HINODE OBSERVATIONS OF CHROMOSPHERIC BRIGHTENINGS IN THE CA II H LINE DURING SMALL-SCALE FLUX EMERGENCE EVENTS

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Abstract

Ca II H emission is a well-known indicator of magnetic activity in the Sun and other stars. It is also viewed as an important signature of chromospheric heating. However, the Ca II H line has not been used as a diagnostic of magnetic flux emergence from the solar interior. Here we report on Hinode observations of chromospheric Ca II H brightenings associated with a repeated, small-scale flux emergence event. We describe this process and investigate the evolution of the magnetic flux, G-band brightness, and Ca II H intensity in the emerging region. Our results suggest that energy is released in the chromosphere as a consequence of interactions between the emerging flux and the pre-existing magnetic field, in agreement with recent 3D numerical simulations.

Subject headings: Sun: activity — Sun: chromosphere — Sun: magnetic fields — Sun: photosphere

1. INTRODUCTION

Numerical simulations predict that magnetic flux emerging into the solar atmosphere interact and reconnect with the pre-existing chromospheric and coronal field. This suggests that flux emergence is a relevant source of energy for the chromosphere (Archontis et al. 2004, 2005). The efficiency of the interaction and the consequent heating seem to depend on the geometry of the two flux systems (Galsgaard et al. 2007). While at large scale these results have been confirmed by high-resolution observations (Moreno-Insertis et al. 2008; Zuccarello et al. 2008), the role of small-scale emergence events in the heating of the upper atmospheric layers, as described by Isobe et al. (2008), is still lacking observational confirmation.

In the absence of other diagnostics, heating events in the chromosphere can be detected through the intensity profiles of the Ca II H and K lines. The correlation between flux emergence and Ca II chromospheric emission was analyzed in detail by Balasubramaniam (2001), who observed anomalous profiles in the K line in an emerging active region. However, very few examples of small-scale transient Ca II brightenings have been reported in the literature, and most of them are related to flux cancellation events (e.g., Bellot Rubio & Beck 2005).

The Hinode satellite, with its unprecedented spatial resolution, offers for the first time the possibility of investigating the processes that occur in the chromosphere during the emergence of magnetic flux at small spatial scales. In this Letter we analyze simultaneous chromospheric and photospheric observations of an emerging flux region taken with the Solar Optical Telescope aboard Hinode. During the emergence event, strong brightenings were detected in the Ca II H line core without relevant counterparts in G-band intensity, which suggests that chromospheric heating did occur at the site of flux emergence.

2. OBSERVATIONS AND DATA REDUCTION

On 2007 September 30, as part of the Hinode Operation Plan 14 (Hinode/Canary Islands Campaign), the NOAA active region 10971 was observed by the Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board Hinode (Kosugi et al. 2007). The field of view (FoV) was centered at solar coordinates (174°, 11°) E, 11° away from disk center.

The SOT spectro-polarimeter (SP; Tsuneta et al. 2008) performed six raster scans of the active region from 08:00 to 14:00 UT; acquiring the Stokes I, Q, U, and V profiles of the photospheric Fe I lines at 630.15 and 630.25 nm. The FoV covered by the SP observations is 164′ × 164′, with an effective pixel size of 0.32′′ (Fast Map mode). Simultaneously, the SOT Broadband Filter Imager (BFI) acquired filtergrams in the core of the Ca II H line (396.85 ± 0.3 nm) and in the G band (430.5 ± 0.8 nm), while the Narrowband Filter Imager (NFI) obtained shuttered Stokes I and V filtergrams in the wings of the Na I D1 line at 589.6 nm. The BFI images have a spatial sampling of 0.05′′ pixels−1 (G band) and 0.1′′ pixels−1 (Ca II H), while that of the NFI filtergrams is 0.16′′ pixels−1. The BFI and NFI time series have a cadence of 1 minute and extend from 07:00 to 17:00 UT, with a small gap between 10:05 and 10:20 UT.

We have corrected the SOT/SP and SOT/FG images for dark current, flat field, and cosmic rays with standard SolarSoft routines. Besides obtaining photospheric and chromospheric information through corrected G-band and Ca II H filtergrams, we have constructed magnetograms from the Na I D1 Stokes I and V images acquired ±156 mA off the line center. From the ratio

\[ \frac{V}{I} = \frac{1}{2} \left( \frac{V_{\text{blue}}}{I_{\text{blue}}} + \frac{V_{\text{red}}}{I_{\text{red}}} \right) \]

we calculate the magnetic flux density \( \Phi_d \) using the weak-field approximation (Stix 2002) as

\[ \Phi_d = 8 \times 10^7 \frac{V}{I} \left( \text{Mx cm}^{-2} \right) \]

(see Guglielmino 2008). To first order, the magnetograms computed in this way are not affected by Doppler shifts. We remind the reader that, at disk center, the Na I D1 line refers to the upper photospheric layers and not to the chromosphere.

For each raster scan of the SP, the profile with the minimum total polarization degree, \( P = \left( Q^2 + U^2 + V^2 \right)^{1/2} \), was selected as a reference profile. All the spectra in the scan were normalized to the continuum of this profile and corrected for limb darkening. Also, a stray-light profile was computed by averaging the reference profiles of the six scans.
Fig. 1.—Vertical component of the magnetic field obtained from the Na i magnetograms at 07:50 UT, at the very beginning of the emergence event (FoV ∼ 60 × 60 Mm²). The square, with a FoV of 8 × 8 Mm², indicates the location of the emerging flux region analyzed in this Letter.

Adopting a grid paradigm, we have inverted the spectra with $P > 2\%$ using the SIR code (Ruiz Cobo & del Toro Iniesta 1992). The inversion yields the temperature stratification in the range $-4.0 < \log \tau_c < 0$ ($\tau_c$ is the optical depth of the continuum at 500 nm), together with the magnetic field strength, inclination, and azimuth angles in the line of sight (LOS) reference frame, the LOS velocity, and the magnetic filling factor, assuming that these quantities are constant with height. Azimuth and inclination angles have been transformed to the local solar frame, whereas the LOS velocity has been calibrated using the mean quiet-Sun intensity profile computed from pixels with $P < 0.5\%$, following the procedure of Martínez Pillet et al. (1997).

Finally, all the SOT/FG and SOT/SP images have been aligned through cross-correlation algorithms.

3. RESULTS

NOAA AR 10971 has a classical bipolar $\beta$ configuration, as can be seen in the Na i D1 magnetogram of Figure 1. The various SOT instruments recorded the emergence of a small bipolar region, which appeared at the internal edge of the main negative polarity. Figure 2 displays a temporal sequence of Na i D1 magnetograms with a cadence of about 20 minutes for the $8 \times 8$ Mm² area marked in Figure 1. The first magnetogram of the sequence, acquired at 07:50 UT, shows the presence of a positive-polarity knot. In the following magnetograms we clearly recognize an increase in its area, as well as the appearance of a negative-polarity patch. The subsequent evolution is characterized by the separation of the opposite magnetic polarities, as indicated by the arrows. The corresponding temporal sequence of Ca ii H filtergrams is also displayed in Figure 2 and shows transient brightness enhancements at the location of the positive footpoint. This emergence event led to the appearance of bright points in the G band (Fig. 3, left panel) and to intensity enhancements in the Ca ii H line core (Fig. 3, right panel).

Maps of the physical parameters derived from the SP raster scans are displayed in Figure 4. They demonstrate the rapid evolution of the small bipolar region: the changes in, e.g., the magnetic field distribution (second and third rows) indicate a very dynamic phase. The small bipolar region shows an emergence zone, i.e., a region between the two main polarities with horizontal fields (Lites et al. 1998), in which upflows of $\sim 1$ km s$^{-1}$ can be seen at 9:18 and 12:23 UT. The footpoints of the emerging region exhibit vertical fields and downflows of 1.5–2 km s$^{-1}$. The initial photospheric total flux content of the emerging region is $\sim 1.4 \times 10^{19}$ Mx, classifying as a small ephemeral region. The bipole axis was inclined about 45° to the north-south direction in the first raster scan, but this angle varied with time. The negative-polarity footpoint soon merged with the dominant negative flux of the active region, disappearing as an individual feature.

In this area we have detected chromospheric Ca ii H brightness enhancements with two main peaks during the observations, each one preceded by a minor peak. As can be seen in Figure 2, the brightenings are associated with the positive-
Fig. 3.—G-band (left) and Ca ii H (right) filtergrams (FoV ~ 80 × 80 Mm²) acquired simultaneously at the time of the second peak in Ca ii H brightness (12:41 UT). The squares have a FoV of 8 × 8 Mm². They contain a bright structure with a shape similar to that of the emerging region observed with the SOT/SP at 12:23 UT (see Fig. 4).

Fig. 4.—Evolution of physical parameters in the emerging flux region. From top to bottom: continuum intensity, magnetic field strength, inclination, and LOS velocity, as derived from the inversion of the SOT/SP scans. The FoV is 8 × 8 Mm², corresponding to the squares marked in Figs. 1 and 3. North is up and west to the right. The white background represents noninverted pixels. The emerging bipolar region is enclosed with a circle in the first scan. In the last row we show Ca ii H filtergrams, with reversed color scale. Vertical arrows indicate blueshifts, whereas horizontal arrows indicate the sites of chromospheric brightenings.
to the positive flux comes from the positive polarities of the emerging region. In Figure 6 we show the flux evolution with time: the chromospheric brightness enhancements clearly correspond to an increase of positive magnetic flux in the upper photosphere. Interestingly, in both cases the maximum Ca \textsc{ii} H intensities are reached some 30 minutes after the positive flux starts to increase.

Taking into account the temporal coincidence between the chromospheric brightenings and the positive flux increase, as well as the spatial coincidence between the location and morphology of the Ca \textsc{ii} H brightenings and the emerging bipolar region (Fig. 2; compare also the second, third, and fifth rows of Fig. 4), we conclude that the localized chromospheric heating is a consequence of the emergence and subsequent interaction of the positive flux of the new bipolar, which cancels with the negative ambient magnetic field.

4. CONCLUSIONS

Using \textit{Hinode} filtergrams and spectropolarimetric measurements, we have studied a small-scale flux emergence event.

Two peaks of chromospheric origin have been detected in the Ca \textsc{ii} H line-core intensity almost simultaneously to a magnetic flux increase in the upper photosphere.

We suggest that the chromospheric brightness enhancements may be indication that two different flux systems undergo magnetic reconnection: the old flux system belonging to the active region and the emerging magnetic field. The energy released in the process heats the chromosphere. The observed Ca \textsc{ii} H brightenings are associated with a relatively modest amount of emerged magnetic flux (only $\sim 4 \times 10^{18}$ Mx compared with the total negative flux in the region of $\sim 2.5 \times 10^{19}$ Mx), which points to a highly efficient heating mechanism. We conjecture that, while the positive flux increases, part of it cancels with the preexisting negative flux, very likely in a process of magnetic reconnection.

Our result suggests that Joule dissipation may be a significant source of chromospheric heating during the reconnection of an emerging flux system with a preexisting magnetic field. This would confirm the predictions of recent numerical simulations (e.g., Galsgaard et al. 2005), also at small scales. Moreover, our work suggests that Ca \textsc{ii} H brightness enhancements can be used as a valuable diagnostics of flux emergence. Further investigations should put this result into a firm observational and theoretical basis.

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