The magnetic Sun

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The nature of our star, the Sun, is dominated by its complex and variable magnetic fields. It is the purpose of this paper to review the fundamental nature of our magnetic Sun by outlining the most basic principles behind the way the Sun works and how its fields are generated, and to examine not only the historical observations of our magnetic star, but, in particular, to study the wonderful observations of the Sun being made from space today. However, lying behind all of this are the most basic equations derived by James Clerk Maxwell, describing how the magnetic fields and plasmas of our Sun’s atmosphere, and indeed of all stellar atmospheres, work and how they influence the Earth.

Keywords: solar activity; solar magnetic fields; flares; mass ejection

1. Background

The Sun is generally ignored. People like the idea of a bright Sun in a clear blue sky, but a few consider our star any further. Those that do, commonly believe that the Sun is a smooth, featureless, inactive body. In fact, this could not be further from the truth. In particular, when viewed in ultraviolet light, the Sun is readily revealed as a place of great complexity, violence and drama, of explosive and eruptive events, and of great beauty, and its activity influences mankind directly.

This may seem far removed from the work of James Clerk Maxwell but, as will be revealed, his work addresses issues at the very heart of the Sun’s activity, and is therefore of relevance to the nature of all stars. Indeed, had he had the luxury of viewing the Sun as we do today, from space, he would no doubt have been overjoyed at how readily one can witness the physical processes he studied.

The Sun is our star, our energy source. The life on Earth is ultimately dependent on the energy from the Sun. It is an average star in middle life, with a mass of $2 \times 10^{30}$ kg and a surface temperature of just under 6000°C. It has a radius of 700 000 km, which is not large by astronomical standards, yet it is only 150 million km away, and that is close by astronomical standards. Indeed, this means it is close enough to readily resolve features on its surface. Putting that in perspective, if the Sun was the size of a large beach ball, the Earth would be the size of a peanut or raisin, at approximately 30 paces; the next nearest star would be thousands of kilometres away on the same scale.

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One contribution of 20 to a Theme Issue ‘James Clerk Maxwell 150 years on’.
With regard to the Sun’s activity, we have known about sunspots for a long time, with records dating back to well before Christ. These are, of course, the dark features that appear on the solar surface. From the early 1600s, when the first telescopic observations were made by Galileo, Harriot, Fabricius and Scheiner, not only did we discover the great detail and complexity of these dark features but also the motions of the sunspots showed that the Sun rotates on its axis approximately once every 25 days. We have counted sunspots for centuries and recognized that they appear in cycles. Every 11 years we see a peak in sunspot numbers, interspersed with troughs in activity where the sunspot numbers drop to near zero. We have also seen the complexity of the solar outer atmosphere, or corona, as revealed during brief eclipses, showing streamers and rays extending from the solar disc into the heliosphere (the area of space, encompassing the planets, which is dominated by the Sun) and varying significantly in complexity from eclipse to eclipse.

2. The Sun’s magnetic fields

The solar spectrum mimics a black-body curve of temperature a little under 6000 K. However, Wollaston (in 1802) and Fraunhofer (in 1817) discovered dark lines in the solar spectrum at very specific wavelengths. These are, in fact, absorption lines due to elements such as sodium and calcium, i.e. for these elements the emission from the solar photosphere (the visible surface) is being absorbed at specific wavelengths due to the energy being absorbed by specific electron transitions in the atoms of the low solar atmosphere. Their precise wavelengths could be identified readily from laboratory observations. It is the detection of the properties of these lines in the solar spectrum that is so important to understand the key to the activity of the solar atmosphere. Indeed, the leap in our knowledge that was essential to this was made by George Ellery Hale at the start of the last century.

Hale invented the spectroheliograph, an instrument for imaging the Sun in monochromatic light. The principle is relatively simple. By splitting solar light using, for example, a prism, one can extract a specific wavelength or colour, using a slit, and by interspersing exposures with motion of the image of the Sun across the slit one can build up images of the Sun in any selected wavelength or, indeed, for any selected element.

If we consider a particular element or, indeed, an ion (where an element has been stripped of electrons), we know that there are specific energy levels that are characteristic of that element or ion. When an atom absorbs incident radiation, or if it emits radiation, it either undergoes a transition between specific states defined by quantum numbers or between a specific ‘bound’ state and an ‘unbound’ state. If one takes hydrogen, for example, one can consider the transition between the states identified by principal quantum numbers, \(n=2\) and \(3\), and that is seen as one absorption or emission line, depending on the situation. However, as recognized by Zeeman, when one applies an external magnetic field to the atoms, spectral lines split into multiple lines, an effect that is now named after him. The split is due to the interaction of the magnetic field with the magnetic dipole moment associated with the orbital angular momentum of the atom. Thus, taking into account the ‘rules’ regarding quantum numbers,
our hydrogen energy levels at \( n=2 \) and \( 3 \) split into \( 3 \) and \( 5 \) levels, respectively. These multiple levels are defined by the magnetic quantum number \( m_l \) and transitions between the various \( n=2 \) and \( 3 \) levels are subject to the selection rule that \( \Delta m_l = 0 \) or \( 1 \) only. Thus, in the spectrum, we see one emission line becomes three on the application of a magnetic field.

If one considers that the external magnetic field is exerting a torque on a magnetic dipole—that is, consider the atom or ion to represent a plane current loop with the electron moving in a circular orbit—we can calculate a magnetic moment and consider the magnetic potential energy of the system in terms of the angular momentum. Knowing that the angular momentum is quantized, we find equally spaced energy levels displaced from the zero field situation by

\[
\Delta E = m_l \mu_B B,
\]

where \( \mu_B \) is the Bohr magneton, \( 9.2740 \times 10^{-24} \text{ J T}^{-1} \).

The leap in our understanding of the Sun, for which Hale must take the credit, was the detection of the Zeeman effect in sunspots. He had demonstrated that strong magnetic fields exist in sunspots, and this was the first ever demonstration of extraterrestrial magnetic fields, which is a remarkable achievement. Hale’s instrument was able to detect fields stronger than 0.1 T (1000 gauss).

From that first detection, we have come a long way. We are now able to map solar surface magnetic fields with far greater sensitivity at high resolution and, whereas Hale’s original measurement revealed only the field in sunspots, we now map magnetic structure throughout the entire solar surface. An example is given in figure 1 using data from the Solar and Heliospheric Observatory (SOHO) MDI instrument (Scherrer et al. 1995). The sunspot regions, known as active regions, do reveal the most complex and strongest magnetic fields, and several such
regions are evident on the disc. In each case, one can see the associated patches of black and white, denoting the different polarities, which could be regarded as the sources and sinks of magnetic field lines. However, even the ‘quiet’ solar surface, away from sunspots, shows a ‘salt and pepper’ of different polarities in small magnetic fragments. It turns out that the basic nature of the solar atmosphere is driven and structured by magnetic fields and that solar activity and, indeed, many processes that influence the Earth are magnetic in nature. Understanding the magnetism of the Sun is a most basic requirement for understanding stars and the impact of the Sun on our activities.

Let us consider briefly where the Sun’s magnetic field comes from. At the Sun’s core we believe that there is a region of temperature approximately 15 million K where thermonuclear fusion is taking place with hydrogen combining to form helium as the principal process. Emitted energy, from the fusion process, will radiate through the body of the Sun. Any ‘packet’ of energy will be absorbed and re-emitted many times and it may take over 100 000 years for it to escape. The region through which this radiation process dominates is the so-called radiation zone. Clearly, this is a region of extreme temperatures where atoms are highly ionized through collisions. However, beyond a certain radius, at approximately 70% of the solar radius, temperatures have cooled enough to allow sufficient recombination of nuclei and electrons to act as a radiation barrier by increasing absorption, making convection the dominant process in bringing energy towards the surface from that point outward.

In addition to the convective motion there is motion of the solar plasma due to turbulence and also solar rotation. The solar rotation is not rigid; we witness a differential rotation where the equatorial regions rotate with a period of ca 25 days and the polar regions rotate over 2 days slower. This overall complex pattern of motions of charged gases is responsible for the generation and the complexity of magnetic fields.

There are two other features of solar magnetic field we must consider to understand the basic principles of the images that are about to see. First, we show Maxwell’s equations

\[ \nabla \times E = -\partial B/\partial t \quad \text{(Faraday’s law)}, \]

\[ \nabla \times B = \mu_0 j + \mu_0 \varepsilon_0 \partial E/\partial t \quad \text{(Ampère’s law)}, \]

\[ \nabla \cdot E = \rho/\varepsilon_0 \quad \text{(Gauss’ law)}, \]

\[ \nabla \cdot B = 0, \]

where \( B \) and \( E \) are the magnetic and electric fields, respectively, and the terms \( \rho, j, \mu_0 \) and \( \varepsilon_0 \) are the charge density, electric current density and the permeability and permittivity constants of free space, respectively. We note that the second term on the r.h.s. of the equation labelled as Ampère’s law, known as the ‘displacement current’, should be credited to Maxwell specifically.

In addition, we note Ohm’s law, namely

\[ j = \sigma (E + \nu \times B), \]

where \( \sigma \) is the electrical conductivity and \( \nu \) is the velocity of the conducting plasma.
If we take the curl of Ohm’s law \((\nabla \times j)\), we can substitute Faraday’s law and Ampère’s law, assuming a small displacement current and derive the equation
\[
\frac{\partial B}{\partial t} = \nabla \times (v \times B) + (1/\sigma \mu_0) \nabla^2 B.
\] (2.1)

This is an important equation and the key parameter in the solar atmosphere is the electrical conductivity. The two terms on the r.h.s. of the equation describe a flow component and a diffusion component and the conductivity controls the balance. In the high temperature, highly ionized solar atmosphere, the electrical conductivity is usually very high, ensuring that the diffusion term is not significant. In this situation, the plasma and magnetic field are effectively frozen to one another. Only under extreme conditions, which will be mentioned later, can the conductivity drop sufficiently for the diffusion to become important.

The second important feature is buoyancy, a process that brings magnetic flux to the surface. Consider a bundle of magnetic field lines, commonly known as a flux tube, within the body of the Sun, and a plasma pressure both inside and outside the bundle. There is also a pressure associated with the magnetic field of magnitude \(B^2/2\mu_0\). In a simple-minded situation of a flux tube contained in a volume void of magnetic field, with identical temperatures inside and outside the flux tube, there will be a pressure balance between the internal and external gas pressures (denoted by \(i\) and \(e\)) given by
\[
P_i + \frac{B^2}{2\mu_0} = P_e.
\]

This suggests that for a balanced situation, \(P_i < P_e\). We can substitute the gas law, \(P = \rho_m RT\), where \(\rho_m\) is the mass density, and find
\[
(\rho_{me} - \rho_{mi})/\rho_{me} = (B^2/2\mu_0 P_e).
\]
Thus, the density in the flux tube is lower than the surrounding density; the flux tube must be buoyant. This is called magnetic buoyancy and drives the emergence of magnetic field into the solar atmosphere.

Armed with these basic concepts, let us explore the observations now being made using modern spacecraft and, in particular, the SOHO spacecraft.

3. A brief review of observations from the SOHO spacecraft

The ESA/NASA SOHO is the world’s flagship solar observatory (Domingo et al. 1995). It is an ESA cornerstone mission, run in collaboration with NASA, and is the most sophisticated, complete space-based solar observatory ever built with instruments designed to study the solar interior, the solar atmosphere and the solar wind. Launched aboard an Atlas rocket on 2 December 1995, SOHO has been operating now for over 12 years and has revolutionized our view of the Sun. The spacecraft does not orbit the Earth but, in fact, orbits the so-called L1 Lagrangian point. This is a location, four times further out than the Moon, in the direction of the Sun, where the gravitational forces of the Earth and Sun allow a balance. Spacecraft can, in fact, orbit that point—1.5 million km sunward of the Earth. This unusual orbit is superb for a solar mission, allowing 24 hour per day observations of the Sun with no eclipses and no radiation belt encounters. In addition, any solar ejecta heading towards the Earth must pass over the SOHO spacecraft.
In a real sense, SOHO has been revealing the true nature of our star and, in this review, we can only hope to tour a set of selected observations and results to browse through some of the many discoveries made using this mission. First, we examine a set of images of the Sun taken using the EIT instrument (Delaboudinière et al. 1995), which are snapshots taken in extreme-UV (EUV) light. As with the spectroheliograph these images are selecting specific wavelengths or colours, except in this case we are using filters and so-called multi-layer technology on the optical surfaces in order to select the required wavelengths. The EUV region is a most important one for solar physicists; it is a region of the spectrum which contains a wealth of spectral emission lines from transitions from a wide range of ions existing across a large spread of temperatures in the Sun’s atmosphere. Thus, it is an essential wavelength range for studies of the Sun’s atmosphere and many of the observations discussed here are taken in the EUV range.

Figure 2 shows a typical view of the Sun taken in radiation emitted from singly ionized helium, i.e. helium atoms that have lost one electron. The particular transition being viewed appears at a wavelength of 304 Å and hence is shown in false colour. In hot plasmas, different degrees of ionization of the ambient atoms/ions are driven by the amount of collisions between the particles; thus, the higher the temperature, the greater the number of collisions and the higher the ionization states (the greater the number of electrons stripped from the atoms). So, we actually know the temperature ranges over which different ions exist. The

Figure 2. An image of the Sun taken by the EIT instrument on board SOHO in light radiated by singly ionized helium, showing 60 000 K plasmas (courtesy SOHO EIT team). A movie version of this image is available (see electronic supplementary material 1), which reveals the dynamic nature of the atmosphere.
singly ionized helium, or He II as it is known, exists typically at temperatures of approximately 60,000°C. By solar standards, that is actually quite cool. The image we are seeing is revealing low plasmas in the solar atmosphere.

There are just a few basic phenomena making up the structure of the Sun’s image as shown in figure 2. The mottled pattern known as supergranulation, is, in effect, the imprint of the convection patterns in the body of the Sun, seen in the low atmosphere. Rather like looking down on a pan of boiling water, this pattern

Figure 3. An image of the Sun taken by the EIT instrument on board SOHO in light radiated by iron, ionized eight times, revealing million K plasmas (courtesy SOHO EIT team). A movie of this high-temperature corona, taken in light from highly ionized million K iron is available (see electronic supplementary material 2), which shows the dynamic nature of the corona.

Figure 4. Co-pointed images of a small portion of the solar disc, taken by the (a) CDS and (b) MDI instruments on board SOHO, showing the ultraviolet and magnetic activities in the vicinity of one supergranular cell (courtesy SOHO CDS and MDI teams). Blue and yellow patches show the differing polarities of the magnetic structure in (b). A movie version of this figure is available (see electronic supplementary material 3) demonstrating well the dynamic nature of these events.
of convection cells displays the motions, cell growth and decay that you would intuitively expect. We are seeing cells that may be 30 000 km across. The image also shows a number of bright regions. These are the so-called active regions, the sites which contain the familiar sunspots. However, it is clear that there is more to these regions than the sunspot phenomenon, because the bright He II regions show a great deal of complexity. On the solar limb (the edge of the disc), we also see several features where helium emission is revealing material that is either being ejected into space or is trapped above the solar surface. The most striking one of these (bottom left) is indeed erupting and is known as an erupting prominence. A prominence is a solar phenomenon that results from the evolution of a magnetic arcade system, resulting in cool plasma being trapped in linear structures above the magnetic neutral lines. Such systems occasionally erupt.

Another aspect of the magnetic ‘story’ is shown in figure 3, also taken by the EIT instrument but this time in radiation from iron ionized eight times, Fe IX, at 171 Å. This ion is formed at approximately 1 million K. Whereas the helium images showed the cooler plasmas from lower in the solar atmosphere, we are now seeing the hottest coronal plasmas. This reveals more information about the basic nature of the solar atmosphere. It should be noted that figures 2 and 3 were not taken simultaneously but have been selected to demonstrate particular features. At first glance, it is difficult to see how such images can relate to the helium images, though it is clear that they must be intimately related. We note three basic features of these coronal images. First, we see dark areas, known as coronal holes, where we believe the magnetic field lines are open to space and, thus, the hot plasmas are not confined. Such regions are not well developed in the image of figure 3, the best example being at the lower polar region. We also witness the regions of relatively unstructured diffuse emission, which could be termed quiet corona. Within all these quiet and coronal hole regions, one can see small bright patches, known as bright points. However, perhaps the most striking structures are clear loop structures that appear in hierarchies of all scales throughout the globe but are especially compact and complex in the active regions. These are the brightest, and hottest, regions, and when one compares images taken at the same time, they clearly coincide with the bright, complex helium emission described above.

What we are seeing in an active region is an area where the magnetic complexity has built up with loop systems jostling each other and confining hot plasmas in the corona. Movies of datasets such as these reveal significant amounts of motion in the loop structures.

These ultraviolet images, and movies made of such images, are revealing a solar atmosphere that is dramatically complex and violent, yet quite alien and beautiful. We witness a spectrum of phenomena on all scales.

Figure 4 is an example of what we see on the smallest scales. Figure 4a encompasses just one supergranular cell, some 30–40 000 km across, and shows bright patches revealed around the cell boundary, in radiation from oxygen ionized four times (O V), a transition at 630 Å. This observation, using the SOHO CDS instrument (Harrison et al. 1995) is revealing 250 000 K plasma. This is an intermediate temperature in the solar atmosphere. The brightenings are typically Earth-sized and are transient in nature. They have become known as blinkers (e.g. Harrison et al. 1999) and the transient nature of these events, plus their global distribution have led to a plethora of studies investigating the
possibility that they are revealing fundamental, globally distributed phenomena relating to plasma heating and acceleration in the solar atmosphere. Such brightenings are commonly seen over the entire solar disc mainly in the lanes or network between the supergranular cells.

Other small-scale phenomena include bi-directional jets known as explosive events, also found in the cell boundaries, as well as hotter events that appear rather like small flares, often termed microflares or even nanoflares, using a loose definition based on the relative energy content to a typical flare (see review by Harrison et al. 2003).

A clue as to what is happening can be found by looking at the small-scale magnetic structure of a region of quiet Sun where one finds the salt and pepper of small magnetic fragments of differing polarities. This is shown in figure 4b; in this case the magnetic polarities of the fragments are denoted by yellow and blue. One can readily see that despite the apparently random nature of the fragment distribution, a comparison between figure 4a,b shows that the fragments are clustered in the supergranular cell boundaries, as are the blinker flashes.

The basic nature of what we are seeing can be explained using the discussion above. Magnetic fragments emerge as a result of buoyancy, and are likely to emerge within the up-flow regions of the convection cells, i.e. in the middle of the cell viewed in figure 4. The plasma and fields are frozen into one another so the flow to the outer edge of the supergranular cell will carry the magnetic fragments and they will cluster around the edge of the cell, where the supergranular flow is downwards. Thus, the network is a region where, potentially, we have magnetic complexity as fragments merge and interact, and one can see a correlation between the brightest blinkers and the complexity of the magnetic fragments in figure 4.

The interaction between the magnetic structures on these ‘small’ scales can lead to various small-scale phenomena. Compression of the magnetic fields can be detected as brightening due to the increase in density; alternatively the magnetic fields could reform in some way, through a process known as magnetic reconnection, which can accelerate plasma beams. Thus, these processes and phenomena are basic to the way a stellar atmosphere works and are generating a lot of interest in the solar research community.

However, standing to one side for a moment, we have witnessed the detection of complex magnetic structures in the Sun’s atmosphere, trapping ionized gases up to temperatures of millions of K. We have seen the interplay between the Sun’s convection and the buoyancy-driven emergence of magnetic fragments which, due to the frozen-in condition, migrate across the cells and interact with one another to produce small-scale phenomena which are a key to the fundamental processes in the atmosphere of a star. In terms of Maxwell’s underlying aim to unify the understanding of electromagnetic processes, he would have loved to witness all of this. We have a veritable playground for demonstrating the concepts behind his research.

We ought to expand further on two phenomena mentioned above. First, we have described the frozen-in condition and discussed how the magnetic fragments emerging in a supergranular cell will move with the plasma. However, how do we know whether the plasma moves with the magnetic field or vice versa and which will dominate?
We talk of the plasma parameter beta, $\beta$. This is quite simply the ratio of the gas pressure to the magnetic pressure, i.e.

$$
\beta = \frac{2\mu_0 P}{B^2}.
$$

In a low $\beta$ plasma, the magnetic pressure dominates, i.e. the magnetic field effectively ‘dictates’, whereas for a high $\beta$ plasma, the plasma pressure dominates and carries the magnetic field. In the solar interior, the $\beta$ value is very high: the magnetic fields are carried by the plasma and follow the plasma flow. However, in the solar atmosphere, where the density is much lower, the $\beta$ value is much less than 1.0. Thus, as shown in the coronal images above, we see hot plasma trapped in the magnetic loops. The complexity of the active regions is driven by the fact that the motion of the plasmas in the body of the Sun, where the $\beta$ value is high, is such that the magnetic fields above will follow. This motion, driven by the convection patterns, turbulence and the differential rotation serves to produce extremely complex magnetic structures in the overlying corona.

We have also touched on a process known as magnetic reconnection. The basic idea is that a magnetic configuration, such as two merging loops, can become more and more complex and may transform to a simpler (lower energy) configuration through a process whereby magnetic field lines reconnect. This process can result in the release of energy in plasma heating and acceleration. However, for lines to reconnect, we require to break free from the restriction of the frozen-in condition; field lines must migrate towards one another to reconnect. Thus, the diffusion term of equation (2.1) must become significant. Theoretical approaches, then, concentrate on constructing situations where the electrical conductivity can decrease, through conditions such as increased turbulence in localized areas where the lines can reconnect. This becomes an important driver behind much larger phenomena than the small-scale transient events already discussed, i.e. the events known as solar flares.
Indeed, figure 5 shows a solar flare taken using the NASA Transition Region and Coronal Explorer (TRACE) spacecraft (Handy et al. 1998). The image is directed towards an active region on the limb, taken in light from million K iron ionized eight times. TRACE is an independent, high-resolution spacecraft operated in parallel with SOHO. Figure 5 shows a particularly nice solar flare. The complex magnetic fields have been driven to a situation where breakdown has occurred and, presumably through magnetic reconnection, the magnetic fields have simplified and energy has been dumped into the local plasmas, revealed in the high-temperature emission as well as in streams of energetic particles in space. These fundamental ideas behind solar flares have been in vogue for some years but the high-resolution displays afforded by SOHO and the TRACE spacecraft, shown here, have provided unprecedented views of these dramatic events. Such flare events can release typically $10^{25}$ J of energy in some tens of minutes. The rate at which such events occur varies across the solar cycle, and we can witness anything from several flares per day, to none. Quite naturally one would expect solar flares to occur in the regions of the greatest magnetic complexity, the active regions, and this is indeed always the case. Despite a basic understanding of the underlying physical processes, a detailed understanding of the flare process, in particular including a thorough understanding of the onset mechanisms (for example, what precisely leads to the onset of the magnetic reconnection?) and learning how to predict flares, requires much more research.

One might think of a solar flare as an explosion low in the solar atmosphere, driven by the magnetic complexity within an active region. However, there is another major form of solar activity which occurs on a much larger scale and releases similar amounts of energy per event. These are the so-called coronal mass ejections (CMEs).

A CME is an eruption, where the Sun’s atmosphere sheds up to $10^{13}$ kg of matter in each discrete event, typically at speeds of several hundreds of km s$^{-1}$. Such an eruption can often include a prominence eruption (see above), but the CME involves a much larger structure than the embedded prominence. Figure 6 shows a CME taken using the LASCO instrument aboard SOHO.

LASCO (Bruckner et al. 1995) produces artificial eclipse images in order to view the diffuse outer corona and any ejection events; such features could not be seen in contrast to the solar disc in the absence of the occultation. The location of the Sun in figure 6 is given by the white circle. One can see rays and streamers around the disc, which are depicting the solar magnetic fields extending into the heliosphere. Coronagraphs typically operate in visible light so one is actually detecting Thomson-scattered photospheric light off free electrons confined to the magnetic structures. Thus, increased brightness is indicating increased density. The striking feature of the image is, of course, the CME on the top r.h.s. This event shows a clear outer loop which, at the time of the image, was, in fact, larger than the solar disc. One frequently sees a cavity behind such an outer loop plus inner structure, which actually relates to any prominence material ascending within the CME.

Such events are spectacular. However, one has to remember that they are weak when compared with the intense solar disc. Indeed, although they carry so much mass, this is small by solar standards. This is illustrated well by the fact that if you want to identify the original CME source region, for example, by studying the ultraviolet images of the solar disc from EIT, it is often very difficult to identify where the event came from. Indeed, figure 7 shows a bright CME.
ascending above the solar eastern (left-hand) limb and five images taken in the emission at 360 Å from Fe XVI (iron ionized 15 times) at 2 million K. These five images, taken with 50 min cadence do not readily reveal the source of the CME.

Figure 6. An image of a CME taken in visible light using the SOHO LASCO instrument (courtesy SOHO LASCO team). The associated movie (see electronic supplementary material 4) shows two ejecta: first on the lower left and then a more substantial event on the lower right of the Sun. These are the CMEs. However, coincidentally, we also see two sungrazing comets approach the Sun early in the sequence.

Figure 7. A source region of a CME. (a) The five frames show coronal plasmas on the underlying limb region at the time of the projected onset. (b) Differencing the frames shows dimming, identifying mass loss. (c) The image taken by the SOHO LASCO instrument shows a CME (C) ascending above the left-hand equator (A, B and D are other discrete CME features noted by the LASCO observers). (Adapted from Harrison (2006).)

ascending above the solar eastern (left-hand) limb and five images taken in the emission at 360 Å from Fe XVI (iron ionized 15 times) at 2 million K. These five images, taken with 50 min cadence do not readily reveal the source of the CME.
However, differencing the frames, as shown in the figure 7b, shows a significant area of dimming identifying a region of mass loss equivalent to the mass in the ascending CME. There was no other associated activity with this CME onset.

There is much discussion about the relationship between flares and CMEs; they can certainly occur in close association (see Harrison 2006 and references therein). However, the principal reason for showing these data here is to demonstrate one further aspect of magnetic activity on the Sun. Observations like this show that the CME is not a direct coronal response to a flare and it seems that the CME can be driven only by a magnetic instability or lack of equilibrium, driven by increasing the magnetic complexity over a large area. The result is a magnetic arcade system ballooning out into space. The investigation of how such large magnetic systems can erupt in this way is being vigorously pursued by a large community worldwide; we would like to be able to predict the eruption of such events.

There are a number of models that attempt to describe how magnetic systems can simply erupt in this way. This includes, for example, the interaction of large magnetic loops where magnetic reconnection allows a large region to break out. Alternatively, one can model a magnetic arcade and simply apply some shear to the arcade, such that plasma flow on either side of the arcade pulls adjacent magnetic ‘footpoints’ apart. This can cause the arcade to rise and ultimately to reach a position of non-equilibrium.

4. Discussion

This review has really only touched upon the results from our recent observations of the Sun. We have necessarily explored just a few observational sequences that serve to illustrate the magnetic nature of the Sun and its activity. For a much more detailed recent account, readers could refer to Dwivedi (2003).

However, in reviewing the relevant magnetic processes of the Sun and in exploring how such processes are revealed in our recent observations, we find a wonderful demonstration for the power of Maxwell’s equations.

It is clear that the Sun is not the featureless inactive star that many anticipate, but, indeed, has a complex violent environment driven by the interaction between magnetic fields, turbulence, convection and differential rotation. It is clear that to understand even the smallest scale processes in the solar atmosphere, we can shed light on how all stars work and begin to learn to understand and, indeed, predict the onset of the largest events, the flares and CMEs, which are of interest in understanding not only their role in the evolution of the corona but also their impacts on the Earth. In short, the Sun is very much a magnetic star.

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References


