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Why is the Sun's corona so hot? Why are prominences so cool?

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Over the past several decades, solar physicists have made steady progress in answering the two long-standing questions, but puzzles remain.

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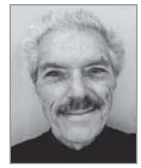


On the 21st of this month, millions of enthusiasts in the US will be treated to a total eclipse of the Sun. During two minutes of darkness, they will see—weather permitting—the extremely faint outer atmosphere of the Sun, the corona. They may also see red feathery sheets of gas called prominences immersed in the corona.

Since the 1940s astronomers have known that the corona is a million kelvin hotter than the photosphere, the Sun's visible surface. Yet prominences have about the same temperature as the surface. Both of those results are puzzling. How can one account for the existence of a million-degree corona virtually in contact with the 5500 K photosphere? How are prominences formed and maintained in the hot corona?

Many partial answers have been proposed, but the details are controversial and general consensus is lacking. The complexity of the problem has grown almost as quickly as the quality of observations has improved. Nonetheless, some broad areas of agreement have emerged in recent years.[1]

A hot solar corona

The high temperature of the solar corona was deduced in four steps. During the total solar eclipse of 7 August 1869, astronomers Charles Young and William Harkness independently discovered a bright line in the coronal spectrum that couldn't be attributed to any known element. More unidentifiable lines were discovered in later eclipses. A hypothetical new element associated with the lines was christened "coronium."

Some 60 years later, physicist Bengt Edlén recorded the spectra of atoms that had lost many electrons. Then in 1939 astronomer Walter Grotrian noticed that Young's and Harkness's coronium line coincided in wavelength with one of Edlén's lines of 13-times-ionized iron. With that clue, Edlén identified some dozen coronium lines as coming from highly ionized iron, nickel, and calcium. Such ions can only exist in a plasma at temperatures between 1 million and 5 million kelvin.

Herbert Friedman confirmed the high coronal temperatures in 1949 by measuring the Sun's x-ray emissions with a rocket-borne detector. By the 1970s rocket flights of x-ray telescopes had revealed several features of the corona at a resolution of a few arcseconds (1″ = 730 km on the Sun). Some of those features are highlighted in figure 1. A strong positive correlation was found between the x-ray brightness of active regions—hot plasma-filled aggregations of looped magnetic field lines—and the strength of their surface magnetic fields. That important clue suggested that magnetic fields must play an important role in heating the corona.

In a parallel development, Eugene Parker predicted in 1958 that a hot corona must expand into space as a solar wind. The Soviet satellite *Luna 1* detected the wind in 1959 and the US *Mariner 2* spacecraft confirmed the result in 1962. At Earth's orbital position, solar-wind streams have been measured with speeds as high as 700 km/s.

Researchers agree that the most likely source of energy to heat the corona and accelerate the wind lies in the Sun's subsurface convection zone. Over time scales of minutes to hours, hot plasma swirls up from the Sun's interior at velocities of a few kilometers per second, cools at the surface, and then descends back down. How could some of that kinetic energy be carried upward to coronal heights of 10^4–10^5 km and then be thrown farther out as the solar wind? Magnetohydrodynamic waves of some kind could be the answer.

Box 1 gives a brief primer on the properties of magnetohydrodynamic waves. From the 1960s into the 1980s, physicists applied those wave properties to construct tentative models of real situations. To take a common example, they could model a coronal loop, a loop of plasma trapped along a magnetic field line, as a tube of hot plasma shaped into an arch by its internal magnetic field. The field lines are rooted at both ends in the convection zone, where they are buffeted by the churning of convection cells. Those field-line motions, if sufficiently rapid, could generate magnetic waves that carry energy upward into the loop. Theoretical models indicate that although many types of waves are possible, Alfvén waves are the most effective in reaching coronal heights. Unfortunately, because Alfvén waves do not compress the surrounding plasma, solar physicists must identify some other mechanism that transfers the wave energy to the plasma; many candidates have been proposed.

A promising candidate is Alfvén-wave turbulence. As the wave undulates up from the Sun's surface, it encounters a steep decrease in plasma density at the boundary between the corona and the chromosphere below. An interesting loop model[2] showed that most of the incident wave energy is reflected downward at that transition region (TR). That motion leads to

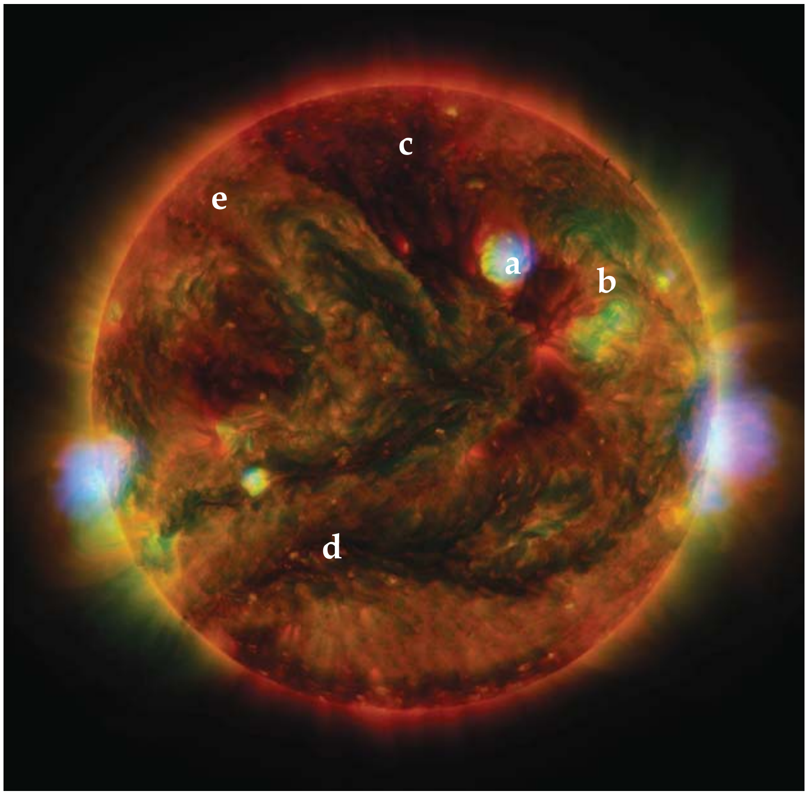


FIGURE 1. THE X-RAY SUN imaged by three space telescopes. This composite image of the Sun combines high-energy x rays (blue) imaged with the *Nuclear Spectroscopic Telescope Array*, low-energy x rays (green) imaged with the Japanese *Hinode* spacecraft, and extreme-UV spectra (yellow and red) imaged with the *Solar Dynamics Observatory*. The labels correspond to **(a)** a hot active region with a high concentration of looped magnetic field lines, **(b)** loops extending from one active region to another, **(c)** a cool x-ray dark hole over the Sun's north pole where copious ions and electrons spew out along open magnetic field lines that don't loop back down to the Sun, **(d)** small active regions called bright points, and **(e)** unresolved background. (Courtesy of NASA/JPL-Caltech/GSFC/JAXA.)

counterpropagating waves and nonlinear interactions among waves. The result is plasma turbulence and strong heating of the TR. A small percentage of the wave energy can reach the coronal part of the loop and heat it. With sufficient incident wave energy, radiative and conductive energy losses in the corona can be balanced by the energy carried up by the waves.

Alternatively, slow convective motions might shift some of the field lines until they cross their neighbors, much like strands of hair in a pigtail braid. Magnetic pressure builds up and thin sheets of electrical current are induced where oppositely directed magnetic field lines threaten to intersect. At some critical point, crossed lines in the magnetic braid break apart, reconnect in a new topology, and dump their energy into heating the surrounding plasma. Simulations show that magnetic reconnection acts to simplify the magnetic field configuration.

Reconnection of magnetic field lines is a complex three-dimensional process.[3] Thomas Gold suggested in 1964 that reconnection could explain solar flares, the sudden explosive brightening of active regions. In 1972 Parker described coronal heating via reconnections as "topological dissipation." Since then solar physicists have extensively employed the mechanism to interpret solar flare observations.

Satellite observatories

Reconnection of stressed magnetic field lines is probably a pervasive process on the Sun. It is a viable mechanism for sporadic heating of coronal loops, on a par with Alfvén waves. In 1988 Parker proposed that the corona is heated by field-line braiding and reconnections producing swarms of what he called nanoflares that are orders of magnitude weaker than the faintest flares seen so far. Both Alfvén-wave dissipation and braiding and reconnection persist as the main themes in research on coronal heating. The two are not mutually exclusive; waves can dissipate by reconnections, and reconnections can excite waves.

Until the 1970s frustrated observers had yet to positively detect magnetohydrodynamic waves or reconnections that might heat the corona. But then a sequence of space-based solar observatories began to transform the situation. *Skylab* (1973–79) was followed by *Yohkoh* (1991–2001), the *Solar and Heliospheric Observatory* (*SOHO*, 1995–present), the *Transition Region and Coronal Explorer* (*TRACE*, 1998–2010), *Hinode* (2006–present), and the *Solar Dynamics Observatory* (*SDO*, 2010–present). Each satellite could probe coronal structures of different temperatures by imaging at various UV, extreme-UV (EUV), and x-ray spectral lines. And each instrument improved on its predecessor's spatial, temporal, and spectral resolutions.

With improved data, researchers hoped to distinguish specific heating mechanisms. One of the first attempts was the search for Parker's nanoflares. In 1995 Toshifumi Shimizu compiled *Yohkoh* images of active regions to determine the distribution of EUV brightening events in the energy range 10^{27}–10^{30} ergs (1 erg = 10^{-7} J). When he extrapolated the distribution to nanoflare energies, Shimizu found that the frequency of events was insufficient by a factor of five to produce the required heating rates. Later data from *Yohkoh*, *SOHO*, and *TRACE* reinforced the result. It seemed that nanoflares either have a different event frequency–energy distribution than observed in large flares, or they do not exist.

Since the turn of the millennium, observations from *Hinode*, *SOHO*, and *TRACE* have revealed a bonanza of data showing oscillations and possibly traveling waves in the corona and TR plasmas. Damped coronal loop oscillations, localized Doppler shifts of UV spectral lines, and transient EUV brightenings are tantalizing aspects of a dynamic Sun.[4] Whether those motions and sudden brightenings are relevant to the heating problem is a question researchers are working hard to answer. In the meantime, transverse oscillations of whole loops, observed from *SOHO* and *TRACE*, open the possibility of deriving such important quantities as the strength of the coronal magnetic field and the plasma fill factor (the ratio of x-ray- and EUV-emitting volume to total volume) of a loop. Coronal seismology is becoming a valuable new diagnostic tool.

In 2007 Steve Tomczyk and associates detected coronal Alfvén waves from their Doppler velocity, intensity, and polarization signals.[5] They employed Tomczyk's specialized instrument, the coronal multichannel polarimeter, mounted on a

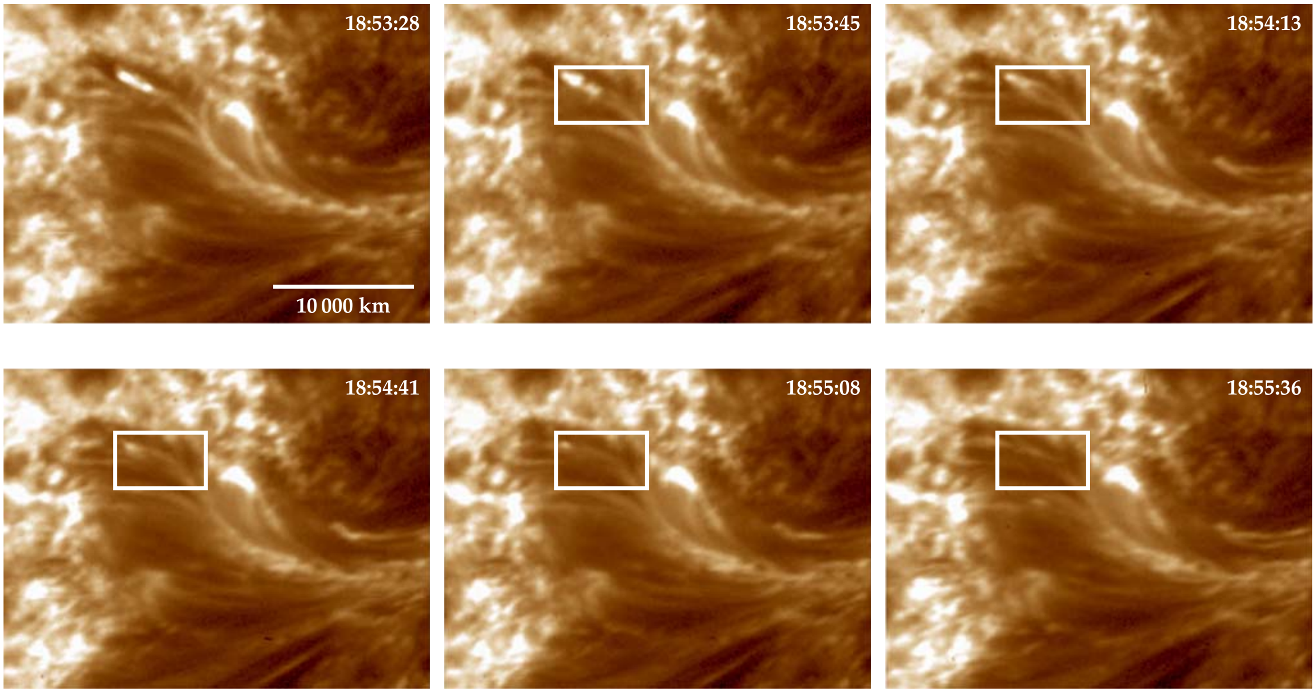


FIGURE 2. CORONAL MAGNETIC THREADS imaged at 19.3 nm, at 0.2 arcsecond resolution, by the rocket-borne high-resolution coronal imager. The two-minute time series shows the unwinding of a braid of threads in the area inside the rectangle. (Adapted from ref. 7.)

ground-based telescope, to observe the corona at the 1074.7 nm spectral line of eight-times-ionized iron. The waves they detected, however, were too weak to heat the corona.

Then in 2011 Scott McIntosh and colleagues reported detecting Alfvénic waves in thin plasma jets called type II spicules, that speed upward through the TR.[6] Some spicules reach as high as 20 000 km above the Sun's surface in 100 s and then fade in brightness. Their plasma temperatures rise from 10 000 K at low heights to at least 100 000 K at their tops.

McIntosh's team used the atmospheric imaging assembly (AIA) aboard the *SDO* to view several heights above the Sun's surface, and at two wavelengths simultaneously: 30.4 nm (emitted by ionized helium at 10^5 K) and 17.1 nm (emitted by eight-times-ionized iron at 10^6 K). The 870 km horizontal spatial resolution and 8 s temporal resolution of the AIA enabled them to track vertically traveling disturbances.

The researchers observed rising spicules swaying sideways a few times during their brief 100 s lifetimes. The velocity amplitudes (20–25 km/s) and upward propagation speeds (some 100 km/s) of the wiggles suggest the existence of passing Alfvén waves. At the same heights, the researchers detected fast, rising disturbances with coronal temperatures, possibly with oscillations. The team estimates that the waves carry sufficient power to heat the quiescent corona and drive the 1000 km/s solar wind.

McIntosh and his colleagues propose that spicules heat to 1 000 000 K at altitudes below 20 000 km and that this hot plasma fills the upper parts of coronal loops. Alfvén-wave heating would continue near the apex; downward heat conduction and "evaporation"—a suggestive description of how plasma is heated and rarefied—of the top of the chromosphere would follow. That scheme contrasts with conventional models in which evaporation alone supplies most of the energy. Further observations are necessary to settle the issue.

Nanoflares revisited

Parker's nanoflare proposal involved the slow braiding of coronal field lines and the impulsive release of stored energy. Until recently, no direct evidence for braiding had been published,

BOX 1. MAGNETOHYDRODYNAMIC WAVES

When shaken by external forces, a bundle of magnetic field lines and the plasma filling them can develop traveling waves. Three types of waves are possible in an ideal plasma that has zero electrical resistance. Longitudinal plasma-density waves propagate at the local speed of sound in the direction of the field. They are just sound waves, albeit in a gas of charged particles. Alfvén waves are periodic transverse displacements of the lines of force. The surrounding plasma wiggles along with field lines but it is not compressed as happens with sound waves. Alfvén waves travel at a speed that increases as the local plasma density decreases and as the magnetic field strength increases. Magnetosonic waves are hybrids of sound waves and Alfvén waves. Because they combine longitudinal compression of the plasma and the transverse displacement of the lines of force, they propagate at an angle to the field lines. In a nonideal plasma with finite electrical resistance, ion acoustic waves—sound waves that interact with the electromagnetic fields present—and other types of waves are possible.

Magnetic waves transport energy in proportion to the square of their amplitudes and to their propagation speed. They also transport the momentum of their entrained plasma. In addition, they can easily dissipate their burden of energy by forming sonic shocks that radiate strongly and generate heat. Because Alfvén waves cause no plasma compressions, they can propagate in tenuous plasmas with virtually no energy losses.

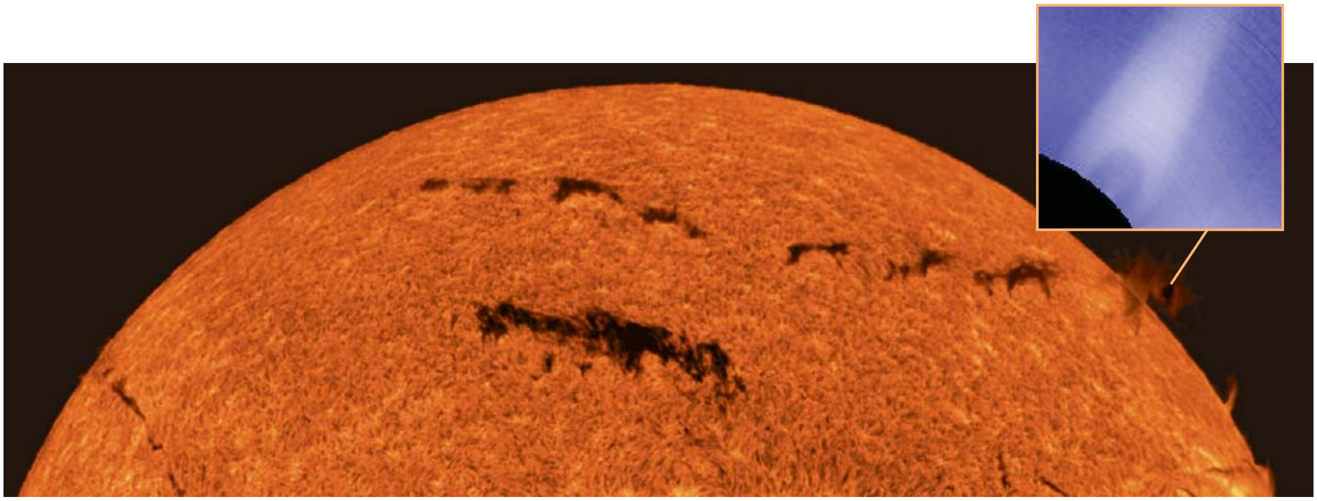


FIGURE 3. A POLAR CROWN FILAMENT, so named for appearing to encircle one of the Sun's poles, seen against the Sun's disk by the Big Bear Solar Observatory in California on 21 July 2002. The filament wraps around the Sun and, at the edge of the disk, becomes a prominence. The inset shows the corresponding coronal cavity observed in white light with Mauna Loa Solar Observatory's Mk4 instrument. (Courtesy of Big Bear and Mauna Loa Solar Observatories.)

presumably because subarcsecond-resolution observations over many minutes are required to record such an event.

Four years ago Jonathan Cirtain and colleagues claimed to have succeeded.[7] Their high-resolution coronal imager instrument, capable of an unparalleled resolution of 0.2″, was carried aboard a rocket. They reported images of magnetic braids caught in the act of reconnecting, relaxing, and dissipating enough energy to heat the plasma to 4 000 000 K. A time series of images was obtained at a wavelength of 17.1 nm, which is emitted at a temperature of about 1 600 000 K. The images, such as the ones in figure 2, are stunning, but the braiding and relaxation are not immediately obvious. A second flight, scheduled for July 2016, had to be aborted because of a mechanical failure. We look forward to hearing more from Cirtain's group.

Peter Cargill, James Klimchuk, and their collaborators have investigated the nanoflare mechanism of coronal heating for two decades. In 1994 Cargill hypothesized that loops are composed of hundreds of subarcsecond magnetic strands that are not resolved by contemporary EUV and x-ray instruments. Each strand is heated and cooled independently. Thus a loop contains strands with different densities and temperatures, some as high as 10^7 K. A satellite instrument would record merely the temporal and spatial averages of strand emissions.

Using multistrand nanoflare models, Spiros Patsourakos and Klimchuk calculated TR- and coronal-line profiles that compared well with spectroscopic observations from *Hinode*. Recently, predicted temperatures as high as 6×10^6 to 9×10^6 K have been confirmed by rocket-borne x-ray detectors.[8]

Cool prominences in the hot corona

Prominences are luminous cloud-like plasma structures floating in the much hotter and more tenuous corona. In Italy during an eclipse on 8 July 1842, Francis Baily noted that the prominences did not follow the lunar motion and thus must be part of the Sun's atmosphere. With the advancement of spectroscopy, astronomers Pierre Janssen and Norman Lockyer showed in 1868 that radiation from luminous prominences came from individual spectral lines. Their reddish hue is due to the dominant Balmer line of hydrogen (656.3 nm).

The use of spectrohelioscopes to isolate single spectral lines thereafter enabled systematic observations of solar prominences. Since those 19th-century observations, the study of prominences in the solar corona has been a vital and challenging research area in solar science.[9,10] Increasingly higher-quality data gathered by ground- and space-based instruments have led to new insights into the complex magnetic and multithermal nature of solar prominences.[11]

In 1903 Ferdinand Ellerman and George Ellery Hale showed that prominences visible beyond the edge of the solar disk and filaments, dark elongated structures seen against the backdrop of the solar disk, are really the same thing. Figure 3 shows a prominence wrapping around the Sun and becoming a filament. That they are darker than the chromosphere means that the temperature of the filament plasmas must be somewhat lower than the 10 000 K chromospheric temperature.

Radiative transfer modeling of prominence plasmas enables one to retrieve plasma parameters—temperature, density, pressure, and degree of ionization—as well as prominence mass (see N. Labrosse in reference 10, chapter 6). Spectral diagnostics based on UV and optical radiation yield temperatures of 6000–8000 K and particle densities of 10^{10}–10^{11} cm^{-3}. Those densities are a million times less than in the photosphere below but 100–1000 times greater than in the surrounding corona.

The magnetic nature of prominences and filaments became clear when Hale discovered solar magnetic fields in 1908. Then around 1950 Harold Babcock and Horace Babcock invented the magnetograph, an instrument that enabled the father–son team to map weak magnetic fields over the solar surface. In 1955 they observed a large filament stretching along the division between two patches of opposite magnetic polarities in the photosphere. Such a boundary is now dubbed a polarity inversion line (PIL).

Ten years later colleagues Sara Smith, Harry Ramsey, and Robert Howard confirmed the strong correspondence between the locations of solar filaments and PILs. An arcade of coronal loops reaching 50 000–70 000 km into the solar corona are rooted on either side of a PIL. The space under the loops constitutes a magnetic channel in which filaments may form.

In the opening image of this article—taken from Svalbard,

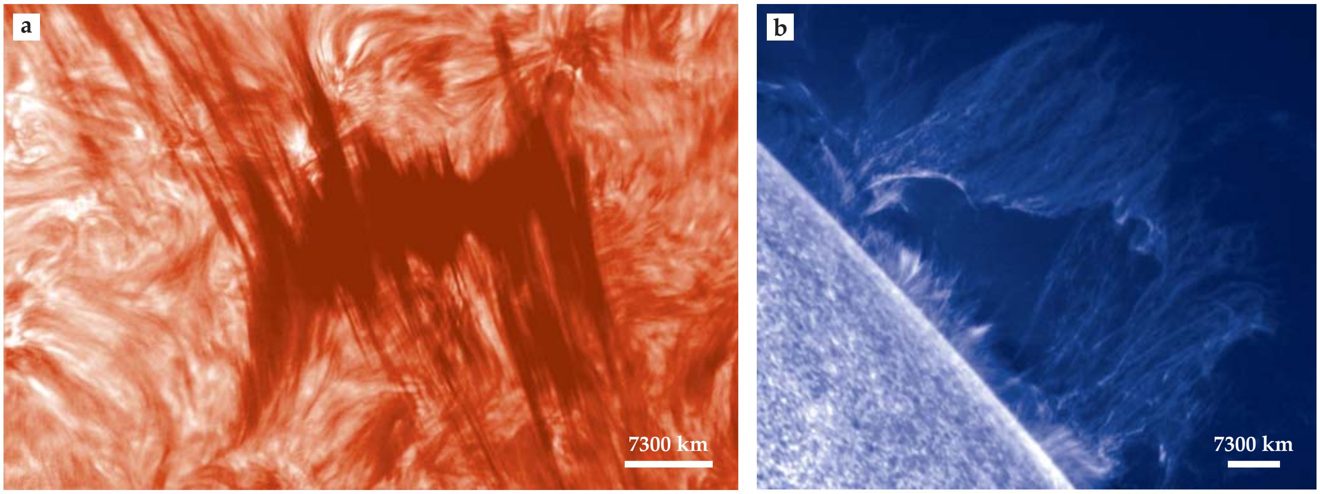


FIGURE 4. QUIESCENT SOLAR PROMINENCES. (a) A high-resolution hydrogen Balmer-line (656.3 nm) image of a fragmented prominence was observed with the Swedish Solar Telescope on 22 August 2004. Viewed from above, a prominence is known as a filament. **(b)** A quiescent prominence, observed in the ionized calcium H line (396.8 nm) on 3 October 2007, was imaged with the solar optical telescope on board the *Hinode* satellite. (Panel a courtesy of the Swedish Solar Telescope; panel b adapted from A. Hillier et al., *Astrophys. J.* **756**, 110, 2012.)

Norway, during the 20 March 2015 eclipse—an example of such a loop structure can be seen above the prominences at the upper left lunar edge. Early eclipse observations showed faint regions called coronal cavities between prominences and their surrounding coronal loop systems. The role and significance of those magnetically insulated, low-density, hot regions immediately above the much denser plasma of prominences are still debated (see S. Gibson in reference 10, chapter 13).

Magnetic data of the solar disk show that PILs and the associated channels circle over long stretches of the solar surface, much like seams on tennis balls. Only a fraction of the total length contains observable filaments. The magnetic environments of solar filaments and prominences influence their birth, existence, and disappearance. Magnetic fields provide support against gravity and thermal shielding from the surrounding hot coronal plasma.[12] Channel fields are nonpotential, which means that some factor—here, the overlying coronal arcade—prevents the field lines from taking on the familiar arc shape. Thus the channel field lines and associated filaments are generally flat and run horizontally along the channel direction. The interrelated handedness or chirality of filaments, channels, and coronal arcades[13] is described in box 2.

The average magnetic field on Earth's surface is 0.5 gauss (10 000 G = 1 tesla). By comparison, the magnetic fields in filaments and prominences are typically in the range of 5–30 G (see B. W. Lites in reference 9, page 101). That field range implies that the local magnetic pressure inside the structures is generally larger than the local gas pressure. The partly ionized prominence plasma is thereby "frozen" to the magnetic field and may flow freely only in the direction of the field. In other words, filaments and prominences are not amorphous blobs; they appear as sharp, detailed portraits of the corresponding magnetic fields. High-resolution observations of the solar disk leave little doubt that the filaments consist of thin, largely parallel, thread-like structures, as shown in figure 4a. The smallest measured angular widths of such threads—0.3″, which correspond to about 250 km on the Sun—strain the spatial resolution of today's best instruments.

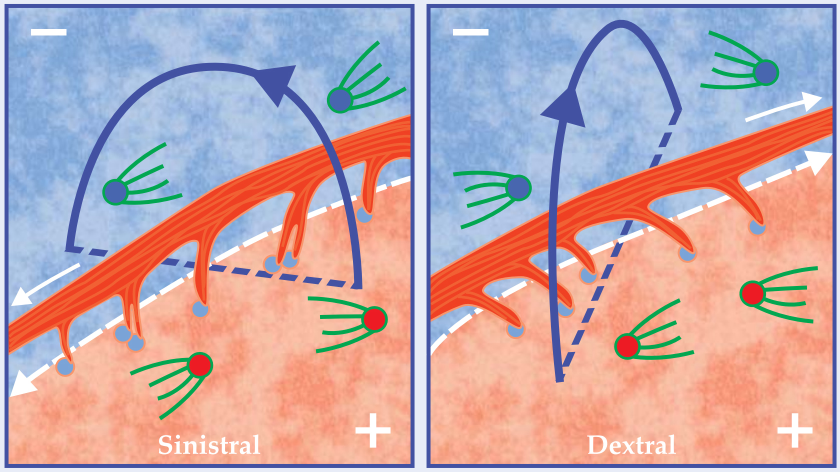
Structure and dynamics

Largely vertical, thread-like structures are often observed in tall, so-called quiescent hedgerow prominences,[14] such as the one shown in figure 4b. Time sequences of well-resolved prominence threads reveal downward mass-flow velocities around 3 km/s, much slower than free-fall speed. Upward flow along the threads is seen as well. Thus forces other than gravity may govern the motion of the prominence plasma.

Models still struggle to explain how cool plasma in vertical and tilted threads can extend over heights that span several gravitational scale heights without collapsing. Observations of prominences with the solar optical telescope aboard *Hinode* show large-scale, slowly rising plumes. The recently discovered features suggest a Rayleigh–Taylor instability: At the interface between two fluids with the denser layer on top, any disturbance that displaces a volume of the lighter fluid upward grows over time.

Small-amplitude plasma oscillations with velocity amplitudes up to 3 km/s represent another central feature in filament and prominence dynamics. They are generally believed to be magnetohydrodynamic waves (see J. L. Ballester in reference 10, chapter 11). As with coronal loops, the turbulent convection layers of the photosphere and below, where the magnetic threads are rooted, are the likely source of the magnetohydrodynamic wave flux. In partly ionized filament and prominence plasmas, such waves will generate collisions between neutral and ionized particles that dissipate some of the wave energy and heat the plasma. In addition, dissipated wave energy may contribute to acceleration and flow of the plasma along both horizontal and tilted magnetic threads. However, the energy balance of the plasma is mainly controlled through the absorption and emission of EUV radiation by neutral hydrogen and ionized helium.

BOX 2. MAGNETIC HIGHWAYS



Solar filaments—or prominences, as they're called when they protrude over the edge of the solar disk—possess handedness or chirality, as do the channels they run through and the coronal-loop arcades overhead.[13] As illustrated in the figure, the three chiralities are intimately related. The main upper body of the filament (red), usually called the spine, stretches through the corona above the boundary between two opposite-polarity regions on the photosphere called a polarity inversion line (PIL). Viewed from the positive polarity side of the PIL, the magnetic fields in the filament channel (white arrows) can point either to the left or to the right. Left-pointing channels are classified as sinistral and right-pointing ones dextral.

The aptly named chromospheric fibrils (green) are threads of plasma that follow field lines emanating from or converging into areas of concentrated magnetic fields (red or blue circles). In general, the fibrils may orient in any direction and sometimes form bridges over the PIL. However, filaments only form when all the fibrils reflect the chirality of the filament channel.

The other characteristic filament structures are the barbs that divert filament threads away from the spine and into the chromosphere and photosphere below. If one imagines the filament spine as a highway with traffic moving in the field direction, the barbs of sinistral filaments bend away like left-handed exits and the barbs of dextral filaments bend away like right-handed exits.

The origin of filament handedness may be in the presence of weak minority-polarity fields (blue dots) on only one side of the channel. How those fields arise is still unclear. Nonetheless, the barbs appear to connect to those minority-polarity patches or perhaps to tiny PILs around them.

Interestingly, the coronal loops (blue arcs) have the opposite chirality as the filaments and channels they overlie. From a bird's-eye view, the loops that make up an arcade line up at an angle relative to the filament that runs below. When the filament is sinistral, the loops skew to the right and when the filament is dextral, the loops skew to the left.

The handedness of filaments displays a remarkable large-scale hemispheric pattern. Dextral filaments predominate in the northern hemisphere, whereas sinistral filaments predominate in the southern hemisphere. The most illuminating observational discovery about filament channels in recent years has been the recognition of a unique pattern of coronal structures that line the two sides of long filaments. Called coronal cells, the magnetic structures form a network of bright centers separated by dark boundaries.[18] The locations and orientations of the PILs result from interactions between large-scale coronal cells and the Sun's differential rotation. (Figure adapted from ref. 13.)

Observed EUV and UV spectral lines from highly ionized carbon, nitrogen, sulfur, oxygen, and iron in prominences imply the existence of plasma ranging in temperature from 10 000 K to 2 000 000 K. That hot plasma resides in a thin, high-temperature-gradient skin around the prominence called the prominence–corona transition region. The PCTR is an unavoidable consequence of the thermally insulating magnetic fields. Because transverse conductivity is strongly suppressed in the prominence, plasma flow is restricted to the direction of the imbedded field. Thus the boundary between prominence and corona must necessarily be thin. The thickness of the PCTR is only a fraction of what can be resolved by current instruments. Nonetheless, its existence is supported by model simulations. (For details, see S. Parenti and J.-C. Vial in reference 9, page 69, and S. Parenti in reference 10, chapter 3.)

Solar prominences remain stable for days and even weeks within their magnetic channel cages. Ultimately, the majority erupt into the corona and farther into interplanetary space. Several hours before a prominence ignites, it slowly rises at 0.1–1 km/s. Then it undergoes rapid upward acceleration to 100–1000 km/s. That sequence of events is thought to be the result of a gradual demise of force equilibria between the prominence and the overlying coronal arcades; a catastrophic loss of force balance results (see G. Aulanier in reference 9, page 184). An erupting prominence and the associated expulsion of the surrounding coronal loop system can lead to one of the most dramatic solar events: a coronal mass ejection, in which magnetic fields and enormous amounts of plasma explode into space. (See the article "Solar eruptive events" by Gordon Holman, PHYSICS TODAY, April 2012, page 56, and N. Gopalswamy in reference 10, chapter 15.)

Solar science is still struggling to explain how prominences and filaments form in the much hotter and rarefied coronal regions. Yuri Litvinenko and collaborators explored the idea that new filament threads are continuously generated by magnetic reconnections along the PIL, which bring magnetic flux and its associated mass into the filament (see S. F. Martin in reference 10, chapter 9). As described in box 2, a filament consists of a main body called a spine and a set of barbs that protrude away from the spine and then down to the photosphere. The observed ubiquitous flow of plasma along the threads of spines and barbs at 10–20 km/s could imply ongoing circulation of filament plasma,[15] which could result from photospheric matter being injected into and subsequently expelled from filaments.

High-resolution observations have shown that footpoints, where barbs connect to the photosphere, are closely associated with small, canceling, bipolar magnetic regions.[13] Magnetohydrodynamic simulations show that localized heating at footpoints of magnetic barbs may lead to surges of plasma evaporating from the chromosphere to the corona. Repeated impulsive heating of barbs at chromospheric heights followed by condensation and radiative cooling agree well with the dynamics observed in prominences.[16] Models in which prominence and filament plasmas circulate between injection, condensation, and drainage are promising and are starting to challenge more static models.[17]

The future heats up

These are exciting times for solar physicists. NASA's *Parker Solar Probe* and the European Space Agency's *Solar Orbiter*, both set to launch in 2018, will venture closer to the Sun than any spacecraft has before. On the ground, the 4-meter Daniel K. Inouye Solar Telescope in Hawaii, when completed in 2018, will become the world's largest solar telescope. The Atacama Large Millimeter/Submillimeter Array in Chile, best known for its stunning images of exoplanets, is in the commissioning phase for solar observations. Those and other next-generation instruments give solar physicists much to look forward to.

Observations in the past several years have netted fresh clues about the dynamics of coronal loops for researchers to follow. Meanwhile, the magnetic, thermal, and dynamic structures of prominences that thread those loops are now reasonably well determined from observations and model simulations, although puzzles remain. With the superb observations afforded by new instruments and corresponding advances in modeling, researchers can expect to make deep progress in understanding how the corona is heated to millions of kelvin and how prominences emerge and survive in that environment. Of course, answers to existing questions will inevitably raise new questions.

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