EMERGENCE OF SMALL-SCALE MAGNETIC LOOPS IN THE QUIET-SUN INTERNETWORK

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ABSTRACT

We study the emergence of magnetic flux at very small spatial scales (less than 2") in the quiet-Sun internetwork. To this aim, a time series of spectropolarimetric maps was taken at disk center using the instrument SP/SOT on board Hinode. The LTE inversion of the full Stokes vector measured in the Fe i 6301 and 6302 Å lines allows us to retrieve the magnetic flux and topology in the region of study. In the example presented here, the magnetic flux emerges within a granular structure. The horizontal magnetic field appears prior to any significant amount of vertical field. As time goes on, the traces of the horizontal field disappear, while the vertical dipoles drift—carried by the plasma motions—toward the surrounding intergranular lanes. These events take place within typical granulation timescales.

Subject headings: Sun: magnetic fields — Sun: photosphere — techniques: polarimetric

1. INTRODUCTION

The magnetic flux emerges on many different spatial scales on the solar surface in the form of bipolar regions connected by magnetic loops. Timescales span from weeks (or even months) for tens-of-Mm active regions, to several minutes for very small scale magnetic structures at the resolution limit of modern solar telescopes.

The nature of internetwork (IN) magnetic fields is now being debated heatedly in solar physics. While some authors defend the idea of strong kG field strengths associated with small filling factors (see, e.g., Sánchez Almeida & Lites 2000; Domínguez Cerdeña et al. 2003), other work suggests the predominance of weak magnetic fields (Lin 1995; Lin & Rimmele 1999; Khomenko et al. 2003) in the range of 300–500 G. Manso Sainz et al. (2004) and Trujillo Bueno et al. (2004) have reported the detection of an ubiquitous unresolved turbulent magnetic field by measuring the Hanle effect in the scattering polarization signals of suitably chosen spectral lines. Regardless of their nature, the emergence of these small-scale IN magnetic fields is most likely related to the convection process underneath the photosphere (De Pontieu 2002; Cheung et al. 2007). The horizontal internetwork fields (HIFs) reported by Lites et al. (1996), with typical sizes of 1" and lifetimes of ~5 minutes, suggest that small magnetic loops are being advected toward the surface by the upward motion of the plasma inside the granules. If HIFs are indeed emerging flux, Lites et al. (1996) estimated that the rate of magnetic flux driven to the surface by this mechanism is greater than the rate of flux emergence in bipolar sunspot regions averaged over the whole solar cycle.

The measurement of the full topology of a magnetic loop requires accurate spectropolarimetric 2D maps of the four Stokes parameters, with high S/N, high spatial resolution, and consistent seeing conditions (Martínez González et al. 2007). The spectropolarimeter (SP; Lites et al. 2001) of the Solar Optical Telescope on board Hinode (Kosugi et al. 2007) meets all these requirements, and the space-based observations guarantee the total absence of seeing-induced cross-talk among the Stokes measurements.

Here we present clear evidence of the emergence of a small-scale IN magnetic loop in the quiet-Sun photosphere obtained from measurements performed with the SP on board Hinode. We followed the event in time from the moment it showed a measurable magnetic signal until it was fully emerged and developed.

2. OBSERVATIONS

The data presented here were obtained with Hinode’s SP on 2007 March 10. They are a part of a 5 hr long time series of spectropolarimetric maps (4" wide and 82" long) taken on the quiet-Sun disk center with a time cadence of ~2 minutes per map. Each map was constructed from 25 consecutive positions of the spectrograph slit, with an integration time of 4.8 s per position. The slit was set to scan westward at 0.16" per step, ending in a series of 4" wide maps with a spatial resolution of ~0.32". The spectral region measured by SP contains two photospheric Fe i lines (at 6301.5 and 6302.5 Å). The full Stokes (I, Q, U, and V) profiles were obtained for every position along the slit with a spectral sampling of 21.5 mÅ pixel$^{-1}$. The noise level in the continuum polarization of ~1.2 × 10$^{-3}I$, together with the high spatial resolution and the absence of seeing-induced crosstalk, makes it possible to detect the small-scale weak magnetic signals we are looking for.

In order to find flux emergence events in the quiet-Sun photosphere, we searched the time sequence of magnetograms (constructed from the information contained in the Stokes Q, U, and V profiles) for isolated regions of emerging flux within the
Fig. 1.—The $4' \times 4'$ box shown in four consecutive snapshots of the time series, separated by 125 s. The black and white background shows the granulation pattern measured by the integrated continuum intensity. Red, green, and orange contours represent positive circular, negative circular, and linear net polarization signals, respectively. The outer contour levels correspond to 3 $\sigma$ in the case of Stokes $V$ and 6 $\sigma$ for the net linear polarization. Note the clear spatial correlation between the emerging magnetic flux and the granule location.

IN, avoiding the persistent strong magnetic flux concentrations of the network areas.

Figure 1 shows an example of one of these events happening throughout four consecutive snapshots (separated in time by 125 s) of the data set in a $4' \times 4'$ box. The gray-scale background shows the integrated continuum intensity, which reveals the underlying photospheric granulation pattern. The over-plotted contours show the areas with nonnegligible polarization signals. While the orange contours show the net linear polarization signals [$\sqrt{Q^2 + U^2}$], the green and red ones represent the negative and positive circular polarization, respectively. In the first snapshot, the locations of all significant magnetic signals are contained within the intergranular regions, in agreement with the widely accepted picture of the magnetic flux tubes being advected to the intergranular lanes. In the second snapshot, a nonnegligible amount of linear polarization (horizontal magnetic field), flanked by two weak opposite polarity circular signals (vertical magnetic field), emerges from inside a granule in the center-left region of the box. This configuration is consistent with the topology of a small magnetic loop with

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Fig. 2.—Magnetic field properties of the region shown in Fig. 1. Time increases from left to right. The top and middle rows show the evolution of the apparent longitudinal and transverse magnetic flux densities, respectively (white contours delimit the granular-intergranular boundaries). The bottom row shows the magnetic field inclination (color-coded pixels) and its azimuth (arrows) yielded by the LTE inversions.
and the line-of-sight velocity were allowed to vary with four linear or circular polarization signals. While the temperature topology, we carried out full Stokes LTE inversions (with various assumptions (forcing the magnetic field to be constant with height or allowing for a linear variation, fixing the filling factor to 1 or allowing for a free amount of stray light) resulted in different values of the retrieved flux density, although the fitting performance of the code is comparable in all cases. For this reason we decided to compute the apparent longitudinal and transverse magnetic flux densities directly from the integrated polarization signals (without further model assumptions) as explained in Lites et al. (2007a), but we adopted the inversion results concerning the magnetic field topology (which remains consistent independently of the assumptions).

The top and middle rows of Figure 2 show the computed longitudinal and transverse apparent flux densities in the $4'' \times 4''$ box throughout the time sequence. The white contours delimit the granule-intergranule boundaries. The bottom row of Figure 2 represents the field orientation as retrieved by the LTE inversions, with color-coded pixels accounting for the inclination values and arrows showing the direction of the magnetic field azimuth. Although the 180$^\circ$ ambiguity is not resolved, the arrows were drawn to point toward the positive polarity. For $t = 0$ s (boxes in the first column) there is barely any magnetic signal in the center-left side of the box. Only 2 minutes later (second column), a new concentration of mostly horizontal magnetic flux appears. The magnetic field is parallel to the solar surface, and its azimuth makes an angle of $\sim 60^\circ$ with the east-west direction. In the third snapshot ($t = 250$ s), this magnetic “blob” has stretched in the linear direction and clearly developed into a loop-like structure, with two opposite magnetic poles connected by horizontal magnetic field. The total new longitudinal magnetic flux measured at the footpoints of this loop turns out to be $\sim 10^{13}$ Mx. In the last snapshot (6 minutes after the first one), the central part of the loop is not detectable anymore, but the vertical dipoles still remain visible, although they have drifted away toward the boundaries of the granule from which they emerged.

Due to the azimuth ambiguity there are two possible topology configurations (Fig. 3, sketches A and B) for the magnetic loop seen in the third column of Figure 2. If we consider the facts that the plasma motion is upward inside the granule (the spectral profiles are clearly blueshifted) and that the horizontal magnetic flux is the first to appear—followed by the vertical dipoles—the most likely picture in this particular case is the one presented in sketch B of Figure 3. We can understand the whole emergence event as follows: as the loop rises in the atmosphere, its top part reaches the surface before its footpoints can make it to the same level (see Fig. 3, sketch B). The expansion of the structure as it develops, together with the fact that it seems to be reaching higher layers in the atmosphere, makes the horizontal magnetic signal in the center of the loop undetectable to the Fe I lines at the end of the sequence.

![Fig. 3.—Possible magnetic field configurations due to the azimuth ambiguity. Horizontal parallel lines represent the solar surface. Sketch B represents the evolution of the most likely configuration, as the flux tube arises above the surface pulled by the upward granular plasma motions.](image)

its footpoints standing at each side of the region of linear polarization signal. Two minutes later, this structure becomes more developed, spanning over a direction that forms an angle of $\sim 60^\circ$ with respect to the horizontal axis (east-west direction) of the box. In the last snapshot we can see how the linear signal has disappeared while the remaining longitudinal magnetic flux has been swept toward the surrounding intergranular lanes, presumably driven by the horizontal plasma motions.

Note that the magnetic flux contained within the intergranules in the first snapshot is trapped there throughout the whole sequence. It is only the new emerging flux that appears cospatial with granule locations.

3. MAGNETIC FLUX DENSITY AND FIELD TOPOLOGY

In order to quantify the actual magnetic flux density and its topology, we carried out full Stokes LTE inversions (with LILIA; Socas Navarro 2001) of those pixels with nonnegligible linear or circular polarization signals. While the temperature and the line-of-sight velocity were allowed to vary with four and two nodes, respectively, the rest of the physical magnitudes were assumed constant during the inversion process. A fixed stray light profile (obtained from an average of nonmagnetic data profiles) accounted for the nonmagnetic atmospheric component.

Intrinsic field strength measurements in small-scale unresolved fields using the Fe I line pair can be rather uncertain for such weak concentrations (Martínez González et al. 2006), although Orozco Suárez et al. (2007) show that this seems to be a problem arising from poor spatial resolution. LTE inversions should give reliable values for the magnetic flux density. However, some of the polarization signals here are marginally above the noise level, and different trial inversions performed with various assumptions (forcing the magnetic field to be constant with height or allowing for a linear variation, fixing the filling factor to 1 or allowing for a free amount of stray light) resulted in different values of the retrieved flux density, although the fitting performance of the code is comparable in all cases. For this reason we decided to compute the apparent longitudinal and transverse magnetic flux densities directly from the integrated polarization signals (without further model assumptions) as explained in Lites et al. (2007a), but we adopted the inversion results concerning the magnetic field topology (which remains consistent independently of the assumptions).

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4. CONCLUSIONS

We present observational evidence for an emerging small-scale magnetic loop structure in the quiet-Sun disk center. For the first time, the full topology of an emerging magnetic loop in the quiet-Sun IN was followed in time from the moment it showed the first hints of a signal until it was fully developed. Magnetic flux emerges within a granular region, showing strong horizontal magnetic signal flanked by traces of two vertical opposite polarities on each side of it. As time goes by, the traces of the horizontal field disappear while the vertical dipoles drift—carried away by the plasma motions—toward the surrounding intergranular lanes, where they stay trapped for a while and aggregate to other magnetic field concentrations resulting in larger flux elements. This emergence event brings to the surface $\sim 10^{17}$ Mx of apparent longitudinal magnetic flux and does not seem to have any significant influence on the shape of the underlying granulation pattern. This is in agreement with the simulations presented in Cheung et al. (2007), where small-scale flux tubes with less than $10^{18}$ Mx of longitudinal flux are not sufficiently buoyant to rise coherently against the granulation and produce no visible disturbances in it.

From this example it seems that, although the flux emerges cospatial with a granule, the time that this small loop stays inside the granular structure is typically small (several minutes). The convective motions carry the vertical magnetic flux toward the intergranular lanes, where it stays confined for longer times. Similar studies on magnetic flux from remnant active regions (Ishikawa et al. 2007) point to the same conclusions. This could explain why the transverse magnetic flux observed at disk center is, in general, cospatial with granules while the longitudinal flux tends to be concentrated in the intergranular lanes (Lites et al. 2007b). This idea is also in agreement with Harvey et al. (2007), who showed that the seething horizontal fields they measured with the GONG network instruments and the vector spectromagnetograph of SOLIS (VSM) seem to be driven by granular and supergranular convection. According to these authors, the absence of longitudinal and latitudinal dependence on the full disk measurements favors the idea that these fields are created and destroyed by local processes.

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