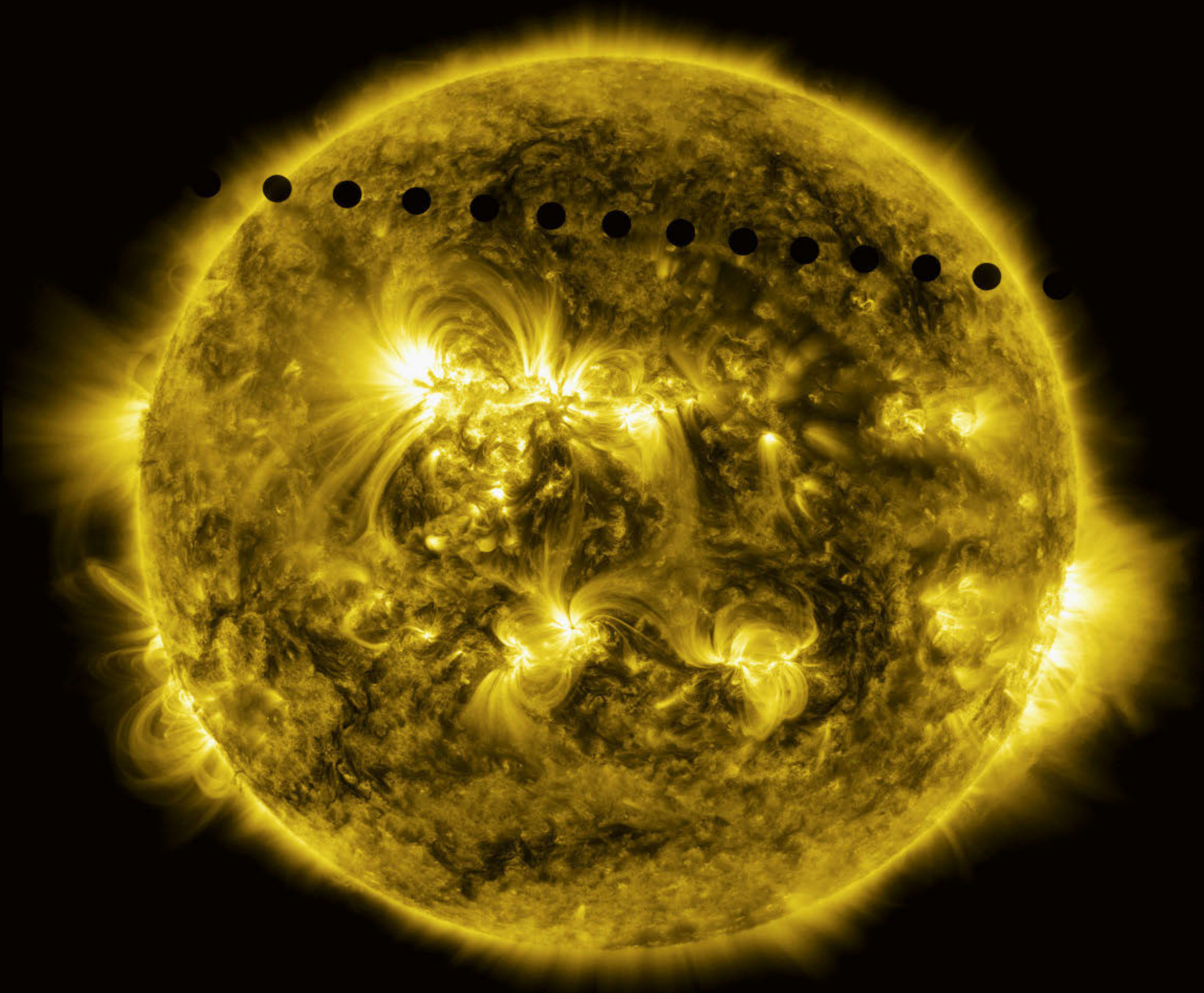
INTERNATIONAL
SPACE
SCIENCE
INSTITUTE

SPATIUM

Published by the Association Pro ISSI

No. 44, November 2019

Solar Magnetic Activity
with Lessons from Stars and Exoplanets



Editorial

During lectures for the public and for students, we sometimes provocatively ask the audience to list all possible forms of energy on Earth – and to name their elementary source. Of course, it is impossible to find even the most exotic appearance of any energy to be other than of solar or stellar origin. From time to time, it is just useful for us all to remember how generously we are fed with energy from our life-giving star. Consequently, the study of the Sun and its analogues is one of the main quests in astrophysics. However, there is still much work on this side to be done. As the high-energy part of the solar radiation is blocked by the terrestrial atmosphere, going to space is crucial for observations in this wavelength range. Various missions have collected valuable data to help us understand the processes and learn how our power station works. Still, so many things are as yet not known:

How exactly is the energy generated in nuclear reactions in the core that is driving the solar dynamo distributed far out into the solar atmosphere? The solar magnetic field plays a key role in this. It acts on all scales, from the dynamo and its roughly 11-year cycle down to the most tiny and fractal structures.

Investigation and measurement of the solar magnetic features is not easy. However, the Sun is not the only star we can observe; there are more players in this league of "cool stars". With recent missions observing other stars and their companions (meaning Earth's extra-solar-system colleagues, the exoplanets), we hope to gain more information using a wealth of statistics. This field of solar and stellar research is within the expertise of Dr. Karel Schrijver who skilfully guided his audience along measured and simulated magnetic field lines during a proISSI lecture in May 2019.

His presentation is the basis for the current Spatium. Once more, the editor is grateful to Prof. Martin Huber and Dr. Andreas Verdun for careful reading of the manuscript.

Anuschka Pauluhn
Mönthal, November 2019

Impressum

ISSN 2297–5888 (Print)
ISSN 2297–590X (Online)

Spatium
Published by the
Association Pro ISSI

INTERNATIONAL
SPACE
SCIENCE
INSTITUTE

Association Pro ISSI
Hallerstrasse 6, CH-3012 Bern
Phone +41 (0)31 631 48 96
see
www.issibern.ch/pro-issi.html
for the whole *Spatium* series

President
Prof. Adrian Jäggi,
University of Bern

Editor
Dr. Anuschka Pauluhn
CH-5237 Mönthal

Printing
Stämpfli AG
CH-3001 Bern

Title Caption
On 5 and 6 June 2012, the AIA Atmospheric Imaging Array (AIA) instrument aboard the Solar Dynamics Observatory (SDO) observed a rare transit of Venus. The image (taken in the 171 Å channel, showing the solar coronal glow from gases at temperatures near 1 million Kelvin) is a composite of slices, put together to show the track of Venus across the Sun. Credit: NASA/GSFC visualization studio.

Solar magnetic activity, with lessons from stars and exoplanets*

by Karel Schrijver, Johannes Geiss Fellow, International Space Science Institute, Bern, Switzerland

The Sun's mysteries

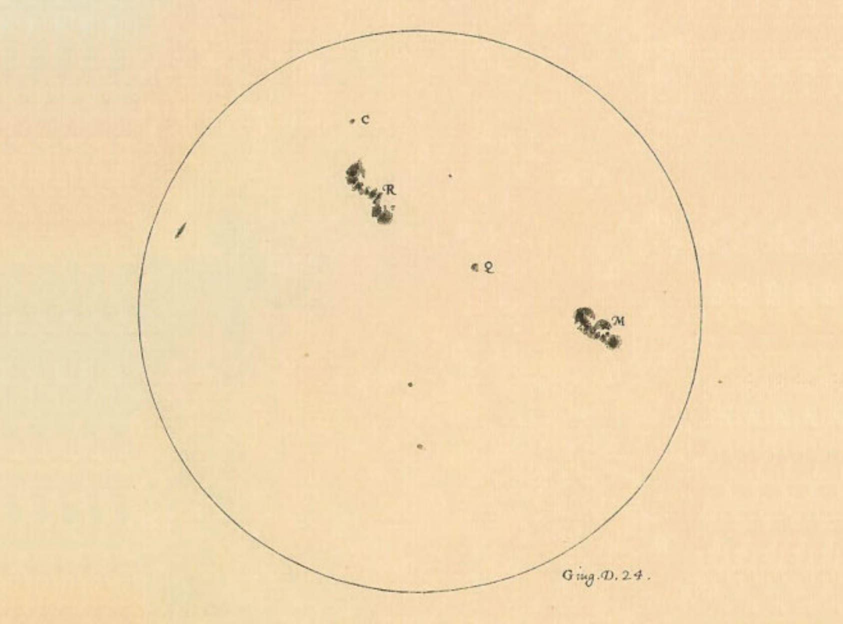
Our Sun became more mysterious when the first telescopes were pointed at it early in the 17th century: the Sun was found not to be the immaculate sphere of predominant supposition, but was instead seen to display dark spots on its surface **(Figure 1)**. Not only did these spots serve as markers revealing that the Sun is a rotating body, they also changed in appearance themselves within a matter of days demonstrating their transient nature, although what that nature really was remained a puzzle for a long time. Over the following centuries it became clear that the number of sunspots waxes and wanes in a quasi-regular 11-year cycle, that their appearance shifts in latitude through this cycle (**Figure 2**), and that the Sun's outer layers are rotating differentially such that the equatorial spin period is shorter than the polar spin period (**Figure 5**).

The Sun's mysteries deepened once the quantitative tools of physics were developed to determine the age of the Earth: how had the Sun maintained its energy output for some 4.5 billion years? The answer to that question was developed in the first half of the 20th century as astronomers discovered that the Sun was primarily made of hydrogen and helium, while physicists worked out the details of what that implied: the Sun's core is a vast fusion reactor, primarily converting hydrogen into helium.

Once spectroscopy, the method to analyse light, was sufficiently developed, more mysteries arose: how does the Sun create its ever-changing magnetic field, and why are sunspots the sites of the strongest concentrations of that field? How can it be that the Sun's outermost atmospheric layers are up to a thousand times hotter than its surface? We now know the foundations of the answers to these and many other questions about the Sun, but much work remains to refine them.

Why are astrophysicists so interested in the puzzles of the Sun? One reason is that it is a fascinating and beautiful, ever-changing object that begs to be observed and understood. As it is by far the nearest star, what we learn about the Sun guides our thinking about what happens in, on, and around most other stars in the Universe. Another reason is that we have realised that the Sun's variability often influences our technological infrastructures. This happens both high up in space and around ground level, through what has become known as space weather. In this article, I will take you on a tour of some of the things we learned about the Sun's magnetism, and how we continue to do so.

Figure 1: One of the earliest sunspot drawings, made by Galileo Galilei on 24 June 1612. Galileo had modified the design of the astronomical telescope, invented around 1609, to image the Sun on paper, and then drew the visible sunspots. That sunspots have a magnetic nature was discovered by George Ellery Hale in 1908.



---

* This issue of Spatium is based on a proISSI seminar held by Dr. K. Schrijver on 8 May 2019.

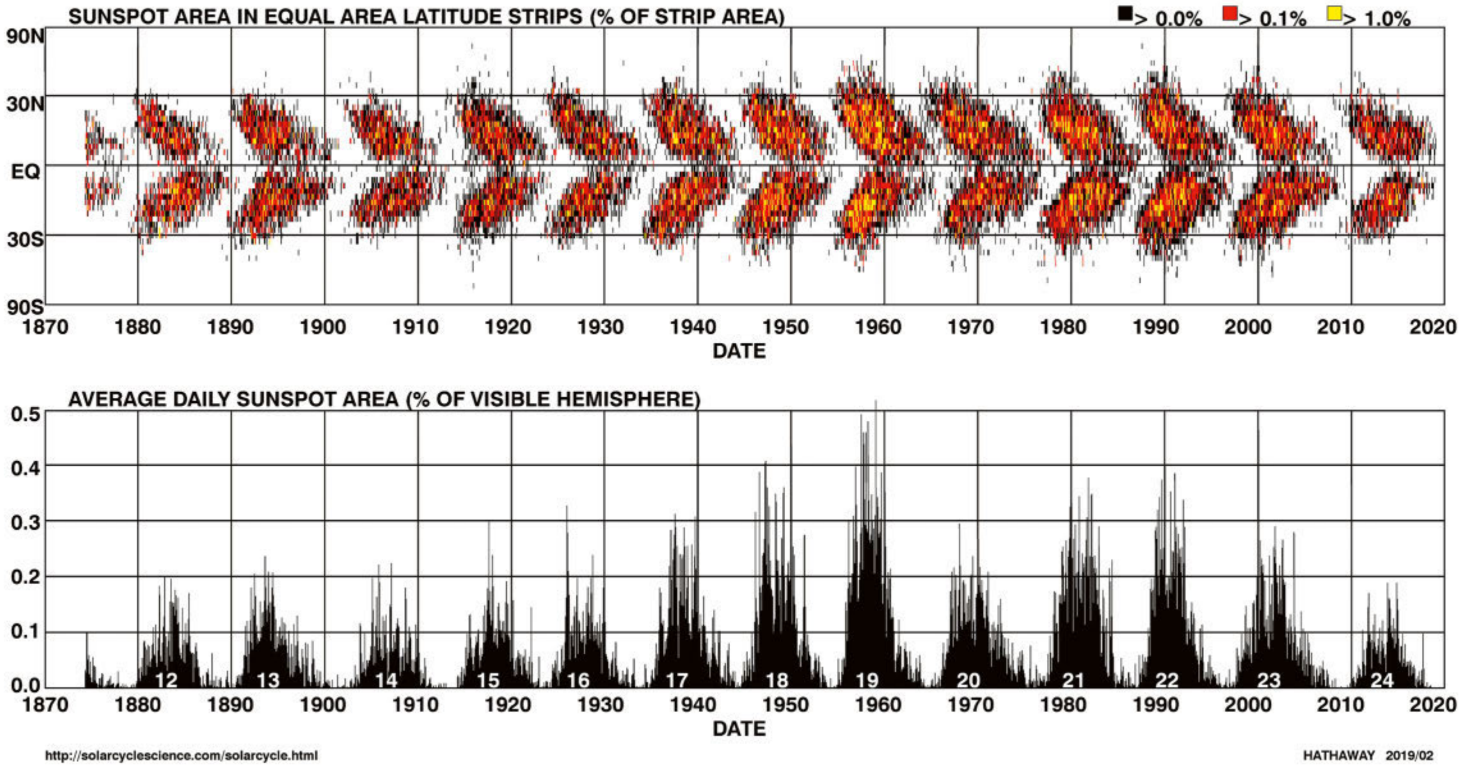
One among the stars

Although often described as an average star, the Sun is not of average size, mass or brightness. The intrinsic brightness of stars ranges from supergiants that are tens of thousands of times brighter than the Sun down to red dwarf stars that are a thousand times fainter **(Figure 3)**.

The number of stars that form throughout the Galaxy increases smoothly as we look from heavy to lighter stars. Those that form as less-massive stars have longer life spans: whereas heavy stars survive for only a few million years, the lightest can continue to fuse hydrogen for hundreds of billions of years. One result of these trends in formation frequency and lifetime as a function of stellar mass is that the Sun is surrounded by mostly smaller peers: our star is the fourth largest, heaviest, and brightest among the 50 stars in the solar neighbourhood.

Although on the larger side of average, the Sun by no means stands out as unusual otherwise. It has an average mix of chemical elements and is halfway in its lifetime of about 10 billion years as a mature star. Even in its companions it is not unusual: roughly every second star that we see in the sky is single like the Sun; the others are either pairs of stars orbiting each other or, ever less frequently, triplets, quadruplets, or even larger multiples. We have learned over just the past quarter-century that even having a planetary system is normal for a star: the majority of the very roughly 100 billion stars in the Milky Way galaxy have at least one exoplanet in orbit around them. Most of these orbit a magnetically active star, in many ways comparable to our Sun.

Figure 2: Top: The butterfly diagram, plotting the latitudes at which sunspots appear versus time. The colouration indicates the fraction of the solar surface covered by sunspots. The first such diagram was made by Walter and Annie Maunder in 1904. **Bottom:** Total sunspot area over time and the numbering of the sunspot cycles. Sunspot records go back to the early 17th century, see, e.g., http://sidc.oma.be/silso/. Credit: David Hathaway, NASA.



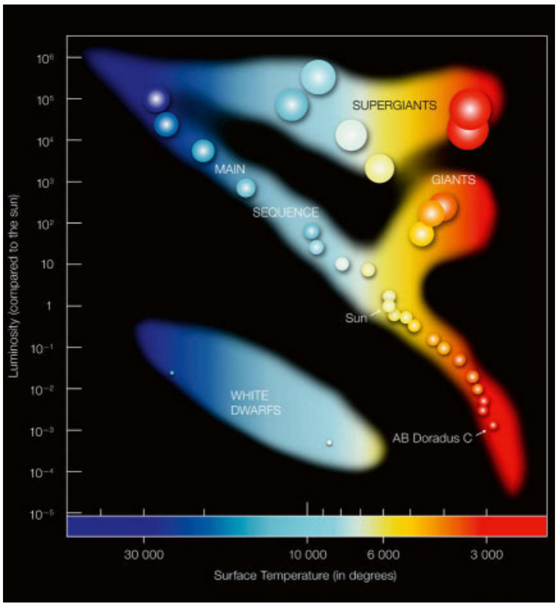


Figure 3: The Hertzprung-Russell diagram displays the luminosities of stars as a function of their surface temperatures. Mature stars, spending most of their lifetime fusing hydrogen into helium, lie on the diagonal branch, the so-called main sequence. When their fuel begins to run out, they leave the main sequence to become giant red stars. The more massive ones become giant red stars. Once a star like the Sun has consumed all of its fuel, it evolves into a compact white dwarf, a glowing stellar ember the size of the Earth. The bubbles indicate relative sizes of stars, but in reality the contrast is much larger: supergiant stars can be hundreds of times larger than the Sun, while white dwarfs are a hundred times smaller. Credit: ESO.

Listening to the Sun

For half a century now, astrophysicists have been recording sound waves to probe the interior of the Sun. The waves are generated as a byproduct of the overturning movements of the gas in the convective envelope of the Sun, most readily in the near-surface layers. The pressure fluctuations propagate through the interior of the Sun with little dampening. When they propagate into the solar interior, their paths are bent back towards the surface as a result of the increasing temperature and the associated increase in propagation speed. When they reach the solar surface, those with a period exceeding a few minutes are reflected. Together, these two effects create a cavity within which resonant interference develops into millions of standing waves with periods of around five minutes: the Sun rings like a bell, but in a multitude of tones simultaneously. At the surface, these standing waves can be detected in one of two ways: (1) as intensity fluctuations, owing to compressions and rarefactions by the waves, and (2) as Doppler shifts, owing to the undulating motions. Modes with high degrees (with many nodes across a surface at constant radius) probe, primarily, the near-surface layers, while low-degree (nearly purely radial) modes probe much of the solar interior. Disentangling the multitude of modes requires precise and sustained observations, measuring velocities of the order of 20 cm/s from uninterrupted measurements spanning several months at least. The result is the equivalent of a medical ultrasound scan of the Sun's internal structure and – through Doppler effects on the sound waves – of large-scale subsurface wind patterns, referred to as flows. This practice, known as helioseismology, has helped in many distinct ways to better understand the Sun and, with that, other stars: it has validated stellar structural models, established the age of the Sun, and even guided particle physicists to new realisations about the processes by which neutrinos of one type can turn into another.

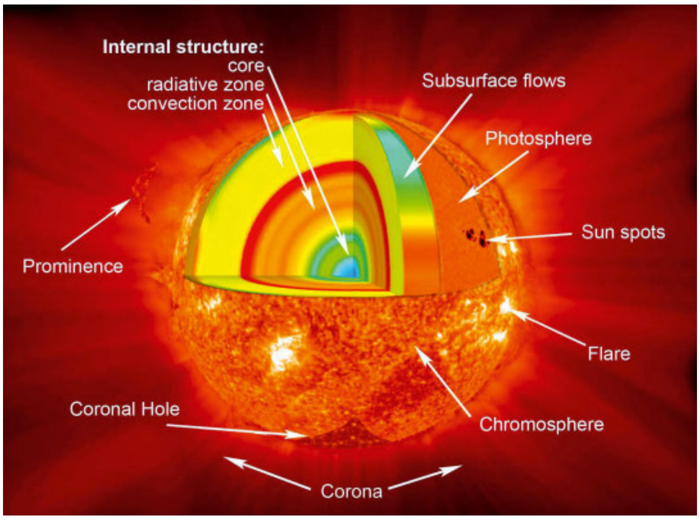


Figure 4: The internal structure of the Sun. Energy is released by nuclear fusion in the core, moves in a scattering exchange with ionised matter through the surrounding radiative zone, until overturning convective motions become the dominant transport process in the outer envelope. From the Sun's surface outward, the gas is essentially transparent to the bulk of the light, but special filters and telescopes can show the structures in the outer regimes of the chromosphere (around 20 000 degrees) and the corona (above a million degrees). Credit: NASA.

The Sun's interior

Helioseismology has led to a detailed knowledge of the stratification of density and temperature throughout the Sun **(Figure 4)**. It confirmed that the Sun's deep interior, although entirely gaseous, is rotating at the same angular rate throughout, thus spinning just like a solid body. Energy is transported outward from the nuclear reactions in the core by a random walk of photons. These frequently exchange energy with ions and electrons as they scatter between them. Until, that is, they reach a layer on their way around the solar interior in which the temperature is sufficiently low for a substantial number of neutral atoms to exist in the mix. At that point, some 200 000 km below the surface, the opacity of the gas increases and energy transport in the form of electromagnetic radiation becomes impeded. There, another mode of energy transport begins to dominate: convective overturning motions carry thermal energy upward until ultimately, about 700 000 km from the centre, radiation can freely escape into space from the solar photosphere, the layer with a thickness of some 100 km that we experience as the solar surface.

The rotation of the Sun, once every 25 days on average, leads to Coriolis forces acting on the convective motions, as they do on Earth, for example, in low and high-pressure areas in the troposphere. Helioseismology has revealed that rotation and convection set up large-scale winds throughout the convective envelope. The equatorial zones rotate faster than the high-latitude zones, in such a way that the Sun's rotation rate is mostly constant with depth along a radial line through the envelope, but that it is decreasing with increasing latitude (as shown on the right in **Figure 5**). In addition to this azimuthal (east-west) motion there is also a meridional (north-south) pattern. It is most readily seen at the surface as an equator-to-pole flow reaching a maximum of about 15 m/s at mid-latitudes. The return flow at depth is still being investigated: the denser interior counterflow is much slower and therefore harder to measure. It remains unclear whether there is only one global overturning motion like a giant conveyor belt (as depicted on the left in **Figure 5**) or whether circulations are layered, possibly two or three cells deep, within the envelope.

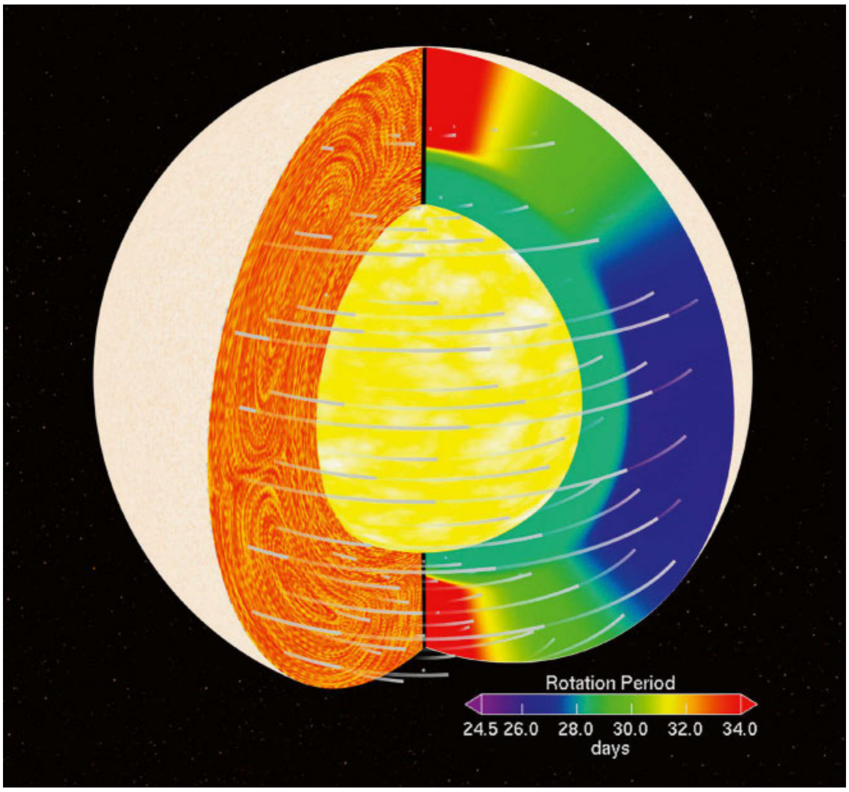


Figure 5: Illustration of the components of the largest-scale flows within and somewhat below the solar convective envelope as revealed by helioseismology. Right side: the Sun's latitude-dependent rotation within the convective envelope morphs into a near-rigid rotation deeper down. Left side: the meridional circulation, here shown with a single overturning cell for each hemisphere, is poleward near the surface and equatorward at depth. This flow is so slow, deep down, that its actual pattern is yet to be determined. Credit: NASA.

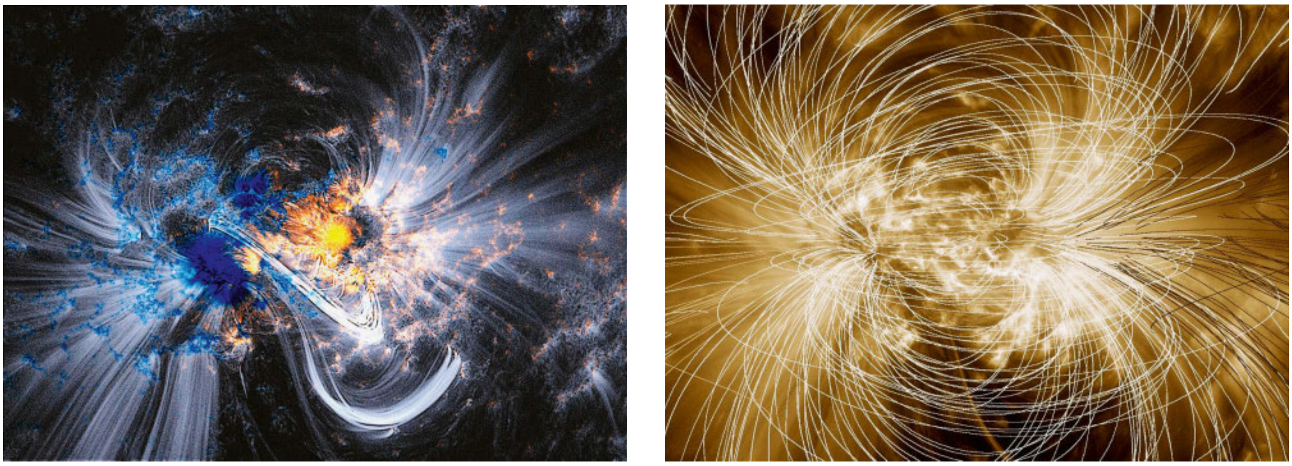


Figure 6: A map (magnetogram) of the magnetic field of active region AR 12192, observed by the Solar Dynamics Observatory (SDO), showing the two opposite magnetic polarities in blue and yellow. The coronal magnetic field above the surface is visualised through the bright, thin coronal loops in the slightly-sharpened EUV (171 Å channel) image blended on top.

For comparison, another SDO EUV (193 Å) image of the same site is shown with field lines computed assuming there are no electrical currents above the surface. The mismatch of the pattern of the observed loops with that of the model field shows that strong electrical currents exist above this region. Such currents contain energy that can be released in a solar flare, coronal mass ejection, or both. Credit: SDO/AIA team at Lockheed Martin Solar and Astrophysics Lab, and NASA.

The magnetic Sun

It took decades of observations, but we now know that all stars that generate a dynamic magnetic field like that of the Sun have one thing in common: they all have a convective envelope around an essentially stationary (although spinning) interior. All such stars have surface temperatures on the cool end of the stellar range, and they are therefore commonly known as "cool" stars. Their relatively low surface temperature makes them appear yellow, orange, or red, and places them on the righthand side of a diagram commonly used by astrophysicists, the so-called Hertzsprung-Russell (or HR) diagramme **(Figure 3)**.

The magnetic phenomenon that was first discovered is that of the sunspot **(Figure 1)**. We have known these to be clusters of intense magnetic field since spectroscopic measurements were developed to demonstrate that in 1908, but their behaviour had been studied for almost three centuries before then. Sunspots are temporary structures, surviving for days or at most about two weeks. Their overall numbers wax and wane on a quasi-regular 11-year time scale in what is known as the sunspot cycle (bottom panel of **Figure 2**). In each cycle, successive generations of sunspots emerge from the interior, first at mid-latitudes, then the band of emergence shifts towards lower latitudes, and as one cycle fades away near the equator, another begins at mid-latitudes (upper panel in **Figure 2**).

Sunspots are part of so-called "active" regions that result from the emergence of a bundle of magnetic field from the interior. As the arched bundle breaches the solar surface, pairs of adjacent patches of opposite magnetic polarity form (see the blue-yellow background image in the left panel of **Figure 6**). Sunspots commonly form within the regions with large magnetic fluxes. The sizes of bipolar regions range from the largest at some 200 000 km across down to the observational limit of magnetographs around a few thousand kilometres, with the number of regions rapidly rising as sizes decrease. Active regions are by definition bipolar regions large enough to have sunspots at some time in their lives. Roughly one out of every two such regions emerges close to the site of previous active regions, often while the previous active region still persists at that location. This is referred to as a sunspot nest.

Some days to a week after emergence, after a phase of moderate coherence, the bipolar regions are shredded into fragments by the turbulent convection. The fragments begin a meandering random walk superposed on the large-scale flows of differential rotation and meridional advection. As they do so, they often collide with other such parcels of magnetic flux. If of equal polarity, a larger conglomerate of flux temporarily forms. If of opposite polarities, fluxes cancel, in the process removing equal amounts of oppositely signed flux until the smaller of the two disappears. This cancellation works in time series of magnetic-field maps almost as an arithmetic summation of signed fluxes. In reality, on the Sun, the physics involves reconnection of magnetic field, followed by either retraction or expulsion of the newly connected arches from the surface layers. The multitude of small bipolar regions, the so-called ephemeral regions, play an important role in this. They maintain the small-scale mixture of opposite polarities of much of the solar surface, the so-called "quiet" (i.e., not belonging to an active region) Sun, and is there the foundation of the faint and relatively-cool quiet corona. The cancellation and replenishment processes of ephemeral regions with other flux help maintain a smaller-scale population which more readily disperses stochastically. Consequently, the outcome of this magneto-chemistry of clustering and cancellation is a patchwork of pepper-and-salt polarities, mixed on a range of scales. All this aids in the dispersal of flux as well as in the heating of the atmosphere through the frequent reconnection of field driven by the motions below.

Figure 7: The multi-temperature solar atmosphere: a composite of images by the SDO telescopes. From right to left: the visible-light solar surface; 1600 Å image of the high surface layers and in part the transition region to the hot corona; He II 304 Å of the high chromosphere; and a three-channel composite of the corona (171 Å, 193 Å, and 211 Å) with blue, green, red roughly corresponding to 1 MK, 1.5 MK, and (2 to 3) MK. Credit: SDO/AIA team at the Lockheed Martin Solar and Astrophysics Lab.

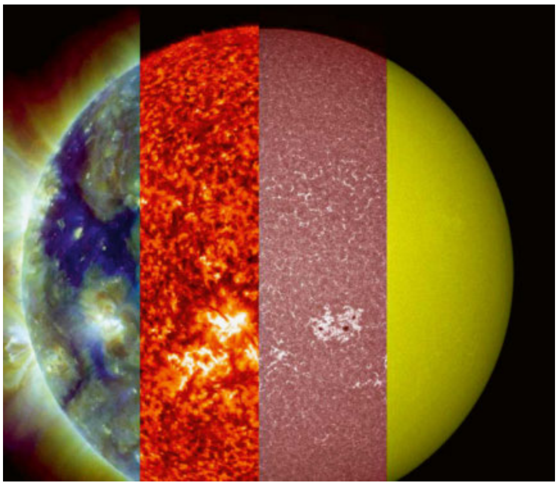
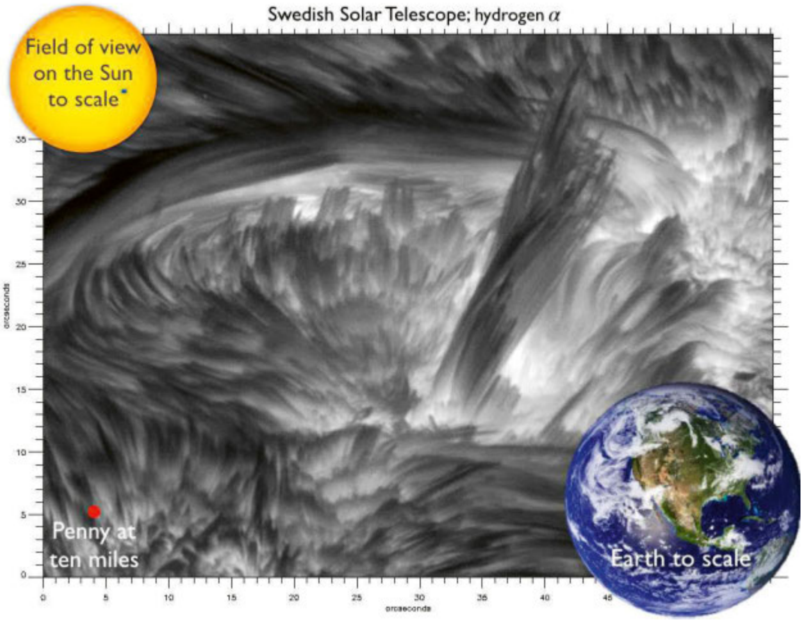


Figure 8: A segment of the Sun's chromosphere. This domain immediately above the solar surface can be seen only in a few specific colours emitted by some of the dominant chemical elements. In this case, the images are taken in light of non-ionised hydrogen (Hα). Hot, ionised material can only move along the magnetic field. Frequent collisions between neutral atoms and ions enforce largely joint motions. As a consequence, this image of the neutral gas reveals the structure of the magnetic field, such as the near-vertical fibrils that extend from a sunspot region underneath. They appear clipped at the top where the temperature shoots up to a million degrees or more so that neutral hydrogen disappears as it is ionised. A nearly horizontal set of fibrils outlines a twisted field structure, here forming a small current-carrying filament. Credit: Swedish Solar Telescope team.



Dynamos in cool stars

Observations of stars have revealed that all cool stars display signatures of magnetic activity, typically more pronounced for more rapidly rotating stars. From that we learned that convection and rotation (and thus the Coriolis force) are key to stellar dynamos.

Although the primary ingredients of solar-like stellar magnetic activity are known – rotation and a convective envelope reaching up to the stellar surface – there is no comprehensive first-principles dynamo theory. We do not know why the Sun is as active as it is although it is compatible in its activity with other cool stars of comparable spectral type and spin rate. We do not understand why the Sun has a pronounced yet somewhat unsteady 11-year cycle. In fact, we are realising that cycling stars are in the minority among the cool stars, while among the really Sun-like stars of comparable rotation rate, the Sun appears to be the only one with a clear activity cycle. That latter point needs further study because the number of such stars that have been monitored for their activity over many years is rather lower than what we would need for a firm conclusion.

Despite this ongoing puzzle about stellar dynamos, numerical models are helping to rapidly advance our insights. The interaction between magnetic field and convective motions mediated by the magnetic Lorentz force is ever more realistically included and studied down to increasingly smaller scales. The tremendous density contrast between the bottom and top of the convective envelope, and the attendant enormous scale difference of the convective motions (from 50 000 km to 50 km) that needs to be included in models, is covered increasingly well as computers become more powerful.

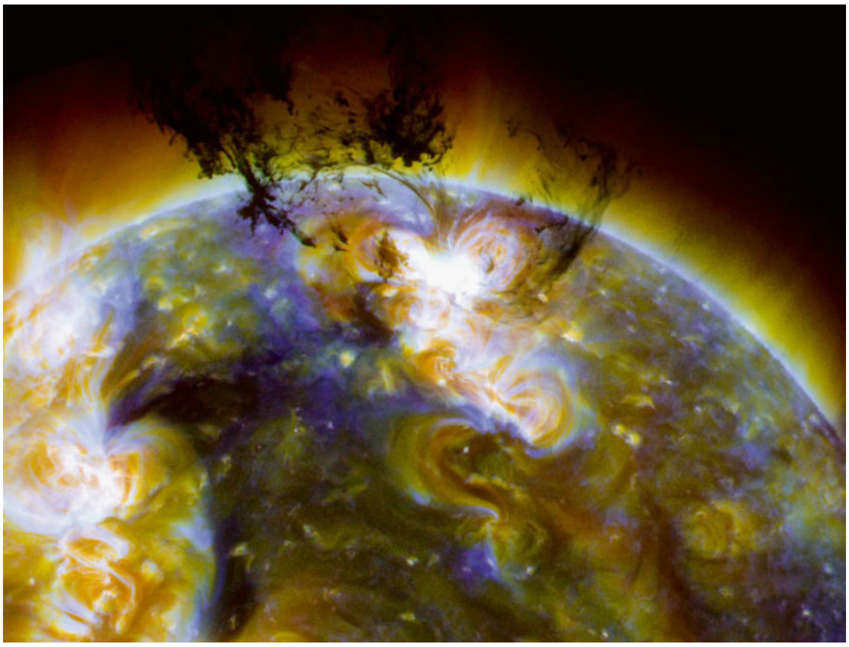


Figure 9: A massive explosion rocked the Sun on 7 June 2011, lifting an enormous amount of cool, dark, EUV-absorbing material into the high corona. The event is shown here (with the solar rotation axis moved by about 120° counterclockwise) in a combination of three false-colour SDO images with blue, green, and red for temperatures around 1 MK, 1.5 MK, and (2 to 3) MK, respectively. Most of the cooler material eventually fell back onto the Sun, heating up to a million degrees or more on impact from the gravitational energy of the fall. This is expected to resemble what happens when forming stars capture gas from their surroundings. Credit: SDO/AIA team at LMSAL, and NASA.

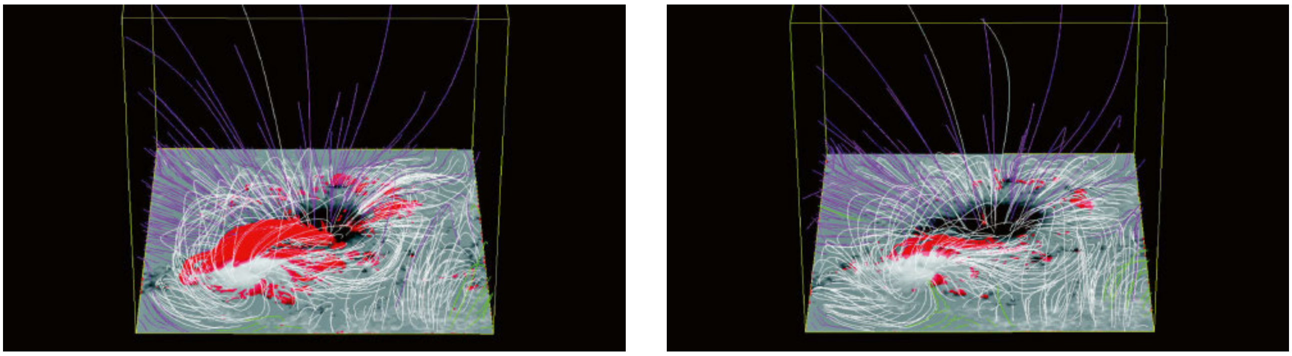
Understanding why and where flux bundles form as the origin of bipolar regions (including the persistence of sunspot nests) remains a challenge. The same is true for understanding how certain flux bundles can reach the surface as such coherent and strong structures as they are. It is in these surface layers where observations show that convection shreds the flux bundles, and where thermal radiation suddenly has a freely available escape route out of the Sun in contrast to their confinement in the dense, opaque layers below. Most state-of-the-art dynamo models are still restricted to the deeper layers, leaving the last few per cent of the solar radius untouched. Flux-emergence models that show how the field may behave in those near-surface layers typically start with a ready-made flux tube that is introduced into, or even simply released from, the bottom end of such limited-volume models that reach just a few percent (tens of thousands of kilometres) into the Sun.

Because of these numerical challenges, closing the life cycle of field (from formation in the deep envelope, through transport to and across the surface, to ultimate retraction upon cancellation to seed the next cycle) remains beyond our capabilities even in the most advanced radiative magneto-convective codes. To bridge this gap, researchers work on innovative combinations of magneto-convective modelling for the deeper interior linked to empirically-guided, highly-simplified flux transport across the surface. These modelling combinations appear to be a promising avenue of research for limited-time cycle forecasting, but they are only temporary stepping stones towards understanding of dynamos in cool stars in general.

Cool spots, hot faculae

The magnetic field in sunspots is strong enough to impede convection near the surface. With less heat being supplied from below, the temperature inside the fields settles to a lower equilibrium, and the gas to a lower brightness, than in the surrounding area. This leads to cool, dark spot cores. This also causes the photosphere, the apparent solar surface, inside the spot to lie below its surroundings because the gas density falls off more rapidly at the lower temperature. Light leaks in sideways providing energy to the interior, but for the large flux bundles that make sunspots, the cooling area of the spot interior is too large to maintain the gas there at temperatures similar to those of the surrounding solar surface. In contrast, for slender flux bundles, which have only somewhat smaller intrinsic field strengths at the surface, radiation leaks in sideways in much greater proportion to the cooling interior. Thus, a slender tube can maintain an internal temperature and brightness similar to the values of the gases in its vicinity. For very slender tubes the photosphere also lies below that of their surroundings. Here we can even peak into deeper, hotter, brighter layers. These form the so-called faculae, small bright patches, the ensemble of which results in much of the visible brightening of the active region. The effect of the multitude of slender flux tubes with some sunspots dotting the solar surface is that at cycle maximum the Sun appears brighter by a few tenths of one per cent, while sunspots then cause temporary dips in the solar irradiance as they cross near the central meridian.

Figure 10: Visualisations of the magnetic field over active region AR10930 before (left) and after (right) a large flare, shown against the corresponding map of the vertical magnetic field at the surface. Sample field lines outline the field (coloured when they reach outside the box). The red volumes show where the most intense electrical currents run. Much of the energy associated with these currents was used to power the solar flare and eruption, leaving a much-weakened pattern after the event. Figure 3 from Schrijver et al. (2008).



The hot outer atmosphere

Another puzzle begins just above the solar surface. The first layer following the photosphere is the chromosphere, named after its red glow from the prominent Hα-line of the hydrogen spectrum that is seen around the lunar limb during total eclipses. It is mostly transparent except in the strongest spectral lines of common chemical elements. This domain is hot enough to be largely ionised, but atoms will have typically lost only one or two electrons at a gas temperature that is some three to four times that of the solar surface (which itself lies around 5800 K). Above that, at heights of some 10000 km and above, lies the corona: that domain reaches temperatures of typically 20 to 50 times that of the surface and more, and radiates primarily in the extreme ultraviolet (EUV) and in soft X-rays. The corona is visible to the unaided eye only during total solar eclipses through sunlight that is scattered off the free electrons that it contains. Hydrogen and helium, the dominant elements anywhere in the Sun, are fully ionised there and thus have no contribution in the ensemble of EUV and X-ray spectral lines. Elements such as the fairly abundant carbon, nitrogen, oxygen, and iron retain some electrons even at million degree temperatures, and they consequently dominate the coronal emission (**Figure 7**).

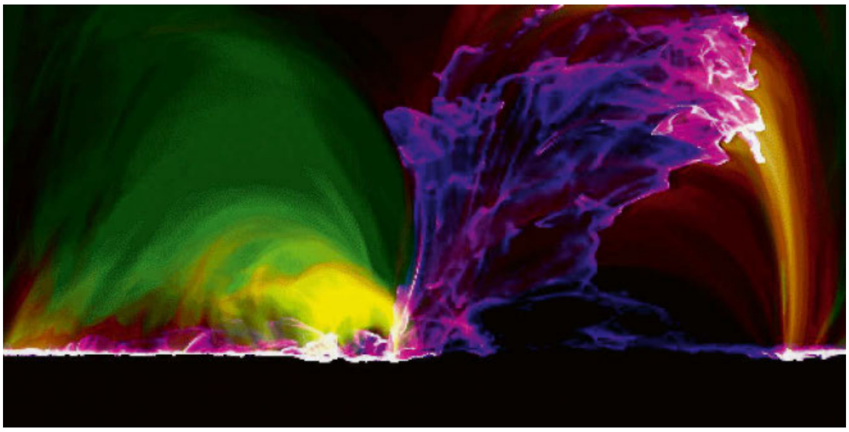


Figure 11: This visualisation is a side-view snapshot from a computer model of a solar flare. The violet, red, and green represent temperatures below 1 MK, between 1 MK and 10 MK, and above 10 MK, respectively. The model extends vertically from 10000 km below the surface (a relatively cool and opaque domain shown in black) to 40000 km above the surface. In this model, a rising flux tube emerged through the surface, destabilised, and erupted in a solar flare, with matter ejected, some falling back, rising in temperature through resistive heating and then cooling by radiation and conduction. After Cheung et al. (2019), from https://news.ucar.edu/132648/emergence-eruption.

In most of the solar corona, and in much of the solar chromosphere, the energy density in the magnetic field outweighs that in the thermal motions of the ions and – if present – neutral atoms. Therefore, it is the magnetic field that prescribes the shape of atmospheric structures: ions and electrons can move along, but not perpendicular to, the magnetic field. This results in essentially linear atmospheric structures that move with the field as that responds to flows at the surface and below. Collisions between ions and neutral atoms at these heights also cause the neutrals to be dragged along. The result is an atmosphere in which emitting and absorbing clouds outline the magnetic field (**Figures 6, 7, and 8**).

Ever since the late 1940s, when scientists realised just how hot the corona is, the processes that heat the outer atmosphere of our star have been the subject of research. This remains a challenge, although it has shifted in nature. There is so little gas in the atmosphere of the Sun that it takes only a minute fraction of the Sun's energy budget to keep it hot. The problem is not the amount of energy, but how that is delivered in the right form to create the very high temperatures: sunlight, no matter how much energy it contains, cannot do that because it cannot raise a temperature above its own characteristic equivalent of 5800 K.

At first, sound waves were thought responsible, and solutions were sought for hot coronal structures stable enough to persist for many hours. These had been inferred from the low-resolution and low-cadence observations in the early days of space science. Now, we re-

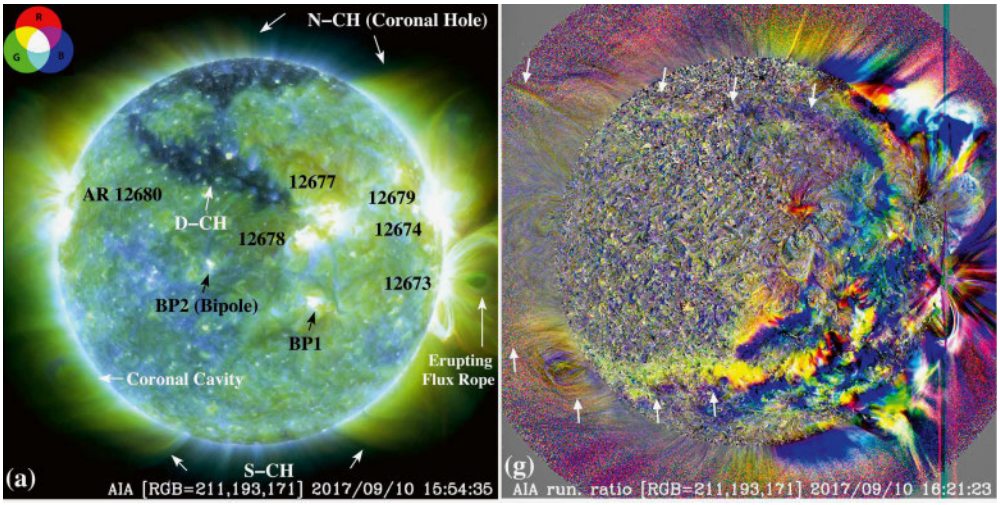


Figure 12: Solar eruptions can cause perturbations to rock much of the outer atmosphere, sometimes right across the Sun, such as in this case for a flare from AR 12673 (on the limb, at lower right). **Left:** False-colour composite of the solar corona, about 5 minutes before the flare reached peak brightness, combining channels 211 Å (red, most sensitive to gases at about (2 to 3) million degrees), 193 Å (green, characteristic of about 1.5 MK), and 171 Å (blue, peaking around 1 MK). It shows the erupting flux rope and identifies active regions and other features. **Right:** This panel shows only what is still changing 45 minutes after the eruption started: neutral grey is unchanging while bright (or dark) grey means overall brightening (or dimming). Changes in colour indicate plasma heating when yellow or red, or cooling when blue. The shock wave and other perturbations have by then reached across much of the Sun (with a diameter of 1 400 000 km). (Part of Figure 1 from Liu et al. (2018), which shows more snapshots over time.)

alise that forms of energy suitable for heating the solar atmosphere have to do with the magnetic field: dissipation of electrical currents and magnetic waves, in some mixture that likely depends on the environment, lead to an ever-changing cloudscape of atmospheric features evolving on time scales of the order of tens of minutes.

Whatever the processes are in detail, we now know they happen similarly in all cool stars: there is a basal chromospheric level of heating that is likely related to acoustic waves and maybe also to a small-scale turbulent dynamo, but beyond that the magnetic phenomena of all cool stars behave comparably in heating their atmospheres. In fact, once the radiative loss in one activity diagnostic is measured, all others can be estimated with fair accuracy using power-law relationships. The existence of such power laws hints at self-similarities in the processes[1], regardless of surface gravity or convective properties. For the Sun and Sun-like stars, power-law relationships valid on the scale of active regions transform into similar ones for stars as a whole, at different activity levels as a consequence of how field is injected and transported across the surface.

Computer experiments are also rapidly advancing in fidelity in this challenging area. Radiative exchange, transient ionisation effects, and ion-neutral interactions have been demonstrated to be important for the chromosphere. For the corona, coupled cascades between turbulently-driven electrical currents and wave-mode couplings are essential ingredients in the overall process of heating solar and stellar atmospheres.

Solar flares and eruptions

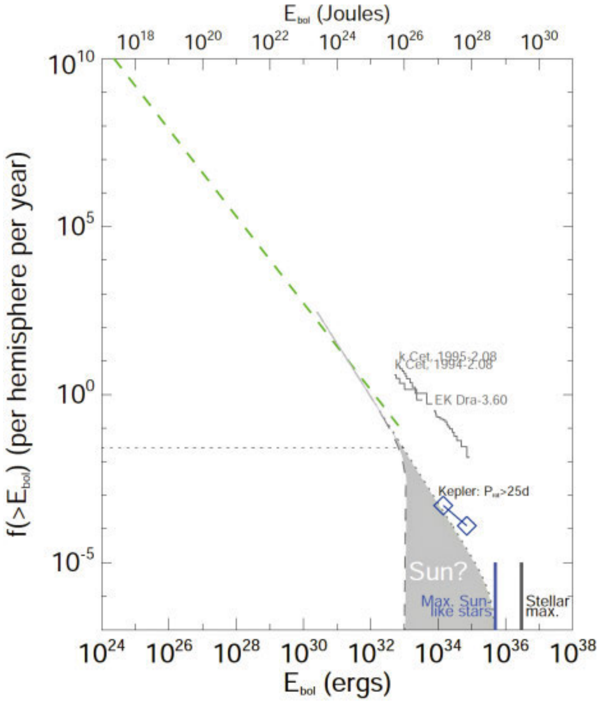
The magnetic bundles that breach the solar surface to form active regions often carry strong electrical currents. Such currents can also be the result of the movements of the field that are forced by (sub-)surface convection, by the interaction with neighbouring regions, or with intruding flux bundles (as in sunspot nests). The currents reflect stresses in the field; these may be relaxed through instabilities, that at least change the field geometry (and may thus not require electrical resistivity), but generally also its topology (requiring magnetic reconnection, and thus resistivity).

---

[1] In fact, the self similarity or scale invariance is the most prominent feature of a power law: if the argument of the function $f(x) = a\,x^p$ is multiplied (scaled) by a factor c, $f(cx) = a(cx)^p = ac^p\,x^p = Cf(x)$, the result is proportional to the original function. The process looks similar on all scales.

The instabilities that occur in these fields lead to explosive energy transformations from magnetic energy to energy of motion. This commonly results in energy budgets of comparable order of magnitude for heat (and its cooling radiation), energetic particles (most of which deposit their energy lower in the atmosphere, there creating the flare ribbons at the foundations of the most recently reconnected magnetic field), and bulk outward motion. The latter involves eruptions, many of which propagate into the heliosphere as coronal mass ejections (CMEs), particularly frequently for the most energetic events.

Figure 13: Number of flares per year (averaged over the solar cycle) that exceed a total radiated (bolometric) energy E_{bol}. The green dashed line is a fit to solar data connecting feeble EUV network flares and powerful active-region X-ray flares, with X-ray flare data shown separately by the grey line. A horizontal dotted line marks the detection limit for space-based solar observations. The grey area identifies the uncertainty that currently exists for extreme solar events: straight down if extremely energetic flares do not occur on the Sun, or curving more slowly if they do. Frequencies of stellar flares observed with the Kepler satellite for Sun-like stars at about solar rotation rates are shown by diamonds; they suggest that extreme solar flares should be anticipated to occur infrequently. Maximum flare energies reported for all magnetically-active stars and for truly Sun-like stars are indicated by vertical lines. The X/EUV flare frequencies for the stars κ Cet and EK Dra, Sun-like but spinning much faster, are shown for reference, normalised downward to the frequency expected for a Sun-like star as inferred from Kepler data. From Schrijver and Beer (2014).

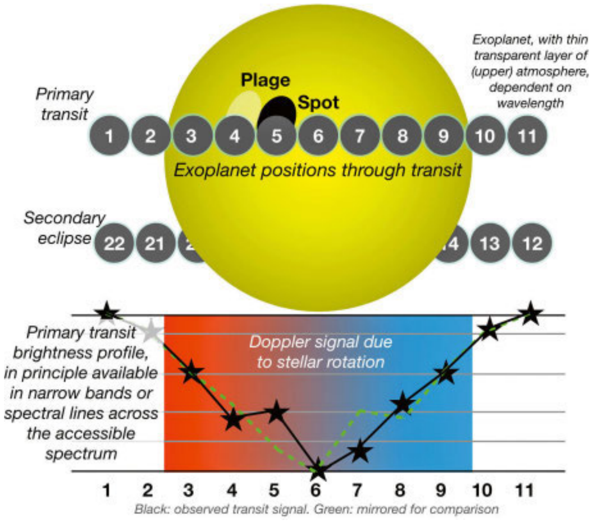


The instabilities leading to eruptive and explosive phenomena **(Figure 9)** result from the sudden conversion of magnetic energy into other forms **(Figure 10)**. This appears to be associated with the onset of accelerated reconnection; arguments about whether that is the cause or the consequence of the energetic events continue. What has become clear, though, is that the instability can occur because of different conditions. Magnetic flux may already be so strongly stressed upon breaching the solar surface that, for example, a kink instability (as happens in twisted rubber bands and garden hoses) is unavoidable. Other ways to destabilise the field and to release the energy stored in the magnetic field are by emerging new flux moving into pre-existing configurations or through (sub-)surface flows that stress the field. Yet another pathway to instability is that the surrounding field may change so that its stabilising influence is reduced. Observations show that all of these cases occur. Machine learning has reached a state that its predictive skills are comparable to those of observers with years of experience. Now we need to learn what the computers have picked up on.

Model calculations (such as the magnetic field shown in **Figure 10**, computed from vector-magnetic maps before and after a flare and eruption) are being used to understand how we can differentiate these cases and predict the outcome. The most challenging cases are comprehensive flux-emergence models that can take flux bundles from deep within the virtual Sun into the atmosphere, to simulate eruptions and their geometry there **(Figure 11)**.

In recent years, we have realised that the large eruptions that form coronal mass ejections are part of a continuum of ever more frequent eruptions as we look towards smaller scales: for example, with size expressed as a heliocentric opening angle, the frequency of eruptions from multitudes of small bipoles of some 10 000 km across to the rare million-kilometre filament eruptions form a continuous, smoothly-decreasing distribution. With access to X-ray, (E)UV, and visible-light images, we are seeing that the flare ribbons of high-energy active-region eruptions have EUV counterparts in large quiet-Sun eruptions: there may be a shift towards lower energies across the colour spectrum as we look towards weaker-field settings, but the basic phenomena related to the post-eruption reformation of ruptured arcades of magnetic field appear similar. *SDO* observations of the full Earth-facing side of the Sun, supplemented by far-side images from the *STEREO* spacecraft, revealed the long-range connections in the Sun's magnetic field: smooth reconfigurations or sudden shock waves from one region can travel far **(Figure 12)** and may trigger destabilisation in others, sometimes at large distances. Studies of ensembles of flares and eruptions over multiple years showed that our thinking needed correction: where long-duration flares were thought to be those involved in CMEs, new analyses show the distinction to lie in the scale of the destabilising field, not in whether a CME formed or not: larger structures simply tend to take longer to evolve. Computer models help us interpret these aspects.

Figure 14: Principles of transit spectroscopy. As an exoplanet transits a magnetically active star, it provides information on the limb-darkening of the stellar surface and on possible active-region and spot features. The starlight propagating through the planetary atmosphere provides information on the chemical makeup and stratification of that atmosphere. Entering and exiting from the secondary eclipse, when the exoplanet moves behind the star, reflected and scattered light from the exoplanet may be most readily separated from the starlight to extract spectral signatures of the atmosphere. The stellar and planetary signals can in principle be separated by studying a variety of ionic, atomic, and molecular lines across much of the colour spectrum throughout the transit.



Of stars, ice, and trees

The variable output in sunlight, solar energetic particles, and magnetised solar wind affects all bodies that orbit the Sun. For Earth, this collective of phenomena driven by solar magnetic variability is known as space weather. Its effects are by no means limited to space: aspects of space weather include interruptions in radio communications, malfunctions of satellites, noise on navigation and positioning signals, harm to astronaut health, variations in the quality of electric power, and even catastrophic loss of large transformers triggering regional electricity blackouts.

Observations of the Sun and of Sun-like stars have greatly advanced our knowledge of the processes that drive space weather as well as constrained their statistical likelihoods. One thing remains a major challenge, though: establishing the worst-case scenario. Many frequency distributions of various aspects of solar activity exhibit power-law distributions, smoothly connecting the frequent, weak events to the rare, most-powerful events **(Figure 13)**. But the most extreme drivers of space weather may not be the once-in-a-century events that we have observed to date. Stars like the Sun have been seen to flare with energies at magnitudes exceeding hundredfold the largest directly-observed event on the Sun. However, for stars of solar age and mass, such superflares are rare indeed, occurring perhaps once in a million years. It is the events of intermediate energies that may happen once every 1 000 or 10 000 years that we need to worry about: they could have disastrous impacts on our technology-reliant society.

Monitoring of many thousands of cool stars for years on end, as done by the *Kepler* satellite while it hunted for exoplanets, also provided a treasure trove of information about stellar magnetic activity and the occurrence of extreme flares on stars like the Sun. The statistics are still insufficient: single, solar-age, Sun-like stars of roughly solar rotation period appear to be able to generate infrequent superflares, but neither the flare frequency nor the full characteristics of the superflaring stars have been sufficiently elucidated, so uncertainty remains (shown by the grey area in **Figure 13**). Hunts for radio-nuclide signatures in natural terrestrial records (in ice sheets and tree rings) and in lunar rocks (working as dosimeters on the lunar surface) suggest that at least energetic-particle storms have not exceeded historically-recorded levels by much over the past millions of years. Whether that means the Sun does not generate more extreme events than observed in the space era, or whether there is some limit to the energetic-particle population separate from that of flare impacts remains under study.

Observatories, models, and transits

Fundamental questions of solar magnetic activity involve plasma-field interactions leading to, among other things, astrophysical dynamo processes and magnetic instabilities. These are also fundamental to understanding the formation of stars and planetary systems, and the habitability of exoplanets. Because of that, we can expect advances in the adjacent fields of astrophysics and planetary-system physics to support advances in solar physics, and *vice versa*. Observations of stars are continuing from ground- and space-based observatories. With NASA's *Kepler* satellite's monitoring mission terminated, new generations of instruments are coming. Among them, NASA's *TESS* (Transiting Exoplanet Survey Satellite), ESA's *Gaia*, the upcoming ESA/Swiss *CHEOPS* (CHaracterising ExOPlanet Satellite), and NASA's *JWST* (James Webb Space Telescope), for example, have the potential of finding not only more exoplanets and studying their atmospheres, but also of gathering more information on their host stars and their dynamos **(Figure 14)**.

But also in its own right, the future of the field of solar magnetic activity remains bright: in the virtual world, computers are ever more powerful, and their abilities for high-fidelity modelling are rapidly advancing; data mining techniques are making use of growing observational archives. Artificial intelligence is speeding up what we learn from observations and, presumably, will soon do the same by scanning ensembles of numerical models. The most prolific space-based observatory yet to look at the Sun, NASA's *Solar Dynamics Observatory,* remains functional after almost a decade of continuous observing, while high-resolution spectroscopic observations of small areas continue with NASA's *IRIS* (Interface Region Imaging Spectrograph) and JAXA's Hinode. NASA's *Parker Solar Probe* is exploring the innermost heliosphere to understand the solar wind and the formation and propagation of energetic particles. Among the ground-based observatories is NSO's new, large *DKIST* (Daniel K. Inouye Solar Telescope) in Hawaii that is nearing completion. And ESA's *Solar Orbiter* is about to embark on the exploration of the Sun from a close-in and out-of-ecliptic orbit. Our learning continues…

Further reading

For images of the current Sun, or any other date during the SDO mission, see http://suntoday.lmsal.com.

The journal "Living Reviews in Solar Physics" provides freely accessible review papers on a wide range of broad topics, including those covered in this article. See http://www.springer.com/journal/41116.

Spatium No 2, von Steiger, R., Das neue Bild der Sonne, Nov. 1998.

Spatium No 8, Beer, J., Sun and Climate, Nov. 2001.

Spatium No 17, Balogh, A., The Heliosphere: Empire of the Sun, Oct. 2006.

Spatium No 22, Parker, E., Solar Magnetism – Discovery and Investigation, Aug. 2008.

Benz, A.O., Flare observations, Living Rev. Sol. Phys. 14:2., https://doi.org/10.1007/s41116-016-0004-3, 2017.

Cheung, M.C.M., Rempel, M., Chintzoglou, G., plus 11 authors, A comprehensive three-dimensional radiative magnetohydrodynamic simulation of a solar flare, Nature Astronomy, Volume 3, 160, 2019.

Liu, W., Jin, M., Downs, C., plus 3 authors, A Truly Global Extreme Ultraviolet Wave from the SOL2017-09-10 X8.2+ Solar Flare-Coronal Mass Ejection, ApJL 864, L24, 2018.

Schrijver, K., One of ten billion Earths: How we learn about our planet's past and future from distant exoplanets, Oxford University Press, 2018.

Schrijver, C.J. and Beer, J., Space Weather From Explosions on the Sun: How Bad Could It Be?, EOS: Transactions AGU 95(24), 201, DOI: 10.1002/2014EO240001, 2014.

Schrijver, C.J., Beer, J., Baltensperger, U., plus 9 authors, Estimating the frequency of extremely energetic solar events, based on solar, stellar, lunar, and terrestrial records, JGR (Space Physics), DOI: 10.1029/2012ja017706R, 2012.

Schrijver, C.J., DeRosa, M.L., Metcalf,T., plus 14 authors, Non-linear force-free field modeling of a solar active region around the time of a major flare and coronal mass ejection, Astrophysical Journal 675, 1637, 2008.

SPATIUM

The Author

Karel Schrijver is a stellar astrophysicist and writer specialising in the study of the Sun and the space around it, stellar magnetism and its impacts on the environments of planets, and the science of space weather. He received his doctorate in 1986 at the University of Utrecht, the Netherlands, on the topic of solar and stellar magnetic activity. After postdoctoral appointments at the University of Colorado and the European Space Agency, and a fellowship of the Royal Netherlands Academy of Sciences, he joined the Lockheed Martin Advanced Technology Center where he eventually became a Senior Fellow. He was lead scientist and Principal Investigator for two of NASA's scientific spacecraft studying the Sun: the Transition Region and Coronal Explorer (TRACE) and the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). He has published over 260 research publications and articles.

Karel's interests include disseminating newly developed understanding of our neighbouring star and its influence on society to students and the public. For two three-year terms, he served as dean for the NASA Heliophysics Summer School that resulted in a 5-volume book series on heliophysics as an integrated science for which he was the lead editor. He co-authored the first textbook on *“Solar and Stellar Magnetic Activity”*, and recently completed a textbook on the *“Principles of heliophysics”* for advanced undergraduate students and beginning graduate students. Lately, he has been working on popular science books, publishing *“Living with the stars”* (2015) on the multitude of connections between the human body, the Earth, the planets, and the stars, and *“One of ten billion Earths”* (2018) about exoplanetary systems in general and how we learn about our own planet's past and future from distant exoplanets in particular.

He has served in multiple NASA advisory functions, was a member of the Space Studies Board of the National Research Council, and chaired the Road Map Panel for Space Weather Science for the International Council for Science’s Committee on Space Research (COSPAR).

He has been appointed ISSI's Johannes Geiss Fellow 2018.