ON THE POLARIMETRIC SIGNATURE OF EMERGING MAGNETIC LOOPS IN THE QUIET SUN

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ABSTRACT
The abundance of Stokes V profiles dominated by one lobe at the locations of emergence of Ω-shaped magnetic loops is evaluated. The emergence events were found in Hinode Solar Optical Telescope/spectro-polarimeter time sequences of quiet-Sun regions. Such a study has the aim of confirming a prediction based on the basic geometrical and physical properties of emerging magnetic loops: Stokes V profiles dominated by one lobe are possibly the main polarimetric signature of these structures. In agreement with this prediction, 47% of the Stokes V profiles analyzed have an amplitude asymmetry |δa| > 0.3, while in the quiet Sun the abundance is of about 30%. This excess with respect to the quiet Sun is found consistently for any value of the threshold on the amplitude asymmetry. Such a result proves the goodness of the physical scenarios so far proposed for the interpretation of loop emergence events and may prompt the use of Stokes V profiles dominated by one lobe as a new proxy for their identification in observations with a good spectral sampling.

Key words: Sun: magnetic topology – Sun: photosphere – Sun: surface magnetism – techniques: polarimetric

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1. INTRODUCTION

The Solar Optical Telescope spectro-polarimeter (SOT/SP; Lites et al. 2001) on board the JAXA mission Solar-B (Hinode; Kosugi et al. 2007) allows one to perform high spatial resolution (0.3 arcsec) and high polarimetric sensitivity (10−3) of the quiet-Sun continuum intensity) spectro-polarimetric observations of the solar photosphere in the Fe i 630 nm lines. Since its launch in 2006, SOT/SP provides the solar community with the conditions to achieve a breakthrough in the investigation of the quiet-Sun magnetism.

Recently, great attention has been dedicated by the solar community to the study of magnetic field emergence events in SOT/SP data. These were first pointed out either as small-scale magnetic loops (loop cases; Centeno et al. 2007) or magnetized emerging granules with a single magnetic polarity (unipolar cases; Orozco Suárez et al. 2008). Later, in Martínez González & Bellot Rubio (2009), an extensive analysis of approximately 50 emerging loops anchored to the solar photosphere (Ω loops) was presented. In Martínez González et al. (2010) both the topology and the dynamics of an emerging Ω loop were derived. A similar study was presented in Ishikawa et al. (2010). More studies of magnetic field emergence events can be found in the literature: the ones of Martínez González et al. (2007), and Gómöry et al. (2010) performed on data from the Tenerife Infrared Polarimeter (TIP; Collados et al. 1999), and the ones of Guglielmino et al. (2012), and Palacios et al. (2012) performed on data from the Imaging Magnetograph eXperiment (IMaX; Martínez Pillet et al. 2011). A complete understanding of the emergence of magnetic fields in the quiet Sun could considerably improve our knowledge of the solar photosphere (see the references in the introduction of Martínez González & Bellot Rubio 2009).

In spite of the rich literature on the emergence of magnetic fields in the solar photosphere, there is still a lack of knowledge about the typical polarimetric signatures associated with these events. In this work, the first analysis of the shapes of Stokes V profiles measured at the locations of Ω loop emergence events in SOT/SP data is presented. The main goal of this study is to confirm the following prediction that can be outlined by considering the basic geometrical and physical properties of emerging Ω loops: Stokes V profiles dominated by one lobe are possibly the main polarimetric signature associated with such events in the quiet Sun.

This Letter is organized as follows: the polarimetric signatures which are expected to be observed at the locations of an emerging Ω loop are described in Section 2; the data set and the analysis method adopted are presented in Section 3; the results of the analysis confirming the prediction made in Section 2 are presented and discussed in Section 4; and the conclusions are outlined in Section 5.

2. ON THE POLARIMETRIC SIGNATURE OF AN EMERGING Ω LOOP

Figure 1 shows a schematic drawing of an Ω loop which is emerging in a field-free environment at the disk center. More precisely, Figure 1 represents the two phases which allow one to identify a loop emergence event in time sequences of polarimetric data. In this figure, the different layers of the solar photosphere are marked with average values of the optical depth at 500 nm (τ500). In the initial phase (panel (a) in Figure 1), the top of the loop, dominated by transversal magnetic fields with respect to the line of sight (LOS) of an observer (e.g., ∆θ≠1), enters the photosphere, producing a linear polarization signature (usually on top of granules, e.g., Ishikawa et al. 2010). In the following phase (panel (b) in Figure 1), the loop emerges above the photosphere and two circular polarization signatures with opposite polarities, produced by the longitudinal fields with respect to the LOS, are observed (e.g., by the observer ∆θ=2). The polarization signatures associated with these two phases of a magnetic loop emergence event are commonly used as proxies to identify emerging loops in polarimetric observations of the quiet Sun (see the references in Section 1).

However, an in-depth understanding of Ω loop emergence events requires dealing with the details of polarization
measurements. In Ishikawa et al. (2010, Figure 8), the authors derived the physical properties of an emerging Ω loop by collecting one-dimensional (1D) slices retrieved from inversions of polarization measurements. It is worth pointing out that the authors had to deal with Stokes V profiles with strong asymmetries: two Stokes V profiles dominated by one lobe were observed in two of the pixels of the loop (see Figure 3 of Ishikawa et al. 2010). In the following it is shown that it is possible to predict that this kind of profile is possibly the main polarimetric signature associated with emerging Ω loops.

The LOS Obs2, crossing one of the loop’s footpoints in Figure 1, passes first through a field-free layer which fills the region \( \tau_{500} = 0.01-0.1 \), and then through a magnetized layer which fills the region \( \tau_{500} = 0.1-1 \). If the location of the footpoint crossed by Obs2 is an upflow (as usual in emergence events), the plasma velocity along the LOS in the region \( \tau_{500} = 1 \) is negative and of the order of several kilometers per second, while the same quantity in the region \( \tau_{500} = 0.01-0.1 \) is expected to be considerably smaller in absolute value (see, e.g., Viticchié & Vitas 2011). From the extensive literature on the formation of strongly asymmetric Stokes V profiles in visible spectral lines from 1D stratifications, one can conclude that an atmospheric configuration like the one described above can give rise to a Stokes V profile dominated by the blue lobe under very different conditions: for either sharp or smooth transitions between the magnetized region and the field-free one, for either strong or weak magnetic field regimes, for either vertical or inclined magnetic fields with respect to the LOS. Conversely, if the footpoint is located in a downflow, a profile dominated by the red lobe is very likely to be formed (Viticchié & Vitas 2011; Sainz Dalda et al. 2011). Similar arguments can be used to predict that the atmospheric properties along the LOS Obs3 can give rise to Stokes V profiles dominated by one lobe as well (Grossmann-Doerth et al. 2000; Viticchié & Vitas 2011; Sainz Dalda et al. 2011). Figure 3 of Ishikawa et al. (2010) offers one a fast verification of the prediction outlined above. In Section 4, much stronger arguments in favor of the connection between Ω loop emergence events and the observation of Stokes V profiles dominated by one lobe are presented.

The polarimetric signatures produced by the emerging Ω loop in Figure 1 are assumed to have dimensions larger than the
resolution element of modern SP observations, i.e., the loop structure is resolved.\(^1\) This assumption does not imply that the magnetic fields of the loop are completely resolved, but rather implies that a dominant \(\Omega\) shaped magnetic structure can be pointed out from the data. This structure is the one which is considered to be dominant in each pixel of the observed loops. For this reason one can use the properties of 1D stratifications to predict the asymmetries of Stokes \(V\) profiles at the locations of emerging magnetic loops.

3. DATA SET AND ANALYSIS METHOD

In order to have a large statistics of Stokes \(V\) profiles from the locations of emerging magnetic loops, one can use the time sequences analyzed in Martínez González & Bellot Rubio (2009). This is so far the study with the richest record of emergence events of \(\Omega\) loops in the quiet Sun. In detail, all the time sequences reported in Table 1 of Martínez González & Bellot Rubio (2009), with the exception of the sequence of September 26 (due to problems in downloading the data set from the Hinode archive), were analyzed. One can refer to both Table 1 and the second paragraph of Section 2 of Martínez González & Bellot Rubio (2009) for the description of the data sets.

As reported in Section 2, a magnetic \(\Omega\) loop can be identified in polarimetric data as “a linear polarization signature flanked by circular polarization signatures with opposite polarities" (e.g., Martínez González & Bellot Rubio 2009). In the analysis presented here, those events in which the linear and circular polarization signatures had, at least for one wavelength, \(\text{max}(|Q|, |U|) > 8 \times 10^{-3}\) and \(\text{max}(|V|) > 6 \times 10^{-3}\) in each pixel, respectively, were considered. Besides this, a minimum area of 4 pixels for each polarization signature was required.\(^2\) Each emergence event was taken out of the time sequences by picking out a sub-sequence of sub-fields (of \(\simeq 2.7 \times 2.7 \text{ arcsec}^2\)) around the location where the emergence was found to take place. Spurious polarimetric signals due to magnetic fields in the selected sub-fields were then carefully removed along the whole sub-sequence by visual inspection.

An example of an emergence event extracted from the analyzed sequences is shown in the upper row of Figure 2 in which both the linear and the circular polarization signatures that allow one to point out the \(\Omega\) loop were marked (contours). A total of 40 events were found in the analyzed sequences; these presented a large variety of properties which were investigated in detail in Martínez González & Bellot Rubio (2009). Here, the abundance of Stokes \(V\) profiles dominated by one lobe at the locations of the circular polarization signatures of the loops was studied.

The lower row of Figure 2 shows a fraction of the Stokes \(V\) profiles at the locations of the circular polarization signatures of the emergence event in the upper row. In detail, among the Stokes \(V\) profiles observed at the locations of the circular polarization signatures of the \(\Omega\) loop, the ones with \(|b| = |a_b| - |a_i|/|a_b| + |a_i| > 0.3\) were represented.\(^3\) \(b\) is the amplitude asymmetry of a Stokes \(V\): the higher the \(|b|\) the more the Stokes \(V\) is dominated by one lobe.

\(^1\) For a discussion on the polarimetric signature produced by unresolved magnetic loops refer to Steiner (2000).

\(^2\) Strong and well-resolved polarization signatures with a maximum Stokes \(V\) amplitude above three times the polarimetric sensitivity of the observations, i.e., \(1.7 \times 10^{-3}\) in units of the average continuum intensity (see Martínez González & Bellot Rubio 2009), were considered. The higher threshold for the individuation of the linear polarization signature allows one to point out sound cases.

\(^3\) In the formula, \(a_i\) (\(a_b\)) is the amplitude of the blue (red) lobe.
One can understand the formation of the Stokes $V$ profiles in Figure 2 by referring to Section 2 and Figure 2 ($\Theta \delta a$). The signature with the positive polarity, mostly located in a downflow, is characterized by Stokes $V$ profiles dominated by the red lobe. The negative one, located on a bright granule, is characterized by profiles dominated by the blue lobe. The observations of these polarimetric signatures were predicted in Section 2.

By exploiting all the 40 $\Omega$ loop emergence events individuated in the analyzed time sequences, one can analyze more profiles and, eventually, evaluate the abundance of Stokes $V$ profiles dominated by one lobe at the locations of such events. To do this, all the Stokes $V$ profiles from the circular polarization signatures which allow one to identify the emergence events were collected; these were 12,256 profiles. Those profiles with $|\delta a| > 0.3$ were the ones considered to be dominated by one lobe (see, e.g., Figure 2).

4. RESULTS AND DISCUSSION

The Stokes $V$ profiles with $|\delta a| > 0.3$ make up 5799 of the 12,256 of the whole archive (i.e., 47%). This means that nearly one in every two Stokes $V$ profiles observed at the locations of emerging magnetic loops is dominated either by the blue lobe or by the red lobe. Such a result confirms the prediction made in Section 2 and allows one to put forward Stokes $V$ profiles dominated by one lobe as a new proxy for emerging $\Omega$ loops in polarimetric observations with good spectral sampling. Even though the abundance here derived stemmed from an arbitrary threshold on the amplitude asymmetry of the analyzed circular polarization signals, the plenitude of Stokes $V$ profiles dominated by one lobe at the locations of emerging magnetic loops can be proved in an alternative way. Figure 3 shows the abundances for different values of the threshold ($k$ in Figure 3) on the amplitude asymmetry in both the sample described at the end of Section 3 and the complete quiet-Sun data set of all the time sequences. On the one hand, the result reveals that the abundance strongly depends on the threshold value. On the other hand, it shows that there is a considerable excess of profiles with large $|\delta a|$ at the locations of loop emergence events with respect to the quiet Sun. This result does not depend on the value of the threshold and further supports the prediction made in Section 2.

Polarimetric observations of loop emergence events performed with other instruments do not present the same abundance of extremely asymmetric profiles. Gömöry et al. (2010) presented a study of the shapes of Stokes $V$ profiles observed in the two infrared (IR) Fe I lines at 1565 nm with TIP (Collados et al. 1999) at 1 arcsec spatial resolution. The profiles they showed in Figure 2 are anti-symmetric profiles. Such a lack of asymmetry can be understood by referring to Grossmann-Doerth et al. (1989) in which the authors explained the different conditions which produce strong asymmetries in Stokes $V$ profiles in the visible and in the IR. In Guglielmino et al. (2012), the authors pointed out the observation of asymmetric profiles in one emergence event observed with IMaX (Martínez Pillet et al. 2011) in the Fe I 520 nm line. A detailed analysis of the profiles observed by IMaX at the locations of emergence events would be important to complement our study.

Finally, the results presented here allow one to complement the knowledge about the origin of Stokes $V$ profiles dominated by one lobe observed by SOT/SP in the quiet Sun. In detail, in Viticchiè & Vitas (2011) the authors reported on the observation of such profiles at the borders of network patches in the data set of Lites et al. (2008), while in Orozco Suárez et al. (2008) these were found at the locations of unipolar emergence events.

5. CONCLUSIONS

The first study of the shapes of Stokes $V$ profiles observed at the locations of emerging magnetic $\Omega$ loops found in SOT/SP time sequences of the quiet Sun is presented. It focuses on those loops which can be pointed out, adopting the standard method based on the detection of both linear and circular polarization signatures in Hinode time sequences of the quiet Sun (see, e.g., Martínez González & Bellot Rubio 2009). Forty-seven percent of the profiles observed at the locations of such events have an amplitude asymmetry $|\delta a| > 0.3$, i.e., are dominated by either the blue lobe or the red lobe. Such a value quantifies the excess of the profiles dominated by one lobe at the locations of magnetic loop emergence events with respect to their abundance in the complete quiet-Sun data set of all the time sequences.

This result confirms the prediction of the Stokes $V$ profiles that are expected to be observed at the locations of emerging loops outlined in Section 2. The different lines of sight crossing the structure of a loop are expected to define 1D stratifications which are known to produce Stokes $V$ profiles dominated by one lobe under very different conditions in visible spectral lines (Grossmann-Doerth et al. 1989, 2000; Steiner 2000; Viticchiè & Vitas 2011; Sainz Dalda et al. 2011). The large abundance of these profiles at the locations of loop emergence events confirms the goodness of the physical scenarios so far proposed to interpret such events (e.g., Martínez González & Bellot Rubio 2009) and may prompt the use of Stokes $V$ profiles dominated by one lobe as proxies to individuate emerging magnetic loops in SP observations with good spectral sampling.

The work presented here must be considered as a starting point for more refined studies of emergence events which, for example, might be aimed at pointing out various emergence configurations, understanding the temporal evolution of the Stokes $V$ profiles as a loop emerges/evolves, and measuring the siphon flows into the loops.
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