On the Identification of Small-Scaled Heating Events in MHD Simulations of the Solar Corona

by

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“It is nice to know that the computer understands the problem, but I would like to understand it too.”

E.P Winger
Before you lies the Ph.D thesis “On the Identification of Small-Scaled Heating Events in MHD Simulations of the Solar Corona”. It has been written for the degree of Doctor of Philosophy at the University of Oslo. The research described herein was conducted under the supervision of the Associate Professor Dr. Boris Vilhelm Gudiksen in the Institute of Theoretical Astrophysics, Faculty of Mathematics and Natural Sciences, between October 2014 and October 2018. The research was supported by the Research Council of Norway through its Centres of Excellence scheme.

The work presented here came about after special interest on the particular subject. The study of the heating mechanisms in the outer part of the solar atmosphere, the corona, has always been an attractive topic of research to me. The last four years, I only focused on one specific heating mechanism, the small-scaled impulsive heating events occurring endlessly in the corona. Those events are related with highly distorted magnetic field structures, and magnetic reconnection.

The purpose of this work is to study the contribution of small-scale events in heating the solar corona, and contribute to the knowledge by deriving my own conclusions and comparing those with the literature. I achieved that by employing numerical simulations and existing post-processing tools for data analysis. The former helped me to generate realistic data of the solar atmosphere, and the latter to probe data in three dimensions and identify heating events.

This work, however, came to life after personal struggling amidst doubts, gaps in knowledge and code crushing. Despite the struggling, I enjoyed every bit of information I acquired.

This thesis is divided into three parts. In part I, the Background, I provided all the necessary background information so as to understand part II, i.e., My work. In part II, I described my work including details about my motivation to carry out the specific research, the results in my publications, and future opportunities. In part III, I included my publications.

Charalambos Kanella

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Working on this topic was a challenging but worthwhile adventure. Challenging because I had to deal with problems that had not singular or explicit solutions and I had to be innovative and thoughtful. Worthwhile because after each challenge, I gained experience and I felt stronger and wiser. For this, I would like to pay my gratitude to the persons who helped me the most, and stood by my side throughout the whole duration of this experience.

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Part I

Background
Common intuition suggests that temperature should drop for increasing distance from the source of heat. However, the outer part of the solar atmosphere is significantly hotter than the solar surface. This phenomenon is named the “coronal heating problem”, which remains unsolved after almost eight decades. That is because the complex structure of the solar atmosphere cannot give a straight-forward answer to the exact nature of the heating mechanism.

The very large mechanical energy generated by flows in the photosphere and the convective zone carry more than enough energy to heat the corona. The “coronal heating problem” therefore can be reduced into two problems: an energy transport problem and an energy dissipation problem.

All these years, the scientific community has formulated wealth of models that could explain the heating mechanism(s) taking place in the corona. It is now conventional to attribute the heating mechanism to be related to the magnetic field. We learned however that mechanisms that are unrelated to the magnetic field are not working. For example, energy transport via mass convection from the photosphere to the corona, or sound waves have been proven insignificant to the heating requirements. The latter does not work because that type of waves dissipates or reflects before reaching the corona (Carlsson & Stein, 2002; Carlsson et al., 2007). In addition, mechanisms related to the magnetic field have also proven not applicable. For instance, although small velocity amplitude magnetohydrodynamic (MHD) waves can reach the corona, they do not carry enough energy (Hara & Ichimoto, 1999). Only Alfvén waves can travel towards the corona and carry enough energy, however their dissipation is not easy because special conditions must apply (van Ballegooijen et al., 2011; Asgari-Targhi & van Ballegooijen, 2012).

The solar magnetic field establishes a link between the photosphere and the corona that enables the mechanical energy to be transported via Poynting flux (Klimchuk, 2006; Hansteen et al., 2015). That energy is then stored in the magnetic field in the form of currents, which express the distortion of the magnetic field. The inclination between currents and magnetic field is a key-factor on the work spent. If currents and magnetic field are in parallel, then no work is spent because the Lorentz force is zero, and energy is stored without energy dissipation. In case however, there is an inclination between the two, then work is done and currents dissipate.
in the presence of resistivity, releasing a part of the stored energy (Low, 1990). Most interestingly, when currents become perpendicular with respect to magnetic field, then the magnetic field topology changes drastically by magnetic reconnection, releasing large amounts of energy (Parker, 1972).

Magnetic reconnection is manifested in observations as flares. Depending on the energy output of flares, they rank from large flares \(10^{32}\) erg down to the postulated nanoflares \(10^{24}\) erg. Nanoflares are of special interest because, according to Parker (1972, 1988), if numerous such events occur at every instant, they could heat the corona. Unfortunately, due to current state of the instrumentation employed to observe flaring events, it is still impossible to observe nanoflares.

Statistics however could shed some light on the importance of nanoflares as a heating mechanism in the solar corona. Observations of flares show that the frequency of energy release from such events is distributed as a power-law function, \(N(E) \propto E^{\alpha_E}\), where \(\alpha_E\) is the power index, and \(N(E)\) the number of flaring events with energy ranging between \(E\) and \(E + \delta E\). According to calculations made by Hudson (1991), if the energy power index is larger than two, then nanoflares are energetically more important than larger flares, and thus the unobserved nanoflares could be the ones heating the corona. However, locating the energy power index in flare observations is still a matter of debate because results do not agree. According to Hannah et al. (2011), the reason that different studies derive a large range of power-indices is a product of the method used to extract results and the different instrumentations used in different periods during the solar cycle. This is because, observational and instrumental biases create uncertainties in the estimation of flare parameters. In addition, technical aspects of the technique used to find the power-law index and the fitting method of the power-law curve also play a significant role.

The most important goal of this work is to locate and follow the evolution of three-dimensional heating events linked to magnetic reconnection so as to check their contribution to the heating of the corona. We do that in a controlled experiment that allows us to avoid the major observational challenges. For this task, realistic numerical simulations of the solar atmosphere are extremely useful. However, our task would be incomplete if not having a solid method of identifying the heating events. To achieve that, we employ a relatively new method popular in bio-informatics and medical imaging that is used for multi-dimensional image analysis.

Having the opportunity to identify such heating events, empower us not only to check directly the contribution of small-scale heating events in the corona (e.g., identify energy power-index), but also to study them in detail. More precisely, we can identify the volume they occupy, their duration, and find any potential relation between the quantities. This could be very useful for observers since they could derive conclusions about one quantity by observing another. In addition, we can now identify an even lower energy
cut-off that an event release compared to observations. Another objective of this work is to understand where heating events occur with respect to the magnetic field. In addition, knowing the volume of the events, we can check how they manifest in three-dimensions.

The ability of locating heating events in a numerical simulation, extracting evolution, temperatures, pressures etc, we can form a better view of how heating events manifest themselves in observations and also to understand the reasons we cannot observe small-scale events in the real case. To achieve that, we use the parameters (e.g., temperature and electron density) calculated in the simulation, and synthesise observations in regions exhibiting heating events and in regions considering the whole corona, and then compare the two regions.

Part I contains all the necessary background information to understand the work contacted here and it is organised in the following way: In Chapter 1, we describe the complex structure of the solar interior and atmosphere emphasising on the magnetic field. In Chapter 2, we explain what the “coronal heating problem” is, discuss about cooling processes in the corona and talk about the two major categories of candidate mechanisms for heating the region. In Chapter 3, we elaborate on the heating mechanism we study in this work. Finally, in Chapter 4 we describe the solar atmospheric model and how we simulate it.
A Brief Description of The Sun

The purpose of this chapter is to render briefly the complex structure of the Sun giving emphasis on the magnetic field structure. As we will see in the succeeding chapters, the magnetic field plays a central role in this study because it is the cornerstone in the process that heats the outer part of the solar atmosphere, the corona.

1.1 The structure of the Sun

The Sun has a complex interior and an atmospheric structure with many layers. The interior of the Sun, as shown in Fig. 1.1, consists of the core, the radiative zone, the tachocline, and the convective zone. Illustrated in Fig. 1.2, the solar atmosphere is composed of the photosphere, the chromosphere, the transition region, and the corona. Although we describe each layer separately, the interior and the atmosphere are dynamical systems, in which each layer interacts with the surrounding layers. Hence, no quantity or boundary presented in this section are temporal or spatial constants. But for simplicity, we use the approximated values derived from models.

The interior

The core is the energy factory of the Sun that generates energy via nuclear fusion, and occupies a quarter of the solar radius (García et al., 2007). The averaged temperature in the core is as high as 15 MK, and the averaged density is $150 \, \text{g/cm}^3$ (Basu et al., 2009).

The energy generated in the core is transferred via radiation. Photons travel within an opaque medium from the core up to 70% of the solar radius; this region is the radiative zone. Temperature at the bottom of the region is 7 MK and drops to 2 MK with distance. Likewise, mass density at the bottom of the region is around 20 g/cm$^3$, and decreases a factor of
100 at the region’s top. Due to the large mass density, a photon travels only short distances. Since density (pressure) and temperature drop with height, at some point energy cannot be transported via radiation any further and convection instability occurs. At this point, energy transport through convection takes action. It is the region where the *convective zone* begins.

The process of energy transport in the convective zone is similar to a pot of hot water before boils. Like a stove heating the bottom of a pot, so does the radiative zone. Like the rising of patterns of upwelling hot water, which rise to heights where temperature is low, and they cool down, so do hot pockets of plasma, which form thermal cells of rising hot and sinking cold material. The cooling process of thermal pockets of gas happens due to radiation at the solar surface, during which the volume of the pockets decreases, increasing their density, and then falling back to the solar interior. An apparent feature of the process is the formation of granules at the solar surface. The whole process is nicely illustrated by Wedemeyer-Böhm et al. (2009) in Fig. 1.2 in the region below $\tau_{500} = 1$.

The *tachocline* (Spiegel & Zahn, 1992) is a thin interface (i.e., 0.04 solar radius) between the radiative and convective zone. The region exhibits large shear because the radiative zone rotates like a solid body, while the convective zone has a combination of flows: the up-down radial motions of thermal cells, and the differential rotation (horizontal motions) of an equator that reformulates faster than the poles. Some solar dynamo models show that the tachocline plays an important role on intensifying the magnetic field by twisting the poloidal field and creating thus a toroidal field (Tobias, 2002).

**The atmosphere**

The first layer of the solar atmosphere, and the visual surface of the Sun is the *photosphere*. It has thickness around 500 km, and particle density that is $10^{17}$ cm$^{-3}$ (i.e., mass density $2 \times 10^{-7}$ g/cm$^3$). The region radiates like a black body at effective temperature around 6000 K. Temperature decreases with height as density does, reaching a minimum value of 4000 K at which simple molecules can be formed. The region is almost fully neutral having only 3% ionized hydrogen (Rast et al., 1993).

The layer atop the photosphere is the *chromosphere*. It is a 2000 km thick layer, in which temperature decreases to 4000 K for short distance, but then increases with distance reaching values as high as 35000 K. Mass density drops from $2 \times 10^{-7}$ g/cm$^3$ to $1.6 \times 10^{-14}$ g/cm$^3$ with distance (Kontar et al., 2008). In this region, helium is partially ionized, and spectra is governed by emission lines. The chromosphere is considered as a dynamic and intermittent layer, in which wealth of phenomena occurs. As summarized in Fig. 1.2, examples of phenomena are spicules, current sheets, fibrils, propagating magnetohydrodynamic (MHD), and shock waves (Fontenla
1.1. The structure of the Sun

Between the chromosphere and the corona there lays a thin interface (200 km), the **transition region**. Temperature in this region increases rapidly reaching a value around 1MK. The very steep temperature gradient owning to the fact that after helium has been fully ionized due to small rise in temperature, Lyman continuum cannot radiate effectively and remove energy as in the chromosphere, thus the temperature increases.

Figure 1.2 summarizes the solar atmosphere, and the processes therein. Yet, the illustration contains enough information about the coupling between different atmospheric domains. The different processes in different domains ensures the intermixing of the regions and amplification of the complexity of the atmospheric structure.

The corona

The outer layer of the solar atmosphere is the **corona**. It starts, roughly, at 3 Mm above the photosphere and has a temperature of roughly 1 MK temperature and particle density that is equal to $10^8 \text{ cm}^{-3}$ (mass density $10^{-16} - 10^{-14} \text{ g/cm}^3$) for the quiet Sun. To better describe the region, we
Chapter 1. A Brief Description of The Sun

Figure 1.2: The Quiet Sun Atmosphere By Wedemeyer-Böhm et al. (2009). Solid lines depict the magnetic field lines of a magnetic network. The same lines are also used to illustrate canopies atop the internetwork regions that also divide the atmosphere into a canopy, and a sub-canopy domain. The cartoon also illustrates magnetic networks forming in between supergranulation flows. Thin dashed lines represent field lines anchored to the footpoints of the internetwork. Smaller scales of flows in the convective zone create granulation apparent in the surface (z=0 Km). From the granular regions, a weak field extends forming the low-lying magnetic carpet in shapes of small loops (point B). Red areas, lower in the atmosphere, represent the reversed granulation pattern in the middle photosphere. Magnetic field also extends higher in the atmosphere having a rather complex behaviour since it is subjected to gas flows. Points D-F show special cases of wave-canopy interactions. Alfvén waves, shock waves, current sheets, spicules, fibrils are included in the illustration. Note that distances in the sketch are not scaled.

divide it into three domains that depends on the magnetic field activity, i.e., active regions, coronal holes, and quiet Sun.

**Active regions:** Strong magnetic field concentrations form active regions in the corona. When observed in the optical spectrum or magnetograms, active regions consist of groups of sunspots in the photosphere. Sunspots appear in groups of two with a leading polarity followed by an opposite polarity, however other configurations are not prohibited. Grouping of sunspots suggests that the magnetic field in sunspots consists of closed field lines. Dynamical processes take place in active regions due to magnetic flux emergence, magnetic reconnection, and magnetic flux cancellation. Examples of such processes in the corona are flares, coronal mass ejections, cusp-shaped loops, filaments, and sigmoid structures. Particle acceleration is another process happening during magnetic reconnection and it is speculated
to causes chromospheric plasma evaporation (Testa et al., 2014). The hot evaporated chromospheric plasma is traveling upwards and fill the corona forming coronal loop structures that have hotter and denser plasma than the ambient corona; those are the post-flare loops observed in soft X-rays and extreme ultraviolet (EUV) wavelengths.

**Coronal holes**: Concentration of magnetic field lines that extend into the interplanetary medium form coronal holes. Those regions are responsible for flushing plasma out of the corona in the form of solar wind.

**Quiet Sun**: The remaining region that does not include active regions and coronal holes is called the quiet Sun. This terminology suggests wrongly that dynamical processes does not happen in this region. A more sufficient definition of this regions is that quiet Sun is closed magnetic field regions excluding active regions and coronal holes.

### 1.2 Magnetic field in different domains

With the aid of the sketch in Fig. 1.2, drawn by Wedemeyer-Böhm et al. (2009), we describe the magnetic field in the solar atmosphere.

**Magnetic field in the photosphere**

The magnetic field in the photosphere is subjected to the hydrodynamic flows of the gas because magnetic pressure forces are for the most part lower than gas pressure forces. For this reason, convective flows in the granule interiors push the magnetic field horizontally towards granule’s exteriors (Galloway & Weiss, 1981) and thus, there is field concentration in the intergranular with field strengths of the order of a few kilo-Gauss. On the other hand, the magnetic field in the granular interior is weak with values of the order of a few hundreds of Gauss (Steiner et al., 2008). Note that solar sunspots have not magnetic field stronger than approximately 3 kG.

The magnetic field at the granule’s exterior extends above the granulation and has a scale height proportional to the granular size.

**Magnetic field in the chromosphere and corona**

When large-scale convective flows rise in the solar surface, then supergranules can be formed. In such case, magnetic field scale-height also increases, and thus magnetic field spreads higher than the magnetic “carpet” (small scale canopies or loops). When supergranules expel magnetic field towards their boundaries, magnetic network patches are formed. High resolution
observations reveal that these network patches are groups of magnetic flux bundles of different strength (Orozco Suárez et al., 2007).

Magnetic field above magnetic network patches extends high in the atmosphere and, according to Schrijver & Title (2003), it could account for as much as half of the total magnetic flux. There are two magnetic field configurations that form depending on the polarity of the magnetic field. On the one hand, when neighbouring field polarity of opposite polarity meet, then magnetic reconnection occurs and magnetic field reforms dynamically. On the other hand, in case of similar polarity, then magnetic field forms flux funnels extending high in the atmosphere that can reach the corona. In the solar atmosphere, there is a virtual surface where the speed of sound is equal to the Alfvén speed. This surface is equivalent to the surface where the plasma parameter $\beta$ is $\beta = 1$. In this region, shock waves are generated and affect the shape of the small-scale magnetic field (Wedemeyer et al., 2004). The surface forms a boundary at which wave-modes convert or refract (Rosenthal et al., 2002). Hence, that surface also divides the atmosphere into two regions that have different dynamical behaviors. The transport of information above that surface is fast but the field is so strong that not much happens, whereas in the area below the surface the timescale is only few minutes set by the granulation.

In general, magnetic field magnitude drops with distance. A rough approximation that is not necessary the rule is that the horizontal component of the magnetic field in the chromosphere is stronger than the vertical one, whereas magnetic field in the corona is mainly vertical. Magnetic field higher in the the atmosphere expands and becomes space filling because magnetic pressure forces are much larger than gas pressure forces.
Coronal Heating

In the current chapter, we describe the problem we cope with in this study, videlicet “the solar corona heating problem”. Then, we describe the cooling processes in the corona, next we point out the source of energy, the medium responsible for transferring the energy into the region, and the candidate mechanisms responsible for releasing the energy and heating the corona.

2.1 Solar corona heating problem

In Chapter 1, we have described the profiles of temperature and mass density of the solar atmosphere in the quiet Sun. We have also seen that the solar corona has very high temperature and very low density with respect to regions at smaller heights. Our experience and intuition suggest that when stepping back from a heat source (for example, a fireplace), then temperature drops. However, in the case of the solar corona, temperature increases while density drops. This peculiar behaviour was first identified by Grotrian (1939) and Edlen (1943) by identifying highly ionized elements (FeIX and CaXIV). Ever since various models of heating mechanisms have been developed to explain that phenomenon.

The responsible mechanism for heating the corona must satisfy few criteria. It must have a source of energy, and explain the transport, and dissipation processes of energy into the region. A promising heating mechanism must also persist ceaselessly, otherwise radiative losses from the whole wavelength spectrum, and thermal conduction will remove the heat once and for all.

It is conventional to attribute the medium of transferring the energy generated by the mechanical drivers to the magnetic field. We know that other mechanisms do not work. For example, energy cannot be transported towards the corona through mass flows, or heat conduction. In addition, numerical models by Carlsson & Stein (2002), and observational constrains
Fossum & Carlsson (2005); Carlsson et al. (2007) indicate that acoustic waves are diminished, or reflected before reaching the corona. In fact, the authors showed that the acoustic waves cannot heat the chromosphere due to the aforementioned reasons. On the other hand, small velocity amplitude magnetohydrodynamic (MHD) waves can propagate until the corona, however they carry only small amount of energy Hara & Ichimoto (1999); Tomczyk et al. (2007). Only Alfvén waves can propagate until the corona and carry enough energy, but they cannot be dissipated easily van Ballegooijen et al. (2011); Asgari-Targhi & van Ballegooijen (2012). In the succeeding sections, we elaborate on the energy requirements needed to heat the region, the source of energy, how the energy is transported to the corona, and finally what are the most famous candidates for releasing the energy.

2.2 Energy requirements

Mechanisms responsible for cooling the solar corona are mainly thermal conduction and radiation. Conduction distributes energy from hotter to cooler regions, whereas radiation removes energy from the system instantly due to the low particle density in the region and the large mean free path of photons.

Thermal conduction is effective only parallel to the magnetic field because, according to Spitzer & Härm (1953), charge particles in the perpendicular direction are subjected to the Lorentz force, which bends the particles’ trajectory parallel to the field. Energy transported via thermal conduction can be described through the following equation of the Spitzer’s conductive flux:

\[ F_c = -\kappa_0 T^{5/2} \frac{\partial T}{\partial s} \] (2.1)

where, \( \kappa_0 \) is a constant with units Wm\(^{-1}\)K\(^{-7/2}\), \( T \) is temperature, and \( s \) is the direction along magnetic field. Equation 2.1 shows that heat conduction is highly sensitive to temperature amplitude and temperature gradients.

The typical radiative loss from the quiet Sun is around \( 8 \times 10^5 - 10^6 \) erg cm\(^{-2}\)s\(^{-1}\) (Withbroe & Noyes, 1977; Withbroe, 1988). Density in the corona is very low, and thus, plasma in the corona is optically-thin and the processes of radiation are different than those in lower and denser layers. Radiation in the corona mostly consists of X-rays and EUV emission lines of which the intensity is proportional to the squared electron density. Emissions lines are dominant due to spontaneous de-excitation of metals, which have been excited from electron collisions. Radiative cooling and cooling via thermal conduction in the corona are expected to be of the same order in the quiet Sun (Withbroe & Noyes, 1977).
2.3 Candidate mechanisms for heating the solar corona

Heating must balance cooling processes in the corona in order to justify the observed temperature values. Identifying however the most important heat contributors is not so easy. The difficulty is due to three major reasons: First, present models fail to explain certain observational signatures, such as over-dense coronal loops, chromospheric evaporation, nature of spicule heating and acceleration (Pontieu et al., 2009), or the ubiquitous average redshift observed in emission lines in the transition region (Peter & Judge, 1999). Secondly, the atmospheric conditions in the corona do not support the dissipation of energy as required by certain models (e.g., special cases of wave heating, such as phase mixing (Soler & Terradas, 2015)). Thirdly, the energy release explained by some models is not enough to heat the corona (e.g., acoustic waves).

It is now conventional to attribute the initial source of energy to the energy generated by mechanical drivers. Those drivers are flows in the convective zone, and random footpoint motions in the photosphere that generate so much energy that only a fraction of that energy can heat the entire corona Gesztelyi et al. (1986).

There is only one sufficient way to transport mechanical energy from the solar surface to the corona, and this is via magnetic field. Energy can be transported from the solar surface towards higher layers in the atmosphere via Poynting flux, which is expressed in the following equation:

\[
\mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}}{\mu_0} \tag{2.2}
\]

where, \(\mathbf{E}\) is the electric field vector, \(\mathbf{B}\), the magnetic field vector, and \(\mu_0\) the vacuum permeability. The vertical component of Poynting flux consists of two parts. The first part (eq. 2.3) describes the work done by horizontal motions of the granulation on the vertical component of the magnetic field. The second part (eq. 2.4) describes the work done by vertical transport of the horizontal magnetic field. According to models by Hansteen et al. (2015), both components are equally important in transferring energy in the solar atmosphere. The same authors found that both components are highly variable temporally and spatially. They also found that both components have opposite signs most of the time throughout almost all space (that includes the region from the photosphere to the corona), the net result however is an upwardly directed flux.

\[
S_{v,1} = -\frac{1}{\mu_0} B_z (u_y B_y + u_x B_x) \tag{2.3}
\]

\[
S_{v,2} = \frac{1}{\mu_0} u_z (B_x^2 + B_y^2) \tag{2.4}
\]
Chapter 2. Coronal Heating

After the energy has been transported towards the corona, there must be a mechanism that dissipates the energy stored in the magnetic field. Models of heating mechanism in the corona are classified into two categories. Each category of models depends on the comparison between the timescale of the driver at the solar surface, and the timescale of the response of the magnetic field when disturbances propagate along it with the Alfvén velocity (Klimchuk, 2006).

If the driver moves faster than the Alfvén transit time, then the generated electric currents vary faster than the magnetic field can relax. In such case, the models of heating mechanism incorporate Alternating Currents (AC) that incorporate wave heating. Examples of this category of models are Alfvénic resonance (Hollweg, 1985), resonant absorption (Ionson, 1978; Poefts et al., 1989; Erdelyi & Goossens, 1994), phase mixing (Heyvaerts & Priest, 1983; De Moortel et al., 1999), and MHD turbulence (Inverarity & Priest, 1995). The description however of AC heating models falls outside the scope of this work. Since this work does not focus on the AC coronal heating models, we will make no further reference.

When the driver moves magnetic field’s footpoints slower than the time needed by the magnetic field to adjust (Alfvén transit time), then coronal currents are direct (DC category of models). Examples of DC models are dissipation of direct currents via magnetic reconnection (Sturrock & Uchida, 1981; Parker, 1983a, 1988), viscous turbulence (Heyvaerts & Priest, 1992; Einaudi et al., 1996), and Ohmic dissipation, which incorporates current cascade (Hendrix et al., 1996; Galsgaard & Nordlund, 1996; Gudiksen & Nordlund, 2002).

In this work, we focus on the magnetic reconnection expressed through Ohmic dissipation of currents that release the stored energy in the magnetic field (Galsgaard & Nordlund, 1996) in an impulsive manner. The formation of currents occurs due to magnetic field gradients when excess of energy above the lowest energy level of the magnetic field, i.e., the potential state, is stored in the magnetic field. In the following chapter, we describe thoroughly this heating mechanism and the conditions for current formation.
In Chapter 2, we have mentioned the reservoir of energy; that is the mechanical energy of flows in the photosphere and the convective zone. We have also identified the medium for transferring that energy; that is the magnetic field. In this chapter, we will elaborate on what happens next. In Sect. 3.1, we will explain how the energy is built-up and stored in the magnetic field and in Sect. 3.2, we will explicate on how the candidate mechanism can release the stored energy. Finally, in Sect. 3.3, we will explain what statistical tool is needed to identify the importance of the candidate-mechanism for heating the corona.

3.1 Energy build-up

A magnetic field in its lowest energy state is a potential field, and it is expressed in equation 3.1 via a scalar potential function \( \phi \) as follows:

\[
B = \nabla \phi
\]  

When considering the expression of current density in MHD, i.e., \( J = \frac{1}{\mu_0} (\nabla \times B) \), and the expression in eq. 3.1 for the magnetic field, then the current density is zero. Therefore, a potential field is current-free and no Lorentz force is exerted from this type of field.

Poynting flux, as we have described in Sect. 2.3, transports energy from the solar surface to the corona, and the magnetic field stores the energy. Hence, the magnetic field is no longer a potential field because excess of energy above the energy level of a potential field is stored in the form of currents due to formation of magnetic field gradients Galsgaard & Nordlund (1996); Gudiksen & Nordlund (2005).
Chapter 3. The Promising Heating Mechanism

The alignment of the currents (electric field) and the magnetic field is very important. As expressed in the following formula, when currents are field-aligned, then the Lorentz force is zero, and thus, energy can be stored in the form of currents without any work spent.

\[
J \times B = 0
\]

(3.2)

Note that there are several mechanisms for creating currents in the corona. Currents can be formed in the convection zone via twisting a magnetic flux tube and then emerge, and reach the coronal heights (e.g., Mikic et al. (1988)). Alternatively, currents can be formed in the corona either by twisting (e.g., Rosner et al. (1978); Klimchuk et al. (2000); Reale et al. (2016) ), or braiding of the magnetic field (e.g., Parker (1983a,b); Priest et al. (2002); Fuentes & Klimchuk (2010)).

3.2 Energy dissipation

In regions with finite resistivity (\(\eta\)), cross-field currents (\(J\)) can dissipate energy via Joule heating (\(Q_J = \eta J^2\)). Joule heating, as shown in numeric models performed by Galsgaard & Nordlund (1996), scales with the driving speed, the magnetic energy density, and the distortion of the magnetic field.

Depending on how large the magnetic field gradients are, the magnetic energy dissipates either due to Joule heating or magnetic field reconnection where energy is released in an impulsive and intermitted manner expressed (partially) also via Joule heating. Joule heating is generated due to stressing of the magnetic field, and according to numerical simulations performed by Gudiksen & Nordlund (2005); Hansteen et al. (2010, 2015), it drops with height roughly the same way as magnetic energy does.

The evolution of currents is of the same order as the evolution of the magnetic field because the two are correlated via the magnetic field gradients (\(J \sim \nabla \times B\)). In fact, as shown in models of magnetic field stressing employed by Galsgaard & Nordlund (1996), the formation of currents takes usually few seconds, while current dissipation can take from few to thousands of seconds.

Current fragmentation is expected to take place where resistivity is very low. Currents tend to fragment because plasma moves in different directions that could also cause turbulence (Heyvaerts & Priest, 1992); in such cases velocity gradients suggest viscosity. The fragmentation may continue until the typical scale of the currents reaches the physical scales where resistive diffusion (Nordlund & Galsgaard, 2012), or friction take action. This is the process of current cascade that had been proposed by van Ballegooijen (1986). This way, a hierarchy of spatial scales of currents is achieved.

Field-aligned currents is a key element in heating the corona because they store excess of energy above the potential field level (Sakurai, 1979).
To dissipate that energy currents must become cross-field in the presence of finite resistivity that release a part of the excess energy via Ohmic (Joule) heating (Low, 1990). When dissipation is so large that the topology of the magnetic field changes, then magnetic reconnection occurs (Parker, 1972).

Magnetic reconnection is a topological phenomenon where the spatial continuity of the magnetic field breaks (Vasyliunas, 1975). A magnetic field is spatially continuous when each of its spatial derivatives, i.e., $\partial B_i / \partial x_j$, is finite in space. Magnetic reconnection in the corona involves two opposite directed magnetic fluxes in close proximity that change their topology.

Even though we know the process of magnetic reconnection, the theoretical reconnection rate is not as high as the observed one. In order to overcome this problem, resistivity should be locally enhanced. There is evidences from various simulations that resistivity increases locally at the reconnection sites. In particular, in MHD simulations performed by Sato & Hayashi (1979), who tested driven reconnection where external forces pushes material into a current sheet, fast reconnection rates were achieved when resistivity was enhanced locally. Likewise, in a spontaneous-type reconnection experiment, Ugai & Tsuda (1977) showed that microscopic-scale instabilities (e.g., tearing instability Furth et al. (1963)) inside the current sheet enhanced resistivity locally and magnetic reconnection proceed rapidly.

### 3.3 Statistical analysis of solar flares

A flaring event, is a sudden and local brightening in the atmosphere of the Sun, visible across the whole spectrum, and it is associated with a fast reconfiguration of the magnetic field. A flare is a manifestation of magnetic reconnection, which converts the stored energy of the magnetic field into thermal and non-thermal energy.

The frequency of flare energy release exhibits a power-law distribution (e.g., Vlahos et al. (1995); Isliker et al. (2001)). According to Parker (1972), if the frequency of small-scaled flares, the so-called nanoflares, is large, then flares could heat the corona. Equivalently, according to van Ballegooijen (1986), if multiple small-scaled transverse current sheets can be formed, then corona can also be heated. However, such small-scaled events cannot be resolved in observations by current instrumentation. Following the idea of flare power-law distribution, Hudson (1991) calculated that the power index of the energy power-law of flares must be smaller than minus two in order for the small-scaled events to become energetically important. Therefore, we could implicitly infer the importance of small-scale events by observing larger flares, derive their energy distribution, fit a power-law and find the powerlaw index.

Deriving however the correct power-law index has proven a difficult task because of technical and physical aspects of biases introduced in
Chapter 3. The Promising Heating Mechanism

the statistical analysis. Technical aspects of biases could be related to instrumental noise or when determining the power-law index. Regarding the latter, according to Parnell & Jupp (2000); Benz & Krucker (2002), a combination of reasons affect the results of a statistical analysis, yielding a variety of indices. More precisely, as summarized by Aschwanden et al. (2014), different studies of peak flux observations show indices within the range \([1.2–2.1]\). Reasons that could effect the power-law index are for example the definition of flaring event or the technique used for their detection. In addition, the power-law fitting method, the goodness of sampling at the lower and higher ends of the distribution, the total number of events, and the correct subtraction of noise level Hannah et al. (2011)

Regarding the physical aspects of biases, there are also several parameters that could add biases in flare analysis. For example the determination of flare energy is not trivial because thermal energies must be calculated. Since there is only information from projected areas, assumptions about the third dimension should be made. Also, large uncertainties added when trying to calculate temperature and emission measure (EM), which are necessary quantities for calculating thermal energy. These two parameters are usually calculated by fitting an isothermal model spectrum to flare spectrum, however isothermal models do not represent usually the real case. Given the aforementioned sources of biases, the use of numerical models becomes a necessity because we can overcome many of those biases. In the following chapters, we describe the numeric solar atmospheric model we employed in this study.
The aim of this chapter is to render the importance of numerical models in solar physics (Sect. 4.1), and to explain how numerical modelling helped me to cope the problem I investigated (Sect. 4.2). In the same section, I will also describe the details of my numerical simulation. In Section 4.3, I will describe the physical model of the heating mechanism in the solar corona that I worked on.

### 4.1 The role of numerical models

In Figure 4.1, Norman illustrates and explains quite well the links between observation, theoretical, and computational astrophysics. The relation between observation and theory has a long-standing history, with the former providing evidences to either verify, reject, limit or adjust the latter, and the latter provides formulations, hypotheses or explanations to observations. In this work however, we are mostly interested in the synergy between theoretical and computational heating models of the solar corona, and also the relation between computational modeling and observations.

Theory and computation are interrelated. Theory is the “foundation stone” of any numerical model that sets the mathematical formulation, which is essential for the construction of simulations. It determines the parameter space needed for solution derivation or parameter behavior study. Analytical properties described through theory, such as conservation laws, can be introduced in numerical models, and describe better the physical aspects of a problem. Analytic solutions, essential in theory, can be used for testing computational models. On the same token, complex results from numeric models can be interpreted using simplified theoretical, analytical models. Numeric models can also serve as realizations or laboratories for theoretical models, which are so complicated that they cannot have an
analytical solution. Therefore, simulations intend to reveal essential physics in real processes.

Computational models must be compared with observations, otherwise they are meaningless. Therefore, observations is a test that a simulation needs to pass to validate its correctness.

Simulations are important because they build physical intuition about the problem through our understanding and interpretation of the governing equations. However, the degree of realism of numerical simulations is something that worries scientists. In case of the solar atmosphere, Pereira et al. (2013) showed that 3D models of the solar atmosphere are in good agreement with observational diagnostics of the solar temperature profile (e.g., continuum centre-to-limb variations, absolute continuum fluxes, and the wings of hydrogen lines). Therefore, the authors showed explicitly how realistic 3D modeling could be. In addition, tests of codes, such as the CO$^5$BOLD (Freytag et al., 2012), the MURAM (Vögler et al., 2005; Rempel et al., 2009; Rempel, 2014), and the Bifrost (Gudiksen et al., 2011) pass reality checks by comparison with observations, and even though the three codes solve equations with different numerical methods in different simulation boxes and grid-sizes (Beeck et al., 2012), their agreement gives us confidence.

4.2 Numerical model with Bifrost

Numeric algorithms can simulate a physical system such as the Sun by solving a set of non-linear equations, incorporating boundary conditions and starting from an initial condition.

In order to have a realistic simulation of the solar atmosphere, the numerical model must generate observables akin to observations. For this reason, simulations should use a realistic equation of state that incorporates composition and ionization degree of the solar gas. A realistic simulation should also incorporates a realistic radiation transfer with opacities that
correspond to the true ones as much as possible, and energy transfer via thermal conduction. A simulation should also achieve stability via numerical resistivity, which is adjustable depending on the region. In addition, magnetic field configuration must correspond to a real case and appear similar to one observed in a magnetogram. A realistic simulation must also reproduce the temperature, pressure, density, velocity and magnetic field profiles deduced from observations.

Usually, in numerical three-dimensional magneto-hydrodynamic (3D-MHD) modeling, there are two approaches to simulate a star, e.g., the Sun. You can simulate the whole Sun within a computational box, the so-called “star in a box” simulation. The other way is to simulate a small volume of the star so that a box covers part of its horizontal area, and part of its radial direction; this type of simulations is called “box in a star” simulation.

Magnetohydrodynamic Partial Differential Equations

The *Bifrost* code is a massively parallel code that simulates a stellar atmosphere from the convective zone up to the corona. The code uses an explicit schema to solve the standard MHD partial differential equations on a staggered mesh of a Cartesian grid using 6th order differential operators, 5th order interpolation operators, and a 3rd order Hyman method with variable time-step. The code solves the following set of equations:

\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \mathbf{u} \]  
\[ \frac{\partial \rho \mathbf{u}}{\partial t} = -\nabla \cdot (\rho \mathbf{u} \mathbf{u} - \tau) - \nabla P + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} \]  
\[ \mu_0 \mathbf{J} = \nabla \times \mathbf{B} \]  
\[ \mathbf{E} = \eta \mathbf{J} - \mathbf{u} \times \mathbf{B} \]  
\[ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \]  
\[ \frac{\partial e}{\partial t} = -\nabla \cdot e \mathbf{u} - P \nabla \cdot \mathbf{u} - \Lambda + Q_c + Q_J + Q_{Vi} \]

where \( \rho, \mathbf{u}, \tau, \) and \( P \) are the density, velocity vector, viscous stress tensor, and gas pressure respectively. \( \mathbf{J}, \mathbf{B}, \mathbf{E}, \mathbf{g}, \eta, \) and \( e \) are the electric current density vector, the magnetic flux density vector, the electric field vector, gravitational acceleration, magnetic diffusivity, and internal energy per unit volume respectively. \( Q_c \) is the heating/cooling derived through the Spitzer thermal conduction along the magnetic field (Spitzer, 1962); \( Q_J \) represent the Joule heating term, as expressed in eq. 4.7; \( Q_{Vi} \) is the viscous heating; \( \Lambda \) represents the cooling or heating generated by the emission and absorption of radiation.

Equation 4.1 represents the conservation of mass; Equation 4.2 is the momentum equation in which term \( \mathbf{J} \times \mathbf{B} \) represents the Lorentz force;
Equation 4.5 is the Maxwell-Faraday equation. In equation 4.6, the term \( \nabla \cdot e \mathbf{u} \) represents the energy flux, and the term \( P \nabla \cdot \mathbf{u} \) expresses mechanical work (positive value denotes expansion).

The Ampere’s law expresses the relation between current density and magnetic field. In non-relativistic approximation, Ampere’s law is simplified to equation 4.3 because the temporal variation of the electric field is significantly smaller than the curl of the magnetic field. Therefore, current density is proportional to the distortion of the magnetic field. Current density in the presence of finite resistivity generates Joule heating that has the following formula:

\[
Q_J = \eta J^2
\]

Equation 4.4 is obtained via Ohm’s law and shows that a non-relativistic plasma feels two types of electric field. One direct electric field \( \mathbf{E} \) that plasma “feels” at rest, and another electric field \( \mathbf{u} \times \mathbf{B} \) that the plasma “feels” when it moves.

**Radiative transfer**

The *Bifrost* code is flexible in introducing new physics in its equations since different parts of the solar interior and atmosphere incorporate different processes. For example, *Bifrost* incorporates full radiative transfer including scattering between optically thin and thick regions in the convective zone. In addition, *Bifrost* uses non-gray radiative transfer including scattering Hayek et al. (2010) in the photosphere and lower chromosphere, while it uses a chromospheric radiation approximation in the upper chromosphere. In the corona, it uses optically thin radiation.

Optically-thin radiative transfer in the outer part of the atmosphere (i.e., from the chromosphere towards the corona) assumes ionization equilibrium. The radiation in the upper atmosphere is due to resonance lines of multiple ionized atoms, such as carbon, oxygen, and iron. Radiative transfer in this region can be reduced to radiative cooling in the following manner:

\[
Q_{\text{thin}} = -n_H n_e f(T)
\]

where \( n_H \) is the number density of hydrogen, which is derived from the plasma density assuming solar abundance; \( n_e \) is the number density of electron. \( f(T) \) is a temperature function, which can be computed assuming ionization equilibrium (details can be found in Gudiksen et al. (2011)). Equation 4.8 holds for temperature values larger than 20,000 K.

Radiative transfer in the chromosphere is achieved by optically thin radiation in continuum, and optically thick radiation due to a wealth of spectral lines from hydrogen, calcium, and magnesium. In the chromosphere, in which optical depth is significant, the source function and opacities cannot
be calculated by assuming local thermodynamic equilibrium. Therefore, radiative loss in those lines has to follow the following approximation:

\[ Q_{[H,Ca,Mg]} = -C(T) [H,Ca,Mg] n_e \rho \phi_{[H,Ca,Mg]}(m_e) \]  

(4.9)

where \( \rho \) is the plasma density, and \( C(T) n_e \rho \) gives the total collisional excitation rate; \( \phi(m_e) \) gives the probability that the radiated energy escapes the atmosphere. \( m_e \) is the column mass, which in addition to \( C(T) \) are calculated for each element from 1D radiative transfer computations using RADYN code (Carlsson & Stein, 1995), and 2D computations using Multi3D (Leenaarts & Carlsson, 2009). How the lines and continua are introduced in these functions is described in Carlsson & Leenaarts (2012).

In the convective zone and the interface between this region and the photosphere, it is necessary to compute the full radiative transfer because of the combination of those regions covers optically thin and thick regimes.

Due to the relatively short time-scales of the photon scattering in the convective zone with respect to the time-scales of the region’s evolution, it is possible to neglect the temporal dependency in the radiative transfer equation. Therefore, the expression takes the following form:

\[ \hat{n} \cdot \nabla I_{\lambda}(x, \hat{n}) = -\chi_{\lambda}(x)I_{\lambda}(x, \hat{n}) + j_{\lambda}(x, \hat{n}) \]  

(4.10)

where \( I_{\lambda}(x, \hat{n}) \) is the monochromatic specific intensity of a beam with direction \( \hat{n} \) at location \( x \); \( \chi_{\lambda} \) and \( j_{\lambda} \) are the monochromatic gas opacity, and emissivity respectively that are strongly dependent on wavelength.

In addition, opacity is not treated as monochromatic opacity because of a wealth of lines. Instead, we use a smaller number of mean opacities. Therefore, the radiative heating rate, calculated from the first moment of equation 4.10, using mean opacity with index \( i \) takes the following expression:

\[ Q_{\text{rad},i} = -\nabla \cdot F_i = 4\pi \chi_i(J_i - S_i) \]  

(4.11)

where \( F_i \) is the radiative energy flux, \( J_i \) the mean intensity, and \( S_i \equiv j_i/\chi_i \) the source function.

\( Q_{\text{thin}} \) and \( Q_{\text{rad},i} \), in equations 4.8 and 4.11 respectively, are incorporated in energy equation 4.6 via the \( \Lambda \) radiative parameter.

**Equation of state**

Depending on the experiment, different modules of equation of state (EOS) can be used in the code. The EOS used in our simulation is calculated using the Uppsala Opacity Package (UOP, Gustafsson, B. 1973, Uppsala Astr. Obs. Ann., 5, No. 6). In this package, we assume LTE for atomic level populations, and instantaneous molecular dissociation equilibrium. For the calculation of the specific EOS table the ratio of the specific heats is chosen to be \( \gamma = 5/3 \), and radiative equilibrium is also considered.
Resistivity - Diffusivity

Due to the explicit nature of Bifrost, resistive terms are necessary to keep the code stable. The code uses a diffusive operator, which splits in two parts. The first part describes a global diffusion, which is at least a factor of 10 smaller than the one we would have to apply in case of a single global diffusive term. The second part describes local diffusion that depends on the grid-size to resolve currents sheets.

Boundary conditions

Boundary conditions can be set as requested by the user according to the nature of the experiment. In this work, we use periodic boundaries in the horizontal plane, while the upper boundary in the vertical direction is open allowing magnetic field and material to leave the system. The lower boundary allows inflowing gas so as to maintain the convective flow. In addition, the entropy added to the system through the lower boundary maintains the effective temperature in the photosphere.

Grid architecture

The simulation box starts at 2.5 Mm below the continuum optical depth $\tau_{500} = 1$ covering a part of the convective zone, and extends 14.3 Mm above the photosphere into the corona, while the horizontal dimensions are $24 \times 24 \text{ Mm}^2$. The simulation box is resolved into $768^3$ grid cells. Therefore, the spatial resolution in the horizontal directions is 31.25 km, while the vertical spacing of the grid varies so as to resolve the magnetic field, temperature and pressure scale heights. More specifically, the vertical grid spacing is as small as 26 km in the photosphere and chromosphere, and increases smoothly with height reaching values as high as 165 km in the corona.

Initial atmosphere

The simulation starts from a hydrodynamic (HD) simulation that has achieved a relaxed state. The HD simulation has size $6 \times 6 \times 3 \ \text{Mm}^3$, in the horizontal plane and vertical direction respectively. The convection zone occupies most of the vertical direction, i.e. 2.4 Mm, while the residual is the atmosphere. We expand the horizontal plane by padding the $6 \times 6 \ \text{Mm}^2$ domain so as to first create a $12 \times 12 \ \text{Mm}^2$ domain, and then a $24 \times 24 \ \text{Mm}^2$ domain. During each expansion step, we add a small random perturbation, and we run the simulation long enough so as the periodicity of the padded boundaries disappears. Next, we run the simulation for 10 hours of solar time in order to achieve a relaxed hydrodynamic state. Then, we add a chromosphere and a corona that are in hydrostatic equilibrium. For that, we use another simulation’s temperature structure as initial condition. From
4.2. Numerical model with Bifrost

this point, we start counting time, and leave the simulation to run for few hundreds of seconds of solar time, to eliminate irregularities in the chromosphere. Then, temperature starts to decrease, and at that point we introduce the large scale magnetic field that we describe in the following section.

Magnetic field configuration

The current simulation incorporates a magnetic field of two strong magnetic polarities. The two polarities are located 8 Mm apart in the photosphere and they are connected through a magnetic loop-like configuration. To create such a configuration, we introduce a vertical magnetic field during the initial phase of the simulation at the lower boundary and extrapolated it through the whole atmosphere assuming potential magnetic field. But the potential character of the field disappears quickly due to the motions of the convective zone. Later on, we continuously introduce a horizontal 100 G magnetic field, together with some random field so to achieve a “salt and pepper” magnetic structure in the photosphere, as illustrated in Fig. 4.2.

![Figure 4.2: Vertical component of the magnetic field in the photosphere. Here, the term photosphere refers to constant height for which the mean temperature is 5780 K. The thick white dashed line shows the location of the horizontal section.](image)

Magnetic field in the Sun is temporally and spatially variable. As illustrated in the left-top panel in Fig. 4.3, the magnetic field module in
Chapter 4. Solar Atmospheric Model

the convective zone is almost three orders of magnitude stronger than in the corona \(^1\) and it decreases exponentially with distance in the region above the photosphere. Given the fact that gas pressure drops faster than the magnetic pressure with height, magnetic field expands and becomes space-filling at heights that correspond to the chromosphere and higher (see right-bottom panel in Fig. 4.4). While the horizontal average of the magnetic field between the convective zone and the transition region does not change significantly with time, it increases slightly above that height as time progresses.

Solar Structure

To check the realism of our numerical model, we need to observe how realistic is the variation of parameters as regards time and space. For this reason, we observe and describe the variation of the magnetic field, Joule heating, temperature, density, velocity, and Poynting flux.

Like the magnetic field, Joule heating also changes with regard to location and time. As shown in the right-top panel in Fig. 4.3, Joule heating above the photosphere decreases exponentially with distance, whereas below the photosphere there is strong Joule heating that is almost constant with distance. The strong Joule heating in the sub-photospheric layer owns to the generation of large magnetic field gradients (and thus strong currents) due to the shuffling of strong magnetic field in the convection zone. The Joule heating varies largely in the region above the photosphere. Joule heating variation is more prominent in the upper atmosphere because the magnetic field drops exponentially with distance, and therefore the distortion of the magnetic field can occur easier than in stronger magnetic field configurations. For this reason, Joule heating in the right-top panel in Fig. 4.5 fluctuates more intensively in the upper than in the lower atmosphere.

An implicit outcome of Joule heating (and other heat sources such as viscous heating, thermal conduction, or mechanical work) is the rise of temperature values if heating overcomes various cooling processes. As in reality so as in our simulation, the temperature configuration is neither temporal nor spatially invariant. As illustrated in the left-upper panel in Fig. 4.4, the vertical slice of the temperature structure along \(y = 12.5\) Mm reveals a temperature configuration that is not a nicely stratified configuration like the one-dimensional models imply, e.g., VAL C model (Vernazza et al., 1981). In fact, plots of the horizontal average of the temperature as a function of height (i.e., Fig. 4.3) show that the temperature profile is not a single-valued function that is constant in time. More precisely, plots of evolution of the horizontal average of the temperature (Fig. 4.5) shows that temperature varies as time elapses. After the initiation of the simulation,

\(^1\)Note that positive distance in Fig. 4.3 indicates depth below the photosphere
Figure 4.3: Evolution of the horizontal averages of four parameter profiles within the temporal window [630–3000] s. The four quantities are: the module of the magnetic field, the Joule heating, the density and the temperature with as a function of height. Time progress as from violet to red colors. Negative values correspond to the solar atmosphere, whereas positive value to the solar interior. Ordinate axes are in logarithmic scale, and units are the intrinsic Bifrost units. Credits: Viggo Hansteen.
temperature increases with time until a balance between heating and cooling is reached.

Like temperature, the density structure cannot be described though a single function either. Even though the horizontal average of density as a function of distance in the right-bottom panel in Fig. 4.3 shows that the quantity drops exponentially, the horizontal slice of the atmosphere shows that the density structure is more complicated. As shown in the left-bottom panel in Fig. 4.4, the density profile of a vertical slice of the simulation box reveals high-density loops that connect the two magnetic polarities. In the horizontal slice there are not only high- and low-laying loop-structures, but structures with irregular shapes that surround the two polarities also exist.

Density varies also as time progresses. As shown in the right-bottom in Fig. 4.3 at fixed heights and in the left-bottom panel in Fig. 4.5, the horizontal averaged of density increases with time in the corona, whereas it stays almost constant in the underlying regions. The density rise in the corona happens due to upflows of material that can be identified from the negative vertical velocity value in the right-bottom panel in Fig. 4.5. Such upflows of material are speculated to be evidences of chromospheric evaporation.

A realistic atmospheric model of the Sun, like the one we explore, should exhibit a wealth of flows. The right-top panel in Fig. 4.4 is an example of how the vertical component of the velocity field \( u_z \) looks in a vertical slice of the solar atmosphere in our simulation. Upflows (positive values) dominate in regions above the two magnetic polarities, whereas, in between, an intermix of flows exists. More precisely, at heights that correspond to the chromosphere up to the lower corona, a mixture of positive and negative direction of vertical flows exists, but the mean velocity, as illustrated in the lower bottom panel in Fig. 4.5, is a temporally varying upflow.

In Figure 4.5, Joule heating, velocity field, density, and temperature exhibit a fluctuating character as a result of global oscillations. Global oscillations appear in the lower boundary due to reflection of acoustic waves. Therefore, there is excitation of p-modes, similar to the real Sun, however the energy of the waves spreads over a limited number of modes generating large amplitude oscillations. The oscillations are apparent in all four parameters in Fig. 4.5, up to 2 Mm height, but oscillations in higher heights mix with propagating waves.

As we also mention in Sect. 2.3, the vertical directed Poynting flux splits into two terms: one that incorporates the work done by horizontal motion on the vertical field (see eq. 2.3), and another due to the transport of horizontal field by vertical flows (see eq. 2.4). From now on, we will refer to the first term as term I, and the other as term II.

As can be seen in Fig. 4.6, both terms are temporally and spatially variable. More precisely, both Poynting flux terms are highly time-variable above the photosphere and they have large values but with different signs,
4.3. Physical model

Until now we have talked about the atmospheric model simulated with Bifrost. We have also talked about details of the code and how it solves the governing physical processes at each layer in the atmosphere. In this section, we will summarise the physical model, which we believe describes the process of heating the solar corona. More precisely, we will clarify the source of energy, the medium that transfers and stores the energy in the corona, and the triggering mechanism of releasing that energy.

**Figure 4.4:** Slice of the atmosphere along $y \approx 12.5$ Mm at $t = 2990$ s, as illustrated in Fig. 4.2 (dashed line). Left-top panel illustrates the temperature, right-top panel the vertical component of velocity field, left-bottom panel shows the scaled density with respect to the averaged horizontal density, and right-bottom panel the module of the magnetic field.

so they mostly cancel out. The net result of the temporally averaged total Poynting flux is an upwardly directed flux that drops exponentially with distance. Note also that in regions above the chromosphere, the averaged work done by horizontal motions (term I) is directed upwardly, whereas, the averaged work done by the vertical transport of horizontal magnetic field is directed downwards. The direction of the Poynting flux is important because Poynting flux is the process of transferring large amounts of energy from the solar surface to the corona.
The mechanical energy generated by the flows in the photosphere and convective zone is so large that only a fraction could heat the corona (Gesztelyi et al., 1986). The scientific opinion agrees that the medium of transferring the mechanical energy to the corona is the magnetic field, which extends throughout the atmosphere of the Sun establishing a link between the solar surface and the corona. More precisely, energy travels towards the corona via the vertical components of the Poynting flux (Klimchuk, 2006; Hansteen et al., 2015).

The injection of energy into the corona transforms a potential magnetic field into a non-potential field. A potential field is a field in its lowest energy state, and any excess of energy above that state involves the formation of magnetic field gradients, and consequently the formation of currents that stores that extra energy (Galsgaard & Nordlund, 1996; Gudiksen & Nordlund, 2005). The process of the formation of the magnetic field gradients involves shuffling and braiding of the magnetic field caused by
4.3. Physical model

Figure 4.6: Poynting flux as a function of height from $t = 2000$ s to $t = 3000$ s. Time progresses from purple to red curves. The thick black line illustrates the time average of the total Poynting flux. Dashed lines depict the vertical Poynting flux associated with horizontal motions, and solid lines depicts the total vertical Poynting flux. Credits: Viggo Hansteen.

The flows at the footpoints of the magnetic field. When the flows are slower than the response of the magnetic field, then direct currents form.

However, the magnetic field cannot be distorted infinitely; at some point a fraction of the stored energy can be randomly released. The maximum amount of energy that can be released is the difference between the stored in the non-potential field, and the one stored in the potential field which is replenished continually as long as the solar surface keeps moving.

Depending on the inclination between the electric field and the magnetic field, different processes can happen. When the electric field is parallel with the magnetic field, then the exerted Lorentz force is zero. In case where there is an inclination between the two, then Lorentz force is finite and work is done. As a consequence, the energy that is stored in currents dissipates via Joule heating in the presence of finite resistivity (Low, 1990). The most interesting case is when the electric field and the magnetic field are perpendicular, then the magnetic field topology changes significantly.
and magnetic reconnection occurs (Parker, 1972).

When magnetic reconnection occurs, non-thermal electrons can be accelerated transporting a part of the released energy. Electrons follow the magnetic field configuration, and travel towards the dense chromosphere interacting with the chromospheric material, and increasing its temperature. A rise in temperature leads to evaporation of chromospheric material that brings hot and dense material into the corona. This phenomenon, feeds magnetic field structures in the corona with material forming overdensed coronal loops. In addition to non-thermal particles, energy is also transported through a combination of other mechanisms. For example: excited waves, plasma flows at the reconnection sites, radiation, and thermal conduction.

We have seen that magnetic reconnection and resistive currents can release energy in the upper solar atmosphere, however if there is not any mechanism of introducing new magnetic flux, then the magnetic field will be soon dissipated and disappear. Rempel (2014) showed in simulations that when assuming zero magnetic field at the bottom boundary, then small scale dynamo located in the layer at height 1-2 Mm below the photosphere can account to roughly 50% of the presumed magnetic field strength. Therefore, the introduction of magnetic flux is necessary. In our case, even though we do not assume processes of global dynamo, we introduce horizontal magnetic field at the bottom boundary simulating such processes.

Magnetic reconnection is a topological phenomenon, hence identifying each event is difficult without studying each region in detail, however the implicit effects of magnetic reconnection could be identified. The best chances we have to study such topological events is to investigate the Joule heating term that describes regions with large magnetic gradients. In this work, we study heating in the solar corona via Joule heating that hopefully is correlated with magnetic reconnection. Regions with strong Joule heating can imply regions with high probability of magnetic reconnection because they signify highly distorted magnetic field. To locate such regions, we must identify local enhancements in the Joule heating term.
Part II

My work
Motivation of this research

In 1943, Edlen, following the work of Grotrian (1939), had identified that the spectral lines attributed to the hypothesized chemical element “coronimum” was no other than highly ionized iron spectra lines, Fe-XIV line at 5303Å, and Fe-X at 6374Å, formed in the the corona. Those lines echoed temperature values higher than 1,000,000 K. Ever since, the science community focused on identifying the reason why the corona has so large temperature values, since according to the second law of thermodynamics, temperature in an isolated system must drop for an increasing distance from the source of heat.

One promising heating mechanism of the corona is multiple small-scaled heating events occurring endlessly, and releasing energy into the region. Distortion of the magnetic field generates field-aligned currents that stored energy in the corona (Sakurai, 1979). When currents become cross-field in a finite resistive medium, then energy is released via Joule heating (Low, 1990). When the magnetic field topology changes drastically, then magnetic reconnection happens releasing energy impulsively (Parker, 1972).

To put so much effort into understanding the behaviour of our nearest star is not only matter of curiosity. It is also very important to be able to predict its explosive, and hazardous character exhibited during strong magnetic reconnection events.

Many studies devoted on the importance of small-scale events by quantifying the energy release from the manifestations of magnetic reconnection, i.e., flares. Numerous studies in hard X-rays (peak flux), e.g., (Datlowe et al., 1974; Lin et al., 1984; Crosby et al., 1993; Lee et al., 1993; Tranquille et al., 2009), in soft X-rays, e.g., (Hudson et al., 1969; Drake, 1971; Lee et al., 1995; Veronig et al., 2002; Yashiro et al., 2006), in EUV, e.g., (Krucker & Benz, 1998; Parnell & Jupp, 2000; Aschwanden et al., 2000; Uritsky et al., 2007), and in H-α, e.g., Georgoulis et al. (2002) predominantly showed that small-scaled events cannot be the main contributor of heating in the corona.
Chapter 5. Motivation of this research

The main tool for checking if small-scale events are energetically important is statistics. Energy released from flares range from $10^{32}$ erg for large flares down to $10^{24}$ erg for the speculated and still unobserved nanoflares. Interestingly, the frequency of energy release from individual events is distributed as a power-law function. As calculated by Hudson (1991), if the energy power index is smaller than minus two, then small scale events are more important than larger ones.

Observations of flares however are not so conclusive because many factors influence results. For instance, background and foreground sources of heating contaminate images with information other than energetic events. In addition, to determine the thermal energy of flares, the volume must be found. Finding however the volume from two-dimensional images is not trivial; in such case, assumptions must be made. Different passbands generate different projected areas due to difference in density values at different temperatures. Given the fact that there is not evidence that the projected area is somehow correlated with the third dimension, 2D areas cannot be used to infer the volume of an event (Morales & Charbonneau, 2009). Temperature is another quantity needed to calculate the thermal energy of an flaring event. Temperature however is calculated by fitting isothermal models to flare spectrum; isothermal models however are not a realistic approximation. Identifying the duration of a flare is not always an easy task either because flare identification algorithms depend highly on the method and criteria used therein. Sampling and selection biases are also factors that increase the vagueness in flare studies; the definition of events and the instrumental resolution are factors that also affect flare observations.

A way to perform an experiment and avoid the major drawbacks of observations is to simulate a realistic solar atmosphere and perform our analysis using proper tools. Fortunately, we have both and that allows us to tackle one of the most fascinating mysteries in astrophysics with confidence.

The entire meaning of this work is summarized by the following research goals:

<table>
<thead>
<tr>
<th>The main motivation of this work is to:</th>
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<tr>
<td>1. Test the hypothesis: “Given that the energy from impulsive events is distributed as a power-law function, is the absolute value of the power-law index larger than two?”</td>
</tr>
<tr>
<td>2. Draw further conclusion on the importance of small scale events with respect to smaller and larger scales than nano-flares.</td>
</tr>
<tr>
<td>3. Derive power indices of other quantities such as volume and duration of heating events.</td>
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</table>
4. Study different aspects of heating events, such as height of event triggering in the corona, shapes of 3D events, geometrical parameters (area, eccentricity and orientation of major axis of fitted ellipsoid) of 2D horizontal slices of the 3D events, their location with respect to the magnetic field, the evolution of energy release from individual events, and the correlation between energy, duration and volume.

5. Explore the observational traces from regions exhibiting only heating events neglecting information from background or foreground sources of heating.

6. Compare synthesized images where we assume only information from heating events with those assuming information from the total height of the corona.

7. Check if real observations will be able to identify small-scale events, and study the reason current instrumentation cannot observe small-scale heating events.

Goals 1 to 4 are tackled in papers I and II, while Paper III is devoted to investigate goals 5 to 7. Next, I enumerate the steps I took to endeavour the challenges of my goals.

Means to achieve my goals:

1. Run a 3D MHD simulation that describes a magnetic network. The Bifrost code simulates an atmosphere suitable for generation of current sheets and triggering of magnetic reconnection in the corona.

2. Identification of 3D local enhancements of Joule heating. Those are regions that exhibit high probability of magnetic reconnection since they describe highly distorted magnetic field in a resistive medium.

3. Repeat the process for a number of consecutive snapshots, and identify the evolution of the 3D events.

4. Extract energy, volume, duration, geometric parameters of 2D horizontal slices of 3D events, and calculate the number of events.

5. Find the differential size distribution of different quantities and fit power-law function when applicable.
6. Divide identified events in three classes regarding the released energy so that they correspond to microflares, nanoflares and picoevents. Find the total energy that corresponds to each class.

7. Compare parameters.

8. Visualize 3-D Joule heating events and results.

9. Construct synthesized intensity maps that correspond to the filters of Atmospheric Imaging Assembly (AIA) instrument onboard Solar Dynamic Observatory telescope.

10. Cross correlate the EUV/AIA light-curves and create time-lag maps.

11. Calculate the emission measure using the electron density and temperature calculated in the Bifrost code.

Below, I included the list of my papers, while the full text of each paper can be found later in this thesis. In the following Chapter, I describe the most important findings of this Ph.D. thesis.

5.1 List of publications

I Identification of coronal heating events in 3D simulations
www.aanda.org/articles/aa/abs/2017/07/aa30748-17/aa30748-17.html

II Investigating 4D coronal heating events in magnetohydrodynamic simulations

III Emission of Joule Heating Events in Simulations of the Solar Corona
Charalambos Kanella & Boris V. Gudiksen (awaiting for referee’s report in A&A)
Results in publications

My original contribution to knowledge is summarized in the following three papers. The first two papers deal with the identification of three- and four-dimensional heating events respectively. Paper III is dedicated to the synthesis of observables for two cases, which we compare. In the first case we assume emission from regions in the corona that exhibit only heating events, and in the second case we assume emission from the whole corona.

6.1 Paper I

This paper discusses the implementation of a multi-thresholding technique used on data of a 3D MHD simulation. The technique aims to locate three-dimensional Joule heating events in the solar corona simulated with the Bifrost code.

Our model describes a magnetic field network embedded in the quiet Sun, while horizontal magnetic field is added continually at the bottom boundary. Flows in the convective zone and the photosphere shuffle the magnetic field that extends throughout the whole atmosphere. Stressing the magnetic field causes magnetic field gradients, which generates currents. The formation of currents is a way of storing the mechanical energy in the magnetic field generated by the flows in the lower layers. Currents in the presence of finite resistivity release energy via Joule heating that heats the region. When currents (electric field) and magnetic field are perpendicular, meaning that the field gradients are large, then magnetic topology changes dramatically and magnetic reconnection occurs. Therefore, local Joule heating enhancements express regions that exhibit high probability of magnetic reconnection.

After simulating the solar atmosphere, as we describe in Sec. 4.2 and 4.3, and considering only the solar corona, we identify local three-dimensional enhancements of the Joule heating term. In this paper, we report on the
Chapter 6. Results in publications

distribution of the rate of energy release, the volume occupied by the heating events, and their location of ignition in one snapshot.

In the current study, we locate 4136 Joule heating events, and extract the released energy and volume occupied by each event. Energy rate and volume vary significantly. We find that energy rate spans approximately four orders of magnitude starting from $10^{17}$ erg/s and the volume spans around two orders of magnitude starting from $10^{21}$ cm$^3$. When plotting the differential size distribution (histogram frequency over bin-size) of each quantity, and fitting a power-law function, we identify one power-law index, $\alpha_P = 1.5 \pm 0.02$ for the energy rate, and two indices for the volume, i.e., $\alpha_V = 1.3 \pm 0.03$, and $\alpha_P = 2.53 \pm 0.22$. Those indices favor energy release in large events.

Even though we encounter similar problems as observers do in their analysis, in the analysis of our numerical model, we identify smaller energy rate and volume than observations. This is because analysis of numerical models and observations encounter different limitations.

The energy released from heating events consists a fraction of the total Joule heating (12%). The energy that cannot be identified with our identification method is a combination of a low-energy release mechanism, and unresolved small-scaled events. Therefore, the power-law index of energy in this study is the lower limit.

In this study, we also locate the height of each event’s maximum value of energy release and plot it against the maximum value. We confirm other studies (Gudiksen & Nordlund, 2002) that found most of the energy is released in the lower corona and heating decreases with height.

Note also that we don’t find any linear correlation between volume of events and energy rate due to the large dispersion of data-points of both quantities.

Interestingly, our results are similar to other studies that aim to identify heating events in simulations (Bingert & Peter, 2013; Guerreiro et al., 2015; Moraitis et al., 2016). We all find power-indices of energy flatter than two, suggesting that large energetic events are more important than less energetic ones.

6.2 Paper II

This paper reports on the identification of 145306 heating events in the simulated solar corona and their evolution in time. Note that we use the same model as in paper I and the duration of investigation is 570 s of solar time.

Detecting individual events enables us to study different parameters, such as energy release, mean volume occupied during the total duration of an event, and duration. In order to explore these parameter collectively, we
calculate the differential size distribution, i.e., counts of histogram over the bin-width of a size, per bin and fit a power-law function when applicable.

We find an energy slope $\alpha_E = 1.41 \pm 0.01$, which is similar with the lower end of what has been observed in different studies. In addition, we are able to push the lower boundary of the energy of individual events down to $10^{20}$ erg, while the upper boundary of energy is as large as few $10^{27}$ ergs.

Regarding the identified volume, we find that three broken power-law functions can describe the distribution of the volumes, which spans between $10^{21}$ cm$^3$ and $10^{24}$ cm$^3$. The mean volume power indices are 1.12, 2.35$\pm$0.01, and 4.2$\pm$0.25 that correspond to 74.54%, 25.25%, and 0.02% of the total number of events respectively. Note that only the flatter slope falls close to the observed volume power indices, which range between 1.5 and 2.08 (examples in table 9 in Aschwanden et al. (2014)). When plotting the cumulative differential function of the quantity, we find that the distribution is very steep in the first 85% of the smallest volumes (volumes less than $2 \times 10^{22}$ cm$^3$).

Regarding duration, we find a power index equal to 2.87, which lays within what has been observed, i.e., values between 2 and 5 that varies with respect to the location in the solar cycle.

Trying to overcome the biases imposed by the power-law fitting techniques, we divide the identified events into three classes: Pico-, nano, and micro-events. Pico is for events that release energy less than $10^{24}$ erg, nano for events that span between $10^{24} - 10^{27}$ erg, and micro for events that release energy in the range $10^{27} - 10^{30}$ erg. We find that 93.5% of the total number of events are pico-events, 6.4% are nano-events, and the rest is micro-events. This trend is consistent with a flat power index of energy like the one we find. However, when calculating the sum of energy for each class, we find that nano-events release most of the energy. More precisely, nano-events release as much as 82%, pico-events release 8% and micro-events release 10% of the resolved energy. Conclusively, even though we find an energy power index that favours the formation of large (energetically) events, the division into three classes reveals that nano-events release in fact most of the energy among all classes of events.

Energy release from identified heating events corresponds 8% of the total Joule heating released in the corona. This fraction corresponds to an energy flux that is two orders of magnitude larger than the typical radiative loss from the quiet sun, i.e. $8 \times 10^5 - 10^6$ erg cm$^{-2}$s$^{-1}$ (Withbroe & Noyes, 1977; Withbroe, 1988). Even though the largest fraction of the energy flux is transported towards the transition region via thermal conduction, corona needs only a tiny fraction of that energy to maintain its temperature.

In our analysis, we also report on parameters that describe the collective character of events from a more generic point of view. We report on the evolution of the number of events, the total energy density rate, the resolved energy density rate, and the total volume of the resolved events. We find
that there is very good relation between the evolution of the number of events and the total resolved volume, indicating that the distribution of volumes at each instant is, broadly speaking, constant, while at the same time the fraction of resolved energy with respect to the total energy stays almost constant with time. The fraction of energy being almost constant means that the resolved energy follows the evolution of the total energy, inferring that there is no distinctive difference between joule heating events and the mechanism that generates the residual (unresolved) heating.

Comparing the energy release from each event, the averaged volume and the duration of events enables us to identify relations between the quantities. The comparison between the three parameters reveal scaling-laws that follow power-law functions. However, data-points are very dispersed, especially closed to the lower boundaries of the quantities. Given the dispersion of data, the scaling-laws show that the energy of a heating event depends mostly on the duration and less on the averaged volume.

We also report on the location of heating events formation with respect to the magnetic field configuration. In general, the most elongated and largest events form in regions where the vertical component of the magnetic field is small, and usually at the interfaces between regions with different magnetic connectivity. The reason is that the magnetic field there can form currents easily. Whereas in regions with strong magnetic field, joule heating events have smaller volumes because magnetic field cannot form gradients easily.

In this paper, we also look into the shapes of the identified 3D events at specific instances. Particular emphasis is given to the distribution along height of geometrical parameters derived when fitting ellipsoids on the 2D slices of 3D events. The geometrical parameters are the area, the eccentricity and the orientation of the major axis of the ellipsis with respect to the x-axis of our simulation box in Cartesian coordinates. The non-constant nature of the identified events prevails in plots of those parameters. For instance, the area increases or decreases coherently until the limits we imposed in our identification method is reached, unless a large magnetic field distortion occurs locally and suddenly.

Even though identifying the contribution of small-scale events in heating the corona by exploring a numerical simulation with the specific identification method has been proven a difficult task, the results point in a specific direction. Multiple events with small spatial extent, which live shortly and have stochastic nature is the largest population of events in the current study.

\section{Paper III}

This paper represents our effort to understand the manifestation of Joule heating events in observations by synthesising three observational tools using
the Bifrost data. The tools are: Synthesised Extreme Ultra-Violet (EUV) filters of the Atmospheric Imaging Assembly (AIA) instrument, Emission Measure (EM), and time-lag maps using synthesised AIA/EUV filters. This paper also discusses the difference between regions that exhibit only heating events and regions that consider emitting material from the whole corona; that region describes mostly constant Joule heating. Note that we use the same model as in Paper I and Paper II, and the duration of investigation is 2850 s of solar time.

Our investigation is based on three pillars. First, we observe the manifestation of the identified heating events and constant Joule heating in the three observational tools. Secondly, we study the differences between radiation from only heating events and radiation from the whole corona. Lastly, we aim to explain for what reasons we cannot detect nanoflares in observations.

Off-limb and top-view of the three observation tools give the impression that heating events are thin elongated coronal strands. Those strands however are combination of heating events at different locations, ignited at different times that also are at different cooling phases. Combination of numerous events along the line-of-side exhibits a temperature range that spans in a relatively small temperature spectrum. Combination of strands embedded in the diffuse region of constant Joule heating compose multi-thermal coronal loops.

For the reason that strands and constant Joule heating are manifestations of the same heating mechanism, and since strands are parts of loops moving together, we find that they exhibit similar characteristics. For instance, the location of coronal strands with respect to the magnetic field is similar to that of constant heating. Unfortunately, we were not able to identify the exact mechanism of the diffuse emission, i.e., emission from regions that does not include heating events.

In the current study, we find that the EUV diffuse emission is at least one order of magnitude larger than radiation from heating events. More specifically, our analysis showed that the EUV diffuse emission at fixed positions exhibits flickering in the light-curve evolution with amplitude larger than the difference between diffuse emission and emission from only heating events.

In this study, we also report on the multi-thermal character of structures apparent in plots of the EM as a function of temperature. In the case of heating events, we observe multiple peaks due to the combination of multiple events at different location with different temperatures at different cooling phases. In the case of constant heating, we notice that the EM as a function of temperature exhibits a more coherent behaviour. These behaviours are indicators of the difference between the dynamic character of energy release from heating events and the smooth energy release from the residual region.
We also confirm that the degree of heating from heating events depends on the frequency of events exhibited locally and the magnitude of the energy release. The higher the frequency, the shorter the waiting time between consecutive events, and thus, the more prominent the heating is. In such a case, emission measure is more prominent in hotter temperature bins. Not only large frequency of events generates large emission measure, we find that few but strong energetic events generated in regions with large magnetic field magnitude can also generate large emission.

In time-lag analysis, we discover that the time-lag maps of the two regions, i.e. diffuse region and region exhibiting only heating events, are significantly different. Yet, the averaged temporal offsets (neglecting the zeroth values) are similar and in some cases those of the heating events are larger. The reason is that the light-curves are composed of signals from several events at different heights, at different cooling phases. It is similar to the case in which an event occurs during the cooling phase of another event prolonging its decay phase.

In the current paper, we also report on the calculation of the timescale of the theoretical radiative cooling when radiative cooling is the dominant cooling mechanism in an optically thin atmosphere. We find a small difference between that and the one calculated via cross-correlation of the AIA filters, with the former being slightly larger than the latter.

Being able to identify heating events and compose synthetic observations allows us to identify the reasons we cannot resolve small scale events in real observations. In the current study, we find evidence for justifying the reasons we cannot resolve small-scale events in synthetic observations of the EUV filters of the AIA instrument, even when using better resolution. Those are: 1) Heating events generate intensity and emission measure that are at least one order of magnitude smaller than those of constant heating, therefore any traces of heating events are hidden under the constant heating. 2) No distinctive difference is apparent between the characteristics of the two regions during visual inspections. 3) Since strands are parts of loops that follow their motions, we cannot differentiate the two in real observations.
CHAPTER

Future opportunities

The work done during my Ph.D. can be extended into other regions that need a method to identify and explore local enhancements of quantities suffering from large background noise or other sources of contamination. For instance, it can be extended to the study of current sheet formation in the chromosphere, or the photosphere in three-dimensional numeric simulations so to explore the footpoints of Quasi-Separatrix-Layers.

In studies in which numeric resolution is larger than the one we use here, velocity gradients are also larger. Therefore, viscous heating can become a very important term in terms of heating the solar corona. In such case, our segmentation method could also be implemented on the viscous heating term and make analysis in parallel to Joule heating. That analysis would be useful especially in regions that is speculated that exhibit magnetic reconnection. In such analysis, the effects of magnetic reconnection and how exactly energy is released could be explored in greater detail revealing very interesting aspects of the process.

After the identification of the local enchantments of heating terms in MHD simulations, codes that include multiple species, such as particle-in-cell (PIC) codes, could be used to simulate what happens locally and to check how particles are accelerated. One could also study what kind of instabilities, if any, are triggered at those regions. That analysis would shed some light on the processes that lead to local increase of the resistivity and viscosity.

Another use of our study is to synthesize spectra of other observational instruments for regions that exhibit only heating events. For instance, in simulations where the temperature reaches 10 MK, we could synthesize hard X-rays, soft X-rays or other spectral lines of IRIS, and Hinode that focus on the transition region and the chromosphere. This kind of work could also help us to set better constrains on what scales of heating events could be observed in potential future missions.
Another possibility of our work is to use machine learning (ML). ML could unveil a new path on data analysis in solar physics. Using our method of identifying heating events in simulations and by formulating parameters that could be used in ML algorithms, we could train models that could identify heating events that a segmentation method cannot resolve. Machine learning could also help solar physicist to identify new patterns in data related to magnetic reconnection and corona heating. Combining therefore simulations, synthetic observations, real observations and machine learning could ultimately help, if ever possible, to identify which parameters-observables can be used on the prediction of hazardous solar flares and coronal mass ejections.

Even with the most sophisticated methods of identifying multi-dimensional structures, and tools that analyse solar images, the complexity of a problem never vanishes, it is only reduced. In the study of the solar coronal heating, we will never be sure if we have identified the maximum possible amount of heating from impulsive events. In observations, we have limitations imposed by several factors such as: high signal to noise level, overlapping of filter’s temperature response functions, projection effects, temporal and spatial overlapping between heating events, resolution, contamination from foreground and background sources of heat. Even if we use numerical simulations to reduce few of the obstacles that observations bear, yet there are other important problems imposed by the nature of the solar corona. For instance, as far as we understand, there is no way to know about the background heating and how it is related to unresolved heating events. As far as we know, there is no method to identify heating events that release energy below the background heating or noise level. Supervised machine learning however could help us to identify few unresolved heating events because such algorithms explore data in higher dimensions.
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Part III

Publications
Identification of coronal heating events in 3D simulations.

Charalambos Kanella & Boris V. Gudiksen
www.aanda.org/articles/aa/abs/2017/07/aa30748-17/aa30748-17.html
Identification of coronal heating events in 3D simulations

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ABSTRACT

Context. The solar coronal heating problem has been an open question in the science community since 1939. One of the proposed models for the transport and release of energy generated in the sub-photospheric layers and photosphere is the magnetic reconnection model that incorporates Ohmic heating, which releases a part of the energy stored in the magnetic field. In this model many unresolved flaring events occur in the solar corona, releasing enough energy to heat the corona.

Aims. The problem with the verification and quantification of this model is that we cannot resolve small scale events due to limitations of the current observational instrumentation. Flaring events have scaling behavior extending from large X-class flares down to the so far unobserved nanoflares. Histograms of observable characteristics of flares show powerlaw behavior for energy release rate, size, and total energy. Depending on the powerlaw index of the energy release, nanoflares might be an important candidate for coronal heating; we seek to find that index.

Methods. In this paper we employ a numerical three-dimensional (3D)-magnetohydrodynamic (MHD) simulation produced by the numerical code Birost , which enables us to look into smaller structures, and a new technique to identify the 3D heating events at a specific instant. The quantity we explore is the Joule heating, a term calculated directly by the code, which is explicitly correlated with the magnetic reconnection because it depends on the curl of the magnetic field.

Results. We are able to identify 4136 events in a volume \(24 \times 24 \times 9.5 \text{ Mm}^3\) (i.e., \(768 \times 768 \times 331\) grid cells) of a specific snapshot. We find a powerlaw slope of the released energy per second equal to \(\alpha_E = 1.5 \pm 0.02\), and two powerlaw slopes of the identified volume equal to \(\alpha_V = 1.53 \pm 0.03\) and \(\alpha_S = 2.53 \pm 0.22\). The identified energy events do not represent all the released energy, but of the identified events, the total energy of the largest events dominate the energy release. Most of the energy release happens in the lower corona, while heating drops with height. We find that with a specific identification method large events can be resolved into smaller ones, but at the expense of the total identified energy releases. The energy release that cannot be identified as an event favors a low energy release mechanism.

Conclusions. This is the first step to quantitatively identify magnetic reconnection sites and measure the energy released by current sheet formation.

Key words. keywords: Magnetohydrodynamics: MHD – Sun: Corona – Sun: Flares

1. Introduction

The solar corona is counter intuitively much hotter than the solar photosphere. Energy cannot be directly transported from the photosphere to the corona through heat conduction or mass motions therefore dividing the so-called “coronal heating problem” into two problems: An energy transport problem, and a dissipation problem. It has been shown that sound waves are not able to carry energy into the corona (Carlsson & Stein (2002); Carlsson et al. (2007)), leaving the magnetic field as the main ingredient in the transport problem.

The tremendously large mechanical energy generated by the motions of the photosphere and the underlying convective layers can heat the solar corona if energy can be transported and released there (Gold 1964). The magnetic field, anchored in the photosphere, extends through the solar atmosphere, enabling the mechanical energy to propagate via Poynting flux towards the corona. If the energy initially has no release mechanism, the energy is stored increasingly in the magnetic field until an instability occurs and suddenly a fraction of the stored energy is released.

Since the ceaseless motion of the anchored magnetic field shuffles the magnetic structures, magnetic gradients can increase and magnetic reconnection can be triggered, creating the instability necessary to dissipate the stored energy (Parker (1983b); Parker (1983a)). This is the mechanism of flares, and due to the large magnetic field gradients, current sheets are formed at the reconnection sites. For a given distribution of magnetic polarities in the photosphere, the potential current-free field in the atmosphere is the lowest possible energy state of the field. A field configuration with the same photospheric polarity distribution, but a higher energy, has the energy stored in electric currents distributed throughout the field. As a consequence, a part of the stored magnetic energy is released via Ohmic (Joule) heating (Low 1990), leaving behind a newly formed magnetic configuration simpler than before (Galsgaard & Nordlund 1996).

According to Priest & Titov (1996); Priest & Forbes (2002) and Priest & Pontin (2009) there are four types of reconnection, each with a dissipation site with a different shape. First, there is the so-called “spine reconnection” in which the current and therefore the dissipation site is located along a field line that passes infinitely close to a null point, the spine. Secondly, there is the so called “fan reconnection”, in which the dissipation site is located at the fan surface (a set of field lines that leaves or approaches the null point forming a plane incorporating the null point. Separator reconnection, in which the dissipation sites lay along a separator that is separating two or more regions; regions
where the topology of the magnetic field is different. The final type of reconnection is in a “quasi-separatrix layer” (QSL). Here no null points or separatrices need to be present, but these are regions where the magnetic field has large gradients. Reconnection in QSLs is related to the slip-running reconnection as shown by Janvier et al. (2013) in numerical simulations. Which type of reconnection occurs depends on the nature of the footpoint motions and the structure of the magnetic field.

According to Parker (1972) and observations (Parker 1988), the nanoflare heating model can heat the solar corona, if a very large number of these events occurs endlessly in order to satisfy the energy requirements of the corona to sustain the high temperature. Despite the progress of the instrumentation employed to observe the sun and especially the flaring events, it is still impossible to observe nanoflares. According to observations, the frequency of energy release from flaring events is distributed as a powerlaw function, \( N(E) \propto E^{-\alpha} \), where \( \alpha \) is the powerlaw index and \( N(E) \) the number of events in the energy range \( E \) and \( E + dE \). What makes the power index important is the fact that if the index is larger than two, then nanoflares have a larger contribution to the energy budget than large flares (Hudson 1991), thus making the nanoflare model a powerful candidate for coronal heating.

Numerous theoretical investigations (Lu & Hamilton (1991); Georgoulis & Vlahos (1996); Morales & Charbonneau (2008); Hannah et al. (2011); Aschwanden et al. (2014)) into how the size distribution (i.e., powerlaw distribution) of flares is formed suggest that flares are manifestations of loss of equilibrium in a system that evolves naturally towards a nonequilibrium state. Flares appear when a critical point is passed and the system relaxes by releasing a fraction of the stored energy and thus, self-organisation is achieved and the system reaches a less stressed state. This picture was conceived first by Bak et al. (1988) for avalanches in sandpiles and used in solar physics by Hudson (1991), in which the powerlaw size distributions is a result of the stochastic energy release. In other words, it is impossible to predict how much energy the system will release when loss of equilibrium occurs, but we can expect that small events are more likely to occur than larger ones, and the maximum energy release that could be released is the total excess of energy stored in the magnetic field.

It is extremely difficult to specify the powerlaw index of the frequency distribution because of the observational biases. Observations struggle with the determination of structures along the line of sight and the noise from background and foreground sources. For instance, observations of flaring events suggest that the spectral index of the thermal energies for M- and X-class GOES class flares is \( \alpha_0 = 1.66 \pm 0.13 \) ( & Shimizu 2013). However, the determination of thermal energies requires knowledge of the volume occupied by the flaring events (Benz & Krucker 2002). Since, the projected area is the only geometrical aspect extracted from observations, scaling laws must be used in order to make assumptions for the third dimension (e.g., Benz & Krucker (2002); & Shimizu (2013)). In addition, as revealed by Morales & Charbonneau (2009), the projected area of flares, and thus, the assumed volume, depends on the projection (e.g., Fig. 3 in the same reference). For instance, different spectral lines target different depths in the solar atmosphere and, therefore, different flare areas are observed. Also, the temperature and emission measure needed to calculate thermal energy can be found through the fitting of an isothermal model spectrum to either the flare spectrum or the ratio of images in multiple wavelengths. Conclusively, the ambiguities of the models fitted in combination with the bias on the observational parameters result in large uncertainties.

A broad range of powerlaw slopes has been derived for different size distributions (see table 4 in Aschwanden et al. (2014)). Different slopes of the frequency of occurrence of solar flares in different passbands have been extracted; for example \( \alpha = 1.2 - 2.1 \) for peak fluxes and \( \alpha = 1.4 - 2.6 \) for powerlaw slope of total fluence in EUV, UV and Hα. These results point out a high dependence of the statistical analysis on many parameters, such as the method used to detect and select flaring events, the event definition, the synchronicity of the images in different spectral lines or filters, the goodness of sampling at the lower (due to finite resolution) and higher ends (due to incomplete sampling, which causes truncation effects), the number of events, the identification of the duration of a flaring event, the fitting methods and the error bars used in fitting, and finally, the correct subtraction of background heating and noise. A combination of all these criteria are found to affect the powerlaw index (Parnell & Jupp (2000); Benz & Krucker (2002); Aschwanden (2015)). As stated also by Hannah et al. (2011), the large range of powerlaws in different studies from various researchers (see Fig. 2 in Hannah et al. (2011)) depends on the methodology and instrumentation used in different periods during the solar cycle.

The last confusing factor is that the powerlaw indices quoted are often for very different things, such as size, max temperature, fluence in different filters, and so on, which is also done above.

Magnetic reconnection is strictly an aspect of the magnetic topology and cannot be directly observed; only its effects can be observed. In order to have a magnetic reconnection event, the magnetic field must be highly distorted. An explicit consequence of the magnetic field distortion in magnetohydrodynamics (MHD) is the formation of electric current sheets, of which the magnitude depends on the degree of distortion (curl of magnetic field). The current sheets release energy locally via joule heating, and the magnetic field relaxes to a lower energy state. Due to the difficulty of locating magnetic reconnection events in observations and simulations, joule heating is the best next available proxy that might trace those events. At the moment, exploring this quantity is our best chance to study the environment around a magnetic reconnection event or a collection of such events; for example, a nanoflare storm (Viall & Klimchuk 2011). However, we should not forget that there may be locations of highly distorted magnetic field, without magnetic reconnection, but those regions are also important because they trace large magnetic activity.

Observations have so far not been able to decide the importance of flares in coronal heating, so in this paper we will use a different method. 3D MHD numerical models together with the correct identification algorithm can detect flaring events and extract them from the simulation data and flare parameters can be derived. Because of the completeness of the data in the simulation we can derive the following parameters for each flare (heating event): Volume, energy release, maximum energy release rate and height of formation. The correctness of these parameters of course relies on the numerical code being able to reproduce a realistic model of the solar atmosphere. This paper does not discuss the ability of the numerical code to do so (see Leenaarts et al. 2009, for such an investigation), but merely describes our post processing methods and results of those methods.

The remainder of this paper is organised in the following way: In Sect. 2.1 we briefly describe the Bifrost code (Gudiksen et al. 2011) used to simulate the sun from the convection zone up to the corona. In Sect. 2.2, we explain the method used to identify
heating events, while in Sect. 3, the results of our investigation along with the statistical analysis (i.e., in 4) are discussed. Finally, in Sect. 5 we sum up the main points of the current work and discuss in detail what we find.

2. Method

2.1. Bifrost simulation

The Bifrost code (Gudiksen et al. 2011) is a massively parallel code, that can simulate a stellar atmosphere environment from the convection zone up to the corona. It can include numerous special physics and boundary conditions so as to describe the stellar atmosphere in a more detailed manner. It solves a closed set of 3D MHD partial differential equations together with equations that describe radiative transport and thermal conduction. The system of equations is solved on a Cartesian grid using 6th order differential operators, 5th order interpolation operators along with a 3rd order method for variable time-step.

The code includes different processes occurring in the convection zone, photosphere, chromosphere, transition region and corona. In the convection zone, the code solves the full radiative transfer including scattering. The code treats the radiative transfer in the corona as optically thin. In the region of the chromosphere, where the atmosphere is optically thin for the continuum but optically thick for a number of strong spectral lines, the radiative losses are calculated from the procedure derived by Carlsson & Leenaarts (2012).

Both the radiative and conductive processes are described via the equation of internal energy which has the following form:

$$\frac{\partial e}{\partial t} + \nabla \cdot eu = Q_s - \Lambda - P \nabla \cdot u + Q_l + Q_v,$$

where $e$ is the internal energy per unit volume, $u$ the velocity vector, $P$ the gas pressure, and $Q_s$ the heating/cooling derived via the Spitzer thermal conduction along the magnetic field (Spitzer 1962). $Q_l$ represents the Joule heating, $Q_v$ the viscous heating, and $\Lambda$ the cooling or heating produced by the emission and absorption of radiation.

In the current work, we simulate the region from the solar convective zone up to the corona. The simulated volume starts 2.5 Mm below the photosphere and extends 14.3 Mm above the photosphere into the corona. We use periodic boundary condition in the horizontal x–y plane; in the vertical z–direction, the upper boundary is open, while the lower boundary is open, but remaining in hydrostatic equilibrium enabling convective flows to enter and leave the system. By controlling the entropy of the material flowing in through the bottom boundary, the effective temperature of the photosphere is kept roughly constant at 5,780 $\times$ $10^3$ K. The simulation box has a volume equal to $24 \times 24 \times 16.8$ Mm$^3$, which is resolved by 768 $\times$ 768 $\times$ 768 cells. Therefore, the horizontal grid spacing $dx = dy = 31.25$ km, whereas the vertical grid spacing varies to resolve the magnetic field, temperature, and pressure scale heights. Hence, the vertical spacing ($dz$) is approximately equal to 26.09 km in the photosphere, chromosphere and transition region, while it increases up to 165 km at the upper boundary in the corona. This simulation incorporates two strong magnetic regions of opposite polarity, which are connected with a magnetic structure with a loop-like shape. The magnetic field is initially set vertically at the bottom boundary and extrapolated to the whole atmosphere assuming potential field, while a horizontal 100 Gauss field is fed continuously in at the lower boundary producing random salt and pepper magnetic structures in the photosphere. Further details of the simulation setup can be found in Carlsson et al. (2016) which explains a similar setup, except the one describe in Carlsson et al. (2016) also includes the effects of non-equilibrium ionization of hydrogen.

To quantitatively study the effects of magnetic reconnection, we choose to analyze the joule heating term, which is calculated directly in Bifrost through Ohms law, using a non-constant electric resistivity. The resistivity (magnetic diffusivity) used in Bifrost code is numerical so as to ensure stability of the explicit code. The numerical resistivity is one of the diffusive terms used in the solution of the standard MHD partial differential equations. Bifrost employs a diffusive operator which is split into two major parts: a small global diffusive term and a location-specific diffusion term (Gudiksen et al. 2011). The numerical resistivity is constructed as a function of the grid size, so as to prevent current sheets from becoming unresolved; this gives rise to Reynolds numbers with order of magnitude larger than one. The exact formulation of the resistivity is described in equation 5 in Guerreiro et al. (2015). The electric resistivity is kept as low as possible, while still stabilizing the code. That means that the resistivity is not uniform in the computational box and it is larger than the microscopic resistivity throughout. The resistivity in the highest-current regions is consequently larger than everywhere else, but the sun also seems to have a method of increasing the resistivity locally, otherwise fast reconnection would not be possible (Biskamp (1986); Scholer (1989)). How the sun is able to increase the electrical resistivity locally is not known, but several methods are possible, such as instabilities in the central current sheet leading to small-scale turbulence. How the resistivity behaves is unknown, except that it does increase in reconnection sites in the solar atmosphere. Bifrost therefore uses the most conservative value of the electric resistivity available, which is the value of the resistivity that keeps the code stable.

2.2. Identification method

We choose a region of interest (ROI), which starts from the lower corona, 3.28 Mm above the photosphere, where the temperature is on average equal to 1 MK, and extends up to the top of the simulation box. The volume of interest is resolved by $768 \times 768 \times 331$ grid cells, spanning $24 \times 24 \times 9.5$ Mm$^3$.

Identifying locations with current sheets seems at first simple. Locating 3D volumes with high Joule heating should be easy enough, but it turns out not to be so simple. The problem we encounter is that the current sheets in 3D are generally not 2D flat structures, as the cartoon-like pictures of 2D reconnection would suggest, but much more complex. Often the “background” current level is higher in places with many current sheets, so it is not easy to separate one current sheet from another. That is in some ways similar to the problems experienced by observers, where the background is causing large problems for the interpretations. The method we have identified as the best is a powerful numerical tool, named “ImageJ”, used in medical imaging and bio-informatics to perform multi-dimensional image analysis (Ollion et al. 2013; Gul-Mohammed et al. 2014). ImageJ is an open-source tool in which users contribute by creating plugins for different purposes, making them available to everyone. In our case, we use the plugin “3D iterative thresholding” (also known as AGITA: Adaptive Generic Iterative Thresholding Algorithm (Gul-Mohammed et al. 2014)), which first detects features for multiple thresholds, and then tries to build lineage between the detected features from one threshold to the next, and finally chooses the features that fall within the pre-specified criteria. Therefore, different features can be segmented at different
of the ROI. The powerlaw fitting consequently has to take these occurrence of small-scale events. The largest events will naturally be missing due to the limited volume and energy density of the ROI. The powerlaw fitting consequently has to take these limitations into account, and more free parameters then need to be included in the fit:

$$N(x) = n_0 \cdot (x + x_0)^{-\alpha}, \quad (2)$$

where $x$ denotes the specific quantity and $n_0$ is a constant that depends on the total number of features ($n_f$) in a range bounded from the maximum ($x_2$) and minimum ($x_1$) values

$$n_0 = n_f (1 - \alpha)[x_2^{1-\alpha} - x_1^{1-\alpha} + 1], \quad (3)$$

where $n_f = \int_{0}^{\infty} N(x) dx$ is the result of normalisation. Thus, we try to fit $n_0$, $\alpha$, and $x_0$ of equation 2 via $\chi^2$ minimisation. The specific powerlaw fitting technique reduces the number of data points needed to fit the powerlaw, but in our case the difference between the identified events and the reduced ones is insignificant.

3. Results

The method mentioned in the previous section represents an effort to identify discrete heating events. We try to separate those events from other sources of heating that are not included in the Joule heating term.

Our method identifies initially large features, which are clusters of events and each comprised of more than 10^4 grid-cells. They are mostly located at the bottom of the corona, where most of the current sheets are formed, a result similar to what was observed by Gudiksen & Nordlund (2005). Features that have large horizontal cross-sections at the bottom of the corona lead to large volume when we perform the clustering method of Hoshen & Kopelman (1976). From looking at a 3D rendering of the large events and plotting the energy release along random lines throughout their volumes, it is clear that very large events are collections of many small events closely packed in space. Our method is clearly not able to identify features that are this closely packed.

The volume of the events is 4% of the total coronal volume and the total energy contained in all events is only 12% of the total Joule heating in the corona. The remaining 88% of joule heating is a combination of unsatisfied threshold criteria, which either do not satisfy the minimum resolution criterion or the method is unable to find the full extent of an event. The unresolved features with a volume less than 125 grid cells account for less than 0.1% of the total joule energy term in ROI, so the unresolved features are not a significant source of error.

Most of the heating events are located at the bottom of the corona, a fact that can be deduced from the density of features in Fig. 1. Both illustrations in Fig. 2 show that the heating events extend upward or hover in the corona. The analysis also shows that they usually have three shapes: Fan-like, spine-like, and loop-like shapes. The same shapes have also been observed in simulations by Hansteen et al. (2015).

4. Statistical analysis

In Fig. 2 we are seeing the result of the heating events imprinted at a random moment in their life, and in the following we do statistics on these events.

In Fig. 3, we plot the differential size distribution of released energy rate over logarithmic bin. The differential size distribution is defined as the number of features with sizes within a certain bin, divided by the bin size. To calculate the number of bins,
we use the formula derived by Aschwanden (2015). The formula has the following form:

\[ n_{\text{bin}} = 10 \log_{10} \left( \frac{x_{\text{max}}}{x_{\text{min}}} \right), \]  

where \( x_{\text{max}} \) and \( x_{\text{min}} \) are the maximum and minimum values in the data set, respectively. We notice that the distribution of the released energy rate follows a powerlaw function, which has the following form:

\[ y = n_0 x^{-\alpha}, \]  

where the powerlaw index has a value of \( \alpha = 1.5 \pm 0.04 \). The error is calculated as \( \alpha / \sqrt{N_F} \), where \( N_F = 1368 \) is the number of events and the powerlaw function is fitted within a range of released energy rate spanning from \( 2 \times 10^{18} \) erg/s to \( 2 \times 10^{22} \) erg/s.

The volume of events is also important. In Fig. 4, we plot the differential size distribution of volume, along with the fitted powerlaw function. What we find is two spectral indices \( \alpha_V = 1.53 \pm 0.03 \) within a range between \( 10^{21} \) and \( 10^{23} \) cm\(^3\) and \( \alpha_V = 2.53 \pm 0.22 \) within a range between \( 10^{23} \) and \( 2 \times 10^{24} \) cm\(^3\). To find which scale of events’ volume is the most important in terms of space filling, we plot in Fig. 4 the cumulative size distribution of this size. It seems that large-scale events, that is, structures larger than \( 10^{23} \) cm\(^3\), which correspond to 137 events occupy 40% of the resolved volume in the ROI.

We also check for any correlation between volume and energy release per volume. Figure 5 depicts the two quantities plotted against each other for all identified events. The two quantities seem not to have any clear correlation. Features of any volume span more than three orders of magnitude, and features with any energy rate density span two and half orders of magnitude in volume.

To further test the connection between volume and the energy release rate per volume, we perform Spearman’s rank and Pearson linear correlation. The rank correlation showed a merely bad global correlation, that is, \( \rho = 0.4 \) (this correlation varies between 0 and 1, smaller values indicate good rank correlation), whereas there is very weak linear correlation (i.e., \( \rho = 0.53 \)) between the two quantities (Pearson correlation varies between -1 and 1).

Figure 1 shows the maximum energy release rate of each event as a function of the height at which the specific maximum energy release is located. If we assume that the location of the maximum energy release is the location where an event is initially triggered, then the plot suggests possible height of instability triggering.

From the normalized cumulative plot, and from the plot itself, we observe that the lower corona contains not only most of the heating events but also the most energetic ones. Almost 40% of the total number of events are located between 3 and 4 Mm above the photosphere. The number of events in larger heights up to 14 Mm above the photosphere is distributed almost evenly while the maximum energy release rate drops with height. There-
calculated as over 137 data points in the range between $10^{22}$ and $10^{24}$ cm$^3$. In layers, a trend also observed by Gudiksen & Nordlund (2002).

Fig. 4: Plot of differential size distribution of the identified features’ energy rate in logarithmic scale representing $N = 4136$ identified features (diamonds). A powerlaw index $\alpha = 1.50 \pm 0.02$ is found, having goodness-of-fit $\chi^2 = 14.28$; the error is calculated as $\alpha / \sqrt{NF}$, where the number of features of the fitted function is $NF = 3818$ (dashed line), excluding data with energy rate less than background value $x_0 = 4 \times 10^{17}$ erg/s.

Fig. 5: Plot of energy release rate over volume versus volume of identified features in logarithmic scale.

tify three dimensional joule heating events at a randomly selected snapshot from a numerical simulation of the solar corona.

Using the Bifrost code, we simulate the solar environment enabling us to identify events in the modeled solar corona with high resolution. Those events release power that spans almost four orders of magnitude starting from $10^{17}$ erg/s, and has volume spanning three orders of magnitude starting from $10^{21}$ cm$^3$. The events follow a powerlaw over many orders of magnitude just like many other self-organized critical systems, suggesting that the formation of these structures share the same physical mechanism that scale in the energy and volume regimes.

The outcome is the result of the stochastic nature of magnetic reconnections’ ability to release energy stored in the magnetic field, when it reaches a threshold. The stochastic nature originates from the fact that magnetic reconnection triggers an instability in which a random fraction of the energy stored in the magnetic field is released. In some cases observations show that this system appears to have memory of previous energy releases as magnetic reconnection events are sometimes observed to happen at the same location within a short amount of time, such as in homologous flares (Fokker 1967). This is, in our opinion, caused by the stochastic nature of the total energy release. If the energy released is relatively small compared to the surplus energy stored in the magnetic field at a specific location, then the fact that energy is released might produce conditions where only a small increase in the stored energy can lead to yet another energy release.

We find that there is no global linear relation between energy release and volume, and the Spearman’s rank correlation shows a merely bad correlation.

Generally, the heating is mostly concentrated at the bottom of the corona and gradually drops with height because the magnetic field magnitude also drops with height; a fact that was pointed out and explained by Gudiksen & Nordlund (2002). A consequence of the distribution is that energetic events are more likely to be generated in the lower corona.

The differential size distribution of released energy rate and volume follow a powerlaw distribution. What we find are slopes that favor the release of energy in large events.

As illustrated in Fig. 2, the method can resolve large structures into smaller ones and identify where most of the heating occurs locally even though some of the energy is no longer in

5. Discussion and Conclusions

This paper discusses the implementation of a multi-thresholding technique implemented in 3D MHD simulation aiming to iden-

fore, the heating in the lower corona is larger than in the upper layers, a trend also observed by Gudiksen & Nordlund (2002).
identified events. The unresolved energy might be attributed to two categories of mechanism: technical and physical. In the first category, unsatisfied thresholding criteria, unresolved features or numerical heating due to noise have an impact on identifying real heating events. The unresolved energy could be due to heating from other sources, such as MHD waves that distort the magnetic field, or remnants of current sheets after energetic events that burn slowly (Janvier et al. 2014). Finding dissipating MHD wave modes in this snapshot is beyond the scope of this work.

Our method cannot identify all the energy released as events. If the large part of the total Joule heating, which is not identified as events in this work, actually is small events, then they would be added to the low-energy tail of our powerlaw plots and would then increase α. Without any evidence for this being the case, we cannot say if the remaining 88% of the total Joule heating is in the form of small events. If they were, we would most likely see a powerlaw index being close to or above two since most of the energy would then be delivered through small events. We are at the moment considering paths to establish this.

The time evolution of the heating events is another unknown which is beyond the scope of this work. What we analyze is the fingerprints of heating events at a specific time. We do not take into account the lifetime of the events. Several authors have reported lifetimes of small and large events not being the same or even the increase and decrease of heating events being dissimilar (Lee et al. (1993); Morales & Charbonneau (2008); Christe et al. (2008); Hannah et al. (2011)). Therefore, the duration of the heating events, which is usually considered in observations, may affect the calculated powerlaw indices when energy release is studied, instead of energy rate as we do in the current analysis.

We are able to extract information about the released energy rate and volume ranges of identified events. The smallest event we identify is significantly smaller than the lower limit for what we can observe. Even though we have much more information available through our numerical model, it is interesting how similar the problems of identifying events are from an observational and numerical stand point. The problems arise due to different limitations.

The results of our method can be compared with similar studies that also investigate the Joule heating term in simulations or observations using different methods for identifying heating events. For example, Bingert & Peter (2013) divide their simulation box into cubes of identical sizes and the temporal dimension to constant time-intervals and finally they count the energy released in those boxes. Moraitis et al. (2016) use a partialional clustering code. The code uses the Manhattan distance to group 3D voxels above a threshold into clusters. Guerriero et al. (2015) find all the local maxima of Joule heating terms in a 3D MHD simulation. They then try to identify 3D events by locating the minimum value above a threshold, the threshold is defined as a constant fraction of the local maximum value. Regardless of how each study defines a heating event, all authors find that the released energy follows a power-law distribution with slopes flatter than two. Interestingly, Bingert & Peter (2013) also find that heating in the corona drops with height. It is remarkable that our power-law index for the rate of energy release and that of the energy release found by Bingert & Peter (2013) are very similar.

In addition, our power-law of volumes at the right part of the knee is almost identical with that found by the same authors for the same range of volumes. While being able to identify smaller structures with our method, we see that the slope becomes flatter.

Our identification method is a first step towards finding the powerlaw exponent of the distribution of heating events. The ex-

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Investigating 4D coronal heating events in magnetohydrodynamic simulations

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ABSTRACT

Context. One candidate model for heating the solar corona is magnetic reconnection that embodies Ohmic dissipation of current sheets. When numerous small-scale magnetic reconnection events occur, then it is possible to heat the corona; if ever observed, these events would have been the speculated nanoflares.

Aims. Because of the limitations of current instrumentation, nanoflares cannot be resolved. But their importance is evaluated via statistics by finding the power-law index of energy distribution. This method is however biased for technical and physical reasons. We aim to overcome limitations imposed by observations and statistical analysis. This way, we identify, and study these small-scale impulsive events.

Methods. We employed a three-dimensional magnetohydrodynamic (3D MHD) simulation using the \textit{Bifrost} code. We also employed a new technique to identify the evolution of 3D joule heating events in the corona. Then, we derived parameters describing the heating events in these locations, studied their geometrical properties and where they occurred with respect to the magnetic field.

Results. We report on the identification of heating events. We obtain the distribution of duration, released energy, and volume. We also find weak power-law correlation between these parameters. In addition, we extract information about geometrical parameters of 2D slices of 3D events, and about the evolution of resolved joule heating compared to the total joule heating and magnetic energy in the corona. Furthermore, we identify relations between the location of heating events and the magnetic field.

Conclusions. Even though the energy power index is less than 2, when classifying the energy release into three categories with respect to the energy release (pico-, nano-, and micro-events), we find that nano-events release 82% of the resolved energy. This percentage corresponds to an energy flux larger than that needed to heat the corona. Although no direct conclusions can be drawn, it seems that the most popular population among small-scale events is the one that contains nano-scale energetic events that are short lived with small spatial extent. Generally, the locations and size of heating events are affected by the magnitude of the magnetic field.

Key words. keywords: Magnetohydrodynamics: MHD – Sun: Corona – Sun: Flares – methods: statistical

1. Introduction

The mechanical energy contained in the flows of the convective zone and the photosphere is so big that only a fraction is needed to heat the solar corona (Gesztelyi et al. 1986). It is conventional to attribute the medium of transferring the energy generated by the mechanical drivers to the magnetic field. Other mechanisms have been proven not to work. For instance, energy cannot be transported from the photosphere to the corona via mass convection, nor via sound waves because this class of waves is dissipated or reflected before reaching the corona (Carlsson \& Stein 2002; Carlsson et al. 2007). Small velocity amplitude magnetohydrodynamic (MHD) waves can reach the corona, but those do not carry enough energy (Hara \& Ichimoto 1999; Tomczyk et al. 2007). The only waves that can penetrate into the region and transport enough energy are Alfvén waves, however dissipating these waves is not so easy (van Ballegooijen et al. 2011; Asgari-Targhi \& van Ballegooijen 2012).

The magnetic field, anchored in the photosphere, extends throughout the solar atmosphere, establishing a link between the photosphere and corona. This link enables mechanical energy to propagate towards the corona via the Poynting flux (Klimchuk 2006; Hansteen et al. 2015). There are two components of the vertical Poynting flux: the horizontal motions of the vertical component of magnetic field and the transport of the horizontal field by vertical motions. Both of these components transport energy into the corona.

The energy carried by the Poynting flux is stored in the form of currents. The process involves injection of energy that transforms a potential into a non-potential field. As a consequence, magnetic field gradients appear that are responsible for current sheet formation. Current sheets store any excess energy above the energy level of a potential field (Galsgaard \& Nordlund 1996; Gudiksen \& Nordlund 2005). In MHD, current sheets express the magnetic field gradients, i.e. $\mathbf{J} \propto \nabla \times \mathbf{B}$. However, the magnetic field cannot store infinite energy. At some point, a critical value is reached and energy is released impulsively in a stochastic manner. The maximum amount of energy that can be released is the non-potential magnetic energy, which is replaced continuously owing to the motions of the mechanical drivers in the photosphere and convective zone. As shown by Hansteen et al. (2015), the total energy input in the coronal region is “spatially intermittent and temporally episodic”, but in the long-term heating is almost constant.

The inclination between currents in current sheets and a magnetic field plays an important role in the work done. When a current is aligned with the magnetic field, then the exerted Lorentz
force on the plasma is zero, i.e. $J \times B = 0$. However, when there is an inclination between current and magnetic field, the Lorentz force is then non-zero and work is done. Then, energy stored in the currents in the presence of finite resistivity is dissipated, and cross-field currents release a part of the stored energy via joule heating (Low 1990). If currents (and thus electric fields) are perpendicular to the magnetic field, then the magnetic field topology changes significantly and magnetic reconnection occurs (Parker 1972).

The non-potential magnetic field can be mapped through quasi-separatrix layers (QSL) (Aulanier et al. 2006); QSLs are the equivalent to separatrices in 2D. While the stressing of the magnetic field continues and currents form, QSLs become thinner and magnetic field gradients larger until reconnection takes place (Aulanier et al. 2006). The high current density, helps to increase the resistivity locally and allows the magnetic flux of opposite polarity to reconnect. During magnetic reconnection several processes take place, such as direct thermal heating via joule heating, energy transport via acceleration of particles, excitation of waves, and shock generation.

Current sheets have scales that vary in a hierarchical manner from bigger to smaller scales. Current sheets can reach scales so small that magnetic energy dissipation via joule or viscous heating is feasible. Fragmentation of current sheets occurs mostly in regions with very large resistivity. The fragmentation stops when currents have scales, where resistive diffusion (Nordlund & Galsgaard 2012) or friction can act (van Ballegooijen 1986). Currents evolve on similar timescales as the magnetic field does. According to Galsgaard & Nordlund (1996), current sheet formation takes a few seconds, while current sheet dissipation can take from few to thousands of seconds.

The observational traces of magnetic reconnection are flares. Flares range in energy output from large ($10^{12}$ erg) to the smallest postulated but so far unobserved nanoflares ($10^{24}$ erg), spanning many orders of magnitude.

Statistics of flares are important because nanoflares, according to Parker (1972, 1988), can heat the solar corona if a very large number occur. According to observations, the frequency of energy release from flaring events is distributed as a power-law function $N(E) \propto E^{-\alpha}$, where $\alpha_E$ is the power index of energy, and $N(E)$ the number of events in the energy range $E$, and $E + dE$. If the index is larger than two, then nanoflares are more important energetically than large flares (Hudson 1991). Constraining the value of the power-law index has been the goal of numerous observational campaigns and investigations, but the value of the power-law index is still disputed. Examples of such observations are the following: in peak of hard X-rays (HXR), Christe et al. (2008) found $1.58 \pm 0.02$; in the fluence of HXR, Pérez Enriquez & Miroshnichenko (1999) and Crosby et al. (1993) found $1.39 \pm 0.01$, and $1.48 \pm 0.02$ respectively; in the fluence of soft X-rays (SXR) and peak of SXR, Drake (1971) found $1.44$ and $1.75$, respectively; in the peak of ultraviolet (UV) and extreme-ultraviolet (EUV) intensities, Aschwanden & Parnell (2002) found $1.71 \pm 0.1$ in 171Å, $1.75 \pm 0.07$ in 191Å, and $1.52 \pm 0.1$ in aluminium-magnesium filter on the Yohkoh spacecraft. Since very small events cannot be resolved by the current instrumentation and the observed power-law indices are smaller than two, taking the raw numbers from these works indicates that the power-law index is less than two, suggesting that large flaring events are more significant energetically than smaller flaring events.

Other quantities that describe heating events also follow power laws. For example, the duration of each event exhibits a power-law slope in observations that depends on the solar cycle. The slope has minimum value during the solar minimum and maximum during solar maximum. In fact, Aschwanden & Free-land (2012) found in 35 years of GOES observations that during solar minimum the slope is as small as 2, while during solar maximum the slope ranges from 2 to 5. In the literature, the volumes of flares are usually calculated by making strict assumptions, making them less reliable, but producing a power-law distribution with power-law indices that vary between 1.5 and 2.08 (examples are in table 9 in Aschwanden et al. (2014)).

However, finding the power-law index for flare distributions is not trivial owing to observational biases. Finding the volume of a flare is difficult because of our inherently 2D observations. Both background and foreground contamination makes the estimation of the distance taken up by the flare along the line of sight very difficult. The determination of thermal energies requires the knowledge of the volume occupied by the flaring events (Benz & Krucker 2002). We are only able to deduce information from observations about the area perpendicular to the line of sight, and therefore scaling laws depend on assumptions to calculate the volume (e.g. Benz & Krucker (2002); Aschwanden & Shimizu (2013)). There is no direct connection between the dimension of a flare in each of the three spatial dimensions, so we cannot find the volume of a flare from two measured dimensions (Morales & Charbonneau 2009). The passband used for the observations also produces different projected areas since they are sensitive to gas at different temperatures and the densities at the different temperatures are rarely equal. Finding the duration of flares is not trivial because flare identification algorithms depend on the identification technique and criteria used therein. These problems create uncertainties in the estimated parameters of the flares.

Sampling or selection bias is another problem that is rarely taken into account. Typically, the method used to detect and select flaring events produces these biases. The synchronicity of observations from different passbands has different effects on small and large flares. Short events are affected by the integration time, either because the events are drowned out by background (if the integration time is long) or under sampled (if the time between exposures are long). Resolution also under-represents low energy events, because small events produce smaller peaks if they have subpixel sizes. Larger flares can be subject to biases if the total observation time is too short. Finally, distributions can be skewed if a large number of small unresolved events are labelled as a single large event. The fitting method, the error bars used in fitting, and the correct choice of background heating and noise subtraction affect the power-law index (Benz & Krucker 2002). As stated also by Hannah et al. (2011), the large range of power-law slopes found in different studies from various researchers is also a product of the method used to extract results and the instrumentation employed during different periods during the solar cycle.

In this study, our most important goal is to study 3D heating events related to magnetic reconnection and evaluate their contribution towards heating the corona. This must happen in an experiment that overcomes most of the observational restrictions. To achieve this, we simulate the solar atmosphere using the Bifrost code (Gudiksen et al. 2011), use a relatively new method to identify 3D heating events, and follow their evolution in time.

Being able to identify 3D events gives us the opportunity to study them in detail. More specifically, we want to check to what extent small-scale events contribute to coronal heating, and to identify if there is a lower energy cut-off. In addition, we want to assess the contribution of joule heating events with respect to the total joule heating and magnetic energy in the corona. We also want to explore how heating events manifest themselves in
3D space, and check their evolution in time. Another objective of this study is to check if we can identify any scaling laws between energy, duration, and volume that could help observers to derive conclusions by observing one parameter instead of another. Moreover, we want to locate where heating events occur with respect to the magnetic field and compare the results with the literature.

This paper discusses the properties of heating events related to magnetic reconnections that have been identified in a 3D simulation. We study their individual and collective behaviours under the prism of coronal heating. The remainder of this paper is organised in the following way: In Sect. 2.1, we briefly describe the Bifrost code (Gudiksen et al. 2011); in Sect. 2.2, we describe the method used to identify the evolution of joule heating events, and the rest of the parameters. Section 3 reports on the findings. More specifically, Sect. 3.1 includes the results of our investigation on the geometrical properties of the 3D structures we identify, while Sect. 3.2 contains the distributions and power-law fits of duration, energy, and mean volume together with the cumulative distribution function (CDF) of the last quantity. We perform a statistical analysis of several parameters in Sect. 4. Finally, in Sect. 5, we discuss our findings and derive conclusions.

2. Method

In the current section, we briefly describe the Bifrost code used to create the snapshots of the solar atmosphere we will be analysing in this work. We also describe the method employed to detect heating events spatially and temporally in the region of interest (ROI).

2.1. Bifrost simulation

The Bifrost code (Gudiksen & Nordlund 2005; Gudiksen et al. 2011) is a 3D MHD code that can simulate a stellar atmosphere from the convective zone up to the corona. It can include numerous special physics and boundary conditions to model stellar atmospheres adequately. This code solves a closed set of MHD partial differential equations along with equations describing radiation transport, thermal conduction along the magnetic field, and a realistic equation of state. A Cartesian grid is used to solve the system of equations using sixth order differential operators, fifth order interpolation operators, and a third order Hyman method with variable time step. The description of the non-grey radiative transfer includes the scattering between optically thin and thick regions of the photosphere and chromosphere to model the region properly (Hayek et al. 2010), and a chromospheric radiation approximation where the energy balance is critically dependent on the scattering in strong spectral lines and optically thin radiation in the upper atmosphere.

The energy equation used in Bifrost is of special interest in this work. The radiative and conductive processes can be described through the following equation of the evolution of the internal energy:

$$\frac{\partial e}{\partial t} + \nabla \cdot e u = Q_C + Q_R - P \nabla \cdot u + Q_J + Q_N,$$  \hspace{1cm} (1)

where $e$ is the internal energy per unit volume, $u$ the velocity vector, $P$ the gas pressure, and $Q_C$ the contribution from the Spitzer thermal conduction along the magnetic field (Spitzer 1962). The parameter $Q_J$ represents the joule heating, $Q_N$ is viscous heating, and $Q_R$ energy contribution from the emitted or absorbed radiation.

In this paper, we also employ the simulation used by Kanella & Gudiksen (2017). We use the data from a simulation that includes a region enclosed between the solar convective zone and the corona. The simulated convective zone extends 2.5 Mm below the photosphere and the simulated box reaches 14.3 Mm above the photosphere. In the vertical direction $z$, the upper boundary is open, while the lower boundary maintains the convection flow by giving the inflowing gas enough entropy to maintain the correct effective temperature of the solar photosphere, i.e. 5780 K. In the horizontal $x$-$y$ plane, the numerical volume is periodic.

The simulation box contains $768 \times 768 \times 768$ cells and spans a physical volume of $24 \times 24 \times 16.8$ Mm$^3$. The horizontal grid spacing $(dx = dy)$ is constant and equal to 31.25 km, while the vertical grid spacing varies to resolve the magnetic field, temperature, and pressure scale heights. The vertical spacing $(dz)$ is roughly 26 km in the photosphere and chromosphere and increases slowly up to 165 km at the upper boundary. This simulation was created to resemble a structure of magnetic field network embedded in the quiet Sun (QS). The configuration contains two relatively strong magnetic regions of opposite polarity, which are connected with a magnetic structure that has a loop-like shape. Throughout the simulation a horizontal field of 100 gauss is injected in the inflowing regions at the lower boundary. This injection maintains the well-known salt and pepper magnetic field. A more detailed description of the simulation set-up can be found in Carlsson et al. (2016); the only difference is that the set-up described in Carlsson et al. (2016) also incorporates the effects of non-equilibrium ionisation of hydrogen.

For our analysis, we chose a ROI that corresponds to the corona. The ROI starts at a height of 3.28 Mm above the photosphere, where the temperature is equal to 1 MK, and extends up to the top of the simulation box excluding a few cells zones because they are affected by boundary conditions. Therefore, the volume of interest is $24 \times 24 \times 9.5$ Mm$^3$ and corresponds to $768 \times 768 \times 331$ grid cells.

2.2. Identification method

To study the effects of magnetic reconnection quantitatively, we choose to analyse the joule heating term in equation 1. The grid size is of the order of a few decades of kilometres and represents scales that are much larger than the physical scales at which physical resistivity and viscosity are effective. Therefore, Bifrost uses the minimum numerical diffusivity (resistivity), which ensures the stability of the code. Further details about the numerical resistivity and the heating term can be found in our previous work (Kanella & Gudiksen 2017) and in Gudiksen et al. (2011).

In our previous work (Kanella & Gudiksen 2017) we described the details of the numerical tool, i.e. ImageJ (Collins 2007; Ollion et al. 2013), and algorithm used to identify 3D structures in each snapshot, i.e. Adaptive Generic Iterative Thresholding Algorithm (AGITA) (Ollion et al. 2013; Gulumhanned et al. 2014). In the following, we describe the identification method and the quantity used for this purpose in different terms so as to understand the underlying process.

Magnetic reconnection is a topological phenomenon, therefore the identification of each event is difficult without a detailed study of each region, however the implicit effect of reconnection can be located. The best proxy we have to study such topological events is to investigate the joule heating term in the Bifrost code. Joule heating depends, among other parameters, on current density, which in MHD expresses the degree of magnetic field gradients. When there is inclination between the magnetic
field and currents, then work is done, and it is a requirement that part of the current is perpendicular to the magnetic field in order for the magnetic field to reconnect.

The method we employ in this work and in Kanella & Gudiksen (2017) depends on the ability of the algorithm to find spikes (local maxima) in the joule heating in 3D space, and follows the negative gradient in all directions with a constant pre-specified step. The process is performed for various thresholds (specified by the pre-specified step), each time with a lower boundary in joule heating at \( E_0 \). The process is repeated until the gradient at some level of the heating becomes a very small fraction of the local maximum that has volume that does not overlap with other identified structures. The 3D iso-surface of the joule heating at level \( E_0 \) around that local maxima gives the event volume, and thus the total energy of the event can be calculated. The strongest point of the method is the fact the method identifies different volumes at different values for \( E_0 \). The method is then repeated for the next local maxima. The results for each \( E_0 \) value for each spike are saved so as to which feature we consider the best option. For this purpose, we use pre-specified geometrical criteria, such as the largest volume between pre-specified limits.

It is important to point out, that this method does not attribute all the joule heating to identified heating events. A significant amount of joule heating is not attributed to events, either as a consequence of the choice to stop the event volume at the \( E_0 \) level or simply because the events are not strong or large enough. We note that the value of the pre-specified step that controls the \( E_0 \) threshold influences the volume of the identified structures. When the step is too large, then few, but large, structures are identified, whereas for a very small step numerous smaller structures are identified. For a decreasing step value, the total resolved energy becomes smaller and smaller. In our previous study (Kanella & Gudiksen 2017), we explained in a more technical manner how we choose the pre-specified step.

We perform the same procedure for 57 simulation snapshots, which are separated by 10 seconds, starting from \( t_1 = 830 \) s of solar time in our simulation. In order to find the connection between features and establish the link between 4D structures, we follow the evolution of each feature. Starting from snapshot \( i \), at time \( t_1 \), we check if there are other feature(s) at the same coordinates in the next snapshot \( i + 10 \) s, if yes then they share a common label, and our algorithm checks in the new coordinates of the new features (at \( t_1 + 10 \) s) for any features in the next snapshot (at \( t_1 + 20 \) s). The procedure continues to the next snapshot until no feature is identified, then the algorithm proceeds to the next feature in snapshot \( i \) at time \( t_1 \). Then, the same procedure continues for the features of the next snapshot, but only for those that had not been connected with other features in prior steps. Summarising the process, features that overlap even with one pixel in the fourth dimension are considered to be one single event progressing in time.

3. Results

Using our method, we identify 145306 features in 570 s of solar time. Figures 1 and 2 illustrate examples of our findings at \( t = 1130 \) s. We plot field lines over joule heating events to render the magnetic field topology in the corona with respect to the location of events. We choose 75 by 75 starting points for the field lines, equally distributed in the horizontal plane at the base of the corona. In Fig. 1, we represent the 2D slices of 3D joule heating events at the base of the corona together with contours of the vertical component of the magnetic field. Our aim is to identify any possible correlation between the magnetic field and density of heating events. Visual inspection shows that elongated and relatively large events form at low magnetic field magnitudes and preferably at regions where the magnetic field changes polarity. The relatively smallest identified events, however develop within regions of large magnetic field magnitudes.

The location of joule heating events is associated with the magnetic field configuration; it is required that there are large gradients in the magnetic field. The gradients of the magnetic field induce currents, which are partly dissipated through electric resistivity in the form of joule heating. We note that the magnitude of an event depends on the available magnetic energy. The magnetic energy in the corona is generally a function of the height above the photosphere, and does not vary significantly in the horizontal direction, because the magnetic field dominates the plasma and is configured in a force free state or at least very close to a force free state (Gudiksen & Nordlund 2005).

We calculate the amount of joule heating attributed to heating events by our algorithm in every snapshot. The evolution of the resolved energy density in the ROI is presented in Fig. 3, along with the evolution of the energy density of the magnetic field, and total energy density of the joule heating. We note that we employed the identification method on the energy density rate, and we converted the quantity to energy density by multiplying by the duration between snapshots.

The difference between total joule heating and joule heating attributed to heating events is what we refer to as residual heating, which on average consists of 90% of the total joule heating. We speculate that source of the residual energy is a combination of background heating, numerical noise, and unresolved events. Background heating may be due to a lower energy release mechanism that heats the region in a less or non-impulsive manner. Examples of this process are MHD waves that could induce currents or remnants of current sheets after an impulsive event that burn slowly (Janvier et al. 2014). Another possibility is the equivalent of the original nano-flare picture by Parker (1983), in which all flares were collections of nanoflares in small or large numbers; using this method to identify events, we suffer the same problems as observers, in that we cannot distinguish a sea of low energy events from an almost constant background heating.

Assuming that the events we identify are not just a conglomeration of much smaller events, an interesting aspect of simulating the Sun is that you can resolve 3D heating events and follow...
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Fig. 2: Magnetic field lines over-plotted together with identified features, in which each colour represents a different feature, at $t = 1130$ s. Different panels illustrate different orientations of the x-y plane.

Fig. 3: Plot of evolution of the following normalised quantities to their respective amplitude. Magnetic energy density (line) with maximum value $4.6 \times 10^6$ erg/cm$^3$, joule heating density of the identified features (dashed line) with maximum value $10^5$ erg/cm$^3$, total joule heating density released in the ROI (dash-dotted line) with maximum value $9.3 \times 10^5$ erg/cm$^3$, and ratio of resolved to total joule heating density (dots) are shown.

their evolution. In Fig. 4, we show the evolution of energy release rate in four cases. Panels a and b represent long duration energetic events, which release energy in a non-monotonic fashion; panel c illustrates energy release of a nanoflare-like event that is resolved by four steps. Assuming that a heating event should have impulsive and gradual phases, panel d depicts an unresolved heating event because it has only a decline phase.

In this work we tried to identify as many heating events as possible using an unbiased method. The events we identify are believed to be mostly reconnection sites, and the reconnection site itself most likely leads to non-uniform heating all the way to the resistive scale. That is caused by the current sheets being inherently unstable in 3D, creating plasmoids of all sizes in the current sheets (Dahlburg et al. 2016). It is therefore questionable whether we can actually define and identify single events and this raises the question of whether the size we attribute to an event is not just a question of resolution. Testing different simulation grid sizes however falls outside the scope of this work, but it might be worth studying that in the future.

Other methods that could assign more of the total released joule energy are possible, but because of our motivation, this method seems the most appropriate. It is extremely difficult to correctly distribute the dissipated energy between the events, making it necessary to discard a large amount of energy in these high dissipation areas. The method we employ is selected to be conservative in the sense that we do not want to mistakenly attribute more energy to an event than we can be certain is part of that single event, and we are able to set strict rules that define an event.

3.1. Geometrical parameters

The shape and volume of each identified event varies significantly, as shown in Fig. 5 for the two events. To quantify this, we explore three geometrical parameters of 2D slices of a 3D event with respect to height $z$ after we fit an ellipsoid to each slice. We choose to fit an ellipsoid at the 2D slice of each feature because the majority of shapes in the horizontal slice of the simulation box at the base of the corona, as illustrated in Fig. 1, could be approximated with such a surface. The parameters describing an ellipsoid are easy to be understood, and the process to do so is very easy and reproducible. The parameters we inves-
an electricity along height, which are probably not physical, but simply we observe sharp spikes in the changes in orientation and eccentricity. In such cases, the geometrical parameters could change unless a sudden and large magnetic field distortion occurs locally. Hence, it is also presented in each case.

tigate are the following: cross-section (area), eccentricity, and orientation (between -90 to 90 degrees) of the ellipsoid’s major axis with respect to the x-axis. In Fig. 5, we plot two examples of two apparently different shapes.

We expect the area to increase or decrease coherently until the limit of our conservative resolution, i.e. around 4500 km², unless a sudden and large magnetic field distortion occurs locally. In such cases, the geometrical parameters could change irregularly.

The example on the right of Fig. 5 represents a structure that has a very thin upper half part close to the resolution limit; hence we observe sharp spikes in the changes in orientation and eccentricity along height, which are probably not physical, but simply an effect of the resolution.

3.2. Histograms: Energy, mean volume, and duration

Isolating heating events enables us to explore different parameters, such as energy release, mean volume, and duration of heating events. Because the volume of each identified event evolves and changes with time, we calculate the mean volume of each identified event throughout its evolution. Mean volume is the total of volumes of an identified event at each snapshot for its total duration divided by the number of snapshots. These parameters can be interpreted collectively via histograms. For this reason, we calculate the differential size distribution (DSD), i.e. number of identified events per logarithmic bin width. In cases in which the DSDs can be approximated by a power-law distribution, we fit one that has the following expression:

$$\frac{dN(x)}{dx} = A x^{-\alpha}.$$  \hspace{1cm} (2)

where the left-hand side is the DSD, \( \alpha \) the power index, and \( A \) a constant.

The bin width or number of bins is chosen with the Freedman-Diaconis rule, which is not very sensitive to outliers and is suitable for data with heavy-tailed distributions. This rule uses a bin width equal to \( 2 \times IQR(x) \times N^{-1/3} \), where \( IQR \) is the interquartile range of the data and \( N \) is the number of observations in the sample \( x \).

Energy, duration, and mean volume exhibit power-law distribution as illustrated in Figs. 6, 7, and 8 respectively. To find the power index, we fit power-law functions using the \( \chi^2 \)-minimisation technique. However, because of the knee on the lower end of the energy histogram, we choose the maximum DSD value and the corresponding parameter value to be the lower boundary at which we fit the power-law function. The minimum parameter value is considered to be the minimum resolved value and that is \( E_0 = 1.1 \times 10^{20} \) erg. The power-law index is \( \alpha = 1.41 \pm 0.01 \) and is fitted over 91% of total number of events. The energy released by the events that are not included in the power-law fitting have insignificant contribution to corona heating. The fitted power law in the duration histogram uses the total number of identified events and the slope is \( \alpha = 2.87 \pm 0.01 \). The three fitted power-law functions of the mean volume have slopes equal to \( \alpha = 1.12, \alpha = 2.35 \pm 0.01, \) and \( \alpha = 4.2 \pm 0.25 \), which correspond to 74.54%, 25.25%, and 0.02% of the total number of events, respectively.

In the histogram of mean volume (i.e. Fig. 8), we find that data can roughly be approximated by three broken power-law functions, but we find that the best way to describe the mean volume is via a CDF. The mean volume spans three orders of magnitude from volumes around \( 10^{21} \) cm³ up to volumes around \( 10^{24} \) cm³. We find that the CDF is very steep in the first 85% of volumes (volumes less than 2 \( \times 10^{22} \) cm³), whereas the distribution in the rest becomes flatter.

Power laws and their indices are a useful tool for the distribution of a quantity and for checking the importance of smaller scales with respect to larger scales. However, fitting a power law is sometimes not trivial and the process usually adds bias to the analysis because it depends on several factors. For example, how well the data are distributed and the bin size and fitting techniques used. Panels a, b, and c in Fig. 4, show the energy rate evolution of three identified events, but could be a combination of several events occurring successively in close proximity. Especially in the case of the identified structure in panel c, where the energy rate increases almost four orders of magnitude in just 10 s, which is a rather peculiar behaviour for a single event. Our method is not able to resolve the events and they appear as a single event. Being unable to resolve every single event affects the derived power laws of all the heating event quantities, such as duration, energy, and volume. The effect on the power-law index can either preserve the index, if small events are just merged into larger events, but does so evenly along the whole energy spectrum. Generally, however this induced bias, flattens power laws...
and this means that we have calculated the lower limit of the power-law indices.

For general interest, we also look at the events tabulated in the classical event sizes. In table 1 we have divided the events into three classes: Pico is for events releasing energy less than $10^{24}$ erg, nano for energy release ranging between $10^{24} - 10^{27}$ erg, and micro for events spanning between $10^{27} - 10^{30}$ erg. We calculate the standard deviation of the duration, the average and total energy and energy rate for each of the classes. We note that the uncertainty in duration is relatively large for the first two classes of events. In fact, the one standard deviation of duration for this cases suggests values lower than the 10 s time step used in this analysis. This behaviour happens owing to the very large spread of data points. We find that 93.5% of the identified events correspond to very small events (pico-events) and have an averaged duration equal to 13 s, while nano- (6.4%) and micro-events (0.03%) have averaged durations equal to 48 s and 283 s, respectively. Nano-events are responsible for releasing most of the energy followed by micro-flares.

Table 1: Five parameters (fraction of events, total, mean ($\mu$), standard deviation (\(\sigma\)), minimum, and maximum value) that describe the three classes of 145306 heating events for duration, rate of released energy, and released energy.

<table>
<thead>
<tr>
<th></th>
<th>Pico</th>
<th>Nano</th>
<th>Micro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fract. of events</td>
<td>93.5%</td>
<td>6.4%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Duration [s]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>13.13</td>
<td>48.03</td>
<td>283</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>7.62</td>
<td>51.84</td>
<td>186</td>
</tr>
<tr>
<td>Energy Rate [erg/s]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.27E+26</td>
<td>4.41E+27</td>
<td>5.24E+26</td>
</tr>
<tr>
<td>$\mu$</td>
<td>3.14E+21</td>
<td>4.71E+23</td>
<td>1.31E+25</td>
</tr>
<tr>
<td>Energy [erg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.75E+27</td>
<td>2.11E+29</td>
<td>7.27E+28</td>
</tr>
<tr>
<td>$\mu$</td>
<td>4.97E+22</td>
<td>2.25E+25</td>
<td>1.82E+27</td>
</tr>
</tbody>
</table>

4. Statistical analysis

Heating events identified can be viewed in two ways. There is the global view, in which parameters describe the collection of events, and the local view, in which the events themselves are analysed.

To investigate the global view, fig. 9 shows the identified number of features (NOF), total energy density rate ($P_{dTot}$), resolved energy density rate ($Pdr$), and total volume of resolved events ($Vr$). These parameters are plotted as a function of time, and it can be seen that all of them behave somewhat stochastically. It can be seen that in broad terms, the number of identified events and their total volume follow each other well, which must mean that the volume distribution is almost constant in time. At the same time, the fraction of the energy density that is identified as events is then also almost constant in time. The combination of the two sets of curves shows that even though the volume of the events is almost constant, both the energy density released and the fraction of that which is identified changes by almost a factor 10.

The local view compares parameters for each of the identified events. Fig. 10 compares the duration of each of the events with the total energy density of the events and the average volume of the event. It is interesting to see how large the spread in
energy is for the short-lived events, where the spread is 7 orders of magnitude, while the longest living events only vary in total energy output by roughly a factor 10. Similarly, the average volume of the events vary by more than two orders of magnitude for the short-lived events, while the long-lived events are generally all of a volume close to $10^{23}$ cm$^3$. Comparing the average volume with the energy density released by the events, shows again large spreads, but the spread is almost the same for both variables.

5. Discussion and conclusions

In MHD simulations, images such as Figs. 1 and 2 can shed some light on the details. The general trend is that the most elongated and also largest heating events are formed where the vertical component of the magnetic field, $B_z$, is small and usually at the interfaces between regions with different connectivity (white and light shades of purple and green areas). Large concentrations of smaller events are present predominately in regions with high magnetic field strengths, however the number of events seems to be quenched in regions with the highest flux densities. The explanation for that can be the fact that the stronger the magnetic field, the more difficult it is to form magnetic field gradients.

The non-constant nature of the identified structures is confirmed in the 2D geometrical parameters of the events cuts in Fig. 5. While identified structures tilt and extend to any direction in the simulation box, the parameters change significantly from one height to another. Such irregularities might occur owing to large gradients of the magnetic field, viz. region exhibiting high probability for magnetic reconnection, but could also be evidence that the cross sections of the currents are fractal-like in structure.

The close correlation between the global parameters in Fig. 9 shows that the volume taken up by the heating events and the total number of these events is almost constant in time. In principle, we cannot conclude anything about the distribution of the event volumes from this evidence alone. But since neither the total volume nor the total number of events change and the inspection of the DSD for energy shows no difference in shape throughout the simulated timespan, we must conclude that the size distribution and energy distribution of the events are both constant; this is the case in spite of the large changes in the total energy and resolved energy at about $t = 1100$ s.

The resolved energy density rate follows the total energy density rate, which can also be seen in Fig. 3. As the method consistently catches roughly 10% of the released energy, there is a reason to believe that the residual heating is not a due to a different physical mechanism, as that most likely would not produce a constant ratio when the total energy dissipated by more than a factor two.

Figures 10 and 11 show that the energy in the heating events are not given. The total energy delivered by a single heating event is highly dependent on the duration and less dependent on the average volume. Since there is an enormous spread in total energy for heating events of the same duration, it means that the scaling laws between duration, volume and energy are somewhat curious. Initially we imagined that this might be because these scaling laws were between integrated values in the 4D space time, but the scalings between the 4D variables themselves are worse. It is not easy to produce simple arguments regarding why the scaling law indices have the found magnitudes and requires the energy density rates to be complicated func-
tributed in a way that follow three broken power-law functions, temporal cadence in their observations to capture such short-lived. If this is the case, then observers would need a very short less than 10 s—suggest that the majority of events are short of the identified events are not resolved temporally, i.e. they live maximum value of \( \alpha = 1.74 \pm 0.01 \).

Identifying single or groups of events might affect the power-law distribution of various parameters such as duration and energy, however we still can derive some conclusions on the impact of heating events on coronal heating. In our results, we observe that the total joule energy density is smaller by more than two orders of magnitude than the energy density of the magnetic field in the corona (Fig. 3). As a consequence, only a fraction of the magnetic energy is needed to heat the corona. A fraction of the total joule heating in the corona is attributed to energy released from impulsive events. This fraction varies between 2% and 14% indicating the dynamic and intermittent character of heating from impulsive events. In general, the energy rate related to heating events corresponds to 8% of the total energy rate of joule heating released in the corona throughout the total time of investigation. The energy rate released from heating events is approximately 5.4 \( 10^{27} \) erg/s in a volume equal to 24x24x9.5 M\( \text{m}^3 \); the resolved energy rate corresponds to energy flux that is 9.4 \( 10^9 \) erg cm\(^{-2}\)s\(^{-1}\). Therefore, the energy flux from impulsive events is two orders of magnitude larger than the typical radiative loss from the QS, i.e. 8 \( 10^8 - 10^9 \) erg cm\(^{-2}\)s\(^{-1}\) (Withbroe & Noyes 1977; Withbroe 1988). We note however that a big part of this flux is also transported via thermal conduction into the transition region, for example pulses of thermal conduction as described in the dissipative thermal flare model (Brown et al. 1979; Smith & Lilliequist 1979).

In this work, we are able to push the lower boundary of identified events down to the energy magnitude of \( 10^{20} \) erg, i.e. minimum value of pico-size events. In addition, we derive the duration power index \( \alpha \). This—together with the fact that 75% of the identified events are not resolved temporally, i.e. they live less than 10 s—suggest that the majority of events are short lived. If this is the case, then observers would need a very short temporal cadence in their observations to capture such short-lived events. Moreover, we find that our volume data are distributed in a way that follow three broken power-law functions, for which we agree with the literature for only the slope that describes the smallest volumes and corresponds to 75% of the total number of events. The cumulative function of the quantity suggests that the majority of events have relatively small volumes. Generally, we find that there is no general rule for how energy is released in individual heating events because results are biased because of event overlap. In Fig. 4 for example, we see that small-scale events can be short and impulsive with single peaks and their impulsive phase sometimes last longer than the decay phase, while in some other instances the opposite occurs. These behaviours however, could also be artefacts of the identification method.

Identifying the contribution of small-scale events in heating the solar corona by employing numerical simulations and a conservative identification method has been proven not to be an easy task. Certainly, the results presented in this work are unable to give a clear answer to the question of whether coronal heating is dominated by reconnection events and their distribution. But the results point in a certain direction. Numerous and short-lived, with small spatial extent, and stochastic nature are the most abundant population of events in this work. We calculate the energy flux corresponding to nano-events, events with energy within the nanoflare energy range, and we find that this is more than enough to sustain the energy requirements of the corona. Like observers, we also identify a flat energy power-law distribution. This is because small events cluster together forming larger events. A piece of evidence that confirms the clustering of small heating events is the multiple peaks in the evolution of energy rate (panels a and b in Fig. 4). Therefore, an identification method is not able to resolve events temporally and spatially below certain limits owing to physical (e.g. background heating) and technical limitations (e.g. threshold criteria). Regardless of the identified sizes of the heating, most of the events occur in regions with low magnetic fields because magnetic fields there can be contorted with ease. However, in regions where the magnetic field magnitudes are large and changes are harder, the resulting heating events release larger amounts of energy.

The present work is a first step towards finding the contribution of small-scale events related to a highly distorted magnetic field in a specific coronal environment and the values we report seem to be lower limits. It is important, for all future investigations of small-scale heating events, that observational and methodological biases are investigated when an attempt is made to find the elusive power-law index \( \alpha \) for the distribution of heating events in the solar corona.

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Fig. 11: Plot of energy vs. mean volume together with power-law fit of the data points that correspond to a duration larger than 50 seconds as identified (blue) in Fig. 10 and a power-law fit assuming all data points (red line). The power-law index of the former is \( \alpha = 1.35 \pm 0.01 \), and corresponds to 53% of the total number of heating events (76538 out of 145306), while the power law of the latter is \( \alpha = 1.74 \pm 0.01 \).
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Emission of Joule Heating Events in Simulations of the Solar Corona

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Emission of Joule Heating Events in Simulations of the Solar Corona

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ABSTRACT

Context. Nano-scale events in cooperation with steady heating from a slow heating mechanism, such as slow-burning current-sheets, could be able to heat the corona, however their observational traces are hard to detect via current instrumentation. After we locate heating events in MHD simulations and synthesise observational data, we extract observational signatures of small-scale events.

Aims. Our mission is threefold. First goal is to observe the manifestation of small-scale events in three observational tools: Intensity maps of three Extreme Ultra-Violet (EUV) filters in Atmospheric Imaging Assembly (AIA) instrument with resolution better than that in AIA images, Emission Measure (EM) analysis, and time-lag maps. Secondly, to identify the reason we cannot quantify the energy release from observed events, and thirdly to study the differences between the radiation from isolated heating events and the one from the whole corona.

Methods. We employ a three-dimensional magnetohydrodynamic (3D-MHD) simulation using the Bifrost code. We simulate the atmosphere of a network embedded in the quiet Sun (QS), and we identify 3D heating events in the corona in several time-steps. Then, we synthesise the three observational tools for two cases: First, we consider information from the total column mass in the corona, and second, we consider only regions that exhibit heating events.

Results. We report on the differences between the two regions of investigation that also consist the evidences to justify why observers cannot identify small-scaled heating events in observations. We found that the combination of multiple heating events at different cooling phases along the line of side gives the impression of thin elongated threads of events. For this reason, the EM as a function of temperature has a multi-thermal distribution. Both radiation and emission measure of the isolated heating events have values at least 10 times smaller than the signal calculated from the total corona. We also found that heating events move together with diffuse emission from the slow heating mechanism and for this reason we cannot differentiate the two. In addition, we find that the frequency of heating events and the intensity of those affect the EM distribution as a function of temperature. We also find that filter’s intensity, EM and time-lag maps of heating events are different than those incorporating information from the total column mass of the corona. However, both regions have on average comparable values, which are slightly smaller than the analytical cooling time-scales calculated for an optically thin and radiation-dominated atmosphere.

Key words. keywords: Magnetohydrodynamics: MHD, Sun: Corona, Sun: Flares, Sun: UV radiation

1. Introduction

After almost eight decades of wondering how the solar corona reach the high temperatures we observe (Grotrian 1939), the explanation is one of the longest-standing questions in astrophysics. One possible heating mechanism is nanoflares (Parker 1983a,b): Numerous small-scale impulsive events based on the idea of magnetic reconnection. Though this mechanism is theoretically very promising, in practice however, its validation has been proven a difficult task.

The research community has so far been unable to validate the proposed mechanism due to the limitations of current instrumentation. Solar flares in general, follows a distribution where the number of flares per energy interval is a power-law with a critical power law index $-\delta$. A lot of effort has gone into identifying the value of $\delta$ because if the value of $\delta$ is above two, the nanoflares will dominate the energy output from solar flares.

The frequency of large flares is not large enough so as to to maintain the solar corona at MK temperatures, so if flares are to be the main heat source of the corona, nanoflares needs to provide more energy than the larger flares. Until now, a large fraction of observational studies has provided values of $\delta$ less than two (an overview is given in table 9 in Aschwanden et al. (2014)), but more importantly the value of $\delta$ seems to be dependent on the region investigated and more importantly on the instrument used. It is at the same time very difficult to estimate the full energy release from a flare, for a number of reasons. The intensity observed in a spectral window range can give an estimate of the energy, but the density and temperature is hard to quantify as is the flare size along the line of sight. For these reasons other more easily observational parameters are often collected, most often the peak flux. The complication is of course that the peak flux and the total released energy might not have a common proportionality factor at both low and high energies, making an estimate of the powerlaw exponent for the peak flux of flares potentially different than for the total energy. For certain instruments with longer exposure times, the exposure time makes the peak flux an integration over the true flare evolution. It is likely that small energy flares lasts a shorter time than high energy flare, and such an integration effect would then affect short lived and long lived flares differently.
To form a better view of how heating events manifest themselves in observations, and to understand the reasons we cannot quantify the energy release from observed heating events, we simulated a part of the solar corona, using the Bifrost code. Then we used a relatively new method to identify three-dimensional heating events, and we followed their evolution in time. Finally, we synthesised observations both from the whole corona, but also for the flaring regions in isolation to compare the two cases. The observations we synthesised are the three single peak EUV channels (171Å, 193Å, 211Å) of AIA (Title et al. 2006; Lemen et al. 2012) on the Solar Dynamic Observatory (SDO, Schwer et al. (2002)). From these synthetic observables, we calculate Emission Measure (EM), and time-tag between the pairs the AIA filters.

This paper discusses the difference between the radiative signal from the heating events in isolation, and the signal from the whole simulated corona. The remainder of this paper is organised in the following way: In Sect. 2, we explain the methods and tools employed to generate and analyse the data. In Sect. 3, we briefly describe the Bifrost code, the physics of the model, and the parameters chosen for analysis; in Sect. 4, we display the results of our investigation, and in Sect. 5, we discuss our findings and derive some conclusions that might help observers in the study of a magnetic network embedded in the QS.

2. Methods and tools
In this and previous work (Kanella & Gudiksen 2017), we identify Joule heating events in simulations of a solar magnetic network region using the numerical code Bifrost (Gudiksen et al. 2011). For the details of the numerical code and the simulation, we refer to these two papers, and will only briefly describe the code and simulation here.

3. Model
In this section we first describe the numerical code very briefly and the physical processes involved in the simulation, then we explain the code set-up, and finally, we elaborate on the model used for the purpose of this paper.

3.1. Numerical method
The Bifrost code (Gudiksen et al. 2011) is a massively parallel code that can simulate a stellar environment from the convective zone up to the corona with decent resolution. The code can describe the different parts of the solar atmosphere in detail using several physical processes and boundary conditions as requested by the user. It solves a closed set of 3D-MHD partial differential equations together with equations that describe radiative transport and thermal conduction. It solves the system of equations on a Cartesian grid using 6th order differential operators, 5th order interpolation operators along with a 3rd order Hyman method with variable time-step.

The code considers the different physical processes that occur in the convective zone, the photosphere, the chromosphere, and the corona and for each simulation, it is possible to include or exclude some of these processes depending on the subject of the study. The simulation results we have used are similar to the simulation available as part of the IRIS data release (Carlsson et al. 2016), except this time the detailed Hydrogen non-equilibrium ionisation is not included. It does include full radiative transfer that incorporates the scattering between optically thin and thick regions in the atmosphere; the radiative transfer in the outer part of the solar atmosphere that is optically thin from the upper chromosphere up to the corona; the radiative transfer in the chromosphere that is thin in the continuum, and optically thick in numerous spectral lines as well as thermal conduction along the magnetic field.

Radiative and conductive processes are parts of the equation of internal energy, which has the following form:

$$\frac{de}{dt} + \nabla \cdot e\mathbf{u} = Q_e - \Lambda - P\nabla \cdot \mathbf{u} + Q_I + Q_{VI}$$

where \(e\) is the internal energy per unit volume, \(\mathbf{u}\) the velocity vector, \(P\) the gas pressure, \(Q_e\) the heating/cooling derived via the Spitzer thermal conduction along the magnetic field (Spitzer 1962), \(Q_I\) represents the Joule heating, \(Q_{VI}\) the viscous heating and \(\Lambda\) the cooling or heating produced by the emission or absorption of radiation. Third term on the RHS expresses mechanical work, while the two terms on the LHS represent how internal energy changes in a Lagrangian system of reference.

In our analysis, a necessary quantity for the calculation of the synthetic AIA filters is electron density. To calculate electron density, \(n_e\) we assume ionisation equilibrium.

3.2. Simulation set-up
We simulate the Sun, spanning a volume 24 × 24 × 16.8 Mm³, and separated into 768³ gird-cells. The cell-size in the horizontal plane is constant (i.e., \(dx = dy = 31.25\) km), where the vertical grid-spacing varies so as to resolve the magnetic field, temperature and pressure scale heights. Vertical spacing therefore has values as low as 26.1 km in the photosphere, chromosphere and transition region, increases slowly up to 165 km in the corona. The vertical axis starts 2.5 Mm below and ends 14.3 Mm above the photosphere. The horizontal boundary conditions are periodic, and the vertical (i.e., z-direction) are open. The lower boundary remains in hydrostatic equilibrium allowing convective flows to enter and leave. By controlling the entropy of inflowing material at the bottom boundary, the effective temperature at the photosphere is kept constant at 5780 Kelvin.

The main free parameter in the code set-up is the magnetic field. It has the form of two relatively strong magnetic regions with opposite polarities to imitate a network region. The magnetic field at the first step of the simulation is vertical at the bottom boundary, and extrapolated assuming potential field. We continually introduce a 100 Gauss horizontal field in the bottom boundary. This injection ensures the well-known salt and pepper structure of the magnetic field in the QS (Carlsson et al. 2016, more details can be found in).

3.3. Model description and general behaviour
Magnetic network should produce copious reconnection events, due to the small scales of the magnetic flux distribution, so this should be an ideal region to study small scale reconnection events. Since magnetic reconnection is a topological phenomenon, it is difficult to identify each reconnection event without a detailed study of the magnetic configuration of each event, but the indirect effect of reconnection is easier to identify. Therefore, the study of the Joule heating term in the Bifrost code is our best proxy for such topological events. Magnetic reconnection depends, among other things, on the degree of magnetic field distortion; currents are manifestations of magnetic field distortion in MHD and when there is inclination between the magnetic field and currents, magnetic reconnection can occur.

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In this model, the solar corona is heated mostly by the Joule heating term included in Equation 1. A fraction of this term owns to impulsive heating events, while the remaining is due to a combination of slow-burning currents due to a lower energy release mechanism and unresolved small-scale heating events which are not detected by our method (Kanella & Gudiksen 2017). The code computes the Joule heating via a non-constant electric resistivity. We keep numerical resistivity as low as possible so as to achieve stability of the explicit code (Gudiksen et al. 2011). Resistivity on scales larger than the particle resistivity, is a combination of the unresolved structure of the magnetic and electric fields. It is obvious that the sun is able to employ a resistivity which is much larger than the theoretical particle resistivity most likely due to small scale instabilities in the current sheet. Knowing how resistivity behaves is difficult, but we know that resistivity in magnetic reconnection sites must be high enough to satisfy the fast magnetic reconnection rate observed in the Sun (Biskamp 1986; Scholer 1989). More details about the numerical resistivity and the heating term can be found in our previous work (Kanella & Gudiksen 2017).

We choose to investigate coronal heating and cooling in a fixed-size box specified at a specific temporal window. Our region of interest (ROI) starts at height 3.28 Mm above the photosphere at which temperature is 1 MK at $t = 1130$ s of solar time, and extends until 12.8 Mm above the photosphere. ROI is resolved by $768 \times 768 \times 331$ grid-cells that is equivalent to a $24 \times 24 \times 9.5$ Mm$^3$ box. We investigate a temporal window that starts at 650 s of solar time and finishes at 3500 s, having a snapshot cadence of 30 s.

The beginning of the time sequence is still affected by the initial conditions. Vertical flows are apparent throughout the whole corona at any instant. At the beginning of the simulation, we notice downflows at every layer (see bottom right panel in Fig. 1). At time, around 800 s of solar time, the averaged flow changes direction. At this point and for almost 800 s, $u_z$ amplitude varies largely and drops while time elapses. After this point, the atmosphere progresses towards a more stable configuration.

Figure 1 demonstrate the evolution of the planar averaged temperature $T$, mass density $\rho$, Joule heating $QJ$, and vertical velocity $u_z$ at 6 different heights in the solar corona. Except $u_z$, all quantities are stratified along height throughout the total temporal window of investigation. Focusing at a fixed time, we notice that Joule heating decreases with height. The reason is because Joule heating scales with the magnetic energy density that also drops with height. Mass density drops with height as well, whereas temperature increases. All four parameters in Fig. 1 show significant changes in the first 1500 s. Later in time, when the simulation has settled down and balance between heating and cooling has been achieved, changes in the four quantities are smaller. The density profile closer to the lower corona exhibits more fluctuations than the higher corona probably due to upflows of evaporated chromospheric plasma. Fluctuations in the vertical component of the velocity field might be due to the net effect of propagating waves, and upflows from evaporated chromospheric plasma.

The evolution of the planar averaged Joule heating in the corona exhibits a fluctuating behaviour that persist at every height in the solar corona. The reason is the random nature of the magnetic field distortion that depends on the energy release of the Joule heating term. When an energy release happens, then stresses in magnetic field relax, while the mechanical drivers in the photosphere and the convective zone build up energy again, thus making it possible for another release of energy.

Electron density drops exponentially with height, and fluctuates with time the same way as mass density does in the lower left panel in Fig. 1. We expect radiation to behave similarly because emission scales as a function of square electron density. Electron density fluctuations in the lower corona are greater than those in the upper part because chromospheric evaporation adds hot material to the corona. It is speculated and implicitly observed (Testa et al. 2014) that magnetic reconnection accelerates electrons towards the chromosphere causing evaporation. In our case, we do not simulate accelerated electron. Instead, if pulses of heating leave the corona via thermal conduction (i.e., dissipative thermal flare model by (Brown et al. 1979; Smith & Lilliequist 1979)), then chromospheric evaporation is also triggered in a similar manner, simulating similar effects like the ones accelerated electrons cause.

The method we employ and which is described in both Kanella & Gudiksen (2017, 2018) relies on being able to find spikes in the Joule heating, and follow the negative gradient in all directions until the gradient at some level of the heating $E_0$ becomes very small. The 3D isosurface of the Joule heating at level $E_0$ around that spike then gives the event volume, and the total energy of the event can be calculated. Then, the method is repeated for the next spike. This method makes it possible to use different values for $E_0$ for each spike. Note that $E_0$ is a free parameter and chosen based on pre-specified criteria, such as the maximum volume among all volumes with different $E_0$.

The method consists of identifying different events at different thresholds and chooses the ones that satisfy pre-specified criteria. The volume which does have Joule heating, but which is not identified as being part of an event is puzzling. There is no single and typical effect that leads to the volumes with Joule heating not identified as an event in this study, but we will in this work refer to those regions as diffusion regions. It is interesting how the percentage we resolve with our method (i.e., 2 %–13 %) is closed to the diffuse emission in between strands of well-defined loops. Such diffuse emission composes 60 % – 90 % of the total emission in the EUV of active regions (Del Zanna & Mason 2003; Viall & Kilcullen 2011).

Our identification method is a conservative method because we try to avoid to attribute mistakenly more energy to an identified event. Therefore, the results presented in Kanella & Gudiksen (2017, 2018) could not give us a straight forward answer to
the question of coronal heating being dominated by small-scaled magnetic reconnection events.

Since observations cannot distinguish nanoflares and constant Joule heating by low gradients in the magnetic field, we synthesise AIA filters in our simulations to study emission in both regions found in this simulation.

We choose to analyse the EUV passbands of the AIA instrument. AIA instrument observes the solar atmosphere in seven filters covering a variety of UV, EUV, and visible bandpasses. Six of these filters emit mainly due to iron emission lines, the importance of lines depends on the Region Of Interest (ROI): Different lines have different contributions in the chromosphere (CH), quiet Sun (QS), Active Region (AR), and flares. Assuming optically thin plasma and ionization equilibrium the intensity of an AIA filter is then expressed as:

\[ I_{AIA,\text{filter}} = \sum_{T_e} R_{\text{AIA}}(n_e, T_e) \phi(T_e) \Delta T \tag{2} \]

where \( \Delta T \) is equal to 0.1 dex Kelvin, \( R_{\text{AIA}} \) is the instrument response function and \( \phi(T_e) \) is the differential emission measure (DEM).

Figure 2 illustrates the temperature sensitivity of the three AIA filters we use in this study as a function of electron temperature normalised to their respective maximum values (i.e., \( R_{\text{AIA}}(T_e) \) in Equation 2). Filters 94 Å and 131 Å have double temperature sensitivity at both low and high temperatures, while filter 335 Å has broad temperature sensitivity, therefore those filters are not useful in our study. Filters 171 Å, 193 Å, and 211 Å are narrow bandpasses with a single peak, which makes those filters good observational tools for studying the quiet Sun.

In general a loop heated by a flare will lose energy initially by conduction and then by radiation, passing through pass bands with decreasing temperatures: 131 Å (10 MK), then into 94 Å (6 MK), 335 Å (3 MK), and finally 211/193/171 Å (1–2 MK).

The EUV filters of AIA span across a wide temperature spectrum, which makes them a strong observational tool. AIA images have pixel size equal to 1.2 arcsec (900 km), which is not small enough to resolve loop braiding that is essential to observe magnetic reconnection directly. Therefore, small-scaled changes in the coronal structure remain unresolved because resolution must be less than 300 km (Brooks et al. 2013). For this reason, we will not use the AIA's resolution, we will use instead our simulation's horizontal grid-size.

To study emission, we synthesise three observational tools, namely *synthetic AIA filters*, *cross-correlation*, and *emissions-measure*. Our method is different from others in a way that we apply those tools not only on 2D images of a simulated solar corona (we call that "all region" case), but also on images where we only consider contributions from regions that exhibit heating events (we call that "flaring" case).

### 3.4. Synthetic AIA filters

In this subsection, we describe how we synthesise the EUV AIA filters using data from the MHD simulation. To calculate filters’ intensities, we use the aia_get_response.pro function included in the SolarSoft version of IDL. The current function used at the time of calculation (5 December 2016) is version 6 dated on 11th of March 2016. The temperature response functions, as illustrated in Fig. 2, use atomic data from the CHIANTI database version 7.1.3 (Dere et al. 1997; Landi et al. 2013) assuming coronal abundances. The temperature response function of each EUV filter is a contribution from numerous spectra lines and continuum; a list with count rates predicted for several ions for each filter is tabulated in O’Dwyer et al. (2010). Then, we introduce the calculated electron density together with the response function into Equations 2, and calculate the intensity. We repeat the procedure also to generate off-limb view of the solar corona.

### 3.5. Cross-correlation and cooling time-scale

Cross-correlation and derived time-lag maps compose a useful tool of checking the sequence of filters in which cooling proceeds after a heating event has occurred in the solar atmosphere. Cross-correlation is widely used to study either the impulsive or the constant heating character of coronal loops (e.g., Viall & Klimchuk 2012, 2016; Lionello et al. 2016; Tajfirooz et al. 2016; Tajfirooz et al. 2016).

In the current study, we use MATLAB’s *crosscorr* function to compute the cross-correlation coefficients and time-lags between a pair of signals. The light-curves are normalised so as the auto-correlation of each component is one, the coefficients therefore range between 0 and 1. We then choose the maximum coefficient, and the corresponding time-lag between the two sequences. The process is repeated for the three combinations between the AIA EUV filters in Fig. 2 at each pixel (i.e., in total 768×768 pixels) for light-curves starting at 650 s and ending at 3500 s having a 30 s cadence. We repeat the method assuming information from only regions that exhibit Joule heating events. In this case, we only consider pixels that had at least one identified heating event along the line-of-side in the 3D ROI.

To better understand the cooling process we compare the observed time-lag values between filters with the theoretical cooling timescales derived when considering only radiation-driven cooling. We use the formula of radiative cooling timescale derived by Bia et al. (2016). In an optically thin atmosphere dominated by radiation the temperature evolution formula has the following form:

\[ 3n_e k_B \frac{dT}{dt} = n_e^2 A(T) \approx n_e^2 \chi T^{-1} \tag{3} \]
where $\Lambda(T) = \chi T^{-1}$ is the radiative loss function (e.g., Cox & Tucker (1969)). For the temperature range $10^4 < T < 10^7$, constants are equal to $\chi = 1.2 \times 10^{-13}$ and $f = 1/2$. Integrating equation 3 and reforming the result we derive the radiative cooling timescale $t_{cool}$, which has the following form:

$$t_{cool} = \tau_r \left(1 - \frac{T(t)}{T_0}\right)^{3/2} \sec$$

(4)

where $\tau_r \approx 2.5 \times 10^3 \frac{\nu_n}{n_e}$. Note that cooling proceeds from $T_0$ to $T(t)$ in time $t = t_{cool}$. We use the averaged electron density of our ROI that is $n_e = 2.32 \times 10^8$ cm$^{-3}$. The temperature values are the ones that correspond to the peak of the temperature response function of each filter. Those are: $T_{171\AA} = 8.9 \times 10^6$ Kelvin, $T_{193\AA} = 1.6 \times 10^6$ Kelvin, and $T_{211\AA} = 1.8 \times 10^6$ Kelvin.

3.6. Emission-measure

Another powerful tool is emission-measure because it quantifies the amount of emitting material. To calculate EM in MHD by integrating the squared $n_e$ along the line-of-sight we investigate. This way, we construct EM maps in top- and side-view. Another strategy we employ in this work is the selection of small patches in the top-view images and calculation of an averaged EM in the region as a function of temperature.

4. Results

Next follows our results of our analysis. In Sect. 4.1, we describe results from radiation analysis; in Sect. 4.2, we describe results from cross-correlation analysis and finally, we present outcomes from the emission-measure analysis in Sect. 4.3.

4.1. Radiation

The results presented in this section are based on the resolution of the simulation. For comparison, we reduced our resolution down to AIA pixel, and found that the averaged intensity of the 2D image of the 171 Å filter agreed with Rafferty et al. (2011). Their observations, like ours, corresponded to emission from a magnetically active patch embedded in the QS.

We now investigate intensity in AIA passbands from the in- 3D image of the 171 Å filter agreed with Raftery et al. (2011). From cross-correlation analysis and finally, we present outcomes from the emission-measure analysis in Sect. 4.3.

4.2. Cross-correlation analysis and radiative cooling

In Fig. 6, we illustrate time-lag maps for two cases: the total column mass and locations of Joule heating events. Table 1 tabulates the averaged time-lag for all region and flaring only region cases of each pair neglecting zero values. Surprisingly, the averaged time-lags of the two regions are similar though the maps are entirely different. Coherent structures of non-zero temporal offsets are mostly appeared in the central region where magnetic cancellation is the strongest. Whereas, in the images of only heating events, concentrations of seemingly elongated and irregular-shaped features around the magnetic polarities and in between space are apparent. The differences between the time-lags of each pair for every region is also apparent in the percentages of surface coverage by non-zero time-lags included in table 1. Note that positive temporal offset between filters with the specific ordering we use in our study indicates cooling, whereas negative offset indicates heating.

In the current study, we notice that time-lag maps are mostly dominated by zero temporal offsets due to overlapping of the temperature response functions of AIA filters. Our conclusion is based on the fact that since cooling proceeds very fast the number of pixels that exhibit zero time-lags will be larger between filters if their temperature functions overlap more than others. For example, the relatively smaller percentage of surface coverage by non-zero time-lags we observe in pair 211–193 Å (see table 1) than in pair 211–171 Å owns to the larger overlapping between the temperature response functions of the former pair. This result agrees with what suggested by Viiall & Kilmchuk (2012), who explained that zero temporal offsets are due to very fast cooling.
Fig. 3: Top row: Intensity of three EUV AIA filters for the total column mass case (i.e., all regions). The three red cycles, selected in 171Å filter at $t = 2990$, track intensity at every time-step. Second row: Same as in top row but for regions that exhibit only heating events (i.e., flaring). Third to fifth rows: Plots of the evolution of intensity. Red coloured lines depict intensity calculated assuming total column mass, while blue-coloured lines depict intensity evolution for regions that exhibit only heating events. Pixel size is the simulations pixel size.
Fig. 4: Top row: Intensity of three EUV AIA filters for the total column mass case (all region). Red line represents a slit with one pixel width atop a loop-like structure chosen at \( t = 2990 \) s in 171Å filter. Second row: same as in top row but for regions exhibiting heating events. Third to fourth row: Time-distance maps of intensity. Dashed-white line indicates the time-step we place the slit. Velocity calculated in range denoted by the blue line. We measure distance and velocity from the south side of red and blue lines respectively. Intensity has units DN/s/pix.

Using equation 4, we calculate the theoretical cooling timescale of an optically thin atmosphere that is static and its cooling process is dominated by only radiation. The ordering of the theoretical cooling time is similar to the time-lag values from cross correlation; the closest the temperatures are the quicker the cooling proceeds. Note also that the theoretical coolings are arranged in the ROI. In EM maps, we distinguish three different regions of emitting plasma as those are positioned with respect to the magnetic field configuration. Those regions are: Magnetic polarities, regions around the polarity inversion line (PIL), and the rest of the region, which we call residual region.

Fig. 5: Side-view of AIA filters’ intensity at \( t = 2990 \) s for total column mass case (top row of panels), and regions displaying only events (bottom row of panels). Intensity has units DN/s/pix.

Fig. 6: Top Row: Time-lag maps between pairs of filters considering for total column mass of the solar corona. Note that negative values indicate that the first component lagged with respect to the second one. Bottom Row: Same as in top group of images, but for regions that exhibit only heating events. Note that the percentages of surface coverage by non-zero time-lags are denoted in table 1. The magnetic field has decisive role on how heating and cooling is arranged in the ROI. In EM maps, we distinguish three different regions of emitting plasma as those are positioned with respect to the magnetic field configuration. Those regions are: Magnetic polarities, regions around the polarity inversion line (PIL), and the rest of the region, which we call residual region.

4.3. Emission-measure analysis

We use emission-measure to study the multi-thermal properties of the plasma in the solar corona by combining the EUV filters of AIA instrument.

Illustrations of emission measure in Figs. 7 and 8 map out the heating in the corona in top- and side-view respectively for different temperature regimes. We calculate EM for two cases: Emission assuming the total column mass of the ROI including flaring and diffuse regions, and emission considering only regions identified as heating events. We calculate that diffuse regions account 96%–99% of the total emission through the time of investigation.

The magnetic field has decisive role on how heating and cooling is arranged in the ROI. In EM maps, we distinguish three different regions of emitting plasma as those are positioned with respect to the magnetic field configuration. Those regions are: Magnetic polarities, regions around the polarity inversion line (PIL), and the rest of the region, which we call residual region.

We notice that emitting plasma from the total column mass, and from only regions exhibiting heating events follows similar trends at any instant. EM structure at \( t = 2990 \) s shows that emitting plasma in the two coolest temperature spectra is faded.
Fig. 7: EM in four temperature regimes at $t = 2990$ s of solar time for the case in which we consider information from the total column mass of the corona (top row of panels), and for the case in which we consider only heating events (bottom row of panels).

Fig. 8: Same as in Fig. 7 but EM here is projected in side-view.

and positioned everywhere in the low-corona except around and above the strong polarities (see Fig. 7). On the contrary, plasma in the third temperature spectrum occurs primarily in regions around the two polarities, and stretches towards the top boundary of the ROI (Fig. 8). Plasma in the fourth temperature spectrum lies across the PIL in the mid- and upper-atmosphere, whereas EM in the lower corona is significantly fainter.

To further check the differences between the two regions, and their thermal properties, we also compute the averaged EM as a function of temperature in three areas chosen in 193 Å filter at $t = 2990$ s (Figs. 9, and 10). We plot the averaged EM as a function of temperature using temperature binning equal to 0.01 dex Kelvin. We choose a smaller binning than usually observers use because it provides more detail. We choose regions (a), (b), and (c) atop a diffuse loop, at the core of an intense loop, and atop the negative magnetic polarity respectively. The three rectangular shapes are identical and have dimensions 50 $\times$ 40 grid cells, equivalent to 1562 $\times$ 1250 Km$^2$ surfaces. We also calculate the average number of events per pixel throughout the 2850 s of investigation and we find 186, 105 and 76 events in regions (a), (b), and (c) respectively. We notice that the number and the location of heating events with respect to the magnetic field affect the temperature of the emitting material and the amplitude of the emission. The larger the frequency of events, the higher the emission is in hot temperature bins.

Figures 9, and 10 also display the multi-thermal behaviour of loops and what we call here strands. In the former case, the EM spans coherently and almost monotonically within a large range of temperatures, whereas in the latter case multiple EM peaks dominate in the distribution of EM.

5. Discussion and Conclusions

We consider the emission from a coronal strand in our synthetic images to be a combination of heating events at different locations and different times, that are at different cooling phases and their combination exhibits a temperature range that spans a relatively small spectrum of values. A group of strands, as illustrated in Figs. 3, 5, 7 and 8, blend with the diffuse region and together compose a multi-thermal coronal loop.

Since the observed strands are parts of loops, and they are manifestations of the same heating mechanism, both exhibit similar characteristics in the same locations. The strands in the corona, like the diffuse region of a loop-like structure, appear only in the lower corona across the PIL and in regions with strong magnetic flux cancellation (Figs. 7 and 8). Hot material is
mostly located at the magnetic poles in the lower corona where magnetic energy is very large. Hot emitting material also appear everywhere in the mid- and upper-corona because magnetic field in those regions is weaker, and thus distortion of the magnetic field occur with ease triggering multiple events and heating the region. This result agrees with the study of (Jiang et al. 2015), who found that high intensity is emitted in regions exhibiting frequent microflares. Strands and diffuse region exhibit strong EM in the temperature range $\log_{10}(T(6.05 - 6.35))$ Kelvin in the low- and mid-corona. This result owns to the fact that small motions in the photosphere create magnetic field blending (and thus heating) in the lower corona that is larger than magnetic field blending at locations higher in the atmosphere.

Extreme Ultra-Violet emission as observed via the AIA instrument mostly consists of radiation from the diffuse regions. Light-curves of regions with diffuse emission in AIA filters (see red light-curves in Fig. 3) display flickering behaviour. The mechanism of flickering could be due to the bursty and highly intermittent character of Joule heating events. However, the evolution of the signal received from events (blue light-curves in Fig. 3) is at least one order of magnitude fainter, a value that is smaller than the magnitude of flickering. Post-effects of impulsive events could also justify to some extend the flickering. According to Kato et al. (2016); Provornikova et al. (2017), sound waves triggered after a heating event travel and interact with plasma. In addition, Tajfrouze et al. (2016); Tajfrouze et al. (2016) found that flickering was caused by pressure waves triggered by highly discontinuous heating that travelled back and forth along the observed threads of combined events. Identification of pressure waves in our analysis is out of the scope of this work, but it might be worth studying such effects in greater detail in the future.

The difference between the identified strands and diffuse region is not only apparent in the various intensity maps but also in the time-distance maps of intensity that trace the motion of the structures. For example, the specific loop we investigate in Fig. 4 has a lateral motion that is apparent in all intensity-time-distance maps, exhibiting coherent but fading intensity. The same time-distance maps of the heating events display a different behavior. The short-lived signatures of events with small spatial extent seem to follow the motion of the loop by appearing at the same locations in the equivalent time-distance map of the loop.

In our analysis, we find that most of the emission is generated in diffuse regions. The mechanism of the diffuse emission is, according to Viall & Klimchuk (2011, 2012); Fuentes & Klimchuk (2016); Lionello et al. (2016); Dahlburg et al. (2016), either due to steady heating from a slow heating mechanism, e.g., slow-burning currents, or due to frequent heating events that give the impression of continuous diffuse heating. From our analysis, we cannot identify which is the exact heating mechanism of the diffuse region. The uncertainty is due to resolution issues that every identification method encounters. If the slow heating we see is indeed superpositions of small numerous heating events, the simulation is not able to resolve them, and the individual energy contributions is very low.

The magnitude of heating in the corona from heating events depends on two factors: the frequency of events, and how strong they are. Regarding the frequency of events, the emission measure in region (a) in Fig. 10, in which we have calculated the largest number of events, lies preferably in the hottest temperature bins while the EM in region (b), where less events occur, lies within a cooler temperature range. This is because the higher the frequency of the heating events, the shorter the waiting time between successive events. Therefore a region does not have time to cool down significantly with respect to regions that exhibit less frequent events; a conclusion that is consistent with Fuentes & Klimchuk (2016); Barnes et al. (2016). The amount of energy released from the heating events also plays an important role. The EM in region (c), which is atop the strong magnetic polarity, where small number of impulsive heating events occur, shows that few but energetic events keep the plasma hot. It is obvious that without the explicit identification of heating events, what we have deduced from our analysis about heating events cannot be explicitly inferred.

The combination of multiple heated structures at different locations with different temperatures exhibits an overall multi-thermal behavior, which is apparent in plots of EM as a function of temperature (see Figs. 9 and 10). Multiple peaks and minima in the latter figure suggest a combination of multiple strands experiencing either heating events or are at different cooling phase along the line-of-sight. For example, region (b) in Fig. 10 exhibits multiple peaks across a large range of the temperature spectrum because it is a region that has cool low-laying, and hot high-laying emitting material (see off-limb view of EM maps in Fig. 8). Similar multi-thermal behavior is also apparent in the EM as a function of temperature when considering emission from the total corona, EM distribution in that case however is smoother.

An important question is whether we can observe signatures of multi-temperature strands in real QS observations, or traces of different frequency of small-scaled heating events. Unfortunately, diffuse emission, as displayed in AIA images and EM maps hides the information we receive from heating events.

If observers will be ever able to isolate small-scaled heating events and perform cross correlation between different filters, they will notice that the resulting time-lag maps of only heating events are very different than those of the diffuse region. Those time-lags maps exhibit regular and irregular shapes of small chunks that compose thin and elongated shapes around the magnetic polarities and their in between space, such as those in the intensity maps in Fig. 3. They will notice that these structures consist of groups of smaller short-lived bursts that have similar time-lags. Interestingly, they will also observe that the averaged non-zero time-lags of heating events are comparable, and in some cases even larger, than the ones of the diffuse region (see table 1). The reason is that heating events’ light-curves consist of multiple events occurred at different heights that have various cooling phases. This is similar to the case of having a major event that during its evolution another event occurs prolonging its EUV emission. This case is well studied by Qiu & Longcope (2016), who found that when heating events occur during the impulsive phase of another event, then the decay of EUV emission is prolonged. Hence, the gradual phase of a heating event is not considered solely abundant by only cooling.

The discrepancy between the theoretical radiative cooling timescale and the one derived via cross correlation of the AIA filters implies that radiation cannot be the only effect responsible for cooling. In the loops investigated here, the strands never reach the radiation dominated cooling phase, where radiation should be the dominant cooling mechanism. This either means that the loops are then reheated before the radiation dominated phase begins, or the density is dropping sufficiently quickly to extend the radiative cooling time scale to the point where the conduction can stay important. In this work, we are able to synthesize three observational tools and watch how heating events are manifested. In synthetic AIA filters, the combination of multiple heating events along the line of sight and strands of different cooling phases and loca-
tions give the impression of individual threads of radiating material. The radiation from the heating events is very weak, a fact that is also repeated in the emission-measure analysis. Emission measure reveals also that the combination of multiple heating events along the line-of-sight exhibits multi-thermal emission. This is because the signal at specific locations consists of low-laying and hot high-laying material. Cross-correlation analysis shows that small-scaled events on average have relatively large temporal-offsets due to the way a light-curve is formed: multiple heating events in strands that then cool down through the synthetic AIA filters. Interestingly the temporal offsets of filters’ pairs are comparable with the analytic radiative cooling timescale calculated for a radiation dominated cooling atmosphere.

We believe that real observations cannot detect small-scale events, at least with the EUV filters of the AIA instrument, even when considering smaller pixel-sizes. The evidences of such statement are the following: 1) Intensity and EM from heating events are at least an order of magnitude smaller than the values calculated using the total column mass of the corona. 2) Heating events and diffuse region exhibit similar characteristics in visual inspection of EM and intensity maps. For example, cool low-laying and hot high-laying loops incorporate similar characteristics with strand structures of heating events. Another example is the similarity in the top-view appearance of both regions. 3) Since identified events are parts of a loop, they follow the motions of the latter without having the chance to differentiate from it.

For the best identification of small-scale heating events, the resolution limit and the ability to study the size of an event along the line-of-side are vital. In current study, the projected areas of the 3-D heating events are so small that have values well below the 900 km × 900 km pixel-size of the AIA instrument. In fact, the identified events cover surfaces with values around few simulation’s pixels (our simulations pixel size is 31 km). A necessary condition for the best possible identification of heating events that will allow to infer about the released thermal energy is also the size of an event along the line-of-side. The reason is because the combination of numerous projected events at different cooling phases along the line-of-side can give a different impression of how an event looks like than how it is in reality.

In conclusion, our model and identification method performed in 4-D space-time can provide information that observations are incapable due to their limitations.

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