Evidence of quiet Sun chromospheric activity related to an emerging small-scale magnetic loop

P. Gömöry¹, H. Balthasar², and K. G. Puschmann²

¹ Astronomical Institute of the Slovak Academy of Sciences, SK05960 Tatranská Lomnica, Slovakia
e-mail: gomory@astro.sk
² Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, D14482 Potsdam, Germany
e-mail: hbalthasar@iaip.de, kgp@iaip.de

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ABSTRACT

Aims. We investigate the temporal evolution of magnetic flux emergence in the quiet Sun atmosphere close to disk center.

Methods. We combine high-resolution SoHO/MDI magnetograms with TRACE observations taken in the 1216 Å channel in order to analyze the temporal evolution of an emerging small-scale magnetic loop and its traces in the chromosphere.

Results. At first place, we find signatures of flux emergence very close to the edge of a supergranular network located at disk center. The new emerging flux appears first in the MDI magnetograms in form of an asymmetric bipolar element, i.e. the patch with negative polarity is roughly two-times weaker than the corresponding patch with opposite polarity. The average values of magnetic flux and magnetic flux densities reach \(1.6 \times 10^{18} \text{Mx}, -8.5 \times 10^{17} \text{Mx}\), and \(55 \text{Mx cm}^{-2}, -30 \text{Mx cm}^{-2}\), respectively. The spatial distance between the opposite polarity patches of the emerged feature increases from about \(2''\) to \(5''\) during the lifetime of the loop which was not longer than 36 min. A more precise lifetime-estimate of the feature was not possible because of a gap in the temporal sequence of the MDI magnetograms. The chromospheric response to the emerged magnetic dipole occurs \(-9\) minutes later with respect to the photospheric magnetograms. It consists of a quasi-periodic sequence of time-localized brightenings visible in the 1216 Å TRACE channel apparent for \(\sim 14\) minutes and being co-spatial with the axis connecting the two patches of opposite magnetic polarity.

Conclusions. We identify the observed event as a small-scale magnetic loop emerging at photospheric layers and subsequently rising up to the chromosphere. We discuss the possibility that the fluctuations detected in the chromospheric emission probably reflect magnetic field oscillations which propagate to the chromosphere in form of waves.

Key words. Sun: magnetic topology – Sun: surface magnetism – Sun: photosphere – Sun: chromosphere

1. Introduction

Magnetic structures emerging in form of small-scale loops in the quiet Sun atmosphere and associated dynamics have recently come to the center of attention. Systematic studies of these features became possible mainly through space-born observations acquired with a new generation of instruments like the spectro-polarimeter (SP; Lites et al. 2001) of the Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board the Japanese space mission Hinode (Kosugi et al. 2007) or the Imaging Magnetograph eXperiment (IMaX; Martínez Pillet et al. 2011) of the balloon-borne observatory SUNRISE (Solanki et al. 2010) as they provide extended time-series of data with very high spatial resolution which is needed for the loop detection (see e.g. works of Centeno et al. 2007; Martínez González & Bellot Rubio 2009; Ishikawa et al. 2010; Wiegelmann et al. 2010; Martínez González et al. 2010, 2011, 2012; Guglielmino et al. 2012; Orozco Suárez & Katsukawa 2012; Palacios et al. 2012; Vitič et al. 2012). However, Martínez González et al. (2007) and Gömöry et al. (2010) showed that also observations obtained with ground-based instruments which are equipped with an adaptive optics system [e.g., the German Vacuum Tower Telescope (VTT; Schröter et al. 1985) with the Kiepenheuer Adaptive Optic System (KAOS; von der Lühe et al. 2003)] are suitable to study processes related to small-scale loop emergence.

Small-scale loops represent a significant fraction of the magnetic flux in the quiet photosphere (Martínez González et al. 2007) and are thus important for a more complex description of the latter. Martínez González & Bellot Rubio (2009) performed an extensive statistical analysis of 69 emerging loops and found that 16 of these features even reach the transition between the upper photosphere and the lower chromosphere and that 10 of them can be seen yet in emission in Ca \(\text{II}\) H filtergrams. But, limitations in the used datasets did not allow them to identify any loop in the layers sampled by Hα emission. Such evidence was given by Yurchyshyn et al. (2010) who observed the trailing part of an active region and found that even a very small dipole (spatial extent of \(\sim 0.5''\)) can rise high enough and heat up sufficiently to be detected in the upper chromosphere where it exhibits significant activity.

These observational results support findings of Trujillo Bueno et al. (2004) who argued that the magnetic energy stored in the quiet photosphere is sufficient to balance the radiative losses of the chromosphere. Similar results were found by Ishikawa et al. (2008) for plage regions. Moreover, MHD simulations of Isobe et al. (2008) suggest that small-scale loops that emerge in the photosphere can really reach chromospheric heights and get reconnected with the local expanding vertical magnetic fields, thus heating the surrounding chromospheric plasma. All these facts assign an important role to small-scale magnetic loops in transport and dissipation of magnetic energy for heating the chromosphere. However, different mechanisms
To do so, several instruments have still to be affirmed, especially with respect to results showing a lack of total energy flux transported to the chromosphere by acoustic waves (Carlsson et al. 2007), although newer results obtained by Bello González et al. (2009, 2010) point out that the acoustic energy flux might have been underestimated in the past due to insufficient spatial resolution. In contrast, Beck et al. (2013a) suggest that magnetic heating processes are more important for the chromospheric energy balance than commonly assumed, when they compare photospheric magnetic fields obtained from spectro-polarimetric observations in the Fe I 630.25 nm line of the Polarimetric Littrow Spectrograph (POLIS; Beck et al. 2005) with results retrieved after the application of a recently developed LTE-inversion strategy (Beck et al. 2013b) on POLIS Ca H spectra.

However, while some simulations show that emerging loops can reach the chromosphere, simulations of magneto-convection by Stein & Nordlund (2006) predict that these loops should disintegrate as they rise through the lower solar atmosphere, thus an energy transport connected to these features should be implausible. Moreover, a large variety of chromospheric dynamics can be modeled with a wave-driven reconnection (e.g. De Pontieu et al. 2009). The latter could indicate that the small-scale emerging fields are at least not the only contributor to the chromospheric energy balance.

The discrepancies mentioned above do not allow to make any general conclusions in this research field so far, thus emphasizing the need of further observational studies. A complete understanding of magnetic flux emergence in quiet Sun could considerably improve not only our knowledge about the photosphere but also shed light on the problem of chromospheric heating.

In this work, we present a case study of an emerging small-scale loop that appeared close to a supergranular network boundary at the disk center and exhibited significant chromospheric activity.

2. Data and data reduction

The analyzed data-set was obtained within the Joint Observing Program JOP 171 which was performed during several days in the second half of October 2005. This observing program was dedicated to study properties of the quiet solar atmosphere from photospheric layers up to the corona. To do so, several instruments on board the Solar and Heliospheric Observatory (SoHO) and the Transition Region And Coronal Explorer (TRACE) were involved in the data acquisition process.

In this paper, we analyze a particular dataset of a quiet Sun region close to disk center obtained on 25 October 2005 between 13:17 and 13:56 UT. We focus on the time series of high resolution magnetograms from the Michelson Doppler Imager (MDI) on board SoHO (Scherrer et al. 1995) and TRACE (Handy et al. 1999a) filtergrams taken in the 1216 Å channel. Context images showing the common field of view (FoV) in all observations are displayed in Fig. 1.

The MDI longitudinal magnetograms have a FoV of 614′′×384′′ (1024×640 pixels). Their spatial resolution in the high-resolution observing mode was 1′′25 with a corresponding pixel size of 0′′6×0′′6. The instrumental detection threshold for the magnetic flux density is approximately 17 Mx cm−2 (Schrijver et al. 1997). Therefore, all pixels with a signal below this limit were excluded from further analysis. The magnetograms were taken with a regular 1 minute cadence, but their sequence was interrupted between 13:45 - 13:53 UT. All MDI data were downloaded already in the pre-processed form.

The TRACE data cover a FoV of 384′′×384′′ (768×768 pixels) with a spatial resolution of 1′′0 and a corresponding pixel size of 0′′5. The sequence of 1216 Å filtergrams was taken with a cadence of ~45 s which was interrupted several times by a cycle of exposures acquired in white-light, 1550 Å, 1600 Å, 171 Å, and 196 Å channels. These additional data were taken for context and co-ligment purposes. All raw images acquired by TRACE were corrected for instrumental effects (i.e. subtracting dark current and pedestal, correcting for exposure time, for radiation spikes and for saturated pixels) using the standard procedures included in the Solar Software (SSW) IDL routines provided by the TRACE team (Freeland & Handy 1998). The data were corrected also for solar rotation.

Note that the data acquired in the 1216 Å TRACE channel do not include only the desired Ly α emission, but also signals from UV emissions near 1550 Å and longer wavelengths.

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1 JOP 171 details: http://sohowww.nascom.nasa.gov/soj/Ops/jop171
Fig. 2. Temporal evolution of the emerging magnetic dipole. Background images have been taken in the TRACE 1216 Å channel. The superimposed contours represent the magnetic signal detected in the SoHO/MDI data. The magnetic field contours are plotted at \( \pm 25, \pm 40, \pm 55 \) and \( \pm 70 \) Mx cm\(^{-2}\) with red (blue) contours referring to positive (negative) magnetic polarity. The yellow contours mark the pixels which were used for the calculation of both the magnetic flux density and the total magnetic flux at the footpoints of the emerging loop under study. The recording time of the particular 1216 Å images is presented at the upper right corner of each sub-panel. The corresponding magnetograms are almost co-temporal (with a maximal time difference < 30 s). (A color version of this figure is available in the online journal.)

Handy et al. (1999b) described a method how to extract the “pure” Ly\( \alpha \) emission from observations taken in the 1216 Å channel using filtergrams acquired in the 1600 Å channel. Because of the absence of a co-temporal sequence of 1600 Å images in our dataset, we could not apply this method for the present data. The same authors claim that only \( \sim 60\% \) of the signal recorded in the 1216 Å channel originates from Ly\( \alpha \) emission. Moreover, the emission recorded in this channel covers the temperature range \( 1.0 - 3.0 \times 10^4 \) K (Handy et al. 1999a), i.e., not only the formation temperature of the Ly\( \alpha \) line which is \( \sim 2.0 \times 10^4 \) K (e.g. Vourlidas et al. 2001). Therefore, we consider the TRACE 1216 Å data only as an approximation of chromospheric emission and we do not draw any conclusions about absolute intensity changes.

A precise coalignement of the MDI and TRACE data had to be performed before the analysis. We used white-light images recorded simultaneously with both instruments for this purpose. As an independent check, we used the co-spatiality between the
brightest chromospheric structures visible in the 1216 Å channel (chromospheric network) and magnetic features.

3. Results

We visually inspected the SoHO/MDI high-resolution magnetograms for emerging magnetic dipoles that exhibit also some activity in chromospheric emission. The evolution of such a feature emerging at the vicinity of a network boundary is presented in Fig. 2. Note that we used a non-linear time scale for the presentation of the sequence of TRACE 1216 Å images with superimposed contours of SoHO/MDI magnetograms to provide a better description of the various phases taking place during the evolutionary process.

In the first two snapshots (taken at 13:14:15 UT and 13:16:36 UT) several magnetic elements are visible. These features represent the pre-existing magnetic field forming the network boundary which also remains detectable during and after the time span under investigation. Between 13:17:10 - 13:18:20 UT, a new patch of positive polarity and subsequently (at 13:20:05 UT) another tiny area of new negative polarity become apparent. Finally, at 13:21:15 UT, the new magnetic feature is well visible. Since longitudinal magnetograms are blind to horizontal fields, we were not able to correctly describe the complex topology of the emerged feature. However, such bipolar events can be best explained either by an emerging Σ-like loop or a submerging feature with Π-like shape. In both cases, the patches of opposite polarity correspond to the footpoints of the emerging feature.

Later on, at 13:25:59 UT, chromospheric brightenings co-spatial with the new patch of negative polarity appear and persist. After several minutes (at 13:28:32 UT) enhanced chromospheric emission becomes visible also in regions covered by the positive-polarity patch. From 13:30:51 UT to 13:33:11 UT enhanced chromospheric activity is already apparent along the whole axis of the feature, where we define the axis as the straight line connecting the two patches of opposite polarity. From 13:34:21 UT until 13:40:42 UT, the 1216 Å channel emission becomes again spatially separated and brightenings related to the negative patch start to weaken at the end of this period. Between 13:41:51 UT and 13:45:21 UT, the northern negative-polarity footpoint is still visible in the magnetograms, but does not leave longer its detectable fingerprints in chromospheric emission. Finally, at 13:53:10 UT and later, there is no clear evidence of the negative footpoint or its recurrent appearance (we remind that there is a gap in the magnetograms between 13:45 - 13:53 UT).

Concerning the northern positive-polarity patch, we note that its interaction and consecutive merging with the nearby network boundary complicates its life time estimate although significant emission in the co-spatial area in the chromosphere persists even after its disappearance. Both interaction and consecutive merging with the network boundary can be best seen by means of the contours related to the positive polarity patch in Fig. 2 at 13:30:51 UT and later on.

Figure 3 shows the temporal evolution of the longitudinal magnetic flux densities at the footpoints (upper panel) and the chromospheric emission along the axis of the emerging magnetic feature (lower panel). We calculated the longitudinal magnetic flux densities at particular positions across the footpoints by averaging over all pixels that are located perpendicular to the loop axis and that do not exceed the lateral extension of the two patches of opposite polarity. The changes in flux density show a time delay between the two opposite polarity patches and point to an asymmetric nature of the detected dipole. While the longitudinal magnetic flux densities related to the positive polarity patch reach roughly 55 Mx cm$^{-2}$ and remain more or less constant during the whole lifetime of the small-scale magnetic feature, the negative polarity patch reaches on average only -30 Mx cm$^{-2}$. Nevertheless, the magnetic flux densities of both polarities have very similar values at the very beginning of the event, when also the negative patch reaches ~33 Mx cm$^{-2}$. Corresponding values of the total magnetic flux related to the positive and negative polarity patches (not shown here) are roughly $1.6 \times 10^{18}$ Mx and $-8.5 \times 10^{17}$ Mx, respectively. As in case of the flux density, also the total flux related to the small-scale feature is at least balanced at the beginning of the feature emergence, with an absolute value of the total magnetic flux of $\sim 1.5 \times 10^{18}$ Mx for both polarities. Both magnetic flux density and total magnetic flux have been calculated within the areas highlighted by yellow contours in Fig. 2.

The spatial distance between the footpoints of the emerging feature at photospheric level is steadily increasing during first phases of the event from $\sim 25.5''$ up to $\sim 5.5''$. However, just towards the end of its lifetime the emerging small-scale magnetic loop
The delay between magnetic feature emergence and chromospheric response, the latter being first visible in the region co-spatial to the negative polarity patch. Later on, the chromospheric brightenings appear in form of isolated, quasi-periodical bursts, which are visible along the whole axis connecting the two patches of opposite polarity. The duration of the observed chromospheric activity is ~14 minutes.

The quasi-periodic nature of the chromospheric emission related to the flux emergence is also visible in Fig. 4. This plot shows the 1216 Å channel emission at locations of the emerging feature associated with strongest magnetic field. The increase of the chromospheric signals visible during the main phase of activity shows time delays in the range of 2.3 to 3.7 minutes. However we could not assign any characteristic period to this oscillatory behaviour. Nevertheless, although the intensity enhancements show a time delay between the patches of positive and negative polarity, the temporal differences between the particular peaks are the same for both footpoints (at least within the temporal resolution of the data), thus increasing the statistical significance of these events.

### 4. Discussion

In Table 1, we compare the physical parameters of the detected bipolar magnetic feature with typical values determined for emerging small-scale magnetic loops from the photosphere to higher atmospheric layers (Martínez González & Bellot Rubio 2009). Note that a proper determination of the magnetic field strength from the derived longitudinal magnetic flux densities was impossible because of the missing information about azimuth, inclination and filling factor of the magnetic field lines forming the emerging feature. Since the magnetic field should be more or less vertical at the footpoints (because of the geometry of the loop), the lacking information concerning the inclination is not that crucial. If we assume a filling factor close to unity for these areas, then the real magnetic field strength is roughly equal to the measured magnetic flux density. However when assuming a much smaller filling factor, the real magnetic field strength would increase easily up to kG values. Anyways, the comparison of the individual parameters shows that the values estimated for the magnetic feature under investigation are consistent with typical characteristics of small-scale magnetic loops reaching chromospheric heights. Exceptions are the determined longitudinal magnetic flux values in both footpoints which are at least one magnitude larger than those of typical loops, thus being rather comparable with extreme cases of the latter features.

This might be due to the limited spatial resolution of the MDI magnetograms, resulting in an overestimation of the total area covered by the footpoints of the emerging dipole and the calculated total magnetic flux values. This, together with the fact, that the emerging dipole was first detected in the magnetograms and only later also at chromospheric heights supports the hypothesis that the observed structure can be identified as a rising small-scale magnetic loop, exhibiting significant activity in the upper atmosphere.

On the other hand, one could object that the almost ideal co-spatiality of the patches harboring opposite magnetic polarity with the 1216 Å emissions points to a non loop-like shape of the detected feature. The expected quasi-circular topology of the detected feature would require that the spatial extent between areas of chromospheric emissions should be smaller than the distance between the patches of opposite polarity. However, Martínez González et al. (2010) demonstrated that at the first stages, during the loop emergence into photospheric layers, the loop has a flattened geometry and keeps its shape throughout the photosphere. However, when passing the transition between photosphere and chromosphere, the magnetic field at the footpoints becomes almost vertical and the loop has a arch-like (or arch-like) shape. Given this result, the co-spatiality detected in our data even strengthens our interpretation.

The axial distance between the footpoints of the loop shows a steady increase in the early phase of the event (Fig. 3, upper panel). After reaching a maximum distance, the footpoints remain their position nearly constant to each other until the disappearance of the loop. This is a typical behaviour for a small-scale magnetic loop within a granule. These loops are first advected by granular flows, and their size increases. The almost linear increase of the axial loop dimension indicates that the footpoints do not undergo a free random walk. Later, when reaching the intergranular lanes, the footpoints remain stable and the loop does not change anymore significantly its axial extension. However, a small decrease of the axial loop extension visible after ~13:36 UT might indicate a subsequent submergence of the loop which is also supported by the co-temporal weakening of chromospheric emission that vanishes at the end. However, the decrease in the axial extension of the loop towards the end of its lifetime could just reflect nothing else than the noisy behavior of the SoHO/MDI magnetograms.

This noisy behaviour also did not allow us to study directly possible oscillations of the magnetic flux density at the footpoints. However, we clearly detected a quasi-periodic behavior of the emissions recorded in the 1216 Å channel (Fig. 4). We estimated the damping time of these fluctuations to ~14 minutes and their related periods to 2.3 3.7 minutes. These results are in good agreement with findings of Martínez González et al. (2011) for stronger magnetic patches. The latter authors analyzed high-resolution spectro-polarimetric data obtained with

| parameter | detected feature (positive; negative polarity) | typical loop |
|-----------|-----------------------------------------------|--------------|
| longitudinal magnetic flux [Mx] | 1.6×10^{10}; -8.5×10^{10} | 2×10^{10} - 2×10^{17}/1.9×10^{18} |
| longitudinal magnetic flux density [Mx cm^{-2}] | 55; -25 | 20 - 40/75; 8 |
| distance between the two footpoints | from ~2;3 to ~5;0 | 0;6 - 5;5 |
| lifetime [min] | ≤36 | 2 - 40 |
| delay between photospheric and chromospheric activity [min] | ~9;0 | 5 - 13 |

* - extreme cases

Table 1. Physical parameters of the detected bipolar magnetic feature compared with typical values determined for emerging small-scale magnetic loops by Martínez González & Bellot Rubio (2009).
SUNRISE/IMaX and found that areas of circular polarization patches, containing constant magnetic flux, can oscillate, implying that the magnetic flux density fluctuates in antiphase. Typical periods of these oscillations range between 4 and 11 minutes in the case of weaker flux patches and between 3 and 5 minutes in case of stronger ones. The detected oscillations can be strongly damped or amplified within a time interval of 5–30 minutes. In their paper, the authors guess that these oscillations could propagate even up to chromospheric layers in the form of waves and dissipate their energy through formation of shocks. Thus the pattern detected in the 1216 Å intensity evolution of our data might also be the result of such events.

Further evidence of oscillations of magnetic flux where found in relation to plages and pores (Fujimura & Tsuneta 2009) confirming that this phenomenon is also present in other solar features. Also Beck et al. (2013a) suggest that magnetic heating processes are more important for the chromospheric energy budget as commonly assumed. However, weather acoustic waves or magneto-acoustic waves related with e.g. small-scale magnetic loops suffice in heating the solar chromosphere might be answered only by future high spatial resolution observations that combine both photospheric spectro-polarimetry and chromospheric spectroscopy, e.g. by parallel observations with the GREGOR Fabry-Pérot Interferometer (GFPI; Puschmann et al. 2012a,b,c) and the planned Blue Imaging Solar Spectrometer (BLISS; Puschmann et al. 2012b, 2013) at the 1.5-meter GREGOR solar telescope (Schmidt et al. 2012a,b).

The small-scale loop under investigation emerged as a dipole which polarities exhibit different field strengths most of its lifetime. Thus the total magnetic flux of the emerging feature seems to be unbalanced. However, this unexpected result could just reflect the difficulties in separating the positive footpoint of the loop from the stronger network fields nearby because of its permanent interaction with the latter and its final merge. Another possible explanation could be based on the different spatial extension of both footpoints. For the positive polarity patch, the magnetic flux could be concentrated within a much smaller area, implicating flux densities well above the detection threshold, while for the negative polarity the opposite could be the case. Simpler conditions can even lead to measurements of unipolar fields in quiet Sun (Lamb et al. 2008).

5. Conclusions
We observed a magnetic feature present in SoHO/MDI magnetograms and TRACE 1216 Å channel filtergrams however with a time lack of ~9 minutes in the latter. We identified this structure as a small-scale magnetic loop emerging into the photosphere and reaching chromospheric heights later on. We interpreted quasi-periodic variations found in the chromospheric emission related to the loop as a consequence of magnetic field oscillations at the footpoints resulting in a wave propagation towards higher layers. The asymmetric appearance of the loop could implicate that the footpoints cover areas of different sizes.

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