MAGNETIC FLUX EMERGENCE - I

Magnetic flux emergence corresponds to the mechanism leading to the **establishment of magnetized structures in the solar atmosphere**. The magnetic flux emergence is directly traced on the solar surface (in visible-white light) by the presence of dark, mainly round-shaped areas, called **sunspots**, surrounded by brighter regions called **plages**. Measurements of magnetic fields at the solar surface shows that sunspots tend to be grouped in pairs, one with positive and one with negative magnetic polarity. Such a group of sunspots forms what is called an **active region**. The occurrence of large-scale magnetic flux emergence follows the solar cycle periodicity and is governed by the **solar dynamo process**.

The solar surface is also covered by the so-called magnetic carpet with small magnetic bipoles scattered everywhere over the solar surface. These bipoles are due to the recycling of magnetic field by convection (granules and supergranules). This process is beyond the scope of the present discussion of magnetic flux emergence. This article deals with observable properties of magnetic field emergence in emerging flux regions (EFR) in the solar atmosphere and is complementary with the article on numerical simulations of magnetic field emergence.

Magnetic flux emergence is responsible for the formation of **sunspots** and active regions.

Observable properties of emerging flux regions

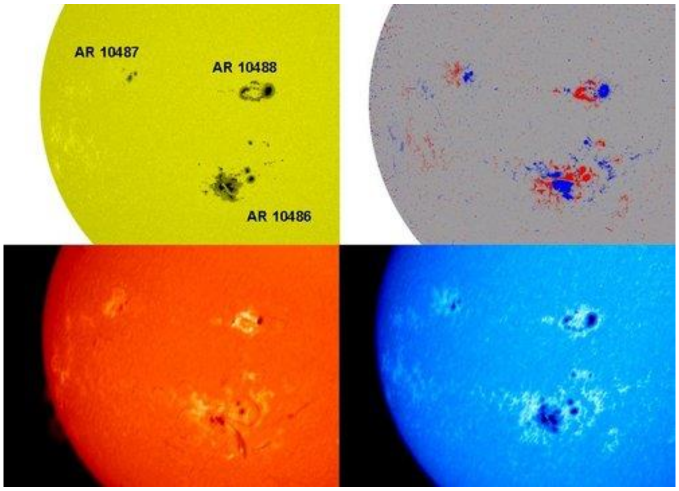

Figure 1: Typical examples of active regions in the solar atmosphere. The AR 10488 is an emerging stressed active region, the AR 10486 is a mature, fully developed and complex one, the AR 10487 is a simple bipole. The active regions

are observed at the photospheric level with sunspots (**top left panel**: white light image), at the chromospheric level with sunspots, plages, filaments (**bottom left panel**: Hα image; **bottom right panel**: Ca K1 image) and present an intense magnetic flux (**top right panel**: photosphere longitudinal magnetogram, blue (resp. red) code for positive (resp. negative) fields).

The birth of an active region is manifested by the appearance of **small magnetic bipoles** at the limit of the spatial resolution of present-day solar telescopes. The two opposite magnetic polarities of each bipole move apart at a relatively large speed (~5 km/s) in the initial phase and then slow down. New flux emerges continuously in the central part between the main polarities. The newly emerged magnetic polarities separate and reach the already emerged main polarities with high velocities: larger spots form by the coalescence of smaller magnetic elements. The growing phase of the EFR lasts about 3-5 days. The flux in an active region, for sunspots to be observed, is usually larger than 10^{21} Mx in each polarity.

During this growing phase, the distribution of the emerging magnetic polarities tends to adopt an ellipsoidal-shaped pattern (as AR 10488 in Figure 1). Progressively the leading sunspot and the trailing sunspot of opposite polarities grow and take on structure of a mature sunspot--a dark, circular umbra surrounded by a lighter penumbra with radial spokes. The line separating the two opposite polarities is called the magnetic field inversion line and has commonly a North-South direction, perpendicular to the generally East/West axis linking the center of the opposite magnetic polarities (for example AR 10487 in Figure 1). In some cases the magnetic inversion line is tilted and no longer perpendicular to the axis of the active region. In addition, some sunspots may rotate with an angular speed that can reach more than 1 degree per hour. Such sunspots display a characteristic pattern called **tongues**, with elongated magnetic areas oriented East-West, similar to an horizontal Taijitu (yin-yang) symbol: ☯ (see for example the active region of Figure 3). This pattern is due to the asymmetry of the azimuthal component of the magnetic field and traces the presence of twisted magnetic fields (see also Sect. 2.2. Such a configuration is favorable for major solar activity events, such as flares (central part of AR 10488 in Figure 1).

The distribution of sizes of active regions ranges from extended energetic active regions to the smallest ones called Ephemeral Active Regions that consist of tiny bipoles. All these regions can lead to powerful energy release that can contribute to coronal heating either by their strength or by their number.

The two following movies present examples of observed EFR.

- AR 8844 (gif; size: 7.3Mo)): Flux emergence observed with Flare Genesis Experiment [1] in January 2000.
- EFR within AR 10926 (avi; size: 8 Mo)): Flux emergence observed with Hinode/SOT in December 2006.

Emergence and solar activity

Origin of emergence

How does an active region appear on the solar surface? This question has intrigued many astronomers since the first telescopic observations of sunspots by Galileo in the early 17 th century. The generation of the solar atmospheric magnetic field lies deep below the solar surface between the convection zone and the radiative zone in a shell called the **tachocline** (located at about 0.7 solar radius). There, the differential rotation of the sun transforms part of the global kinetic energy of the solar rotation into magnetic energy by means of **solar dynamo** processes.Dynamo theory predicts that the intensity of the magnetic field in that region can reach 10^5 Gauss (~10 Tesla). Solar rotation stretches the magnetic field so that it adopts the shape of a torus in the tropical latitudes (royal zones) with stressed and twisted magnetic **flux tubes**. The triggering mechanism allowing the flux tubes to rise toward the solar surface is still unclear (buoyant instabilities may be involved, see review by Fan 2004) but it is generally accepted that the emergence process is driven by **buoyancy**. Buoyancy appears since the magnetic flux tubes, being in mechanical equilibrium with their surrounding environment but having a larger magnetic pressure, have a lower plasma density. This model is referred to as the Omega–shaped (concave) loop model of emergence (Zwaan et al. 1985). The sunspots are cross-sections of the emerging flux tubes with the solar surface (see Figure 1 and Figure 2).

Injection of magnetic energy and helicity

Associated with the injection of magnetic flux, the emerging process leads to the transfer of magnetic energy from the solar interior to the solar atmosphere. Indeed the emerging flux tube contains a significant amount of magnetic energy. This magnetic energy is the main source of energy in active regions and thus the main driver of solar activity. In a given emerging flux tube, the transported magnetic energy is all the more important as the magnetic field is far from its lowest energy state. An efficient way for magnetic flux tubes to carry a significant amount of energy is when the field lines are twisted or writhed, *i.e.* there is an important non-axial (mainly azimuthal) component of the magnetic flux. Every emerging flux tube forming an active region has a certain level of twist, and transports therefore magnetic energy. The level of twist/writhe in the emerging flux is quantified by the magnetic helicity. Magnetic helicity is transported from the solar interior into the solar atmosphere and is conserved during this process. Indirect signs of the twist of the emerging flux tubes can be observed as rotating sunspots and tongues. Actually, numerical simulations of magnetic field emergence have demonstrated that a minimum twist is necessary for flux tubes to conserve their integrity when rising through the convection zone.

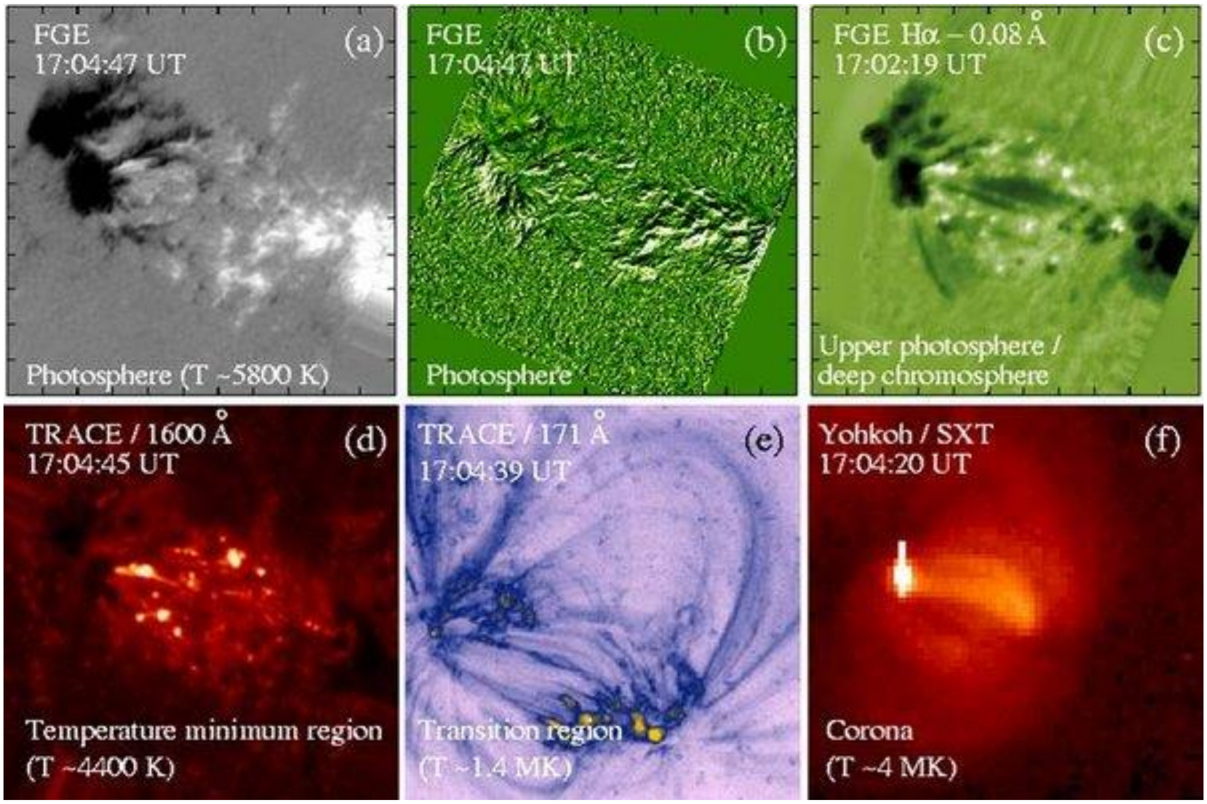

Figure 2: Multi-wavelength observations of an emerging active region observed on 25 January 2000 by FGE. **(a)**Vertical photospheric magnetic field (white is positive, black is negative magnetic polarity respectively). The magnetic field between the two main spots appears very fragmented. **(b)** Vertical component of the sheath current density calculated from the magnetic field vectors. **(c)** Off-band Hα filtergram showing EBs (Ellerman bombs as bright dots) and AFS (arch filament system as dark elongated structures), **(d)** deep chromosphere image with EBs. **(e)**EUV view of the transition

region showing coronal loops. **(f)** The soft X-ray emission from the overlying corona. Tick mark interval = 7250 km. The 6 images represent the same field of view (Adapted from Georgoulis et al. 2004and Schmieder et al. 2004).

Chromospheric and coronal heating

Coronal observations of active regions, in the UV or X-ray ranges, show the presence of **loops** joining the sunspots of opposite magnetic polarities, see Figure 2e and Figure 2f. These loops are bright in various wavelengths, from the extreme ultraviolet, corresponding to about 1 million K plasma (Figure2c), to the soft X-ray region (Figure 2f), which indicates the presence of four-million K plasma. They appear to have been formed independently (Schmieder et al. 2004). Many heating mechanisms have been invoked:turbulence, formation of current sheet above the new emerging flux, magnetic reconnection, etc., but there is no widely accepted model.
During the emergence, the evolution of the magnetic fields in the photosphere creates extremely complex patterns of strong vertical **electric currents**, see Figure 2b These electric current patterns clearly reveal the filamentary nature of the emerged magnetic fields, which induce a highly structured three-dimensional configuration of magnetic loops in the overlying solar corona.

Flaring activity

The magnetic emerging flux brings a great amount of magnetic energy to the surface. Extremely twisted/writhed flux tubes carry the most magnetic energy and helicity, and tend to give birth to very complex active regions (in terms of photospheric magnetic field distribution), which are the more likely to produce large flares.

In addition, by itself, the interaction of the emerging flux with pre-existing magnetic system leads to violent solar activity. Magnetic flux emergence triggers **flares, eruptions, surges, jets and coronal mass ejections(CMEs)** (Shibata et al. 1989). The magnetic energy is transformed into kinetic, thermal and non-thermal energy. Large-scale twisted emerging flux forming complex active regions with mixed polarities leads to large flares, small-scale emerging flux may also trigger important activity but that depends strongly on the environment of the emerging flux; the topology of the surrounding fields is a crucial factor.

The amount of magnetic energy and helicity in the emerging flux tubes and the link between the emerging flux and the size of flares and eruptions are key problems in present solar physics.

Obviously, observations of emerging photospheric magnetic fields are essential to our understanding of solar activity.

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