REVIEW

Magnetic flux emergence and associated dynamic phenomena in the Sun

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We present a review of the process of magnetic flux emergence in the Sun. We focus on observations and numerical experiments that explore the dynamical rise of magnetic fields from the solar interior to the corona. We describe the response of the highly stratified solar atmosphere on flux emergence and, consequently, we present a comprehensive picture of the coupling between solar dynamic events and flux emergence. We discuss potential applications of this process in other astrophysical environments.

Keywords: Sun; magnetic fields; flux emergence

1. Introduction

Magnetic flux emergence in the Sun is the process through which the magnetic fields rise from the solar interior to the solar surface and above. The sites where the rising magnetic fields intersect the photosphere are called emerging flux regions (EFRs) [1,2]. Observations of the solar surface reveal that magnetic flux emerges over a range of different spatial and temporal scales (figure 1a): on small scales to form the internetwork field and on large scales to build up active regions (ARs) [4]. The characteristic turnover time of small-scale flux emergence is only a few minutes while the lifetime of ARs (ephemeral to large scale) may persist for up to days or several weeks. Therefore, one may naturally assume that the large-scale flux emergence is responsible for the most long-lived dynamic events in the Sun.

The purpose of this review is to report on the progress that has been made in (i) exploring the nature of flux emergence on multiple scales and (ii) studying the coupling between flux emergence and dynamic phenomena at various atmospheric heights. In §2, we will refer to selected observational aspects of flux emergence, which will be used for comparison with the numerical experiments. A series of numerical results, based on idealized and realistic experiments, will be described with the aim of providing an updated view of the undergoing research on this subject. Idealized simulations (in §3) are commonly used for investigating the large-scale evolution in EFRs, despite the fact that they lie in simplified

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concepts. On the other hand, realistic simulations (in §4) have been mainly used to study the small-scale emergence of magnetic flux. The results of these experiments are complementary and together they reveal a coupling between apparently independent phenomena. Also, many events are present in both types of experiments, ultimately implying the common nature of the dynamic evolution of emerging magnetic fields. In §5, we describe other astrophysical examples employing the process of flux emergence.

2. Observational aspects of magnetic flux emergence

Emergence of magnetic flux at the photosphere is a multi-scale dynamic process: it occurs on all scales, from pores to sunspots and ARs. Observations [5] have revealed that, as the magnetic field emerges at the solar surface, many small-scale and fragmented magnetic elements with mixed polarity appear and disappear during the evolution of the magnetic flux system. Eventually, a large-scale and well-developed bipolar structure is formed, while some of the small-scale elements are absorbed to the main bipole and others are cancelled in place with opposite polarity features.

In many EFRs, the topology of the magnetic field, in the intermediate regime between the two main polarities, adopts a ‘sea-serpent’ configuration [6]. In fact, it has been found [6] that undulations in ‘sea-serpent’ photospheric magnetic fields have wavelengths which are consistent with the most unstable wavelength of the Parker instability. On the other hand, granular convection is a natural
mechanism that can drive small-scale flux emergence at the solar surface. Further investigation is required to reveal whether it is the interplay between the two mechanisms that is responsible for the process of multi-scale flux emergence.

Observational studies of interacting magnetic elements in EFRs [6,7] have also revealed small-scale brightenings, which occur at the interfaces between the magnetic fields that come into contact. The brightenings have the characteristics of Ellerman bombs (i.e. short-lived, small-scale bright points observed best in the wings of the H\textsubscript{α} line). It has been suggested that magnetic reconnection between opposite polarity magnetic elements in the low atmosphere is a plausible mechanism for producing Ellerman bombs.

A common feature in EFRs is the presence of magnetic tongues or tails of the two main polarities, on the two sides of the polarity inversion line (hereafter, PIL) [8,9]. The PIL (sometimes also referred to as the neutral line) is a line separating areas of opposite polarity magnetic flux. As the magnetic field emerges at the solar surface, the magnetic elements of opposite polarity may possess a shearing motion, of a few km s\(^{-1}\) along the neutral line [10–12]. The shearing is induced by the relative motion of the two polarities, as they run in anti-parallel directions along the PIL. Shearing motions over the neutral line, in the transition region, chromosphere and corona (with a magnitude of about 20 km s\(^{-1}\)) have also been observed [13,14].

The gradual and persistent emergence of magnetic flux in EFRs may lead to the formation of a longer magnetic flux system, which can expand into the corona. Indeed, long ‘arch filament’ systems, visible in the H\textsubscript{α} line, have commonly been used to identify EFRs [15]. The rise and expansion of the magnetic field in EFRs results in downflows at the outskirts of the emerging field lines. Photospheric downflows observed in EFRs, using spectroscopic and circular polarimetric data [2,15], have a typical value of 2–3 km s\(^{-1}\). Downflows have also been observed along the line of sight in developed AR loops at chromospheric and coronal levels [16,17], with a typical value of 10–15 km s\(^{-1}\) at the height of the chromosphere and 20–30 km s\(^{-1}\) within corona.

Flux emergence in developing ARs often leads to the formation of sunspots. As we mentioned above, this process might occur through successive merging of small-scale magnetic flux elements with like polarities. These elements are parts of bipolar structures that have previously emerged at the solar surface. Another mechanism could be the emergence of a single (usually twisted) magnetic flux tube from the solar interior to the surface. Indeed, numerical experiments (see §3) indicate that sunspots form where the axial magnetic field of the emerging flux tube intersects the photosphere. Now, observations [18,19] have revealed that sunspots may possess rotational patterns around their vertical axes. One possible origin for the sunspot’s rotation is the presence of marked vortical plasma motions in the convection zone or in the photosphere. As an example, opposite vortical flows have been detected [20] in the depth range of 0–12 Mm around sunspots. These observations are in agreement with the argument [21] that vortical motions may exist in subphotospheric layers and play an important role in the formation of magnetic twist. Vortical motions may also be associated with the emergence of a twisted flux tube from the solar interior (see §3). Further study is required to investigate the potential relationship between the twisting/untwisting motion of the field lines as they emerge and expand into the solar atmosphere and the rotational motion of sunspots.

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An important issue is whether twisted flux tubes (TFTs) bodily emerge through the photosphere. Observations [22] of ARs using the Solar Optical Telescope (SOT) on board Hinode and TRACE have demonstrated (although not conclusively) that a twisted magnetic field can emerge as a whole above the photosphere and form an AR filament channel. Similar observations [23] have reported on the emergence of a helical flux rope from below the photosphere into the corona, along the PIL of an AR. On the other hand, numerical experiments have demonstrated that magnetic fields often experience partial emergence (see §3b). Therefore, the bodily emergence of twisted flux tubes through the solar surface is an important and open question.

Many dynamic phenomena in the Sun are associated with the emergence of magnetic flux. Observations of Hα and Hβ surges in EFRs [24] have shown the ejection of cool and dense plasmoids adopting a solenoidal structure. Multiple X-ray plasmoid-like ejections, with a blob or loop-like structure, have also been associated with impulsive flaring events, as reported by observations [25] of the soft X-ray telescope (SXT) on board Yohkoh. In other cases, the formation of jets is found to occur simultaneously with an episode of flux emergence from the solar interior [26,27]. In a similar manner, observations [28] have recorded a jet-launching event in a coronal hole following the appearance of a bipolar region at the photosphere. Various properties of coronal hole jets have been revealed by Hinode/XRT observations, such as the inverted Y shape of the jet or the horizontal drift of the jet during these events. Other interesting observations [29,30] have revealed that jets (e.g. coronal hole jets, polar X-ray jets) undergo apparent motions perpendicular to the jet direction at amplitudes between 5 and 15 km s⁻¹. Additional studies (both numerical and observational) are required to investigate the role of flux emergence and reconnection in the possible driving of these motions (see §3c).

On large scales, flux emergence within or nearby a pre-existing AR can lead to profound flaring activity [31] driven by the build-up of intense shearing at the interface between the interacting fields (i.e. emerging and pre-existing). Such interaction may also lead to the onset of fast and persistent outflows at the edges of the EFR. These outflows could be reconnection jets or pressure driven outflows [32–35] depending on various conditions, such as the relative orientation of the magnetic fields in contact. The emergence of magnetic fields throughout the highly stratified solar atmosphere could also be associated with many other dynamic phenomena. For example, Hinode observations have revealed that the chromosphere is an extremely dynamic layer consisting of a variety of waves, spicule-like features [36] and numerous jets [37]. Can flux emergence be potentially effective in triggering such events and under what conditions? The interplay between multi-wavelength observations and advanced three-dimensional forward modelling is crucial in order to achieve progress in understanding the atmospheric response to flux emergence.

Outside of ARs, the quiet Sun is filled with small-scale mixed polarity magnetic fields. Of particular importance is the existence of magnetic fields at internetwork areas, which cover the majority of the solar surface. It is estimated that much more flux (approx. four orders of magnitude) emerges in the internetwork than in ARs [38]. Spectropolarimetric observations in the near-infrared and in the visible spectral ranges show that the typical magnetic field strength in the internetwork is approximately 500 G [39], which may indicate a rough equipartition between...
magnetic energy density and kinetic energy density of the background plasma flows. In general, the network magnetic field consists of horizontal and vertical magnetic flux elements and is known to have an intrinsic strength on the order of a kilogauss [40].

An important question about the horizontal internetwork fields (HIFs) is their origin. One explanation is that HIFs represent concentrated loops of flux carried to the surface by the upflows of granular convection or by magnetic buoyancy [41,42]. The rate at which magnetic flux is carried to the quiet photosphere by the loops can be estimated to be $1.1 \times 10^{24}$ Mx over the solar surface per day, which is much larger than the corresponding flux emergence rates in ARs [43–45]. On the other hand, a determination of the fluxes of the observable magnetic features at the solar surface [46] have revealed that all measured fluxes between $2 \times 10^{17}$ and $1 \times 10^{23}$ Mx follow the same flux distribution: a power law with a slope of $-1.85 \pm 0.14$. The study was based on the analysis of magnetograms from SOlar and Heliospheric Observatory (SOHO)/Michelson Doppler Imager and Hinode/SOT data. This result suggests that either all the observed magnetic features at the surface are generated by the same mechanism or that they undergo local processes (e.g. coalescence, cancellation) resulting in a scale-free distribution. Moreover, Thornton & Parnell [47] found that the flux distribution of newly emerged features also follows a power law, with a slope of approximately $-2.7$. This result provides more support for the first hypothesis, namely that all magnetic features are created by a (dynamo) mechanism that acts in the same way on all scales. More observational measurements and numerical experiments of flux emergence are required to confirm the above results.

Finally, observations [48] have demonstrated that the emergence of flux on granular scales is capable of transporting a considerable amount of horizontal fields to the quiet-Sun photosphere and in plage regions. Based on observations [49], reconstruction of internetwork fields indicates that many of the local magnetic field elements are segments of loop-like structures, which are found to emerge in granules. In the following, we concentrate in particular on numerical experiments investigating the process of flux emergence through the highly stratified solar atmosphere.

3. Idealized experiments

A series of experiments [50–53] have mainly focused upon the emergence of a magnetic TFT model through a highly stratified atmosphere, which consists of an adiabatic layer that represents the convection zone, an isothermal photosphere, a transition region with a steep temperature gradient and a stably stratified, isothermal corona. To model the evolution of the system, the magnetohydrodynamic (MHD) theory is commonly used in these experiments. Many of the numerical models are idealized, involving an internal energy equation that includes only the adiabatic, ohmic and viscous heating terms. Despite simplifying assumptions, these experiments provide a successful description of the large-scale evolution of the emerging fields in the solar atmosphere. In the following, we report on the response of the atmospheric layers on the TFT emergence models. Results describing the emergence of magnetic fields with a different initial magnetic field configuration are discussed in §2d.
(a) Emergence at the photosphere

Convection zone simulations have shown that, in order for the magnetic field to remain coherent during its rising motion, the field must be twisted [54]. Therefore, the majority of flux emergence models use a horizontal TFT as an initial magnetic field configuration at the upper layers of the convection zone. A three-dimensional Cartesian coordinate system is used, where the axis of the tube is along the $y$-direction, the $x$-axis is in the transverse direction and the $z$-axis is vertical (along height) to the tube. The axial magnetic field component (e.g. $B_y$) is given, as commonly used, by a simple Gaussian profile

$$B_y = B_0 \exp \left( -\frac{r^2}{R^2} \right),$$

(3.1)

where $r = \sqrt{x^2 + (z - z_c)^2}$ is the radial distance from the axis of the tube, initially located at a height $z_c$. $B_0$ is the magnetic field strength on the axis of the tube and $R$ is the radius of the tube. The magnetic field lines are uniformly twisted around the central axis of the tube, $B_\theta = \alpha r B_z$, with $B_\theta$ the azimuthal component of the magnetic field, $\alpha$ the twist of the field lines about the tube’s axis and $B_z$ the vertical magnetic field component.

In most experiments, the subphotospheric magnetic field is required to be in total force balance with its surroundings by modifying the local gas pressure. The magnetic flux tube is then made buoyant by applying a density deficit along its axial direction. More precisely, the deficit is reduced away from the centre (where the tube temperature equals the external temperature) and towards the ends of the tube following the Gaussian profile,

$$\rho = \rho_b(z) + \rho_{\text{def}} e^{-y^2/\lambda^2},$$

(3.2)

where $\rho_b(z)$ is the background density profile and $\rho_{\text{def}}$ is the (negative) density deficit. The parameter $\lambda$ represents the half length of the buoyant part of the tube and the density deficit has its maximum value at the centre, leading to magnetic buoyancy instability [4,55]. As a result, the central segment of the tube rises through the convectively stable subphotospheric layer adopting an $\Omega$-loop shape.

The emergence of the $\Omega$-shaped magnetic field at the photosphere is followed by the formation of a bipolar pair of sunspots and a small or ephemeral AR (figure 1b). Eventually, the opposite polarity sunspots (shown in figure 1b) move away from each other, towards an east–west direction along the polarity inversion line of the EFR. The motion of the plasma in opposite directions, on the two sides of the PIL, results in a pronounced shear flow [51,52]. It has been suggested that the origin of these shearing plasma motions is nonlinear Alfvén waves, which are magnetically driven by the tension of the emerging field lines. The existence of these waves may provide an explanation for the shear flows observed in emerging bipolar ARs.

As the sunspot separation proceeds, a rotational flow appears in each of the polarity flux concentrations [56]. This motion becomes prominent in the late emergence, when the emerging field intersecting the photosphere becomes vertical. Idealized TFT experiments have demonstrated that the rotational flows are due
to torsional Alfvén waves propagating along the TFT [57]. Then, magnetic twist and helicity are steadily transported, from the twisted emerging field into the higher atmosphere.

During the emergence within the solar interior, the rising magnetic field expands. After its arrival into the surface, the emerging field undergoes a profound expansion due to the diminishing pressure scale height and the sub-adiabatic stratification of the model photosphere. The photosphere is an isothermal layer that does not support convective motions. Therefore the magnetic field that rises into the surface is no longer buoyant compared with the surrounding plasma. It spreads out horizontally with a speed that is determined by the buoyancy force of the emerging field [58]. An important result in TFT models is that the main axis of the emerging tube reaches a stage where it struggles to emerge above 2–3 photospheric pressure scale heights. As the axis remains at the photosphere and the magnetic field spreads horizontally, the associated dense material of the axial field drains poorly, preventing the axis from getting more buoyant, and emerges into the higher atmosphere. This is a generic result found in TFT experiments, independently of the exact form of the initial perturbation (e.g. density deficit, vertical velocity perturbation) that drives the TFT emergence. It has been found that magnetic fields with a sharply bending initial shape undergo a more dynamical emergence above the photosphere (see §2d).

TFT models [3] are in qualitative agreement with the observations by showing that elongated magnetic tails are formed in the wake of the two opposite polarities, as the field scatters at the photosphere. The appearance of the tails is owing to the projection of the azimuthal magnetic field component at the surface. This indicates that the field must be twisted when it emerges at the photosphere. If the emerging field is weakly twisted, the EFR consists of magnetic flux patches of mixed polarity. Some of these patches are joined by the same field lines, forming an overall magnetic system with undulations (i.e. a series of interconnecting U- and Ω-like segments of field lines). Undulations develop when the weakly twisted field at the photosphere becomes unstable to the Parker buoyancy instability. These experiments reveal that the existence or absence of magnetic tails in ARs may provide information about the amount of twist present in the emerging fields. More realistic simulations (in §4) demonstrate that the ‘sea-serpent’ configuration of the magnetic field in EFRs is the result of the interaction between fully developed convective motions and emerging field lines.

Other observed features in emerging ARs that are reproduced in TFT experiments include the following. (i) In many TFT experiments [50,51,53], the orientation of the magnetic loops above the photosphere resembles the topology of ‘arch filament’ systems as indicated by Hα images. Spectroscopic evidence indicates that the tops of these arch filaments are rising in the chromosphere with velocities of about 10 km s⁻¹. In TFT experiments, the apex of the emerging field, with an initial field strength of approximately 15 kG at 2–3 Mm underneath the photosphere, has been estimated to rise with similar speeds. Also, because of mass conservation, the fast rise and expansion of the magnetic plasma causes strong downflows along its periphery. The downflow velocities at various atmospheric heights fit well the corresponding flows observed in EFRs (see §2). It is worthwhile mentioning that the choice of the initial parameters (e.g. magnetic field strength and twist) and the initial conditions (e.g. density deficit profile along the tube)
of the system affects the buoyancy of the emerging field and consequently the magnitude of the produced up/down flows at various atmospheric heights. Also the overall time scale of the emergence in TFT experiments is typically 1–2 orders of magnitude shorter than in observed examples. This is mainly due to the fast driving of the system by the imposed density deficit along the field. (ii) Shearing motion along the neutral line has been found to occur in idealized experiments of EFRs. It has been demonstrated that shearing and converging flows (i.e. towards the neutral line) are important processes leading to the ‘eruption’ of coronal flux ropes (see §2b). By ‘eruption’, we mean the sudden release of tension or pressure that results in the expulsion of magnetized plasma. (iii) The field strength for the rising magnetic field close to the photosphere compares favourably with the values obtained in observations. For instance, a flux tube with a field strength of 6500 G, which is located 1.7 Mm underneath the photosphere, yields values of approximately 500 G for the first elements reaching the photosphere.

The TFT experiments have shown that there are two distinct phases during flux emergence. In the first phase, the magnetic field rises to the photosphere where it suffers horizontal spreading. The second phase is marked by a three-dimensional expansion of the magnetic field above the surface. In this phase, the dense material of the emerging flux can be transported into the atmosphere through the development of a magnetic buoyancy instability. Following the pioneering work by Thomas & Nye [59] and Acheson [55], the critical condition for the emergence into the upper atmosphere is

\[-H_p \frac{\partial}{\partial z} (\log B) > -\frac{\gamma}{2} \beta \delta + \hat{k}_\parallel^2 \left(1 + \frac{\hat{k}_z^2}{\hat{k}_\perp^2}\right).\]

In this criterion, we have the pressure scale height, \(H_p\), the magnitude of the magnetic field vector, \(B\), the ratio of specific heats, \(\gamma\), the plasma-\(\beta\) and perturbations with wavevector \(k\) (where \(\hat{k}_\parallel\) and \(\hat{k}_\perp\) are the horizontal components parallel and perpendicular to the magnetic field and \(\hat{k}_z\) is the vertical component). The superadiabatic excess, \(\delta\), is given by \(\delta = \nabla - \nabla_{ad}\), where \(\nabla\) is the actual logarithmic temperature gradient in the equilibrium stratification and \(\nabla_{ad}\) is its adiabatic value.

As the magnetic field continues to emerge from the solar interior to the photosphere, a magnetic layer is formed at the surface where magnetic pressure builds up and eventually exceeds the gas pressure. The above criterion is satisfied at heights where plasma-\(\beta\) becomes smaller than 1. After the development of the instability, the magnetic field can rise into the ambient atmosphere, where it experiences a profound expansion due to the steep decrease in the background gas pressure along its height. The expanding coronal field adopts a fan-like shape, reminiscent of the configuration in solar AR magnetic loops. The rise of the emerging field into the corona and the occurrence of associated dynamical phenomena is discussed in the following section.

(b) Flux emergence into a field-free atmosphere

A series of idealized experiments have been performed to study the emergence of magnetic flux into a neutral atmosphere. In these experiments, there is no ambient magnetic field in the atmosphere, prior to the emergence. Therefore,
the rise of the magnetic field into the atmosphere is marked by an unimpeded expansion that occupies the available atmospheric volume. The upward motion of the field is driven by the magnetic pressure force that overwhelms the gas pressure force of the external plasma. The expansion is adiabatic and, thus, a cool segment of magnetized plasma emanating from the EFR appears to rise into the hot upper solar atmosphere [53]. This is likely to occur as a result of the absence of radiative heating in the energy equation. On the other hand, realistic experiments (see §4) have revealed a similar emergence process of cold plasma into the corona.

A considerable amount of flux is transferred into the corona during the late stage of emergence. More than 60 per cent of the initial axial flux emerges above the transition region about 50 min after the onset of emergence from the subphotospheric layers [60]. Magnetic energy and helicity flux increase monotonically after the emergence into the photosphere. In the early phase of emergence, helicity is injected by direct emergence while in the late phase horizontal motions at the low atmosphere are dominant and they drive the injection of energy and helicity via shearing and rotational motions at the footpoints of the emerged field [57,61]. A self-similar behaviour in the amount of the tube flux transported into the atmosphere is found when the field strength of the emerging field is modified [58].

An important question is whether TFTs bodily emerge through the photosphere. TFT experiments have shown that a rising flux tube does not emerge as a whole structure, but it undergoes a partial emergence [62,63]. The original axis of the flux tube that comes from the solar interior remains in the low atmosphere. A distinct, new flux rope is formed above the original axis, which eventually erupts into the corona. The formation of the new rope is the result of the combined action of horizontal motions (i.e. shearing and converging flows), leading to internal reconnection of sheared field lines. The initial rise of the new flux rope is driven by the pressure gradient and the Lorentz force. As it rises, reconnection underneath the rope becomes efficient, leading to the acceleration of the rope by the tension of the reconnected field lines. Because of the rapid reconnection of the field, heating is produced at the site of internal reconnection. The erupting magnetic field comprises twisted field lines that carry dense plasma in their dips. The material emerged into the corona by the flux rope is generally 2–3 orders of magnitude heavier than the background plasma. The overall configuration consists of an envelope coronal magnetic field, a fast-rising flux rope within the envelope, a cavity-like feature above the flux rope and a hot structure underneath it (figure 2). Under certain conditions, the magnetized expanding volume may rise with a velocity that exceeds the local Alfvén speed [3]. Although it rises with a high speed, the flux rope cannot fully escape into outer space. This type of eruption is considered as a ‘confined’ eruption. Eventually, the flux rope slows down because of the downward tension force that the envelope field lines exert on the upcoming field. As a result, the rope rises into the corona and it approaches a quasi-static equilibrium, which is retained for a few Alfvén crossing times. An open problem is whether the final stage of the flux ropes in these experiments may account for the stable configuration of a filament-like structure. To address this question, one should take into account the fact that the solar atmosphere is magnetized. Therefore, a main aim is to understand the interaction between the emerging and the pre-existing magnetic fields in the solar
atmosphere. The effect of this interaction on the evolution of coronal flux ropes is discussed in §2c. A detailed review on solar prominences and coronal flux rope dynamics is given by Mackay et al. [65].

Other TFT experiments [57] have demonstrated that the rotational motions of the footpoints twist up the inner emerged field lines and rotate them into an inverse configuration, which leads to the development and upward motion of a coronal flux rope structure. In this scenario, the eruption is not a true plasma motion, but an apparent rising motion of twisted field lines. The eruption is followed by reconnection in a current sheet underneath the rope. The reconnection process removes some of the dense plasma trapped at the dips of the field lines. The latter process together with the tension of the reconnected field lines enhance the acceleration of the rope.

A general result in TFT experiments is that the erupting rope consists of sigmoid-shaped field lines [52,57,66,67]. Also the reconnection site underneath the rope does not consist of a single S-like current sheet but of a network of multi-scale current layers [67], which all together form a sigmoidal structure. The field lines going through the current layers adopt sigmoid shapes. Therefore, successive heating of the field lines as a result of reconnection causes these field lines to brighten up in a similar way to the X-ray sigmoid-shaped loops in ARs [68]. It is thought that the multi-scale current layers appearing during the eruption of the sigmoidal structure are quasi-separatrix layers.

(c) *Flux emergence into a magnetized atmosphere*

The solar corona is a highly complex environment that encompasses a large variety of phenomena and dynamic processes. A key parameter that distinguishes
the plasma dynamics in the solar corona is the plasma-$\beta$ parameter (i.e. the ratio of the thermal to the magnetic field pressure). In the corona, plasma-$\beta$ is much smaller than 1 since the dominant element that controls plasma dynamics is the strong magnetic field. Therefore, a magnetized atmosphere is essential to be included in flux emergence experiments that deal with the atmospheric response to emergence. The interaction between the emerging flux and pre-existing magnetic fields plays an important role in determining the dynamical evolution of several coronal phenomena. The first series of experiments including a magnetized atmosphere in two dimensions [69] and three dimensions [53,60,70], revealed a series of important results.

(i) **Current sheets**

When the emerging and the ambient magnetic fields come into contact, a strong current layer builds up at the interface. The detection of numerous magnetic separators in three-dimensional flux emergence experiments has been investigated by Parnell et al. [71]. The Joule dissipation associated with the magnetic reconnection between the rising flux tube and the coronal magnetic field heats the plasma mostly in this region. In idealized simulations, the plasma at the interface is heated gradually up to $10^7$ K. Whether such individual sheets prove efficient at maintaining high temperature in the solar corona remains to be addressed.

(ii) **Plasmoids**

Resistive tearing mode instabilities at the interface result in the formation of plasmoids, which have the shape of solenoids lying along the current sheet. Their field lines link up with either the subphotospheric field or the coronal field. Eventually, they are expelled from the current sheet as a result of a reconnection imbalance between the two reconnection x-lines (i.e. the lines along which oppositely directed magnetic field lines reconnect) on their sides [72]. When they are formed at higher atmospheric layers, the plasmoids confine hot (approx. $10^5$–$10^6$ K) and less dense plasma (but still approx. 1 order of magnitude larger than the background plasma density). Thus, the Alfvén speed and the plasmoid ejection velocities become supersonic and comparable to the external Alfvén speed. 2.5-dimensional experiments of flux emergence in a breakout configuration [73] demonstrated that multiple coronal plasmoids (or flux ropes) can be formed during flux emergence, but it was found that the transport of energy in the corona is small so that the ropes do not finally erupt.

(iii) **Jets**

TFT experiments have demonstrated that the interaction between an emerging and a pre-existing ambient coronal magnetic field results in a pair of high-velocity (e.g. more than 100 km s$^{-1}$) jets that emanate from the rims of the current sheet [74]. These are reconnection jets driven by the tension force of the reconnected field lines, which are ejected sideways out of the current sheet. Because of reconnection, magnetic energy is partly released as heat via Joule dissipation and hot plasma is also ejected together with the field lines. In general,
these jets are seen to be regions of high gas pressure, temperature and velocity and they may be observed as X-ray jets.

Three-dimensional experiments [75] have revealed that the inverted Y-shaped jets (i.e. jet-and-vault structure) observed by Hinode/XRT in coronal holes are a natural consequence of flux emergence and interaction with a pre-existing open field akin to those in a coronal hole. They have also reported on the horizontal drift of the jet–vault structure, with properties consistent with the statistics of this type of event. The produced jets may reach peak speeds around \(400\,\text{km}\,\text{s}^{-1}\) and temperatures up to \(3 \times 10^7\,\text{K}\). Similar idealized models [30] have succeeded in producing hot and cool jets, which can be accelerated simultaneously by magnetic reconnection in the transition region/upper chromosphere, driven by flux emergence.

An interesting result is that flux emergence simulations [30] reveal that jets (e.g. coronal hole jets, polar X-ray jets) undergo apparent motions perpendicular to the jet direction at amplitudes between 5 and 15 km s\(^{-1}\). The period of the oscillation is calculated to be around 200 s. Since the jet is believed to be along the magnetic field, the propagation of the oscillation could be interpreted as evidence of propagating Alfvén waves. It is possible that these waves are associated with reconnection, and may contribute to the heating and acceleration of the solar wind when the magnetic field is open [76].

In all the above models, there is a pre-existing magnetic field in the corona (i.e. the ambient magnetic field), which is assumed to be uniform and horizontal or oblique. To include a non-uniform, more realistic, coronal field one may use the emergence of a flux tube. The expansion of the outermost emerging field lines will fill the atmosphere with a non-uniform field (in direction and field strength) across the background stratification. This is called the envelope field. The emergence of a second TFT into this ambient field has been successfully incorporated into experiments investigating (i) the dynamic rising motion of coronal flux ropes [77], (ii) the emission of jet-like upflows at the edges of ARs [33,78] and (iii) the effect of oscillatory reconnection in producing recurrent jets in three dimensions [79].

In general, the existence of an overlying coronal magnetic field prior to the emergence plays a crucial role in determining the potential eruption of a coronal flux rope in EFRs. TFT experiments have clearly demonstrated [64] that coronal eruptions are confined by the envelope field when there is no ambient magnetic field, efficient enough to remove flux and the downward tension of the envelope field. The efficient release of tension is subject to the physical properties (e.g. field strength, relative orientation) of the ambient field [80]. For instance, for any relative contact angle (between the interacting magnetic fields) that favours reconnection, ‘ejective’ eruptions occur earlier when the ambient field is strong. The ‘ejective’ eruptions possess a two-phase rising motion (i.e. first, a slow and, second, a fast rise phase) with velocities that may exceed the local Alfvén speed in the corona. The erupting plasma experiences a runaway situation, in which both the external and internal reconnections assist the flux rope to accelerate into the outer solar atmosphere and escape far out of the envelope field.

(d) Flux sheet and toroidal tube models

Another way to model the emergence of magnetic flux is to use a toroidal tube as an initial configuration for the buoyant magnetic field underneath
the photosphere [81]. The footpoints of the toroidal field are anchored in the subphotospheric layers (e.g. 2.5 Mm below the surface). The geometrical shape is such that the legs of the toroidal tube are oriented almost vertically with respect to those of the initial horizontal field in the TFT experiments. This makes the draining of plasma along the legs of the toroidal tube much more effective. It has been found [81,82] that, for magnetic field strengths $B \geq 9$ kG, the original axis of the toroidal tube emerges into the corona. In the horizontal tube models, plasma draining from the emerged arcade flows down to the photosphere and collects in multiple dips where the axis is trapped. In the toroidal loops, the heavy material does not flow on top of the axis, preventing its further ascent, but it drains down to the solar interior along the vertically oriented legs of the tube. These experiments revealed that the geometry of the emerging field is crucial in determining the rising motion of the axial field into the solar atmosphere.

The initial configuration of a magnetic flux sheet has also been used to study flux emergence from the solar interior to the corona. Two-dimensional simulations [83] have shown the usual ‘two-step emergence’ process, where the field emerges and spreads out at the photosphere first and then it rises into the corona. More precisely, it was found that a magnetic flux sheet which is located 20 Mm below the solar surface, with axial flux $10^{21}$–$10^{22}$ Mx and field strength $10^4$ G, can rise into the corona and build loops with 80 000 km width, 40 000 km height, while the field strength of the footpoints at the surface is about 1200 G. The cases with smaller initial field strength fail to emerge above the photosphere. For higher field strengths (e.g. $B = 10^5$ G) the magnetic field rises into the corona, but the coronal loops present irregularly strong flux densities at the footpoints.

Two- and three-dimensional flux emergence experiments [84,85] with magnetic flux sheets embedded into a superadiabatically stratified layer (mimicking the convection zone) have led to a series of important results. The widely accepted scenario for flux emergence is the formation and expansion of $\Omega$-shaped loops under the action of the Parker instability. This instability has the maximum growth rate at a wavelength $\lambda$ approximately 10–20 $H$, where $H$ is the scale height (e.g. approx. 200 km at the photosphere). Therefore, a number of magnetic loops may rise from the flux sheet at the photosphere, if it is sufficiently long [84]. Moreover, the experiments have shown that the emerging loops expand and reconnect with each other, forming longer coronal loops with a size of approximately 30 000 km. This process of resistive flux emergence might account for the formation of long arch filament systems in developed ARs.

A key feature in these simulations is the accumulation of dense material at the dips of the undulating field lines. The dips are located in between neighbouring emerging $\Omega$-loops, which may reconnect at the low atmosphere and form new magnetic systems adopting the shape of magnetic islands (or flux ropes in three dimensions [85]). These new structures submerge rapidly within the unstable subphotospheric layer, taking with them the dense plasma that was trapped in the $U$-dips. Under the action of this mechanism, the heavy material is removed from the rising field lines, which are therefore free to emerge into the outer solar atmosphere (figure 3). Moreover, the process of reconnection in the low atmosphere can explain some of the characteristics of Ellerman bombs, such as the local temperature and density enhancements and the existence of...
Figure 3. (a) Emergence of magnetic flux in a ‘sea-serpent’ configuration. Reconnection between neighbouring magnetic loops (shown by the blue and white field lines) leads to formation of new flux ropes that submerge carrying dense plasma. The unload of heavy material assists the further emergence of the magnetic loops into the corona. Arrows show the direction of the magnetic field vector. The vertical slice shows magnetic field strength (blue is strong, yellow is weak). (b) Close-up of the new magnetic flux rope (from the simulations by Archontis & Hood [85]). (Online version in colour.)

(bidirectional) plasma flows. The aforementioned experiments have indicated that the process of reconnection-driven emergence may account for the manifestation of EBs. However, one should not exclude the possibility that compression between magnetic fields could also lead to the occurrence of local conditions similar to those found in EBs. This is likely to occur in three-dimensional experiments [85] where the undular modes of the Parker instability develop into interchange-like modes for the magnetic field and there is a nonlinear dynamic coupling between fields emerging with different orientations from various sites. This produces a magnetic network of rising loops at the photosphere, over a range of temporal and spatial scales. The multi-scale emergence of flux across the atmosphere generates a series of interesting phenomena such as: (i) the formation of bright features at different atmospheric heights, (ii) the emission of plasma flows that may correspond to X-ray jets or Hα surges, depending on the physical properties of the ejecting plasma, and (iii) flux cancellation events at the low atmosphere and intensification of the magnetic field due to partial evacuation of the plasma.

4. Realistic experiments

To date, there has been a number of realistic numerical experiments, in the context of studies of quiet-Sun magnetic fields and emerging ARs. These experiments are realistic in the sense that radiative processes, for instance, are not ignored and the effect of fully developed convection is taken into account. Therefore, the dynamics and energetics of plasma between the solar interior and the ambient atmosphere can be described in a realistic manner, using, for example, synthetic magnetograms and continuum intensity images. In the following, we present a brief description of some key results arising from these simulations and a comparison with observations.

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(a) Photosphere: quiet-Sun magnetic fields

There are various theoretical scenarios for the nature of the quiet-Sun fields. One is the emergence of magnetic flux from the deep solar interior in the form of small-scale bipoles or with the shape of more extended horizontal fields in granules. Numerical simulations have been performed to test this scenario and their results will be discussed below. Another possibility is the action of a local dynamo driven by near-surface convective flows, which provides a clear dominance of the horizontal field in the photosphere [86,87]. The ratio between horizontal and vertical fields found in these simulations is comparable to the values reported by observations [88]. The appearance of ubiquitous horizontal field at the surface has also been confirmed by other dynamo simulations including a stratified atmosphere [89]. Moreover, MHD experiments have shown that, even when the initial subphotospheric magnetic field is vertical, the interaction with the convective motions creates relatively weak, horizontal field in granular and intergranular lanes [90]. The horizontal field adopts a less coherent structure than a flux tube and the associated field lines have a random connectivity below the surface. An alternative scenario is the recycling of flux from a decaying active or ephemeral region. It is possible that the background flux gets dragged down by convective downdrafts and then emerges again as it is caught by granular upflows. The aforementioned cases are not yet fully clarified. There are several advantages and disadvantages associated with each case. However, it is not unlikely that all the above mechanisms act as contributed sources of the internetwork flux.

(b) Photosphere: emerging flux regions and active regions

Radiative MHD simulations have been performed to study the effect of the near-surface convective motions on the emergence of magnetic flux at the photosphere. The first simulations in this series [91] used an initial TFT at 1.35 Mm underneath the surface with initial longitudinal flux up to $10^{19}$ Mx. Consideration of the force balance on the tube determines that, if the tube has a field strength $B_0 = (H_p/R_O)^{1/2} \times B_{eq} = 4600–9200$ G, it overcomes the drag force exerted by convective downflows; otherwise, it is passively advected by the flows. In the above expression, $H_p$ is the local pressure scale height, $R_O$ is the radius of the tube and $B_{eq}$ is the field strength at which the kinetic energy density of the local background plasma and the magnetic energy of the tube are in equipartition.

In the case of emerging fields with $B < B_O$, the upflows/downflows advect segments of the magnetic field so that it eventually adopts a ‘sea-serpent’ configuration. This suggests that the undulating configuration of the emerging field is due to interaction with granular convection [92]. The U-loops of the emerging undulating loops are dragged down into (new) intergranular lanes in decaying granules [93] and towards the subsurface layers [94]. The retraction of photospheric horizontal fields is followed by reconnection at the vertical segments of the U-loops, leading to formation of new flux ropes. It is suggested [93] that this mechanism may provide a possibility of recurrent formation of twisted flux tubes within the solar interior. The formation of new flux ropes in the solar interior, following the emergence of undulating magnetic fields, has previously been reported in idealized experiments [84,85].
On the other hand, if $B$ is strong enough to resist transformation by the convective motions, it can even modify the granulation pattern. In this case, the magnetic field undergoes a dynamic photospheric emergence and expansion. The emergence occurs preferentially within the interior of granules. The expansion drives horizontal outflows away from the emerging region, disturbing the pre-existing flow pattern. In general, the level of deformation depends on the properties of the emerging field, such as the buoyancy and the twist. After the initial emergence, a weak magnetic field is expelled into the network of intergranular downflow lanes by the diverging granular flows. Therefore, the magnetic field adopts the shape of emerging loops with their footpoints threading the intergranular lanes.

Some common results produced by the aforementioned simulations are as follows. (i) The arrangement of the surface field after the initial flux emergence resembles the ‘salt-and-pepper’ pattern of quiet-Sun magnetic fields. (ii) There are instances when flux concentrations of like polarities meet and appear to coalesce and cases with flux cancellation due to the encounter of opposite polarities. After coalescence, the resulting small-scale concentration becomes brighter. (iii) The appearance of stronger fields several granulation time scales after the initial flux emergence suggests that convective intensification operates.

A series of full MHD with non-grey, non-LTE radiative transfer and heat conduction experiments were performed and reported on the emergence from the solar interior into the corona [95]. In agreement with previous idealized experiments (see §3), they did not find any rigid emergence of the initial flux rope above the photosphere. As time goes on, the evolution proceeds as follows. At 200 km above the photosphere, the adiabatic expansion produces cooler, darker regions with the structure of granulation cells. The granular cells, where the flux tube emerges, become larger and darker as they expand. These large cells cool as their size increases, owing to both radiative losses and adiabatic expansion.

Hot bright network points, near the edges of the rising flux tube, are seen to be related to contraction of the fluid. These bright points in intensity are related to large vertical velocities, but also to the high temperatures of the surroundings, a large vertical vorticity and compression of material. The heating process for these bright points is clearly related to the high velocity convergence and high vorticity. Similar bright points are found at larger heights, up to 500 km above the photosphere, although with a larger horizontal extent. In general, their temperature is 500–1500 K more than the background plasma.

Another series of three-dimensional experiments have reported on the emergence of an untwisted horizontal magnetic flux with the same entropy as the background non-magnetized plasma [96]. The magnetic field was carried by upflows from a depth of 20 Mm underneath the solar surface. Similar to other experiments, the interaction with the convection creates $\Omega$- and U-loops from the initially horizontal field. A parametric study of the initial field strength revealed remarkable differences from the photospheric appearance of the emerging flux. Fields with a 10 kG strength show small magnetic buoyancy effects. They are basically advected by the convective flows reaching the surface in the typical fluid rise time. Fields with 20 kG experience stronger buoyancy and even modify the convective flows as they rise to the surface. In this case, there is enough magnetic flux that concentrates in large regions at the photosphere, with field strengths of about 2 kG at continuum optical depth unity. This pronounced concentration
of flux results in the formation of pores. On the other hand, the magnetic loops, which are formed as a result of the large buoyancy, emerge and form exceptionally large and hot granules at the photosphere. Therefore, there is a strong indication that magnetic fields cannot be as strong as 20 kG at 20 Mm depth except if they have lower entropy than the surrounding free plasma. New experiments are expected to be performed and demonstrate how these results depend on the initial conditions and choice of the parameters of the system. A thorough review on magneto-convection is given by Stein [96].

First results for the self-consistent formation of an AR with coherent spots have been reported in radiative MHD experiments of flux emergence [97]. A magnetic field with a semi-torus configuration is kinematically advected through the bottom numerical boundary, which is located at 7.5 Mm underneath the solar surface. The usual horizontal expansion spreads the field over a large area. First, small-scale magnetic elements appear at the surface. Eventually, these small-scale magnetic fragments coalesce into larger flux concentrations until they reach values of approximately $10^{19}$ Mx. Then, they appear as dark pores in intensity images. The dispersed fragments develop into compact features when excess mass is removed from the emerging structure. This is an important step during the spot’s formation. The mass is unloaded owing to draining of plasma and reconnection at the U-loops of a ‘sea-serpent’ emerging field. After the removal of mass, magnetic flux migrates into two concentrated trunks to form spots. The existence of coherent magnetic roots, which belong to the initial emerging field, underneath the surface also influences the dynamic evolution of the magnetic fragments at the surface, via the Lorentz force. These experiments have also reported on the magneto-convective nature of umbral dots, penumbral filaments and light bridges in sunspots. For a comprehensive review on sunspots and associated features, the reader is referred to the article by Rempel [98].

(c) Chromosphere

The evolution of the plasma in the chromosphere produces a variety of interesting features, such as cool patches, hot strands in between EFRs and a series of high-temperature points at the edges of the cool patches [93,95]. The cool plasma rises through the transition region and lower corona and lifts chromospheric plasma to heights of roughly 6 Mm. These cool, Lorentz force-driven bubbles are long lived with a temperature of approximately 2000 K in the chromosphere. Emission from the central parts of the flux tube dims successively at all heights of the atmosphere. Such successive dimming has been observed by the SOT and EIS instruments on board the Hinode spacecraft [99], for lines up to 1.2 MK. Each cool patch is associated with an anomalous granule at the surface. The low temperature is due to the initial adiabatic expansion of the field at the chromosphere. The expansion causes a significant decrease of density and temperature, which goes below the radiative equilibrium level. The entropy of the cool patches is much lower than the average entropy of the background plasma. The hot strands are formed by compression of the plasma at the sites between the cool patches. These are also sites where Joule dissipation can cause a gradual enhancement of temperature. There is no evidence of radiative heating. Their temperature is in the range 4000–6000 K. The high-temperature chromospheric
points are formed as a result of an increase in the entropy or as a result of the compression of plasma [93,95]. Further research is required for a more generic explanation of this local heating mechanism.

The issue of heating/cooling of emerging magnetic fields has also been studied on the basis of partial ionization [100]. To emerge into the solar corona, the magnetic field must pierce the partially ionized layers of the lower atmosphere. There, the ion-neutral collisions lead to an increased resistivity for currents flowing across magnetic field lines. In idealized experiments, the atmosphere is fully ionized, and the flux emergence leads to an unrealistic low-temperature region in the overlying hot corona. Including neutrals removes the low-temperature region and lifts less chromospheric plasma within the corona. Therefore, the inclusion of such a neutral layer is important in order to obtain the correct perpendicular current and the adequate temperature profile.

The interaction of the emerging flux with an ambient field leads to the formation of features with a dynamic evolution similar to that observed in type I spicules (i.e. parabolic height–time profiles, upward/downward motion at speeds approximately 10–30 km s\(^{-1}\)) [101]. In general, spicules found in these simulations have shorter lengths and smaller velocities when the pre-existing field is higher. These spicules are likely to be driven by magneto-acoustic shocks, which form when waves that are generated in the photosphere/lower chromosphere propagate through the chromosphere and develop into shocks because of the rapid drop in density with height. It is often found that a moderate dissipation of currents is the driving mechanism of these jet-like features. The magnetic energy release sources are found in the upper photosphere and lower chromosphere. In some cases, the spicules occur at the footpoints of pre-existing coronal loops, as a result of the interaction between the emerging flux and the ambient field. Therefore, some of these events might be related to magnetic field line reconnection, although spicules have been identified also in sites where reconnection of field lines is not favourable. Other possible processes that may cause the onset of spicules are: p-mode oscillations, collapsing granules and convective buffeting of flux concentrations.

\((d)\) Corona

In idealized experiments, shear flows along the PIL grow rapidly, providing a possible source of energy for the onset of large-scale coronal eruptions. A similar process has been found to occur in TFT experiments with a realistic convective envelope [94]. During the emergence of flux, shearing photospheric motions develop and extend into the corona with a magnitude of about 20 km s\(^{-1}\). It is not unlikely that shearing motions provide a mechanism that transfers the energy from the subphotospheric layers into the corona.

Preliminary results on the response of the magnetized corona on emerging fields have been reported in realistic experiments [95]. The magnetic field pierces the photosphere and eventually it starts reconnecting with the pre-existing magnetic field in the chromosphere/corona. It was found that the greater the amount of flux that enters the photosphere, the larger the Joule heating associated with reconnection. Joule heating is more pronounced at the boundaries of the cold magnetized volume that rises into the chromosphere and lower corona. Because of the interaction, the temperature in the corona may increase by about 1 MK,

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depending on the field strength of the ambient field. For stronger ambient fields, the increase is more pronounced and coronal lines, such as Fe XII or Fe XV, increase their intensity rapidly.

The reconnection between granular-scale emergence events and vertical magnetic concentrations in the lower atmosphere (e.g., chromosphere) may heat the local plasma, give rise to spicule-like jets and emit high-frequency waves that propagate into the corona [90]. These phenomena could be considered as probable candidates for the atmospheric heating and the acceleration of the solar wind.

5. Flux emergence in astrophysics

The emergence of magnetic flux is a fundamental astrophysical process and a possible driver of the observed, ubiquitous activity in astrophysical plasmas. In the case of the Sun, the solar magnetic fields emerge in the outer atmospheric layers, presumably under the action of the magnetic buoyancy instability, producing a plethora of dynamic phenomena as described in the previous sections. The processes of magnetic buoyancy instability and magnetic flux emergence have been considered in theoretical and numerical studies to explain observations of dynamic phenomena in various astrophysical objects. As an example, Parker [102] first applied the concept of the buoyancy instability to galactic discs and interstellar gas–magnetic field systems. In the following, we refer briefly to such cases.

Wide-field imaging in the galactic centre (as recorded by the galactic centre molecular cloud survey by the NANTEN 4 m telescope) has revealed huge loops of dense molecular gas with strong velocity dispersions [103]. There are large line-of-sight velocity gradients (approx. 30 km s$^{-1}$) along the loops and large velocity dispersions at their footpoints. These characteristics are typical features of solar magnetic loops formed by the emergence of buoyant magnetic fields. Therefore, although the physical properties of these galactic loops are different from the solar loops (e.g., they have a length of several hundred parsecs and width of approximately 30 pc, within approximately 1 kpc from the centre), the mechanism driving the rise of the loops in the two different environments appears to have similar characteristics.

Now, to explain the existence of the molecular loops one has to take into account that the presence of magnetic fields in the central hundred parsecs of the Milky Way is substantially stronger than elsewhere in the Galaxy. These magnetic fields have the potential to affect the dynamics and the motion of molecular gas. Based on these facts, numerical studies [103,104] have shown that the observed loops are the result of the Parker buoyancy instability, which occurs in the nuclear disc. Under the action of the instability, the magnetized gas develops into loops that have a nearly parallel or twisted magnetic field. This process is analogous to the formation of emerging solar loops, which originate from an undulating magnetic field. Similar numerical studies [105] have interpreted that the molecular loops emerge from low-temperature layers just like the dark filaments observed in H$_{\alpha}$ images of EFRs in the Sun. Other global MHD experiments [106] have shown that buoyantly rising magnetic loops can emerge from differentially rotating turbulent gas discs in a solar-like manner.
Another example is the launching of jets from magnetized accretion discs in various astrophysical objects. Three-dimensional MHD simulations in dynamo-active accretion discs have reported on the effect of the magnetic fields on the formation of jets (see Kato [107] and references therein). The existence and origin of large-scale magnetic fields in various astrophysical objects is not well understood yet. Therefore, they focused more on the effect of small-scale magnetic fields confined within the accretion disc. They found the natural emergence of dynamo-generated magnetic fields from the disc (the so-called magnetic tower) and also the formation of jets accelerated by the magnetic pressure force of the small-scale emerging fields. A similar process (i.e. the interaction between small-scale emerging loops or between emerging and pre-existing magnetic fields) has been repeatedly considered as a likely triggering of solar jets.

The idea of the magnetic buoyancy instability has been invoked to study the nonlinear evolution of magnetic fields in gas discs (e.g. accretion discs, galactic gas discs) via numerical simulations [108]. It has also been used to explain the origin of the hot, X-ray gas in the galactic halo. Experiments [109] have shown that magnetic loops inflate from the galactic disc after they become unstable to the Parker instability. Collision of the emerging magnetic loops with anti-parallel ambient magnetic fields leads to the formation of currents in the galactic halo. The onset of reconnection in these current sheets heats the gas quickly: a magnetic field of $B \approx 3\mu G$ can heat the gas to a temperature of about $10^6\text{K}$. In a similar manner, dissipation of energy via reconnection driven by flux emergence could be considered as a possible heating mechanism of the outer solar atmosphere.

6. Summary

In this review, we discussed the manifestation of magnetic flux emergence in the solar surface and the subsequent atmospheric response. Numerical experiments (idealized and realistic) and observations have revealed that a variety of phenomena occur, over a large range of spatial and temporal scales, at the solar surface and within the highly stratified atmosphere of the Sun. Such examples are the granular-scale emergence of magnetic flux to form the magnetic carpet and the large-scale emergence that results in the formation of ARs and coronal eruptions. Some of the major open questions and problems were highlighted in §2 and throughout this review. It is certain that we have made progress through theoretical considerations, numerical modelling and observational studies of the flux emergence process and the onset of associated phenomena (jets, eruptions of coronal flux ropes, etc.). Also, important advances have been achieved in understanding the various physical processes separately, but we are still missing an ultimate, extensive view of the atmospheric coupling as manifested via flux emergence.

To accomplish this, numerical experiments should be performed in numerical domains with (i) high enough resolution to capture granular and sub-granular scales, (ii) large physical horizontal size to study processes on AR scales, (iii) an extensive height range to capture the deep solar interior and the highly stratified solar atmosphere, and (iv) realistic treatment of thermodynamical processes (e.g. radiative transfer, heat conduction). Observations, on the other
hand, must continue to provide data with high temporal/spatial resolution. In addition, simultaneous recording of flux emergence at all atmospheric layers (including complementary measurements by spectroscopy and helioseismology) is required for a progressive study of this highly dynamic process. The combination of such advanced numerical models and observational methods is important and exciting and it is considered as one of the most challenging problems in modern solar physics.

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References

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