Magnetic Flux Emergence in the Solar Photosphere

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Abstract. The most prominent magnetic structures on the surface of the Sun are bipolar active regions. These magnetic complexes are comprised of a hierarchy of magnetic structures of different sizes, the largest of which are sunspots. Observations indicate that the appearance of active regions on the solar surface result from the emergence of bundles of magnetic flux from the underlying convection zone. We study the emergence process by means of 3D radiation MHD simulations. In the simulations, an initially buoyant magnetic flux tube is introduced into the near-surface layers of the convection zone. Subject to the buoyancy force, the flux tube rises towards the photosphere. Our simulations highlight the importance of magneto-convection on the evolution of the magnetic flux tube. The external convective flow field has an important influence on the emergence morphology of the emerging magnetic field. Depending on the initial properties of the magnetic flux tube (e.g. field strength, twist, entropy etc.), flux emergence may lead to a disturbance of the local granulation pattern. The observational signatures associated with emerging magnetic flux in our simulations are in qualitative and quantitative agreement with observational studies of emerging flux regions on the Sun.

1. Introduction

Solar magnetic fields on the surface of Sun exist and evolve over a wide range of length- and time-scales. The most prominent magnetic features on the solar surface are sunspots. Sunspots do not reside on the solar surface as isolated magnetic structures in a non-magnetic background. Between the sunspot and the quiet Sun, there is a whole hierarchy of magnetic features including pores, micropores, chromospheric plages and faculae. An active region is an extended bipolar configuration on the solar surface resulting from the emergence of buoyant magnetic field that has risen through the convection zone (Parker 1955). The birth of active regions on the solar surface does not result from the emergence of a monolithic magnetic loop through the surface. Rather, flux appears at the surface as a collection of smaller bundles \( \Phi \sim 10^{19} \text{ Mx} \), Zwaan 1985). Once emerged, the magnetic flux in these bundles may coalesce into
larger entities, like the two polarities of an active region. The onset of the birth of an active region is characterized by the appearance of a compact and very bright plage. If sufficient flux has emerged, pores and possibly sunspots appear. These tend to be formed near the leading and following edges of the expanding plage (Zirin 1972; Zwaan 1985).

In this paper, we study magnetic flux emergence by means of numerical MHD simulations. Although a number of existing studies in the literature have addressed the topic of flux emergence, the main focus of those studies was on the dynamics of magnetic fields in the corona. Moreover, the effect of radiative heating/cooling and convection is typically ignored. In this study, our aim is to examine in detail the effects of (magneto-)convection and radiative energy exchange on emerging flux.

2. Simulation setup

Numerical simulations of solar near-surface convection has firmly established the surface granulation of the Sun as a radiative convection phenomenon (Nordlund 1985; Stein and Nordlund 1998). For a proper treatment of the dynamics in the near-surface layers of the convection zone and the photosphere, we need to take into account the following effects: radiative energy exchange, partial ionization on the equation of state and magnetoconvection. These effects are all treated by the MPS/University of Chicago Radiative MHD code (Vögler 2003; Vögler et al. 2005), which we used to perform a series of magnetic flux emergence simulations.

As a first step, the code was run to obtain a 3D, purely hydrodynamic (i.e. no magnetic fields) model of near-surface convection and the photosphere (see Cheung et al. 2007, for details on how we obtained the 3D hydrodynamic model). At the beginning of each flux emergence simulation, we introduced an initially horizontal, buoyant magnetic flux tube in subsurface layers of the domain. The longitudinal and transverse components of the magnetic field are respectively given by $B_l(r) = B_0 \exp\{-r^2/R_0^2\}$ and $B_\theta(r) = \lambda r B_l/R_0$, where $r \in [0, 2R_0]$ is the distance from the tube axis. The initial magnetic configuration is specified by three parameters: namely the initial field strength at the tube axis ($B_0$), the characteristic radius of the tube ($R_0$) and the dimensionless twist parameter $\lambda$.

The simulations reveal a richness in the complexity of photospheric magnetic fields that is interesting from both the MHD and the observational perspectives. Since it is not possible within the space of a few pages to convey all the results, we restrict our attention to the influence of magnetoconvection on the morphology of emerging magnetic flux.

3. Influence of magnetoconvection on emergence morphology

As a case study, let us first look at a simulation run with $B_0 = 2500$ G, $\lambda = 0.5$ and $R_0 = 200$ km. This field strength corresponds to an axial plasma-$\beta \sim 20$ (ratio of magnetic and gas pressures). The magnetically buoyant flux tube has a tendency to rise. Due to aerodynamic drag (Parker 1975), however, the upflows aid the rise of segments of the tube while the downflows try to suppress the rise of other segments (Fan et al. 2003).
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Figure 1. Emergence of a weak magnetic flux tube into the photosphere. *Left column:* time sequence of the emergent continuum intensity at 5000 Å, $I_{5000}$ with color contours indicating the vertical component of the magnetic field at $\tau_{5000} = 0$ with the levels $\pm[50, 100, 200, 400]$ G. Green (red) contours indicate magnetic upward (downward) directed field. *Right column:* the inclination angle of the surface magnetic field. An inclination $0^\circ$ ($180^\circ$) indicates upwards (downwards) directed vertical field.

The ability of the convective flows to influence the evolution of the flux tube can be measured in terms of the ratio of drag and buoyancy forces experienced by the tube. For this particular case, the drag exerted by the downflows clearly dominates the buoyancy force. As a result, segments of the tube aligned along downflows are kept submerged, whereas segments in the way of upflows are transported upward and eventually emerge at the surface (i.e. photosphere). The observational signature of the dynamical influence of convection on flux emergence is illustrated by the time sequences shown in Fig. 1. Clearly, magnetic flux emerges only within granule interiors.

The convective flow also controls the evolution of the field after emergence. As seen in Fig. 1, the emerged field is expelled to the intergranular boundaries on the order of the granulation timescale ($\sim 5$ min) after initial appearance. This behavior is in accordance with the well-known behavior of flux expulsion in magneto-convection studies (e.g. Weiss 1966) and with observations of small-
Figure 2. Appearance of a transient, elongated dark lane marking the emergence site \((y \sim 6 \text{ Mm})\) in a simulation run with a strong flux tube with high initial field strength \((B_0 = 8500 \text{ G})\). The grey shading represents the normalized emergent continuum intensity at \(t = 11.2 \text{ min}\). The yellow contours indicate magnetic upflows with speeds of \(v_z = 0.5 \text{ km s}^{-1}\) and \(1 \text{ km s}^{-1}\), respectively. This figure shows that the anomalous dark lane is co-incident with moderate upflowing material threaded by the emerging magnetic field.

scale flux emergence (De Pontieu 2002). Thereafter, the magnetic field is kept nearly vertical in the intergranular lanes. In case a magnetic flux structure meets another of like polarity, the two may coalesce to form a magnetic element with more flux. On the other hand, the meeting of flux elements of opposite polarity leads to flux cancellation.

In a separate simulation run, we began with a flux tube whose initial field strength was much higher \((B_0 = 8500 \text{ G}, \text{ other initial properties unchanged})\). In this case, the buoyancy and drag forces (the latter exerted by the downflows) are of comparable magnitude. This means that the downflows are still able to distort the shape of the flux tube, but it no longer completely controls the dynamics. In fact, the emergence of the magnetic tube in this case leads to a transient disturbance of the granulation pattern, as is shown in Fig. 2. Marking the emergence site of the tube \((y \sim 6 \text{ Mm})\) is the appearance of a somewhat incoherent, but elongated dark lane which has a lifetime of about 10 minutes. Here, unlike in the normal granulation pattern, the dark patches in this transient lane are coincident with upflowing material (which is threaded by magnetic fields). The transient appearance of elongated dark lanes aligned with upflows has been reported as a robust feature of many emerging flux regions (Zwaan 1985; Strous and Zwaan 1999). Our simulations indicate that this anomalous feature is a result of the overshooting of magnetic fluid into the stably stratified photosphere (see Cheung 2006, for more details).
4. Conclusions

Depending on the initial properties of a magnetic flux tube, its evolution may be passive with respect to the convective flow or may disturb the local granulation pattern. Since we treat radiative energy exchange in a realistic fashion, the observational signatures of emerging flux in our simulations are in agreement with observational results. The simulations, together with the new data coming from the Hinode mission, will allow us to study flux emergence on the solar surface in unprecedented detail.

To conclude this paper in a broader context, we expect the convective flow in the envelopes of active cool stars to have a similar effect on emerging flux as occurs on the Sun. Active regions on these stars probably develop as the result of the emergence of a collection of small bundles. Depending on the size and strengths of these bundles, the convective flow may dominate (at least influence) the emergence properties of magnetic flux. If one were able to make observations of the stellar surface at the scale of the surface granules, then one would likely find magnetic complexes structured on the scale of the granulation.

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References

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