y-x plane, there is intuitive appeal in equating the LOS velocity to the vertical component and the apparent velocity to the horizontal component of a PMJ’s motion. However, this is only true (enough) when observing objects close to disk-centre, and the closer towards the limb of the sun the area of interest is located, the more this relationship reverses. Strictly speaking, when considering apparent and LOS velocities in detail, the observing angle needs to be considered. However, in practice, most observations of PMJs have been undertaken at rather modest observing angles (close, or rather close to disk centre). Hypothetically some PMJs may exhibit significant mass motions that are undetectable in LOS velocity measurements because the motions are perpendicular to the LOS. However, as PMJs tend to follow the magnetic background field, at disk centre this should only be the case when the field lines are entirely parallel to the horizontal, such as at the edge of the penumbra. On the other hand, observations would have to be very far from disk centre in order for LOS velocities to be near-zero even if true mass motions were present. Furthermore, PMJs appear on all sides of sunspots, meaning that systematic offsets would be reversed for opposite sides along the line-of-sight. In any case, PMJ velocities in the literature would still show a representative spread in values for both diagnostics, no matter what the systematic errors are for individual samples of PMJs due to projections effects in a particular study.

With all this said - what can apparent and LOS velocity measurements actually tell us about PMJs? It is especially through the investigation of whether there are large discrepancies in the values of apparent and LOS velocities of PMJs that we may learn about their evolution. If they differ, PMJs may exhibit actually differing (mass-) velocities along the plane-of-sky direction and along the LOS, or alternatively, large discrepancies in their values may be due to the differing methods used to obtain them. As detailed above, LOS velocities are associated with actual mass motions while apparent plane-of-sky velocities only track the movement of visual features, which may or may not be due to true mass movements. Therefore, significant mass motions in PMJs should produce both high apparent velocities, but also high LOS velocities - given that the PMJs are observed at an appropriate angle, for which we would expect a significant motion towards the observer. Reciprocally, if any significant apparent velocities (and the visual features) of PMJs are not due to actual mass motions, one would expect to measure high apparent velocities, but only low or negligible LOS velocities. So, what are the actually observed velocities of PMJs, and are there any tell-tale discrepancies?

**Observed and inferred PMJ velocities**

I will immediately answer the just stated question: to date, observations of PMJs have failed to reveal typical LOS velocities that are on par with the typical apparent velocities of PMJs. Below, I will outline the severity of this discrepancy.

Apparent propagation speeds of PMJs have been studied as part of several studies, some of which also studied LOS velocities, in others, only LOS velocities were reported. Apparent propagation speeds have shown the widest spread in values, ranging from a
3. Penumbral microjets

Table 3.3: PMJ apparent velocities in the literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>App. vel. [km/s]</th>
<th>Height range</th>
<th>Main diagnostic(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 100</td>
<td>Chr.</td>
<td>SOT: Ca $\pi$ H</td>
<td>Case studies, “rise- velocity”, time-space gradient(s).</td>
</tr>
<tr>
<td>2</td>
<td>(≤ 1.5, ≃ 20)</td>
<td>Chr.</td>
<td>SOT: Ca $\pi$ H</td>
<td>Motions were <em>perpendicular</em> to the PMJs’ long axis. Unspecified sample size, ≃ tens.</td>
</tr>
<tr>
<td>3</td>
<td>(20, 50)</td>
<td>Chr.</td>
<td>SOT: Ca $\pi$ H</td>
<td>Unspecified sample size, ≃ tens.</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>Chr.</td>
<td>DST: Ca $\nu$ 8542 Å</td>
<td>Growth rate of 1 example PMJ</td>
</tr>
<tr>
<td>5$^f$</td>
<td>42</td>
<td>Chr.</td>
<td>IRIS SJI: Mg $\alpha$ k</td>
<td>$\mu$, $N = 6$</td>
</tr>
<tr>
<td>5$^f$</td>
<td>30</td>
<td>Chr.</td>
<td>IRIS SJI: Mg $\pi$ k</td>
<td>$\mu$, $N = 11$</td>
</tr>
<tr>
<td>6$^g$</td>
<td>(14 ± 10)</td>
<td>TR</td>
<td>IRIS SJI: Si iv</td>
<td>$\mu$, $N = 90$</td>
</tr>
<tr>
<td>7</td>
<td>(11, 17)</td>
<td>Chr.</td>
<td>SST: H$\alpha$</td>
<td>$N = 10^b$</td>
</tr>
<tr>
<td>8$^f$</td>
<td>(150, 370)</td>
<td>Chr.</td>
<td>SST: Ca $\pi$ H line</td>
<td>$N = 45$, initial PMJ brightening</td>
</tr>
<tr>
<td>8$^f$</td>
<td>(5, 14)</td>
<td>Chr.</td>
<td>SST: Ca $\pi$ H line</td>
<td>$N = 45$, later PMJ propagation</td>
</tr>
</tbody>
</table>


*Height ranges are abbreviated by, Pho.: photosphere, Chr.: chromosphere, TR: transition region.*

*Main Wavelength channel/diagnostic method used for the apparent velocity measurement, others may have been used in combination. The “+” denotes the combination of methods/channels. SOT: Solar Optical Telescope, DST: Dunn Solar Telescope, IRIS: Interface Region Imaging Spectrograph, SST: Swedish 1-m Solar Telescope.*

*d-f: Values are for objects here considered PMJs, though in the references they were described as, d: “bow-shock-type-transients”, e: “true microjets” (vs. d), f: “large penumbral jets”. *

*g: Values are for TR bright dots that were found to be associated with PMJs, with the average speed having direction towards the umbra.*

*h: The apparent/ plane-of-sky velocity was measured twice during the lifetimes for each of the (N = 10) PMJs, yielding double (N = 20) the measurements.*

*i: For ref. 8, the first entry is the range of velocities that could be inferred for the initial brightenings along the extent of observed PMJs, while the second is the typical range of velocities for PMJs during subsequent evolution.*

few km s$^{-1}$ to above 200 km s$^{-1}$, across at least eight studies that report such values. On the other hand, across at least seven studies that reported any LOS velocity for PMJs or any associated features, the range of values spanned from about 0 km s$^{-1}$ to an upper limit of 6.94 km s$^{-1}$ (the latter of which was found in Paper III). As such, there is a limited overlap in values, but only for the very smallest recorded apparent velocities of PMJs, and here there are some caveats that I will return to in due course. We will also need to return to a more nuanced discussion of apparent values, especially in light of more recent observations and apparent velocity measurements.

In order to demonstrate the range of values for both apparent and LOS velocities of
Table 3.4: PMJ line of sight (LOS) velocities in the literature.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>LOS vel. [km/s]</th>
<th>Height range</th>
<th>Main diagnostic(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≈ 1</td>
<td>Pho.</td>
<td>SOT: Fe i Stokes V</td>
<td>For ≈ 36 PMJ-linked ≤ 0.5″ downflows.</td>
</tr>
<tr>
<td>2</td>
<td>No strong shifts</td>
<td>Chr.</td>
<td>DST: Ca ii 8542 Å LC</td>
<td>PMJ case-studies.</td>
</tr>
<tr>
<td>3</td>
<td>≤ few km s⁻¹</td>
<td>Chr. - TR</td>
<td>(SST: Ca ii 8542 A LC)+ (IRIS, LCS: Mg ii k&amp;h, C ii-pair, Si iv-pair)</td>
<td>For 8-22 events with response in some or all lines.</td>
</tr>
<tr>
<td>4</td>
<td>−0.160</td>
<td>Chr.</td>
<td>SST: Ca ii 8542 Å LC</td>
<td>μ, N=3953</td>
</tr>
<tr>
<td>5</td>
<td>No clear up-/down-flows</td>
<td>Pho.</td>
<td>SST: Fe i 630 nm line pair</td>
<td>Milne -Eddington inversion, N = 37, μ; N=37</td>
</tr>
<tr>
<td>6</td>
<td>(−1.1 ± 0.6)</td>
<td>Chr.</td>
<td>SOT: Hα bisectors</td>
<td>μ, N=10.</td>
</tr>
<tr>
<td>6</td>
<td>(−1, −2)</td>
<td>Chr.</td>
<td>SOT: Fe i + Ca ii 8542 Å</td>
<td>STiC NLTE inv., 1 PMJ.</td>
</tr>
<tr>
<td>7</td>
<td>(−0.17, 0.81)</td>
<td>Chr.</td>
<td>SOT: Ca ii 8542 Å</td>
<td>N_{A+B} = 33 + 44</td>
</tr>
<tr>
<td>7</td>
<td>(0.22, 0.97)</td>
<td>Upper Chr.</td>
<td>IRIS, LC: Mg ii k</td>
<td>N_{A+B} = 33 + 44</td>
</tr>
<tr>
<td>7</td>
<td>(−0.06, 0.68)</td>
<td>Upper Chr.</td>
<td>IRIS, LC: Mg ii h</td>
<td>N_{A+B} = 33 + 44</td>
</tr>
<tr>
<td>7</td>
<td>(−0.20, 0.34)</td>
<td>Mid-Chr.</td>
<td>IRIS, peaks: Mg ii k</td>
<td>Avg. peak DS, N_{A+B} = 33 + 44</td>
</tr>
<tr>
<td>7</td>
<td>(−0.53, −0.01)</td>
<td>Mid-Chr.</td>
<td>IRIS, peaks: Mg ii h</td>
<td>Avg. peak DS, N_{A+B} = 33 + 44</td>
</tr>
<tr>
<td>7</td>
<td>(−2.81, 0.63)</td>
<td>Upper-Chr.</td>
<td>TR, IRIS, LCS: C ii 1334 Å</td>
<td>N_{A+B} = 22 + 29</td>
</tr>
<tr>
<td>7</td>
<td>(4.53, 6.94)</td>
<td>Upper-Chr.</td>
<td>TR, IRIS, LCS: C ii 1335 Å</td>
<td>N_{A+B} = 18 + 31</td>
</tr>
<tr>
<td>7</td>
<td>(−0.73, 1.73)</td>
<td>TR.</td>
<td>IRIS, LCS: Si iv 1394 Å</td>
<td>N_{A+B} = 26 + 35</td>
</tr>
<tr>
<td>7</td>
<td>(−0.12, 3.2)</td>
<td>TR.</td>
<td>IRIS, LCS: Si iv 1403 Å</td>
<td>N_{A+B} = 17 + 27</td>
</tr>
</tbody>
</table>


b Negative velocities denote upflows/blue-shifts. Values given as, (x,y) are inclusive ranges.
c Approx. height sensitivity. Pho.: photosphere, Chr.: chromosphere, TR: transition region.
d Spectral line feature(s) primarily used for the LOS velocity measurement (others may have been used in combination). LC: line core, DS: Doppler shift, C ii pair: C ii 1334 Å & 1335 Å Si iv pair: Si iv 1394 Å & 1403 Å. “+”: denotes the combination of methods/ channels, SOT: Solar Optical Telescope, DST: Dunn Solar Telescope, IRIS: Interface Region Imaging Spectrograph, SST: Swedish 1-m Solar Telescope.
e “μ, N = X”: averages (or μ₁/₂: median), for N nr. events. Sample-sizes may be given for value-ranges.

PMJs found in the literature, I have reproduced and summarized all that I could find. First, in Table 3.3, I have attempted to reproduce the wide range of apparent velocities that have been measured for PMJs in the existing literature. Similarly, in table 3.4 I have
attempted an equally comprehensive reproduction of the measured LOS velocities of PMJs. Again, any errors in the reproduced values are my own, and any omissions are not by design. Similarly as for the overview of PMJ lifetimes, both tables indicate which telescopes and diagnostics were primarily used to obtain the measured values. For the different values, I have also indicated whether values are derived from case-studies or from larger samples of PMJs, and indicated whether there are any peculiarities of note for the measurement at hand. I have tried to strike a balance between legibility and informational content, and naturally I direct the reader to the relevant publications if an entry is unclear or particularly intriguing.

Inspecting the two tables, our initial answer is reaffirmed; typical apparent velocities far exceed those along the line-of-sight. When inspecting the maximum apparent velocities that have been measured, this discrepancy is particularly egregious, with differences that are about as large as the maximum apparent velocities themselves, on the order of a couple of hundred of km s\(^{-1}\). Despite the great variety of nuance accompanying the various measurements of both apparent and LOS velocities, and the necessary caution that must be expressed in relation to possible projection effects for both, this difference is of such magnitude that it far exceeds the effects of any such confounders. This is especially the case when considering the consistency of the measured LOS velocities, for which we would expect at least some large outliers, even if some of the low velocities could be explained by projection effects.

Harkening back to the introduction of this section, we can also make some broad comparisons of typical apparent and LOS velocities to typical Alfvén and sound speeds. Beginning with the lower LOS velocities, it is evident that for the majority of studied PMJs, that their LOS are on the order of only a few km s\(^{-1}\), with values close to zero km s\(^{-1}\) not being uncommon. The highest LOS velocity measured has already been mentioned, and was found in Paper III. Here, the estimated upper limit on PMJ LOS velocities was found for heights just below the TR. This upper limit of 6.94 km s\(^{-1}\) was derived from 49 line-core offsets from suitable C \(\text{ii}\) 1335 Å line profiles from across two datasets of PMJs. Without delving into excessive detail, the line cores of the C \(\text{ii}\) 1334 Å and the C \(\text{ii}\) 1335 Å line form just below TR heights, and their line-core offsets were shown to correlate to LOS velocities at this height with a correlation coefficient of 0.69 and 0.63 by Rathore et al. 2015. As such, it is not one of the most reliable spectral line diagnostics available for measurements of LOS velocities, but it is still significant when considering a sizeable sample size of events. For reference, the correlation coefficient found for the LOS velocity at the formation height of the line cores of the Mg \(\text{ii}\) k & h lines, the upper chromosphere, and their line-core offsets was found to be close to unity in Leenaarts et al. 2013b. The values of LOS velocities were close to zero in the upper chromosphere when derived from the line core offsets of the Mg \(\text{ii}\) k & h lines for PMJs drawn from the same datasets as those LOS velocities derived from the C \(\text{ii}\) 1335 Å line in Paper III. Furthermore, the line-core offsets of the Si \(\text{iv}\) 1394 Å & 1403 Å, which are well-established diagnostic proxies for LOS velocities in the lower TR, had typical values close to zero, with a maximum of 3.2 km s\(^{-1}\). In any case, even accepting the upper limit of 6.94 km s\(^{-1}\) at face value for LOS velocities just below the TR for PMJs - this is still below the typical local sound speed at such heights, which is a little higher than 10 km s\(^{-1}\). For lower heights, all publications indicate LOS velocities of only a few km s\(^{-1}\), which is also below the local sound speeds for the various heights,
The dynamics of PMJs

since the sound speed is about 6 km s\(^{-1}\) in the penumbral photosphere. As such, it is a reasonable conclusion that all reported LOS velocities for PMJs are congruent with sub-sonic velocities.

Depending on the definition, it is somewhat more problematic to make a definitive statement on whether the LOS velocities of PMJs show indications for any “significant” mass-flows. Reviewing table 3.4, and keeping the upper limit on LOS velocities in mind, it is however possible to make the proclamation that PMJs do not harbour mass-flows with velocities greater than a few km s\(^{-1}\), and most likely no more than about 7 km s\(^{-1}\). In my own estimation, this is certainly congruent with a lack of “significant” mass flows. Furthermore, inspecting table 3.4 for typical values, we see that although some LOS velocities can reach upper values of a few km s\(^{-1}\), many have absolute values limited to 0 – 1 km s\(^{-1}\) or 0 – 2 km s\(^{-1}\) at most, certainly fitting a definition of non-significant mass-flows.

Moving on to the apparent velocities of PMJs, we find a much greater spread of values than for the LOS velocities. Both values of only a few km s\(^{-1}\) and values up to about 370 km s\(^{-1}\) can be inferred from observations. However, modest values of tens of km s\(^{-1}\) are much more typical. Risking the danger of appearing biased, a highlight of some of the recent results from Paper II of this thesis are of particular interest when discussing apparent PMJ velocities, since the paper specifically aimed to illuminate this topic. The paper is also where the upper limit of 370 km s\(^{-1}\) on apparent velocities for PMJs can be inferred - but with important caveats. In the paper, we showed that the measurement of apparent velocities can be highly dependent on the cadence of the observations, which complicates the matter of interpreting the apparent velocities found in earlier publications. For the study, we employed observations in the Ca ii H line from the SST with very high cadences of \(\approx 1\) s to observe and analyse the evolution of PMJs. PMJs were specifically selected on the basis that seeing conditions during their lifetimes were of sufficient quality to study their fine-scale evolutions close to the resolution limit of the telescope. The study revealed that the initial brightening phase of PMJs can be very rapid, as already mentioned as pertaining to PMJ lifetimes. The initial rapid brightening of one particular PMJ “propagated” over a distance of several hundred kilometres in only 1 – 3 seconds. This propagation however was more akin to a uniform brightening and had no distinct source at either end of the PMJ. This was also the case for many of the other PMJs studied, where no specific source for the initial brightening could be identified, with brightenings instead appearing along the entire length of the PMJs. After the initial brightenings of PMJs, most exhibited apparent velocities on the order of only about 5 – 14 km s\(^{-1}\), much lower than for the initial rapid brightenings. Since the initial brightenings of PMJs could be observed to extend over spatial scales of hundreds of kilometres over timescales of only a few seconds, it is evident that similar rapid temporal evolution cannot have been captured adequately with the much slower cadences of observations in previous publications. When observed at poorer cadences, such brightenings may instead have been interpreted as indicative of lower speeds, since the temporal scale is limited by the cadences. Alternatively, when employing somewhat fast cadences, but still slower than on the order of 1 – 2 s, propagation speeds that have high values may still be inferred, but a lack of directionality in the propagation may be obscured by the insufficiently fast cadence. Still, the propagation speeds that were observed for some PMJs, which were observed after the initial rapid brightenings in
the high-cadence observations of Paper II, were nonetheless comparable to velocities reported in earlier work. The interpretation of some of these propagation speeds were further complicated however; some PMJs showed a shrinking from their footpoints, and an extension at their tops, leading to an apparent propagation, others however, only exhibited an apparent movement of their top or their bottoms, making the inference of clear-cut propagations dubious. Furthermore, some PMJs had no truly discernable propagations of their brightenings, and faded gradually along their entire lengths until dissipating.

Overall, as PMJs have been observed to exhibit typical apparent velocities on the order of tens of km s$^{-1}$, with some publications reporting velocities on the order of $\approx 100$ km s$^{-1}$, this fits rather well with the variability in how the evolution of PMJs may be captured with regards to the variability in cadences, and when and how PMJs are captured during their evolution. This then ties into the discussion of PMJs with regards to our two velocity scale-values, that of the sound speed and the Alfvén speed. Since the apparent velocities of PMJs range from negligible or a few km s$^{-1}$, up to tens and hundreds of km s$^{-1}$, they can have values both below and above the sound speed. However, given the very rapid brightenings and propagation velocities observed in some publications, it is unlikely that PMJs propagate with velocities close to the sound speed in a meaningful sense. The caveat here is that perhaps the propagation speeds of PMJs following the initial, more rapid, brightening of PMJs as observed in Paper II, may be more in line with acoustic speeds. However, this would be a tenuous inference to make.

The large spread in values, the various confounding factors due to the variation in cadences of the observations employed and the difference in the temporal scales of the initial PMJ brightenings and their subsequent evolution are all factors that make it hard to assign a “true” apparent velocity to PMJs. The relationship of the apparent velocities of PMJs to the Alfvén speed is therefore difficult to discuss in a definitive way; however, with the above discussion of the very rapid propagation speeds for the initial brightenings of PMJs in mind, we may be able to explain why many measured apparent PMJ velocities may have been underestimated to varying degrees due to a lack of sufficiently fast cadences. However, the local Alfvén speed can also vary substantially in the chromosphere, for which PMJ propagation velocities are typically derived. From the lower chromosphere to the upper chromosphere, the Alfvén speed can take values from about 10 km s$^{-1}$ to 200 km s$^{-1}$ respectively, allowing for a large range of “reasonable” values of apparent velocities that may still be congruent with Alfvénic speeds. Luckily, studies employing numerical inversions have recently made it possible to probe individual PMJs in detail, and to probe the atmospheric conditions that they are associated with, rather than relying on only canonical values for the characteristic local sound and Alfvén speeds to compare PMJ velocities with. Due to this fact, there is growing evidence that PMJs may propagate at Alfvénic speeds through more detailed looks at their evolution.

In the study, Esteban Pozuelo et al. 2019, two example PMJs and their immediate surroundings were inverted using the STiC code, employing the full Stokes profiles of the Fe $\text{I}$ 6301.5 Å and 6302.5 Å line-pair, the Ca $\text{II}$ 8542 Å line and the Ca $\text{II}$ K line, as observed by the SST. Using the magnetic field strengths and plasma densities inferred from the inversions of the two PMJs, they estimated corresponding local Alfvén speeds at different heights. For optical depth $\tau$ at the wavelength $\lambda = 500$ nm, and
The dynamics of PMJs

As already mentioned, at least a subset of PMJs appear to consist of double-structures. These PMJs are seemingly split along their length, as first observed by Ryutova et al. 2008, who explained their formation by way of a bow-shock process (see Sect. 3.3.2 for the previous discussion). In table 3.3 the velocity range that the double-structures of these PMJs exhibited are also reproduced; these apparent velocities were perpendicular to the long-axis of the PMJs. With values in the range of \( \leq 1.5, \approx 20 \) km s\(^{-1}\), the motion of these double-structures seem to be slower than the typical motions of PMJs in the direction of their long-axes. Also as mentioned, in Paper II, we also observed that a sizeable proportion of PMJs exhibited double-structures (31%, or 14 out of a total of 45). While we did not measure explicit velocities for these features, the speed of their evolution were also clearly much slower than the rapid brightenings along their lengths.

Since the velocities of PMJ double-structures seem to be slower than their long-axis motions on the whole, the underlying process may somewhat separate from the one giving rise to the general brightening of PMJs overall. If PMJs indeed propagate at

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corresponding heights, \( \log(\tau) = -2.5, \log(\tau) = -3, \log(\tau) = -3.5 \) and \( \log(\tau) = -4 \), they derived local Alfvén speeds of 25, 35, 55, 150 km s\(^{-1}\) respectively. As the authors pointed out, these speeds fit broadly with the range of different apparent PMJ velocities reported in the literature, as is also evident from table 3.3. Going into further detail, in Buehler et al. 2019, the authors performed a numerical inversion of a specific PMJ at different times of its evolution at two different pixel locations. This was achieved by employing the STiC inversion code on the full Stokes components of the Fe I and Ca ii 8542 Å lines, as observed by the SST’s CRISP instrument. Importantly, the apparent propagation speed of the PMJ was also measured in H\(\alpha\) filtergrams. The PMJ had an apparent velocity of 15 – 16 km s\(^{-1}\) during its lifetime. At chromospheric heights, the inversion revealed slight upflows, with very low LOS velocities on the order of 0 – 2 km s\(^{-1}\). Crucially, the inversion also enabled the estimation of the local Alfvén speed, which was found to be 20 km s\(^{-1}\) at heights between \( \log(\tau) = -3 \) and \( \log(\tau) = -4 \) (for optical depth \( \tau \) at the wavelength, \( \lambda = 500 \) nm). The PMJ thus reached an apparent velocity that was about 75% of the local Alfvén speed. The authors argued that due to projection effects, the PMJ’s true propagation velocity would be even higher in actuality, implying that this may make up for the difference between the PMJ’s apparent velocity and the local Alfvén speed. Considering that the cadence of CRISP’s H\(\alpha\) observations used for estimating the apparent velocity was 39 s, and with the benefit of hindsight given the results from the high-cadence observations in Paper II, it is also possible that the apparent velocity may have been underestimated due to the less-than ideal cadence.
Alfvénic speeds along their long-axes, on the basis of the observations outlined above, it may be feasible that the bow-shock process described by Ryutova et al. 2008, or a similar process, gives rise to the slower motions perpendicular to their long axes as the PMJs evolve following their initial Alfvénic propagation.

Evidence for twisting in PMJs

There is some evidence for twisting motions around the long-axis of PMJs, first observed by Tiwari et al. 2018, for two data-sets of large penumbral jets (here, I will treat these simply as above-average sized PMJs). The authors of the study speculated that PMJs may exhibit twisting motions, since coronal jets exhibit such motions. Although such coronal jets have typical sizes that are a hundred times larger than those of PMJs, they arise over areas that have mixed-polarity fields in the photosphere, as had been observed for PMJs previously (Tiwari et al. 2016) and in the paper itself.

The authors thus computed Dopplergrams from IRIS Mg $\text{\textit{ii}}$ at offsets of $\pm50$ km s$^{-1}$ around the line-core to investigate possible twisting motions. The Dopplergrams were used under the general assumption that twisting motions would translate into a shift of intensity into the red or blue on either side of the Mg $\text{\textit{ii}}$ line-core. A clear twisting signal would thus manifest as a red-shift on one edge of a PMJ, and moving across the width of the PMJ, a blue-shift on the opposite side (or vice-versa). Since the IRIS spectrograph only observes along given slit-positions, non-ideal angles of intersection between a slit-position and any given PMJ may lead to a detection of only a red or blue shift. Two datasets of 6 and 11 PMJs from different sunspots were studied, with all of the PMJs selected on the basis that they showed some evidence for twisting motions. Out of all of PMJs, 11 PMJs showed enhancement transitions from red-to-blue or vice-versa, while the rest only showed a blue or a red enhancement in their Dopplergrams.

To investigate the relative prevalence of such signals, in Paper III we investigated the presence of twisting motions in PMJs using both Mg $\text{\textit{ii}}$ and h Dopplergrams computed at offsets of $\pm40$ km s$^{-1}$ as well as in bisectors computed for both lines. Here, we found that only a small relative number of PMJs, 5 out of 77, or 6%, exhibited clear red-to-blue (or vice versa) enhancements congruent with twisting motions, while a larger number showed intensity enhancements towards the red, 7 out of 77, or 6%, or towards the blue, 21 out of 77, or 27%. However, all Mg $\text{\textit{ii}}$ profiles had a tendency towards slight blue-ward asymmetries, and enhancements towards one wing of Mg $\text{\textit{ii}}$ PMJ profiles cannot be seen as clear indication of twisting motions.

Overall, there might be some PMJs that exhibit twisting motions, but such behaviour appears to be far from ubiquitous. An interesting avenue for further study would be fine-scale investigations of the actual Doppler-velocities that may be associated with such twisting motions. Furthermore, it is conceivable that the double-structures that some PMJs exhibit may be associated to the observations indicative of twisting motions; it is possible that the Dopplergrams may be sensitive to the motions of the two-part structures of PMJs. In such a scenario, the two structures would separate at a given velocity, perpendicular to their long axis, and such motions may produce similar signatures as those normally associated with twisting, depending on how the two structures are oriented compared to the observer. If the two structures partially overlap in relation to the observer, a blue and red asymmetry in associated Mg $\text{\textit{ii}}$ profiles may
be observed along a PMJ’s width-axis, while if one the structures obscures the other completely, only an asymmetry towards one of them may be observed. A study that investigates both these two aspects may be able to illuminate both these properties of PMJs.

### 3.4.3 PMJ energetics

Only rudimentary explorations of the energetics involved in the manifestations of PMJs have been made to date. The first estimation for the amount of energy involved in PMJs was made upon their discovery, by Katsukawa et al. 2007. Here, the authors assumed that a magnetic reconnection event heated the volume of a typical PMJ to a uniform temperature, and then estimated the thermal energy within the volume of a PMJ. The thermal energy was therefore estimated simply by

\[ E = \frac{3}{2}nk_bTV. \]

The variables denote: \( n \), the number density of the plasma, \( k_b \), the Boltzmann constant, \( T \), the temperature and \( V \), the volume of the PMJ. For the PMJ’s temperature and the atmospheric properties they assumed, \( T = 10^4 \) K, \( V = (2000 \text{ km} \times (300 \text{ km})^2 \) and \( n = 10^{18} \text{ m}^{-3} \). This yielded the thermal energy estimate\(^2\) of \( E = 4 \times 10^{16} \) J = \( 4 \times 10^{23} \) erg. This general estimate for the thermal energy of PMJs yielded the first yard-stick comparison to other solar events. The authors pointed out that the amount of energy was comparable to the lowest energies of nanoflares in the corona, hinting that perhaps PMJs could also be involved in heating the corona.

In the years since, as already extensively discussed, PMJs have become associated with upper-chromospheric and TR temperatures in observations, which are greater than the temperature assumed above of \( T = 10^4 \) K, although no coronal signatures have been found. Modelling efforts have also produced jet-like events that may reach temperatures of about \( 10^5 \) K in the pair of papers Sakai and Smith 2008 and Sakai and Smith 2009 (which we will return to below). Assuming a chromospheric temperature instead, the same thermal energy estimate from above produces energies that are also one order of magnitude higher, \( E = 4 \times 10^{17} \) J.

Of course, PMJs would be expected to have a wide variety of thermal energies, even given this simplistic estimate, dependent on their total volume. The assumed length and width of 2000 km and 300 km respectively in the initial estimate have not proven to be atypical in later observations, although, as discussed in Sect. 3.3.2, especially shorter lengths are common. However, also exceptionally large PMJs have been observed. In Tiwari et al. 2018, the authors estimated the thermal energy of a “large penumbral jet” with a length and a width of 3000 km and 1350 km respectively, using the same approach as described above, with the same assumption on the number density and the temperature, \( T = 10^4 \) K. They found, \( E = 1.1 \times 10^{18} \) J = \( 1.1 \times 10^{25} \) erg, which is a full two magnitudes greater than the estimate by Katsukawa et al. 2007. Of course, increasing the temperature to \( T = 10^5 \) K, found in the TR, would increase the thermal energy by an additional magnitude. Again, while typical PMJ sizes are smaller than this exceptionally large example of a penumbral jet, it is evident that PMJs can

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\(^2\) I have taken the liberty to correct the given energy estimates. Upon inspection, the original values from the letter seem to have been calculated by multiplying by \( \frac{3}{2} \) in the thermal energy equation, rather than \( \frac{3}{2} \), of course this is an error that has no impact on the relevant magnitude of the energies involved, especially given the wide range of PMJ volume parameters that are reasonable to assume.
3. Penumbral microjets

have a wide variety of energies associated with them, spanning several magnitudes, even when considering only simple estimates. In Tiwari et al. 2018, the authors also presented numbers for a large penumbral jet using “crude” estimates for the kinetic energy, \(E_k = 10^{19}\) J = \(10^{26}\) erg, the potential energy, \(E_p = 10^{18}\) J = \(10^{25}\) erg and the total magnetic energy, \(E_m = 10^{22}\) J = \(10^{29}\) erg. Here, they pointed out that only 0.1% of the total magnetic energy of such a jet needed to actually be converted into thermal energy in order to achieve the previously estimated thermal energy.

In the pursuit of studying PMJs which the authors hypothesized to be caused by bow-shocks, in Ryutova et al. 2008, they presented a more in-depth treatment for the energy release of such bow-shock events. Here, they estimated the energy release of a straightening flux-tube by calculating the difference in the potential energy and the kinetic energy of the flux tube. Without delving into details, for their observed (bow-shock) PMJs, they estimated the released energy to lie in a range of \(3 - 6 \times 10^{19}\) J or \(3 - 6 \times 10^{26}\) erg. They also derived the average thermal energy of an example bow-shock PMJ, finding a value of \(W_{\text{thermal}} = 4 \times 10^{19}\) J = \(4 \times 10^{26}\) erg. We see that these energies are of about one order of magnitude above the thermal energy computed for the large penumbral jets in Tiwari et al. 2018, which was computed for a temperature of \(T = 10^4\) K.

As such, it is reasonable to assume ranges of thermal energies for PMJs ranging all the way from \(10^{16}\) J or smaller (for smaller PMJ sizes or lower temperatures), up to values on the order of \(10^{19}\) J or more.

Employing a 3D 2-fluid approach, modelling efforts by Sakai and Smith 2008 have shown that simulated PMJs may reach temperatures of up to \(1.2 \times 10^5\) K, lending more credence to the rough estimates using temperature of such scales, as given above. We will return to this specific paper, and other modelling efforts of PMJs and what they imply in Sect. 3.6.

In terms of estimates for temperature increases associated with PMJs, and where such increases may take place, observations have offered some indications. Already in Reardon, Tritschler, and Katsukawa 2013 the authors speculated that PMJs are formed close to the temperature minimum of the solar atmosphere, owing to their discovery of the distinct (lopsided) moustache shape of the PMJ line profile in the Ca ii 8542 Å line. Since then, Esteban Pozuelo et al. 2019, showed that the line profiles of PMJs in the Ca ii K line show similar asymmetries and line-wing enhancements as in the Ca ii 8542 Å line. The Ca ii K line is similarly sensitive to the temperature minimum as the Ca ii 8542 Å line, which may lend further credence to such an interpretation. A more direct indication of a temperature increase for PMJs was inferred by Buehler et al. 2019. In the study, numerical inversions of SST observations showed that a sample PMJ exhibited an increase in temperature both at its foot-point and its head as it brightened, with the temperature increase appearing to propagate along its length and upwards. The temperature increase was evident at the PMJs foot-point between heights of \(\log(\tau_\lambda)\) of −2 and −4 (for \(\lambda = 500\) nm), but was most pronounced at upper end of the range, in the chromosphere. At this height, the temperature increase compared to before the PMJ’s onset was about 900 K. There is also limited evidence that some PMJs can be associated with temperature increases in the upper photosphere; in Paper III we found that some PMJs, between 11% and 21% of the studied cases, exhibited emission in the wings of the Mg ii triplet blend (found in the wavelength region between the Mg ii k &
h lines). Emission in the wings of the Mg II triplet blend is associated with an increase in temperature in the upper photosphere, typically on the order of 1500 K (Pereira et al. 2015).

At the very least, the broad range of PMJ energies estimated above provide constrains for future modelling efforts. So far, such efforts have not focused on a detailed analysis of the energy output in PMJ events, but this would be of great interest in the future. The latter is especially the case as the detailed energetics in PMJs are exceedingly difficult to infer from observations alone, and especially models that provide synthetic spectra may yield diagnostic measures to estimate the energies involved in the evolution of observed PMJs. Modelling efforts in which the heights at which PMJs deposit their energy can be varied, and an investigation of how the variation of such heights may alter observables, may also be of great benefit in untangling both the energetics and the subsequent propagation of PMJs. Given our limited observations of the temperature stratifications of PMJs, such efforts may also guide us in this regard.

3.5 Nuances in the magnetic setting of PMJs

By necessity, the introduction of this section must begin by referring the reader back to sect. 3.3, where the spatial setting and morphology of PMJs was discussed; as pointed out before, since PMJs are located in the penumbrae of sunspots, they are intrinsically intertwined with the magnetic field and its evolution. As such, when we discussed the the spatial configuration and the morphology of PMJs in the general, by extension, we also discussed the basics of their magnetic setting. I will therefore dive straight into some of the more nuanced properties of PMJs and their magnetic settings, rather than retread too much old ground. For this purpose, I will focus on three studies that studied the magnetic setting of PMJs in particular detail.

In Esteban Pozuelo et al. 2019, the authors employed observations by the SST’s CRISP and CHROMIS instruments. The CRISP instrument provided profiles in the Ca ii 8542 Å and Fe I lines, capturing the full Stokes parameters for the lines, while CHROMIS provided the first Ca ii K observations of PMJs. Of most relevance here, observations of PMJ polarizations signals, Milne-Eddington inversions and numerical inversions employing the STiC code provided new insights in the magnetic setting of PMJs. The authors identified 37 individual PMJs by their tell-tale appearance in the wings of the Ca ii 8542 Å line. For the numerical inversions however, only two PMJs were studied due to the numerical cost.

Firstly, PMJs were shown to exhibit enhanced polarization signals in the Ca ii 8542 Å line. Furthermore, magnetograms in the far-red of the Ca ii 8542 Å line confirmed that PMJs coincide with the location of opposite-polarity patches, and although some locations harboured such patches but not PMJs, it was possible to detect PMJs via such opposite polarity patches. By applying the weak-field-approximation to the outer lobes of the Ca ii 8542 Å Stokes V, the authors inferred the LOS magnetic field strengths of PMJs. However, for most PMJs these values were only barely discernable from those of their surroundings. Inspecting the magnetic field through numerical inversions for the

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3Since I reference this paper heavily in this section, a particular note of disclosure: I was one of the secondary co-authors of this paper.
two sample PMJs, this was later explained by the fact that the magnetic field strength also has a significant contribution from the horizontal component of the magnetic field. The authors also employed the Milne-Eddington approximation on the Stokes signals of the Fe\textsc{i} line, and studied the net circular polarization (NCP) of the line. The latter provided an indicator for the magnetic field gradients. They found that PMJs predominantly appear at locations where the magnetic field inclinations exhibits strong horizontal gradients; these locations coincided with photospheric spine-intraspine locations or the outer penumbral boundary, where the magnetic field lines descend. However, there were no clear signals for the NCP. For a more detailed study, the authors performed a numerical inversion for the two previously mentioned sample PMJs at peak brightness (in the Ca\textsc{ii} 8542 Å line) and their immediate surroundings. They employed the NLTE STiC code and utilized the Ca\textsc{ii} 8542 Å, the Fe\textsc{i} and the Ca\textsc{ii} K lines in the inversion. Firstly, this confirmed that these PMJs appeared at the border-sites of the photospheric spine-intraspine magnetic field. Both PMJs were associated with field strengths on the order of about 1 kG at lower heights corresponding to log(τ) of \(-2.5\) to \(-3.5\), with the field strength weakening further up into the chromosphere. Both showed some weakening of the fields along their lengths, to about 0.6 kG. The two PMJs had magnetic field line inclinations of of 110° and 115° that became more horizontal at greater heights, confirming that PMJs most likely follow the magnetic field line inclinations found in the chromosphere. Overall, the paper confirmed many aspects of the magnetic setting of PMJs that had been observed or suspected earlier; they appear at sites of opposite polarity patches and at sites of strong horizontal gradients of the magnetic field, which coincide with the boundaries of the photospheric spine-intraspines pattern and the outer boundary of the penumbra. Furthermore, PMJs have inclinations that become more horizontal with height, and they likely harbour field strengths of about 1 kG, which weaken with height.

Yet more insight was added to the magnetic setting of PMJs in Buehler et al. 2019. Here, the authors employed both numerical inversions using the STiC code and also employed the weak-field-approximation in order to investigate the line-of-sight magnetic fields of two PMJs for which there was sufficient signal. I will focus on the results from these avenues of investigation here. Also, of particular note is that some temporal evolution in the magnetic setting of the PMJ(s) was studied, in contrast to the PMJs studied in Esteban Pozuelo et al. 2019, for which properties were predominantly investigated at peak-brightness. For Buehler et al. 2019, inversions were performed on all four Stokes parameters in the Fe\textsc{i} and Ca\textsc{ii} 8542 Å -lines with the NLTE STiC inversion code, with observations yet again obtained by the SST’s CRISP instrument. For a sample PMJ, the inversions showed that the LOS magnetic field was stronger in the photosphere than in the chromosphere both before and during the main brightening, and both at the foot-point and at the head of the PMJ. In the photosphere, the LOS field strength was 700–800 G for the PMJ. During the PMJ’s lifetime, it could be observed that the chromospheric LOS magnetic field strength increased by about 100 G from before the PMJ’s onset to during the PMJ’s brightening. Before the PMJ’s brightening, the LOS field strength in the chromosphere was 450 G at its foot-point, and 350 G at its head. During the PMJ’s brightening, these rose to 550 G at its foot-point, and to 470 at its head. This showed that there is in increase in the chromospheric magnetic field strength during a PMJ’s lifetime. The total magnetic field strength was about 1 kG in the
Nuances in the magnetic setting of PMJs

photosphere and 700 G on average for the chromosphere. The authors also employed the weak field approximation on the Ca \(\text{ii} \) 8542 Å line. This enabled the retrieval of the LOS magnetic field strength in the chromosphere at both the foot-point and the head of two PMJs at different times. One of the PMJs was the PMJ just discussed. Again, this showed that the PMJ was associated with an increase in the chromospheric magnetic field strength of about 100 G. Furthermore, an offset in the onset time for the field strength increase could be observed for both PMJs. The increase could be observed first at the footpoint positions of the PMJs before it subsequently became apparent at the PMJs’ heads. These time offsets approximately corresponded to the plane-of-sky (POS) velocities of the PMJs. The POS velocity was measured for the main brightening of the PMJ in the H\(\alpha\) line. This made it plausible that the magnetic field perturbation travelled at the same propagation speed as the brightening of the PMJs themselves. This paper thus showed that PMJs seem to exhibit increases in their LOS magnetic field strength on the order of 100 G in the chromosphere, with fields being a few hundred Gauss stronger in the photosphere. Furthermore, it indicated that such field strength increases may travel along their host PMJs at the same velocity as their associated brightenings. Lastly, the authors also estimated the Alfvén velocity at chromospheric heights for their primary example PMJ; this Alfvén velocity was found to be 20 km s\(^{-1}\), and the plane-of-sky velocity of the PMJ was found to be 15-16 km s\(^{-1}\), with the just mentioned magnetic field strength perturbation propagating at a similar velocity. The authors thus speculated that if projection and other effects could be accounted for, that PMJs very well may propagate at the Alfvén velocity, both in terms of their brightenings, but also the changes in the magnetic field associated with them. Overall, this paper corroborated that PMJs appear to be associated with magnetic field strength increases that are strongest at photospheric heights and that weaken with height. Furthermore, these increases seem to travel along the length of PMJs, with the same approximate velocity as the propagation speed of their intensity brightening, which was observed to have a value close to the local chromospheric Alfvén velocity.

The third important study to be discussed in this section is Siu-Tapia et al. 2020. For the study, the SST observed a sunspot and observed all Stokes parameters in the finely-sampled Ca \(\text{ii} \) 8542 Å line, achieving a total scan time of only 17 s, optimizing between temporal and spectral resolution. This was of particular importance as the paper focused on short-lived PMJs, or those PMJs with lifetimes of < 2 minutes. The authors identified a total of 36 such PMJs. The high cadence and full Stokes parameters captured in the Ca \(\text{ii} \) 8542 Å line allowed a proper temporal analysis of the observed PMJs’ magnetic setting, which had been lacking for a larger number of PMJs of any type, as seen above. For our interests, the most salient information on the magnetic field configuration of the studied PMJs was found through the application of the weak-field approximation (WFA). The WFA was applied separately to the line core (out to offsets of ±0.3 Å) and to the line wings beyond. This was done to generate separate diagnostics for chromospheric and photospheric heights respectively, since the different wavelength regions of the line each are sensitive to these two different height regimes. After the WFA analysis, the authors presented three representative groups of PMJs that showed different types of behaviour, and then summarized the behaviour of all PMJs. For the photosphere, all 36 PMJs showed significant changes in the magnetic field configuration. The authors identified three general types of evolution in the photosphere. For the first
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group, comprised of 25 of the 36 PMJs, there was a transient increase of both the field inclination and the field strength during maximum brightness. These PMJs were slightly clustered at the limb-side penumbra, but appeared everywhere. For the second group, comprised of 9 out of 36 PMJs, the photospheric magnetic field became more inclined as for the first group, but the field strength instead showed an overall decrease in strength during their brightening. For the third group, comprised of only 2 out of 36 PMJs, the brightening regions showed a mixed type of magnetic field evolution. For these PMJs, the magnetic field became stronger and slightly more vertical in the central part of the brightening, but weaker and more inclined near their borders. For some PMJs across the three groups, there were indications for polarity changes, but bad Stokes V signals made these uncertain. The magnetic field strengths and inclinations for all PMJs (excluding the third group that had mixed configurations) stood out clearly in their diagnostic values during the maximum brightenings of the PMJs compared to before and after. On average, the enhancement in field strength for those PMJs that did not have mixed configurations was about 100 G and the field inclinations increased by 10 degrees compared to the local average value. The pre- and post-PMJ times showed very similar magnetic field properties, implying that PMJs did not leave lasting imprints on the magnetic field. Further, the immediate surroundings of PMJs at a distance of 1.5” showed much smaller changes in the magnetic field overall, by a factor of at least 10, which also showed that the PMJ-events were very localised. In the chromosphere, changes in the magnetic setting of the PMJs were much weaker than in the photosphere. In most cases, changes were so small that they were at the noise level of the WFA or could not clearly be distinguished from small-scale fluctuations. However, four PMJs did show responses in the chromosphere. For these PMJs, there were slight increases in the total magnetic field strengths at maximum brightness, but the inclinations showed no clear trend in their evolution. However, the changes found for the chromospheric surroundings of the PMJs were even smaller than those found inside the PMJs, implying that the very slight changes observed for some of the PMJ areas were not due to systematic errors, but correlated to an actual absence of change in the magnetic settings of the PMJs. All in all, this study showed that short-lived PMJs have clear responses in the photosphere, usually increasing in strength, but with about 25% of cases showing a decrease at peak brightening. Furthermore, the PMJs typically exhibited only modest increases in the magnetic field strength in the chromosphere. Importantly, they also showed that the magnetic field configuration found at the sites of PMJs shows little change in its properties before and after the appearance of PMJs. The observed changes in the magnetic field strength for the PMJs, on the order of 100 G, were also pointed out to be consisted with the values reported in Buehler et al. 2019.

In aggregate, the three studies just discussed point us to some further tentative conclusions as to the magnetic setting and evolution of PMJs not already mentioned in previous sections. PMJs seem to be associated with 1 kG magnetic field strength at their peak brightness, which is mostly localised at photospheric heights, with lower strength higher up. Furthermore, any changes in the field are much more pronounced at photospheric heights. The increase of the magnetic field strength is typically on the order of 100 G or so. The inclination of the magnetic field in PMJs also appears to increase at photospheric heights during their brightening. Also, it appears that the magnetic field strength perturbation in PMJs may have the same velocity as the brightening of the PMJs,
which may also correspond to the local Alfvén velocity of the plasma. Lastly, PMJs do not appear to leave lasting imprints on the magnetic field configuration where they appear. So far, no direct observations of the magnetic reconnection process believed to cause PMJs has been observed; however, the observations just laid out here offer strong evidence that such reconnection events may take place in the lower photosphere, or may take place at spatial scales in the photosphere below the current resolution of our observations. This is due to the observation that the magnetic field evolution at the sites of PMJs is clearly most pronounced at photospheric heights, and while it is detectable at chromospheric heights, weakens above the photosphere. This offers strong evidence for the interpretation that PMJs are caused by reconnection events triggered in the photosphere or low photosphere rather than at greater heights.

3.6 The numerical modelling and simulation of PMJs

In this section I will first give an overview of the unfortunately rather brief history of simulating PMJs. Afterwards, I will offer some brief commentary on how these efforts may fit into the broader context of studying PMJs. In the brief review, I will focus mainly on the types of codes used to model PMJs, and above all, the concrete results that were obtained in the relevant study. For detailed model setups and their particularities, I direct the reader to the relevant papers themselves, as I will only provide general outlines here.

With that said - what sort of digital simulacra of PMJs have been devised over the years, and what can they tell us about their actually observed counterparts?

The first attempt to model the formation of PMJs was made in Sakai and Smith 2008. Here, a 2-species fluid consisting of charged protons and neutral hydrogen was simulated in 3-dimensions. Charged and neutral particles were coupled only through collisions, and while the energy equation included Joule heating, heat conduction, and collisional heating, the radiative cooling term was neglected. The setup for the simulation represented an idealized form of the configuration proposed for the formation of PMJs in Katsukawa et al. 2007. It was initialized with two horizontal penumbral filaments with axial flows along them and with a vertical magnetic flux-tube rising between them. In addition to the slow flow along both horizontal penumbral filaments, a higher velocity flow of neutral hydrogen was imposed along only one of them, mimicking non-steady flows. Through collisional coupling, the faster flow quickly accelerated the charged protons in the plasma. The accelerated plasma then collided with the vertical flux tube, causing a magnetic reconnection event. The magnetic reconnection in turn gave rise to bi-directional outflows, directed upwards and downwards along the flux-tube with a slight inclination as they propagated. This was broadly congruent with the observed inclinations of PMJs as observed in Jurčák and Katsukawa 2008. Protons in the simulated jet were heated up to $1.2 \times 10^5$ K and the mass flows in the modelled jets reached a maximum velocity of about 4.1 km s$^{-1}$. Further tests showed that the density ratio of neutral Hydrogen to protons was very determinative for the maximum jet-velocities produced, and the simulation was also capable of producing super-sonic jets with velocities of about 16 km s$^{-1}$ (twice the speed of sound) when altering its
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value. This opened for the possibility of both slow and faster PMJs, depending on the specific local conditions of the plasma.

Only a short while later, the paper Sakai and Smith 2009, followed up on its predecessor above, employing the same code. This time however, the simulation was restricted to a 2-dimensional plane. The plane was oriented such that it intersected two “horizontal” current loops, i.e. penumbral filaments (this time with no vertical flux tube between them). A flow of neutral particles was imposed along the filaments, mimicking the penumbral Evershed flow. A flow of neutral hydrogen was also directed across the cross-section of the two current loops; this forced the two loops to collide, deform, and ultimately forced the magnetic fields to compress into a current sheet. Finite plasma resistivity dissipated the current sheet, letting the filaments merge. Joule heating then increased the temperature of the ions along the current sheet. Driven by the momentum of the initial neutral-hydrogen flow, an outflow of ions took place up and down between the two loops, producing jet-like structures and stretching the current sheet. It was found that the initial velocity of the collisional flow greatly impacted the rate of magnetic reconnection; an initial flow velocity of only 0.1 times the sound speed increased the reconnection rate 50-fold compared to a spontaneous reconnection process with zero flow velocity. It was the momentum of the neutral-hydrogen flow that forced the penumbral filaments to coalesce and the current sheet to stretch, and the authors pointed out that a single-fluid MHD simulation would not have been able to reproduce this process - an important reminder that single-fluid representations are limited in describing processes where the interaction between charged and neutral particles is both complex and important.

Viewed in tandem, the two papers just described thus demonstrated by way of 2-fluid simulations that reconnection events triggered by collisional flows between penumbral filaments may produce PMJ-like jets. The two papers also showed that the formation of both sub- and super-sonic jets is plausible. They also showed that they may reach TR temperatures of approximately $10^5$ K.

Next up, in Magara 2010, the authors performed a 3D MHD simulation. In this simulation the atmosphere’s properties with height were more realistically captured than for the two simulation papers discussed prior; the atmosphere was stratified such that the density and gas pressure fell with height while the average temperature increased, although the gravitational acceleration was assumed to be constant. However, consisting at its core of a standard set of MHD equations, the approach was strictly single-fluid. The simulation was initialized such that the model atmosphere contained a single, nearly-horizontal magnetic flux tube and a relatively vertical magnetic background field, representing a simplified scenario of a single penumbral filament interacting with the penumbral background field. Also important to note is that the magnetic reconnection produced in the simulation was a pseudo-magnetic reconnection process, caused by artificial numerical resistivity, rather than by a “true” finite plasma resistivity formulated explicitly; the MHD simulation ignored diffusive effects and (as mentioned) partial ionization. Once running, the simulation produced an interesting result; it gave rise to an intermediate region in the magnetic field where it transitioned from the background field to the flux tube, where magnetic reconnection took place and produced a jet-like structure that was aligned with the background field. The intermediate region was characterized by a transitional magnetic field interposed between the penumbral
The numerical modelling and simulation of PMJs

filament and the background field. This region acted as a protective layer between the two, which meant that the penumbral filament’s dynamical structure was left intact following the reconnection event. The jet consisted of a high-density blob ejected upwards by a sling-shot process caused by the bending magnetic fields during the magnetic reconnection event in the intermediate region (not inside the actual filament). The jet had a length of about 1000 km and reached a velocity of 20 km s\(^{-1}\) (almost reaching local Alfvénic speeds). It was noted that the protective intermediate region could potentially explain why penumbral filaments remain such stable features in penumbrae, despite the continual magnetic reconnection events taking place there as indicated by the continual observations of PMJs; however, as noted by the authors, the simulation did not include multiple penumbral filaments and such an inclusion may significantly alter the formation of such an intermediate region.

Lastly, in Nakamura, Shibata, and Isobe 2012, a single-fluid MHD simulation was performed. Here, atmospheric stratification, gravity, heat conduction and viscosity were neglected. The configuration of the simulation aimed to mimic the magnetic field configuration of the penumbra, consisting of the weaker and more horizontal magnetic field associated with penumbral filaments that alternates with a stronger magnetic field that is relatively vertical (the background field). Therefore, it consisted of a weak field region and a strong field region with a shear angle of 45° between them, separated by a current sheet. The aim was to explore how an asymmetry in the field strengths of the two regions may affect the simulation’s evolution. Two cases were therefore investigated - one with equal, or symmetric, magnetic field strengths, and one for which the magnetic field strength was twice as strong in one region as compared to the other. For both cases, localized resistivity was implemented in the current-sheet region, in order to accommodate fast reconnection with artificial viscosity. For the symmetric case, the resultant magnetic reconnection produced plasma flows perpendicular to the reconnecting field lines. For the asymmetric case, it lead to jet-like flows along the reconnected field lines instead, caused by an equalization of gas-pressure following the reconnection process. The first scenario did not match observations of PMJs, which appear to follow the background field (Jurčák and Katsukawa 2008). However, the second scenario fit neatly both with the actual magnetic field configuration observed in penumbrae as well as with observed PMJ inclinations. The behaviour of the asymmetric setup also fit with the results of the previous discussed simulations, where the produced jets also followed the background field. The jets produced in the asymmetric case had only modest velocities, with a maximum of 5 km s\(^{-1}\) (under assumption of a local Alfvén speed of 10 km s\(^{-1}\)). Since these fell far short of the apparent velocities initially observed for PMJs by Katsukawa et al. 2007, the authors pointed out that this may be congruent with PMJs constituting a propagating brightening (as had been suggested for the “not true” PMJs observed in Ryutova et al. 2008). The authors also sought an alternative explanation for how modest 5 km s\(^{-1}\) mass flows could produce mass flows on the order of 100 km s\(^{-1}\) at greater heights; they performed an ad-hoc 1D hydrodynamic simulation of a gravitationally stratified atmosphere in which density falls with height. This 1D atmosphere was perturbed by a modest mass motion at low heights, which then propagated upwards as an MHD slow wave, increasing its velocity to about 100 km s\(^{-1}\). This demonstrated that modest mass-flows may conceivably lead to supersonic mass-flows higher in the atmosphere as they propagate and increase their
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velocity as slow-mode waves.

Considered in aggregate, the four simulation efforts described above definitively demonstrated that some magnetic reconnection process between the background magnetic field and that associated with penumbral filaments in the penumbrae of sunspot can lead to heated plasma outflows, and thus PMJs. The different mechanisms described in the presented studies are all plausible, and each have points in their favour and must all be seen in light of their limitations. However, from the above papers we can draw some tentative conclusions; magnetic reconnection happening under conditions typical for the penumbra at photospheric heights most likely produces true mass-flows with modest, sub-sonic velocities for mass flows. This can be concluded from the values found in Sakai and Smith 2008, Sakai and Smith 2009, and Nakamura, Shibata, and Isobe 2012. At the most, mass-flow velocities only reached about 20 km s\(^{-1}\) as found in Magara 2010, which still falls below many observed apparent velocities. Higher mass-flow velocities may be feasible for chromospheric conditions (Sakai and Smith 2008 and Sakai and Smith 2009) and may perhaps be explained by MHD slow-mode waves triggered by initially slower mass flows (Nakamura, Shibata, and Isobe 2012). However, so far all somewhat-direct indications for heating and magnetic reconnection at the site of PMJs point to approximately photospheric heights (Paper III) and tentative observations of downflows at PMJ sites are also more congruent with photospheric altitudes (Katsukawa and Jurčák 2010, Jurčák and Katsukawa 2010). Going forward, more simulations of PMJs would be of great value, as they could now be further constrained by the increased body of observational information that also continues to accumulate.

3.7 Some parting looks at PMJs

In aggregate, the preceding sections have hopefully painted a rather comprehensive picture of how PMJs appear, evolve, and where they do so. The most important topic to address at this point is what this implies about the overall nature of PMJs, beyond their immediately observable properties, in particular with regards to their origin and their propagation in the atmosphere. Here, I will attempt to tie together the implications of the preceding section to do just that. During the course of this attempt I will focus on qualitative considerations. I will direct the reader to relevant preceding sections for context, and will point to previously mentioned publications where particular speculations are explored with more rigour.

As should have become increasingly evident in the preceding sections, I favour an interpretation of the existing evidence that implies that PMJs propagate with little involvement of significant mass motions. The stark difference in the observations of line of sight velocities and the apparent velocities of PMJs was hopefully amply demonstrated in sect. 3.4.2, in which I summarized their observed values, showing that LOS velocities mostly only reach a few km s\(^{-1}\), while apparent velocities range from a few km s\(^{-1}\) to several hundred. This discrepancy seems to be best explained by a lack of significant mass motions. Furthermore, the observed apparent velocities seem to be congruent with local Alfvén velocities when inspected in detail and compared to local atmospheric properties. In particular, the tentative observation in Buehler et al. 2019 that both the apparent velocity of the brightening and the evolution of the magnetic field
perturbation of a studied PMJ are close to the local inferred Alfvén velocity, provides further evidence for such an interpretation. More generally, the much-varied apparent velocities of PMJs are usually congruent with the wide range of Alfvén velocities expected for the similarly wide range of heights at which PMJs can be observed directly as brightenings, from the chromosphere to the TR. This observations remains true, even when tempered by the discussion of how the apparent velocities of PMJs may be impacted by limited temporal resolution, as given in sect. 3.4.2 and in more detail in Paper II.

In sect. 3.6, where I summarized the efforts to simulate the formation of PMJs, the velocities of the mass motions found in simulations were also consistently lower than those found in actual observations; sometimes, this was to the consternation of the authors. In Nakamura, Shibata, and Isobe 2012, the authors sought to explain how the mass motions on the order of 5 km s\(^{-1}\) that were produced in their single-fluid MHD simulation of PMJs could be reconciled with the much higher observed apparent velocities of PMJs. For this, they invoked a 1D hydrodynamic simulation that produced a MHD slow wave that eventually reached velocities on the order of 100 km s\(^{-1}\). Such an explanation is unnecessary if the actual mass motions never actually reach such high velocities. Instead, the lack of high mass-velocities produced in simulations is possibly best explained by simply taking them at face value.

As discussed in both Paper II and Paper III of this thesis, we (the authors of the two papers) support the interpretation for the propagation of PMJs as put forth in Esteban Pozuelo et al. 2019. The interpretation put forward in the latter is itself heavily inspired by the proposed formational mechanism for type II spicules somewhat recently proposed in De Pontieu, Martínez-Sykora, and Chintzoglou 2017. Type II spicules share a distinct discrepancy in their LOS velocities and their apparent velocities with PMJs. Type II spicules exhibit rise-velocities of 30 – 150 km s\(^{-1}\) when viewed at the limb (de Pontieu et al. 2007; Pereira, De Pontieu, and Carlsson 2012), and in the TR they are observed to reach apparent velocities of 80 – 300 km s\(^{-1}\) (Tian et al. 2014b; Narang et al. 2016). While the difference is not quite as stark as for PMJs, the Doppler velocities found for type II spicules are also much more modest when compared to their apparent velocities, as is the case for PMJs. Doppler velocities for type II spicules are observed to fall in the range of 20 – 50 km s\(^{-1}\) (Rouppe van der Voort et al. 2009; Sekse, Rouppe van der Voort, and De Pontieu 2012). In the TR, these values tend to be somewhat higher, in the range of 50 – 70 km s\(^{-1}\) (Rouppe van der Voort et al. 2015), although these still fall short of the observed apparent velocities.

In De Pontieu, Martínez-Sykora, and Chintzoglou 2017, this discrepancy between apparent velocities and Doppler velocities was resolved with the aid of advanced MHD simulations. Here, it was shown that type II spicules can be explained by a fast heating front that moves along the spicule’s structure, causing a brightening, but which does not carry with it high velocity mass motions. For more details, I direct the reader to the paper in question. In Esteban Pozuelo et al. 2019 it was thus proposed that a similar process may be at work in PMJs with a perturbation front arising in the deep photosphere, which subsequently dissipates its energy along the length of the PMJ up through the atmosphere. As previously discussed, an increase in temperature in the chromosphere and photosphere has found support in the inversion results by both Esteban Pozuelo et al. 2019 and Buehler et al. 2019. as well through the observation of emission in the
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Mg \textsc{ii} triplet blend for some PMJs, as found in \textit{Paper III}. The observation of increases in the magnetic field strengths at photospheric heights that weaken with height, observed in \textit{Esteban Pozuelo et al. 2019, Buehler et al. 2019, and Siu-Tapia et al. 2020}, also fits with an interpretation in which the triggering event of PMJs originates at photospheric heights or below.

In totality and broad strokes, the above fits with the scenario of an upwards-propagating heat front that travels at the local Alfvén speed first proposed by \textit{Katsukawa et al. 2007}. Indeed, as suggested upon their discovery, it is also predominantly the measurement of Doppler velocities that has pointed us to such a scenario, as they have revealed the stark discrepancy between the line of sight and apparent velocities of PMJs in the years since. As they are conveniently included at the end of this thesis, I direct the reader to the discussion in both \textit{Paper II, and Paper III} for more discussion on the formation of PMJs and their possible propagation in the form of heating-fronts.

Of course, further observations, and especially modelling efforts, are still highly desirable to illuminate the formation of PMJs. However, it appears that their propagation most likely involves some sort of process akin to the one proposed for type II spicules. In order to elucidate the particulars of this process, an MHD modelling effort as carried out for the type II spicules in \textit{De Pontieu, Martínez-Sykora, and Chintzoglou 2017} would be of great value for the case of PMJs. However, such efforts are complicated by the extreme and complex environment that PMJs are found in.

In addition to more advanced modelling efforts, regardless of the details that characterize their propagation, the great prize in the study of PMJs will be the actual observation of the magnetic reconnection events that are thought to cause them. Such an observation has proven elusive so far, and it may be necessary to employ the next generation of solar telescopes such as DKIST (\textit{Rimmele 2019}) and the EST (\textit{Collados et al. 2013}) for this task. These telescopes will both feature unprecedented 4-m aperture sizes, but also the capability to deliver not only the high spatial resolution, but also the high temporal and spectral resolutions necessary to observe the fine details of PMJs, while also providing the full Stokes parameters that will be necessary to perform the detailed numerical inversions vital to probe the atmospheric conditions of PMJs and their surroundings.

After these parting looks at PMJs we will at last turn to the next and final chapter. There, I will introduce the background and motivations that fuelled the publications included in this thesis in some more detail. Then, at the very long last, we will come to the actual publications themselves.
Chapter 4

On the thesis papers and their motivations

In this final chapter, I will give a summary of the most salient parts of the studies that make up the original research of this thesis. Perhaps more importantly, I will try to elucidate the motivations that prompted their writing, a topic that is usually not afforded as much space when writing the papers themselves, and I will also offer up some musings inspired by their topics or methods. After, the papers will be allowed to speak for themselves and any concrete numbers and results can be perused at leisure where they are reproduced. Hence, here I will write about any results in somewhat broader terms and I will instead aim to focus on the different methods used in the research and on any ramifications or nuances to the results that were perhaps not as easily included in the papers themselves, at least not without straying too far from the actual research. So, with that said, let us begin this last chapter in earnest - at long last the end may be in sight.

4.1 Microjets in the penumbra of a sunspot

The first publication included in this thesis is Paper I, or Drews and Rouppe van der Voort 2017, with the title, “Microjets in the penumbra of a sunspot”. This first entry began its life as part of the work for the master thesis that preceded this doctoral thesis, but it saw large expansions, additions and refinements after those more humble beginnings, and before it finally saw peer-reviewed publication in the form of Paper I. One of the motivating factors for the work was to perform a study of PMJs in a resolved spectral line, rather than basing it only on wide-band observations, which had been the case for earlier work on PMJs. This would allow an actual analysis of spectral features, rather than only observing PMJs as brightenings in relatively wide-band observations in the Ca ii H line in which PMJs had been observed previously. For this purpose, the SST provided detailed observations in the Ca ii 8542 Å line together with reference wide-band Ca ii H line observations of a sunspot, recorded in June of 2010. As work began, PMJs had not yet been described in the Ca ii 8542 Å line, but before the master thesis was finally submitted, the first distinctive spectral profiles of PMJs in the Ca ii 8542 Å line were published in Reardon, Tritschler, and Katsukawa 2013. The spectral profile shapes presented for the two example PMJs in the cited work proved to be congruent with our own preliminary observations; PMJs tended to exhibit a lopsided-moustache shape with a blue-over-red asymmetry in the Ca ii 8542 Å line. Despite being beaten to the punch in the presentation of this novel result, the work in the master thesis, and what would eventually culminate in Paper I, was ultimately not motivated solely by a chance to report the first resolved PMJ spectral profiles.

The work culminating in Paper I was in large part inspired by the desire to investigate
not only PMJs and their spectral features, but to do so on a large scale with the aid of an automated detection code and with the help of automated methods for analysis. Furthermore, I had the ambition that the automated detection method was to actually utilize the spectral information available in the entire Ca II 8542 Å spectral line, rather than only be based on simpler considerations such as brightness measures at single wavelength points, for which the brightness of PMJs is compared to their background environment in order to detect them. Also, the tantalizing promises by machine learning were too enticing, and I too wanted to partake in the fad of the times - I had big data after all; countless pixels through time, each possessing 37 data points (one for each of the Ca II 8542 Å sampling points in the line), seemed to promise grand opportunities for more complex methods of detection and analysis. Ultimately, this ambition proved fruitful, although the ambition had to be scaled to my fledgling abilities, and therefore led to the utilization of what is commonly described as the simplest of the machine learning algorithms, the k-Nearest Neighbour (k-NN) scheme. Here I will point out some of the considerations that went into the application of the automated detection pipeline that was ultimately developed for Paper I, and then point to what we may glean from this in pursuit of further forays into machine learning in solar physics. However, I will do this rather colloquially, since the actual details and the different steps of the pipeline are described in the paper itself - here the purpose is to explain the motivation and background of the work instead.

The k-NN scheme works by a simple principle: a library, or reference set of data, is collected, and each entry is labelled by the type of object it represents. For the present case, this meant that entries were either classified as PMJs - or as not-PMJs, i.e. anything else. A sufficiently large and varied reference set is vital to the proper application of the k-NN scheme. It needs to cover both a representative variety of the objects of interest, but reciprocally, it must also encompass sufficiently varied and representative examples of whatever makes up the background “noise” in the dataset, meaning anything that we are not interested in identifying. Each reference object, or pixel, in the reference library thus consists of a data vector with the dimensionality of the given data-space - in this case, the 37 dimensions corresponding to the 37 spectral positions that the Ca II 8542 Å line had been sampled in by SST’s CRISP instrument. Then, given an unknown pixel, the simple euclidean-, or vector-, distance is computed to every entry in the reference library. The distances are then sorted from shortest to longest. Finally, a number of k nearest neighbours, where k typically is an odd low-valued integer, in the list are checked for their type. If a majority of the polled k-nearest-neighbours are of type “object of interest”, the new vector is labelled as the same, if they are not, it is labelled accordingly. The process then repeats for every single data-vector, or pixel position with its associated spectral information in our case, until all pixels are classified. The algorithm is thus quite straight-forward, but also computationally expensive. The selection of k must be tailored to the dataset for best results, and furthermore, accuracy in the classification must be verified by running the code blindly on pre-classified reference data.

In practice, it was also necessary to compress the SST Ca II 8542 Å observations of the target sunspot. Since the line was sampled at 37 distinct spectral positions, this made for a 37-dimensional vector identifying any given pixel position for any given time-frame. In informatics, data-spaces with many dimensions are not only unwieldy and computationally expensive to deal with, but the vital step in the k-NN scheme is
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at risk of failure for datasets with too many dimensions. As noted, after a dataset of reference vectors is assembled for the k-NN scheme, any unknown vector belonging to a new pixel that is to be classified as an object or non-object of interest has its multi-dimensional euclidean distance computed to all vector-entries in the reference dataset. A problem arises when computing distances in high dimensional spaces, dramatically dubbed “the curse of dimensionality”, which can entail that distance measures become less meaningful. To reduce the computational demands in analysing individual pixel position (each corresponding to a 37-dimensional data-vector), a method called principal component analysis, or PCA, was applied. Without delving into the specifics that are spelled out in the paper, applying the PCA involves computing the covariance matrix of the dataset, quantifying both the variance along individual dimensions and how they correlate with variations in the other dimensions. Here, the variance is taken as a proxy for information content in the data. Then, the data is projected along a new set of basis vectors, such that the data is linearly independent along the new dimensions. Each of the new dimensions is therefore no longer correlated - this is useful because the new basis vectors can also be ordered such that the data along basis vectors that have very little variance, i.e. informational content, can simply be discarded. This process can be strictly quantified, and the PCA performed in the paper achieved a compression of the observations in the Ca ii 8542 Å spectral line to 19% of its original size, while retaining 97% of its variance, or informational content. This also reduced the dimensionality of the data to 7 principal components, corresponding to the 7 basis vectors that were retained. Perhaps intuitively surprising, producing sample-images of the Ca ii 8542 Å spectral line observations projected along the 7 principal component basis-vectors produce very recognizable images, that also capture very distinct features of the solar atmosphere that one would otherwise recognize at specific heights or as specific structures. Figures 4.1 and 4.2 show Ca ii 8542 Å spectral line observations reordered along the new principle component basis, with one frame shown for each of the 7 different principal components ultimately used, all for for the same time frame in the observations. The images are both tantalizingly familiar and somewhat alien when comparing them to the regular observations in the Ca ii 8542 Å line. For several of the principle component images, PMJs are already quite evident as small brightenings.

Following the PCA and finally the application of the k-NN algorithm on the compressed data set, the code produced binary bitmaps in black and white, dividing the penumbra into areas deemed to be PMJs or not-PMJs by the algorithm. Following more mundane methods of tracking areas over time, removing spurious detections and noise, this ultimately produced a large number of PMJs that were tracked through time and space. In fact, a total of 453 PMJs were tracked, corresponding to about ten times that number, 4253, of individual PMJ areas when simply adding up all PMJs identified across frames without considering their correlation in time - providing a tremendous opportunity to gather statistics on sizes, lifetimes, locations in the sunspot, as well as making it possible to generate a variety of average spectral profiles, and enabling the investigation of spectral profile-shape dependencies with regards to PMJ locations within the sunspot and more. All this was carried out, and I refer to the paper for the actual values and details. Main results were robust size and lifetime measures for PMJs based on the large dataset, the result that spectral profile-shapes in the Ca ii 8542 Å line are not dependent on their location within the penumbra and the clear result that
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Figure 4.1: Observations in the Ca ii 8542 Å line by SST’s CRISP instrument of the sunspot of AR11084, but realigned along the basis of the 7 Principal Components (PCs) as found by an application of principal component analysis. Shown are example images along the first four principle component vectors for the same time frame in the observations, in direction left-to-right, top-to-bottom. Data along lower-numbered principal components has greater variance than those for higher-numbered principal components. The tick-mark separation is 1”.

PMJs tend to cluster in hot-spots. The latter are regions in which PMJs appeared and re-appeared throughout the observations.

This study clearly demonstrated the vast potential inherent in more advanced numerical methods for the detection of solar objects. However, it also proved that such implementations can be quite time-consuming, and that they typically must be carefully tailored to the observational dataset at hand. Furthermore, since the k-NN algorithm depends on a robust reference library, its inception already necessitates the identification of many of the objects of interest, in this case PMJs, which means that a lot of manual
Figure 4.2: Shown are images of Ca \( \text{ii} \) 8542 Å observations realigned along principle components 5 – 7 of the same basis as shown in Fig. 4.1, see its caption for details. The tick-mark separation is 1”.

identification must still be performed before the automated pipeline can take over. For observations that have very uniform properties, such as the precise locations of sample points in a given spectral line, such reference libraries could be reused and built upon with successive studies. However, a lot of solar observations, especially from ground-based telescopes, are often different in both subtle or significant ways even when they are observed in the same spectral line by the same instrument. This makes the development of detection codes that are reusable across datasets challenging. As mentioned in Chapter 2, space-based telescopes often have more standardized observation libraries, and they often also have more standardized observing programs with less customizability than what is common at for example the SST. Anyone developing detection pipelines for solar phenomena, utilizing machine learning or not, is therefore generally best advised to tailor them to well-established sources of data with reliable parameters, that are easily
available and that come with well-documented metadata. Efforts to serve up science-ready and well-documented data are becoming an ever greater ambition in solar physics, and this is already well-exemplified for the IRIS and Hinode satellites and their freely available observations, easily obtainable from their respective online libraries. Efforts to make data from the SST more widely available, with more standardized metadata included, were also already mentioned in Chapter 2, and the first paper detailing efforts in making science-ready SST and IRIS co-observations freely available are described in Rouppe van der Voort et al. 2020.

The other studies included in this thesis did not see the application of any wholly automated object-detection or analysis, opting for more “mundane” methods in selecting PMJs. We will turn to these and their motivations below.

4.2 Penumbral microjets at high spatial and temporal resolution

The second publication included in this thesis is Paper II or Rouppe van der Voort and Drews 2019, with the title, “Penumbral microjets at high spatial and temporal resolution”. While a lot of fine-scale and meticulous scrutiny of PMJs was performed for this study, its motivation and its main results are refreshingly straight-forward given the discussion in the last section. Penumbral microjets had been reported to host very high apparent velocities from the time of their discovery by Katsukawa et al. 2007, with velocities on the order of 100 km s$^{-1}$.

This was increasingly puzzling as a result, since other measures for the velocity of PMJs failed to provide evidence for any significant Doppler velocities, either from direct observations or through inversions. No significant line-core shifts were found for PMJ profiles in the Ca ii 8542 Å line in Drews and Rouppe van der Voort 2017, though this may be due to Ca ii 8542 Å line core simply not being directly responsive to the dynamic parts of PMJs. However, neither were any significant Doppler-shifts of any chromospheric or TR spectral lines observed by Vissers, Rouppe van der Voort, and Carlsson 2015, when the first TR responses to PMJs were presented. Furthermore, in Esteban Pozuelo et al. 2019, the investigation of potential velocity gradients in photospheric LOS velocities of PMJs through use of SST Fe i observations failed to show any significant gradients. Here, a measurement of of chromospheric LOS velocities through spectroscopic analysis of different features in the Ca ii K line profiles also failed to show evidence for LOS velocities above a few km s$^{-1}$ at the highest. Additionally, inversions of PMJ spectral profiles by both Esteban Pozuelo et al. 2019, and Buehler et al. 2019 also failed to provide evidence for significant up- or down-flows along the LOS of more than a few km s$^{-1}$ for PMJs. Lastly, preliminary results from the then-unpublished Paper III in this thesis, later to become Drews and Rouppe van der Voort 2020, also failed to show evidence for significant mass-motions in the photosphere, chromosphere or the TR in a large dataset of PMJs (more on this below). As such, the discrepancy between apparent plane-of-sky velocities of PMJs stood in stark contrast to the lack of observations indicating significant LOS velocities. Even assuming that PMJs primarily move along the horizontal, even though they had been shown to generally follow the penumbral background field, and thus should have at least
some upward or downward component to their motions, the lack of observations of even moderate line of sight velocities for PMJs remained puzzling.

With this general incongruity in mind, Paper II saw its formulation. As has been repeated often in Chapter 3, PMJs have been speculated to be the result of either true mass motions that travel upwards through the atmosphere, due to the high apparent velocities that have been observed, or alternatively, to be due to some kind of heating front that propagates upwards through the atmosphere, causing a brightening, with only modest or no significant mass motions. This was already speculated upon their discovery by Katsukawa et al. 2007. Since other studies had failed to offer concrete evidence for actual mass flows, as sketched out above, we resolved to test whether the observations of high, supersonic apparent-velocities of PMJs could perhaps be amended by newer and improved observations at higher cadences, in order to more accurately investigate the motions of PMJs as they propagate. Earlier estimations of the apparent velocities of PMJs had typically been carried out by use of Ca ii H line observations from Hinode’s SOT. Further, the apparent velocities were typically measured by use of gradients in time-space diagrams, which highlighted the expansion of PMJs along a given direction with time, with the slope determining the velocity. The cadence of Hinode’s SOT that was used for the discovery of PMJs by Katsukawa et al. 2007, was 8 s. We speculated that in a scenario in which a some sort of heat front propagating through the atmosphere was the actual underlying process that may explain PMJs, that this front may propagate at speeds exceeding both the sound-speed as well as the previously observed apparent velocities. Furthermore, we then posited that if this process was observed at sufficiently high cadences that this brightening’s true velocity may be discernable, both in image-sequences, but also in the gradients of time-space diagrams. The reciprocal thought was that these fast brightenings had been observed as apparent velocities on the order of 100 km s\(^{-1}\) in Ca ii H line observations with slower cadences, and could be explained by a lack of sufficient temporal resolution in the observations, which may have smeared out the even-faster propagation of the PMJs across time-frames. Furthermore, the assumption was that apparent velocities inferred from observations with very fast cadences may turn out to be so fast that they would ultimately be incongruent with any reasonable scenario involving significant mass motions in PMJs. Instead, this would indicate evidence in favour of PMJs primarily being the manifestation of sudden brightenings due to a fast-propagating heating front of some sort.

To test whether we could put the lie to our thoughts, we employed observations of a sunspot from two different days by the SST in the Ca ii H line. These had a spatial resolution close to the telescope’s resolution limit in the line of 0.8” for much of their durations, due to both excellent seeing conditions and the subsequent image reconstruction through the use of the SST’s MOMFBD pipeline. Most importantly, the observations had a very fast cadence of only 1.02 s. In the study we identified 45 PMJs for detailed analysis, primarily selected for whether seeing conditions were good enough throughout their lifetimes in order to unambiguously track their propagations in the Ca ii H line image sequences. This was of particular importance since even small amounts of seeing had the ability to interfere with our very precise measurements of the PMJs’ extents and evolutions. Here, I will forgo delving into the specifics, the nuance, the other significant results as well as the words of caution that are provided
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in the paper itself, and only summarize the main results of our endeavours. Ultimately, Paper II did indeed reveal that PMJs observed at very high cadences propagate as very sudden brightenings along pre-existing fibril structures over hundreds of kilometres on typical timescales shorter than 10 s. Furthermore, we failed to identify clear roots or source-points for most of the PMJs, the presence of which would at least naively be expected for a scenario in which a localized acceleration of mass takes place. Following the initial brightening that is characteristic of PMJs, subsequent motions of the heads of PMJs had more modest velocities, between 4 - 14 km s\(^{-1}\), although only half showed any significant motion of the tops at all. We thus concluded that PMJs are indeed most likely to form through to some kind of heating front that propagates through the plasma, with only minimal accompanying mass motions.

In the next paper up, we looked at yet more direct measures that should be sensitive to any potential mass-motions inside PMJs, examining the problem of what sort of plasma motions actually take place in PMJs from additional vantage points, among other topics.

4.3 A multi-diagnostic spectral analysis of penumbral microjets

The third and final publication included in this thesis is Paper III, or Drews and Rouppe van der Voort 2020 with the title, “A multi-diagnostic spectral analysis of penumbral microjets”. This study is perhaps the most scattered in terms of the topics or areas of interest that it covers amongst the three papers that are included in this thesis. The paper is also the only of the three that utilized not only observations from the SST, but also simultaneous observations from the IRIS satellite’s slitjaw imager and its slit spectrograph. This enabled an investigation of PMJs that does not arbitrarily confine them to discrete heights in the solar atmosphere, and instead allows a description that is rather aptly described as holistic - despite the word’s reputation for undeserving preponderance in grant proposals.

A guiding theme in the investigation of PMJs in this paper is indeed the view of PMJs as objects that exist and extend throughout much of the solar atmosphere and its layers, rather than view them as phenomena primarily confined to the chromosphere for example. This was made possible and facilitated by the great range of spectral lines that were observed for the purposes of the study. The SST and IRIS co-observed a well-formed sunspot hosting PMJs on two consecutive days. The SST provided highly spatially and spectrally resolved observations in the Ca \( \text{ii} \) 8542 Å and H\( \alpha \) lines, providing images from the photosphere and through the chromosphere as well as spectral profiles. Meanwhile, IRIS observed in a so-called medium-sparse 8-step raster configuration, and therefore provided the ability to obtain PMJ spectra in the chromospheric and TR IRIS line at 8 discrete vertical lines that intersected the sunspot, as well as providing accompanying slit-jaw images. The lines from the IRIS slit-spectrograph that were used in the various analyses were the Mg \( \text{ii} \) h & k lines, the Mg \( \text{ii} \) 2798.75 Å & 2798.82 Å triplet blend, the C \( \text{ii} \) 1334 Å & 1335 Å lines, and the Si \( \text{iv} \) 1394 Å & 1403 Å lines. These lines provide information that originates from all the way down in the photosphere (the Mg \( \text{ii} \) triplet blend), but with most spectral information originating from
A multi-diagnostic spectral analysis of penumbral microjets

the chromosphere and upwards to the TR. With the two telescopes combined, a rather impressive number of nine distinct spectral lines or narrow wavelength regimes were analysed for the study, all observed simultaneously - a great testament to the value of co-observations with different telescopes and the utilization of different instruments capable of observing in different wavelength regimes. For more details on the observations, the reader is of course kindly directed to the actual paper below.

In many ways, Paper III picked up the torch where the paper Vissers, Rouppe van der Voort, and Carlsson 2015 left it to illuminate the path ahead. In the cited paper, PMJs were for the first time investigated in co-observations by the SST and IRIS, and were also for the first time observed in the various IRIS channels that are sensitive to heights from the chromosphere to the TR. Therefore, it was also in Vissers, Rouppe van der Voort, and Carlsson 2015 that it was first confirmed that PMJs exhibit signals not only in the chromosphere, as previously shown, but also in the TR. It also clearly linked the appearance of PMJs in SST Ca ii H line-wing images to those in the Mg ii k, C ii and Si iv IRIS slit-jaw images by way of striking “rainbow” images, that inspired similar images in Paper III. Such rainbow images greatly aided in the bulk-analysis of many PMJs at different heights. However, while Vissers, Rouppe van der Voort, and Carlsson 2015 identified a large number of PMJs, a total of 180 events, that could all be observed in SST and in IRIS slit-jaw images, only a total of 22 events both crossed the IRIS slit-spectrograph positions and also showed any signal in IRIS lines, some of them in only a few lines. As such, the possibility for larger scale statistics and spectral analysis was somewhat limited.

For Paper III, we wished to perform such a larger-scale investigation of PMJs in the IRIS lines. Indeed, we wished to investigate a sufficiently large number of PMJs that crossed the IRIS spectrograph slits so that we could be reasonably certain that a possible trend in the dataset pointing towards a consistent lack of signal in any specific lines was due to actual lack of emission, and not due to poor sampling or coverage. In the end, we selected a total of 77 PMJs over the two days of observations, primarily identified by their bright emission and appearance in the Ca ii 8542 Å line. The depth in the analysis of the spectral information available from the IRIS spectrograph also went far beyond what had been possible to carry out previously. This analysis was made possible by a series of papers on “The Formation of IRIS Diagnostics”. These analysed the diagnostic potential of IRIS lines through the use of a BIFROST model atmosphere and synthetic spectra derived thereof. In particular, the papers investigating the diagnostic potential of the Mg ii h, k, the Mg ii triplet blend (Leenaarts et al. 2013a; 2013b; Pereira et al. 2015), and the C ii 1334 Å and 1335 Å lines (Rathore and Carlsson 2015; Rathore et al. 2015), were vital to this work. This series of papers demonstrated the great diagnostic potential of the mentioned IRIS lines and enabled the probing of atmospheric dynamics within PMJs throughout the atmosphere. The analysis of many of the IRIS spectral line diagnostics described in this series of papers makes up a large bulk of the work presented in Paper III. For the most part, these provided estimates for line-of-sight velocities or limits thereon, and their gradients. This turned out to provide yet further evidence that PMJs do not seem to harbour significant mass-flows, since the diagnostics only indicated very modest flow velocities or gradients where they were detectable. Of further interest, the analysis of the Mg ii triplet-blend near the Mg ii k line also provided a way to probe the presence of sudden temperature increases in the upper photosphere.
or lower chromosphere. Through this, we observed tell-tale signatures congruent with a sudden temperature increase on the order of 1500 K in the upper photosphere or lower chromosphere at the site of a few select PMJs. This was a tantalizing observation that may be indicative of energy releases by magnetic reconnections at this height, even though only a small subset of PMJs had clear signatures indicating as much. Three other main aspects of the paper were largely inspired by results or observations published in other works.

In Paper III, we also investigated whether or not we could find evidence that PMJs rotate about their long-axis, as had been reported for large PMJs in Tiwari et al. 2018, and found through the use of dopplergrams in the IRIS Mg \( \text{\textsc{ii}} \) line. We also had the opportunity to evaluate whether any such twisting motions were a common property of PMJs, since we did not specifically select any of our PMJs on the basis that they showed indications of spinning, and rather only investigated this after having already selected our PMJs. We also expanded the analysis to the computing of dopplergrams in both the \( \text{Mg} \text{\textsc{ii}} \) \( \text{\textsc{i}} \) and its sibling, the \( \text{h} \) line, as well as computing bisectors for both of the lines as well. Ultimately, we found some evidence that some PMJs may rotate about their long axis, but did not find that many or a majority of PMJs show clear evidence for spinning.

Since the SST provided high-resolution observations in not only the \( \text{Ca} \text{\textsc{ii}} \) 8542 Å line, but also in the \( \text{H} \alpha \) line, we had the opportunity to investigate the then newly-discovered dark features that PMJs exhibit in the \( \text{H} \alpha \) line, as reported by Buehler et al. 2019. In the cited work, it was shown for the first time that PMJs exhibit dark features in the blue wing of the \( \text{H} \alpha \) line that were co-spatial with the known brightenings of PMJs in the inner wings of the \( \text{Ca} \text{\textsc{ii}} \) 8542 Å and \( \text{Ca} \text{\textsc{ii}} \) K lines. Furthermore, PMJs also exhibited dark-features in the \( \text{H} \alpha \) core at the end of PMJs’ lifetimes. In Paper III we confirmed the findings that PMJs present as dark features in the \( \text{H} \alpha \) line wing, but we also found that PMJs exhibit dark features in the inner line wing of the \( \text{Ca} \text{\textsc{ii}} \) 8542 Å that are co-spatial with those in the \( \text{H} \alpha \) line wing, preceding and following the typical brightening of the PMJs in the inner wing of the \( \text{Ca} \text{\textsc{ii}} \) 8542 Å line. As such, we concluded that this was further evidence that PMJs form at the sites of pre-existing fibrilar structures.

As a last major area of investigation, we analysed spectral time-slices of the \( \text{Ca} \text{\textsc{ii}} \) 8542 Å and all the IRIS lines (though not including the triplet blend), in order to ascertain whether or not the onset-times of PMJs was markedly different in lines corresponding to different heights in the solar atmosphere. This was in large part prompted by the observations made in Samanta et al. 2017, in which transition-region Bright Dots (BDs) observed in IRIS slit-jaw images were linked to PMJs observed in the \( \text{Ca} \text{\textsc{ii}} \) H line by Hinode’s SOT. As previously discussed in Chapter 3, the peculiar result in the cited paper was that those BDs that could be linked to PMJs (half of all observed BDs) clearly tended to precede their associated PMJs in time. This was puzzling, since this would imply that PMJs may have their origins in the TR and go on to heat material further down after their onset, rather than the inverse. The latter is of course the commonly accepted scenario, whether or not PMJs propagate as true mass motions or as a heat front. Our cadence in the IRIS channels was much slower, about 40 s, than the limiting cadence in the cited work of about 10 seconds. However, while the average of the time-difference in onset between the preceding BDs and their associated PMJs was on average about 15 to 16 s, many of the BDs preceded their PMJ counterparts by more than a minute. As such, at least some of our PMJs that exhibited signal in
all atmospheric layers would have to exhibit some detectable systematic offset in their onset-times between channels in order to be congruent with the results in Samanta et al. 2017. Ultimately, we could not find any clear systematic offsets on time-scales equal to or greater than our limiting cadence of 40 s, suggesting that PMJs propagate from the chromosphere to the TR over 40 s or less. This incongruency in results remains puzzling, and further inquiry is warranted in order to rule out smaller systematic differences in onset time for PMJs at different atmospheric heights. However, especially since Paper III also showed tentative signs that heating does indeed occur in the upper photosphere at the location of PMJs, the suggestion that they do in fact originate in the TR was made less likely. The already mentioned studies, Esteban Pozuelo et al. 2019, and Buehler et al. 2019 have also shown evidence of temperature increases at chromospheric heights for PMJs through inversions, and in the case of Esteban Pozuelo et al. 2019, it was shown that detected increases in the magnetic field strength diminished with height for a sample PMJ, rather than the inverse. All these findings and more indicate that the scenario in which PMJs form through magnetic reconnection at photospheric to chromospheric heights is the most likely, at least barring further observations to the contrary.

Overall, Paper III covered a lot of metaphorical ground in its analysis, and it should be allowed to present its detailed results for itself below. Its main takeaways can probably be summarized by the following run-on sentence; It failed to show any evidence for significant mass-flows in PMJs throughout the solar atmosphere, ranging from the chromosphere to the TR, but did find tantalizing signatures of temperature increases at upper photospheric heights at the tail-ends of PMJs, furthermore, it presented evidence that PMJs appear to form along pre-existing fibrilar structures, and that PMJs appear with time-differences lower than 40 s throughout the atmosphere, and finally, it was found that the majority of PMJs typically do not exhibit twisting motions. Such wide-ranging and comprehensive investigations through such a wide range of atmospheric heights could not have been carried out without the combination of different telescopes and instruments, underscoring the importance of such collaborations.

Now, finally, with the discussion of the papers that are included in this thesis behind us, we can at long last move on to the scientific work that hopefully justifies the many words that have been written thus far. I also hope that the preceding pages have helped prepare the reader for the actual academic work below, rather than only add to any prior confusion. And so, with these final words we part ways. I would like to thank the reader for both their stamina and to congratulate them, assuming that they made it this far. I would also like to thank for their continued attention and for however much focus I may have been able to command. Finally, I beg forgiveness for my continuing tendency to add just another sentence or two; I’d especially like to do so for those times when perhaps fewer would do.
Bibliography


Bibliography


Papers
Paper I

Microjets in the penumbra of a sunspot

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Microjets in the penumbra of a sunspot

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ABSTRACT

Context. Penumbral microjets (PMJs) are short-lived jets found in the penumbra of sunspots, first observed in wide-band Ca II H line observations as localized brightenings, and are thought to be caused by magnetic reconnection. Earlier work on PMJs has focused on smaller samples of by-eye selected events and case studies.

Aims. It is our goal to present an automated study of a large sample of PMJs to place the basic statistics of PMJs on a sure footing and to study the PMJ Ca II 8542 Å spectral profile in detail.

Methods. High spatial resolution and spectrally well-sampled observations in the Ca II 8542 Å line obtained from the Swedish 1-m Solar Telescope (SST) were reduced by a principle component analysis and subsequently used in the automated detection of PMJs using the simple machine learning algorithm k-nearest neighbour. PMJ detections were verified with co-temporal Ca II H line observations.

Results. We find a total of 453 tracked PMJ events, 4253 PMJs detections tallied over all timeframes, and a detection rate of 21 events per timestep. From these, an average length, width and lifetime of 640 km, 210 km and 90 s are obtained. The average PMJ Ca II 8542 Å line profile is characterized by enhanced inner wings, often in the form of one or two distinct peaks, and a brighter line core as compared to the quiet-Sun average. Average blue and red peak positions are determined at $-10.4$ km s$^{-1}$ and $+10.2$ km s$^{-1}$ offsets from the Ca II 8542 Å line core. We find several clusters of PMJ hot-spots within the sunspot penumbra, in which PMJ events occur in the same general area repeatedly over time.

Conclusions. Our results indicate smaller average PMJs sizes and longer lifetimes compared to previously published values, but with statistics still in the same orders of magnitude. The investigation and analysis of the PMJ line profiles strengthens the proposed heating of PMJs to transition region temperatures. The presented statistics on PMJs form a solid basis for future investigations and numerical modelling of PMJs.

Key words. Sun: atmosphere – Sun: chromosphere – Sun: photosphere – sunspots – Sun: magnetic fields

1. Introduction

Penumbral microjets (PMJs) are short-lived, elongated, transients in the chromosphere of sunspot penumbrae. They were discovered (Katsukawa et al. 2007) in Ca II H line sequences from Hinode’s 3 Å wide imaging filter in which PMJs display a 10–20% brightness enhancement as compared to surrounding penumbral structures. In the Hinode observations, PMJs have typical lifetimes of up to one minute, lengths between 1000 and 4000 km, widths of about 400 km, and apparent rise velocity faster than 100 km s$^{-1}$ (Katsukawa et al. 2007).

Penumbrae are known to host strong convectively driven plasma flows and magnetic fields that vary significantly at small spatial scales, both in inclination and magnitude (see e.g., Borrero & Ichimoto 2011). In this magnetically stressed environment, magnetic reconnection appears to be a viable candidate as driver of PMJs. This is supported by the measurements of the apparent inclination of PMJs with respect to the photospheric penumbral filaments (Katsukawa et al. 2007) and magnetic fields (Jurčák & Katsukawa 2008). Further indications of the reconnection scenario come from Katsukawa & Jurčák (2010) who report the association of small photospheric downflow patches with some PMJs. These could be interpreted as the downward flows from magnetic reconnection above the photosphere. Evidence of progressive heating along PMJs is reported by Vissers et al. (2015; Fig. 5), who find clear responses in Mg II k, C II, and Si IV slit-jaw images of the Interface Region Imaging Spectrograph (IRIS) to PMJs observed in Ca II lines. Emission of C II and Si IV towards the top of PMJs suggests heating to transition region temperatures.

Reardon et al. (2013) study transients in a sunspot penumbra from spectral imaging data in the Ca II 8542 line. Aided by co-temporal Hinode Ca II H imaging, they identify several PMJs in their dataset. The Ca II 8542 line profiles show enhanced emission in the wings out to ±0.5 Å with peaks at about ±0.3 Å and a line core that shows little difference compared to the surroundings. They point out the similarity with Ca II 8542 spectral profiles of Ellerman bombs, for example as shown in Vissers et al. (2013).

In this study, we expand on the observational characterization of PMJs by analyzing a high spatial-resolution time series of both narrow-band Ca II H filtergrams and spectral imagery in Ca II 8542. We employ an automated detection scheme to built a large statistical sample of PMJs. The detection scheme neatly takes advantage of the many sampling positions in the Ca II 8542 line, utilizing the full line profile. The dimensionality of the observations in wavelength positions is first reduced by employing principal component analysis (PCA), and is then used in detections performed employing the k-nearest neighbour (k-NN) algorithm, followed by object tracking and statistical analysis.
2. Observations

Active region AR11084 was observed on 28 June 2010 with the Swedish 1 m Solar Telescope (SST, Scharmer et al. 2003a) on La Palma. The field of view was centred on the near-circular sunspot with fully developed penumbra at heliocentric coordinates \((X,Y) = (710, -339)\) \((\mu = \cos \theta = 0.55, \text{ with } \theta \text{ the observing angle})\). The seeing was excellent for the full 41 min duration of the time series, which started at 09:18:29 UT, and the image quality further benefited from the adaptive optics system (Scharmer et al. 2003b) and image reconstruction with the Multi-Object Multi-Frame Blind Deconvolution method (MOMFBD, van Noort et al. 2005). We analyzed data from instruments on both branches of the optical beam: from the CRISP Imaging SpectroPolarimeter (CRISP, Scharmer et al. 2008) on the long-wavelength branch “red beam”, and filtergram imaging in \(\text{Ca} \text{\scriptsize{II}} \text{H}\) on the short-wavelength branch “blue beam”.

With CRISP, we sampled the \(\text{Ca} \text{\scriptsize{II}} 8542\ \text{Å}\) line at thirty-seven line positions, with equidistant 55 m\(\text{Å}\) steps out to \(\pm 880\ \text{m}\(\text{Å}\) \(=\) 1032 m\(\text{Å}\), and additional sampling at \(\pm 948\) and \(\pm 1034\) m\(\text{Å}\). CRISP has a full width at half maximum (FWHM) of 110 m\(\text{Å}\) at 8542 Å, therefore the \(\text{Ca} \text{\scriptsize{II}} \text{H}\) line is critically sampled throughout the central part of the spectral line profile. We acquired eight exposures per spectral sampling that were used for MOMFBD image reconstruction. In addition, single-wavelength spectro-polarimetric samplings of the \(\text{Fe} \text{\scriptsize{I}} 6302\ \text{Å}\) line were acquired. Unfortunately, due to erroneous calibration settings, the precise wavelength for this sampling was unknown, which resulted in noisy and effectively useless maps of the four Stokes parameters. The acquisition time for \(\text{Ca} \text{\scriptsize{II}} 8542\ \text{Å}\) was 8.1 s and the temporal cadence of the time series was 12.4 s. After MOMFBD restoration of the individual spectral-line scans, the data was put together as a time series after correction for the CRISP prefilter (FWHM 9.3 Å for \(\text{Ca} \text{\scriptsize{II}}\)), compensation of the diurnal field rotation, rigid alignment, and destretching. We used early versions of the different procedures that were later put together as the reduction pipeline for CRISP data (de la Cruz Rodríguez et al. 2015) including the post-MOMFBD correction for remaining small-scale seeing deformations that are due to the non-simultaneity of the sequentially recorded narrowband CRISP images (Henriques 2012). The effective field of view of the time series is \(55'' \times 55''\), with a pixelscale of \(0.710\) pixel \(^{-1}\).

In the blue beam, synchronized filtergrams were recorded at a rate of 10.8 frames s\(^{-1}\) in the \(\text{Ca} \text{\scriptsize{II}} \text{H}\) line core, with a filter FWHM of 1.1 Å, and with a wider passband filter, FWHM of 10 Å, at \(\lambda = 3954\ \text{Å}\), between the \(\text{Ca} \text{\scriptsize{II}} \text{H}\) and \(\text{K}\) lines. These two imaging channels were MOMFBD-restored to produce a time series with an effective cadence of half the CRISP data, 6.2 s. The alignment to the CRISP data was performed by cross-correlation of the red and blue wideband channels, which both show the photosphere.

Figure 1 shows example frames from the observations, displaying the sunspot at offsets \(-1032\ \text{m}\(\text{Å}\) and \(-275\ \text{m}\(\text{Å}\) in the \(\text{Ca} \text{\scriptsize{II}} 8542\ \text{Å}\) line. Also displayed are the nominal borders of the umbra and penumbra and the area over which the average quiet-Sun \(\text{Ca} \text{\scriptsize{II}} 8542\ \text{Å}\) line profile used for comparison was computed. A cropped image of the observations also showcases a strong inverse Evershed flow.

3. Methods

Prior to the employment of the pipeline described below, the observations were investigated using the CRISP SPectral EXPloer (Vissers & Rouppe van der Voort 2012, CRISPEx), which was used to interactively browse the MOMFBD-reduced observations. CRISPEx was also instrumental in the by-eye assembly of the reference set of PMJ and non-PMJ objects in the observations for later employment of the k-NN algorithm.

We restrict ourselves to a qualitative description and focus only on the basic concepts and overall structure. For an in-depth treatment, the reader is directed to Drews (2014), Sect. 5, in which the full methodology for the automated detection scheme and detection process is described, and a full explanation of the subsequent object tracking is provided.
Covered in some more detail in the subsections below, the main working steps, starting from the post-MOMFBD SST observations, can be summarized as the following discrete steps:

1. preliminary identification of PMJs in Ca II 8542 Å using Ca II H line observations as reference;
2. principle component analysis: dimensionality reduction and data compression;
3. detection of PMJs using the k-nearest neighbour algorithm;
4. object tracking and statistical analysis.

3.1. Preliminary identifications of penumbral microjets

To justify the claimed observation of PMJs in the Ca II 8542 Å line, a subset of observations was first compared to by-eye detections of PMJs in the co-observed Ca II H line, because the detection of PMJs and their appearance is firmly established in this line (Katsukawa et al. 2007; Jurčák & Katsukawa 2008; Katsukawa & Jurčák 2010; and Jurčák & Katsukawa 2010). Earlier observations of PMJs in Ca II 8542 Å were presented by Reardon et al. (2013), Drews (2014), as well as by Vissers et al. (2015).

A quick qualitative study was enough to show that many, if not most, Ca II H PMJ detections have spatially coinciding similar features in the Ca II 8542 Å line, in particular slightly blue-ward of the nominal line centre wavelength. Similarly as in Ca II H, PMJs appear in selected spectral positions in the Ca II 8542 Å line as short-lived, elongated brightenings in the sunspot penumbra.

This is illustrated in Fig. 2, which shows four example images in the observations at the same time frame. One image is in the Ca II H line, one in the Ca II 8542 line core and two in the Ca II 8542 Å line at an offset of −275 mÅ. Penumbral microjets proved to be most visible in by-eye detections in the Ca II 8542 Å line in images at an offset of −275 mÅ. The arrows in the four panels all point to the same pixel positions, and it is clear that PMJ features are present in both diagnostics, namely in the Ca II H line and the Ca II 8542 Å line scan. This is especially true when comparing features present in the Ca II H line which are clearly visible in the −275 mÅ line offset Ca II 8542 Å images as well. Detection borders of PMJs overplotted in panel (d) highlight that most by-eye selected examples in this frame were caught by the automated detection scheme that will be presented below in Sects. 3.2–3.4.3. Notably, two PMJs as selected by eye on the right of the field of view (FOV) are classified as one event by the automated scheme. Furthermore, one of the events is not detected by the detection scheme, as marked by the second arrow from the left in Fig. 2. Manual inspection using CRISPEX indicate that this event’s spectral profile is not very distinct over a larger area.

From these examples, and other qualitative inspections of PMJs that visually coincided in space in the Ca II H line and in the Ca II 8542 Å line observations, the assumption that these events are the same physical objects is validated. Further investigation of PMJs in the Ca II 8542 Å line and the ascertainment of a distinct spectral line profile is therefore warranted.

3.2. Principle component analysis

The detection of PMJs in the presented automated approach is based on their distinct line profiles in the Ca II 8542 Å line. Intensity differences throughout the field of view, which are due to both limb-darkening and local variations, proved to make detections using the k-NN algorithm difficult. Intensity variations affecting the whole line profile may not impact the shape of the given pixel’s line profile, but may shift the overall intensity,
including key sampling points in wavelength in which PMJs are visible, such that the similarity measures in the algorithm were less meaningful. For this reason, prior to PCA treatment, the observations were first normalized. The normalization consisted of normalizing each line profile in all pixels in all timeframes to its own sum. This preserved the line profile shapes, but removed any overall intensity variations effectively. The preservation of line profile shapes consequently carried over into the PCA-treated observations used in the k-NN detection scheme. Principle component analysis is both a method for data analysis, as well as being a useful tool for data compression. An introductory overview of PCA is given in Shlens (2014).

In PCA, the covariance between variables in a dataset is computed, constructing its covariance matrix. Subsequently, the associated eigen-vectors and eigenvalues of this matrix are found. The eigenvectors correspond to a new set of basis vectors along which the data can be projected, yielding a linearly independent dataset with no cross-correlation between variables. Normalizing the associated eigenvalues, these yield the relative contribution of the new basis vector variables to the total variance of the newly aligned dataset. In this practice, this variance can be equated to the informational contribution from the given new eigenvector. Therefore PCA presents the opportunity for compression of a dataset, because discarding variables along eigenvectors with low informational value does not yield significant information loss overall, and additionally, this loss is quantifiable.

In the present context, the 37 wavelength sample points of the Ca\textsc{ii} 8542 Å line were treated as the variables in a 37-dimensional dataset. Hence, this was the dataset that was analyzed and compressed using PCA as outlined above. For the present pipeline, the computation of the covariance matrix of the Ca\textsc{ii} 8542 Å line observations was performed following Bennet et al. (2009), in which a numerically stable single-pass algorithm is presented. It provides the benefit of a lighter numerical workload whereas a naive, but generally stable, approach requires two passes over the dataset. In this kind of an approach, the mean of a dataset is first computed, followed by the computation of the needed powers of this mean in the second pass. The employed single-pass of Bennet et al. (2009) also avoids common numerical pitfalls in the computation of the covariances in terms of numerical instabilities when they are calculated in a single-pass approach. Using the found eigenvectors and corresponding eigenvalues, it was determined that the variables along seven eigenvectors describe the original observations on an accuracy, or informational content, of 97\%, which was deemed acceptable, whilst yielding a compression of the data to 19\% of the original size. Thus, these seven eigenvectors were chosen as the principle components of the dataset, and the observations were aligned and compressed along them.

Different morphological features, all with distinct spectral profiles, such as long fibrils, umbral flashes and fibrils with strong flows, are clearly identifiable in maps of the different principle components. This lends intuitive credence to the PCA reduction method, in that the different “new spectral” variables still represent real features picked out from the original sampling positions. For examples, we refer to Drews (2014), Sect. 5.

3.3. The k-nearest neighbour algorithm

The k-nearest neighbour algorithm is conceptually simple, yet powerful. This is one of the reasons it is widely applied in signal-processing tasks such as facial and voice recognition as well as machine reading. For an introduction to the specifics of the algorithm, an overview and discussion for improvement of the algorithm is given in Guo et al. (2004). Furthermore, Yang & Liu (1999) compare the algorithm to other classifiers.

Often termed the simplest of the machine learning algorithms, the k-NN algorithm is based on a comparative approach in which the data to be classified is related to a pre-classified reference set of the same type. In practice, this means that a reference set is assembled using expert knowledge or a manual classification scheme, and is then used to classify the rest of the data using a similarity measure. We employed a simple euclidean metric in the 7-dimensional PCA-reduced dataset. A reference set was assembled using by-eye detections, noting the temporal and spatial location in the observations. At present, a reference set corresponding to a total number of 958 positions in time and space was assembled. This reference set is further divided into 168 PMJ positions, comprised of 55 separate events, and 790 background positions of large diversity. These specific numbers were found to yield robust results following a trial-and-error approach, during which we studied the number and variability of reference events needed until the results were satisfactory and consistent. Because the reference set is polled for each automatic identification, an unnecessarily large reference set is to be avoided.

The background positions correspond to datapoints that are clearly not PMJs. The k-NN algorithm uses both object and non-object entries in the reference set, such that each vector in the PCA reduced data has its associated distance computed to all points in the reference set for identification. A number of k-nearest neighbours are then polled, and the point is classified by majority vote. The selection of the parameter k is performed using an accuracy test of cross-classification of the assembled reference set. The classifications resulted in binary maps for each timeframe, consisting of background and PMJ detections that were then further processed, as outlined in Sect. 3.4. Figure 3 shows the Ca\textsc{ii} 8542 Å line profiles of the individual PMJs and background, or non-PMJ positions, that were assembled for the k-NN reference set. It bears remarking that these profiles are separated for the sake of clarity for the two plots, but form one reference set in practice, with profiles marked as PMJ or non-PMJ in the set when polled. The selected PMJ profiles have a wide span in terms of intensity throughout the line, but are well-defined by their shape. This is also illustrated by their included average, which presents itself as a very well-defined PMJ-like profile, as will be made clear in Sect. 4. The non-PMJ profiles span a wide variety of profiles, sampling positions in the quiet Sun, penumbra, umbra, and features such as the strong inverse Evershed flow present in the observations.

3.4. Object tracking, statistical analysis and extraction of the Ca\textsc{ii} 8542 Å line profile

The post-processing of the binary maps of raw PMJ detections output by the k-NN algorithm was performed in several steps, which are described below. First, the binary maps were cleaned of noise and objects tracked through time, as described in Sect. 3.4.1. Following this, base statistics were extracted from the basis of these tracked objects, as described in Sect. 3.4.2. Lastly, line profiles in the Ca\textsc{ii} 8542 Å line were found, and this process is detailed in Sect. 3.4.3.
3.4.1. Noise removal and object tracking

To remove spurious signals, the binary detections output from the k-NN algorithm were first run through an 8-pixel connectivity mask, removing lone falsely identified pixels. Furthermore, a lower “hard” area limit of 20 pixels was implemented on object sizes. Additionally, a “soft” area limit of 50 pixels was also implemented. This means that any areas in the original bitmaps below a size of 20 pixels total were not considered at all. The soft limit meant that if no area of a given tracked object reached a size of 50 pixels during tracking, the tracked areas were discarded. This means that tracked objects could have sizes of below 50 pixels, but only as long as the given object reached a size as large, or larger, than 50 pixels in at least one timeframe. This was meant to ensure that it was possible to catch the smaller beginnings of objects, but to avoid tracking spurious signals that never developed, and thus avoid noise from being tracked for long periods.

These area limits would correspond to cubic areas with sides $4.47 \text{ pixels} = 194 \text{ km}$ and $7.07 \text{ pixels} = 307 \text{ km}$ for the hard and soft limit respectively, although because a fitting of ellipses-shapes is later performed (see below) the spatial limits along one axis may be smaller. The limits given may seem prohibitively large, but are chosen after trial and error and yield reasonable results. The final limits were chosen because lower values allowed small-scale noise in the bitmaps to be tracked and erroneously labeled as PMJs. This noise was mostly caused by a prominent inverse Evershed flow (see Fig. 1) in the lower right of the observations.

The object tracking was performed using relatively simple measures of spatial distances in the observations to relate discrete detections across timeframes. We used a maximum distance between centre-of-mass pixels of 15 pixels $= 652 \text{ km}$ between timeframes. This is equivalent to a projected speed of approximately $52 \text{ km s}^{-1}$, although it must be kept in mind that due to the morphing of detection areas and thus shifts of centre-of-mass pixel positions between frames, this threshold can not be seen as a direct threshold on real movement of detected PMJs.

Detections were also restricted to an outline of the photospheric penumbra, as seen in the wings of the Ca II 8542 Å line, see Fig. 1. Only objects with centre-of-mass pixels inside this outline were included in the subsequent analysis. Furthermore, spurious detections inside an outline of the umbra were also discarded, see Fig. 1. These events were most likely related to umbral flashes, as was evident when investigating using CRISPEX.

3.4.2. Basic statistics extraction

A statistical analysis on the resultant final PMJ detections was then carried out. For estimations of detected object sizes, a fitting of ellipses on the detected objects was carried out. The reasoning behind this was the assumption that jet-like objects such as PMJs should in principle exhibit a somewhat elongated shape. The tracking was thus restricted to PMJs corresponding to best-fit-ellipses with an eccentricity of 0.9, corresponding of an approximate ratio of semi-major to semi-minor axis in the ellipses of 2.3:1. The associated major and minor axes of these fitted ellipses for each single object were employed as estimates for the lengths and widths of the given detections respectively (see Fig. 4 for examples of these fitted ellipses). This allowed for the collection of size-statistics. Angular positions around the centre of the sunspot for detected objects were also computed.

3.4.3. Computing the line profile

The “master” average line profile for PMJs in the Ca II 8542 Å line was computed using the line profiles of the centre-of-mass-pixels and their 8 neighbour-pixels for each individual detection.
The average was thus carried out for only those PMJ detection areas through all timeframes that actually contained the centre-of-mass-pixel, as computed from the detection area for each detection, and this pixel’s 8 pixel-neighbours. This selection was performed to ensure that only line profiles of pixel positions that did not fall outside of the actual PMJ detection areas, and additionally that only pixel positions that represented well-formed PMJs, were used. The former case of a centre-of-mass pixel falling outside its associated detection area could occur due to for example peanut-shaped PMJ areas. The final average line profile is thus based on a subset of the 4253 PMJ detections through all timeframes. This totalled 3953 PMJ detections, because not all PMJ areas contained their theoretically computed centre-of-mass pixel, or because the area did not contain all 8 immediate pixel neighbours of the centre-of-mass pixel.

For the computation of the average line profile a total of $3953 \times 9 = 35,577$ pixel-position line profiles was therefore used. The entirety of pixel positions of all PMJ detection areas were not employed for simplicity, and as not to skew the line profiles towards larger PMJs, that would then have contributed more strongly towards the profile. However, a difference in line profiles between large and small PMJs has not been investigated.

Finally, the individual 9-pixel-average line profiles of each of the PMJs in the mentioned subset were also investigated with regards to distinct peaks in the blue and red wing together with their line-core minimums. The wavelength positions of the peaks and the line-core minimum were estimated by interpolating the individual profiles, and then using a sliding-window approach to find the local peaks and minimum in each given profile. The final average values for the peaks and minimum were then based on the individually found peaks and minima. Profiles for the average of different categories of profiles, meaning profiles with blue and/or red peaks present, profiles with both blue and red peaks present and profiles with just either of the peaks present, were also computed to compare to the main average and each other. The resulting average values for the positions of the minimum, the blue and the red peaks were calculated by averaging the found positions in the individual interpolated line profiles, and are thus not limited to the thirty-seven sampling points. They are therefore subject to greater uncertainty.

### 4. Results

The automatic detection of PMJs as outlined in the last section made it possible to collect a large and statistically significant set of PMJ detection areas with associated properties that could then be investigated. In the sections below the different derived properties and statistical values associated with these events are presented.

#### 4.1. Detection summary

Table 1 summarizes the detections performed by the automatic detection pipeline, together with the most basic statistics derived from them. It is evident that the automatic approach of identifying PMJs using their spectral profile yields a large dataset from which to infer PMJ properties. With a number of PMJs equaling 453 tracked events, derived statistical values are significant. Each individual frame in the detections contains an average of approximately 21 PMJs, and this rate highlights the continuous occurrence of PMJs throughout the observations. Because each of these detected PMJs is tracked through time, but with unique associated properties in each timeframe, the number of individual PMJs summed over all timeframes is greater than the 453 tracked events. This number is 4253 PMJs present throughout all individual frames and corresponds to the 453 distinct, tracked events (see Table 1). However, some further selection was performed before some statistics were computed, namely line profile averaging as well as intensity and line profile feature investigations, see Sect. 3.4.3.

Figure 4 depicts a sample frame from the observations at an offset of $-275 \text{ mÅ}$ in the Ca II $8542 \text{ Å}$ line with PMJ detections shown. Visible in the figure are the overlain PMJ detection areas and the associated computed ellipses that were used to measure the lengths and widths of the PMJ detections.

As a further reasonability check, a check of the relative brightness in the detection areas of all PMJs was performed. The individual average brightness in both the Ca II $8542 \text{ Å}$ line at an offset of $-275 \text{ mÅ}$ and in the Ca II H line core was computed for each PMJ detection area. These were normalized to the average brightnesses for each individual frame of the penumbral region (as outlined in Fig. 1) in each of the two passbands. PMJs are seen as bright features in by-eye detections in both wave-lengths, and thus one would expect an average brightening in the detection areas for both. Furthermore, as a result of the detections being carried out ultimately utilizing the Ca II $8542 \text{ Å}$ line profile, an average brightening in the detection areas in the Ca II H line core would further strengthen the co-occurrence of PMJs in both passbands. We find that 80% of PMJs have an average relative brightening above unity in the Ca II H line core and that 79% of PMJs have an average relative brightening above unity in the Ca II $8542 \text{ Å}$ line at an offset of $-275 \text{ mÅ}$. Furthermore, 71% of detections show a simultaneous brightening above unity in both passbands throughout the times series. These values strengthen the assumption that bright features are being detected in the brightness-independent detection scheme utilizing the Ca II $8542 \text{ Å}$ line profile shape. Because the brightness of the PMJs was estimated as an average of their entire detection area, their brightness as compared to the average of the entire penumbra for a given timeframe may in fact be a conservative comparison. A comparison between, for example, the brightest pixel and the penumbra average for any given PMJ detection would likely yield a higher relative brightness in both passbands. This is due to automatically detected PMJs tending to exhibit a larger area than if selected solely by-eye compared to the surrounding intensity. Comparing PMJ brightnesses to the local average

### Table 1. PMJ detection statistics.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total PMJ detections (over all frames) [count]</td>
<td>4253</td>
</tr>
<tr>
<td>Tracked PMJ objects [count]</td>
<td>453</td>
</tr>
<tr>
<td>Mean PMJ detections per frame [events/frames]</td>
<td>21</td>
</tr>
<tr>
<td>Mean lifetime, tracked PMJs (all) [s]</td>
<td>117</td>
</tr>
<tr>
<td>Mean lifetime, tracked PMJs (&lt;8 min) [s]</td>
<td>90</td>
</tr>
<tr>
<td>Mean length [km]</td>
<td>640</td>
</tr>
<tr>
<td>Mean width [km]</td>
<td>210</td>
</tr>
<tr>
<td>PMJ minimum position’ [km s$^{-1}$]</td>
<td>0.14</td>
</tr>
<tr>
<td>PMJ blue peak offset’ [km s$^{-1}$]</td>
<td>-10.4</td>
</tr>
<tr>
<td>PMJ red peak offset’ [km s$^{-1}$]</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Notes. (a) $N_{\text{min}} = 437$, (b) Based on ellipse fit, (c) Based on the average of the 9-pixel average interpolated line profiles.
brightness of the penumbra may very well have also resulted in a higher relative brightnesses.

4.2. Basic penumbral microjet statistics and properties

Having computed the length and width for all PMJ detections using the minor and major axis of the fitted ellipses (as described in Sect. 3.4.1), they could be presented as distributions. Figure 5 shows these histogram distributions for the lengths and widths of all detected PMJs throughout the observations.

The distributions for lengths and widths seem to be well-behaved with trailing ends tending towards zero, as is expected. The lower ends of the distributions also seem to taper off in the last lower length and width bins. One pixel in the observations corresponds to 43 km, thus both distributions’ lowest length and width bins with entries include sizes larger than this. However, the detections were limited by a lower-limit area, that also effects the lower range. The average width and lengths must thus be interpreted with this in mind. The associated mean length of 640 km and mean width of 210 km (see also Table 1) are reasonable. They are also consistent in rough magnitude with values reported in Katsukawa et al. (2007), namely lengths of 1000–4000 km and widths of approximately 400 km or less for the PMJs in Hinode Ca II H observations. These values are also consistent with the mega-metre range as given in Reardon et al. (2013) when observing individual PMJs or penumbral transients in the Ca II 8542 Å line. Both estimates found here are however still considerably smaller at almost half for both values. In Fig. 6 the distribution of durations of tracked PMJs is provided with a cut-off value of 8 min, representing 96% of tracked detections, not showing outliers.

These outliers were excluded because, for the most part, they represented a small fraction of tracked PMJs that had extremely long lifetimes. The abnormally long lifetimes are most likely due to detections in areas in which PMJ detections were ubiquitous throughout the observations, and where PMJ events overlapped so closely in time and space that they were tracked continuously as one event. Also, spurious and long-lasting detections may also be caused by the strong inverse Evershed flow (see Fig. 1) present on the centre side of the observed sunspot.

4.3. Ca II 8542 Å penumbral microjet line profile

The PMJ line profile in the Ca II 8542 Å line computed from the average of the 3953 × 9 = 35 577 pixel-positions is given in Fig. 7, together with reference profiles for the quiet Sun and the penumbra. The PMJ profile is characterized by enhanced inner wings at about ±385 mÅ and a brighter line core that is at 116% of the quiet-Sun-line-core brightness. The enhancement of the inner blue wing is stronger than in the red wing. The far wings of the PMJ profile approach the level of the average penumbra. This average profile is less pronounced than individual profiles of PMJs selected by eye and by inspecting individual pixel-position profiles, as will be made more evident in Sect. 4.4.

The average PMJ profile that we find is however still consistent with other reported profiles as given in Reardon et al. (2013, their Fig. 4) and Vissers et al. (2015, their Fig. 5). Although it does show a less pronounced peak in the blue and a very weak enhancement in the red compared to most of these published profiles, the profile is still recognizable. It must be emphasized that the profile presented here is an average, computed from many individual profiles, whereas the profiles it has been compared to in previous work are profiles from individual pixel positions of eye-selected PMJs. These individual profiles were most likely selected specifically due to their distinct features, meaning that the average profile presented consequently will present features that are less sharp. Individual profiles of PMJs in the presented observations, including both those selected by eye and those contained in PMJ detection areas, still exhibit such distinct features to a large degree, as will be exemplified in Sect. 4.4.

As mentioned in Sect. 3.4.3, when averaging the master line profile, each individual 9-pixel average profile corresponding to an individual detection was inspected for the presence of a tell-tale blue and/or red peak in the line. As a result, it was possible to create averages of the profiles according to the presence of peaks in the blue and/or red. Thus, averages for the profiles for the cases of both a blue and red peak being present, one or the other being present, or just one of the peaks being present could be computed. Figure 8 shows these average Ca II 8542 Å line profiles for different subsets of PMJ detections.

Fig. 4. Cropped image in the Ca II 8542 Å line at an offset of ~275 mÅ with overlain PMJ detection areas (solid-blue) and corresponding computed best-fit ellipses (dashed-green) at time 23 min 27 s. Also indicated for reference are three pixel positions inside one of the detection areas, one closer to the sunspot centre (turquoise cross), the PMJ centre-of-mass-pixel (red X-mark), and one closer to the edge of the penumbra (blue star). Detailed line profiles for these pixels are shown in Fig. 13.
Fig. 5. Length and width distributions for PMJs throughout all timeframes. (Top) Length distribution with approximate bin size of 145 km, with mean value (dashed) at 640 km indicated, the median value is 489 km. (Bottom) Width distribution with approximate bin size of 48 km, with mean value (dashed) at 210 km indicated, the median value is 165 km. The total sample number of individual PMJs is $N = 4253$.

Fig. 6. Distribution of tracked PMJ lifetimes with an upper cutoff value of 480 s (8 min) and bin size of 29.9 s. $N_{\text{min. distr.}} = 437$ (96% of total tracked PMJs). The mean value of 90 s is indicated (dashed-red), the median value is 75 s.

For completeness, Table 2 summarizes these different groups of profiles. We especially note that only less than half, $N_{\text{profiles with peaks}} = 1868$, of all 9-pixel average PMJ profiles used in the peak detection, $N_{\text{all}} = 3953$, have clear automatically detectable peaks. Furthermore, a vast majority of these were in the blue, with a total number of blue peaks of $N_{\text{blue peaks}} = 1725$.

Fig. 7. Averaged Ca II 8542 Å line profile of PMJ centre-of-mass pixels and their 8 neighbour-pixels (solid-black). For reference, the averages of the Ca II 8542 Å line profile over the whole time series are given for the upper left corner of the full-FOV (dashed-grey) and the penumbra (dashed-dotted-grey). See Fig. 1 for outlines of both areas.

Fig. 8. Average Ca II 8542 Å PMJ line profiles divided by the presence of clear inner-wing peaks: PMJs with only distinct blue peaks ($N_{\text{only blue}} = 1637$, dashed-blue), PMJs with only distinct red peaks ($N_{\text{only red}} = 29$, dashed-dotted-red), PMJs with both distinct blue and red peak simultaneously ($N_{\text{blue and red}} = 114$, dotted-cyan), and PMJs with distinct blue and possible red peaks ($N_{\text{blue with possible red}} = 1725$, dashed-dotted-magenta). We note that this profile nearly overlaps with the only-distinct-blue-peak profile. Included for reference are the profiles of Fig. 7: the full PMJ line profile average (solid-black), the average penumbra line profile (dashed-dotted-grey), and the average quiet-Sun line profile (dashed-grey).
Table 2. Summary of PMJ peak-presence in individual profiles.

<table>
<thead>
<tr>
<th>Peak combinations</th>
<th>Nr. of profiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue and/or red peak</td>
<td>1780</td>
</tr>
<tr>
<td>Both blue and red peak</td>
<td>114</td>
</tr>
<tr>
<td>Blue peak (with possible red)</td>
<td>1725</td>
</tr>
<tr>
<td>Only blue peak</td>
<td>1637</td>
</tr>
<tr>
<td>Red peak (with possible blue)</td>
<td>143</td>
</tr>
<tr>
<td>Only red peak</td>
<td>29</td>
</tr>
</tbody>
</table>

and a total of red peaks of $N_{\text{red peaks}} = 143$. These correspond to percentages of 92% and 8%, of blue and red peaks respectively, of the total number of detected peaks. Furthermore, of all the investigated averaged 9-pixel profiles, 43% exhibit blue peaks whereas only 3.6% exhibit detectable red peaks.

From Fig. 8 it is evident that the average line profile of those profiles that have either both or one peak present (magenta-dashed-dotted in the figure) is near identical to the average line profile for those profiles that have blue peaks but no red peaks present (blue-dashed in the figure). This is concurrent with the fact that there is a much larger number of profiles with blue peaks compared to red peaks. The average line profile of profiles with only red peaks is correspondingly significantly different from both of these profiles and only shows a peak in the red. However we note the low number of twenty-nine profiles in this average. All three profiles are more distinct in appearance than the overall average line profile of all the 9-pixel line profiles (solid-black in the figure).

Finally, and most notably, the average line profile of those profiles with both blue and red peaks present simultaneously, which therefore has well-defined peaks in both the blue and red, more strongly resembles the profiles of by-eye selected PMJs in the present dataset. This will be made more evident in Sect. 4.4. For likely the same reason, this profile also more strongly resembles reported profiles found for by-eye detected PMJs in the Ca\textsc{ii} 8542 Å line given in Reardon et al. (2013, Fig. 4) and several of the distinct profiles presented in Vissers et al. (2015, Fig. 5). The average line profile of those profiles with both blue and red peaks present simultaneously is also of overall greater intensity in both the peaks and the line-core minimum compared to the overall PMJ average profile and the FOV average of the Ca\textsc{ii} 8542 Å line. In fact, the line core has a 145% intensity compared to the quiet-Sun-line-core average, which is a clearly greater enhancement than for the overall line profile average that, as given earlier, exhibited an intensity of only 116% compared to the quiet Sun. This makes it plausible that the higher overall intensity in these types of PMJs makes it easier to pick them out by eye and thus makes the presence of both peaks in these selections more likely, whereas the automatic detection presented may not be as susceptible to this bias after the initial selection of the k-NN reference set. An over-selection of PMJs with strong enhancements in the red wing of the Ca\textsc{ii} 8542 Å line may therefore be likely in by-eye detections.

It is worth noting that the average PMJ profile of the k-NN reference set shown in Fig. 3 exhibits a similar shape to the average profile of detected PMJs with both blue and red peaks present, and thus has more clear peaks than the final PMJ average profile of all PMJ detections. It also has an overall higher intensity than the total average, though not as high as the average with both blue and red peaks present. This similarity is most likely due by-eye selection favouring PMJs with strong enhancements in both the blue and the red as well as overall brighter PMJs, as previously raised.

We investigate the spatial distribution of the PMJ profiles with distinct blue and red peaks. It may be well plausible that the average PMJ orientation is related to the large scale magnetic field topology of the sunspot such that the inclined viewing angle may have an effect on the spatial distribution of the observed PMJ profiles. The results are presented in distribution graphs in polar coordinates, centred on the umbra and the limb direction at approximately 90°.

Figure 9 provides a scatter plot of the peak-intensities versus the angle around the centre of the sunspot of the automatically detected peaks in the red and blue of the Ca\textsc{ii} 8542 Å line for the detected PMJs. There is no clear discernible bias in the plot with regard to the intensity, both for the blue and red peaks. However, there is a readily apparent clustering of red peaks in the range of 315–30 degrees, with two noticeable groups within this range. The group above the zero-degree mark seems to neatly coincide with the principal PMJ hot-spot as described in Sect. 4.4 below (see Fig. 11). The presence of more readily detected red peaks in an area in which many PMJs are found throughout the time series is intuitive, because a higher count of PMJs should lead to a higher count of red peaks as well. On the other hand, the amount of red peaks seems over-represented in the area compared to other areas with significant numbers of PMJs, and may indicate that red peaks are favored in some areas.

In Fig. 10 we provide a scatter plot of the wavelength-positions versus the angle around the centre of the sunspot of the automatically detected peaks in the red and blue of the Ca\textsc{ii} 8542 Å line for the PMJ detections. There is an apparent
bias in the degree of redshift in some of the red peaks, whereas
there is no clear bias in the blueshift of the blue peaks. We can
again discern the general clustering of red peaks in the same
range as for Fig. 9, but this time there is a clear difference in
the two groups within this angular range. The group coinciding
with the PMJ hot-spot (see again Sect. 4.4 and Fig. 11) at slightly be-
low 30 degrees has a clearly lower redshift and is less spread out
in values than the group of red peaks clustered around 330 de-
grees (see also the reference line at 10 km s$^{-1}$ in the figure). The
atypical redshift of the red peaks situated around the 330 degree
mark are likely largely caused by a strong inverse Evershed flow
that moves into the penumbra at this location, which may also
account for the greater overall spread of redshifts in this region.
This region of strong inverse Evershed flow is an extension of
the large dark cloud in the bottom middle part of the right panel
of Fig. 1. We observe these inverse Evershed “clouds” moving
into this part of the penumbra throughout the full duration of
the time series. A detailed inspection of the spectral profiles of
this region with CRISPEX reveals that at times the profiles are
largely affected by this inverse Evershed flow.

There also seems to be an overall higher blueshift in the de-
tected blue peaks of the Ca$\text{\textsc{ii}}$ 8542 Å line profiles on the limb
side of the Penumbra (in the 30 to 180 degree range). This is
counter intuitive to a line-of-sight enhancement of the blueshift,
because this would be expected for the disk side instead. This
will be mentioned further in Sect. 5.

4.4. Clustering and a near-continuous occurrence
of penumbral microjets

Figure 11 depicts a density map of all the individual PMJ detection
pixels, summed over all timeframes. Penumbral microjets are
detected somewhat evenly distributed over the azimuthal di-
rection and mostly in the outer half of the penumbra.

From the density distribution it is evident that there are pre-
ferred sites for PMJ formation and that they are not evenly dis-
tributed throughout the sunspot’s penumbra. We can see a clear
clustering of PMJ detections in certain regions, and two distinct
regions in the upper right corner in particular. These two re-

regions are the sites of a large number of PMJs throughout the
observations.

There is an apparent bias in the number of detections with
regards to position in the penumbra, as it is readily seen that
there are many more detections on the limb side of the sunspot.
The right-upper corner of the penumbra mostly coincides with
the far side of the observer’s line-of-sight, which might possi-
ably contribute to a larger number of clear detections. Reciproc-
cally, the lower side of the sunspot may exhibit a lesser amount
of detections due to foreshortening of the nominally elongated
PMJs. There are however still distinct hot-spots of PMJ-activity
on the same side of the sunspot, meaning that a clustering of
PMJs could not be caused by foreshortening effects to a large
degree.

Figure 12 highlights the behaviour of a “PMJ-hot-spot”, a
site of repeated PMJ activity, that was picked out by-eye using
CRISPEX (see legend for details). The timeslices in particular,
and also the intensity-time plots, highlight how the PMJ-events
seem to present as continuous processes of waxing and waning
in intensity in both the Ca$\text{\textsc{ii}}$ 8542 Å and the Ca$\text{\textsc{ii}}$ H line, as
opposed to very well-defined one-off events with clear onsets
and ends. The event highlighted in these figures is situated in a
PMJ-hot-spot as readily seen in Fig. 11. We can observe the typ-
ical behaviour of PMJs in the present observations, namely that
they are localized to specific regions and seemingly reoccur over
time. This ongoing process of PMJ generation at preferred sites
may possibly be due to favourable magnetic field structures at
these particular sites, leading to repeated magnetic reconnection
in quick succession.

Figure 13 highlights the Ca$\text{\textsc{ii}}$ 8542 Å line profiles of three
specific pixel positions, all contained within a single PMJ detect-
tion area, as shown in Fig. 4. Shown in Fig. 13 are the profiles
for a pixel position on the umbra side of the detection area, the
centre-of-mass pixel position of the area, and a pixel position
on the outer side of the area. These line profile examples high-
light that the automatic detection envelops a larger area than that
which would perhaps be picked out as a singular PMJ in by-eye
detections (see Fig. 4), but that the contained profiles still have
the distinct PMJ shape. In particular, this event may be catego-
rized as two distinct jets using by-eye detections at the shown
wavelength offset, whereas the automated method based on the
line profiles identifies the entire area as one PMJ. The three dif-
frent profiles highlighted all exhibit the distinct PMJ peak in the
blue. There is also a clear enhancement in the red, but this is most
evident for the centre-of-mass position and the reference point
closest to the quiet Sun. The reference profile for the umbra-side
position has some enhancement in the red, but the enhancement
is less clear. The two profiles closest to the quiet Sun are very
much distinct PMJ profiles, whereas the umbra-side profile is
generally more subdued, but still with enhancement in the blue
and red peak positions. The profile also has as a clearly enhanced
line core compared to the penumbra average line profile. These
three profiles are generally very similar to by-eye selected pro-
files (as for example seen in Fig. 12). The profiles in Fig. 13
also exhibit an incremental increase in intensity for the blue and
red peak wavelength offsets as one moves towards the quiet Sun.
This trend is not present for the line core however, because the
line-core intensities remain fairly stable.
5. Discussion

5.1. Similarity to Ellerman bombs

The typical PMJ CaII 8542 spectral profile with enhanced inner wings resembles the characteristic spectral profile of Ellerman bombs, a similarity that was already pointed out by Reardon et al. (2013) and Vissers et al. (2015). Ellerman bombs (Ellerman 1917) are the tell-tale signature of magnetic reconnection in the low atmosphere, usually associated with emergence of strong magnetic flux in active regions (see Rutten et al. 2013, for a recent review). Similarly to Ellerman bombs, magnetic reconnection is the driving mechanism for PMJs that is favored in the penumbra of sunspots.

Fig. 12. PMJ event studied in detail at time = 535 s. a) PMJ marked by a cross in a subfield of the observations in the CaII 8542 Å line at an offset of −275 mÅ. b) PMJ marked by a cross in a subfield of the observations in the CaII H line. c) Timeslices for the full duration of the observations in the sampled CaII 8542 Å line (left) with time of the event indicated (dashed), and in the monochromatic CaII H line core (right). d) CaII 8542 Å line profile of the PMJ event (solid) with the average of the line over the upper left section of the full FOV (dashed) and the average of the line over the penumbra, umbra excluded (dashed-dotted) (see Fig. 1 for these regions), with time of the event given. e) Intensity curve in the CaII 8542 Å line (solid) at an offset of −275 mÅ for the full duration of the observation at the PMJ event location with PMJ event time (dashed). f) Intensity curve in the same position and duration in the CaII H line core (solid) and event time (dashed).

Fig. 11. PMJ densities, with all pixel-detections summed over all 202 timeframes, overlain onto a frame at the midpoint in time of the observations, at an offset of −275 mÅ in the CaII 8542 Å line. The arrow indicates the direction towards disk-centre.
Besides the enhancement of both inner wings in PMJ line profiles, we note that there is a preference for larger enhancement of the blue wing. For those profiles in which the enhancement is in the form of one or two clearly identifiable inner-wing peaks, which number close to half of the detected PMJs, the majority have a blue peak. This is also reflected in the average PMJ profile that displays a clear blue-over-red asymmetry. We investigated whether there is any trend in the spatial distribution of the properties of the inner-wing peaks. If one would, perhaps naively, interpret PMJs as near-vertical plasma upflows, one would expect this to have an imprint on the observed spectral profiles for a sunspot under this observing angle of \( \theta = 57^\circ \). This viewing angle effect is for example very clear for the photospheric Evershed flow in sunspots, for which Dopplermaps show a clear, highly inclined, outflow in the form of redshifts at the limb side and blueshifts at the centre side for those sunspots that are away from disc centre (see, e.g., Scharmer et al. 2011, for a recent example). We find, however, no clear systematic imprint on the spatial distribution of spectral parameters of PMJ profiles. The peak intensity of the inner-wing peaks show no trend in the spatial distribution over the sunspot (see Fig. 9). There may be a trend of higher blueshifts of the blue peaks at the limb-side penumbra (Fig. 10) where the blue peaks are all shifted more than \(-10.5\ \text{km s}^{-1}\). On the centre-side, the shifts are between \(-7\) and \(-14\ \text{km s}^{-1}\). This trend goes against the simple interpretation of the shift of the blue peak as a pure Dopplershift from a upflow in the expanding chromospheric magnetic field of the sunspot. In this kind of a scenario the strongest blueshifts would be found in the centre-side penumbra. We conclude that detailed numerical modelling with a realistic treatment of the radiative transfer in the optically thick penumbral atmosphere is required in order to interpret the PMJ spectral profiles. A complicating factor is the inverse Evershed effect in the form of mostly redshifted clouds that at certain times and spatial locations result in strongly affected line profiles. Part of the profiles that were identified as “red-peak” PMJ profiles were clearly affected by inverse Evershed clouds that were unrelated to PMJs.

### 5.3. Spatial dimensions

From our large statistical sample of automated PMJ detections, we determine PMJ lengths that are on the short side as compared to the measurements from Hinode Ca H observations (Katsukawa et al. 2007). To a large extent this can be attributed to our method’s sensitivity to weaker events and the inclusion of the centre-side penumbra, in which the projected PMJ extensions suffer from foreshortening. The measurements from previous studies have an intrinsic bias towards longer PMJs from by-eye selection.

### 5.4. Lifetimes

We determine an average lifetime of 90 s which is longer as compared to the typical lifetime of less than 1 min reported earlier (Katsukawa et al. 2007). However, we note that we find a large number of short-duration events, concurrent with the median lifetime of 75 s for the 8-min-cutoff PMJ lifetime distribution. We have discarded long-duration detections of >8 min. These were in part resulting from clustering of individual PMJs occurring in close vicinity and rapid succession, and in part due the earlier-described strong inverse Evershed flow on the disk side of the sunspot, that distorts the Ca II 8542 Å line profile, and
causes false identifications. Thus, we cannot exclude the possibility that intermediate duration detections, 3–8 min, are also affected by neighbouring PMJ activity. However, we decided to be conservative in manually sifting though the detection statistics. Furthermore, we again note our method’s sensitivity to weaker events, and that this allows us to track events for longer durations as compared to manual and by-eye selection methods.

6. Conclusions and summary

We studied PMJs using an automated, simple machine-learning detection scheme consisting of an initial principle component analysis for the compression of data, a subsequent application of the k-Nearest Neighbour algorithm, and finally simple object-tracking over the time series. This scheme was applied to high-spatial-resolution observations of well-sampled Ca\textsc{ii} 8542 profiles. We verify that the automated detections of PMJs in Ca\textsc{ii} 8542 match well with PMJs in co-temporal Ca\textsc{ii} H linecore filtergrams, which is the diagnostic used for PMJs in earlier studies. The Ca\textsc{ii} 8542 PMJ line profile is characterized by enhanced inner wings, often in the form of clear peaks, preferably with a distinct asymmetry towards stronger blue-wing enhancement. The line core is enhanced as compared to the quiet-Sun reference spectrum. We detect a total of 4253 PMJs at a detection rate of 21 events per timestep over a duration of 41 min, corresponding to 453 PMJs tracked in time. Ellipse fitting to the PMJ detection areas yields average PMJ dimensions of 640 km length and 210 km width. We measure an average lifetime of 90 s, discarding the longest duration events of >8 min, which are clearly separate but overlapping events in rapid succession or the result of misidentifications. We detect PMJs in all parts of the penumbra, with many detections on both the limb side as well as on the disk-centre side of the penumbra. However, there was still an apparent bias in that there were more detections on the limb- or upper-side of the sunspot, perhaps in part caused by foreshortening effects. We note the existence of clear “hot-spots” with high occurrence rates of PMJs.

We finally remark that our results contribute to a solid observational characterization of PMJs that is needed to provide constraints for theoretical and numerical modelling. Further research will necessarily have to focus on numerical studies to elucidate the precise physical nature of PMJs. Quantification of the heat-energy transfer by PMJs into the higher sunspot atmosphere is one such area of interest for future investigations.

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Paper II

Penumbral microjets at high spatial and temporal resolution

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Penumbral microjets at high spatial and temporal resolution

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ABSTRACT

\textbf{Context.} Sunspot observations in chromospheric spectral lines have revealed short-lived linear bright transients that are commonly referred to as penumbral microjets (PMJs). Details on the origin and physical nature of PMJs are to a large extend still unknown.

\textbf{Aims.} We aim to characterize the dynamical nature of PMJs to provide guidance for future modeling efforts.

\textbf{Methods.} We analyzed high spatial (0′/1) and temporal resolution (1 s) \textsc{Ca}
\textsuperscript{ii} H filtergram (0.1 nm bandwidth) observations of a sunspot that were obtained on two consecutive days with the Swedish 1 m Solar Telescope.

\textbf{Results.} We find that PMJs appear to be the rapid brightening of an already existing (faint) fibril. The rapid brightening is the fast increase (typically less than 10 s) in intensity over significant length (several hundreds of kilometers) of the existing fibril. For most PMJs, no clear root or source from where the brightening appears to originate can be identified. After the fast onset, about half of the PMJs have tops that move with an apparent velocity of between 5 and 14 km s\textsuperscript{−1}, most of them upward. No significant motion of the top is observed in the other PMJs. About one-third of the PMJs split into two parallel and coevolving linear features during the later phases of their lifetimes.

\textbf{Conclusions.} We conclude that mass flows can play only a limited role in the onset phase of PMJs. It is more likely that we see the effect of a fast heating front.

\textbf{Key words.} sunspots – Sun: chromosphere – Sun: magnetic fields

1. Introduction

Observations in the chromospheric \textsc{Ca}
\textsuperscript{ii} lines show dynamic, linear transients in sunspot penumbrae. These so-called penumbral microjets (PMJs) were discovered (Katsukawa et al. 2007) in \textsc{Ca}
\textsuperscript{ii} H time series from the broadband filtergraph (BFI) at the Solar Optical Telescope (SOT; Tsuchiya et al. 2008) of the Hinode satellite (Kosugi et al. 2007). In the Hinode observations, PMJs appear as linear brightenings, typically \~400 km wide and 1000–4000 km long, and they have lifetimes shorter than 1 min. The increase in brightness is on the order of 10–20\% as compared to the penumbral background, and the PMJs stand out against the nearly horizontal photospheric penumbral filaments with elevation angles of between 20° and 60°. Probably the most striking property of PMJs is their rapid appearance: Katsukawa et al. (2007) reported an apparent rise velocity faster than 100 km s\textsuperscript{−1} starting from the root of the microjets during the initial phase of their evolution. Tiwari et al. (2016) argued that microjets in the inner penumbra and larger jets in the outer penumbra should be distinguished. They roughly estimated a speed of 250 km s\textsuperscript{−1} for one such large penumbral jet. This is much faster than the chromospheric sound speed, which is on the order of 10 km s\textsuperscript{−1}.

Magnetic reconnection is the prime candidate process for driving PMJs: with strong magnetic fields with highly variable inclination angles over short spatial scales and considerable dynamic forcing from convective flows, the “uncombed” magnetic field topology of the sunspot penumbra is an environment where magnetic reconnection is likely to occur (for reviews on the sunspot magnetic structure with strong-field vertical spines and horizontal filaments, see, e.g., Borrero & Ichimoto 2011; Tiwari 2017). Katsukawa & Jurčák (2010) found support for this scenario in small patches of photospheric downflows that are associated with chromospheric brightenings: the downflow may be the reconnection outflow, while the opposite-direction outflow may result in an associated PMJ.

Whether the fast apparent rise velocity of PMJs is a true mass flow or the result from a fast propagating wave or heating front cannot be determined from imaging data alone. Spectroscopic observations of the \textsc{Ca}
\textsuperscript{ii} 854.2 nm line show a characteristic PMJ spectral profile with peaks in the wings at about ±10 km s\textsuperscript{−1} (Reardon et al. 2013; Vissers et al. 2015; Drews & Rouppe van der Voort 2017). The extent of these peaks is rarely found to be beyond ±20 km s\textsuperscript{−1} and certainly never toward the extreme velocities of the apparent PMJ rise speed. The central absorption minimum of the \textsc{Ca}
\textsuperscript{ii} 854.2 nm line is typically found to be nearly at rest: for more than 4000 \textsc{Ca}
\textsuperscript{ii} 854.2 nm PMJ profiles, Drews & Rouppe van der Voort (2017) found an average minimum position at 0.16 km s\textsuperscript{−1} Doppler offset\textsuperscript{1}. Furthermore, from multiline inversions of high spatial and spectral resolution \textsc{Ca}
\textsuperscript{ii} K, \textsc{Ca}
\textsuperscript{ii} 854.2 nm, and \textsc{Fe}
\textsuperscript{i} 630 nm observations, Esteban Pozuelo et al. (2019) concluded that the line-of-sight plasma velocities in PMJ atmospheres do not exceed 4 km s\textsuperscript{−1}.

In a study of 3D component reconnection between weak horizontal magnetic field and strong and more vertical magnetic field, Nakamura et al. (2012) found that 5 km s\textsuperscript{−1} jets are generated by a gas pressure gradient along the reconnecting field.

\textsuperscript{1} This value is corrected for a conversion error in the paper.

\textsuperscript{*} Movies are available at \url{https://www.aanda.org}
2. Observations and data reduction

The observations were obtained with the SST (Scharmer et al. 2003a) on the island of La Palma, Spain. The main sunspot in active region AR11084 was observed on 27 and 28 June 2010 at solar heliocentric coordinates \((x, y) = (-820^\prime, -330^\prime)\) under observing angle \(\mu = \cos(\theta) = 0.25\) (27 June) and at \((-720^\prime, -343^\prime)\), \(\mu = 0.53\) (28 June). Here we concentrate on data acquired on the blue branch of the optical path, where we used a pair of synchronized cameras, one equipped with a \(\text{Ca} \, \text{II} \) filter (centered at the line core at \(\lambda = 396.85 \, \text{nm}\) and bandpass \(FWHM = 0.1 \, \text{nm}\), L"of"dahl et al. 2011), and the other with a wideband filter with \(FWHM = 1 \, \text{nm}\), centered between the \(\text{Ca} \, \text{II} \) and \(\text{K}\) lines at \(\lambda = 395.4 \, \text{nm}\), that imaged the solar photosphere. Figure 1 shows sample images of the sunspot. The \(\text{Ca} \, \text{II}\) images for both days show clear PMJ examples in the penumbra on the left side of the frame. Data from the red branch, spectral scans of the \(\text{Ca} \, \text{II}\) line with the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer et al. 2008), were analyzed by Drews & Rouppe van der Voort (2017). High image quality resulted from the excellent seeing conditions, the adaptive optics system (Scharmer et al. 2003b), and image restoration with the multi-object multi-frame blind deconvolution (MOMFBD; van Noort et al. 2005) method. The blue cameras operated at a rate of 10.8 frames s\(^{-1}\), and the data were MOMFBD-restored to a time series with a cadence of 1.02 s by including a set of 11 exposures in \(\text{Ca} \, \text{II}\) and wideband per restoration. For both days, the spatial resolution in the restored time series frequently approached the telescope diffraction limit of \(\lambda / D = 0.08\) (the spatial sampling is 0.034 (or 25 km) pixel\(^{-1}\)). After MOMFBD image restoration, the images were rigidly aligned and destretched to a coherent time series (Shine et al. 1994). For 27 June 2010, the time series has a duration of 01:14:14 UT, starting at 08:58:24 UT, and for 28 June 2010, the time series has a duration of 00:41:42, starting at 09:18:29 UT.

In addition to the main 1 s cadence \(\text{Ca} \, \text{II}\) data sets, we analyzed cotemporal CRISP \(\text{Ca} \, \text{II}\) and CHROMospheric Imaging Spectrometer (CHROMIS) \(\text{Ca} \, \text{II}\) K spectral scans acquired on 3 September 2016 to address differences in detecting PMJs with the 0.3 nm Hinode filter and the 0.1 nm SST filter. The leading part of active region AR12585 at \((-568^\prime, 420^\prime)\), \(\mu = 0.8\), was observed, including a large portion of the limb-side penumbra of the main leading spot. In this part of the penumbra, several clear PMJs were observed in both the \(\text{Ca} \, \text{II}\) and \(\text{Ca} \, \text{II}\) K lines. CRISP sampled the \(\text{Ca} \, \text{II}\) 854.2 nm line at 21 line positions (±60 km s\(^{-1}\), with denser sampling in the core region), and CHROMIS sampled the \(\text{Ca} \, \text{II}\) K line at 22 line positions (±101 km s\(^{-1}\), with steps of 6 km s\(^{-1}\) out to 54 km s\(^{-1}\)). These CRISP and CHROMIS spectral scans were processed with the standard SST reduction pipelines (de la Cruz Rodríguez et al. 2015; L"of"dahl et al. 2018), including MOMFBD image restoration. For more details on these data sets, we refer to Rouppe van der Voort et al. (2017) and Esteban Pozuelo et al. (2019).

3. Methods

In order to minimize uncertainties due to seeing variations, we concentrate our analysis on PMJs during the best seeing periods in our data sets. PMJs were identified visually as transient linear features that clearly display enhanced brightness relative to their surroundings. Efficient identification was achieved with the data exploration tool CRISPEX (Vissers & Rouppe van der Voort 2012). To analyze their temporal evolution, we extracted space-time diagrams along linear trajectories aligned with the main PMJ axis. We find that most PMJs display both minimal sideways motion and minimal curvature, but to account for sideways motion and misalignment, we averaged the space-time diagram over a lateral width of 3 pixels (equivalent to 75 km). The data for the space-time diagrams were extracted such that the end closest to the umbra was taken as the starting point, that is, all paths are oriented radially outward relative to the umbral center. In the discussion of the results, we refer to the direction away from the umbra as “up” and toward the umbra as “down”. The reference time \(t = 0\) s is defined for each PMJ at the time of maximum intensity in the space-time diagram. The measurements of the PMJ length and width were taken at this time, and the maximum intensity served as the reference for the brightness increase (in percent).

As a measure of the seeing variation during the PMJ evolution, the figures presenting the space-time diagrams include a panel with the contrast in the cotemporal (photospheric) wideband images. The contrast is measured as the standard deviation divided by the mean of a relatively quiet area away from the sunspot. While contrast in the granulation pattern certainly does not capture all effects of seeing on image quality, it serves as an indicator of the general quality of the seeing.

The PMJs in our sample display a wide variety in dynamical evolution, and the presentation of our results requires considerable figure space to highlight different aspects of the evolution. For the sake of clarity, we have tried to minimize the number of PMJ examples in the main body of the article. To ensure completeness of the presentation, we include a number of additional examples of PMJ evolution in figures in the Appendix, to which we refer in the Results and Discussion sections.

4. Results

We selected 45 PMJs for further analysis (28 in the 27 June 2010 data set and 17 in the 28 June 2010 data set); for these events the seeing was stable enough throughout their evolution for a proper analysis. The PMJs in our data sets display a wide variation in dynamical evolution. A generally common property is the rapid increase in intensity of a fibril that was already present before the onset of the PMJ. This brightening of the fibril occurs in a matter of seconds and is rather uniform over a significant length. After brightening up, we observe a variety of scenarios: the top of the PMJ may rise, it may retract, or it may not move in a significant manner at all. The motion of the PMJ top is often the continuation of the motion of the fibril top before brightening up, and the fibril may continue with this motion after the brightening has ended and the PMJ is considered to have faded away. If there is PMJ top motion, the apparent speed is typically on the order of 10–15 km s\(^{-1}\). In some cases, the bottom of the PMJ rises toward the end of its lifetime. For PMJs with a rising motion of the top, this results in an apparent proper motion of the PMJ. For PMJs without a rising top, the rising of the PMJ bottom results in an apparent shrinking. We also observe an apparent splitting of the PMJ for a number of cases.
Fig. 1. Observed sunspot in AR11084 on 27 June 2010 (top row) and 28 June 2010 (bottom row). Left panels: wideband images ($\lambda = 395.4$ nm), right panels: cotemporal Ca ii H 396.8 nm images. The white arrows in the lower left point toward disk center. The red lines in the left panels mark the extent of PMJs throughout their lifetime.

In the following paragraphs, we discuss a number of PMJs in detail. We also illustrate the various PMJ evolution scenarios.

Figure 2 shows details of the evolution of two PMJs with a rising top. For PMJ A, at time $t = -17$ s, the brightness of a rather faint fibril starts to rise quickly and increases with more than 20% of the PMJ peak intensity in only 3 s. In only 1 s, from $t = -15$ to $t = -14$ s, the PMJ has brightened over the 90% threshold over a length of 370 km, which is visible in the top colored space-time diagram as the sharp transition from green to red. PMJ A reaches maximum brightness at $t = 0$, at which time the PMJ is above 90% brightness over a length of 670 km and the FWHM of the PMJ measures 1270 km. From $t = 5$ s, the brightness starts to drop quickly, and in 2 s, the brightness has dropped to below 80%. A fibril continues to be visible for at least 20 more seconds, after which the intensity drops to below 60%. During this whole period, the top of the PMJ is moving upward (away from the umbra) with a velocity of about 14 km s$^{-1}$, as indicated by the inclined white line in the bottom space-time diagram. After $t = 0$, the bottom of the PMJ starts to move upward with roughly twice that speed so that the PMJ appears to be shrinking.

Penumbral microjet B displays a similar evolution, with a faint fibril brightening up for a limited duration of time, and at the same time, the PMJ top moves at $\sim 11$ km s$^{-1}$. During the decay of the PMJ, the bottom moves upward with higher speed so that the PMJ appears to be shrinking. Compared to PMJ A, the rise in intensity for PMJ B is more gradual with an increase from $\sim 65\%$ to $\sim 80\%$ over about 30 s, and another 20 s before the intensity rises above 90%. The brightest phase, like for PMJ A, starts abruptly, when at $t = -10$ s, PMJ B brightens above the 90% threshold over a length of 200 km in only 1 s. At the time of maximum brightness, at $t = 0$, the length of the PMJ that is over 90% intensity is about 500 km. After $t = 5$, the intensity drops quickly below the 90% level and continues to decline while the top of the PMJ continues to move up at $\sim 11$ km s$^{-1}$ and the PMJ as a whole appears to shrink. The visibility of the full decay phase is unfortunately difficult to discern as the seeing deteriorates for a short period, as testified by the wideband contrast values.

Penumbral microjets K and L in Fig. A.1 are two more examples of PMJs that have an upward-moving top, with velocities 5 and 11 km s$^{-1}$, respectively. In total, we find that 20 PMJs in our sample (44%) have an upward-moving top during the bright phase of the PMJ.

The top of PMJ C in Fig. 3 moves downward, and the overall impression is that of a PMJ that shrinks over a time period of about 20 s. The apparent velocity of the moving top is about 8 km s$^{-1}$. At the end of the PMJ, just when the PMJ seems to vanish, the seeing becomes very poor and the actual moment of disappearance is completely blurred out. When the seeing improves again after about 15 s, a new PMJ seems to have appeared at a position slightly to the side of the position where the short PMJ C vanished earlier. The top of this new PMJ rises with an apparent speed of about 14 km s$^{-1}$. 

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Fig. 2. Details of the evolution of two PMJs labeled A and B. Left four images: selected moments of the area centered on the PMJ. The time (in seconds) is marked in the lower left corner and is relative to the time when the maximum PMJ signal is measured in the space-time diagram. The four images are all scaled to the PMJ maximum at $t = 0$ according to the gray-scale color bar. The start and end points of the trajectory of the space-time diagram are indicated with orange markers, the thicker marker indicates the start and is closest to the umbra. Two versions of the space-time diagram are shown with two different color tables: in gray scale and rainbow-color scale. A white line indicates the slope of a specified propagation speed. Light curves are shown in the upper right panel; the black and green lines show the intensity at fixed locations in the space-time diagram. These locations are marked in the gray-scaled space-time diagrams. The red line shows the highest PMJ signal during the brightest phase of the PMJ. The orange line shows as reference the intensity in the vicinity of the PMJ but outside the space-time diagram. Its location is marked with the orange cross in the images on the left. The units are arbitrary detector units. The right axis scaling is normalized to maximum PMJ intensity (at time $t = 0$ s). In the lower right corner, the intensity contrast in the wideband channel is shown as an indication of the seeing quality. The right axis scaling is normalized to maximum contrast in the whole time series. Animations of this figure are available online.

Penumbral microjet D in Fig. 3 appears not to be moving at all. A fibril with an intensity of about 80% of PMJ maximum suddenly starts to brighten up over a significant length: it rises above 90% over a length of 650 km at $t = -11$ in only 4 s (with a jump from 50 km to 650 km in only 1 s). At maximum brightness ($t = 0$), the length above 90% is 1145 km. The bright phase above 90% lasts for about 46 s, where the seeing conditions are worse in the last about 30 s. During this whole period, neither the top nor the bottom of the PMJ seem to be moving, so that the PMJ appears to be stationary. We find that the tops of 3 PMJs move downward (7%) and that the tops of 22 PMJs have no clear motion (49%). An absence of clear motion of the top implies an upper limit of about 2 km s$^{-1}$.

The tops of PMJs E and F in Fig. 4 also display no apparent motion. Both are short-lived events (11 and 12 s above 90%), and while PMJ E appears like a mere stationary brightening of the fibril, PMJ F appears to be growing quickly toward the bottom and then to shrink as quickly from the bottom up. The relative intensity of PMJ E increases by about 20%, and that of PMJ F by about 30%.

Penumbral microjet G in Fig. 5 is an example of a PMJ with both a moving top and moving bottom end, which gives the impression of a short object moving with a velocity of 14 km s$^{-1}$. During the brightening phase, at $t = -6$, the intensity rises above 90% over a length of 150 km in 1 s, and later, at maximum brightness at $t = 0$, the length over 90% increases from 224 km to
374 km. PMJ M in Fig. A.1 is another example of a short moving object (12 km s$^{-1}$). In addition, PMJ M is short-lived, with a lifetime of 11 s above 90% of peak intensity.

When we consider the temporal evolution of PMJ G in detail (see the animation accompanying Fig. 5), it appears that the PMJ splits during the later phases. From about $t = 38$, we can discern two parallel linear features at the location where before the PMJ was a single linear feature. This splitting of the PMJ can be observed in more PMJs, and a particularly clear example is PMJ H in Fig. 5. This PMJ splits in the later phase of the PMJ, at time $t = -9$, which is 54 s after PMJ H first reached intensity >90%. The double structure can be discerned long after the PMJ has decreased in intensity: at $t = 39$, with the intensity below 60%, two parallel linear features are still visible. Other examples of PMJ splitting are shown for PMJ N and O in Fig. A.2.

Fourteen PMJs in our sample (31%) split into two separated fibrils at some phase in their evolution.

Penumbral microjet I in Fig. 6 displays an extremely rapid morphological evolution that we only observe for a few cases in our sample. It displays an extreme rise in intensity that is about 75% of the peak PMJ intensity and is highest in absolute detector units compared to the other PMJs. Furthermore, the morphology during the bright PMJ phase varies rapidly from time step to time step, and it seems that the bright fibril breaks up into smaller clumps. These clumps can be seen in the images for $t = -10$, -3, and 0 in Fig. 6. PMJ I shows less of the linearly coherent evolution that we see for most other PMJs, and the question is whether this PMJ should even be regarded as a single “standard” PMJ event. The space-time diagram for this event has a pronounced slope that suggests a propagation speed of about 220 km s$^{-1}$, but the accompanying movie shows that it is questionable whether we observe an actual proper motion of a coherent structure. The movie also clearly shows that neighboring fibrils brighten up in phase with the bright clumps of the event.

A similar occurrence of a complex pattern of small blobs along the PMJ fibril can be seen in the late evolution of the PMJ that appeared after the disappearance of PMJ C in Fig. 3: the accompanying movie shows small, downward-moving blobs from $t = 79$. We also note that both PMJ C and I are located in a region of the penumbra that was marked as a “hot spot” of PMJs in Drews & Rouppe van der Voort (2017), a region where many and sometimes overlapping PMJs occurred. PMJs in this
hot spot often had particularly pronounced Ca ii 854.2 nm spectral profiles.

Penumbral microjet J in Fig. 6 is also located in the hot-spot area and displays an apparent motion of the top of the PMJ that is significantly faster than for the other PMJs: \(~40\) km s\(^{-1}\). The apparent evolution of PMJ P in Fig. A.2 is affected to some extent by seeing variation, but PMJ P seems to display faster upward motion than most PMJs. At some phase in the evolution, around \(t = 38\), there is an apparent rise speed of roughly \(140\) km s\(^{-1}\).

A more detailed look at the onset of PMJs is provided by Fig. 7, which shows details over 11 s around the time when PMJs A, B, E, and F suddenly brighten. Two identical space-time diagrams are shown that zoom-in on the longer-duration space-time diagrams of Figs. 2 and 4. These space-time diagrams have two different types of markers that serve as length indicators: the left diagram has horizontal contour markers of the 80\% and 90\% levels of the peak PMJ intensity at \(t = 0\), and the right diagram has vertical lines that show the extent of the full-width at half-maximum (FWHM) and full-width at quarter-maximum (FWQM) with the maximum measured for each time step. From the FWHM and FWQM markers it is clear that a fibril was present at the space-time path before the sudden increase in intensity. This is also illustrated in the profile panel at the right where the blue profile is from a few seconds before the onset. The blue profiles have similar shapes as the black onset profiles, it is only at lower intensity. The PMJ rises in intensity basically over the full length of the fibril, that is to say, there is no clear high-velocity upward motion from the bottom up, a motion that can be expected from a jet. PMJ A rises over the 80\% level over a length of 350 km in 2 s (from \(t = -16\) to \(t = -14\)) and rises over the 90\% level over 374 km in 1 s. PMJ B rises over 90\% over 200 km in 1 s, and for PMJ E, the length over 90\% increases to 622 km in 3 s. PMJ F rises over 90\% over 150 km in 1 s, and this length increases to 250 km in the next time step. During the same 2 s, the length over 80\% increases with about 620 km–1145 km. Here, the increase in length is mostly from the top down, and the bottom 80\% marker in the left space-time diagram moves with a velocity of about 112 km s\(^{-1}\). The bottom of the 90\% level of PMJ D in Fig. A.4 grows at an apparent speed of 112 km s\(^{-1}\).
Fig. 5. Details of the evolution of two PMJs that occurred in close proximity after one another. Maximum brightness of PMJ G ($t = 0$) occurred 99 s before the maximum brightness of PMJ H. In the image at $t = 38$ of PMJ G, PMJ H can be seen to the left. This is 61 s before the maximum brightness of PMJ H ($t = -61$). PMJ H is a brighter and longer-lived PMJ than PMJ G (in addition to being longer). Both PMJs appear to be splitting during the later phases of their evolution. The format of this figure is the same as that of Fig. 2. Animations of this figure are available online.

Penumbral microjet P in Fig. A.4 zooms in on the phase that has an apparent rise of about $140 \text{ km s}^{-1}$ (as indicated in Fig. A.2). Here, the top of the 90% level rises with a mere $25 \text{ km s}^{-1}$. The apparent rise of the top of PMJ J in Fig. 6 is $40 \text{ km s}^{-1}$. Zooming-in on the onset in Fig. A.4 shows that the top of the 90% level moves with $42 \text{ km s}^{-1}$. Zooming-in on the complex PMJ I in Fig. A.4 shows the fine structure in this event, for which it is questionable whether we can measure a rise velocity similar to that of other PMJ events.

Figure 8 shows histograms of the lengths, widths, brightness increase, and maximum relative intensity for the 45 PMJs in our sample. Length and width are measured as the FWHM at the time of maximum PMJ intensity ($t = 0$). The average FWHM length is 802 km (median 818 km) and the average FWHM width is 179 km (median 170 km). The sharp drop for widths below 100 km is likely due to the spatial resolution of the telescope (diffraction limit equivalent to 60 km). The brightness increase is measured at a fixed location in the space-time diagram (marked with the black line in Figs. 2–6) and is the difference between the minimum at this location and the maximum intensity of the PMJ during its lifetime (i.e., at the time defined as $t = 0$). The average brightness increase is 34% (median 32%). The maximum relative intensity is measured as the maximum PMJ intensity at $t = 0$ relative to the average Ca $\text{II} \, H$ intensity in a relatively quiet area outside the sunspot (57" $\times$ 16" for 27 June 2010 and 57" $\times$ 13" for 28 June 2010). The average maximum relative intensity is 1.5 (median 1.4). The maximum intensity of most PMJs is higher than the average intensity in the quiet regions outside the sunspot.

5. Discussion

The most notable result from our analysis of 1 s cadence Ca $\text{II} \, H$ sunspot time series is that PMJs appear as rapid brightenings of existing, faint fibrils. We observe the rapid brightening as a fast increase in intensity over a significant length of the existing fibril: it may cover several hundreds of kilometers in a few
Fig. 6. Details of the evolution of a complex event (PMJ I, top) and an event that has a $\sim 40$ km s$^{-1}$ apparent rise of the top (PMJ J, bottom). The format of this figure is the same as that of Fig. 2. Animations of this figure are available online.

seconds. The intensity increase is mostly uniform over these lengths, and we do not find systematic evidence that the intensity increase grows from the bottom and up. We find that this behavior is at odds with the description of Katsukawa et al. (2007), who remarked about the evolution that the brightening seems to start from the root of the microjet and that the intensity pattern provides an apparent rise velocity faster than 100 km s$^{-1}$ in the initial phase. For almost all events in our data set, we cannot identify a clear root or source from where the brightening of the PMJs appears to originate. Rather, most of the PMJs brighten coherently over considerable length.

We identify three events that appear to have a $>100$ km s$^{-1}$ rise phase as testified by a steep slope in the space-time diagram: PMJ I, P, and Q. It is questionable that the $\sim 220$ km s$^{-1}$ slope in the space-time diagram for PMJ I in Fig. 6 can be interpreted as the rise of a single PMJ. This event is unlike the other PMJs in our sample and appears as the fast (and likely temporally unresolved) evolution of a collection of separated blobs. PMJ P in Fig. A.2 has a $\sim 140$ km s$^{-1}$ slope in the space-time diagram in the later phase of its evolution. The accompanying movie gives the distinct impression that there is fast upward propagation along the PMJ throughout its lifetime. However, when we zoom in on this rise phase in Fig. A.4, the rise appears to be more on the order of 25 km s$^{-1}$. PMJ Q in Fig. A.3 has a 125 km s$^{-1}$ slope in the space-time diagram and is the only event in our sample that has such fast and apparently resolved rise during the onset of the PMJ. Figure A.4 zooms in on the onset of PMJ Q, and we see a rise of the top of the 90% level of 370 km in 3 s, which corresponds to an apparent rise velocity of about 120 km s$^{-1}$.

At least two PMJs in our sample apparently propagate downward (i.e., in the direction toward the umbra) during their onset: PMJs D and F. The apparent velocity for PMJ F is on the order of 220 km s$^{-1}$ (see Fig. 7), and for PMJ D, it is 112 km s$^{-1}$ (see Fig. A.4).

For the other PMJs, the intensity rise during the onset appears to be coherent over hundreds of kilometers, and there is no clear slope in the space-time diagrams that suggests a rise or downward propagation. During the onset, the length over which a PMJ crosses an (arbitrary) intensity threshold of 90% of PMJ peak intensity can, for example, be 370 km in 1 s (PMJ A), 200 km in 1 s (B), 600 km in 3 s (D), 622 km in
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Fig. 7. Detailed look at the onset of PMJs. Two identical space-time diagrams are shown, with the color-scaling (shown at left) relative to the maximum intensity of the PMJ at \( t = 0 \). In the left diagram, horizontal blue and black lines serve as contours at the 90% and 80% intensity levels, respectively, relative to the maximum of the PMJ. In the right space-time diagram, the vertical lines with arrowheads show the full width at 25% (FWQM, thick purple) and 50% (FWHM, thin yellow) of the maximum intensity at that time step. Right panel: intensity profiles for three selected time steps. Time is relative to the maximum intensity of the PMJ (\( t = 0 \) s). The PMJs are identified by the letters in the upper left corner, which refer to PMJ A and B in Fig. 2 and PMJ E and F in Fig. 4.

Fig. 8. Histograms for the lengths, widths, brightness increase, and maximum relative intensity for the PMJs we analyzed. Length and width are measured as the FWHM at the time of maximum PMJ brightness. For PMJ I, no meaningful length and width could be measured. The brightness increase is measured as the intensity increase at a fixed position in the space-time diagram from the minimum to the maximum PMJ intensity. The fixed position is the black line in Figs. 2–6. The maximum PMJ intensity is relative to the average \( \text{Ca} \\ II \) intensity in a relatively quiet area outside the sunspot.

3 s (E), and 150 km in 1 s (F and G). These numbers do not constitute an apparent propagation speed but rather are a measure of the length over which the PMJ intensity is growing rapidly. After the fast intensity rise during the onset, the length of the PMJ may continue to grow at both the top and bottom ends of the PMJ.

This is another notable result from our analysis: the PMJ evolution after the fast onset. For about half of the selected events, the top of the PMJ moves with an apparent velocity between 8 and 14 km s\(^{-1}\). Most of these rise (20 PMJs), but 3 PMJs have a downward-moving top. For the remaining PMJs (22), there is no significant motion of the top.

For slightly more than half the PMJs (24), the bottom end moves upward toward the end of the PMJ lifetime. For the cases where the upward motion of the bottom end is faster than the top end, the PMJ appears to be shrinking and gives an impression of an outward motion of the PMJ (away from the umbra). See, for example, PMJs A, B, L, and N. PMJs G and M appear to be small elongated blobs that are moving upward throughout their entire lifetime.

Seeing might be the reason that we do not observe the fast rise during the PMJ onset, as earlier reported from Hinode observations. Like for all ground-based observations, seeing distortions and their effect on the analysis are a concern. We note that
Fig. 9. Examples of spectrally resolved PMJs. Panel a: photospheric CHROMIS wideband reference image (center wavelength 395.0 nm and bandwidth FWHM = 1.32 nm). Panel b: CHROMIS Ca ii K image at a Doppler offset of −12 km s\(^{-1}\). Panel c: CHROMIS Ca ii K image integrated over the full sampled spectral profile, convolved with a Gaussian profile with FWHM = 0.1 nm. Panel d: similar integrated CHROMIS Ca ii K image, convolved with a FWHM = 0.3 nm Gaussian, and giving enhanced weight to the two outer scan positions. Panel e: CRISP Ca 854.2 nm image at a Doppler offset of −16 km s\(^{-1}\). The red crosses in the images mark the spatial location in the PMJ for which spectral profiles are shown in panels f and g. The thick solid lines in panels f and g show the Ca ii K and Ca ii 854.2 nm PMJ spectral profiles, and the red crosses mark the spectral positions of panels b and e, respectively. The gray lines are reference spectral profiles averaged over a region outside the active region. Panel f: horizontal lines of width 0.3 and 0.1 nm as reference to the FWHM bandwidth of the Hinode and SST imaging filters. The inset in panel f shows a Ca ii K spectral profile from the FTS atlas (Neckel 1999) against Doppler velocity offset. The dashed lines are Gaussian profiles with FWHM = 0.3 and 0.1 nm.

The seeing conditions were excellent, the adaptive optics system was performing well, and the image restoration contributed to further improve the reduced data. Still, the short-term variability we see in the PMJ evolution can at least partly be attributed to seeing. As a measure of the seeing quality, Figs. 2–6 (and Figs. A.1–A.3) include a panel that shows the contrast variation of the wideband channel. Seeing distortions lead to reduced contrast, and some of the contrast dips correlate well with dips in the PMJ intensity. A clear example is shown for PMJ C in Fig. 3, where a period with very poor seeing after \(t = 10\) results in a clear dip in the PMJ brightness. Another (more subtle) example is PMJ D in the same figure around \(t = 5\), or the variation in the peak intensity for PMJ H (Fig. 5). Nevertheless, we consider it unlikely that seeing distortions are the reason that we do not observe a prevalent >100 km s\(^{-1}\) apparent rise velocity during the onset phase of the PMJs in our data set. We are confident that the data are of sufficient quality to reveal this property if it were present, in particular because we observe a fast apparent rise for PMJ Q and fast downward propagation for PMJs D and F.

When we consider the impact of seeing on the apparent evolution of PMJs in our data, we do caution, however, that it would be challenging to distinguish actual (solar) intensity variations from seeing-induced variations in the short-term intensity variability we see during the bright PMJ phase in the light curves of Figs. 2–6. Intensity modulations may be expected as a result of magnetohydrodynamics (MHD) waves in PMJs, but the effect of seeing on the variability is difficult to quantify.

We note that the appearance of PMJs in imaging data is strongly dependent on the transmission bandwidth of the instrument. For example, the contrast we find for the PMJs in our sample is considerably higher (average 34\%) than the 10–20\% reported by Katsukawa et al. (2007). The Hinode Ca ii H filter has FWHM = 0.3 nm, which is equivalent to an offset of ±113 km s\(^{-1}\) in Doppler velocity. The SST Ca ii H filter has FWHM = 0.1 nm or ±41 km s\(^{-1}\) in Doppler velocity. This means that in principle, a high-velocity feature with a significant line-of-sight component could be Doppler shifted out of the SST bandpass while it would still be covered in the wings of the Hinode bandpass. This effect is not a concern, however, because we only considered PMJs with a sizable linear extension in the sunspot.

Figure 9 illustrates this effect based on CHROMIS Ca ii K spectral imaging (under the reasonable assumption that PMJs show similar spectral properties in Ca ii K as in Ca ii H). A PMJ stands out clearly in the \(K_{\text{SV}}\) peak wavelength in panel b, and is also clearly visible in an image integrated over the full CHROMIS Ca ii K scan accounting for an FWHM = 0.1 nm Gaussian profile (panel c). When convolved with a 0.3 nm wide Gaussian, however, the PMJ is much fainter (panel d; note that the outer wings were linearly extrapolated because the CHROMIS scan only covered out to ±101 km s\(^{-1}\)).

\[ \text{FWHM} = \frac{\text{peak wavelength}}{2 \times \text{FWHM}} \]

\[ \eta = \frac{\text{average Ca ii H intensity}}{\text{average Ca ii K intensity}} \]

\[ \eta > 100 \% \]
reference, panel e shows an image in the Ca\textsc{ii} 854.2 nm wing at the wavelength of the emission feature in the blue wing. Interestingly, the PMJ signal in Ca\textsc{ii} 854.2 nm is considerably shorter and offset toward the bottom part as compared to the PMJ in Ca\textsc{i} K; we attribute this to formation height difference between the two spectral lines.

The PMJ Ca\textsc{ii} 854.2 nm spectral profile shown in panel g shows the typical profile shape with peaks in the blue and red wing. This profile shape was studied in detail by Drews & Rouppe van der Voort (2017) and was reported earlier by Reardon et al. (2013). Panel f shows the Ca\textsc{ii} K profile from the same location in the PMJ, and we see enhancement of the $K_2$ peaks corresponding to the peaks in Ca\textsc{ii} 854.2 nm. Esteban Pozuelo et al. (2019) presented more CHROMIS PMJ Ca\textsc{i} K profiles. These spectral profiles suggest that a 0.1 nm Ca\textsc{ii} (or K) filter has a sufficiently wide spectral transmission bandwidth to integrate the enhanced central reversal emission peaks, which is typical for PMJs. In addition, this more narrow transmission filter has the advantage of receiving only little contribution from the inner wings, which originate from the lower parts of the atmosphere that are unrelated to PMJs.

After considering seeing and the imaging filter properties, we conclude that the high temporal cadence of our data is the crucial difference that explains why we arrive at a different view of the onset of PMJs. The apparent rise velocity of $>100$ km s$^{-1}$ reported by Katsukawa et al. (2007) was based on data with a cadence of 8–16 s. The 250 km s$^{-1}$ estimate for one penumbral jet by Tiwari et al. (2016) was based on 5–15 s cadence data. When we consider that the onset phase is typically shorter than 10 s, it is clear that faster cadence data are required in order to properly resolve the dynamics during the time in which the PMJ rapidly brightens.

Samanta et al. (2017) studied the relation between subarcsecond bright dots in IRIS 1400 Å slit-jaw images and PMJs observed in an 1.58 s cadence Hinode Ca\textsc{i} H time series. Their work does not focus on the speed of the Ca\textsc{i} H PMJs, but they noted that the PMJs appear as sudden brightenings in their space-time diagrams and that it was very difficult to determine their propagation direction and speed. They further remarked that it is unclear whether the PMJs move radially outward from the sunspot. This description agrees well with our results.

We conclude that mass upflows can play only a limited role in the onset phase of PMJs. The intensity light curve (particularly considering the time and length scale) we observe during the rapid rise cannot be reconciled with a pure mass upflow. This was already clear from the spectral inversions by Esteban Pozuelo et al. (2019), who showed that PMJs do not harbor higher line-of-sight velocities than their surroundings and the inferred velocities did not exceed $4$ km s$^{-1}$. Earlier analyses of Ca\textsc{ii} 854.2 nm line profiles by Reardon et al. (2013) and Drews & Rouppe van der Voort (2017) did not reveal any high-velocity spectral signatures. Furthermore, the latter did not find a viewing-angle correlation in the line offset of the Ca\textsc{ii} 854.2 nm profile features, which might be expected if there were a systematic mass flow in PMJs.

This disparity between inferred Doppler velocity and apparent dynamical velocity recalls observed characteristics of type II spicules, although less extreme than for PMJs: Type II spicules display apparent rise velocities at the limb of 30–150 km s$^{-1}$ (De Pontieu et al. 2007; Pereira et al. 2012), and their transition region (TR) counterparts (also known as network jets) appear to move with velocities 80–300 km s$^{-1}$ on the disk (Tian et al. 2014; Narang et al. 2016). Inferred Doppler velocities, however, are typically in the range 20–50 km s$^{-1}$ (Rouppe van der Voort et al. 2009; Sekse et al. 2012) or 50–70 km s$^{-1}$ in TR diagnostics (Rouppe van der Voort et al. 2015).

De Pontieu et al. (2017) used advanced radiative MHD simulations to explain the disparity between Doppler and apparent velocities in spicules. In these simulations, relatively cool spicular material undergoes rapid heating events through the dissipation of currents by ambipolar diffusion. These currents propagate at Alfvénic speeds (well above 100 km s$^{-1}$) through preexisting spicules and cause rapid heating that results in a sudden brightening and associated fast apparent motion in chromospheric and TR diagnostics. They concluded that the observed fast apparent motions in spicules are a signature of a heating front that propagates at much higher velocity than the mass flow in spicules. More support for this scenario was recently found by Chintzoglou et al. (2018), who studied a type II spicule in contemporaneous VAULT2.0 Ly$\alpha$ and IRIS TR observations. A spicule was found to exist at low Ly$\alpha$ intensity already 2 min before it appeared as a fast 300 km s$^{-1}$ network jet in IRIS C\textsc{ii} 1330 Å and Si\textsc{iv} 1400 Å. At the time the spicule appeared as an IRIS TR network jet, the spicule also brightened in Ly$\alpha$. This favors the interpretation that the cool preexisting spicule was heated by rapid current dissipation within the spicule so that it became visible in the TR diagnostics. A multitemperature scenario for spicules was also inferred from combined observations obtained with the SST H$\alpha$ and the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory (SDO/AIA) of the 304 Å and 171 Å lines by Henriques et al. (2016).

Esteban Pozuelo et al. (2019) speculated that this spicule scenario of a heating front also holds for PMJ formation. Several aspects of the observations we presented here further support this view. First, we find evidence that PMJs appear as brightenings of preexisting fibrils. Second, the fast brightenings over the spatial scales we observe cannot be explained by mass motions. If the PMJs brighten as a result of a heating front, the associated current must propagate at extremely high speed because we find no systematic evidence for propagation speeds in our data. We note, however, that the Alfvén speed in the simulated spicules of De Pontieu et al. (2017) ranges between 150–450 km s$^{-1}$. The Alfvén speed in PMJs may be even higher because the magnetic field strength in the penumbra is higher than in the network areas where spicules originate. We further note that the synthetic Si\textsc{iv} emission in the space-time diagrams of De Pontieu et al. (2017) is nearly vertical for the simulated spicules, not unlike the PMJ space-time diagrams we presented here. The apparent motion of the PMJ top that occurs at more sonic speeds ($<14$ km s$^{-1}$) might be due to expansion after the rapid heating phase. The downward motion that we observe for a few PMJs may be contraction due to cooling. In any case, advanced models that correctly model the complex and strong magnetic field environment of the penumbra are required to further advance our understanding of PMJs and the penumbral chromosphere. Our observations provide stringent constraints to such modeling efforts.

A significant number of the PMJs in our sample (14 PMJs, or 31\%) appear to be split into two parallel and coevolving structures during the advanced stages of their dynamical evolution. When we assume that there is no preferred splitting direction, then splitting may be even more common because PMJs that split along a direction with small inclination angle to the line of sight will not be resolved into separated structures. Ryutova et al. (2008) found splitting into double structures to be common in features that they referred to as chromospheric transients. They
studied different Hinode data sets of a sunspot during its passage over the solar disk. They distinguished between microjets and a type of elongated chromospheric brightening that is longer lived, has longer length, and displays clear sideways motion. The latter are interpreted as a result of a bow shock after reconnection in neighboring penumbral filaments. Splitting was found to be common in this type of transient and explained in the context of the bow-shock scenario. We note that the splitting PMJs in our sample are shorter, have shorter lifetimes, and display less sideways motion compared to the characteristics that Ryutova et al. (2008) reported.

For the sake of reference, we have measured FWHM lengths and widths of the PMJs in our sample. They are slightly shorter and narrower than the measurements by Esteban Pozuelo et al. (2019), who based their measurements on locating the boundaries of Ca ii 854.2 nm PMJ spectral profiles. This naturally produces higher values than an FWHM measurement. This might also explain why we found shorter lengths than Katsukawa et al. (2007), while the narrower width can also be attributed to the higher spatial resolution of the SST compared to Hinode.

6. Summary and conclusions

We have studied the dynamical evolution of PMJs in high spatial and temporal (1 s cadence) resolution Ca ii H filtergram time series of a sunspot observed on two consecutive days. With the narrow transmission passband of the imaging filter (FWHM = 0.1 nm), PMJs stand out as high-contrast linear features that do not require image enhancement techniques to facilitate identification. We selected 45 PMJs that had consistent good seeing conditions throughout their lifetimes for further detailed analysis. Our results can be summarized as follows:

1. The PMJs appear to be the rapid brightening of a preexisting (faint) fibril. After the PMJ has faded again, a faint remaining fibril can often be observed.

2. The rapid brightening is the fast increase in intensity over a significant length of the existing fibril. During the onset phase, when the intensity rises at its fastest, the increase can be on the order 10–40% of the peak PMJ intensity in less than 10 s. During the onset phase, the length over which the PMJ rises above a threshold of 90% can be between 150–370 km in 1 s.

3. For almost no event in our data set can we identify a clear root or source from where the brightening of the PMJs would appear to originate.

4. After the fast intensity rise, about half of the PMJs have a top that moves with an apparent velocity of between 5 and 14 km s$^{-1}$. Twenty PMJs have a rising top, 3 have a downward-moving top. The remaining 20 PMJs show no significant motion of the top.

5. Toward the end of the lifetime of little more than half of the PMJs (24), the bottom end of the PMJ rises upward. This can result in an apparent shrinking of the PMJ, and in some cases (if the PMJ top rises as well), the whole PMJ appears to be moving away from the umbral region.

6. The average intensity increase of the PMJs is 34% (ranging between 15% and 75%). Compared to the quieter surroundings of the sunspot, the PMJs reach on average 1.5 times the quiet intensity (ranging between a factor 0.5 and 2.8).

7. The average FWHM length of the PMJs at the time of maximum intensity is 802 km (ranging between 200 and 1630 km), and the average FWHM width is 179 km (ranging between 85 and 415 km).

8. For about one-third of the PMJs (14) we observe a splitting into two parallel and coevolving linear features during the later phases of the PMJ lifetimes.

In conclusion, the most stringent constraints on PMJ modeling efforts are placed by the finding that PMJs show fast brightening of preexisting fibrils over lengths of hundreds of kilometers. The fact that at low temporal resolution the onset phase can be mistaken for mass motion underlines the importance of high temporal resolution when the dynamic solar atmosphere is studied. This is a message that should not be forgotten in an era when high spatial resolution and photon-gathering power is driving the development of instrumentation for the next generation of 4 m class solar telescopes.

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References

Appendix A: Additional PMJ examples

In this appendix we provide more figures with details of the evolution of selected PMJs.

**Fig. A.1.** Details of the evolution of PMJs. The format of this figure is the same as that of Fig. 2. Animations of this figure are available online.
Fig. A.2. Details of the evolution of PMJs. The format of this figure is the same as that of Fig. 2. Animations of this figure are available online.
Fig. A.3. Details of the evolution of a PMJ. The format of this figure is the same as that of Fig. 2. An animation of this figure is available online.
Fig. A.4. Detailed look at the onset of PMJs. The format of this figure is the same as that of Fig. 7.
Paper III

A multi-diagnostic spectral analysis of penumbral microjets

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A multi-diagnostic spectral analysis of penumbral microjets

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ABSTRACT

Context. Penumbral microjets (PMJs) are short-lived, jet-like objects found in the penumbra of sunspots. They were first discovered in chromospheric lines and have later also been shown to exhibit signals in transition region (TR) lines. Their origin and manner of evolution is not yet settled.

Aims. We perform a comprehensive analysis of PMJs through the use of spectral diagnostics that span from photospheric to TR temperatures to constrain PMJ properties.

Methods. We employed high-spatial-resolution Swedish 1-m Solar Telescope observations in the Ca\textsc{ii} 8542 Å and H\textalpha{} lines, IRIS slit-jaw images, and IRIS spectral observations in the Mg\textsc{ii} h \& k lines, the Mg\textsc{ii} 2798.75 Å \& 2798.82 Å triplet blend, the C\textsc{ii} 1334 Å \& 1335 Å lines, and the Si\textsc{iv} 1394 Å \& 1403 Å lines. We derived a wide range of spectral diagnostics from these and investigated other secondary phenomena associated with PMJs.

Results. We find that PMJs exhibit varying degrees of signal in all of our studied spectral lines. We find low or negligible Doppler velocities and velocity gradients throughout our diagnostics and all layers of the solar atmosphere associated with these. Dark features in the inner wings of H\textalpha{} and Ca\textsc{ii} 8542 Å imply that PMJs form along pre-existing fibril structures. We find evidence for upper photospheric heating in a subset of PMJs through emission in the wings of the Mg\textsc{ii} triplet lines. There is little evidence for ubiquitous twisting motion in PMJs. There is no marked difference in onsets times for PMJ brightenings in different spectral lines.

Conclusions. PMJs most likely exhibit only very modest mass-motions, contrary to earlier suggestions. We posit that PMJs form at upper photospheric or chromospheric heights at pre-existing fibril structures.

Key words. Sun: atmosphere – Sun: chromosphere – Sun: photosphere – sunspots – Sun: magnetic fields

1. Introduction

Penumbral microjets (PMJs) are observed in the penumbral fringes of sunspots, and they were first discovered in the chromospheric Ca\textsc{ii} H line (Katsukawa et al. 2007). Time-sequences produced by the Hinode satellite’s 3 Å wide Ca\textsc{ii} H line imaging filter revealed short-lived jet-like objects which were most noticeable in time-difference images. In these original observations, PMJs show a relative brightening of 10\%–20\% compared to their penumbral surroundings, have lengths of 1000 km–4000 km and widths of about 400 km, typical lifetimes of up to 1 min, and apparent rise-velocities of 100 km s\textsuperscript{−1} (Katsukawa et al. 2007). In Katsukawa et al. (2007), the authors speculated that the fast apparent velocities of PMJs could be explained by either a true mass motion caused by a reconnection outflow that exceeds acoustic velocities or alternatively by the evolution of a thermal conduction front that lacks significant mass motions. Through inversions and analyses of PMJ observations, Esteban Pozuelo et al. (2019) posit that PMJs are the result of a propagating perturbation front that originates in the deep photosphere and dissipates energy within the PMJ in a process akin to what has been suggested for spicules in recent times (De Pontieu et al. 2017). This lends support to the thermal conduction front scenario of Katsukawa et al. (2007).

A large automated sampling of PMJs (Drews & Rouppe van der Voort 2017) using highly spatially, temporally, and spectrally resolved Ca\textsc{ii} 8542 Å observations from the Swedish 1-m Solar Telescope (SST) at La Palma gives average PMJ lengths, widths, and lifetimes of 640 km, 210 km, and 90 s (with an 8 minute cut-off), respectively, on the same order of magnitude as previous values. PMJs are thought to be chromospheric in origin (Katsukawa et al. 2007; Jurčák & Katsukawa 2010), but they have been shown to have transition region (TR) responses (Vissers et al. 2015; Tiwari et al. 2016; Katsukawa et al. 2018) and are visible in the Mg\textsc{ii} h, C\textsc{ii}, and Si\textsc{iv} slit-jaw images observed by the Interface Region Imaging Spectrograph satellite (IRIS, De Pontieu et al. 2014). These observations suggest heating to TR temperatures as the studied PMJs show emission in the C\textsc{ii} and Si\textsc{iv} lines towards their tops.

TR bright dots are bright features that are predominantly found in the penumbral fringes of sunspots (Tian et al. 2014; Alpert et al. 2014), and they are visible in TR channels, such as the IRIS SJI 1400 Å and 1330 Å channels. They are usually somewhat elongated and have sizes on the scale of a few hundred kilometres, and upon discovery they were already speculated to be linked to PMJs. Samanta et al. (2017) posit more specifically that PMJs may in fact originate at TR heights in the form of TR bright dots and show chromospheric signatures only after their TR counterparts, and they report observations to this effect. However, the most popular proposed mechanism for the creation of PMJs remains magnetic reconnection in the

\* Movies associated to Appendix B are available at https://www.aanda.org
photospheric penumbra, as initially suggested upon their discovery (Katsukawa et al. 2007). The magnetic reconnection scenario at photospheric or lower chromospheric heights is supported by the measurement of apparent inclinations of PMJs to surrounding penumbral filaments (Katsukawa et al. 2007) and magnetic fields (Jurčák & Katsukawa 2008). Some small photospheric downflow patches are also observed in conjunction with some PMJs (Katsukawa & Jurčák 2010), which may further strengthen the assumption of photospheric magnetic reconnection. There is also numerical work that suggests the plausibility of the photospheric magnetic reconnection scenario (Nakamura et al. 2012), showing that reconnection can indeed give rise to jet-like phenomena that travel in the approximate direction of the surrounding penumbral fibrils and later reach observed apparent velocities as a result of moving from the dense photosphere to the less dense chromosphere by producing a shock.

A distinct PMJ profile in the Ca ii 8542 Å line was first presented by Reardon et al. (2013), displaying peaks in the inner line wings with a blue-over-red asymmetry. The average Ca ii 8542 Å PMJ line profile of Drews & Rouppe van der Voort (2017) did not reveal any significant Doppler shift, nor a viewing-angle correlation between the line offset of the blue or red peaks in the distinct line profile. Large penumbral jets (LPJs) were first described in Tiwari et al. (2016) as larger-than-average and more energetic PMJs that can be found at the edge of penumbrae. Tiwari et al. (2018) present evidence that LPJs may exhibit twisting motions along their long axis. This was accomplished through the analysis of spectral profiles observed using IRIS in the Mg II k line. At least a subset of the objects studied in this and other works that are termed PMJs may instead have been termed LPJs by Tiwari and collaborators. As such, the potential twisting motion of LPJs may also be expected of regular PMJs, and more so of large PMJs at the edge of penumbrae, which are in essence defined to be LPJs in the cited works.

The time evolution of PMJs has only been studied observationally in broad terms, especially when comparing their signatures in different wavelengths and thus solar temperatures through time. Earlier works have focused on lifetimes and apparent velocities of PMJs, usually in specific chromospheric lines. In Rouppe van der Voort & Drews (2019), we argue for a revised view of PMJ temporal evolution in light of highly temporally resolved SST observations of PMJs in the Ca ii H line. PMJs only show modest, true apparent velocities and appear to light up across a significant fraction of their length along existing fibrils in the Ca ii H line. This happens on the timescales of the cadence of the observations of about 1 s. This is hypothesised to be due to a heating front moving through the PMJs, rather than hot material moving upwards in a true mass motion. This interpretation is congruent with the proposed scenario mentioned earlier, which was first put forth by Katsukawa et al. (2007), regarding an evolving thermal conduction front, which was strengthened by the findings of Esteban Pozuelo et al. (2019). To definitively differentiate between a scenario involving true high-velocity mass motions or that of an evolving thermal conduction front, we performed a wide range of Doppler-shift measurements, as first suggested in Katsukawa et al. (2007).

Here, we expand on the investigation of the TR response of PMJs as performed in Vissers et al. (2015) by analysing co-observations from the SST and IRIS, covering the solar atmosphere from the photosphere to the TR. We sampled the photosphere and chromosphere of a fully formed sunspot with detailed line scans of Ca ii 8542 Å and H α with the SST and sampled the upper chromosphere and TR with slit-jaw images and spectra of Mg II, C II, and Si IV from IRIS. We assembled a set of 77 PMJs, which were co-observed with both the SST and IRIS. The PMJs’ IRIS signatures were sampled at IRIS’ spectrograph slit-positions and at all intermediate pixels covered by the SST in the Ca ii 8542 Å and H α lines.

The above enabled us to acquire a wide range of spectral diagnostics at different locations along the PMJs, so that we can analyse spectral features at different nominal heights and throughout the PMJs’ evolution, from formation to dissipation and heights from the photosphere to the TR. We also study possible twisting motions of PMJs utilising the Mg II line and describe concurrent PMJ features in the inner wings of the H α and Ca ii 8542 Å lines. Lastly, we describe the appearance of the various PMJ signals in the different spectral channels through time.

2. Observations

We observed NOAA Active Region AR12533 on April 29 and 30, 2016. The field of view for SST and IRIS was aimed at the centre of the oval sunspot with a fully formed penumbra. On April 29, the AR was at heliocentric coordinates (X, Y) = (623", 19") (μ = cos θ = 0.75, with θ the observing angle). On April 30, it was observed again, but then at heliocentric coordinates (X, Y) = (774", 4") (μ = cos θ = 0.57). The SST seeing was good for the duration of the co-pointing on both days. The data quality was further improved by the adaptive optics system (Scharmer et al. 2003) and subsequent image reconstruction with the multi-object multi-frame blind deconvolution method (MOMFBD, van Noort et al. 2005). The observing procedure and programmes used for both instruments were identical for both sets of observations. We used the CRISP Imaging SpectroPolarimeter (CRISP, Scharmer et al. 2008) instrument to acquire spectrally resolved data in the Ca ii 8542 Å and H α spectral lines. Six exposures were acquired per liquid crystal state and line position, and the Ca ii 8542 Å line scan was completed in ~16 s, and with the H α scan included, the effective cadence of the time sequence was ~20 s. The spectropolarimetric Ca ii 8542 Å data sampled the spectral line at 21 line positions, with a dense (70 mÅ steps) sampling in the line core and an increasingly coarser sampling in the wings out to ±1.75 Å. The H α line was sampled at 15 positions, with 200 mÅ steps around the line core and the last two sampling positions at ±1500 mÅ.

The CRISP data were processed with the CRISPRED reduction pipeline (de la Cruz Rodríguez et al. 2015).

IRIS ran a so-called medium sparse eight-step raster observing programme (OBSID 3620106129) with a 60" long and 0":33 wide spectrograph slit covering a 7" wide area with eight slit positions separated by 1". The exposure time was 4 s and the spectrograms were 2× binned both in the spatial (0":33 per pixel) and spectral domain (26 mÅ per pixel for the FUV spectra and 51 mÅ per pixel for the NUV). The raster cadence was ~40 s. Slit-jaw images (SJI) were recorded in the SJI 1400 Å, 1330 Å, and 2796 Å channels at a cadence of ~20 s, and in the SJI 2832 Å channel at a 122 s cadence. All slit-jaw images were spatially binned to 0":33 per pixel.

Co-pointing proved to be successful, with both instruments imaging the whole sunspot for the two time series at 09:42–11:13 UT and 09:08–10:38 UT on April 29 and 30, 2016 respectively. The SST and IRIS observations were co-aligned through cross-correlation between the Ca ii 8542 Å wing and the SJI 2832 Mg h wing channel.
Going forward, when referring to the observations from April 29, April 30 and the values derived thereof, we use the short-hand terms dataset A and dataset B, respectively.

3. Methods

To investigate the spectral signatures of PMJs in the wavelength passbands available from the SST and IRIS observations, we identified examples of PMJs using the CRisp SPectral EXplorer (CRISPEX, Vissers & Rouppe van der Voort 2012). This allowed us to view the observations simultaneously in the SST Ca II 8542 Å line and the IRIS slit-jaw images, allowing for easier initial identification of sample events crossing the IRIS raster-positions. For the final identification and selection of suitable PMJs that crossed the IRIS spectrograph raster slits, we employed a visual examination of side-by-side images in the SST and SJI IRIS observations together with composite images of them.

PMJs are the brightest at an offset of $\approx 350 \text{mÅ}$ in the Ca II 8542 Å line (Drews & Rouppe van der Voort 2017), corresponding to the typical blue peak position in this line. We created RGB images from Ca II 8542 Å $\approx 350 \text{mÅ}$ images (red), SJI 2796 images (green), and SJI 1400 images (blue). IRIS slitjaw images and images in the Ca II 8542 Å blue wing can be employed to highlight the progression of PMJs through temperatures and corresponding heights that usually correspond to these channels. The inner wings of the CRISP Ca II 8542 Å line are usually associated with the chromosphere, the IRIS SJI 2796 with the upper chromosphere, and the IRIS SJI 1400 with the TR.

The RGB images were adjusted for contrast and intensity ranges in order to aid in qualitatively identifying PMJs. In these images, PMJs often exhibit a distinct “rainbow” signature. This arises from the fact that PMJs typically exhibit spatially offset enhancements in these channels through the different atmospheric heights. This signature is typically orientated along the same direction as the jet-like structure of the PMJ. This behaviour was first described in Vissers et al. (2015). An example of a PMJ in the different mentioned channels and the resultant RGB composite image that displays a rainbow signature is given in Fig. 1. This and other similar figures aided in the further identification of PMJs.

There exists a bias towards the detection of PMJs that have a typical line-profile shape in the Ca II 8542 Å line (as is described and documented in Drews & Rouppe van der Voort 2017), as these were assumed to be a general identifying feature of PMJs. As such, PMJs are assumed to exhibit a signal and typical Ca II 8542 Å line profiles in the vast majority of cases, and we further assume that PMJs that do not exhibit such typical profiles are either rare or cannot truly be classified as PMJs, as these profiles are a firmly established feature of PMJs. In some detected cases, Ca II 8542 Å profiles are subdued or absent, but the corresponding PMJs were still included as long as they otherwise appeared typical, visually speaking.

We justify the above in that we canonically consider PMJs to be primarily chromospheric features, as they would otherwise be indistinguishable from bright dots, for example, and a delineating definition is therefore necessary. In Samanta et al. (2017), a causal connection between TR bright dots and PMJs is proposed. Whether or not bright dots may cause or be linked to PMJs should have no bearing on whether PMJs are canonically required to exhibit a signal in the chromosphere, since the lack of signal in the chromosphere for a “PMJ” would imply that it is a bright dot instead.

Cross-examining and identifying potential PMJs in the different channels, but considering the known and well-described PMJ signatures in the Ca II 8542 Å line, then led to the final selection of PMJs used in further analyses. Selected PMJs were necessarily restricted to those that intersected IRIS slit-positions, so that we could study their spectra. The spectral signatures of these events were investigated in a wide range of lines. With CRISP, we obtained spectral profiles in the Ca II 8542 Å and H α lines. With IRIS, we obtained spectra of the Mg II k, h, and triplet lines, square: C II 1334 Å and 1335 Å lines, triangle: Si IV 1394 Å and 1403 Å lines. The slit positions (of one-pixel width) of IRIS are denoted in each panel by black-dotted lines. Tick marks are spaced 1” apart.

Fig. 1. Example PMJ from dataset B. Observations of (a) the SST Ca II 8542 Å line at an offset of $\approx 350 \text{mÅ}$, (b) the IRIS SJI 2796, (c) the IRIS SJI 1400, and (d) the composite RGB image created from the three preceding images are shown. Tick-mark spacing is 1”. The images were cropped with the PMJ at their approximate centres. Symbols mark the sampling positions for analysis of spectral line profiles. Cross: Ca II 8542 Å, diamond: the Mg II k, h, and triplet lines, square: C II 1334 Å and 1335 Å lines, triangle: Si IV 1394 Å and 1403 Å lines. The slit positions (of one-pixel width) of IRIS are denoted in each panel by black-dotted lines. Tick marks are spaced 1” apart.

Each PMJ was sampled at four different spatial sampling positions, corresponding to the enumerated spectral lines and PMJ parts below. The PMJ parts are described in reference to when they were viewed in all channels (or their composite RGB images). The sampling positions corresponding to different spectral lines and distinct PMJ parts are the following:

1. The blue wing of the Ca II 8542 Å line, corresponding to the chromospheric PMJ footprint;
2. The Mg \(\text{II} \ h \& k\) lines (and the two Mg \(\text{II}\) triplet lines and an adjacent Fe \(\text{II}\) line), corresponding to the mid-point of the PMJ; 
3. The C \(\text{II} \ 1334\,\text{Å} \) and \(1335\,\text{Å}\) lines, corresponding to the tail-end of the PMJ; 
4. The Si \(\text{IV} \ 1394\,\text{Å} \) and \(1403\,\text{Å}\) lines, also corresponding to the tail-end of the PMJ.

As mentioned, all of these positions were chosen to maximise the overall spectral line enhancement in each of the relevant wavelength regions and spectral lines. As such, for the selected positions in the IRIS channels, these do not need nor do they frequently correspond to the brightest pixel positions in corresponding IRIS slitjaw images. This is not only due to the positions being limited to the spectral line-raster positions, but also because the slitjaw images correspond to the wide-band wavelength regions of the relevant channels, and finally because the images are also offset in time to the raster samplings (see Sect. 2).

We also obtained spectral line profiles from two additional sampling positions by utilising our CRISP observations. We sampled one of these in Ca \(\text{II} \ 8542\,\text{Å} \) and one in H \(\alpha\). These sampling positions correspond to dark features in the wings of these two lines that can be found adjacent to the main bright feature identifying PMJs in Ca \(\text{II} \ 8542\,\text{Å} \). All spectral profiles for both Ca \(\text{II} \ 8542\,\text{Å} \) and H \(\alpha\) were drawn from CRISP observations that were downsampled to match the lower pixel scale of the IRIS slitjaw images in order to select appropriate positions concurrent with the slitjaw-selected IRIS-channel positions.

After initial identifications, the spectral signatures of PMJs through time at different positions were investigated. Our spectral analysis includes (among others) the detection of the wavelength positions of peaks and minima in those lines where relevant, and this was followed by the computation of inferred values, such as peak separations, ratios between the intensities of peaks, and others.

The different diagnostics are described in Sect. 4 in the various subsections in which they are presented. The temporal evolution of PMJs was studied in a predominantly qualitative fashion. The approximately 40 s cadence of each individual slit-position of the IRIS raster spectrograph makes a detailed study of behaviour in time tenuous at best, but it does allow for generalised statements about the behaviour across different channels and therefore associated heights in the solar atmosphere.

4. Results

This section is organised as follows. We begin by presenting an overview of the detected PMJs in both of our sets of observations in Sect. 4.1. Here we point to the general appearance of the sampled PMJs and in which diagnostic channels and with what instruments they are detectable, and we present their general appearance in different spectral lines. We also present the first-order signals of the PMJs in all our diagnostics, meaning their visual appearance in images and their appearance in individual spectral lines as detected by our different instruments. We also present average spectral line profiles for all of our PMJs. Here, we also present size estimates for our PMJ events.

In Sects. 4.2 through 4.7, we then present the specific behaviour in particular spectral lines and wavelengths, as well as the second-order diagnostic values inferred from signals in specific spectral lines. These second-order values consist of line profile peak positions, peak separations, line-intensity ratios, and more. We present them where relevant for all of our detected PMJs. Here we also present inferred physical conditions in the solar atmosphere at the site of our studied PMJs as estimated from the second-order diagnostic values.

The sections pertaining to the spectral line analysis of the IRIS line profiles lean heavily on the work presented in the series of papers on The Formation of IRIS Diagnostics, and more specifically the papers dealing with the formation and the analysis of the Mg \(\text{II} \ h, k\), the nearby triplet lines (Leenaarts et al. 2013a,b; Pereira et al. 2015), and the C \(\text{II} \ 1334\,\text{Å} \) and \(1335\,\text{Å}\) lines (Rathore & Carlsson 2015; Rathore et al. 2015a).

After spectral analysis of our PMJs, we performed three more general analyses, which are presented separately. In Sect. 4.8 we present our investigation of dark features observed in the inner line-wings of the H \(\alpha\) line linked to PMJs (first observed in Buehler et al. 2019), which we link to similar darknings in the inner line wings of the Ca \(\text{II} \ 8542\,\text{Å} \) line. We further link the darknings at these wavelengths to the brightenings observed in the Mg \(\text{II}\) line pair. In Sect. 4.9 we investigate the possibility of twisting in PMJs utilising the Mg \(\text{II} \ h, k\) lines using Doppler maps and bisectors. Finally, in Sect. 4.10 we perform a qualitative analysis of the temporal behaviour of our studied PMJs through time across different spectral lines.

4.1. Overview of detected PMJs

A total of 77 PMJs were detected and found suitable for investigation. Dataset A consists of 33 PMJs, and dataset B is made up of 44 PMJs. The locations of all detected PMJs and their primary sampling positions in four of our studied channels are shown in Figs. 2 and 3 for datasets A and B, respectively. Only the sampling positions for the Ca \(\text{II} \ 8542\,\text{Å} \) line, the shared position for the Mg \(\text{II}\) lines, and the position for the Si \(\text{IV}\) lines are shown explicitly for clarity. These positions are representative of the extent of the main body of the investigated PMJs through the different image-channels as these positions usually lie at the foot, midpoint, and terminus of any given PMJ. Also the regions for which we computed the mean spectral profiles of the penumbra for different channels are shown. We find PMJs in both the upper and lower portions of the sunspot where these regions are covered by the IRIS raster. For both datasets, we can see a loose trend of PMJs clustering in so-called hot spots, which is a trend previously described by Tiwari et al. (2016), Drews & Rouppe van der Voort (2017), and Esteban Pozuelo et al. (2019). As can be seen in Figs. 2 and 3, for both dates of observations, there are two clusters of PMJs to the left and right in both the upper and lower parts of the sunspot. The trend is more clearly visible for dataset B, which is likely due to the higher number of studied PMJs in these observations. The different clusters seem to persist in the sunspot between the two different dates, at least to some degree. This reaffirms the clustered appearance of PMJs in such hot-spots. However, there is a necessary selection bias towards PMJs situated in the region covered by the IRIS raster, as only those PMJs that were caught along most of their length by the raster were selected for investigation. Especially for the lower portion of the sunspot for both dates, this creates a preference for PMJs on the left side of the raster space, as the fibril direction trends from left to right in this area. PMJs typically align roughly with the underlying fibrilar structure, and as such the heads of PMJs lie to the right in the present observations, making the selection of PMJs with footpoints on the left side of the raster region more likely.
4.1.1. Videos of PMJ diagnostics

In order to facilitate a holistic overview of individual PMJs using all major first-order diagnostics and their temporal evolution, we created two sets of videos for each dataset that show individual PMJs. Two videos show each PMJ in both datasets at their peak brightness, while the second set shows all PMJs through time for both datasets.

The videos showing all PMJs at only peak brightness for dataset A and B are available in Video 1 and Video 2, respectively. The videos detailing the temporal evolution of PMJs in dataset A and B are available in Video 3 and Video 4, respectively.

A more detailed description of these videos and their layout is given in Appendix B. We strongly encourage readers to view
at least videos 1 and 2 for an overview of all PMJs. Videos 3 and 4 are useful in order to gain an overview of the temporal evolution of specific PMJs. We also particularly suggest inspecting the example PMJs mentioned in the text.

4.1.2. Visual appearance of PMJs

PMJs in our observations adhere to the same type of morphology as when previously studied in a variety of works, and they present as elongated brightenings that appear and disappear on time scales of minutes or less than a minute. This overall appearance also holds true when PMJs are viewed in multiple wavelength channels simultaneously. As mentioned, PMJs often display a rainbow-like signature in composite-channel RGB images, which was used as another aid both in discovering and identifying PMJs, but it was not used as a strict criterion in order to make a positive identification. Figures 4 and 5 display all of the studied PMJs in composite RGB images for datasets A and B, respectively. Many PMJs exhibit a rainbow signature with a connected red-to-green-to-blue elongated structure that reaffirms the observation that PMJs typically exhibit a signal in channels associated with temperatures that correspond to the chromosphere and up to the TR, suggesting that PMJs range through such temperatures.

PMJs do not always exhibit a clear rainbow pattern. In some instances, this is due to the PMJ in question, which simply does not exhibit a signal in the relevant channel. Positing that a PMJ originates in the chromosphere (the validity of which is discussed in Sect. 5), less energetic ones may not reach the relevant temperature (or height) to which the channel corresponds. In other cases, it is due to a failure in capturing the relevant signal. Another source for absent rainbow patterns may result from the automated mixing in the RGB image resulting from the three diagnostic images, which may not always yield favourable visual results. Lastly, in several images, the shadow of the IRIS spectrograph slit is also evident, usually as a purplish line in the images, and it may obscure possible rainbow patterns. Despite a number of PMJs that do not exhibit a rainbow pattern, a majority of the detected PMJs can reasonably be said to display such a pattern for both our dates of observations.

4.1.3. PMJ sizes

We measured a lower bound on PMJs lengths that are based on two sets of sampling positions. The first is the sampling position of Ca II 8542 Å and the second is the sampling position of the Si IV lines. The inferred lengths are the straight-line distances between these two sampling positions for any given PMJ. These sampling positions are located at the nominal peak-intensity pixels at the nominal peak-intensity time. As such, the sampling positions do not measure the maximum extents of our PMJs, as there is often still some appreciable signal away from the given peak-intensity pixel. However, Si IV line core intensities typically dropped dramatically with increased pixel distance from the peak-intensity pixel. Ultimately, the presented lengths must therefore be considered a lower bound on projected PMJ lengths when measured from the chromosphere to the TR. See both the overview in Figs. 2 and 3 and the PMJ RGB-images in Figs. 4 and 5 for reference.

The mean lower-bound lengths with associated standard deviations for our studied PMJs were found to be (2204 ± 195.0) km and (1940 ± 138.2) km for datasets A and B, respectively.

Fig. 4. All PMJs from dataset A. Each panel highlights one PMJ at approximately peak intensity. The field of view for each panel is 7 arcseconds along the x- and y-axis and is centred on each PMJ displayed. The panels display colour composite images produced from Ca II 8542 Å at an offset of ~350 mÅ and the IRIS SJI images in the Mg II k, h, and triplet lines; square: C II 1334 Å and 1335 Å; and triangle: Si IV 1394 Å and 1403 Å. The raster-slit positions (of one-pixel width) of the IRIS slit-spectrograph are indicated and enclosed in each panel with black-dotted lines.

Multi-channel PMJ width estimates necessitate measurements in IRIS SJI 2796 images since PMJs usually display their midsection in this channel. However, widths of most PMJs fell
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would be of dubious value at best. We thus constrain ourselves to the observation that our PMJs have typical widths of 243 km–729 km, corresponding to the widths of 1–3 pixels in the Mg II SJI images.

4.1.4. Overview of PMJ responses in different spectral lines

Figures 6 and 7 show spectral profiles for all of our studied PMJs. The average event profiles and average profiles for the penumbra and the entire FOV for each date observation for all given lines are also shown. We note that Hα line profiles for PMJ dark features are presented separately in Sect. 4.8.

PMJs may exhibit signals in all of the lines. However, the studied PMJs display enhancement more readily in some of the lines than in others.

The figures highlight that there is a large spread in the profiles for all channels, but for both datasets it is evident that PMJs often display strong signals in the Ca II 8542 Å and the Mg II h and k lines compared to the penumbral average, while enhancement in other lines is somewhat less common, especially the Mg II triplet lines. We note that C II 1334 Å & 1335 Å typically exhibit double peaks when in emission, but also some single peaks. When in emission, the Si IV 1394 Å & 1403 Å lines always present as single peaked and near-Gaussian.

There exists one example of a PMJ exhibiting enhancement in the O IV 1401 Å line in dataset B (see Fig. 7). This event also corresponds to the strongest event in terms of intensity for the Si IV lines, and with very defined profiles with strong intensities for the other lines (but with no emission in the Mg II triplet). This may indicate that the specific PMJ event may be heated to temperatures far beyond earlier observed examples. This specific PMJ is presented in Sect. 4.7, albeit briefly, as a single event should not be overanalysed nor overemphasised.

Table 1 summarises the number of PMJs that exhibit clear signals in the various channels studied. A clear signal means that a given line profile shows an enhancement when compared to nearby pixels in space and time, and it is thus based not only on a comparison to the penumbral average for a given line since profile intensities can vary substantially with regards to position throughout the sunspot. This investigation was performed visually to give an estimate of the PMJ signal frequency in the different channels.

4.2. PMJs in the Ca II 8542 Å line

PMJs have been described in the Ca II 8542 Å line in the literature by Reardon et al. (2013), Drews & Rouppe van der Voort (2017), Vissers et al. (2015), Esteban Pozuelo et al. (2019), and Buehler et al. (2019). We investigated the line-core position and the positions of any present peaks in the Ca II 8542 Å line for all of our investigated PMJs. In order to do this, we employed a simple spline interpolation of the line profiles, followed by an approach in which subsections of the profile were iteratively inspected for local peaks and minimums. This process is akin to the one previously employed in Drews & Rouppe van der Voort (2017). This approach always identifies line cores and those inner line wing enhancements that have clear peaks. Inner line wing enhancements that are merely somewhat enhanced compared to the average penumbral Ca II 8542 Å line profile and that may be discernible by eye were not selected. A consistent way to select offset positions for these is non-trivial, and we chose to focus on the cases where the enhancements correspond to clear peaks to avoid ambiguity.

Fig. 5. All PMJs from dataset B. The layout is identical to that of Fig. 4, see its caption for details.
The specific values (see Table 2) for the line core and the blue and red peak offsets for the PMJ line profiles are also in

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general agreement with the literature. The line core Doppler offsets are close to zero, and there is less than 1 km s\(^{-1}\) of apparent shift from the nominal line core for both days of observation. The blue and red peak offsets are found at near-equal positions on the blue and red side of the line core for both dates of observations. The values found for these positions are also in general agreement with the values found for the large dataset of automatically detected PMJs in Drews & Rouppe van der Voort (2017).

Here the average line core, blue- and red-peak offsets in the Ca II 8542 Å line were found to be 0.16 km s\(^{-1}\), −12.12 km s\(^{-1}\) and 11.95 km s\(^{-1}\) respectively\(^1\).

### 4.3. PMJs in the Mg ii h & k line pair

We have presented the average spectral profiles in the Mg II line pair for our two sets of PMJ observations in Figs. 6 and 7. In

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\(^1\) These values were corrected for a conversion error in Drews & Rouppe van der Voort (2017) that stemmed from a wrong constant in a programming routine that converted values from units of Ångstrom to km s\(^{-1}\). As given here, they also follow the sign convention in this paper that negative values are on the blue side of the line-core.

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**Table 1.** Number of occurrences of distinct PMJ signal in different spectral lines.

<table>
<thead>
<tr>
<th>Dataset A, (N_{\text{total}} = 33)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectral line(s)</strong></td>
<td>(N)</td>
<td>(%)</td>
</tr>
<tr>
<td>Ca II 8542 Å</td>
<td>29</td>
<td>(88%)</td>
</tr>
<tr>
<td>Mg II h &amp; k</td>
<td>32</td>
<td>(97%)</td>
</tr>
<tr>
<td>Wings of Mg II 2798.75 Å &amp; 2798.82 Å</td>
<td>7</td>
<td>(21%)</td>
</tr>
<tr>
<td>Triplet blend</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C II 1334 Å &amp; 1335 Å</td>
<td>23</td>
<td>(70%)</td>
</tr>
<tr>
<td>Si IV 1394 Å &amp; 1403 Å</td>
<td>25</td>
<td>(76%)</td>
</tr>
<tr>
<td>**Dataset B, (N_{\text{total}} = 44)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Spectral line(s)</strong></td>
<td>(N)</td>
<td>(%)</td>
</tr>
<tr>
<td>Ca II 8542 Å</td>
<td>40</td>
<td>(91%)</td>
</tr>
<tr>
<td>Mg II h &amp; k</td>
<td>42</td>
<td>(95%)</td>
</tr>
<tr>
<td>Wings of Mg II 2798.75 Å &amp; 2798.82 Å</td>
<td>5</td>
<td>(11%)</td>
</tr>
<tr>
<td>Triplet blend</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C II 1334 Å &amp; 1335 Å</td>
<td>32</td>
<td>(73%)</td>
</tr>
<tr>
<td>Si IV 1394 Å &amp; 1403 Å</td>
<td>37</td>
<td>(84%)</td>
</tr>
</tbody>
</table>

---
Table 2. Ca II 8542 Å line diagnostic values for our studied PMJs.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Line core offset [km/s]</th>
<th>Blue peak offset [km/s]</th>
<th>Red peak offset [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, (N = 33)</td>
<td>(-0.17 \pm 0.00 (N = 33))</td>
<td>(-14.80 \pm 0.02 (N = 16))</td>
<td>(14.55 \pm 0.03 (N = 12))</td>
</tr>
<tr>
<td>B, (N = 44)</td>
<td>(0.81 \pm 0.00 (N = 44))</td>
<td>(-12.93 \pm 0.01 (N = 20))</td>
<td>(15.78 \pm 0.02 (N = 15))</td>
</tr>
</tbody>
</table>

Table 3. Mean values and standard errors for different line diagnostics of the Mg II h & k lines for detected PMJs from datasets A and B.

<table>
<thead>
<tr>
<th>Dataset/ line</th>
<th>Core offset (\Delta v_{k3}) [km/s]</th>
<th>Peak (\Delta v_{k2}) separation [km/s]</th>
<th>Avg. Doppler (\Delta v_{k2}) shift [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A (N = 33))</td>
<td></td>
<td>(33.14 \pm 0.35)</td>
<td>(-0.02 \pm 0.18)</td>
</tr>
<tr>
<td>Mg II k</td>
<td>(0.47 \pm 0.25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg II h</td>
<td>(0.19 \pm 0.25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B (N = 44))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg II k</td>
<td></td>
<td>(31.25 \pm 0.36)</td>
<td>(-0.23 \pm 0.18)</td>
</tr>
<tr>
<td>Mg II h</td>
<td></td>
<td>(0.36 \pm 0.32)</td>
<td>(0.08 \pm 0.26)</td>
</tr>
</tbody>
</table>

Notes. [a] Where “x” in the formulea may be k or h, as relevant for the given row.

4.3.1. Mg II h & k line core shifts

The line core shifts of the Mg II h & k lines, \(\Delta v_{k3}\) and \(\Delta v_{h3}\), both strongly correlate with the line of sight velocity at the formation height of the h3 and k3 features at optical depth unity. The correlation coefficient was shown to be close to unity in Leenaarts et al. (2013b), and these shifts therefore hold great immediate diagnostic value and constitute the most reliable of the Mg II diagnostics, probing either PMJs or the atmospheric conditions in their immediate surroundings. The height of optical depth unity for both h3 and k3 is close to that of the very upper chromosphere, and the Doppler-velocity offsets of the h3 and k3 features can therefore be taken as diagnostic proxies for the line of sight velocities at this height. Table 3 gives the Doppler-velocity offsets of the h3 and k3 features for our sample positions in the Mg II h & k lines for our detected PMJs for both our sets of observations. The measured values are consistent across all four given values, and they are all close to zero with an absolute value range \(\leq 0.97\) km s\(^{-1}\).

4.3.2. Mg II h & k line peak separations

We define the peak separations of the Mg II h & k line as the absolute sum of the Doppler shifts of the two peaks in each Mg II line, \(|\Delta v_{k2}| + |\Delta v_{h2}|\) (where “x” may be k or h). Leenaarts et al. (2013b) and Pereira et al. (2013) show that this quantity correlates with the difference between the maximum and minimum of the atmospheric line of sight velocity between the mid-chromospheric formation heights of the peaks and heights above. The relation is less reliable than the previous diagnostics, with an average correlation coefficient of 0.57, which was inferred for the two lines. Further, it was shown that a temperature maximum in the lower chromosphere can also cause wider peak separations, which means that a discussion regarding this diagnostic must be more nuanced, especially given that PMJs are energetic events that are hypothesised to form in the chromosphere. Table 3 gives the peak separations for the h & k line of our Mg II sample positions of our detected PMJs for both dates of observations.

All values for the peak separations for both dates are rather consistent, with values slightly higher for the k line than for the h line for both dates of observations, and the separations are overall higher for the observations of dataset B. Overall, the peak separation values are of the order of \(\approx 30\) km s\(^{-1}\). This may indicate a maximum velocity difference between the mid-chromosphere and above in this range, assuming there is no temperature maximum in the lower chromosphere. This assumption, however, is challenged in Sect. 5 due to other diagnostics indicating that there may indeed exist such a temperature maximum.

4.3.3. Mg II h2 & k2 peak shifts

Leenaarts et al. (2013b) and Pereira et al. (2013) show that the average Doppler shifts of the Mg II h2 and k2 peaks correlate with the line of sight velocity at the optical depth \(\tau = 1\) height for the peaks in each line. Further, the h2 and k2 peaks are shown to form in the mid-chromosphere, about 1 Mm below their line cores (h3 and k3). The average Doppler shifts of the peaks thus correlate to the line of sight velocity at this height. The average of the correlation coefficients between average peak Doppler shifts for the two lines and the line of sight velocity at their formation heights is 0.66, and thus this diagnostic is somewhat less reliable than the one for the line core Doppler shifts, but it still provides a strong correlation.

From Table 3 we see that the averaged peak Doppler shifts are all close to zero km s\(^{-1}\) in magnitude; the majority of which are negative, indicating an upflow. With standard errors included, we find the very small upper absolute value of \(\leq 0.49\) km s\(^{-1}\) for the average peak Doppler shifts across all PMJs. Overall, negative values may indicate a possible subtle upflow in the lower chromosphere, though in which case it is close to zero in value.

4.4. PMJs in the Mg II triplet region

The Mg II triplet spectral lines are located at wavelength positions 2798.75 Å, 2798.82 Å, and 2791.60 Å and provide diagnostics on the lower chromosphere and the photosphere. Unfortunately the 2791.60 Å position was not covered by our IRIS observations, and its response could therefore not be studied.
The two triplet lines at 2798.75 Å and 2798.82 Å are not distinguishable as separate lines with the resolution of IRIS, and therefore they appear as a blend. We refer to this blended line as the triplet blend going forward. We studied the response of the Mg II triplet blend for our PMJ events and present our findings below.

Pereira et al. (2015) found that emission in the Mg II triplet blend line core is associated with a steep temperature increase in the lower chromosphere. It was found that the Mg II triplet blend typically appeared in emission when there was an increase in temperature of more than 1500 K in the lower chromosphere. In the case that heating occurs deeper down in the atmosphere, at photospheric heights, it was found that typically only the wings of the Mg II triplet blend are enhanced whilst the core itself does not exhibit emission. To our knowledge, PMJs have not been previously shown to exhibit intensity enhancement in any of the Mg II triplet lines. We do not find any PMJs for which we see emission in the core of the triplet blend line, but we do find multiple occurrences of emission in its wings, indicating heating at photospheric heights.

The number of PMJs that show significant emission in the Mg II triplet blend wings as determined by eye are tallied in Table 1, as presented previously. For reference purposes, Fig. 8 shows an overview of PMJ profiles in the wavelength region between the Mg II h & k lines. Clear emission in the triplet blend wings is evident for several PMJs in the different wavelength positions. These events are indicated and correspond to those tallied in Table 1. It must be noted that profiles with enhanced wings in the triplet blend were selected by comparing the wings with the overall intensity of the wavelength region for each given PMJ. As can be seen in Fig. 8, the profiles of PMJs cover a rather large intensity range. Absolute intensities in PMJs selected as showing an enhancement in the triplet blend wings may in some cases have lower intensity in these positions than other PMJs that were not selected. However, the overall intensity of the spectral range between the Mg II k and h lines can vary quite substantially, which may often be attributable to far-wing emission from these two lines. As such, only profiles that show clear enhancement in the triplet blend wings as compared to the surrounding emission were selected, and they were not selected solely on a criteria of absolute intensity levels. We therefore also encourage the reader to specifically inspect the triplet blend plots for individual PMJs in the peak brightness PMJ videos for both dataset A (Video 1) and B (Video 2), which are included in the online material. A sample frame with an accompanying caption, is given in Fig. B.1. The individual triplet blend plots in the videos specifically highlight the marked appearance of emission in the triplet blend wings as compared to its far wings.

We also note that we observe emission in a line adjacent to the two observed Mg II triplet lines that is situated at 2797.868 Å. This line lies between the Mg II triplet blend and the Mg II k line and was recently identified as a Fe II line in Tian et al. (2015). The identification of this line is uncertain, however (see Kowalski et al. 2019), and we limit ourselves to reporting the observation that this line is typically in emission whenever the wings of the triplet blend are also in emission.

We computed the mean values of the intensity at the two Mg II triplet blend wing positions for each PMJ and normalised these to the corresponding penumbral mean. The triplet blend wings are typically mildly enhanced compared to the penumbral mean, with normalised mean values close to 1.2 for the two datasets, with rather Gaussian-like distributions. We see several outliers towards higher relative intensities corresponding to events in which the triplet blend wings are in clear emission.

4.5. PMJs in the C II line pair

We have presented C II line pair profiles for all of our detected PMJs in Figs. 6 and 7. In those cases in which there is an actual enhancement in the line pairs, the profiles present with a double-peak profile in the majority of cases. There exist a few select cases for which we see single-peak profiles. We base our analysis of the C II line pair on Rathore & Carlsson (2015), Rathore et al. (2015a,b).

The C II line pair can, in principle, exhibit quite different types of line profiles, with both single, double, and more peaks, and therefore a proper definition of the line core must be established that covers these different cases. We define the line core as in the previously cited papers; for single peaks, we define it as the local maximum that is close to the nominal line centre and for double peaks as the local minimum of the intensity reversal.
between the two peaks. We do not observe more than two peaks in our investigated profiles.

For the different diagnostics, we utilise the offset values for the line core and the positions of blue or red peaks, when these are present. Our automated method for finding local maxima and minima usually determines the positions of these profile features to a good approximation when validated by eye, although misidentifications are far more common than for the Mg II h & k lines. This is due to the C II line pair observations being far noisier than in the Mg II lines, and because the Mg II h & k lines always present with a well-defined double peaked profile for our sampled PMJs. In contrast, the C II line pair profiles only exhibit appreciable enhancement in a subset of cases, if at all, and in these cases, they also suffer from the poorer signal-to-noise ratio. As such, the diagnostic values inferred from our investigation of the C II line pair should, in general, be viewed as less reliable than those for the Mg II h & k lines. However, given the appreciable number of PMJs that exhibit clear enhancement, our mean values for the various diagnostics should still be viewed as valid for a qualitative interpretation. Further, the fact that we have observed on two different dates and find similar values for our diagnostics on the two dates strengthens their validity.

It is worth mentioning that the C II 1335.4 Å line is comprised of a blend of two lines, namely the stronger 1335.708 Å and the weaker 1335.663 Å component. In general, this means that the diagnostics presented for the C II line pair are less reliable for the C II 1335.4 Å line than for the 1334 Å line.

The diagnostics described below were inferred from those PMJ profiles that have a maximum intensity in the ±50 km s\(^{-1}\) offset region of the nominal line core of the given line that is equal to or greater than that of the mean profile in the same line over the entire field of view for the given dataset. This was done to limit the samples to those profiles which show an enhancement that is actually appreciable as well as to not include values that are either very distorted by noise or that are altogether spurious. All inferred mean diagnostics values for the investigation of the C II line pair for datasets A and B are given in Table 4.

### 4.5.2. C II integrated intensity line-pair ratio and number of peaks

The integrated intensity ratio of the C II 1334 Å and 1335 Å lines can be used as a measure to determine whether it is formed under optically thick or possibly under optically thin conditions. The line intensity ratio is also correlated to the number of peaks present in the given profile, and the number of peaks gives insight into the type of source function that produces their line profiles. We follow the definition of the integrated line ratio of the C II 1334 Å and 1335 Å lines in Rathore & Carlsson (2015), such that we define the intensity ratio as \( R_I = \frac{I_{1335}}{I_{1334}} \). Here, the intensities \( I_{1334} \) and \( I_{1335} \) are the intensities of the two lines integrated over the region of ±20 km s\(^{-1}\) around the nominal line core for each given line. It was shown that this ratio can, in principle, take any value in the case of optically thick line formation, but it has the value \( R_I = 1.8 \) for the case of optically thin line formation. This means that \( R_I = 1.8 \) is compatible with optically thin line formation, but this does not prove it, whilst any other

### Table 4. Average values and their standard errors for different line diagnostics of the C II line pair for different groups of PMJs for datasets A and B are given.

<table>
<thead>
<tr>
<th>Dataset/line</th>
<th>Line core offset ([\text{km s}^{-1}])</th>
<th>Line width (W_{\text{FWHM}}) ([\text{km s}^{-1}])</th>
<th>Line int. ratio (R_I = \frac{I_{1335}}{I_{1334}})</th>
<th>Single peaks</th>
<th>Double peaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>C II 1334 Å</td>
<td>(-2.14 \pm 0.67) ((N = 22))</td>
<td>31.33 ± 12.63 ((N = 22))</td>
<td>13</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>C II 1335 Å</td>
<td>5.20 ± 0.67 ((N = 18))</td>
<td>41.71 ± 11.30 ((N = 18))</td>
<td>7</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>C II line pair</td>
<td>1.20 ± 0.08 ((N = 18))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B ((N = 44))</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C II 1334 Å</td>
<td>(-0.32 \pm 0.95) ((N = 29))</td>
<td>43.19 ± 14.46 ((N = 29))</td>
<td>8</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>C II 1335 Å</td>
<td>6.13 ± 0.81 ((N = 31))</td>
<td>51.36 ± 16.06 ((N = 31))</td>
<td>6</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>C II line pair</td>
<td>1.19 ± 0.07 ((N = 28))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
value indicates optically thick line formation. Furthermore, it
was shown in modelling that the value of $R_l$ is typically lower for
double peak profiles, with values around 1.4, whilst single peak
profiles have typical values around 1.7 (Rathore et al. 2015a).

Table 4 gives the values of the integrated line-pair ratio for
the two dates of observations in column five together with its
associated standard error. The values are consistent and overlap,
given their standard error and give a range of (1.12–1.28). The
values thus indicate optically thick line formation. The values
are also closer to the mean value of $R_l = 1.4$ expected for dou-
ble peak profiles than the one for single peak profiles. This is
congruent with the fact that we find a majority of double peak
profiles when there is enhancement in either of the lines. The
number of single and double peak profiles are given in Table 4.
For all but the case of the C II 1334 Å line for dataset A, we find
a greater number of double peaks than single peaks when there is
any clear enhancement in the given line.

Single peak profiles in both the C II 1334 Å and 1335 Å lines
are formed when the source function of the given line increases
monotonically up to the height where the line core has optical
depth unity. Double peak profiles are formed when there is a
local maximum in the source function deeper down in the atmosphe-
re, and if the source function above this local maximum decreases
in value with increasing height until optical depth unity for the line
core is reached. The C II 1335 Å line overall tends to have a higher
number of double peaks than its counterpart, since its line core forms overall a little higher than that of
the C II 1334 Å line, and thus there is a greater likelihood that
the 1335 Å line core forms at a greater height than a potential
local maximum in its source function compared to the 1334 Å line
(Rathore & Carlsson 2015; Rathore et al. 2015a,b). We see the
latter effect exemplified in Table 4, as there is a greater prevai-
lence of double peaks in the 1335 Å line than for the 1334 Å line
for both dates of observation. Further, as we have a greater num-
ber of double peaks than single peaks overall, we can reasonably
conclude for a majority of cases in which there is an enhance-
ment in the C II line pair that there is a local maximum in the
source function below the formation height of the line cores of
the two lines.

4.5.3. C II 1334 Å and 1335 Å line widths

We measured the line widths of C II 1334 Å and 1335 Å where
the line width for each given line was defined as $w_{\text{FWHM}} = 2 \sqrt{2 \ln 2} \sigma$, where $\sigma$ is the standard deviation of a Gaussian,
and thus $w_{\text{FWHM}}$ is the full width at half maximum of the same
Gaussian. This follows the approach outlined in Rathore &
Carlsson (2015), where it is shown through the use of synthetic
profiles and a model atmosphere that the use of Gaussian fits of
C II 1334 Å and 1335 Å line profiles yield useful estimates for
$w_{\text{FWHM}}$ using the Gaussian standard deviations, even in the case
that the two lines are formed under optically thick conditions and
when they exhibit double peaks. The measured $w_{\text{FWHM}}$ line
widths for C II 1334 Å and 1335 Å for datasets A and B are given
in Table 4, together with their standard errors.

The line widths of the C II 1334 Å and 1335 Å lines were
shown to be correlated to the non-thermal velocity at the heights
at which the cores of the two respective lines are formed in
Rathore et al. (2015a). The line width is also determined by
the thermal velocity, but the line width was further shown to be
predominately determined by the non-thermal velocity for line
widths greater than 6 km s$^{-1}$. Profiles with widths smaller than
6 km s$^{-1}$ were shown to have dominant optically thin compo-
nents. In Sect. 4.5.2, we show that for the case of our observed
PMJs, the line ratios, $R_l$, imply optically thick line formation.
For both dates of our observations and for those PMJ profiles in
the C II lines that exhibit emission, the line widths exhibit val-
ues greater than 6 km s$^{-1}$. As such, our measured line widths can
be used as a diagnostic to probe the non-thermal velocity at the
formation heights of the C II line pair.

To estimate the non-thermal line widths, we used the relation

$$w_{\text{nth}} = \sqrt{w_{\text{FWHM}}^2 + w_{\text{th}}^2}.$$ 

Here, $w_{\text{nth}}$ is the estimate of the non-thermal line width for
any given observed value of $w_{\text{FWHM}}$ (given in Table 4), $w_{\text{th}}$ is the
thermal line width, and $w_{\text{th}}$ is the instrumental line width of IRIS
in the far ultraviolet (FUV) bandwidth. The instrumental width
of IRIS in the FUV is $w_{\text{th}} = 12.8$ mA (De Pontieu et al. 2014), or
$w_{\text{th}} = 5.84$ km s$^{-1}$ for both C II 1334 Å and 1335 Å.

In order to calculate estimates for $w_{\text{nth}}$, we first computed a
fitting theoretical estimate for $w_{\text{th}}$, for which we used the expres-

$$w_{\text{th}} = \frac{8 \ln(2) k_B T_{\text{ion}}}{m_{\text{ion}}}.$$ 

Here, $k_B$ is the Boltzmann constant, $T_{\text{ion}}$ is the temperature of
the C II ion, and $m_{\text{ion}}$ its mass.

In Rathore et al. (2015a,b) it was found that the C II lines are
formed mainly in the optically thick regime, as we observe, and
with a mean formation temperature of 10 kK. More specifically, in
Rathore et al. (2015a) it was found that when the source func-
tion for the C II lines has a peak in the low atmosphere, this leads
to steep emission flanks and a double peak intensity profile. They
show an example of this (their Fig. 17) for which the tempera-
ture in the line forming region is 9.6 kK. Since we see a majority
of double peak profiles and as other results already indicate that
PMJs are due to heating events in the lower atmosphere, a tem-
perature of $T_{\text{ion}} = 10$ kK is thus a reasonable estimate for our
purposes, and we find a corresponding thermal line width for the
C II ion of $w_{\text{th}} = 6.19$ km s$^{-1}$.

Finally, we thus find mean non-thermal line width values of
$w_{\text{nth}}$, 1334, A = 30.2 km s$^{-1}$ and $w_{\text{nth}}$, 1334, B = 42.3 km s$^{-1}$
for the 1334 Å line for datasets A and B, respectively, and $w_{\text{nth}}$, 1335, A =
40.8 km s$^{-1}$ and $w_{\text{nth}}$, 1335, B = 50.7 km s$^{-1}$ for the 1335 Å line for
datasets A and B, respectively. We refrain from providing uncer-
tainty values for these non-thermal line widths, as the assumed
formation temperature of $T_{\text{ion}}$ alone would render these dubious
at best. As we can see, we find a range of values for the two
lines and datasets of $w_{\text{nth}} \approx (30.51)$ km s$^{-1}$. The non-thermal
line widths are also affected by opacity broadening, which most
likely skews them to higher values as typical opacity broaden-
ing values are of the order of 1.2–4 (Rathore et al. 2015a) due
to optically thick line formation and the double peak profiles
that are broader than single peak profiles. Thus, our inferred
non-thermal line width ranges serve as upper limits for non-thermal
velocities in the formation region of the C II line pair at the upper
chromosphere or just below the TR.

4.6. PMJs in the Si IV line pair

The Si IV 1394 Å and 1403 Å lines provide useful diagnostics
to probe the appearance and behaviour of PMJs in the TR. We
have made use of two specific diagnostics in these lines, namely
their respective line core Doppler offsets (Sect. 4.6.1) and the

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Table 5. Average values together with their standard errors for different line diagnostics of the Si\textsc{iv} line pair for the detected PMJs for datasets A and B are given.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Si\textsc{iv} 1394 Å core-offset [km s(^{-1})]</th>
<th>Si\textsc{iv} 1403 Å core-offset [km s(^{-1})]</th>
<th>(R_{\text{core}} = \frac{I_{\text{1394 \ Å}}}{I_{\text{1403 \ Å}}}) [ratio]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ((N = 33))</td>
<td>0.04 ± 0.77 ((N = 26))</td>
<td>1.07 ± 1.19 ((N = 17))</td>
<td>2.00 ± 0.09 ((N = 29))</td>
</tr>
<tr>
<td>B ((N = 44))</td>
<td>0.89 ± 0.84 ((N = 35))</td>
<td>2.09 ± 1.11 ((N = 27))</td>
<td>1.92 ± 0.07 ((N = 43))</td>
</tr>
</tbody>
</table>

The measured diagnostics for Si\textsc{iv} line pair for datasets A and B are given in Table 5, together with their standard errors.

4.6.2. Si\textsc{iv} 1394 Å and 1403 Å line core offsets

The line core offsets of the Si\textsc{iv} 1339 Å and 1403 Å are proxies for the line of sight velocity at the TR formation height of their cores. We ascertained the line core offsets of both lines by fitting PMJ Si\textsc{iv} line profiles with a Gaussian profile and using its centre as an estimate. The means of these measured line core offsets for the Si\textsc{iv} line pair with their standard errors and sample sizes are given in Table 5 for both datasets.

The sampling sizes for both dates and both lines are indicative of the number of profiles in each line for which a Gaussian profile could be fitted with a Gaussian \(\chi^2\) goodness-of-fit value (using the IDL “gaussfit” function) that proved suitable to select those profiles with large enough intensity enhancements and with profiles that are well-shaped enough to extract meaningful line core offsets. For peak-brightness times, these profiles were then verified by eye. These sample sizes therefore also present the number of profiles in each case that correspond to events with visible enhancement in the given Si\textsc{iv} line for the given date.

From Table 5 we see that the mean line core offsets for both dates and both lines are consistently of positive values, and they are close to zero. They have a maximum absolute value of \(\leq 3.20 \text{ km s}^{-1}\), taking standard errors into consideration. As such, we find that the line of sight velocity at the site of PMJ signals in the Si\textsc{iv} line pair at the shared approximate height of line core formation for the two lines is likely no more than a few \(\text{ km s}^{-1}\) and may be close to zero given our standard errors.

4.6.2. Si\textsc{iv} 1394 Å and 1403 Å line core intensity ratios and line morphology

Our Si\textsc{iv} line pair profiles exhibit single peaks and are clearly Gaussian in shape for those cases in which we observe any appreciable intensity enhancement. The line core intensity ratios of the Si\textsc{iv} 1394 Å and 1403 Å lines can be utilised to estimate whether the lines form under optically thick or thin conditions. We calculated the peak intensity ratios of the Si\textsc{iv} 1394 Å and 1403 Å lines, which are defined such that the ratio is given by \(R_{\text{core}} = \frac{I_{\text{line}}}{I_{\text{unit}}}\). Here, \(I_{\text{1394 \ Å}}\) and \(I_{\text{1403 \ Å}}\) are the instrument-count intensities at the position of the line core of the given line.

Under optically thin conditions, the line core intensity ratio for the line pair has a value of \(R_{\text{core}} = 2\), owing to the fact that the 1394 Å line has an oscillator strength that is twice that of the 1403 Å line. If the lines form under optically thin conditions, the 1394 Å should therefore also present twice the absolute intensity in the line core as that of the 1403 Å line. Nonetheless, line formation under optically thick conditions can also produce a line ratio of \(R_{\text{core}} = 2\), and thus this value does not guarantee optically thin formation, but a significantly lower value than this does thus preclude thin formation.

We find typical values for \(R_{\text{core}} \approx 2\). The average intensity line core ratio of the two lines is close to two for both datasets, as shown in Table 5. The range of line core intensity ratios over both dates is \((1.85 - 2.09)\), taking standard errors into account. We can thus conclude that the Si\textsc{iv} 1394 Å and 1403 Å line PMJ profiles may form under optically thin conditions.

4.7. A PMJ in the O\textsc{i} 1401 Å line

We report a single instance of a PMJ exhibiting a clear intensity enhancement in the O\textsc{i} 1401 Å line. This line is more commonly associated with flaring activity in the TR and has a formation temperature of around 140,000 K under equilibrium conditions. It is a diagnostic for lower density plasma than the Si\textsc{iv} lines and as such, it is remarkable that in at least one instance one of our PMJ events appears in this spectral line. The PMJ event in question is dubbed PMJ B21. This event is also our most pronounced PMJ event throughout all of our diagnostics, and it exhibits particularly strong intensity enhancements in most of our studied spectral lines, and especially in the Si\textsc{iv} line pair. It clearly stands out in Fig. 7, and we see a single O\textsc{i} 1401 Å profile that is clearly enhanced compared to those of other events but with a rather irregular shape.

We note that the absence of emission in the O\textsc{i} 1401 Å line for the remainder of our observed PMJs can be interpreted to be due to the fact that PMJs are mostly a phenomenon in the high density, deep solar atmosphere. The formation of the O\textsc{i} lines is affected by non-equilibrium ionisation (Olluri et al. 2013; Martínez-Sykora et al. 2016).

4.8. Concurrent PMJ darkenings in H\alpha and Ca\textsc{ii} 8542 Å and their connection to brightenings in Mg\textsc{ii}

We present observations of darkenings in the inner wings of the H\alpha line associated with PMJ brightenings as well as darkenings in the inner wings of the Ca\textsc{ii} 8542 Å line. Secondly, we present the spatial relationship between the darkenings in both of these lines and the PMJ brightening we observe in Mg\textsc{ii} SJ images.

4.8.1. PMJ darkenings in H\alpha and Ca\textsc{ii} 8542 Å

PMJs have mostly been studied in the Ca\textsc{ii} lines, and not so much in the H\alpha line. Recently, however, Buehler et al. (2019) reported on PMJs that present with darkenings in H\alpha images when studied by eye and are viewed in the inner line core, with accompanying H\alpha line profiles exhibiting subtle decreases in intensity in the inner line core at sites adjacent to PMJs that are
visible in concurrent Ca II 8542 Å line observations. We investigated the appearance of PMJs in H α and Ca II 8542 Å images together with their line profiles at selected locations. We confirm the appearance of dark features in the inner wings of the H α line associated with PMJs.

We also report the existence of dark features in the inner wings of the Ca II 8542 Å line that strongly correlate spatially and temporally with those in the inner line wing of the H α line. Utilising CRISP images at line core offsets of −400 mÅ and −350 mÅ in the H α and Ca II 8542 Å lines, respectively, we found elongated dark features that trace the direction of the surrounding penumbral fibril structures and that sit at the origin of PMJs, preceding and following PMJs in time. We selected sampling positions by eye, targeting dark features for the subset of PMJs for which we could positively identify them.

Figure 9 shows the temporal evolution of example PMJ A10. The PMJ is a very clear example of a PMJ that presents with typical brightening in the Ca II 8542 Å line at an offset of −350 mÅ but that also exhibits dark features in both the H α and Ca II 8542 Å inner line wings, which both have their approximate footpoints at the site where the PMJ bright feature appears.

In the composite images, bright red indicates the presence of dark Ca II 8542 Å −350 mÅ features and bright cyan indicates dark H α −400 mÅ features. Co-spatial dark features in the two channels appear white when they are combined in their respective composite images. The dark features both precede and follow the bright feature in the Ca II 8542 Å line by over 2 minutes. In the case of the dark feature visible in the Ca II 8542 Å line, it becomes rather obscured at peak enhancement of the Ca II 8542 Å bright-feature, and thus it is less identifiable at this time, which probably made identification less likely in earlier observations and studies.

PMJ A10 is a particularly clear example of the behaviour described above. However, we find numerous PMJs in both datasets for which the same trend of near-cospatial dark features in the inner line wings of the H α and Ca II 8542 Å lines, both of which seem to originate at the approximate point of the Ca II 8542 Å bright feature, holds true. Typically the dark features also precede and follow the bright feature in time in the other cases. An additional example of this type is included in Fig. A.1 for the PMJ B21.

We selected all PMJ events for which we could detect dark features in either or both of the inner line wings of the H α and Ca II 8542 Å lines and determined their spectral profiles in these lines at the time of maximum brightness for the typical bright feature that is visible in the Ca II 8542 Å line. For observations in the Ca II 8542 Å line, we selected a number of clear sampling positions and dark features of N_{dark} (Ca II, A) = 25 (=76%) and N_{dark} (Ca II, B) = 31 (=70%) for datasets A and B, respectively. For the H α line we found a number of equivalent dark features of N_{dark} (H α, A) = 29 (=88%) and N_{dark} (H α, B) = 36 (=82%) for datasets A and B, respectively. The percentages are all in relation to the total number of PMJs detected for each dataset. We see that a significant majority of PMJs in both lines exhibit these dark features; there are fewer of them for observations in Ca II 8542 Å. This is most likely both due to the Ca II 8542 Å PMJ bright features obscuring some of the Ca II 8542 Å dark features, as well as a general lower contrast in the Ca II 8542 Å observations compared to those in the H α line. Figure 10 shows all individual Ca II 8542 Å and H α PMJ profiles for these dark features, together with the PMJ mean profiles of these.
The average PMJ profiles in the Hα line for both dates confirm a slight decrease in intensity in the inner line wings of the studied PMJs, which is consistent with the profiles presented in Buehler et al. (2019). The average Ca\textsc{ii} 8542 Å line profiles for our selected dark features show less distinct behaviour, and they have mean profiles that are overall slightly enhanced compared to the penumbral mean profile, even though the CRISP images at an offset of ~350 mÅ clearly show features that are darker than their surroundings. The darkenings found in the images of the inner line wing of the Hα line appear very similar to those as presented in Buehler et al. (2019). The spectral formation process of the dark features in the inner line wings of both the Ca\textsc{ii} 8542 Å and Hα lines has yet to be explained and warrants further investigations, possibly in the form of modelling.

Given that PMJs may be caused by reconnection events and the subsequent heating that takes place in the low chromosphere or photosphere, one may expect to find enhancement in the outer wings of the Hα line as observed for Ellerman bombs (see for example Rutten et al. 2013). So far however, we have not found evidence of any such enhancement in the Hα profiles for PMJs. This can be seen in Fig. 10 for the sampling positions of the inner wing of the Hα line dark features. The lack of any consistent enhancement in the outer wings of Hα compared to the penumbral and full FOV line profile average may warrant further investigations in the future, especially in light of evidence for heating at chromospheric or photospheric heights, such as enhancement in the Mg\textsc{ii} triplet blend. We conclude that dark structures that precede and follow the nominally bright PMJ events in time exist in both the inner line wing of the Hα line as previously reported, but also in the inner line wing of the Ca\textsc{ii} 8542 Å line.

4.8.2. Dark PMJ features in Hα and Ca\textsc{ii} 8542 Å and PMJ brightenings in Mg\textsc{ii}

Figure 11 shows a selection of PMJs from dataset A that show clear dark features in the blue wing of the Ca\textsc{ii} 8542 Å line, the inner blue wing of the Hα line, and that exhibit clear brightenings in IRIS Mg\textsc{ii} SJI images, together with an amalgamation of RGB image that combines these three channels. The RGB image uses the intensity-inverted SST images for the Ca\textsc{ii} 8542 Å (red) and Hα (blue) channels. As such, darkenings yield brighter colours for these two channels. The concurrent darkenings in the two channels that overlap with brightenings in the Mg\textsc{ii} SJI images tend towards bright (white) values. The figure illustrates a clear trend in which the brightening in the chromospheric Mg\textsc{ii} SJI images overlaps with the darkenings in the Ca\textsc{ii} 8542 Å and Hα lines. We find that this trend is typical for both datasets of PMJs and may indicate that these darkenings map to the same chromospheric object as the brightening in the Mg\textsc{ii} channel. PMJs from dataset B that were selected following the same criteria as described above are shown in Fig. A.2.

4.9. Potential twisting of PMJs from Mg\textsc{ii} h & k

Tiwari et al. (2018) present evidence for the presence of twisting motions in large penumbral jets (LPJs) from an analysis of Mg\textsc{ii} k line profiles. Tiwari et al. (2016, 2018) describe LPJs as jets that are, on average, larger than PMJs and that are found predominantly on the edge of the penumbra. We do not make a distinction between LPJs and PMJs in our own work, and many of our PMJs would constitute LPJs under the working definition in Tiwari et al. (2016). Here we investigate the presence of twisting motions in our samples of PMJs.

Tiwari et al. (2018) used Mg\textsc{ii} k Dopplergrams to determine what degree the observed LPJs exhibit rotation. For an LPJ that rotates around a central axis and is intersected by an IRIS raster slit at an angle close to perpendicular, Mg\textsc{ii} k (or h) Dopplergrams should exhibit a blue shift on one side, a red shift on the opposite side of the LPJ, and little or no shifts at its centre. Conversely, for the case of an LPJ intersecting a raster slit while closely aligned along its length, one would expect the possibility of Dopplergrams in which only a red or a blue shift is visible. It must be noted that red or blue signals in Dopplergrams are not necessarily due to true Doppler shifts in the line profiles, and they may instead be caused by asymmetry in the intensity enhancement of the blue and red peaks.

Tiwari et al. (2018) found a significant number of LPJs that exhibited Doppler shifts going from blue to red (or vice versa) in the Mg\textsc{ii} k line along the length of the IRIS raster slit (11 total, 65% of all LPJs), and also a significant number that exhibited only red or blue shifts (6 total, 35% of all LPJs). All LPJs were observed to exhibit either twisting or a distinct blue or red shift.

We utilised both the Mg\textsc{ii} k and h line in our investigation. We generated Dopplergrams and bisectors for all of our detected PMJs in the two lines, not restricting ourselves to any specific angular alignment between our PMJs and the raster slit which caught the event. If twisting is present in PMJs, there should be the possibility of detection of at least one Doppler signal com-
dependent value. We found this necessary as a constant normalisation factor was unsuited to the wide variety of intensity values observed for different PMJs. Highly energetic PMJs with high intensities may exhibit deceptively visually striking blue or red signals in Dopplergrams when intensity differences are normalised by a constant factor that is also used for low-intensity events. We opted for a normalisation factor that is dependent on the average peak intensity of a given PMJ Mg II k or h line profile. For each PMJ event, we computed the mean intensity of the two peaks present in the given line and subtracted the mean far-wing intensity. We thus obtained an approximate measure of the total intensity range for both profiles for any given event, $I_{\text{peak range}}$. We then used the half value of this PMJ- and line-dependent value to normalise the Doppler-intensity differences along all other pixels along all raster slits for a given PMJ. Thus, our normalised intensity Doppler intensity for either Mg II line is defined as $I_{\text{doppler}} = (I_{-40} - I_{40}) / |I_{\text{peak range}}/2|$. Here, $I_{\text{doppler}}$ is the normalised Doppler-intensity difference, and $I_{-40}$ and $I_{40}$ are the intensities at $\pm 40 \text{ km s}^{-1}$ and $I_{\text{peak range}}$ is the scaling intensity described above. A value of one in the Doppler maps thus corresponds to a relative intensity difference as large as half the mean peak intensity enhancement of the event, and it indicates that the blue wing is more enhanced than the red one. A value of $-1$ indicates the reciprocal.

It is not always easy to visually identify the extent of the blue or red shift from Dopplergrams alone and whether reversals along raster slits in profile-types are significant or not. We therefore also calculated bisectors for the Mg II h and k lines. We calculated these for all PMJs along a seven-pixel line along a given IRIS raster slit, centred on our primary sampling position in the lines. The bisectors were computed by calculating the interpolated line-offset values in the given Mg II line at specific intensity values along both the red and blue slope of the red and blue peak, respectively, on each side of the central minimum. We then calculated the mean of the red and blue wing offsets at these intensities, yielding the values of the bisectors between the outer red and blue slope of the Mg II k & h profiles. We calculated the bisectors up to the intensity of whichever peak of the Mg II profiles was the smallest, and down to an intensity found at an offset of $100 \text{ km s}^{-1}$. This avoids bisectors trailing off horizontally as the spectral profiles trend towards the Mg II wings.

For Dopplergrams all scenarios of twisting should be visually identifiable by colour. When inspecting bisectors, one would expect the overall position of the bisectors to shift from red to blue offsets, or the reciprocal, along the IRIS slit in the case for twisting. In the case of solitary shifting of intensity towards the red or blue wings, we would expect the bisectors to exhibit a consistent shift near the actual Mg II sampling position and to be unchanged compared to their typical values for pixel positions that are further distant along the IRIS slit. We find that PMJs have a tendency to have an enhanced blue signal with mean values of $I_{\text{doppler}}$ for dataset A, Mg II h, $I_{\text{doppler, A}} = 0.13$, and for Mg II k, $I_{\text{doppler, A}} = 0.13$. For dataset B, Mg II h, $I_{\text{doppler, B}} = 0.16$, and for Mg II k, $I_{\text{doppler, B}} = 0.15$. This is also reflected visually with most bisector lines falling in the blue, but only at modest offsets of a few km s$^{-1}$. Notably, this stands in contrast to the line-core offsets given in Sect. 4.3 and Table 3, all of which lie in the red although with values $< 1 \text{ km s}^{-1}$. This behaviour is reflective of the dominance of the blue peaks in both the Mg II k & h lines, which in a great majority of cases are more intensive than their red counterparts. This skews both the Dopplergrams and the bisectors slightly towards the blue in most cases. We find only a few cases in which our

Fig. 11. PMJs drawn from dataset A for which dark features in the Ca II 8542 Å blue wing (first column) and the Hα inner blue wing (third column) overlap with brightening in the Mg II SJI channel (second column). Tick marks are spaced 1” apart. PMJs are shown at nominal peak brightness across channels, and each row corresponds to one PMJ with images across channels at the nearest possible timesteps for different instruments, with PMJ identifications indicated for each row on the right. An RGB image combines the channels (fourth row); the intensity inverted channels (bright to dark) of the Ca II 8542 Å blue wing (red), inner Hα blue wing (blue), and the Mg II SJI image (green) are shown.
PMJs exhibit behaviour that is clearly consistent with twisting in which we see a reversal of blue-to-red or vice versa along the IRIS slit direction. There are more occasions of an isolated and significant shift of intensity towards the Mg II line pair wings, but these are also not ubiquitous.

Figure 12 shows Mg II k & h line Dopplergrams produced as described above along all eight IRIS raster slits for the IRIS observation for events C0, A6, A8, and B43. Figure 13 shows profiles along the seven pixels centred on the Mg II sampling position for the same example PMJs. We show only profiles and bisectors for the Mg II k line. Bisectors in the Mg II h line are very similar to those in the other line due to very similar profile shapes, although the k line usually exhibits a greater signal and clearer bisectors.

As reference, in Fig. 12, we clearly observe event C0 to exhibit a transition from red to blue upwards along the IRIS slit, as first described in Tiwari et al. (2018). We see this in the Mg II k line, as first shown in Tiwari et al. (2018), as well as in the Mg II h line, first shown here. As a side effect of our event-dependent intensity normalisation, we also observe a less saturated signal in our Doppler maps for this event. Event C0’s bisectors shown in Fig. 13 also show a clear trend in their overall position and shapes, indicative of a twisting scenario. Here, we go from a bisector with little Doppler shift in either direction at $y = -3$, to progressively stronger red-shifted bisectors for $y = -2$ and $y = -1, to a slight decline in red shift at $y = 0$, and a strong reversal in the bisectors mean value at $y = 1$ towards the blue, with the bisector at $y = 2$ being shifted even more towards the blue, and the bisector at $y = 3$ again diminishing in overall Doppler signal.

Event A6 and A8 exhibit the visually clearest examples of Doppler-signal reversals in our Doppler maps in all our observations, and they are both shown in Fig. 12. The events are located at near-identical positions in the upper right of our observed sunspot, which is close to the outer penumbra, and both originate from the same dataset. Event A6 precedes A8 by only 183 s and as such, the events are most likely an example of the repeating behaviour often seen for PMJs and are strongly related. When observed in the inner blue wing of the Ca II 8542 Å line, both PJMs appear to be of a similar size, of the order of around 1.5″–3″, or approximately 1000–2000 km. This size is consistent with PMJ sizes, and it sits on the lower end of the LPJs presented in Tiwari et al. (2018). Both events intersect the IRIS raster slit at an approximately 45° angle. Both events exhibit a reversal from blue to red upwards along their IRIS slit, with A6 having a stronger signal than A8, and both exhibiting more marked intensity shifts in the wings in the Mg II k line than in the h line. Overall, both events exhibit much smaller differences in the shift of their Doppler-intensity difference than C0, as is evident from their appearance. We note that both events are also notable in that they also correspond to the PMJs that exhibit the strongest signal in the Mg II triplet positions, although whether the two behaviours are related is not clear nor investigated. The bisectors of the two events are also shown in Fig. 13, where A6 again shows a clearer transition of overall blue-shifted Mg II k bisectors that trend towards the red from $y = -3$ to $y = 3$, and A8 shows a much more modest transition, but follows the same trend.

Event B43 is our third-strongest source of evidence for twisting in PMJs. In the Doppler maps given in Fig. 12, the event shows little clear evidence for a reversal in intensity difference along the IRIS raster slit, only clearly showing a strong blue intensity difference at and around the PMJ sampling position. In Fig. 13, however, a clear shift towards the red in the bisector at $y = -3$ can be observed, shifting gradually towards blue-shifted bisectors. In this case, the Doppler map most likely fails to indicate this behaviour due to the overall narrowness of the profile, which therefore does not exhibit strong intensities at offsets ±40 km s⁻¹, and so it fails to depict the shift of intensity towards the wings. This serves to demonstrate the diagnostic value of bisectors in detecting such a signal given the variety of
Fig. 13. Spectral profiles and their bisectors in the Mg II k line for a selection of PMJs and an LPJ. Panels from left to right show spectral profiles and/or bisectors along the relevant IRIS raster slit at y-axis pixel positions from $y = -3$ to $y = 3$ (as labelled) with $y = 0$ being the Mg II h & k sampling position of the event. For each given y-pixel position, the top row shows for LPJ event C0 (see text for details) both the Mg II k spectral profile and its associated bisector (both black solid lines) together with the mean Mg II k profile over the entire field of view of event C0’s observations (black-dashed line). The second row displays only the Mg II k bisectors (black solid line) of the same event; panels for bisectors with mean values $>|\pm 1|\text{km s}^{-1}$ are marked with a blue (negative value) or a red circle (positive value). The panels below show the same plots only for selected PMJ events (as labelled on the left), with spectral profiles and bisectors shown together above rows only displaying bisectors. We note that for the PMJ events, the mean spectral profile (black-dashed line) in the plots is instead the mean PMJ profile of the relevant dataset from which the event is drawn.

Intensity ranges in the Mg II line pair. We detect only two additional events that may show evidence of a transition from blue-to-red or vice versa along the IRIS slit.

Furthermore, while there are cases of PMJs exhibiting significant intensity enhancement in the Mg II line pair profiles towards either the red or the blue, they are not ubiquitous. We summarise the number of PMJs that exhibit possible evidence for twisting and those for PMJs that exhibit only increased enhancement towards the red or blue in either of the lines in Table 6. We find that for the datasets combined that there are 6% or fewer of the PMJs that exhibit evidence of twisting, and 9% and 27% that exhibit a significant red or blue shift,
Table 6. Number of occurrences of twisting and presence of enhanced blue or red signal for PMJs in dataset A and B.

<table>
<thead>
<tr>
<th>Dataset(s)</th>
<th>Twisting [N]</th>
<th>Enhanced red [N]</th>
<th>Enhanced blue [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (N = 33)</td>
<td>2 (6%)</td>
<td>1 (3%)</td>
<td>8 (24%)</td>
</tr>
<tr>
<td>B (N = 44)</td>
<td>3 (7%)</td>
<td>6 (14%)</td>
<td>13 (30%)</td>
</tr>
<tr>
<td>A&amp;B (N = 77)</td>
<td>5 (6%)</td>
<td>7 (9%)</td>
<td>21 (27%)</td>
</tr>
</tbody>
</table>

respectively. Again, we see a bias in a more numerous occurrence of a blue-ward skew in the profiles.

While we are able to detect the profile shape variation in the Mg II line pair along the IRIS raster slit that would be indicative of twisting PMJs, given our discussed diagnostic methods and the few examples we do find, we conclude that there is only a small minority of events that in fact exhibit such behaviour. In the supplementary event-summary videos that depict all PMJs in dataset A and B through time, we include plots of bisectors for both the Mg II k and h line together with corresponding Dopplergrams for these lines.

We caution against a quantitative interpretation of our Dopplergram signals and bisector-shift values. The shifting of enhancement towards either the red or blue wings of the Mg II lines measured by these two diagnostics should not be interpreted as actual velocities. Instead they serve as useful indicators of when line profiles exhibit appreciable asymmetries towards the blue or red in the relevant line and away from the nominally undisturbed average Dopplerogram or bisector values. Such a shift in enhancement is consistent with what one would expect for mass velocities in the same direction, but specific values for Doppler velocities should not be inferred from our diagnostics.

4.10. On the time evolution of PMJs observed in multiple channels

We perform a qualitative study of the temporal behaviour of the spectral line samples that are available from our studied PMJs. The available cadence of the IRIS spectrograph line profiles we have obtained for select positions of our studied PMJs and which limits our investigation is \( \sim 40 \) s. Figure 14 highlights a selection of PMJs from dataset B, showing timeslices with wavelength along the \( \lambda \)-axis and time along the \( \lambda \)-axis for the Ca II 8542 Å line, the Mg II h & k lines, the C II 1334 Å and 1335 Å lines, and the Si IV 1394 Å and 1403 Å lines. For both datasets, we selected a subset of events with the criteria that they exhibit easily identifiable signals in both the chromospheric and TR spectral lines, and that they do so with clear peaks in intensity in their timeslices. We found the same general appearance and trends in both dataset A and B. For reference, the timeslices for dataset A are included in Fig. A.3.

In inspecting the timeslices of PMJ events, there does not seem to exist a clear trend of spectral signals preceding each other. In particular, we do not observe a temporal trend that correlates with what atmospheric temperature that the channels are usually associated with. This finding is congruent with a scenario in which PMJs light up across their entire length through multiple channels in a relatively short amount of time, rather than becoming apparent at different times in different channels during their lifetime.

Samanta et al. (2017) find that PMJs and TR bright dots spatially correlate and that bright dots precede PMJs in time. The authors suggest that bright dots may map to the site of magnetic reconnection at a TR temperature and manifest as PMJs further down in the atmosphere. In the study, half of identified bright dot events identified in IRIS SJI observations are identified to correlate with PMJs that are visible in SOT Ca II H line images and IRIS SJI 2796 observations, thus yielding a sample of 90 bright dot-PMJ linked events. In a large majority of these, the bright dot events precede the corresponding PMJ events by an average of 16.0 s and in some cases by up to a minute.

Samanta et al. (2017) propose a scenario in which bright dots are caused by reconnection events at TR temperatures, which in turn trigger PMJs at lower chromospheric heights. This would imply that our own PMJ signals in TR-sensitive spectral lines should precede PMJ signals in chromospheric spectral lines in at least some cases, and that the inverse should be true in fewer cases. In our own observations, we would expect to observe this effect despite the slow cadence of our IRIS spectrograph spectral line profile observations of \( \sim 40 \) s as we sample PMJs close to peak enhancements and since Samanta et al. (2017) report that bright dots usually precede PMJs of the order of 10 s to 1 min. As noted, we do not find a noticeable effect of this nature in our observations.

5. Discussion: PMJ origins and evolution

In Sect. 4.8 we show that PMJs are associated with dark features, not only in the inner line wing of the H \( \alpha \) line as first shown in Buehler et al. (2019), but also in the inner line wing of the Ca II 8542 Å line. We also found that the “true” PMJ comprised of the bright jet-like feature in the Ca II 8542 Å line may, to varying degrees, obscure its accompanying dark feature in the line at peak brightness and through its evolution, the jet-like structure can be seen to extend along the direction of the dark feature. The dark features in both lines are well-aligned with the underlying and surrounding fibril structure, and they align to a large degree with the chromospheric brightenings associated with PMJs in Mg II IRIS SJI images. The dark features in both lines are also typically present both before and after the main brightening event of the order of seconds to minutes. From this behaviour, it is reasonable to assume that the PMJ brightenings in fact develop along a pre-existing fibril structure. As such, this would be congruous with a scenario in which PMJs evolve out of a fibril that undergoes heating due to a reconnection event and lights up along its length as a heating front passes through and along the fibril with little mass motion actually taking place.

This scenario is also supported by a qualitative summary of the analysis of the spectral diagnostics, as laid out in Sects. 4.2 through 4.6 in which PMJ responses in the Ca II 8542 Å, Mg II h & k lines and the C II and Si IV line pairs are investigated. Here, we have found that the values of Doppler offsets and signals are modest or close to zero. In fact, taken as a whole, both inferred Doppler-LOS velocities and velocity gradients associated with all studied atmospheric temperatures are modest, and they are much lower than earlier reported apparent PMJ velocities in the literature. This suggests that PMJs do not undergo significant mass motions. The measured Doppler offsets for all spectral lines are confounded by the background emission of the chromosphere and TR that surrounds our PMJs. This means that Doppler offsets cannot be interpreted as perfectly analogous to mass flow velocities. However, if PMJs exhibited significant flow velocities, these should still be discernible in our Doppler diagnostcs.
IRIS raster cadence of ~40 s for the different spectral line sampling positions. This implies that PMJs brighten across all atmospheric temperatures at which they appear concurrently, rather than moving from lower to higher temperatures, for example. As noted in Sect. 4.10, however, the limiting IRIS raster cadence does not permit us to conclude that there is no discrepancy in onset times on timescales smaller than ~40 s. Nonetheless, we can rule out a systematic discrepancy in PMJ onset times through the different atmospheric channels that points to earlier onset times in channels associated with either low (chromospheric) or high (TR) temperatures of the order of our cadence. Through the use of inversions with the STIC code (de la Cruz Rodríguez et al. 2016, 2018) and other analyses of PMJ observations made using the CRISP and CHROMIS instruments at the SST, Esteban Pozuelo et al. (2019) found that PMJs most likely exhibit only small mass motions. In De Pontieu et al. (2017), advanced MHD simulations are used to explain the high apparent velocities observed for spicules in chromospheric and TR channels. Here, these high apparent velocities are explained by a heating front that moves along the spicule structure and produces a fast apparent brightening, which is not due to high velocity mass motions. Esteban Pozuelo et al. (2019) posit that such a process may also provide a plausible explanation for the formation of PMJs. The authors argue that PMJs may be explained by a propagation of perturbation fronts that originate in the deep photosphere and then dissipate energy within the PMJ. This was supported by findings that place temperature increases in the low chromosphere and with inversions showing that PMJs heat up with increasing height.

The results of Esteban Pozuelo et al. (2019) and our present investigation also fit with the recent results in Roupee van der Voort & Drews (2019), where fast cadence (~1 s) Ca II H line observations revealed only modest mass motions for PMJs, but where it was found that PMJs nonetheless light up along their lengths over very short timescales along faint but pre-existing fibrils. The discussion in Roupee van der Voort & Drews (2019) also goes into detail in support of the heating-front PMJ scenario first described in Esteban Pozuelo et al. (2019), and we would like to direct the reader here. Both of these studies and the fact that they do not find true mass motions are congruent with our present results discussed above, as well as our findings that we see emission for some PMJs in the wings of the Mg II triplet blend, indicating heating at upper photospheric heights for at least a subset of PMJs. The latter provides further evidence for a magnetic reconnection event taking place in the deeper atmosphere.

The totality of the results presented here and given the findings discussed above can be interpreted to imply that PMJs are manifestations of heating events most likely originating due to heating events at photospheric to lower chromospheric heights and that propagate upwards as a heating front, with only modest accompanying mass motions. This heating front reaches TR temperatures as evidenced by Si IV line pair emission and a single instance of emission in the O IV 1401 Å line.

As in Roupee van der Voort & Drews (2019) and Esteban Pozuelo et al. (2019), these conclusions stand in contrast to earlier results in the literature that have observed PMJs to exhibit apparent velocities reaching the order of 100's of km s⁻¹. As remarked in greater detail in Roupee van der Voort & Drews (2019), it is possible that these higher apparent velocity measurements are due to a lack of temporal resolution in the relevant observations. The fast phase of brightening that takes place over the entirety of the PMJs observed in Roupee van der Voort & Drews (2019) can, if observed with slow cadence observations,
be mistaken for a fast apparent motion, rather than a fast brightening with no clear directionality.

6. Conclusions and summary

6.1. Summary of diagnostics

6.1.1. PMJs at different heights in the solar atmosphere

The different spectral diagnostics that we have used to study PMJs are sensitive to different broad regions in the solar atmosphere. In rough order of atmospheric height, from the photosphere and upwards, we can infer the following:

- Emission in the Mg II triplet wings provides evidence for heating at photospheric heights for a subset of PMJs.
- Mg II h & k average peak Doppler shifts yield estimates for the line of sight velocity in the lower chromosphere that are close to zero.
- Mg II h & k peak separations are measured to be of the order of 30 km s\(^{-1}\). The interpretation of this enhanced separation as a difference in line of sight velocity between the mid- and upper chromosphere has a high uncertainty. It is more likely a result of enhanced heating in the lower chromosphere.
- C II widths yield estimates for the non-thermal line widths and thus upper limits for the non-thermal velocity in the upper chromosphere or just below the TR of \(\approx(30,51)\) km s\(^{-1}\).
- Mg II h & k line core offset values yield estimates for the line of sight velocity in the upper cromosphere, with values close to zero.
- C II line-pair line core offset values yield estimates for the line of sight velocities in the upper chromosphere or TR heights, with absolute values \(\leq7\) km s\(^{-1}\), ranging slightly below and above zero.
- C II line-pair ratio values imply optically thick line formation in the upper chromosphere for these lines.
- The typical number of (double) peaks in the C II line pair implies a peak in the source function of the lines below the upper chromosphere or TR for the majority of PMJs that show an appreciable signal in these lines.
- Values for the Si IV line-pair line core offsets yield estimates for the line of sight velocity at the TR, with modest values of absolute values \(\leq3.2\) km s\(^{-1}\).
- The ratio of the Si IV line pair peak intensity ratios imply optically thin line formation in the TR for these lines.
- One example of emission in the O IV 1401 Å line implies heating to TR or flare conditions in one instance.

6.1.2. PMJ dark features in the H\(\alpha\) and Ca II 8542 Å lines

PMJs exhibit dark features in the inner wings of the H\(\alpha\) line, which was first shown in Buehler et al. (2019). We confirmed these H\(\alpha\) line dark features, and further found that PMJs also exhibit dark features in the inner wing line of the Ca II 8542 Å line, with a large degree of spatial overlap at the wave-lengths. In both channels, the elongated dark features are aligned with the direction of the typical PMJ brightening in the inner line core of the Ca II 8542 Å line, originating at the head of the jet-like PMJ event.

At peak brightness, the Ca II 8542 Å bright feature may obscure the dark feature to some degree. The dark features are observable on timescale of minutes before and after the bright PMJ event itself, and they are aligned with the fibril structure of the sunspot.

This provides evidence for the scenario in which PMJs are heating events that follow the already existing fibril structure. We also find that the PMJ darkenings in the inner wings of the H\(\alpha\) and Ca II 8542 Å lines are spatially well-aligned with the typical PMJ brightenings in the IRIS Mg II SJ1 channel, indicating that these darkenings are chromospheric events.

6.1.3. Twisting motions of PMJs

By using Mg II h & k PMJ spectral profiles along the length of IRIS raster-slit positions, we produced Dopplergrams and bisector plots in order to investigate potential twisting motions in PMJs. We only found a few events that exhibited a reversal of blue-to-red or red-to-blue enhancement in PMJ Mg II h & k line profiles along IRIS raster slits, which is indicative of twisting motions. Only 5 (6%) out of the total 77 studied PMJs exhibited Dopplergram or bisector features that are clearly congruent with twisting motions. We found a further 7 (9%) and 21 (27%) PMJs that exhibited only red or blue enhancement, respectively, in the Mg II h & k lines. We conclude that twisting motions in the PMJs in our datasets are rare and that they are not a universal property requisite for their formation at the scales we observe.

6.1.4. Temporal evolution of PMJs

The temporal evolution of PMJ brightenings when studied across different spectral lines reveals that their onsets do not differ significantly on the timescale of our IRIS raster cadence of \(\approx40\) s. As such, we do not observe that PMJs present at a particular temperature or atmospheric layer corresponding to a specific wavelength before others. If PMJs consist of true mass motions, one would expect discrepancies between onset times between different channels. The limiting cadence of \(\approx40\) s for the IRIS raster channel is less than the upper limit of the time range of 10 s to 1 min differences in onset times between bright dots and associated PMJs reported in Samanta et al. (2017).

6.2. Qualitative summary

The clear takeaway from this work is that PMJs extend through atmospheric layers from the photosphere to the TR and that they are characterised by low Doppler velocities and velocity gradients throughout all atmospheric layers. Further, PMJs are associated with chromospheric dark features in the inner wings of both the H\(\alpha\) and Ca II 8542 Å lines and PMJs develop along the direction of these dark features that are present before and after the PMJ brightening in the inner Ca II 8542 Å wing. The dark features align well with the surrounding fibril structure, which may suggest that PMJs develop along pre-existing fibrils. We find only very few PMJs that exhibit clear indications of twisting. We find evidence of low atmosphere heating in a small number of PMJs due to emission in the wings of the Mg II triplet, indicating that some PMJs may result from heating at photospheric heights. The temporal evolution of PMJs through all studied channels indicates no preference for first-onsets in any one channel on the time scale of the \(\approx40\) s IRIS raster cadence.

We find these results to be consistent with the scenario put forth in Esteban Pozuelo et al. (2019) and Rouppe van der Voort & Drews (2019) that PMJs are the result of a magnetic reconnection heating event at photospheric or low chromospheric heights that propagate heat upwards in the atmosphere through a heating front that travels along a pre-existing fibril. Furthermore, the heating front then causes a brightening along the fibril at
Alfvenic speeds with the PMJ exhibiting only low mass motions. A natural next step in elucidating the nature of PMJs would be MHD modelling of PMJs and the production of synthetic spectral profiles constrained by the now extensive spectral diagnostic values and PMJ properties found here, combined with the previous constraints provided by the literature.

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Appendix A: Supplementary figures

**Fig. A.1.** PMJ B21 and its associated Ca II 8542 Å and Hα line dark features. The layout is identical to that of Fig. 9.

Here we provide supplementary figures showing more examples of specific PMJ behaviours as described in the preceding text.

Figure A.1 shows the Ca II 8542 Å and Hα line dark feature evolution of PMJ B21, analogous to what is shown in Fig. 9.

Figure A.2 shows example PMJs from dataset B with apparent Ca II 8542 Å and Hα line dark features that overlap with Mg II SJI channel bright features, analogous to those shown in Fig. 11.

Figure A.3 shows timeslices for PMJs in dataset B for which intensity brightenings are apparent for most spectral lines, analogous to those shown in Fig. 14.
Fig. A.3. Spectral timeslices for a selection of PMJ events from dataset A that display clearly visible signals. The layout is identical to that of 14.

Appendix B: Information on online supplementary videos

The videos showing all PMJs at only peak brightness for dataset A and B are available in Video 1 and Video 2, respectively.

The videos detailing the temporal evolution of PMJs in dataset A and B are available in Video 3 and Video 4, respectively.

Various plots are provided in the videos; all studied spectral lines (except the Hα line), time- and space-slices in these lines, bisector plots, Mg II h & k Dopplergrams, RGB images of the given PMJs that are marked with spectral profile sampling positions, and Ca II 8542 Å blue inner line wing images of the PMJs.

Videos 1 and 2 show each PMJ for only the peak brightness time frame. Videos 3 and 4 show the temporal evolution of all PMJs in each dataset; each PMJ is shown for 11 time frames, corresponding to five IRIS SJI time indexes before and after the nominal peak brightness time index, as well as the peak brightness time index of the given PMJ itself. This corresponds to showing the diagnostics corresponding to approximately 3 min 36 s for each PMJ. PMJs that appear close to the start and end times of our observation times were truncated in time accordingly.

In Fig. B.1 we show a frame drawn from the video for dataset A. It shows plots and images for the time of peak brightness for PMJ A10. The caption gives details for all plots, and the layout is valid for both the peak-brightness-only videos (1 & 2) and for all time frames in both PMJ temporal evolution videos (3 & 4) for both datasets A and B.
Fig. B.1. Peak-intensity time frame for PMJ A10 from the temporal evolution video for individual PMJs in dataset A. The layout is identical for datasets A and B. The spectral line profiles are shown on the left-hand side; panels from left to right and top to bottom show profiles for the Ca II 8542 Å line, the Mg II k and h lines, the Mg II triplet, the C II 1334 Å and 1335 Å lines, and the Si IV 1394 Å and 1403 Å lines (the latter has O IV 1401 Å indicated). The different line styles denote the following: black solid line, the PMJ line profile at the sampling position; blue and red profiles were sampled at positive and negative vertical offsets from the main sampling position, respectively, with a different line style for each one-pixel difference: solid lines (one-pixel offset); dotted lines (two-pixel offset); dashed line (three-pixel offset); black-dashed line, the average PMJ line profile for the dataset; green-dotted line, the average line profile across all pixels in the observations; and green-dash-dotted line, the average penumbral line profile. Positions of line cores (vertical solid green lines), red peaks (vertical solid red lines), or blue peaks (vertical solid blue lines) are marked for those spectral lines where applicable. Shown to the immediate right of the spectral profiles are space-slices (top) and time-slices (bottom) of the studied spectral lines; each panel is marked accordingly. Horizontal lines mark the sampled y-position for the space-slice panels and the sampling time for the time-slice panels. Given to the right of the space-slices are Dopplergrams in the Mg II k & h lines, each panel is marked accordingly, with vertical and horizontal lines surrounding the Mg II PMJ sampling position and the three pixels below and above it. To the right of the Dopplergrams are individual Mg II k & h spectral profiles for seven pixels along the PMJ IRIS raster slit, with the corresponding bisectors for each spectral line, which are given to the right for both lines. Bisectors that have mean values > ±1 km/s are marked with a blue (negative value) or red circle (positive value). To the right of the timeslices we give the current RGB image centered on the PMJ; the sampling positions for each spectral line is indicated with symbols as given in the spectral line panels. Vertical dashed lines indicate the IRIS raster slit positions. An insert in the upper left shows the same FOV and sampling positions, but in the inner blue wing of the SST Ca II 8542 Å line. Above the RGB image, the PMJ identification and the current sampling IRIS slitjaw image index as well as the absolute observation time in seconds are given.