MAGNETIC FLUX EMERGENCE - II

Emergence-related Phenomena

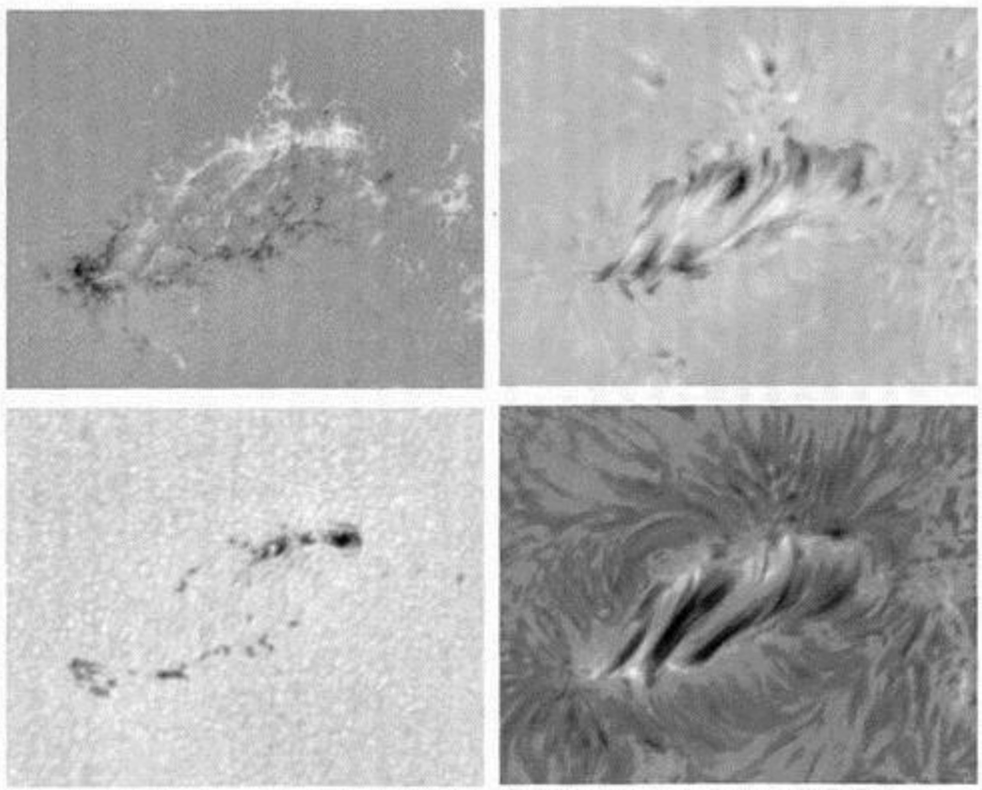

Figure 3: Multi-wavelength observations of an emerging active region, **top left**: magnetogram,**top right**: Dopplershift map, **bottom left**: continuum map, **bottom right**: Hα image with an Arch Filament System. Adapted from Strous et al. 1996

Plages, pores and photospheric transient darkenings

The first signature of the imminent birth of an active region is the appearance of plages. Plages consist of many compact and very bright features that can be observed in chromospheric spectral lines. In these lines, the area in and around the EFR appears brighter than the surrounding quiet-sun regions (see Figure 1, bottom panels, Hα and Ca lines). The plages tend to expand as the emergence proceeds and as the active region grows. Plages are the earlier emergence of magnetic tubes. Inside the magnetic elements, the magnetic pressure leads to a lower plasma density within the tube. When the flux tube are small (diameter < 600km), the deeper hotter layers are thus observed and the flux tubes therefore appear bright. When the flux tubes are getting larger and more intense (by coalescence of smaller flux tubes), convection is inhibited and the transport of heat gets less efficient as compared to the surroundings. These cooler structures appear as dark features in white light and are called pores. The subsequent coalescence of several pores leads to the formation of sunspots.

At the photospheric level, the granulation pattern tends to be modified compared to the quiet-sun. The granulation looks fuzzy and transient dark threads, corresponding to elongated intergranular lanes, can be observed in the continuum and in the core of photospheric lines, in the central part of the EFR (Strous et al. 1999). These transient darkenings have a lifetime of the order of 10 minutes. They are roughly aligned with the axis of the active region and are parallel to the direction of the arch filaments.

Arch Filament System

In the quasi-static phase, the emergence of flux in the chromosphere is characterized by the formation of low-lying dark filaments, called **Arch Filament System** (AFS), see Figure 2c and Figure 3. The solar plasma is compressed by the rising of new flux, and as it becomes denser, it flows down under gravity at both ends of the loops. Downflows are commonly observed at the footpoints of the AFS and up-flows around the apex of the loops (Malherbe et al. 1998, Strous et al. 1996). Typical physical parameters of AFS are the rising speed ~10 km/s, the plasma downflows ~20-50 km/s, the electron density 5-10x 10^{10} in cm^{-3}, the gas pressure 0.15-0.25 dyne cm^{-2}, the life time ~10-20 minutes and the magnetic field of the order of 50G.

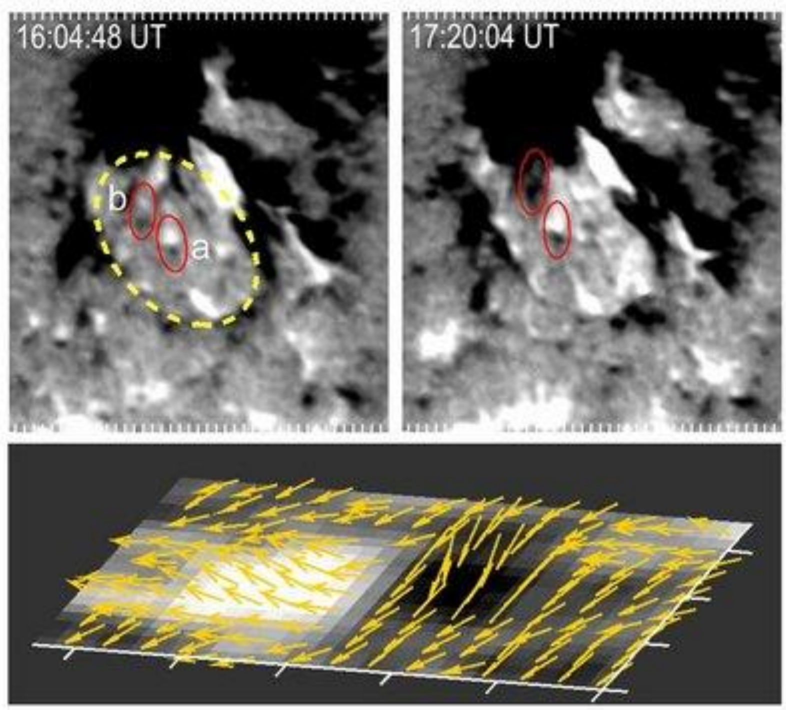

Figure 4: Examples of moving magnetic features (MMF) in a supergranule (**top panels**) and vector magnetic field measurement in a typical moving feature observed by FGE (**bottom panel**; Tick mark interval = 725 km). Adapted from Bernasconi et al. 2002.

Moving magnetic features

New emerging flux tubes are very **fragmented** with strong magnetic flux accumulations distributed to spatial scales at the limit of the spatial resolution of present-day instruments. The observations of the Flare Genesis Experiment's (FGE) launched in 2000 show magnetic structures of the order of its spatial resolution (~0.5 arcsec or ~360 km) (Figure 2a). Hinode/SOT with its better spatial resolution (~120 km) shows even smaller magnetic structures (Otsuji et al. 2007). High resolution observations of magnetic flux emergence reveal many small-scale moving magnetic features, called MMFs, with closely joined pairs of opposite polarities moving coherently (Figure 4). Because of their dipole character they are also referred to as Moving Dipole Features (MDF). They emerge in the center of large convection cells and quickly move as single units towards the cells' edges (~ 0.4 km/s) (Bernasconi et al. 2002). Furthermore, a close look at the direction of the magnetic field vectors clearly indicates that MMFs are **U-shaped (convex) magnetic loops** stitched into the upper photosphere and not the earlier observed Omega–shaped (concave) loops. MMFs look like little wiggling disturbances embedded in a sea of mostly horizontal magnetic field lines. And at the center of MMF poles, persistent flows of material are found downwards into the photosphere. All MMFs are remarkably similar in size, field strength and orientation of the vector magnetic field. This suggests they are formed by an instabilityin the fields that has a characteristic wavelength, in this case it is about 3000 km. These flows further distort the field lines, amplifying each concave depression in them. The bending of the field lines triggers further flow of material towards the center of each depression thus creating U-loops. Each newly formed MMF is swept by the horizontal outward flows within the convection cell towards the edge of the cell where finally the entrained material can slide down into the sunspot or the network.

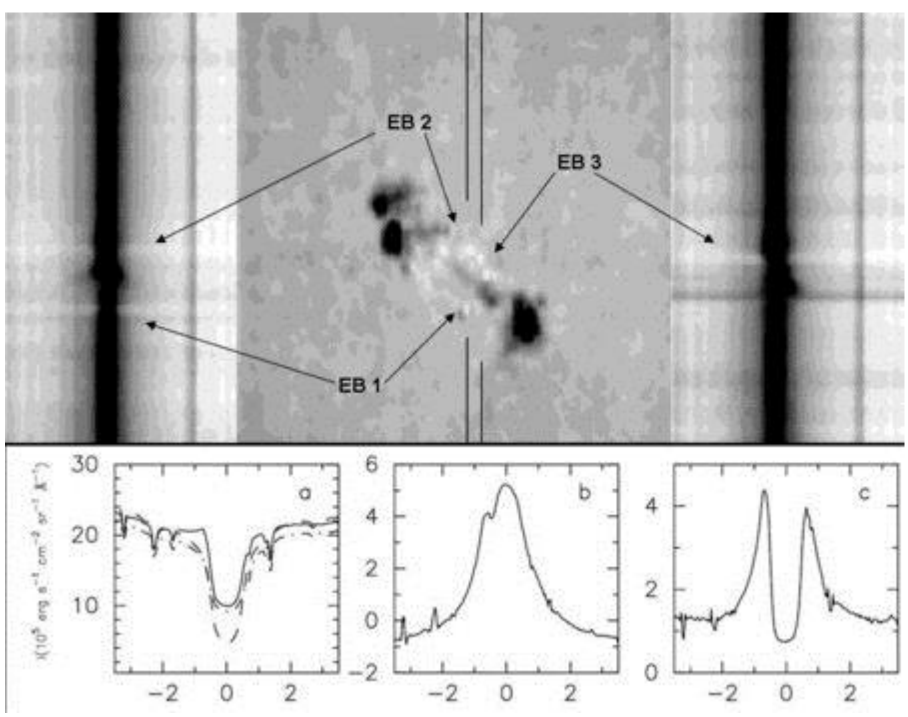

Figure 5: **Top panel:** Typical examples of Ellerman bombs Hα observations obtained with the Imaging Vector Magnetograph at Mees Solar Observatory (Courtesy of Labonté). Three example of Ellerman bombs (indicated as EB1, EB2 and EB3) are presented in an Hα image and in the corresponding spectra (on each side of the image; the spectra have been taken along the vertical dark lines). **Bottom panel:** Example of a high spectral resolution Hα spectrograph of an Ellerman bomb (left, continuous line); with the quiet sun Hα profile subtracted (center) ; with a neighbouring point profile subtracted (right); observed with the MTR mode of the telescope THEMIS (Fang et al. 2007).

Ellerman bombs

Ellerman bombs (EBs) are typical features observed in emerging flux regions. They are observed as**point-like brightenings** in the lower chromosphere (Figure 2c, Figure 2d). They were discovered byEllerman 1917, who called them *solar hydrogen bombs* at that time. They consist of brief emissions best observed in chromospheric lines (Hα, Ca II 8542 A) (Fang et al. 2006, Pariat et al. 2007). The profiles are characterized by a deep absorption at the line center and strong emission in the wings, see Figure 5. The EBs were called " moustaches" because of this peculiar appearance of spectra (Severny, 1958). Each bomb lasts about 10 minutes and may recur after half an hour or more. Detailed morphological and statistical analysis of the EBs show that they share the physics of **small solar flares**, obeying self-similar distribution functions in their total and peak released energies and their durations (Georgoulis et al. 2004). Typical energies of EBs were estimated in the range 10^{27}-10^{28} ergs, which is comparable to that of microflares. Large numbers of EBs could contribute significantly to the heating of the chromosphere in emerging active regions. EBs are manifestations of stochastic, low-altitude, **magnetic reconnection** in the solar atmosphere.

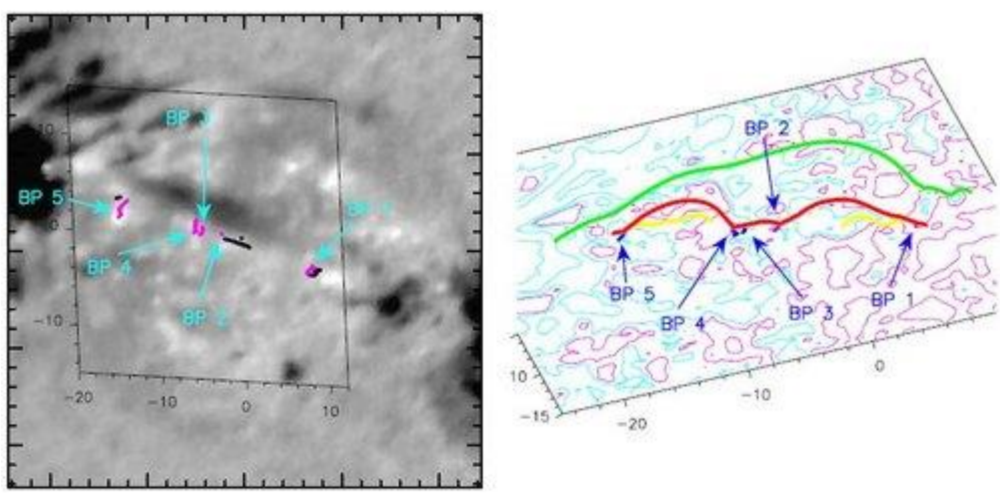

Figure 6: The complexity of magnetic flux emergence in the solar atmosphere. **Left panel**: Spatial correlation of Ellerman bombs observed by an FGE off-band Hα image (bright dots) and the loci of U-loops or Bald-Patches noted as BP (red dots). Bald Patches are areas where the magnetic field vector is tangent to the photospheric plane. **Right panel**: Detail of the magnetic flux emergence process showing a newly emerged magnetic field line (green) as well as an emerging line (red) going through

the five BPs corresponding to some EBs observed in Hα (in the left panel);. These lines come from a magnetic field extrapolation using the FGE photospheric magnetic field as boundary conditions (Adapted from Pariat et al. 2004).

Serpentine field lines

Theprevailing, traditional viewpoint of a smooth emergence of convex active region magnetic loops (Omega–shaped loops) into the solar atmosphere is fundamentally incomplete. This Omega-shaped loop model is valid for large scale emergence and in the mid term of the emergence which has a typical life time of a day. At the solar surface, the observed Omega–shaped loops are formed by the resistive emergence of undulatory flux ropes (Pariat et al. 2004). The upper parts of the emerging flux ropes are significantly deformed and decelerated when reaching the photosphere thus creating a large number of MDFs and localized concave emerging magnetic structures, see Figure 6 For these U – loops to fully emerge into the solar atmosphere the action of magnetic reconnection (via resistive effects, i.e., energy dissipation in electric currents) is necessary. EBs are the signature of the **resistive emergence of undulatory flux ropes** in the solar atmosphere.

Summary

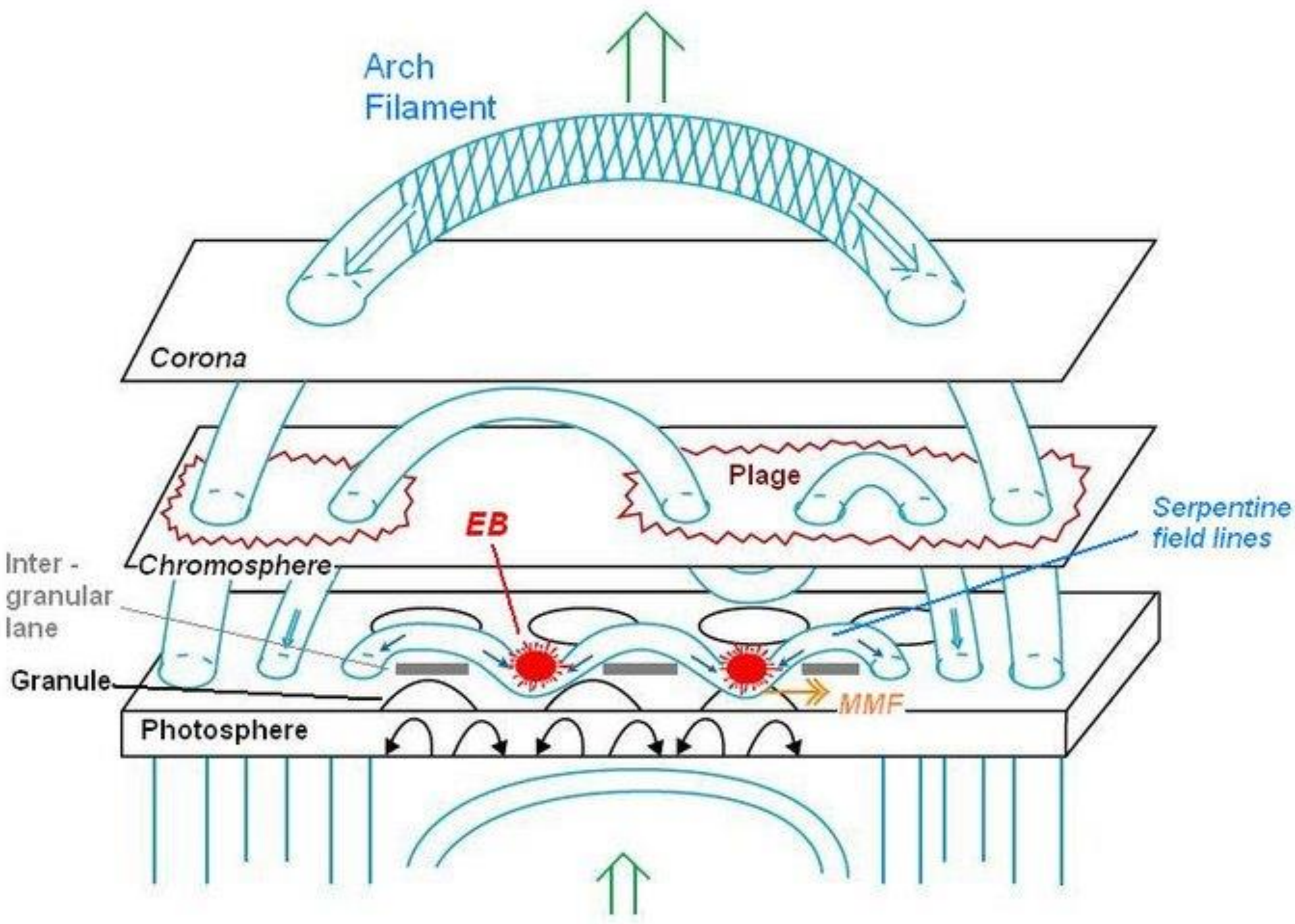

Figure 7: Sketch of the emergence of magnetic flux through the lower layers of the solar atmosphere and related phenomenae: pores/sunspots (located at the intersection of the flux tubes with the photosphere), moving magnetic features (MMF), plages, Ellerman bombs (EBs), arch filaments systems (AFS).

Magnetic flux emergence is an inherently complex process characterized by a significant fragmentation of the magnetic flux bundles. The filamentary nature of the emerged magnetic flux is the reason for this complexity. The signatures of emerging flux tubes are various and can be summarized in the sketch in Figure 7 presenting the evolution of an emerging tube from below the solar surface to the corona. It presents the relation between the different phenomena associated with flux emergence, such as plages, moving magnetic features (MMF), serpentine field lines, Ellerman bombs (EB) and arch filaments (AF). The several dispersed pieces of the flux emergence puzzle fit together into a coherent picture that reconciles flux emergence, magnetic reconnection, and heating in the solar atmosphere (Pariat et al. 2004).

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