The Sun’s global magnetic field

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Our present-day understanding of solar and stellar magnetic fields is discussed from both an observational and theoretical viewpoint. To begin with, observations of the Sun’s large-scale magnetic field are described, along with recent advances in measuring the spatial distribution of magnetic fields on other stars. Following this, magnetic flux transport models used to simulate photospheric magnetic fields and the wide variety of techniques used to deduce global coronal magnetic fields are considered. The application and comparison of these models to the Sun’s open flux, hemispheric pattern of solar filaments and coronal mass ejections are then discussed. Finally, recent developments in the construction of steady-state global magnetohydrodynamic models are considered, along with key areas of future research.

Keywords: magnetic fields; observations; models; open flux; coronal mass ejections; solar filaments

1. Introduction

Magnetic fields play a key role in the existence and variability of a wide variety of phenomena found on the Sun. These range from relatively stable, slowly evolving objects such as sunspots, coronal loops and solar prominences, to highly dynamic phenomena such as solar flares and coronal mass ejections (CMEs). Solar magnetic fields may directly or indirectly affect the Earth through the Sun’s open flux, solar wind and irradiance variations.

Our present-day understanding of solar magnetic fields dates from 1908 when Hale made the first magnetic field observations of sunspots [1]. However, it was not until the systematic mapping of the Sun’s magnetic field that its true cyclic nature became apparent [2]. While significant advances in observations have been made over the last 50 years, only the strength and distribution of the line-of-sight magnetic field component at the level of the photosphere have been regularly measured over solar cycle time scales. Since many important phenomena occur in

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the solar corona, a key component in our understanding of solar magnetic fields is the use of theoretical models to construct (or extrapolate) coronal magnetic fields from photospheric data.

In recent years, the technique of Zeeman Doppler imaging (ZDI) [3] has led to a significant advance in our understanding of magnetic fields on other stars. Results show a wide range of magnetic morphologies across stars of varying mass and spectral type [4]. With the accurate measurement of stellar magnetic fields, techniques developed to model solar magnetic fields are now widely applied in the stellar context.

In this review, we primarily focus on our present-day understanding of global solar photospheric and coronal magnetic fields. Where appropriate, we expand this discussion into stellar magnetic fields to summarize new results. In §2, observations of both solar and stellar magnetic fields are discussed. Following this, magnetic flux transport models used to model the evolution of photospheric magnetic fields are described (§3), along with techniques used to construct coronal magnetic fields (§4). The application of these models to the Sun’s open magnetic flux (§5), hemispheric pattern of solar filaments and CMEs (§6) are then described. In §7, recent advances in global magnetohydrodynamics (MHD) models are discussed. Finally in §8, outstanding problems are outlined.

2. Observations

Presently, three solar cycles of continuous data have been collected by a variety of observatories (Kitt Peak, Solar Heliospheric Observatory/Magnetic Doppler Imager, Synoptic Optical Long-term Investigations of the Sun) showing the distribution and evolution of the Sun’s normal magnetic field component at the level of the photosphere. An illustration of this can be seen in figure 1a (from Hathaway [5]). The image known as the magnetic butterfly diagram illustrates the radial magnetic field as a function of time (averaged in longitude, horizontal axis) versus sine-latitude (vertical axis). The main features in the evolution of the global magnetic field are as follows.

— At the start of each solar cycle (cf. 1975, 1986, 1996), the majority of magnetic flux sits in opposite polarity polar regions. New magnetic flux then emerges in the form of sunspots or large bipoles in two latitude bands between ±30° [7]. As the cycle progresses, these bands approach the equator.

— The new magnetic bipoles lie mainly in an east–west orientation. The leading polarity (in the direction of rotation) has the same sign as the polar field of the hemisphere in which it lies, the following polarity has the opposite sign (Hale’s polarity law). In addition, the majority of bipoles emerge subject to Joy’s law, where the leading polarity lies equator-ward of the following. The effect of Joy’s law can be clearly seen in figure 1a by the latitudinal separation of flux between ±30°.

— Owing to this latitudinal separation, the following polarity may be preferentially transported poleward by meridional flow [8,9]. In contrast, the leading polarity, which lies at lower latitudes, may partially escape the effect of meridional flow to disperse and cancel across the equator. In each hemisphere, more following, than leading polarity, flux is transported.
Figure 1. (a) The solar magnetic butterfly diagram (from Hathaway [5]). Yellow represents positive flux and blue represents negative flux, where the field saturates at ±5 G. (b) Example of a typical radial magnetic field distribution for AB Dor taken through ZDI [6], where the image saturates at ±300 G. White/black denotes positive/negative flux. Owing to the tilt angle of AB Dor, measurements can only be made in the Northern Hemisphere. (Online version in colour.)

poleward, where it cancels with the existing polar field and then builds up a new polar field of the following polarity.
— The reversal in sign of the polar field typically occurs just after cycle maximum. A 22 year magnetic cycle overlies the 11 year activity cycle.

While continuous global measurements of magnetic activity only exist from around 1975, observations of the numbers of sunspots may be used to provide a long-running dataset of solar activity back to 1611 [10,11]. These show that on top of the approximate 11 or 22 year activity cycle, there are strong modulations in the number of sunspots (or flux emergence rate) over periods of centuries. It is possible also for large-scale magnetic activity to disappear. Such an event occurred between 1645 and 1715, where it is known as the Maunder minimum [12,13]. Before 1611, indicators of magnetic activity on the Sun may be found through the use of proxies such as $^{14}$C and $^{10}$Be isotopes. Through this, reconstructions of the level of magnetic activity over the past 10 000 years may be made [14].

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The majority of our present-day knowledge of solar magnetic fields comes from observing the line-of-sight component at the level of the photosphere. To gain a much fuller understanding of the Sun’s magnetic field, vector field measurements are required [15]. These measurements are complicated to make, and in the past, such measurements have only been routinely made for localized areas of the Sun. However, with the new space mission of the Solar Dynamics Observatory (SDO), such measurements should now be made regularly over the full solar disc. This should significantly enhance our understanding of the solar magnetic field.

The typical distribution of magnetic flux on the Sun when averaged over large spatial scales shows strong fields at low latitudes and weak unipolar polar caps. For young, rapidly rotating solar-like stars, very different magnetic field distributions may be found. An example of this can be seen in figure 1b, where a typical radial magnetic field distribution for AB Dor taken through ZDI is shown. Compared with the Sun, key differences include: kilogauss polar fields and the mixing of both positive and negative polarities in the poles. While this is an illustration of a single star at a single time, many such observations have been made across a wide range of spectral classes. In fig. 3 of Donati et al. [4], the varying form of magnetic morphology and strength of the magnetic fields compared with those of the Sun, for a number of stars, can be seen as a function of stellar rotation period and mass. While ZDI magnetic field datasets are generally too short to show cyclic variations, recent observations of the planet-hosting star, τ Bootis, have shown that it may have a magnetic cycle with a period of only 2 years [16]. Indirect evidence for cyclic magnetic field variations on other stars can be seen from the Mt Wilson CaII H+K observations, which use chromospheric observations as a proxy for photospheric magnetic activity [17] and through observations of stellar spots [18]. In the next section, magnetic flux transport models used to simulate the evolution of the radial magnetic field at the level of the photosphere on the Sun and stars are discussed.

3. Magnetic flux transport simulations

Magnetic flux transport simulations [19] model the large-scale, long-time evolution of the radial magnetic field across the solar photosphere. On the Sun, once new magnetic flux emerges, it evolves via large-scale flows such as differential rotation [20] and meridional flow [9]. In addition, convective cells such as super-granulation leads to a random walk of magnetic elements. Over large scales, this random walk may be modelled as a diffusive process. Taking these effects into account, the evolution of the radial magnetic field, $B_r$, at the solar surface ($R_\odot = 1$) is governed by

$$\frac{\partial B_r}{\partial t} = \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \left( -u(\theta) B_r + D \frac{\partial B_r}{\partial \theta} \right) \right) - \Omega(\theta) \frac{\partial B_r}{\partial \phi} + \frac{D}{\sin^2 \theta} \frac{\partial^2 B_r}{\partial \phi^2},$$

where $\Omega(\theta)$, $u(\theta)$ and $D = 200–450$ km$^2$ s$^{-1}$ [21] are the differential rotation profile, meridional flow profile and diffusion coefficient. On the Sun, these three effects act on time scales of 0.25 year, 2 years and finally 34 years.

Magnetic flux transport models have been highly successful in reproducing many features of the evolution of the radial magnetic field. These include the strength of mid-latitude fields and the reversal of the polar fields. Full details

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of this can be found in the review paper by Sheeley [19]. Since the early flux transport models were produced [21], new variations have been developed. These include:

— describing the evolution of the magnetic field through a particle tracking concept, along with including emergence of small-scale fields (ephemerial regions) and magneto-convective coupling [22];
— reformulating the flux transport equation into a ‘synoptic’ transport equation that evolves synoptic magnetic field observations from one rotation to the next [23];
— including a linear decay term for the radial field [24]; and
— coupling the flux transport model with a coronal evolution model so that both the photospheric and coronal magnetic fields are evolved together (see §4c [25,26]).

Owing to advances in measuring stellar magnetic fields, magnetic flux transport models have recently been applied in the stellar context. By increasing the flux emergence rate to 30 times that of the Sun, Schrijver & Title [27] showed how unipolar spots could be produced in the poles of cool solar-like stars. In contrast, Mackay et al. [28] showed that in order to produce strong intermingled polarities within the polar regions of AB Dor (figure 1b), more significant changes are required. These include increasing the emergence latitude of new bipoles from 40° to 70° and increasing the rate of meridional flow from 11 to 100 m s$^{-1}$. This result suggests that on AB Dor, the meridional flow time scale is comparable to that of its differential rotation.

4. Coronal magnetic field models

While the distribution and strength of magnetic fields are routinely measured in the solar photosphere, the same is not true for the solar corona, where such measurements are not presently possible owing to low coronal densities. To study coronal magnetic fields, theoretical models are required. In this section, we restrict the discussion of these models to global ones and in particular to those that use the force-free field approximation. The current state of global MHD models will be discussed in §7.

Within the coronae of stars, the plasma beta is usually small ($\beta = 2\mu_0 p / B^2 \ll 1$). When this condition holds and length scales are smaller than the pressure scale height and velocities much less than the Alfven speed, the Lorentz force is dominant and any magnetic field that is in equilibrium satisfies the force-free field equation, $j \times B = 0$. The electric current, $j = 1/\mu_0 \nabla \times B$, can be written as $j = \alpha(r)B$. The two most useful class of solution occur when $\alpha = 0$ (a potential magnetic field) and $\alpha = \alpha(r)$ (a nonlinear force field). In the following subsections, we discuss the techniques used to construct both global potential and nonlinear force-free models. The first two techniques describe extrapolation techniques where there is no explicit relationship between the coronal fields from one extrapolation to the next. In contrast, the third technique couples the evolution of both photospheric and coronal fields and produces continuous sequences of related force-free fields.
Figure 2. (a) Example of a PFSS extrapolation. (b) Example of a non-potential coronal field produced by the global coronal evolution model of Mackay & van Ballegooijen [26] and Yeates et al. [30]. The images are taken from Yeates et al. [31], where the grey-scale image shows the radial field at the photosphere and the thin lines the coronal field lines.

(a) Potential field source surface models

The most common technique for modelling the global coronal magnetic field is through potential field source surface (PFSS) models [29]. Such models only require the radial magnetic field at the photosphere to be specified, either from observations or theoretical models. The key assumption of a PFSS model is that there is zero electric current in the corona. The construction then reduces to solving Laplace’s equation where an outer boundary condition of $B_\theta = B_\phi = 0$ at a source surface ($R_{ss} = 2.5R_\odot$) is usually applied. In figure 2a, an example of a potential field extrapolation can be seen. This technique has been used to study a wide variety of phenomena ranging from coronal holes [32], open flux (see §5), coronal null points [33] and magnetic fields in the coronae of other stars [34].

(b) Current sheet source surface models

As an improvement to the PFSS model, Zhao & Hoeksema [35] have developed the current sheet source surface (CSSS) model. In contrast to the PFSS model, which has only one outer boundary, in the CSSS model, two boundaries are applied. Between the photosphere and an inner boundary, the ‘cusp surface’, the coronal field is assumed to be potential. However, between this cusp surface and an outer boundary, electric currents may exist that redistribute the coronal field so that it is purely radial and uniformly distributed at this boundary. Such uniform distribution of the radial field has been observed by the Ulysses mission [36], but is not produced by the PFSS models. In recent years, the CSSS model has been used as an alternative to the PFSS model in describing the origin and variation of the Sun’s open magnetic flux (this will be discussed in §5).
(c) Nonlinear force-free global coronal models

Recently, van Ballegooijen et al. [25] and Mackay & van Ballegooijen [26] developed a new technique to study the global, long-term evolution of coronal magnetic fields. The technique couples together two distinct models. The first is a data-driven magnetic flux transport model [37]. This uses observations of newly emerging magnetic bipoles to produce a continuous evolution of the observed photospheric magnetic flux over long periods of time. Coupled to this is a quasi-static coronal evolution model [26,30], which evolves the coronal magnetic field through the sequences of nonlinear force-free fields in response to the observed photospheric evolution and flux emergence. Through this technique, the long-term continuous build-up of free magnetic energy and electric currents in the corona can be followed. Such an evolution of the field is significantly different from extrapolation approaches that do not retain a memory of magnetic flux or connectivity from one extrapolation to the next. Such a memory is required to explain the slow build up of energy needed for many eruptive phenomena found on the Sun. In figure 2b, an example of a nonlinear force-free global coronal field can be seen after 100 days of evolution. Figure 2a illustrates a PFSS approximation corresponding to the same photospheric distribution of magnetic flux. The coronal field in the non-potential model is significantly different and is made up of highly twisted flux ropes, slightly sheared coronal arcades and near-potential open field lines. This technique has been applied to consider the long-term helicity transport across the solar surface from low to high latitudes [37]. In contrast to the technique described above, which constructs nonlinear force-free fields, Ruan et al. [38] have recently developed a technique for the global extrapolation of magneto-hydrostatic fields from fixed radial boundary conditions.

Application of these three coronal modelling techniques to the Sun’s open magnetic flux, solar filaments and finally CMEs is discussed over the next two sections.

5. Open flux

The Sun’s open magnetic flux is part of the Sun’s large-scale magnetic field that extends from the solar surface out into interplanetary space. In interplanetary space, it forms what is known as the interplanetary magnetic field (IMF). Understanding the origin and variation of the open flux is important as

— it is the origin of the high-speed solar wind and
— the IMF directly interacts with the Earth’s magnetosphere and the irregularities or curvatures in the IMF also modulate the flux of high-energy cosmic rays that impact the Earth’s upper atmosphere; such impacts produce \(^{14}\text{C}\) [39] and \(^{10}\text{Be}\) [40] isotopes, and therefore these isotopes, may be used as historical datasets of solar activity.

Our present-day understanding of the Sun’s open magnetic flux mainly comes from an important result from the Ulysses mission. Namely, that the magnitude of the radial IMF component in the heliosphere is independent of latitude [36]. This means that magnetometer measurements at a single location at 1 AU (1.5 \(\times\) \(10^{11}\) m) may be used to deduce the total open flux. In figure 3, the variation of
Figure 3. Graph of (a) open flux variation and (b) sunspot number for cycles 20–23 (from Lockwood et al. [41]).

open flux relative to sunspot number can be seen for the last 3.5 cycles. Over a solar cycle, the open flux varies at most by a factor of 2. However, this variation is not regular from one cycle to the next. A key property of the open flux is that it slightly lags behind the variation in sunspot number and peaks 1–2 years after cycle maximum.

While both direct and indirect observations exist for the Sun’s open flux, such measurements cannot be made for other stars. Owing to this, theoretical models that predict the magnitude and spatial distribution of open flux are used. Within the stellar context, the distribution of open flux with latitude [42] plays a key role in determining the mass and angular momentum loss and subsequently the spin down of stars [43–45].

(a) Theoretical models

Over the last 20 years, a wide variety of techniques have been developed to model the origin and variation of the Sun’s open flux. These may be split into two broad categories: magnitude variation models and spatial distribution models.

(i) Magnitude variation models

The two most successful magnitude variation models are by Lockwood et al. [46] and Solanki et al. [47,48]. A key feature of these models is that they drive the variation of open flux through the direct input of observational data. However, the type of observational data used in each case is very different: one originates from the Sun, the other from the Earth. In the case of Lockwood et al. [46], they use the geomagnetic aa-index [49], which provides a long-running measure of geomagnetic...
activity at the Earth. The aa-index is combined with a physics-based model of the solar wind and Parker spiral theory. The authors then deduce the magnitude of the open flux back to 1860 and conclude that the open flux has doubled over the last 100 years.

In contrast, Solanki et al. [47] construct a semi-empirical model to determine the rate of change of open flux. A key feature of this model is that the variation of open flux is driven by observed sunspot numbers. In addition, the model includes a linear decay term that contains a best-fit time constant ($\tau_0$). The best fit to observed IMF data occurs with $\tau_0 = 3.6$ years. Using observed sunspot numbers, the model computes the open flux back to 1610. The linear decay term allows for secular variations of the open flux and explains why the open flux increases/decreases during short/long cycles. Later extensions of the model included the effect of ephemeral regions [48].

(ii) Spatial distribution models

These models consider the spatial distribution of open flux on the Sun. To do so, they couple together the two components. The first is a description of $B_r$ at the photosphere, specified either through synoptic magnetic field observations or from magnetic flux transport simulations (§3). Secondly, a coronal field model is applied. A wide variety of coronal models, each applying different approximations have been used. These range from PFSS models to CSSS models and more recently to non-potential coronal models. In all of these coronal models, field lines reaching the upper boundary are deemed to be open.

In the study by Wang & Sheeley [50], a combination of synoptic magnetograms and PFSS models were used to compute the open flux from 1971 to 1998. The synoptic magnetograms originated from either Wilcox Solar Observatory (WSO 1976–1995) or Mount Wilson Observatory (MWO 1971–1976, 1995–1998). The authors found that to reproduce a good agreement to IMF field measurements at 1 AU, they had to multiply the magnetograms by a strong latitude-dependent correction factor ($4.5 - 2.5 \sin^2 \lambda$).

The use of such a latitude-dependent correction factor was recently questioned by Riley [51]. The author pointed out that the correction factor used by Wang & Sheeley [50] was only correct for the use on MWO data and did not apply to WSO data. It has its own correction factor of 1.85 [52]. On applying the correct correction factor, Riley [51] showed that PFSS models gave a poor fit to observed IMF data (see fig. 4 of Riley [51]). To resolve the difference, Riley [51] put forward an alternative explanation. He assumed that the open flux has two contributions, the first a variable background contribution, such as that obtained from the PFSS model and secondly a short-term enhancement owing to interplanetary CMEs, which he computed using a simple order of magnitude calculation. Through combining the two, a good agreement to IMF field observations was found.

As an alternative to using synoptic magnetic field observations, magnetic flux transport models have been widely used to provide the lower boundary condition in the study of the origin and variation of the Sun’s open magnetic flux. Initial studies that combined the magnetic flux transport model with a PFSS coronal model found conflicting results. Mackay et al. [53,54] found that commonly used input parameters of the magnetic flux transport model failed to reproduce the main features of the open flux. However, Wang et al. [55] found
that the correct behaviour could be found if the rate of meridional flow was increased to 25 ms\(^{-1}\) and the flux of input bipoles multiplied by a factor of 3. Opposing such a strong variation in the input parameters, Schussler & Baumann [56] put forward another possibility. Through using a variation of the magnetic flux transport model, which included a radial diffusion term for \(B_r\), and changing the coronal model to a CSSS model, they found that the correct variation of the open flux could be obtained. But only if new bipole tilt angles were decreased from 0.5\(\ell\) to 0.15\(\ell\). Later studies by Cameron et al. [57] using the same technique showed that the radial diffusion term was not required if the tilt angles of the bipoles varied from one cycle to the next, such that stronger cycles have weaker tilt angles.

The discussion above shows that the correct variation of the Sun’s open flux may be obtained through a variety of methods. More recently, Yeates et al. [31] showed that, by allowing electric currents to form in the corona, a better agreement to the IMF measurements can be found compared with those from PFSS models. Figure 4a compares various PFSS extrapolations using different magnetogram data (coloured lines) to the measured IMF field (grey line). In this graph, the discrepancy between all potential field models and the IMF is particularly apparent around cycle maximum. To resolve this, Yeates et al. [31] ran the global non-potential model described in §3.3 over four distinct, 6 month periods (labelled A–D in figure 4a). The results of the simulation for period B can be seen in figure 4b. In the plot, the dashed lines denote open flux from various PFSS extrapolations, the grey line the observed IMF field strength and the black solid line the open flux from the non-potential global simulation. This clearly gives a much better agreement compared with the PFSS models. Yeates et al. [31] deduced that the open flux has three main contributions. The first is a background level owing to the location of the flux sources. The second is an enhancement owing to electric currents, which results in an inflation of the magnetic field. This inflation can be seen as the steady increase of the open flux curve over the first rotation to a higher base level. The inflation is the result of large-scale flows such as differential
rotation and meridional flows, along with flux emergence, reconfiguring the coronal field. Finally, there is a sporadic component to the open flux as a result of CMEs.

6. Long-term non-potential simulations of the solar corona

Recently, Yeates et al. [30,58] tested the validity of the non-potential coronal model described in §4c by carrying out a series of detailed comparisons with observations. These comparisons compare output from the model with observational features for both solar filaments and CMEs.

To carry out the comparisons, the authors simulated the coupled evolution of both photospheric and coronal fields over a 6 month period from April to September 1999. To maintain the accuracy of the simulation over the 6 month period, the emergence of new bipoles as determined from observations was also included. In the electronic supplementary material, movie1.mpg, a movie of the simulation can be seen where the photospheric field distribution is given by the grey-scale image (white is positive flux and black is negative flux) and the lines denote the field lines of the nonlinear force-free coronal field as seen in the plane of the sky.

(a) Comparison with solar filament chirality

The first test of the model considers the origin of the hemispheric pattern of solar filaments [59,60], and in doing so determines if the model adequately describes the build-up and transport of helicity from low to high latitudes on the Sun. In recent years, solar filaments have been classified in terms of their chirality [61]. This chirality may take one of two forms: dextral or sinistral. Dextral/sinistral filaments have an axial magnetic field that points to the right/left when the main axis of the filament is viewed from the positive polarity side of the polarity inversion line (PIL). A surprising feature of the chirality of filaments is that it displays an unusual large-scale hemispheric pattern: dextral/sinistral filaments dominate in the Northern/Southern Hemispheres, although exceptions to this pattern do occur. Since filament chirality is directly related to magnetic helicity (dextral \(\sim\) negative, sinistral \(\sim\) positive), the formation and transport of filaments are an indication of the large-scale pattern of magnetic helicity on the Sun, a key feature in explaining many eruptive phenomena. PFSS models cannot study the generation or transport of this helicity across the surface of the Sun. This can only be achieved with models that couple the evolution of both photospheric and coronal fields over long periods of time.

Using the global non-potential simulations, the origin of this hemispheric pattern was considered through a direct comparison between theory and observations [62,63]. To carry out the comparison, Yeates et al. [37] first used H\(\alpha\) observations from the Big Bear Solar Observatory (BBSO) to determine the location and chirality of 109 filaments.

In the second stage, a direct one-to-one comparison [30] of the chirality produced by the model with the observed chirality of the filaments was carried out at the exact location that the filaments were observed. An example of this can be seen in figure 5a, the global field distribution can be seen after 108 days of evolution. A zoomed in area along with simulated flux rope can be seen in
(a) Magnetic field distribution in the global simulation after 108 days of evolution, showing highly twisted flux ropes, weakly sheared arcades and near-potential open fields. On the central image, white/black represents positive/negative flux. (b) Close up view of a dextral flux rope lying above a PIL within the simulation. (c) BBSO Hα image of the dextral filament observed at this location. (Online version in colour.)

Through varying the sign and amount of helicity emerging within new bipoles, Yeates et al. [30] (see their fig. 5b) showed that by emerging dominantly negative helicity in the Northern Hemisphere and positive in the Southern, a 96 per cent agreement can be found between the chirality in the observations and simulations. An important feature is that the agreement is equally good for minority chirality filaments as well as for dominant ones [64]. Another feature is the longer the simulations are run, the better the agreement. This indicates that the Sun has a long-term memory of the transport of helicity from low to high latitudes and that the model has the correct physical effects to describe the build-up and transport of this helicity across the surface of the Sun.

(b) Comparison with coronal mass ejection sites

For the second test, Yeates & Mackay [65] and Yeates et al. [58] considered the formation of flux ropes and their subsequent loss of equilibrium. Over the years, a wide variety of mechanisms have been proposed for the initiation of CMEs [66]. One such mechanism is the flux rope ejection model [67], where surface motions and flux cancellation produce a flux rope that subsequently loses equilibrium.
Within the global simulations of Yeates & Mackay [65], the formation of flux ropes is a natural consequence as flux cancels. As these flux ropes become larger, local losses of equilibrium may occur [26]. In the paper of Yeates et al. [58], these losses of equilibrium are compared with the observed sites of CMEs. First, CMEs are identified from Lasco C2 observations and their initiation location in the low corona determined from cross correlation with Extreme Ultraviolet Imaging Telescope (EIT) 195 Å images. Of 330 CMEs identified, only 98 had a clear low-coronal signature in the EIT images.

These 98 events were then cross correlated with the sites of flux rope ejections from the global model. Agreement could be found in some, but not all cases. Overall, the best correlation between the model and CMEs was 0.49. The authors, however, identified two separate classes of CME. The first are those that do identify with flux rope ejection locations. These account for half of the sample. The other half were those located within the centres of active regions and frequently re-occur over short time scales. The global model was unsuccessful in reproducing these as it does not consider the internal structure or dynamics of active regions. While the comparison was only partially successful, it shows that flux rope formation and loss of equilibrium are important models for CME initiation.

7. Global magnetohydrodynamics models

In recent years, a significant advance has been made in the construction of realistic three-dimensional global MHD models [68,69]. Such models are required to give a self-consistent description between the interaction of the magnetic field and the plasma in the Sun’s atmosphere. Although they give a self-consistent description, these models are at the present time restricted by computational requirements to static photospheric boundary conditions and steady-state coronal solutions.

A key emphasis of this area of research is on the direct comparison of the steady-state solutions with either white-light [70] or multi-spectral extreme ultraviolet (EUV) and X-ray observations [68,69]. Early global MHD models that used a simplified polytropic energy equation were able to produce a good representation of the Sun’s large-scale magnetic field [71], but they were unable to reproduce realistic emission profiles in EUV and X-rays. This was attributed to the fact that they did not produce a sufficiently high density and temperature contrast between open- and closed-field regions. To improve the models, a more realistic energy equation has been incorporated, which included the effects of thermal conduction, radiative losses and coronal heating, along with modelling the upper chromosphere and transition region [68,69].

In figure 6, the results of a comparison of the global MHD model of Lionello et al. [68] with observations can be seen. In the left-hand column, three EUV pass bands (171, 195, 284 Å) along with a Soft X-ray Telescope image can be seen. In the three other columns, synthetic emission profiles constructed from the density and temperature distributions found in the global MHD simulation are shown. Each column uses exactly the same MHD model with the only difference being the form of the coronal heating applied. While each solution produces roughly the same magnetic structure, the most important factor in reproducing the emissions is the coronal heating. The second column that uses an exponential form, which
8. Conclusions

In this review, our present-day understanding of global magnetic fields on the Sun and other stars has been discussed from both an observational and a theoretical viewpoint. For the case of the Sun, we now have long-running datasets
of global magnetic activity. For other stars, we are just beginning to learn of the wide variety of magnetic topologies that exist. In terms of theoretical models, recent years have seen a significant advance in global modelling techniques. Global magnetic fields may be modelled under the nonlinear force-free approximation for long periods of time or for short periods of time using highly detailed MHD models. A key feature of these models is that they have been validated through various comparisons with observations. While our understanding has significantly increased over the last decade, there are several immediate outstanding issues. Four of these are discussed below, where the order in no way reflects their importance.

— While we have a detailed understanding of the normal magnetic field component on the Sun, the same is not true for the vector field. With the SDO, we now have daily full disc vector magnetograms. Analysis of these will gain us an understanding of the emergence and transport of vector fields across the Sun. This will allow us to study the origin and evolution of magnetic helicity, a key component in eruptive phenomena.

— While our understanding of stellar magnetic fields has greatly increased, observations are still sporadic. Long-term datasets of individual stars across different spectral types are required. From this, we may deduce different magnetic flux emergence and transport parameters that are critical for the next generation of dynamo models.

— For theoretical models, regular observations of the vector fields mean that more constraints may be applied to input data that are used to specify the emergence of magnetic flux in models. New techniques must be developed for the incorporation of vector data into simulations.

— Global time-dependent MHD models with evolving lower boundary conditions must be developed to provide a self-consistent model for the evolution and interaction of magnetic fields with plasma.

These issues may be addressed with the current suite of ground- and space-based observatories, along with developing new theoretical techniques. A key element in achieving this goal is the increasing computing power available for both real-time data reduction and theoretical modelling.

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Review. Global magnetic fields


