

# Magnetic Flux Emergence in the Sun

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**Abstract.** Space weather research is closely connected with the study of the solar magnetic activity. In the past years, many solar missions (e.g., YOHKOH, SOHO, TRACE, RHESSI) have provided outstanding observations, which have been used to improve our understanding of the structure and the dynamical evolution of solar magnetic fields. In addition, the newly launched solar missions (e.g., Hinode, STEREO) will study the interaction between the emerging magnetic field and the pre-existing field in the corona (increasing our understanding of the causes of solar variability) and they will also observe the three-dimensional evolution of solar eruptions as they leave the Sun and move into the interplanetary space.

One of the most important processes, responsible for many dynamical phenomena observed in the Sun, is the emergence of magnetic flux from the solar interior in active regions and the modification of the coronal magnetic field in response to the emergence. In fact, magnetic flux emergence might be responsible for the appearance of small-scale events (e.g., compact flares, plasmoids, active-region-associated X-ray brightenings) and large-scale events (e.g., X-class flares and CMEs), which are major drivers of space weather.

However, it is clear that the question of how exactly the magnetic fields rise through the convection zone of the Sun and emerge through the photosphere and chromosphere into the corona has still not been solved. It is believed that understanding the process of flux emergence is an important step towards the understanding of the initiation mechanism of eruptive events in the Sun, which is another topic of great debate.

This paper provides a brief review of the theory and the numerical models, which have been used to study the process of magnetic flux emergence into the outer atmosphere of the Sun. We underline the similarities and differences between these models, and we compare the basic features of the numerical results with observations. Finally, we review the recent progress and discuss what further developments are required in the models to best describe the essential physics in the process of flux emergence.

## 1. Introduction

Most of the solar activity is directly linked to the Sun's magnetic field. Indeed, observations have shown that the Sun's corona is highly structured, being threaded by a complex network of magnetic fields. Understanding the structure and the dynamic evolution of these fields is important because they are the building blocks of solar activity. It is believed that solar eruptive phenomena result from rapid changes in their structures and connections.

The current state of the theory of the formation of the Sun's magnetic field suggests that it is produced by dynamo action in the *tachocline*, an interface layer separating the convection zone from the radiative zone. Then, the dynamo-generated magnetic field is transported from the deep interior of the Sun to the surface by magnetic buoyancy [e.g., Parker, 1955], which may well be coupled with the convective motions [Parker, 1998]. Eventually, the buoyant magnetic fields rise through the convection zone, intersect the photosphere and create the observed sunspots and bipolar active regions [e.g., Zwaan, 1987]. The newly emerged bipolar active regions are called emerging flux regions (EFRs) [e.g., Zirin, 1970]. An extended review on the structure and dynamics of magnetic fields in the solar convection zone can be found in Fan [2004]. The properties of active regions in terms of the dynamics of magnetic flux tubes which emerge from the solar interior to the photosphere have been reviewed by Fisher *et al.* [2000].

Shortly after the appearance of flux at the photosphere, a system of bright loops appears in the EUV and X-ray detectors. Observations of large scale magnetic fields emerging into the corona have been identified by solar satellites in the 1990s (e.g., TRACE and SOHO). The coronal fields are normally outlined by plasma emitting in EUV or X-Rays. Figure 1. is a high resolution image of the Sun taken by the X-ray Telescope on Hinode satellite. This image shows the detailed structure of active region loops and X-Ray bright points, which are seen as concentrations of magnetic loops. The appearance of many brightenings indicate that solar activity occurs all over the Sun.

However, it is exceedingly difficult to measure coronal magnetic fields directly and, thus, we usually use the line-of-sight component of the magnetic field and vector magnetograms from photospheric measurements, to extrapolate the magnetic field in the corona. For the photosphere, direct measurements of the magnetic field, both by satellite instruments (like MDI) as well as ground-based detectors, yield a wealth of information. Vector magnetograms, in particular, permit the reconstruction of all three components of the magnetic field.

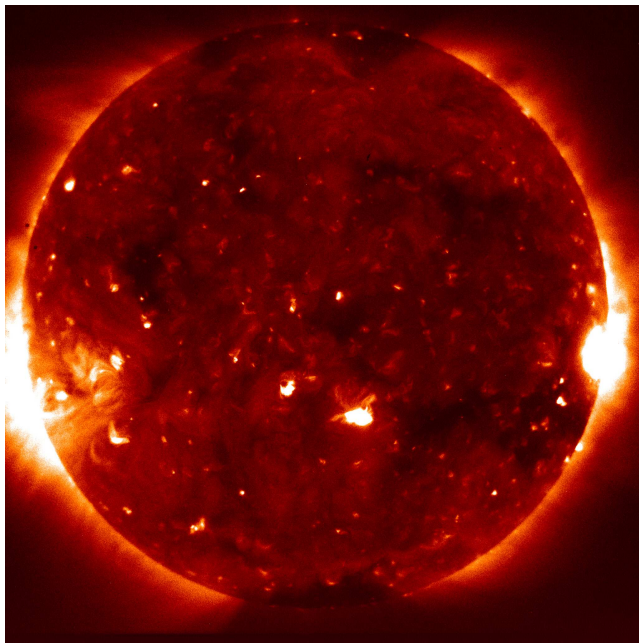
Schrijver *et al.* [2006] evaluated the performance of a series of numerical models, which simulate nonlinear force-free (NLFF) magnetic fields in the solar corona. The numerical experiments were performed using vector magnetic field measurements of active regions. It was found that the solution depends strongly on the implementation of the boundary conditions. The ultimate goal of this comparison between the numerical models is to find a robust method of measuring coronal free energy in solar active regions.

Another approach, which has been used to compute the large scale magnetic field configuration of the solar corona, is the potential field source surface (PFSS) models. These models are simple to develop and implement and they can also resolve larger scale structures than the current MHD models. On the other hand, they use idealized initial conditions and assumptions and they don't treat important processes (such as reconnection) properly. *Riley et al.* [2006] showed that PFSS models are useful tools for computing the large scale coronal field when time-dependent changes in the photospheric flux can be neglected. Also, they found that PFSS models produce similar results with the MHD models for configurations based on untwisted coronal fields.

Observations show that most of the coronal loops seem to join the opposite polarities of the new active regions, while others establish linkages to new active regions, probably through reconnection of magnetic field lines. Space observations from YOHKOH, SOHO and TRACE have revealed evidence of magnetic reconnection [*Martens*, 2003] in emerging flux regions, in flares and it is believed that reconnection could power solar explosions called Coronal Mass Ejections (CMEs). *Antiochos et al.* [1999] presented the first model (known as breakout model), which was consistent with many observational properties and the energy requirements for CMEs. In this model, CMEs are triggered due to reconnection between a sheared arcade and neighboring flux systems.

Eruptive phenomena, such as CMEs, flares and prominences can lead to solar and geomagnetic disturbances [*Taylor et al.*, 1997] and disrupt terrestrial satellites and power systems. Recent models have increased progress on space weather prediction. The warning of an explosive event from space weather on terrestrial and space systems can be provided (a few hours ahead) on the basis of observations of such events from spacecrafts. The exact impact, however, of the potential threat in the Sun-Earth environment requires further development of space weather models [*Brun*, 2007; *Cole*, 2003] and remains a great challenge.

X-Ray images from YOHKOH and vector magnetograms from ground-based observatories have shown the topology of



**Figure 1.** First-light image from the X-Ray telescope on board the Hinode satellite. Credit: The Japanese Aerospace Exploration Agency (JAXA).

growing bipoles in areas of new magnetic flux. The analysis of the proper motions of these bipoles indicates that the flux bundles that they make up the bipoles are twisted before they emerge [*Leka et al.*, 1996]. Measurements of the twist of the emerging flux systems have shown that the change of the twist is rather small during the emergence [*Wang and Abramenko*, 1999]. In addition, photospheric measurements of the vector magnetic field have shown that the mean twist in active regions is right-handed in the southern hemisphere and left-handed in the northern hemisphere [*Pevtsov et al.*, 2001]. Soft X-ray data from observations of active regions have repeatedly shown coronal loops with a bright forward or an inverse S shape. The structures with the forward S shape appear mostly in the southern hemisphere while the inverse S shape structures usually appear in the northern hemisphere. Their shape appears to be helical because their magnetic fields are twisted. Their central part is approximately aligned with the neutral line of the normal component of the magnetic field in the photosphere. Filaments, with a forward or an inverse S shape, may also be visible along the neutral line in sigmoid active regions [*Rust and Kumar*, 1994].

The above mentioned structures are called “sigmoids”. Using YOHKOH solar X-ray images, it has been shown that there is a relationship between structures with a sigmoidal shape and eruptions of flux ropes in the corona [*Sterling*, 2000; *Pevtsov*, 2002]. For example, CMEs appear to originate preferentially in regions of the Sun's corona that exhibit sigmoidal structures [*Canfield et al.*, 1999; *Canfield et al.*, 2000]. Although “sigmoids” play an important role in solar activity and their evolution is closely connected to space weather forecasting [*Sterling*, 2000; *Pevtsov*, 2002], the origin and the lifetime of “sigmoids” are still unknown.

Another interesting issue, closely connected with the study of flux emergence, is the actual structure of the solar magnetic field. Observations have shown that magnetic fields on the photosphere are intermittent and magnetic flux is predominantly concentrated in discrete areas with kilogauss field strengths [*Zwan*, 1987; *Keller and Hagenaar*, 2001; *Socas Navarro and Sanchez Almeida*, 2003]. Resolution is a crucial factor on how one interprets observations since the size of these areas changes from sunspots down to very small scales, which are difficult to resolve with the available observational facilities. In the past few years, many observations have shown that the observed field adopts the form of roundish and discrete flux tubes while recent high-resolution observations (i.e with the Swedish Solar Telescope on La Palma) show that the observed field has an intricate topology. Theoretical arguments support also the intermittent morphology of the photospheric and the subsurface magnetic fields, which are believed to be concentrated into discrete flux tubes. Numerical MHD simulations of magnetoconvection [*Galloway and Weiss*, 1981; *Nordlund et al.*, 1992] have shown that magnetic flux is concentrated in the intergranular lanes by convective motions. Eventually, the magnetic flux adopts the form of flux tubes, which are intensified because of stretching and twisting of their magnetic fieldlines by turbulent fluid motions. It is worthwhile to mention that, magnetoconvection simulations on granule and mesogranule scales in the upper part of the convection zone [*Steiner et al.*, 1998; *Weiss et al.*, 2002; *Stein and Nordlund*, 2006] have shown that the magnetic field lines of the flux tubes at the surface of the Sun are connected to various regimes, with a complex topology, below the surface and, thus, the concept of discrete flux tubes for the weak magnetic fields in the quiet Sun is not clear.

Although it appears that we do not have yet a complete picture of the topology of the magnetic field on or below the photosphere, the concept of isolated magnetic flux tubes has been used extensively over the past decade or so in numerical

experiments of flux emergence from the solar interior into the solar atmosphere. Most of the numerical models use, as initial configuration, a twisted flux tube or a flux sheet below the photosphere. Eventually, the initial flux system becomes unstable to perturbations or instabilities (i.e. the classical Parker buoyancy instability; [Parker, 1978]) and makes its way up through the solar interior developing an  $\Omega$ -loop shape. As the buoyant flux system rises, the top of the  $\Omega$ -loop structure intersects the photosphere and creates sunspots in bipolar regions. Finally, it emerges through the photosphere and chromosphere and expands into the corona. However, even in the simplest configuration, the above phenomenon is highly time-dependent, has a complex three-dimensional geometry and the timescales of the various processes involved are remarkably different in the subphotospheric layers and in the upper atmosphere of the Sun. Hence, numerical experiments are necessary to provide a first physical understanding of the flux emergence process. This paper provides a review of the results of these numerical experiments.

## 2. Emergence into a field-free corona

The emergence of buoyant magnetic flux systems from the convectively unstable solar interior into the higher levels of the atmosphere is still a largely unexplored research domain and has been a subject of vigorous research for the past three decades. In fact, the evolution of the rising flux systems occurs on the basis of the buoyancy instability experienced by the plasma above the photosphere. There has been much interest on the literature in the buoyant instabilities in magnetized and in non-magnetized plasmas (see the review by *Hughes and Proctor* [1998]). In the following, we first report on magnetic buoyancy instabilities in the framework of numerical MHD experiments of flux emergence, then on the issue of twisted flux tubes and finally on the dynamics of flux emergence.

### 2.1. Buoyant instabilities

A first series of numerical experiments were two-dimensional (2D) and explored the excitation of magnetic instabilities of a single flux system (tube or sheet) and its subsequent emergence into a *non-magnetized* corona. *Shibata et al.* [1989a], [1989b] performed 2D magnetohydrodynamic (MHD) experiments to study the non-linear evolution of the ‘‘Parker instability’’, which is a kind of ideal MHD instability driven by magnetic buoyancy. More precisely, they studied the undular mode  $\kappa \parallel \mathbf{B}$  of the magnetic buoyancy instability, where  $\kappa$  and  $\mathbf{B}$  are the wavenumber and the initial magnetic field vector, in an isolated horizontal flux sheet. The background stratified atmosphere in these experiments consisted of two unmagnetized isothermal layers as an simplified version of the Sun’s photosphere/chromosphere and the ambient corona with a higher temperature. Also, small velocity perturbations were initially imposed on the magnetic flux sheet to initiate the instability. They found that as soon as the instability develops the flux sheet rises as a result of enhanced magnetic buoyancy and eventually expands into the corona. The acceleration of the rising loop shows a self-similar behaviour in the low atmosphere. This self-similar solution reveals that the magnetic loop is accelerated by the magnetic pressure gradient force, which dominates the gravitational and the gas pressure gradient force. The results of these simulations were consistent with the observed small rise velocity of magnetic flux at the photospheric heights ( $v \leq 1 \text{ Km sec}^{-1}$ ) and with strong downdrafts ( $v \approx 1\text{-}3 \text{ km sec}^{-1}$ ) at the footpoints of the expanding magnetic loop, which may correspond to observed strong downdrafts near pores.

Simulations by *Kaisig et al.* [1990] included a convectively unstable layer below the photosphere. Then, vertical

velocity fluctuations in the *convection zone* and horizontal shear flows at photospheric heights were considered to study the evolution of the undular mode of magnetic buoyancy of a horizontal flux sheet. The results indicated that the imposed velocity fluctuations can destabilize the initial flux sheet, generating an upward-expanding magnetic loop, as long as it is located within or just above the *convection zone* but not if it is originally embedded in the higher atmosphere. They also calculated eigenfunctions for the linear and non-linear stability problem associated with the particular initial condition that they were using.

*Kusano, Moriyama and Miyoshi* [1998] investigated the Parker mode ( $\kappa \parallel \mathbf{B}$ ) and the interchange mode ( $\kappa \perp \mathbf{B}$ ) of magnetic buoyancy instabilities with the aim to understand the emerging mechanism of magnetic loops in the solar corona. They performed nonlinear, 2D simulations in a weak two-temperature atmosphere, which consisted of the chromosphere and corona. A sheared magnetic flux was initially embedded in the bottom of the chromosphere and random velocity perturbations were added into the equilibrium state to initiate the experiment. They found that if the field is sheared, a new instability could occur through the non-linear process of interchange instability, which leads to the formation of magnetic loops with a mushroom-like structure. Current sheets are formed in the central lower part of the magnetic loops and reconnection occurs. As a result of reconnection, magnetic bubbles are generated and eventually are detached from the original flux sheet and shortly after they rise into the upper atmosphere.

*Matsumoto et al.* [1993] used the same background stratification and similar initial conditions with the previous 2D numerical models, to study the nonlinear evolution of EFRs [e.g., *Zirin*, 1970]. On the other hand, they considered two different types of unperturbed magnetic flux system in the lower atmosphere: a horizontal magnetic flux sheet and a horizontal magnetic flux tube. They performed 3D MHD simulations and they found that the expansion laws, derived in the previous 2D models, are modified because in three-dimensions the expansion of the rising magnetized volume occurs also perpendicular to the fieldlines in two directions. They also found that the evolution of the EFR depends on the initial structure of the magnetic flux system. As an example, the rise velocity of the expanding magnetic loops obtained in these simulations was comparable to the observed rise velocity of arch filaments ( $\approx 10\text{-}15 \text{ Km sec}^{-1}$ ; [e.g., *Chou and Zirin*, 1988]) when the initial flux system is a flux sheet. On the other hand, the rise speed is too small when a magnetic flux tube is considered as the unperturbed magnetic flux system at the beginning of the simulation. Another interesting feature presented in this paper is the evolution of an initial flux system, which consists of a number of isolated flux tubes. In this model the flux tubes interact with each other as they rise and they finally merge into a bundle of expanding magnetic loops. Dense filaments are formed in between the expanding magnetic loops, as the plasma slides down along the outermost expanding fieldlines, with a width about 800 Km and a rise speed  $\approx 10 \text{ km sec}^{-1}$ .

Finally, *Archontis et al.* [2004] showed that over-dense flux can be transported into the atmosphere when the following criterion is satisfied [*Newcomb*, 1961; *Acheson*, 1979]:

$$-H_p \frac{\partial}{\partial z} (\log B) > -\frac{\gamma}{2} \beta \delta + \tilde{k}_{\parallel}^2 \left( 1 + \frac{\tilde{k}_{\perp}^2}{\tilde{k}_z^2} \right) \quad (1)$$

In the above criterion,  $H_p$  is the pressure scale-height,  $z$  is the height,  $B$  is the magnetic field strength,  $\gamma$  is the ratio of specific heats and the plasma- $\beta$  is the ratio of the gas

pressure over the magnetic pressure. There are also perturbations with wavevector  $\mathbf{k}$  (where  $k_{\parallel}$  and  $k_{\perp}$  are the horizontal components parallel and perpendicular to the magnetic field and  $k_z$  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.

A crucial term in the above criterion is the  $\beta\delta$  term. For an isothermal layer  $\delta = -0.4$ . Plasma- $\beta$ , on the other hand, becomes small as the magnetic pressure becomes larger than the gas pressure when the uppermost layers of the tube cross the photosphere. Thus, the right-hand side term in the above criterion becomes smaller than the left-hand side term and the instability is launched, carrying the magnetized plasma all the way up to the corona.

## 2.2. Twisted flux tubes

Observationally, there is evidence that the emerging flux bundles, which rise through the solar interior and create active regions at the photosphere, are twisted and have a coherent configuration during their rise (see Introduction). Also on theoretical grounds, numerical models in two dimensions have shown that an initial twist is required for a tube to retain its coherent structure as it rises through the convection zone. A non-twisted tube splits into a pair of vortex filaments rotating in opposite directions [e.g., *Schuessler*, 1979; *Longcope, Fisher and Arendt*, 1989]. The vortex filaments separate horizontally from each other, due to the buoyancy force on the mass elements of the vortex filaments, and eventually the rising motion of the buoyant tube turns into a horizontal expanding motion. On the other hand, if the flux tube is twisted by a sufficient amount then the magnetic tension of the twisted fieldlines can prevent the formation of vortex filaments and the tube rises as a rigid body through the convective envelope [e.g., *Moreno-Insertis and Emonet*, 1996; *Emonet and Moreno-Insertis*, 1998].

The pitch angle ( $\Psi$ ) of the twisted fieldlines around a horizontal magnetic flux tube has to be above a threshold, for the transverse field to be dynamically important. If the flux tube is, both in pressure balance and thermal equilibrium with its surroundings, it will be less dense than the external plasma (and therefore will rise) by a value of

$$\frac{\Delta\rho}{\rho} = \frac{(\rho - \rho_e)}{\rho} \approx -\frac{1}{\beta}, \quad (2)$$

where  $\rho$  is the density inside the tube and  $\rho_e$  is the density of the background atmosphere.

The pitch angle of the twisted field lines of such a tube has a threshold of order

$$\tan \Psi \geq \left(\frac{R}{H_p}\right)^{1/2} \quad (3)$$

where  $R$  is the radius of the tube and  $H_p$  is the local pressure scale height.

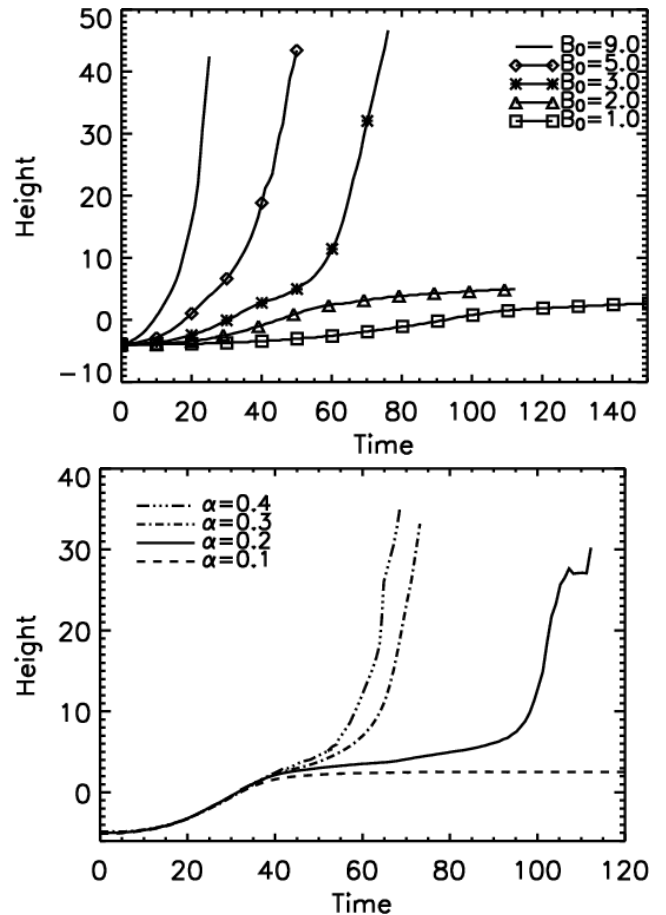
All the above models were two-dimensional. *Dorch and Nordlund* [1998] performed 3D simulations of buoyant magnetic flux tubes ascending through a solar convection zone model, and they showed that a weak random or twisting component is sufficient to make the tube rise as a coherent structure. If the initial flux tube has a non-trivial topology, the flux structure is held together for a long time and is able to keep most of its buoyancy. *Abbett et al.* [2000] found that the break-up of the flux tubes depends on the three-dimensional geometry of the problem. If the curvature of the upper part (apex) of an  $\Omega$ -loop is large, the degree of fragmentation of the loop as it reaches photospheric heights is small. Also, *Abbett et al.* [2001] described how a buoyant flux tube keeps its coherent structure under the action of the

Coriolis force. They also found that in the absence of forces due to convective motions, a magnetic flux tube with strong initial axial field strength will not be able to retain its cohesion. Finally, *Fan* [2001] performed 3D simulations of arched flux tubes, which were formed from a horizontal magnetic layer due to the non linear growth of the undular instability. It was found that the rising arching tubes maintained their coherent structure as they moved through a significant distance inside the computational volume. Thus, although there was no net twist in the tubes, they emerged through the convection zone without significant disruption of their shape.

## 2.3. Dynamics of flux emergence

The dynamical emergence of magnetic flux from the solar interior to the solar atmosphere is a big challenge in numerical simulations. Many numerical experiments have appeared in the literature during the past few years, which yield insights into the dynamics of flux emergence and the topology of the resulting structures. Most of the numerical models have used twisted flux tubes in the lower atmosphere as an initial unperturbed configuration for the magnetic field.

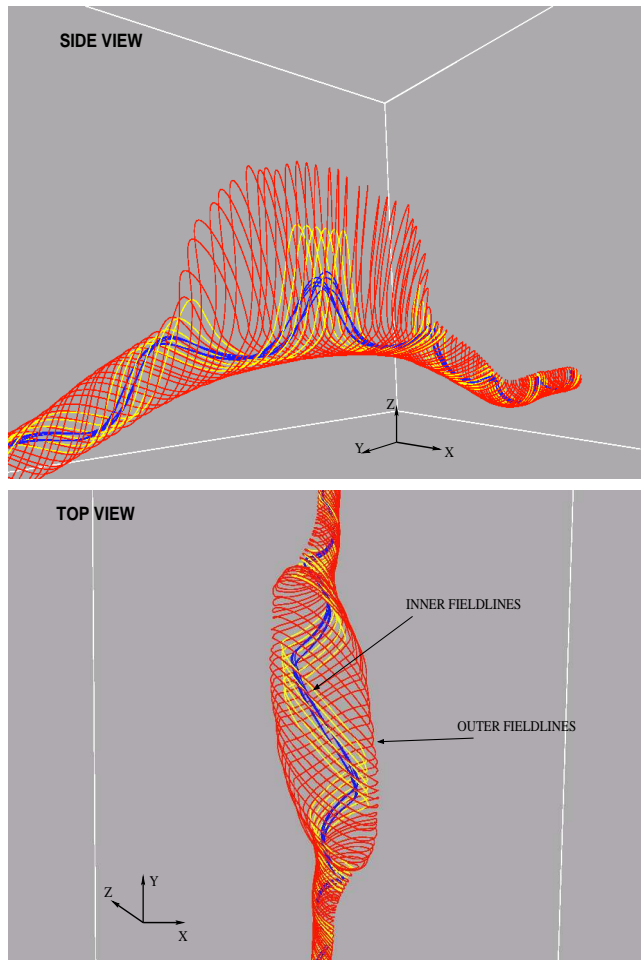
*Magara* [2001] investigated the emergence and expansion processes of a twisted flux tube by means of 2.5D MHD simulations. A highly stratified atmosphere was used, including a layer with increasing temperature with depth for the solar interior, an isothermal layer for the photosphere, a



**Figure 2.** **Top:** The motion of the top of the flux tube in time for different field strengths,  $B_0$ , and fixed twist,  $\alpha = 0.4$ . **Bottom:** Fixed initial field strength and different  $\alpha$ . For details, see *Murray et al.*[2006].

transition region and a high-temperature isothermal corona. Initially, the tube rises through the convection zone by magnetic buoyancy until it reaches the photosphere. However, the photosphere is strongly subadiabatic and, thus, the upper part of the tube slows down when it enters the low atmosphere. The tube is flattened and a contact surface is formed in between the rising tube and the lower atmosphere. Eventually, the Rayleigh-Taylor instability acts on this surface because dense plasma above the surface is located on top of lighter plasma, which is more magnetized. The tube emerges through the photosphere by the Rayleigh-Taylor instability and starts to expand due to the reduction of the background atmospheric gas pressure with height and because the magnetic pressure of the emerging tube becomes larger than the outside gas pressure. However, although the tube expands into the outer atmosphere the main axis of the tube stays at the base or just below the photosphere.

Recently, 3D MHD simulations have been carried out by *Murray et al.* [2006] with the aim to understand the role of twist and magnetic field strength in shaping the emergence process. It was found that when the value of the initial field strength,  $B_0$ , and twist,  $\alpha$ , is low the tube cannot fully emerge into the corona, but it stays in the lower atmosphere because the buoyancy instability criterion in equation (1) cannot be fulfilled. When the twist is fixed and the



**Figure 3.** **Top:** The outermost expanding fieldlines adopt a fan-like shape in the corona. **Bottom:** Fieldlines at lower heights inside the rising flux system are less twisted. The innermost fieldlines have an S-shape configuration.

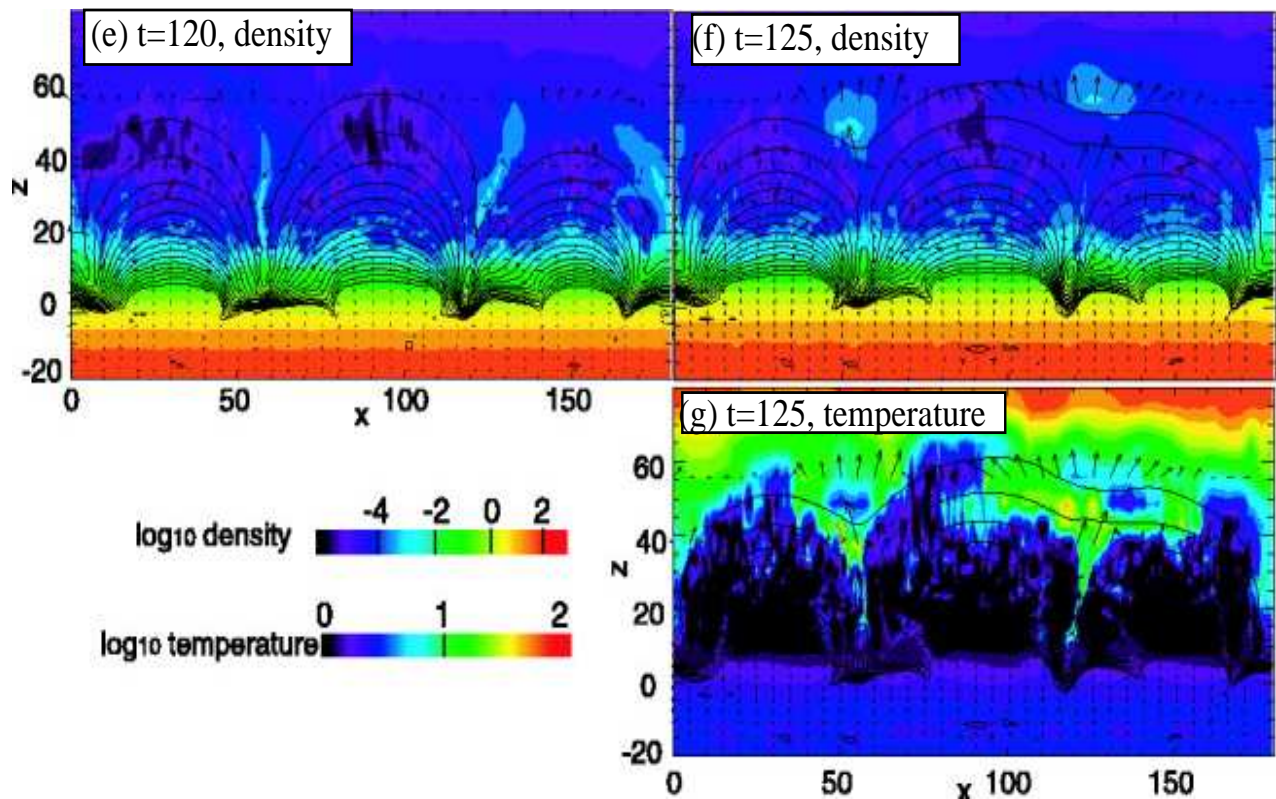
field strength is varied the tube experiences different magnitude of the buoyancy force, which is proportional to  $B_0^2$ . Thus, when the apex of the tube reaches the photosphere, it starts to rise into the upper atmosphere at different times (see Figure 2, top). When the field strength is fixed and the amount of twist is modified the tube rises with different configuration for each  $\alpha$  (see Figure 2, bottom). More precisely, if  $\alpha = 0.1$  the tube flattens out at photospheric heights. For  $\alpha = 0.2$  the tube emerges at two side locations because the draining of plasma from the upper part of the tube is more efficient at these locations. For larger values of twist the tube rises and expands into the corona adopting a dome-like structure. In addition, it has been found [e.g., *Magara*, 2007] that the expansion of an initially high twisted flux tube below the photosphere produces coronal loops with sigmoidal structure while a tube with a weak twist produces expanded coronal loops with no clear signature of sigmoidal structures.

*Fan* [2001] used a density deficit profile to initiate the rise of a flux tube from below the photosphere into the solar atmosphere. The tube is more buoyant at the middle than at the ends and evolves into an  $\Omega$ -shaped loop as it rises and expands in the atmosphere. At the beginning of the emergence a bipolar region is formed with a north-south orientation but later on the sunspots move towards an east-west orientation, parallel to the axis of the emerging tube. In fact, there is a shear horizontal velocity flow on the two sides of the neutral line, which agrees well with the observations of emerging active regions by *Strous* [1996] and was diagnosed as a shear Alfvén wave in the simulations by *Manchester* [2001].

The expansion of an emerging twisted flux tube into the higher levels of the atmosphere occurs in a runaway fashion. This is because the distribution of the magnetic pressure with height above the photosphere in the expanding volume of magnetized plasma is much larger than the gas pressure. The expansion takes place in all three directions: in fact, it expands faster in the horizontal directions than in the vertical directions [e.g., *Archontis et al.*, 2004]. Because of mass conservation, the fast rise and expansion of the upcoming field cause strong downflows along the periphery of the emerging fieldlines [e.g., *Fan*, 2001; *Magara and Longcope*, 2003; *Archontis et al.*, 2004].

The outermost fieldlines of the rising flux system adopts a fan-like shape as it expands into the higher levels of the atmosphere [e.g., *Fan*, 2001; *Magara*, 2001; *Archontis et al.*, 2004]. The inner fieldlines do not follow the same dynamical evolution and adopt shapes, which could appear as sigmoids in the solar corona [e.g., *Magara*, 2004]. Figure 3 shows the shape of different sets of fieldlines in a flux emergence experiment by *Archontis et al.* [2004]. It is worthwhile mentioning that, in most of the above referenced models, the fieldline on the main axis of the initial flux tube rises, but very slowly and, thus, does not really emerge into the corona. This is, probably, because the curvature of this fieldline is very small and the dense plasma does not drain sufficiently to make the buoyancy effects to lift up the axis of the tube. However, fieldlines that are initially located just above the main axis of the tube can emerge into the photosphere because their shape is such that enables the magnetic pressure force to lift them upward. In general, the fieldlines that emerge may be classified into two categories: expanding fieldlines and undulating fieldlines [e.g., *Magara and Longcope*, 2003]. Also, the outermost fieldlines become more twisted, than the inner fieldlines, as they expand and drive horizontal shearing motions in the low atmosphere that contribute to the ejection of magnetic energy and helicity to the outer atmosphere [e.g., *Magara and Longcope*, 2003].

*Abbett and Fisher* [2003] coupled a sub-surface model of an emerging flux tube to a three dimensional model corona. They first modeled the rise of a buoyant magnetic flux



**Figure 4.** Dense, cool material (panels e,f) is ejected together with hot plasma from the reconnection sites (panel g) in a flux emergence model by *Isobe, Tripathi and Archontis* [2007]. At the final stage of the experiment (panel g), reconnected fieldlines join all the individual emerging loops and rise into the outer solar atmosphere.

system in a stable stratified convection zone. Then, they used the time-dependent vector fields and scalar variables in the upper sub-photospheric boundary to drive a 3D model corona. The simulations showed that the time-dependent flows below the surface play a crucial role on the dynamic evolution and subsequent morphology of an emerging magnetic structure. At the beginning of the simulation, the magnetic field that surrounds the emerging system is not force-free. As the emergence proceeds and the vector fields at the photosphere evolve, the overlying magnetic field relaxes to a more force-free state. The development of models where high-resolution magnetograms of active regions will be used to drive dynamic models of the solar corona is an interesting future task.

Most of the MHD models described above do not include a realistic convection zone below the photosphere. A first attempt to include the cell-like convection structure in a flux emergence model was reported by *Amari, Luciani and Aly* [2005]. In this model, a twisted flux tube is kinematically raised by a convection cell in the convection zone and evolves in a full MHD way after its emergence into the corona. A photospheric layer is located in between the convection zone and the corona. The effective resistivity in this layer is larger than in the other two layers (resistivity layer model - RLM). It is shown that electric current and magnetic flux emerge through the resistive photospheric layer into the corona. The emergence of flux leads to an arcade-like configuration at the beginning of simulation, while later on the emerging flux evolves more rapidly adopting the shape of a flux rope.

Also, *Cheung et al.* [2007] modeled magnetic flux emergence in granular convection performing radiative MHD simulations. They showed that convection influences the evolution of the emerging fields before and after they reach photospheric heights. Sub-photospheric upflows can support the rising motion of some segments of the emerging tube while

downflows may suppress the emergence of other segments. It was also found that flux tubes with small longitudinal flux, are not highly buoyant and cannot rise coherently against the convective plasma motions. On the other hand, big flux tubes with large axial flux are able to rise and eventually emerge at the surface disturbing the granulation pattern due to their dynamical horizontal expansion.

*Leake and Arber* [2006] performed 2.5D MHD simulations to simulate the emergence of a twisted flux tube into the solar atmosphere taking into account two processes, which were not included in previous models: the partial ionisation of certain regions of the solar atmosphere and the thermal conduction as a heat transfer mechanism. It was found that when the dense plasma rises and expands into the atmosphere is heated to its original photospheric temperature rather than being cooled (adiabatic expansion). The inclusion of partially ionised plasma in the chromosphere yields more rapid emergence and expansion of the rising field and a greater amount of flux into the corona. An important question then is if the resulting coronal magnetic field is force-free. This is equivalent to say that the current is parallel to the magnetic field and there are no cross-field currents. It is found that when the magnetic field emerges through a partially ionised plasma, the majority of the cross-field current is destroyed, and thus the coronal magnetic field becomes force-free.

*Isobe, Tripathi and Archontis* [2007] used 2D simulations to study the emergence of a very long flux sheet from a superadiabatically stratified layer that represents the convection zone into the isothermal corona. A random velocity perturbation is given in the initial flux sheet to excite the Parker buoyancy instability. A number of loops are formed out of the current sheet. They rise, expand and eventually reconnect at the lower atmosphere. Temperature in the

reconnection outflows is enhanced compared to the background plasma. This may account for the manifestation of Ellerman bombs. During the rise of the loops, dense material is accumulated at the valleys between neighbouring loops. This dense plasma is squeezed because of expansion of the rising loops and creates elongated structures of cold and dense plasma, which eventually is ejected to the outer atmosphere because of reconnection between the loops. At the end of the experiment a very large loop of magnetic fieldlines is formed through successive reconnection of side-by-side emerging loops at different heights of the atmosphere (see Figure 4.). This process is similar to those in the “resistive emergence” model proposed on *Pariat et al.* [2004].

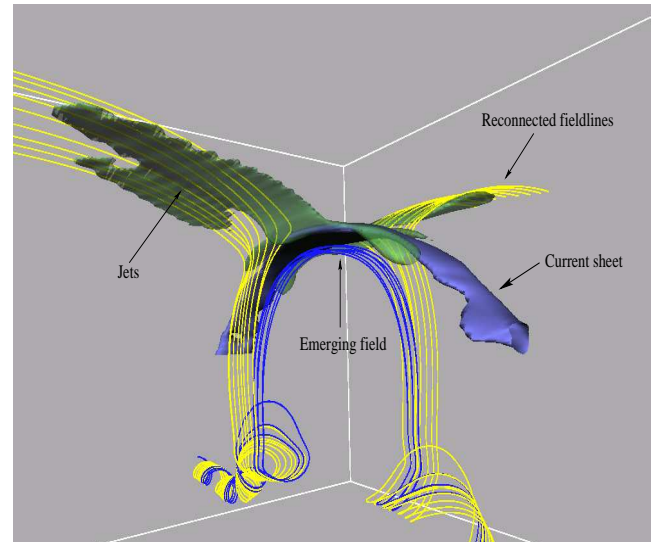
### 3. Emergence into a magnetized corona

Detailed observations of magnetic fields in and around active regions have shown that the emergence of new magnetic flux causes noticeable changes in the topology and geometry of the magnetic flux systems in the corona: first, by creating magnetic links to pre-existing magnetic fields [e.g., *Longcope et al.*, 2005] and second, by triggering the ejection of collimated, high velocity and high temperature outflows of plasma observed in soft X-rays by the YOHKOH satellite [*Shimojo et al.*, 1996; *Shimojo and Shibata*, 2000]. These processes (change of connectivity and emission of jets) can take place through magnetic fieldline reconnection whenever an upcoming and a pre-existing magnetic flux system come into contact. Reconnection is also responsible for significant localized energy release and the formation of a network of hot (with a temperature of few million degree Kelvin) plasma structures observed by the YOHKOH soft X-Ray telescope. Thus, it is very important to understand the dynamical interaction between emerging flux and pre-existing coronal magnetic field and numerical simulations could provide a physical understanding of the afore-mentioned process.

The first models, which studied the presence of a coronal magnetic field and the interaction with the emerging flux system were two-dimensional. *Shibata et al.* [1989] included a simple horizontal field in the corona and a horizontal magnetic flux sheet below the photosphere to simulate the emerging flux. Then, they performed a series of experiments changing the direction of the overlying field [*Yokoyama and Shibata*, 1995; *Yokoyama and Shibata*, 1996]. In the parallel-field case (where the direction of the ambient field is parallel to the direction of the uppermost fieldlines of the rising loop upon contact) the rise velocity of the buoyant loop is drastically suppressed, while in the antiparallel-field case reconnection occurs and the rising motion of the emerging loop does not slow down. In the latter case, multiple magnetic islands are created inside the current sheet, at the interface between the two flux systems. These magnetic islands are cool and dense structures, which were originally formed in the lower atmosphere but are carried up within the current sheet. Eventually, they are ejected sideways from the current sheet and they may be observed as  $H\alpha$  surges (cool jets). Also, the plasma behind the magnetic islands is heated by Joule dissipation to a few million degree Kelvin and is ejected along the reconnected fieldlines to both sides of the current sheet, creating a pair of hot jets. In the case of an oblique ambient field, one jet is ejected upward while the second one moves downward where it collides with smaller emerging loops, which have been formed from the original magnetic flux sheet below the photosphere, creating a fast MHD shock. The collision compresses the plasma and the temperature at the top of the loops increases. These hot loops may account for some observations of microflares or bright loops, which are found slightly shifted from the site of

the fast and hot outflows. In the case of a vertical coronal field the jets are emitted in the vertical direction. However, the general structure and topology around the emerging region is similar to the oblique-field case. The above numerical models reproduce some of the features presented in the emerging flux model for the solar flare phenomenon suggested by *Heyvaerts, Priest and Rust* [1977], the standard CSHKP model of solar flares (originally proposed by *Carmichael*, 1964; *Sturrock*, 1966; *Hirayama*, 1974 and *Kopp and Pneuman*, 1976) that explains their observable features on the basis of magnetic reconnection and the revision of the CSHKP model based on YOHKOH observations by *Shibata et al.* [1995].

The 3D interaction between an emerging magnetic flux tube and a large-scale horizontal coronal field was studied in a series of papers by *Archontis et al.* [2004], *Galsgaard et al.* [2005], *Archontis et al.* [2005], *Archontis et al.* [2006] and *Galsgaard et al.* [2007]. Experiments were performed with the direction of the horizontal ambient field being changed from parallel to antiparallel in steps of 45 degrees. In the antiparallel case, a dome-like current concentration is formed at the interface when the two magnetic flux systems come into contact. Eventually, the current surface concentrates into a curved sheet, which is contained in a vertical mid-plane that is rotated almost 5 degrees away from the initial axis of the flux tube. In fact, the midplane of the current arch is rotated by an angle that increases with the relative horizontal angle between the two flux systems into contact. At the initial stage of contact of the two systems the configuration of the magnetic field vector across the current sheet is similar to the classical 2D X-type configuration. However later on, the orientation of the field across the current sheet resembles a rotational discontinuity such that the magnetic field never goes through a null point. The above change in the profile of the magnetic field vector has important consequences for the reconnection, which occurs in a full 3D manner not only at the top of the interface but all along the current concentration. It was also found that magnetic fieldlines reconnect in a continuous fashion while they are linked to the diffusion region and that many fieldlines that belong initially to the rising flux tube may reconnect more than



**Figure 5.** The curved current sheet (blue), the high velocity outflows (green) and the reconnected fieldlines (yellow) in a 3D flux emergence experiment (*Archontis et al.*, 2005) where the emerging field reconnects with an ambient field with antiparallel orientation.

once (multiple reconnection events). As a result of the reconnection process, the domain below the photosphere and the coronal domain, which were not joint at the beginning of the experiments, become linked to each other through the reconnected fieldlines. In fact, almost 75% of the emerging flux becomes reconnected to the coronal field in the experiment with antiparallel magnetic flux systems.

The three-dimensional current arch is the region where the Joule dissipation has a significant impact on the heating of the plasma. It was found that the temperature in the antiparallel case could be as high as  $10^7 K$  but becomes lower for the cases that are not so favourable for effective reconnection. In any case, it is likely that current sheets, formed between emerging and ambient magnetic fields, may constitute a source of heating for the solar corona. Similar to the 2D models, the above 3D experiments showed that a pair of hot and high-velocity (with the peak velocities typically reaching the local Alfvén velocity) jets are emitted sideways from the current sheet (see Figure 5.) The jets do not look like horizontal thin layers (as in 2D models) but they are curved all along the sides of the current sheet.

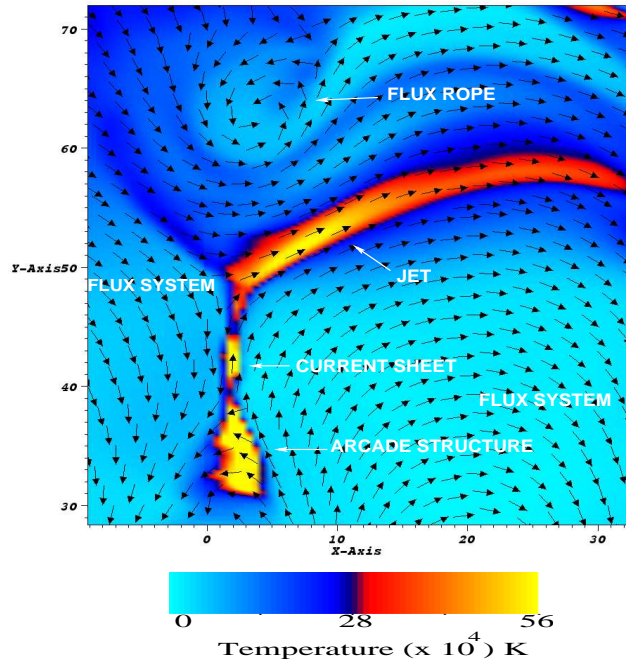
Finally, the formation and evolution of 3D plasmoids was investigated by *Archontis et al.* [2006]. The formation of the plasmoids was possibly due to the tearing mode instability. Two phases were apparent during the evolution of the system. In the first phase, the plasmoids had the shape of solenoids lying along the current sheet with their fieldlines connecting to the subphotospheric field or with the coronal field. At this stage, they are cool (of the order of  $10^4 K$ ) and dense and their velocity upon ejection is as high as  $15 \text{ Km sec}^{-1}$ . In the second phase, where the magnetic field across the current sheet undergoes through a rotational discontinuity, the fieldlines in the plasmoid become much less tightly wound. The plasmoids now confine hot (of the order of  $10^6 K$ ) and less dense plasma while they are ejected out of the current sheet with much higher speed ( $\approx 150 \text{ Km}$

$\text{sec}^{-1}$ ). The ejection of cool plasmoids may be compatible with observations of  $H\alpha$  or  $H\beta$  surges. It is also possible that the UV coil-like structures observed in filament eruptions may account for the appearance of helical flux strands at the second phase of the experiments. We should mention that the energy equation used in these experiments is adiabatic. Also, like other simulations, there is no radiative transfer or explicit coronal heating in the calculations. Yet, ohmic and viscous dissipation are included in the above mentioned experiments.

*Miyagoshi and Yokoyama* [2004] studied the emergence of a flux sheet, by simulating the undular mode of the magnetic buoyancy instability, into an antiparallel ambient field by means of 2D MHD simulations including heat conduction. They found that two different types of jets are formed around the emerging flux region: the classical reconnection jets which are formed because of reconnection between the two antiparallel flux systems and high-density evaporation jets. The basic mechanism for the formation of the evaporation jets is as follows: during reconnection, the magnetic energy is converted into thermal energy, which is transported to the chromosphere along the magnetic field lines by heat conduction. Chromospheric evaporation occurs and dense plasma rises along the reconnected magnetic field creating a secondary pair of jets. However, the temperature of these jets was found to be low because the cooling by conduction was more efficient than the heating by magnetic reconnection.

*Isobe et al.* [2005] performed 3D MHD simulations to study the interaction of an emerging flux sheet with an oblique ambient field. They found that thin current sheets and intermittent heating occurs at the interface between the two magnetic flux systems, as a result of the magnetic Rayleigh-Taylor instability. Dissipation of the filamentary current sheets leads to the heating of the plasma around dense filaments, forming a system of hot and cold loops. The Rayleigh-Taylor instability and the fast magnetic reconnection are coupled in a non-linear way, leading to intermittent, “patchy” reconnection. These results may explain the intermittent nature of coronal heating and the “patchy” brightenings in solar flares.

*Archontis, Hood and Brady* [2007] performed 2.5D MHD simulations of a pair of twisted flux tubes as they emerge from the subphotospheric layers into the solar corona. A key feature in this simulation is that the first flux tube emerges, expands and creates a non uniform (in strength and direction) coronal field that the second tube emerges into. A series of dynamical phenomena is produced by this model in a self-consistent manner. A current sheet, with an arch-like shape, is formed when the two systems start to interact. Plasmoids are formed inside the sheet because of resistive instabilities and when they are ejected out of the current arch they carry cool and dense material with them. As reconnection proceeds, the magnetic topology changes dramatically: there are now four different flux systems separated by a vertical current sheet, a configuration that has been extensively used as an initial condition in many models for studying flares and eruptions of filaments. Indeed, the general characteristics of the arcade structure below the vertical current sheet may account for a compact or an arcade flare associated with flux emergence. Also, hot plasma (jet) is ejected upward from the current sheet and is moving along the reconnected fieldlines at the top of the secondary emerging system (see Figure 6.) The temperature enhancement along the upper part of the secondary emerging flux system may account for a loop brightening.



**Figure 6.** Two flux systems come into contact. Eventually, a vertical current sheet is formed between them, a flux rope is ejected into the outer atmosphere and reconnection jets heat the arcade-like structure at the base of the current sheet and the top-loop of the emerging system on the right side of the current sheet.

#### 4. Flux emergence and eruptions

The emergence of magnetic flux from the solar interior to the high atmosphere of the Sun may be connected with

solar eruptions, such as flares, filaments and Coronal Mass Ejections. In fact, it has been shown [Sterling and Moore, 2005] that even small-scale emergence of flux can change the magnetic topology of a pre-existing active region and trigger an eruption.

Eruptions and powerful explosions (e.g., fast CMEs) is one of the basic topics of research in space weather physics. However, details about how these eruptions are triggered and propagate in the three-dimensional space are still unknown. For details about the theory and the models of CMEs the reader is referred to the reviews by Klimchuck [2001], Forbes *et al.* [2006] and Mikic and Lee [2006]. In the following, we outline results of numerical models that incorporate flux emergence to study eruptions of magnetic flux into the outer atmosphere of the Sun.

Chen and Shibata [2000] proposed an emerging flux trigger mechanism for CMEs using 2D MHD simulations. Their model consists of a quadrupolar field in a two-dimensional Cartesian plane. A detached flux rope is located above the quadrupolar field of the CME source. Two cases were studied. In the first case, magnetic flux emerges within the filament channel with direction opposite to the ambient coronal field, reconnection occurs below the detached flux rope that leads to partial magnetic cancellation and the rise of the flux rope because of loss of equilibrium. In the second case, the flux emerges at the right side outside of the filament channel. Reconnection first occurs between the emerging flux system and the outer fieldlines of the channel but it eventually proceeds in the internal layers of the filament system and, thus, it leads to the eruption of the flux rope similar to the first case. In both cases, a vertical current sheet is formed below the flux rope because of the reconnection between the emerging flux and the ambient field. The upward reconnection jet inside the filament channel pushes the flux rope towards the outer atmosphere while below the current sheet, a cusp-shaped structure with high temperature is formed. The fast ejection of the flux rope may account for a CME ejection while the cusp-shaped structure has the characteristics of LDE (long duration events) flares.

Shiota *et al.* [2005] used the same initial magnetic field configuration as Chen and Shibata [2000] but they also included the effect of heat conduction and discussed the differences. They found that the dynamical properties (such as velocity and magnetic fields) are very similar in the two models but the thermal properties (e.g., temperature, density) are different. For example, the temperature in the reconnection region and within the reconnection outflows becomes lower. Also, the current density at the X-point in the current sheet is larger and the width of the sheet is thinner. Also, they synthesized soft X-ray images from the density and temperature in the numerical results and compared them with YOHKOH observations. They showed the Y-shape of the slow shocks associated with the reconnection, the cusp-shaped arcades below the current sheet and the dimming above them, and a bright feature at the top of the arcades that may correspond to the backbone of flare arcades observed by YOHKOH. Dubey, van der Holst and Poedts [2006] extended the model of Chen and Shibata [2000] by including the effects of gravity, spherical geometry and a stratified ambient medium in 2.5D simulations. They also studied how the rate and the total amount of emerging flux affects the velocity of the resulting CME-like structure (flux rope). It was found that the latter factor plays a more crucial role and the obtained flux rope velocities achieve higher values. However, all these models cannot reproduce the ejection of very fast CMEs.

The emergence of a twisted magnetic flux tube into a pre-existing potential magnetic arcade in the corona has been investigated in the work by Fan and Gibson [2003], Gibson and Fan [2006] and Fan and Gibson [2006]. First, it was found that a strong electric current concentration with

an inverse-S shape is formed as the emerging tube develops substantial writhing as a result of the kink instability. The three-dimensional structure of the current is consistent with the shape of X-ray sigmoids. Another interesting result is that the emerging flux rope split into two parts during its eruption and interaction with the ambient field. One part is being expelled into the outer atmosphere while the other stays behind. Such a partial expulsion is consistent with observations of CMEs. The full eruption of a kink-unstable coronal magnetic flux rope, anchored in the photosphere, was also studied by Török and Kliem [2005]. Their results were in good agreement with the helical shape and the rise profile of a very fast CME. They concluded that the helical kink instability of a flux rope may be the mechanism that triggers many solar eruptions.

Manchester *et al.* [2004] investigated how a part of a twisted flux rope can erupt into the corona. They used similar initial conditions with Fan and Gibson [2001] but they decreased the length of the buoyant section of the rising tube, so that the draining of the mass becomes more efficient. It was found that the magnetic fieldlines inside the expanding volume of the magnetized plasma are stretched as the tube rises and eventually reconnect forming an internal current sheet with an S-shape. Due to reconnection and to self-induced shearing motions in the lower atmosphere, the upper half of the flux rope is detached from the lower half and erupts into the corona. The general evolution of the above system is consistent, at least qualitatively, with observations of CMEs in which X-ray sigmoids may appear after the onset of the eruption.

## 5. Discussion and Conclusions

Some of the most intense episodes of the Sun's activity are related to the dynamic process of magnetic flux emergence from the solar interior into the low-density solar corona. Over the past few years, numerical models of flux emergence have been used to study and explain some of the observed properties of solar active regions and eruptive events. In fact, some of the experiments have been quite successful in reproducing, mostly in a qualitative manner, the appearance and evolution of bipolar regions in the photosphere, the formation of sigmoidal structures strongly reminiscent of the X-ray sigmoids observed in the Sun, the morphology of the magnetic fields in solar coronal loops, the interaction between neighboring emerging flux systems, the ejection of plasmoids and cool ( $H\alpha$  surges) and hot (X-ray reconnection) outflows from sites of strong current concentration, small scale brightening events in the lower atmosphere (e.g., Ellerman bombs), the formation of flares (arcade flares, compact flares, etc.) and finally the eruption of magnetic flux ropes (e.g., CMEs) in the outer atmosphere of the Sun, which are very important components of the Space Weather system. Thus, the results of these numerical experiments help us to construct a better picture of the solar magnetic activity and the agreement between numerical experiments and observations is very promising, but there is much that remains to be done and there is still much to learn about flux emergence and eruptions in the Sun.

During the past few years, there has been a significant number of observations with increased resolution but there is still no complete understanding of: first, the physics behind the process of magnetic flux emergence from the deep solar interior to the outer solar atmosphere and second, how the emerging field interacts with preexisting magnetic structures leading to dynamical ejections of plasma and eruptions of flux. The evolution of such systems constitute a very intricate problem (given the large range of length and time scales, temperature, etc. involved in the process of flux emergence)

and, thus, observations are expected to provide us with information of selected aspects, which then have to fit together to build up a consistent physical picture of flux emergence in a complete manner. Progress will most likely be achieved by the new Solar mission of Hinode, which will take amazing high-resolution observations providing detailed description of the small-scale element and the large-scale magnetic field distribution and their interactions.

On the other hand, there are theoretical difficulties since many numerical models are idealized. For example, the choice of the initial conditions in the majority of the experiments is not strictly in agreement with what has been shown about the evolution of the magnetic fields in *realistic* convection zone models. Also, there are problems if the initial entropy distribution below the photosphere is not well defined, as it influences the buoyancy and the emergence of the magnetic flux system to the photosphere. In addition, the coupling between convection and small-scale flux emergence into the corona has not been investigated so far.

One of the major limitations of the 3D simulations of flux emergence into the atmosphere is the lack of an adequate description of the thermal behaviour of the system. Most of the existing simulations have assumed an adiabatic energy equation (ohmic and viscous dissipation terms are usually included) and this means that the rapid expansion into the corona is accompanied by rapid adiabatic cooling of the emerging plasma. This is not observed on the Sun and, thus, additional physics must be included to model the energy equation (e.g., radiative transfer in photosphere and chromosphere). In the corona, thermal conduction is a dominant term in the energy balance and field-aligned thermal conductivity must be also included along with optically thin radiation.

Also, emergence of magnetic flux within active regions is often associated with flares and CMEs, but there is no generally accepted explanation, so far, of how the magnetic field is stressed in the corona and what the triggering processes are for the onset of the eruptions. Also, there is no definitive modelling (including realistic geometry, kinetic effects and description of the thermodynamics of the plasma) of their three-dimensional magnetic structure and evolution into the heliosphere. Thus, modeling a *realistic* CME and producing results that may be comparable with observations has not yet been achieved.

It is worthwhile to mention that a complete study of flux emergence in the solar atmosphere is a very fascinating and computationally challenging problem. It is indisputable that progress have gained through a series of numerical experiments that have investigated the various physical processes separately. We expect that the individual results will be combined and will lead to important advances about the nature and the dynamics of emerging flux systems in the near future. Finally, detailed global 3D numerical experiments using high performance computing and simultaneous high-resolution observations of the magnetic field structures at different heights of the solar atmosphere, are needed to advance our understanding further about the process of magnetic flux emergence and how it is associated with solar eruptions.

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