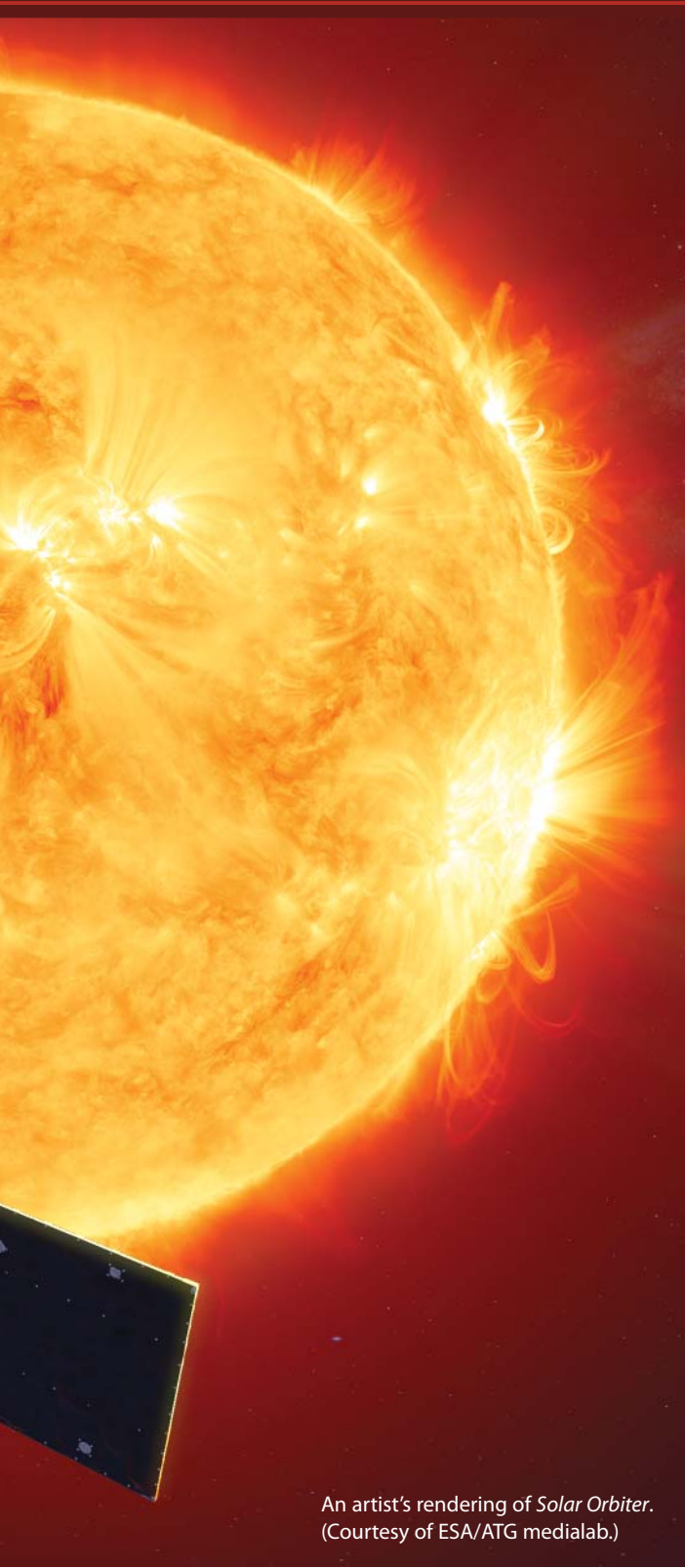


Unveiling the mystery of solar-coronal heating





An artist's rendering of *Solar Orbiter*.
(Courtesy of ESA/ATG medialab.)

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Miniature flares recently discovered by probes that have approached the Sun's surface are helping physicists understand how the Sun's corona reaches temperatures of millions of kelvin.



One of the most vexing questions in modern solar physics is the coronal-heating problem. We all know from our own experience that when we move away from a hot body, the surrounding temperature decreases. So why is the Sun's corona—the atmosphere of hazy plasma that extends millions of kilometers into space and is visible as a pearly white crown during total solar eclipses—so much hotter than the visible surface of the Sun? The temperature difference is tremendous: The average effective temperature of the photosphere—the surface layer of the Sun, where its light originates—is 5800 K. In comparison, the corona's average temperature¹ is a staggering $1\text{--}3 \times 10^6$ K, and parts of it can reach temperatures as high as 10^7 K during highly energetic solar flares.

Since the early 1990s, when a wave of solar space missions returned a previously unparalleled amount of observational information, most solar physicists have believed that wave heating and magnetic reconnection are the most likely mechanisms to explain solar-coronal heating. Although there is not yet a definite solution to the problem, new clues to unveiling the mystery of coronal heating have begun emerging recently, as the European Space Agency's *Solar Orbiter* (*Solo*) and NASA's *Parker Solar Probe* (*PSP*) are venturing closer to the Sun than any spacecraft has ever been before.

The coronal-heating problem

The solar corona and its tremendous temperatures have baffled astronomers for more than a century. Over the last four decades, solar physicists have proposed several theories to explain it, two of which have survived to date as promising candidates. The first is wave heating, which posits that mechanical energy is transported by magnetic waves into the corona and deposited there as heat by wave damping at sufficiently

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low heights.² The second is magnetic reconnection, the tumultuous process in which oppositely directed magnetic field lines break and reconnect in a plasma and convert magnetic energy into thermal energy.¹ Scientists have long believed that some combination of the two processes will explain coronal heating, although the details of that combination are not yet understood.

Magnetic reconnection relies on electric currents that are induced by the solar magnetic field in the electrically conductive plasma. It is the mechanism that causes solar flares, the largest explosions in our solar system. Satellite missions launched in the 1990s, such as the *Solar and Heliospheric Observatory* (SOHO) and the *Transition Region and Coronal Explorer* (TRACE), demonstrated that significant oscillatory activity occurred in the solar corona, part of which came in the form of magnetoacoustic and Alfvén waves. The former are linear magnetohydrodynamic waves that are driven by thermal pressure, magnetic pressure, and tension effects; the latter are low-frequency, transverse magnetohydrodynamic waves that are produced by the oscillatory motion of ions anchored to the magnetic field lines that emerges from the interaction between the magnetic fields and the electric currents in the plasma. Both magnetoacoustic and Alfvén waves can carry energy through the chromosphere and corona for a considerable distance before dissipating into heat. That forms the basis of the wave-heating theory, which was first proposed by Evry Schatzman³ in 1949.

Missions launched in the 21st century have added to the picture. The solar spacecraft *Hinode*, put into orbit in 2006, revealed that the heating of the solar chromosphere and corona may be related to small-scale magnetic reconnections.⁴ The space-based observatory *Interface Region Imaging Spectrograph* (IRIS), launched in 2013, provided evidence that discrete, small explosive events such as smaller nanoflares may contribute to the coronal heating budget.⁵ And *Solo*'s recent discovery of numerous miniature picoflares—even smaller bursts of energy or explosions on the solar surface—that occur randomly and dissipate rapidly has brought solar physicists one step closer to solving the enigma of coronal heating.^{6,7}

Wave heating

It was not until 1997, with the aid of SOHO's Ultraviolet Coronagraph Spectrometer, that astronomers detected the first direct evidence of waves propagating into and through the solar corona in holes (regions of cooler, less dense plasma) high above the Sun's surface.⁸ But those undulations—compressible, slow magnetoacoustic waves—are capable of carrying only 10% of the energy required to heat the corona. On the other hand, incompressible Alfvén waves, which are launched by solar flares, can carry enough energy but do not damp out rapidly once they enter the corona. In addition, solar flares are transient, sporadic events that cover relatively small regions of the Sun's surface. Slow magnetoacoustic waves are longitudinal waves

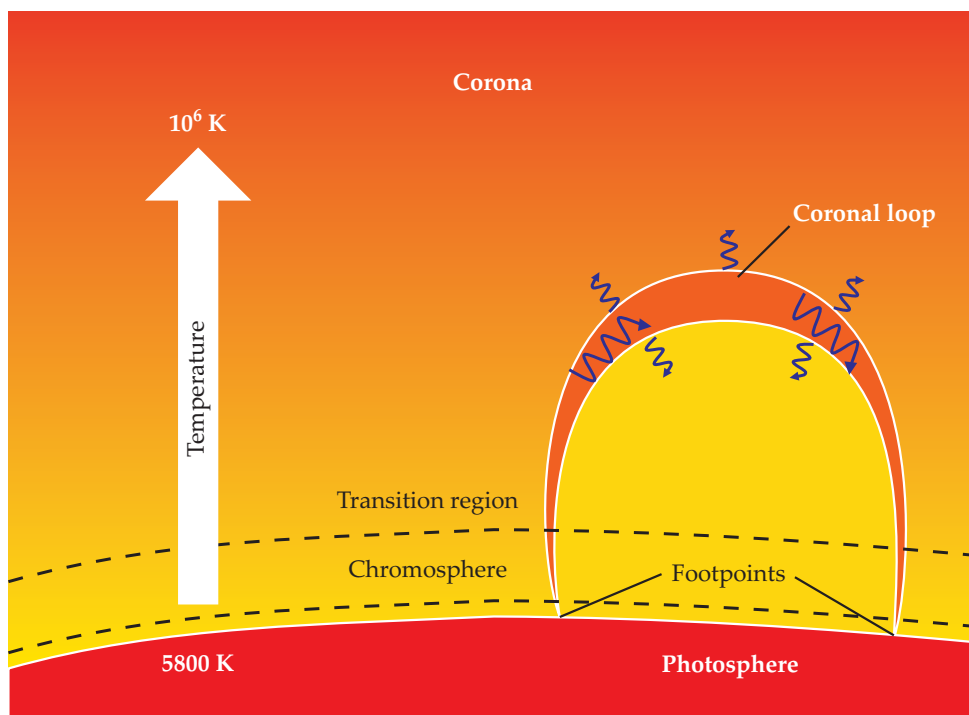


FIGURE 1. THE SOLAR ATMOSPHERE'S LAYERS. The lowest is the photosphere, which comprises the visible portion of the Sun. Next is the chromosphere, which is about 2000 km thick and is visible as a reddish flash during a total solar eclipse. Above that is the narrow transition region, only about 200 km thick, where solar temperatures rise dramatically to 10^6 K. The largest is the corona, which extends millions of kilometers into space and consists of extremely hot plasma. Like the chromosphere, the corona is observable during a solar eclipse. Coronal loops are anchored on both ends at footpoints in the photosphere; they project into the chromosphere and transition region and extend high into the corona. The wavy lines indicate how magnetohydrodynamic waves and heat propagate through one such loop.

that are similar to ordinary sound waves in air. They can exist either as standing waves, which do not have an average net propagation of energy, or traveling waves, which do have an average net propagation of energy.

Coronal loops—arch-shaped magnetic flux tubes filled with chromospheric plasma—are one basic structure along which longitudinal waves stand and propagate in the lower corona (see figure 1). They extend tens or hundreds of thousands of kilometers above the solar surface, and their extremes, known as footpoints, are anchored in the photosphere. The loops are visible in x-ray, UV, and visible wavelengths and can have a variety of temperatures. Cool loops have temperatures below 10^6 K, warm loops hover around that temperature, and hot loops exceed it. Bright coronal loops, which take the form of coronal condensations (regions of warmer, denser plasma) and bright spots, are common around the time of solar maxima. Larger faint loops that last days or weeks are more typical of the quiet corona, when solar activity is low.

In the recent past, solar researchers believed that coronal loops were static, plasma-filled structures. But movies made from observations with TRACE showed bright blobs of plasma

racing up and down the coronal loops. That feature was confirmed by observations by *SOHO*, which also revealed that those blobs move at thousands of kilometers per second. That evidence led researchers to the view that coronal loops are jets of hot plasma that are propelled in opposition to gravity—like an arch of water from a fountain—and flow along the alleys between the strong coronal magnetic fields. Observations also indicated an apparent temperature increase in coronal loops because of a height-dependent weighting function, which implies that they are indeed nonstatic, nonequilibrium states.⁹ Figure 2 shows an image of an active region with many warm coronal loops.

Standing slow waves were seen in hot coronal loops with temperatures beyond 6×10^6 K in the form of strongly damped, large Doppler-shift oscillations, with periods in the range of 9–32 minutes and decay times between 3 and 42 minutes.¹⁰ Observations of propagating slow waves are by far more abundant. Such oscillations have been detected by *SOHO* in hot loops and polar plumes with periods of 10–15 minutes⁸ and by *TRACE* in cooler loops near their footpoints with periods between 2 and 9 minutes.¹¹ But periods as long as 20–35 minutes have also been reported in coronal-hole regions. Those waves were detected as intensity oscillations that propagate in the plasma with approximately the local speed of sound. In addition to compressible and Alfvén waves, solar physicists have also pointed to propagating transverse kink waves in loops and sausage oscillations of flaring loops as further possible explanations for coronal heating.

Although significant progress has been made in understanding the phenomenon, open theoretical and observational questions still remain. For example, there is no definite answer on how propagating and standing slow waves are triggered and excited. Researchers have variously proposed that kink-mode, Kelvin–Helmholtz, Rayleigh–Taylor, thermal, or resistive instabilities could explain coronal heating. The quasiperiodic nature of the outwardly propagating waves observed by *TRACE* suggests that they may well be driven by oscillations in the lower solar atmosphere, which stem from either chromospheric motions or the turbulence of granulation on the photosphere induced by currents of plasma within the Sun’s convective zone, the outermost layer of the solar interior. In addition, multiwavelength observations point to small-scale transient brightenings as a mechanism for exciting propagating slow waves. A further possibility was put forward by Bernard Roberts,¹² who theorized that those waves could be generated impulsively when an energetic event such as a flare arises near the magnetic footpoints of a coronal loop.

Modeling coronal loops

Because slow magnetoacoustic waves are guided along the magnetic field and behave essentially

like ordinary sound waves, most studies of coronal-loop oscillations have relied on numerical solutions of the one-dimensional equations for a compressible fluid, which are extended to include the effects of solar gravity and energy dissipation by viscosity and thermal conduction. Researchers have also examined other effects, including field-line divergence, heating, and radiative losses.

One interesting model calculation is to consider the evolution of a narrow, localized Gaussian pulse in velocity that starts near a coronal-loop footpoint and mimics an impulsive, reconnection-like event. In a homogeneous, isothermal medium where energy dissipation isn’t considered in the calculation, the spikelike pulse will immediately split up into two independent and oppositely moving pulse waves that each travel at the adiabatic sound speed. In response to the velocity pulse, disturbances in the density and temperature arise in the form of Gaussian monocycle waves. As the velocity spike splits up, the monocycle waves detach and produce two pulses of inverted polarity that propagate in opposite directions. Under solar gravity, when one of those pulses propagates up toward the top of the loop, it experiences decreasing densities and therefore decreasing pressures, which increase its amplitude. But the picture changes when the effects of energy dissipation are introduced because the original pulse’s higher-order Fourier modes will decay faster than the fundamental one.

The prediction that a highly localized pulse arising near one footpoint of a coronal loop can effectively excite longitudinal oscillations that propagate along the loop with a velocity close to the local sound speed introduces an alternative mechanism for wave triggering. But we won’t know if the model is valid until we have more detailed observations of coronal-loop oscillations.

Nanoflare and picoflare heating

IRIS was designed to track temperature and hot-gas motions in the lower levels of the solar atmosphere at improved spatial,

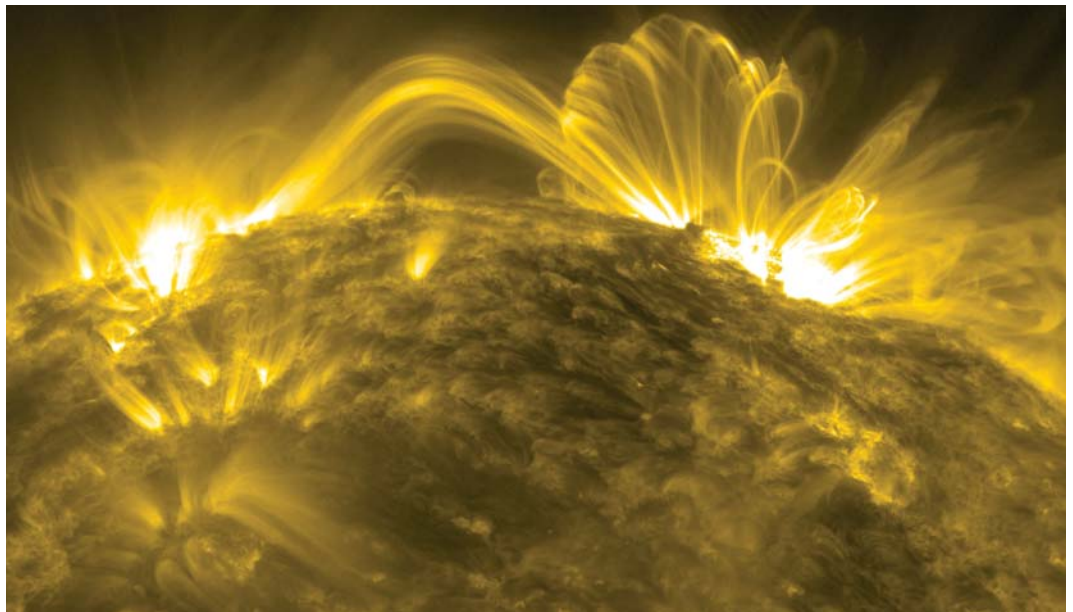


FIGURE 2. AN ACTIVE REGION of the Sun with many warm (approximately 10^6 K) coronal loops, as imaged at $171 \text{ \AA}$ by NASA’s *Solar Dynamics Observatory*. (Courtesy of NASA/*Solar Dynamics Observatory*.)

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temporal, and spectral resolutions. Recent spectrographic observations by *IRIS* demonstrate that heat is delivered in discrete, explosive events—called nanoflares because they are analogous to tiny solar flares—that occur when magnetic fields in the corona crisscross and realign.⁵ The resulting energy is deposited in the corona. Although the explosions are probably only one of a variety of complex processes that cause coronal heating, they may cause the heat to spread out over large regions because the corona behaves as a large thermal conductor.

In comparison with the spectacular high-energy solar flares that occur in active regions of the Sun, nanoflares are low-energy events. Although their frequency has not yet been well established, they are certainly more prevalent than large flares. Those larger events are notorious for producing a wide range of high-energy electromagnetic radiation, including x rays; microflares and nanoflares are considerably more difficult to observe because their x-ray energy content is lower. Figure 3 shows a microflare observed on 4 September 2016 by the Swedish 1-m Solar Telescope on La Palma in Spain's Canary Islands.

The solar-physics community now generally agrees that convective motion below the photosphere is responsible for the random movement of magnetic-loop footpoints, which build up magnetic stresses that are ultimately converted to heat. The invisibility of sunspot-to-sunspot loops, which are rooted in the strongest observed magnetic fluxes, provides fresh evidence that photospheric convective motions are likely drivers of coronal heating. Many solar physicists say that picture, known as the impulsive-heating scenario, is the likely mechanism for heat conversion. Indeed, new evidence for episodic impulsive heating in weak flaring sites associated with coronal loops is emerging in active regions.¹³ But it is unclear if that type of heating can also operate when the Sun goes quiet. Highly sensitive Japanese observations have recently confirmed that nanoflares occurred frequently in a region of the corona where no solar flare activity was taking place (see figure 4).

Because the Sun's UV radiation is mostly blocked by Earth's atmosphere, observing the solar corona typically requires the use of a space-based telescope. But significant data have also been obtained at much lower cost through the launch of UV telescopes on suborbital sounding rockets. NASA's High Resolution Coronal Imager (Hi-C), for example, returned detailed UV images of the solar corona taken during brief suborbital flights in 2012 and 2018. During the latter flight, Hi-C was equipped with a 24 cm mirror, which allowed it to capture an image of the corona every five seconds. Even though the Hi-C flights only lasted a little over 10 minutes, they revealed that sustained magnetic activity is present in the solar atmosphere, which might be responsible for the high temperatures of the coronal plasma.

The Focusing Optics X-ray Solar Imager (FOXSI), which was launched into space for about 6 minutes on three brief flights in 2012, 2014, and 2018, is another example of a solar telescope

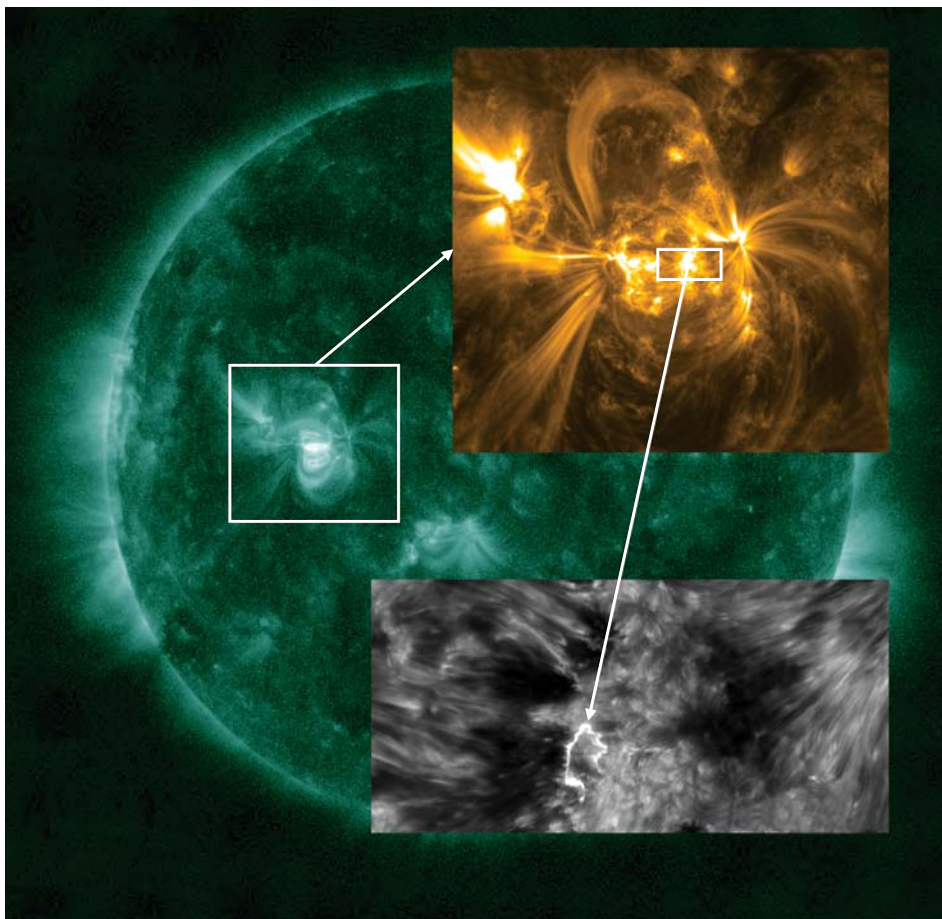


FIGURE 3. A MICROFLARE that occurred on 4 September 2016. In the green image, recorded at 94 Å, a hot coronal loop of more than 7×10^6 K is produced by magnetic reconnection. The upper inset, recorded at 171 Å, shows the active region with bright magnetic loops in high detail, and the lower inset, recorded at 3934 Å, depicts the region where electrons from the reconnection event impact the Sun's lower atmosphere. (Adapted from a composite image by Helle Bakke/Rosseland Centre for Solar Physics/University of Oslo, courtesy of the European Solar Telescope; background and upper inset courtesy of NASA/Solar Dynamics Observatory/Atmospheric Imaging Assembly; lower inset courtesy of the Swedish 1-m Solar Telescope/CHROMospheric Imaging Spectrometer.)

carried on a suborbital sounding rocket. X-ray data obtained by FOXSI revealed that a region of the Sun free of large-size solar flares nevertheless emitted high-energy light. Researchers have ascribed that light to intense nanoflares that crop up and dissipate quickly but produce small regions of extremely hot plasma that can reach temperatures above 10^7 K.¹⁴ At that time the detection of those tiny flares was still beyond the technological capabilities available to solar physicists. But the situation has changed over the last few years: Radio instrumentation has improved to the point that, during the Sun's quiet period, it can now produce high-fidelity images of weak impulsive emissions from the corona with a duration of about one second.

Solar probes

The last five years have also seen the start of two solar missions. The first is the *PSP*,¹⁵ which was launched in 2018. A robotic spacecraft that will fly as close as 8.85 solar radii from the Sun,



the *PSP* aims to investigate coronal heating and the origin of the solar wind. It has been called humanity's first visit to a star (see the article by Nour E. Raouafi, *PHYSICS TODAY*, November 2022, page 28). During its eighth flyby of the Sun, on 28 April 2021, the *PSP* flew within 18.8 solar radii of the solar surface, crossed the Alfvén critical surface—the location where the Alfvén-wave speed and the solar-wind speed are equal—and entered the corona. Data from the flyby showed that the Alfvén critical surface is not a smooth sphere but instead has highly irregular peaks and valleys.

On 11 December 2022, the probe made its 14th flyby of the Sun and got within about 12.2 solar radii of the Sun's surface. Data from that approach are currently being analyzed and will be published this month. The *PSP* will continue to spiral closer to the Sun, and the diminishing distance will give the *PSP*'s telescopes progressively higher spatial resolution so that they can capture solar features in more detail.

The second recent solar mission is *Solo*, a satellite developed by the European Space Agency in collaboration with NASA. Launched in 2020, *Solo* aims to address fundamental open questions in solar physics and heliophysics.¹⁶ Unlike the *PSP*, which focuses on the corona, *Solo* is designed to observe the solar surface. It will eventually come approximately as close as 60 solar radii from the Sun and will provide the closest images ever taken of the Sun's surface. Figure 5 shows an image taken by *Solo* on 7 March 2022. It depicts the full Sun in

FIGURE 4. A SWARM OF NANOFLARES populating the Sun's surface in a region with no discernible solar flare activity. (Courtesy of the Institute of Space and Astronautical Science/Japan Aerospace Exploration Agency.)

extreme-UV light at about 108 solar radii from the Sun's surface—halfway between Earth and the Sun.

Images taken by *Solo* that were released on 16 July 2020 depict miniature flares all over the solar surface, a stunning new phenomenon that can be called picoflares to emphasize that they are smaller than microflares and nanoflares. Those miniature solar flares are short-lived brightenings that last for 10–200 seconds and are 400–4000 km long. Flickering like candles, they reach temperatures over 10^6 K. They are the smallest and weakest solar events ever observed, and their abundance suggests that they may be the missing piece of the coronal-heating puzzle.⁷ Appearing as loop-like, dot-like, or even more complex structures, picoflares have unclear formation mechanisms and connections to the photospheric magnetic field. One possible explanation is that the formation and triggering of picoflares may be related to the magnetic-flux cancellation between weak flux patches.

Solo's first observations, which occurred during the minimum of solar cycle 24, revealed that large-amplitude, nonlinear Alfvén waves that propagate away from the solar surface may also be ubiquitous in slow solar-wind streams, particularly in

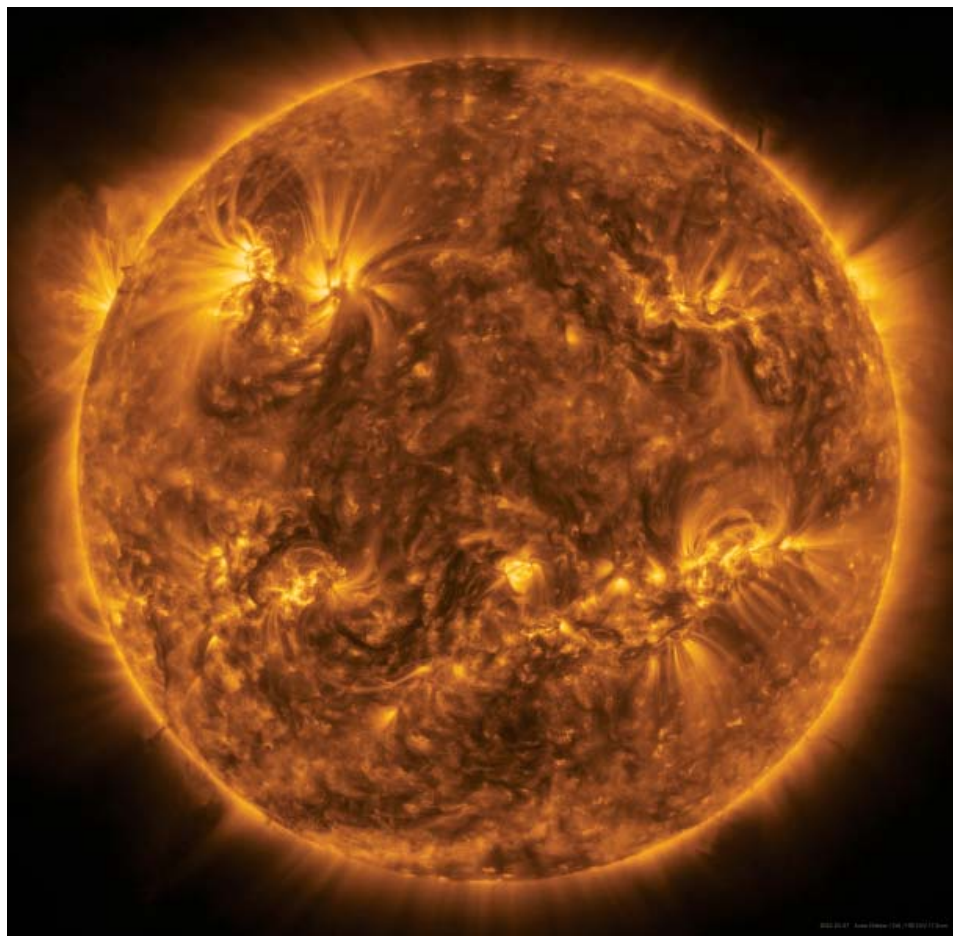


FIGURE 5. A HIGH-RESOLUTION PHOTO of the Sun taken by *Solar Orbiter* on 7 March 2022 when it was at a distance of about 108 solar radii from the Sun's surface. (Courtesy of ESA and NASA/*Solar Orbiter*/Extreme Ultraviolet Imager team; data processing by E. Kraaikamp/Royal Observatory of Belgium.)

a fold in a sheet of plasma. Other scientists unaffiliated with MURaM have pointed out that the corona could be home to even smaller flares that cannot be resolved by presently available technology but might contribute to the overall energy balance in the solar corona.

So are we close to solving the coronal-heating problem? *Solo* will continue to provide higher-resolution images of the Sun's surface as it tightens its orbit around the star. And as it dives deeper into the solar corona, the *PSP* will measure the flow of energy that heats the corona and accelerates the solar wind and determine both the structure and dynamics of the solar magnetic

the inner heliosphere.¹⁷ The *PSP* also made similar observations. But Alfvénic slow wind is more frequently observed during the maximum of solar activity. Over the coming years, *Solo* will fly closer to the Sun and increase its orbital inclination so that it can explore the Sun's polar regions. *Solo* and the *PSP* will both make unprecedented measurements of the inner heliosphere inside Mercury's orbit in 2023–26, the cycle 25 maximum. Those measurements are expected to shed light on the origin and evolution of the Alfvénic solar wind.

Is the mystery ending?

Data from new computer models suggest that there may be additional factors that will help account for coronal heating. Coronal loops, for example, have long been accepted as a part of the Sun's atmosphere. But the groundbreaking Max Planck Institute for Solar System Research/University of Chicago Radiative Magnetohydrodynamics (MURaM) solar model, one of the most realistic and powerful solar simulations ever created, suggests that the situation may be more complicated. The MURaM model extends from about 10 000 km below the Sun's surface to 40 000 km into the corona, which allows scientists to simulate the complete life cycle of a solar flare.¹⁸

The MURaM model indicates that coronal loops can overlap one another when we observe the Sun, which makes it difficult to discern which loops are in the foreground and which are in the background and how thick they are. Researchers who have worked with the model suggest that some of the observed loops might actually be optical illusions that are caused by

field. Data from both probes will help the community better understand coronal heating. But, as Jack Zirker and Oddbjørn Engvold wrote in their solar-corona article a few years ago, "Answers to existing questions will inevitably raise new questions" (see *PHYSICS TODAY*, August 2017, page 36). In any case, the answers to some existing questions will need to wait for the next flybys by *Solo* and the *PSP*.

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