IS MAGNETIC RECONNECTION THE CAUSE OF SUPersonic upFLOWS IN GRANULAR CELLS?

J. M. Borrero1, V. Martínez Pillet2,3, W. Schmidt1, C. Quintero Noda2,3, J. A. Bonet2,3, J. C. del Toro Iniesta4, and L. R. Bellot Rubio4

1 Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, D-79110, Freiburg, Germany; borrero@kis.uni-freiburg.de, wolfgang@kis.uni-freiburg.de
2 Instituto de Astrofísica de Canarias, Avd. Vía Láctea s/n, E-38200 La Laguna, Spain; vmnp@ll.iac.es, cqn@ll.iac.es, jab@ll.iac.es
3 Instituto de Astrofísica de Andalucía (CSIC), Apdo. de Correos 3004, E-18080 Granada, Spain; jti@iaa.es, lbellot@iaa.es
4 Instituto de Astrofísica de Andalucía (CSIC), Apdo. de Correos 3004, E-18080 Granada, Spain; jti@iaa.es, lbellot@iaa.es

Received 2013 January 14; accepted 2013 March 10; published 2013 April 16

ABSTRACT

In a previous work, we reported on the discovery of supersonic magnetic upflows on granular cells in data from the SUNRISE/IMaX instrument. In the present work, we investigate the physical origin of these events employing data from the same instrument but with higher spectral sampling. By means of the inversion of Stokes profiles we are able to recover the physical parameters (temperature, magnetic field, line-of-sight velocity, etc.) present in the solar photosphere at the time of these events. The inversion is performed in a Monte-Carlo-like fashion, that is, repeating it many times with different initializations and retaining only the best result. We find that many of the events are characterized by a reversal in the polarity of the magnetic field along the vertical direction in the photosphere, accompanied by an enhancement in the temperature and by supersonic line-of-sight velocities. In about half of the studied events, large blueshifted and redshifted line-of-sight velocities coexist above/below each other. These features can be explained in terms of magnetic reconnection, where the energy stored in the magnetic field is released in the form of kinetic and thermal energy when magnetic field lines of opposite polarities coalesce. However, the agreement with magnetic reconnection is not perfect and, therefore, other possible physical mechanisms might also play a role.

Key words: polarization – Sun: granulation – Sun: magnetic topology – Sun: photosphere – Sun: surface magnetism

1. INTRODUCTION

In the quiet solar photosphere the energy stored in the magnetic field is comparable to kinetic energy due to convective motions. This gives rise to a rich variety of phenomena that evolve on very short time and spatial scales. The IMaX instrument (Imaging Magnetograph eXperiment; Martínez Pillet et al. 2011a) onboard the stratospheric balloon SUNRISE (Barthol et al. 2011; Solanki et al. 2012) has helped to uncover many of these phenomena (see, e.g., Solanki & The SUNRISE Team 2010), from resolving magnetic flux tubes (Lagg et al. 2010), to finding vortex tubes (Steiner et al. 2010), vortex flows (Bonet et al. 2010), etc. One of these discoveries involves supersonic magnetic upflows (Borrero et al. 2010, 2012). These events are characterized by highly blueshifted circular polarization signals that appear at the center or edges of granular cells and last for about 80 s. Similar events were also subsequently found in data from the SP instrument onboard the Hinode spacecraft (Martínez Pillet et al. 2011b). The fact that magnetic fields of opposite polarity connected by horizontal fields appear in the vicinity of these events in 70% of the cases led us to surmise that they are caused by magnetic reconnection. In this paper, we study them in more detail using a different data set from the IMaX instrument. A comparison between the old and new data sets is provided in Section 2. In Section 3, we describe the criterion employed to select events. The analysis technique, namely, the inversion of the observed Stokes profiles to retrieve the physical conditions of the solar atmosphere, is detailed in Section 4. Section 5 presents our results, while Section 6 briefly addresses the choice of model for the inversion. Finally, Section 7 presents our main conclusions.

2. INSTRUMENTS AND OBSERVATIONS

The data employed in this work were recorded with the stratospheric balloon-borne observatory SUNRISE (Solanki & The SUNRISE Team 2010; Barthol et al. 2011). SUNRISE was launched on 2009 June 8 from Kiruna (Sweden) and landed on 2009 June 13 on Somerset Island (Canada). During this time, SUNRISE’s 1 m telescope took broadband images in different spectral windows with the SUFI instrument (Gandorfer et al. 2011), and spectropolarimetric data of the solar photosphere with IMaX (Martínez Pillet et al. 2011a). An average flight altitude of 35 km allowed SUNRISE to avoid more than 95% of the disturbances introduced by Earth’s atmosphere. In addition, image motions due to wind during the flight were stabilized by the Correlation-Tracker and Wavefront Sensor (CWS; Berkefeld et al. 2011). Owing to the aforementioned advantages, IMaX spectropolarimetric data yielded a spatial resolution of 0′′.25 and a field of view of 50′′ × 50′′. Further image reconstruction based on phase diversity calibration of the PSF of the optical system improved the resolution to 0′′.15–0′′.18.

In Borrero et al. (2010), we employed reconstructed IMaX data that included the four components of the Stokes vector (I, Q, U, V) measured at five wavelength positions across the Fe I 5250.217 Å spectral line. In the following, we will refer to this observing mode as V5-6. In this work, however, we will use a different observing mode, referred to as L12-2. In this mode the intensity I and circular polarization V were measured in 12 (instead of 5) wavelength positions. For reasons that will be explained later, we restricted ourselves to employing non-reconstructed data with a spatial resolution of only 0′′.25.
Figure 1 displays the region of the intensity spectra around the Fe i 5250.217 spectral line, as recorded by the Fourier Transform spectrometer in the quiet Sun (Wallace et al. 1998). Crosses in this figure show the five wavelength positions scanned by the V5-6 data used in Borrero et al. (2010). These were located at \( \Delta = [-80, -40, 40, 80, 227] \) mÅ from line center. Filled circles illustrate the wavelength positions scanned in the L12-2 observing mode. Here, the wavelength range goes from \(-192.5\) mÅ to \(+192.5\) mÅ, in 12 positions equidistantly distributed in steps of 35 mÅ.

The lack of linear polarization profiles \( Q \) and \( U \) in the L12-2 observing mode makes the polarimetric calibration of the data slightly more difficult to implement compared to V5-6. The instrument’s calibration matrix had been theoretically calculated (Martínez Pillet et al. 2011a) and experimentally confirmed at the INTA (Instituto Nacional de Técnicas Aeroespaciales) facilities in Spain (Martínez Pillet 2007; del Toro Iniesta & Martínez Pillet 2012) such that linear polarization cross-talk could be minimized by tuning the voltages of the nematic liquid crystals to the appropriate retardances. Unfortunately, this calibration stage was not performed while mated to the SUNRISE telescope (main and secondary mirrors) which introduced more cross-talk contributions from main and secondary mirrors) which introduced more cross-talk.

Unfortunately, this scanning position is not far enough toward the blue to guarantee that the observed signal at this wavelength is only due to large velocities, as it could also be caused by a magnetic field that shifts the \( \sigma \)-component of Stokes \( V \) into this wavelength. Indeed, displaying \( V(\lambda = \lambda_0 - 192.5\) mÅ) reveals a pattern that closely resembles the network. Thus, this wavelength alone cannot be employed to uniquely identify large upflows.

In order to disentangle network elements from possible supersonic magnetic upflows, we propose a different strategy in which we compare the circular polarization close to the spectral line core and the circular polarization close to the blue continuum. Let us refer to these two quantities as \( V_c \) and \( V_{line} \), respectively. They are defined as

\[
V_{\text{line}} = \frac{1}{3} \left[ \sum_{i=4}^{i=6} V(\lambda_i) - \sum_{i=7}^{i=9} V(\lambda_i) \right]
\]

\[
V_c = \frac{1}{2} \sum_{i=1}^{i=2} |V(\lambda_i)|,
\]

where the index \( i \) runs from the bluemost (\( i = 1 \)) to the redmost (\( i = 12 \)) scanning positions indicated by the filled circles in Figure 1. We note that, in the definition of \( V_{\text{line}} \), we are subtracting Stokes \( V \) in the red wing (\( i = 6, 7, 8 \)) from Stokes \( V \) in the blue wing (\( i = 3, 4, 5 \)). This is done in order to obtain the polarity of the magnetic field vector and has the additional benefit of partially canceling the noise.

In the top left panel of Figure 2 we display \( V_{\text{line}} \) (normalized to the averaged quiet-Sun continuum intensity \( I_{qs} \)) over a portion of the full field of view from one of our available 52 snapshots. The regions of enhanced \( V_{\text{line}} \) correspond mostly to the network elements since the circular polarization close to the line center is large. In the top right panel of Figure 2 we plot, for the same region, the absolute value of the quotient of \( V_c \) and \( V_{\text{line}} \). In this panel, the network appears as those regions where \( ||V_c/V_{\text{line}}|| \rightarrow 0 \). Regions where \( ||V_c/V_{\text{line}}|| > 1 \) denote Stokes \( V \) profiles that are highly blueshifted. Our selection criterion will consider as supersonic magnetic upflows any pixel in the field of view where \( ||V_c/V_{\text{line}}|| > 4 \). In Figure 2, these regions are indicated by the white contours. Note that the selected events
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Figure 2. Top left: close-up (28′′ × 25′′) of a snapshot displaying the total circular polarization around the center of the spectral line $V_{\text{line}}$ (Equation (1)) and normalized to the average continuum intensity over the quiet-Sun $I_{\text{qs}}$. Top right: same FOV as before but showing $\| V_c / V_{\text{line}} \|$, where $V_c$ corresponds to the circular polarization on the blue wing of the spectral line (Equation (2)). Bottom left: same FOV as before but showing the continuum intensity $I_c$ normalized to the average continuum intensity over the quiet-Sun $I_{\text{qs}}$. Bottom right: line-of-sight velocity $V_{\text{LOS}}$ derived from the center-of-gravity of Stokes $V$. In all panels the black and white contours enclose the regions where $\| V_c / V_{\text{line}} \| > 4$. These patches contain pixels that are selected for our study (see the text for details). While the upper panels are unreconstructed, the bottom ones have been subject, for visualization purposes, to image restoration (see Section 2).

also coincide with the center/edges of granular cells where the line-of-sight velocity is blueshifted by about $-2$ km s$^{-1}$ (see black contours in the bottom left and bottom right panels in Figure 2). This confirms that the selected events have the same properties as those studied in Borrero et al. (2010).

The line-of-sight velocity $V_{\text{LOS}}$ displayed in Figure 2 is obtained by calculating the center-of-gravity of Stokes $I$ and correcting for gravitational redshift, convective blueshift, and the wavelength shift across the FOV due to the collimated configuration of the instrument (see Section 9.1 in Martínez Pillet et al. 2011a). We mention this in order to avoid confusion with the $V_{\text{LOS}}$ that will be used in the next sections of this paper, which will be inferred from the simultaneous fitting of Stokes $I$ and $V$.

It is also important to clarify that Figure 2 shows a somewhat exceptional situation, in which three events occur on a small portion of the full field of view. This case has been selected to highlight the properties of the selected events, but by no means corresponds to the typical case seen in the observations. In fact, from the 52 available snapshots, the aforementioned selection criteria selects 857 pixels, belonging to 122 events. This results in an average of 2.3 events in each 50′′ × 50′′
algorithm provides the perturbations in the physical parameters at several optical-depth positions called nodes, which are needed to produce a better fit to the observed Stokes profiles. Each node represents a free parameter in the inversion. The resulting model (from the $\chi^2$-minimization) can then be considered to represent the physical conditions present in the solar photosphere. For some recent reviews on this subject we refer the reader to del Toro Iniesta (2002), Bellot Rubio (2006), and Ruiz Cobo (2007). Since photon noise affects the results of the inversion rather negatively (see, e.g., Borrero & Kobel 2011, 2012) and owing to the fact that image reconstruction techniques slightly increase the noise in the observations, we considered for the inversion the unreconstructed data with a spatial resolution of 0.25 arcsec (see Section 2).

Our inversions have been carried out with a one-component model, in which the photosphere is considered to be laterally homogeneous within each selected pixel. Thus, we only need to consider the vertical variations of the physical parameters in the photosphere. These variations are often treated in terms of the dimensionless optical depth at a reference wavelength of 5000 Å, $\tau_5$, instead of the geometrical height $z$. In general, the physical parameters relevant for the formation of spectral lines are temperature $T(\tau_5)$, line-of-sight velocity $V_{\text{LOS}}(\tau_5)$, and the three components of the magnetic field vector: $B(\tau_5)$ (modulus of the magnetic field vector), $\gamma(\tau_5)$ (inclination of the magnetic field vector with respect to the observer’s line of sight), and $\phi(\tau_5)$ (azimuth of the magnetic field vector in the plane perpendicular to the observer’s line of sight). Other quantities, such as the gas pressure $P_g(\tau_5)$ and electron pressure $P_e(\tau_5)$, as well as the density $\rho(\tau_5)$, are derived from $T(\tau_5)$, the condition of hydrostatic equilibrium, and the equation of ideal gases with a variable mean molecular weight. In our inversions we allow for the following free parameters (nodes): three for $T(\tau_5)$, one for $B(\tau_5)$ (constant value with height), two for $\gamma(\tau_5)$, five for $V_{\text{LOS}}(\tau_5)$, and finally one for the micro-turbulent velocity $V_{\text{mic}}(\tau_5)$ (also constant with height). This adds up to a total of 12 free parameters. The full stratification of the physical parameters with $\tau_5$ is obtained via interpolation across the values at the nodes. In Section 6, we give more details about our choice of model and free parameters, as well as discussing their implications.

It is important to remember here that the L12-2 observing mode does not record the linear polarization profiles ($Q$, $U$; see Section 2). In the case of strong magnetic fields it is plausible to recover, through magneto-optical effects, the azimuth of the magnetic field vector $\phi$ from only Stokes $I$ and $V$ (Ruiz Cobo & del Toro Iniesta 1992). However, it is unclear whether this is also the case when the circular polarization signals are weak ($V/I \lesssim 0.03$; see Figure 1 and also Borrero & Kobel 2011), and the spectral resolution is limited. Therefore, we do not invert the azimuth angle of the magnetic field vector $\phi(\tau_5)$, and instead we fix it at a value of zero. Finally, we note that IMaX’s spectral transmission profile is fully considered in the inversion. This is done by convolving the theoretical Stokes vector before it is compared to the observed Stokes vector at each iteration step, with the instrument’s transmission curve (see Figure 2 in Martínez Pillet et al. 2011a).

In order to improve convergence and to reduce the chances of the Levenberg–Marquardt algorithm falling into a local minimum, each of the 857 selected pixels is inverted a total of 100 times, where the initial values of the physical parameters are randomly chosen each time. From all those 100 independent inversions we retain only the one with the smallest value of $\chi^2$. In the inversion we include the effects of the three snapshot. Unfortunately, the pointing problems described in Section 2 prevented us from having a continuous time series and therefore we cannot track each event in time. Thus, some of those 122 events might correspond to the same one but at different times in their evolution. Consequently, we cannot compare these numbers with the occurrence rates obtained in Borrero et al. (2010).

### 4. INVERSION OF STOKES PROFILES

Once we have the selected pixels that correspond to the possible supersonic magnetic upflows in granules, we proceed to extract physical information from their corresponding Stokes $I$ and $V$ profiles. This is done by means of the inversion of the radiative transfer equation employing the SIR (Stokes Inversion based on Response functions) code (Ruiz Cobo & del Toro Iniesta 1992). Starting with an initial model of the solar photosphere, SIR solves the radiative transfer equation to obtain the theoretical Stokes vector that arises from such a model. The observed Stokes vector is then compared to the theoretical one through a $\chi^2$ merit function. Via a Levenberg–Marquardt method, the original model is then iteratively modified until $\chi^2$ reaches a minimum. At each iteration step, the Levenberg–Marquardt...
Figure 4. Top left: line-of-sight component of the magnetic field vector as a function of the optical depth, $B_\parallel(\tau_5)$. Top right: temperature as a function of the optical depth, $T(\tau_5)$. Bottom left: line-of-sight velocity as a function of the optical depth, $V_{\text{LOS}}(\tau_5)$. Dashed black lines show the results from the inversion of the Stokes profiles $I$ and $V$ from each of the 123 selected pixels that belong to family 1. The red solid line shows the average obtained from the individual results. The blue solid line in the top right panel corresponds to the temperature stratification in the granular model by Borrero & Bellot Rubio (2002). Bottom right: average of the observed (circles) and of the fitted (solid line) Stokes $V$ profiles in all pixels belonging to family 1. The mean value of $\chi^2$ from all the individual inversions is also indicated.

5 In fact, as mentioned in the first paragraph in Section 3, this already happened in the V5-6 data (see Borrero et al. 2010 for details).

5 Inversion Results

The inversion of the Stokes $I$ and $V$ profiles from the 857 selected profiles provides (among other physical parameters) the stratification with optical depth of the temperature $T(\tau_5)$, line-of-sight velocity $V_{\text{LOS}}(\tau_5)$, magnetic field strength $B(\tau_5)$, and inclination $\gamma(\tau_5)$ in all selected pixels. Searching for similarities among all available results turns out to be a difficult task, as the inferred stratifications do not seem to follow, at first glance, any particular pattern. However, if one looks at the optical-depth dependence of the line-of-sight component of the magnetic field vector $B_\parallel = B \cos \gamma$, one realizes that almost all pixels show a change in sign from $B_\parallel > 0$ to $B_\parallel < 0$ (or vice versa) at some optical-depth point $\tau_5$ (height in the atmosphere). This observation allows us to classify the different results as a function of the optical depth where the polarity of the magnetic field reverses. In particular, we distinguish three cases: polarity change at around $\log \tau_5 \approx -1$, $\log \tau_5 \approx -2$, and finally, possible polarity change at $\log \tau_5 < -3$. Hereafter, these families of solutions will be referred to as family 1, family 2, and family 3, respectively. Figures 4–6 show the individual results as a function of $\tau_5$ from the inversion of all pixels belonging to each family (black dashed lines). Each of these figures shows: the line-of-sight component of the magnetic field vector $B_\parallel$ (top left panel), the temperature $T$ (top right panel), and the line-of-sight velocity $V_{\text{LOS}}$ (bottom left panel). For the latter two physical parameters, $T(\tau_5)$ and $V_{\text{LOS}}(\tau_5)$, we also show in solid red lines the average stratification obtained from all the pixels belonging to a given family. For comparison purposes, the top right panels in Figures 4–6 also display the average temperature stratification (blue solid lines) in granules (Borrero & Bellot Rubio 2002). This model is chosen because, as mentioned in Section 3, these events typically occur at the center or edges of granular cells (see also Figure 2). In the following subsections, we will describe each of the aforementioned families separately.
5.1. Family 1: Polarity Change at \( \log \tau_5 \approx -1 \)

This family comprises 123 out of the 857 selected pixels (14.3%). As imposed by our classification criterion, \( B_\parallel \) changes sign at around \( \log \tau_5 \approx -1 \) (Figure 4, top left panel). The temperature shows an enhancement of about 400–600 K in the mid-photosphere and upper photosphere (\( \log \tau_5 \in [-1.5, -3] \)) with respect to a typical granule (Figure 4, top right panel). The line-of-sight velocity (Figure 4, bottom left panel) displays variations from extreme downflows (\( V_{\text{LOS}} \approx -12 \text{ km s}^{-1} \)) in the upper photosphere (\( \log \tau_5 \approx -3 \)) to large upflows in the mid-photosphere (\( V_{\text{LOS}} \approx -7 \text{ km s}^{-1} \) at \( \log \tau_5 \approx -2 \)), and then back to downflows in the deep photosphere (\( V_{\text{LOS}} \approx 3 \text{ km s}^{-1} \) at \( \log \tau_5 \approx 0 \)). Since the speed of sound in the solar photosphere is about \( V_s \approx 7 \text{ km s}^{-1} \), the inferred line-of-sight velocities are close to supersonic. Once we consider that \( V_{\text{LOS}} \) is only a lower limit of the total modulus of the velocity vector, the final velocities are likely to be much larger, hence supersonic. An additional feature is the fact that the line-of-sight velocity remains close to zero where the polarity of the magnetic field changes (\( \log \tau_5 \approx -1 \)).

5.2. Family 2: Polarity Change at \( \log \tau_5 \approx -2 \)

This family contains 434 of the 857 selected pixels (50.7%). As imposed by the classification criterion, \( B_\parallel \) changes sign at around \( \log \tau_5 \approx -2 \) (Figure 5, top left panel). Similar to family 1, the temperature in family 2 also shows enhancements (150–200 K) compared to an average granule. Although not as large as in the first case, the increase occurs over all optical depths (Figure 5, top right panel). The line-of-sight velocities are again large, although in this case they always involve upflows (Figure 5, bottom left panel). These upflows are visible in both the upper photosphere (\( V_{\text{LOS}} \approx -2 \text{ km s}^{-1} \) at \( \log \tau_5 \approx -3 \)) and the deep photosphere (\( V_{\text{LOS}} \approx -7 \text{ km s}^{-1} \) at \( \log \tau_5 \approx 0 \)). Again, the line-of-sight velocity remains close to zero where the magnetic field changes polarity (\( \log \tau_5 \approx -2 \)).
5.3. Family 3: Polarity Change logτ5 < −3?

There are 300 pixels in this family, which corresponds to 35.0% of the total number. As our selection criterion imposes, there is no real change in the polarity of the magnetic field vector (Figure 6, top left panel). Interestingly, $B_\parallel$ decreases as log $\tau_5$ decreases. If the decreasing trend continues toward higher photospheric layers the polarity would eventually switch, although that would happen close to the temperature minimum.

As in the two previous families, the temperature in the mid-photosphere ($\log \tau_5 \in [-1,-2]$) is enhanced with respect to the average temperature of a granule (Figure 6, top right panel). In this case, the enhancement is the largest ($\approx 1000$ K) of the three studied families. Finally, the line-of-sight velocity changes from large upflows in the mid-photosphere, $V_{\text{LOS}} \approx -8$ km s$^{-1}$ at log $\tau_5 \approx -2$ (Figure 6, bottom left panel), to extreme downflows in the low photosphere, $V_{\text{LOS}} \approx 15-20$ km s$^{-1}$ at log $\tau_5 \approx 0$. As in all previous families, the line-of-sight velocity drops to zero as the line-of-sight component of the magnetic field vector vanishes, which now happens in the upper photosphere ($V_{\text{LOS}} \rightarrow 0$ at log $\tau_5 \approx -3$).

6. DISCUSSION OF MODEL CHOICE

In this section, we discuss the choice of model and free parameters in the inversion described in Section 4. To make this choice we look at the observed Stokes profiles and try to establish the most suitable model to fit them. The first step is to realize that, as illustrated in Figure 3, all 857 selected Stokes V profiles feature the almost complete lack of one of the lobes (produced by the $\Delta M = \pm 1$ transitions in the Zeeman pattern) in the circular polarization.

The question is now to decide whether these kind of profiles are really asymmetric, or whether, on the other hand, they are symmetric but the missing lobe in Stokes V is located at $\Delta \lambda < -200$ mÅ, hence lying just outside of the region scanned by IMaX. This question can be answered by looking at the wavelength region around $\Delta \lambda \approx 150-200$ mÅ in Figures 4–6 (bottom right panels). The average observed Stokes profiles (filled circles) for all families around this region is negative and, although small, clearly above the noise level. We have established that this corresponds to the Stokes V signal from Fe i 5250.653 Å by repeating all the inversions described in Section 4, but excluding this spectral line (see Table 1). In this case, the fitted profiles in the bottom right panels in Figures 4–6 (solid black lines) fail to reproduce the negative values of Stokes V around $\Delta \lambda \approx 150-200$ mÅ. With this in mind we now move to $\Delta \lambda < -200$ mÅ and conclude that, if there is a missing positive lobe in Stokes V there, then the signal from Fe i 5250.653 Å at $\Delta \lambda \approx 150-200$ should also be positive. However, it is negative, and therefore we conclude that the observed Stokes V profile from Fe i 5250.653 Å are indeed asymmetric and that there is no missing positive lobe at $\Delta \lambda < -200$ mÅ.

Once we have established that the observed circular polarization profiles are highly asymmetric, we follow Solanki & Montavon (1993) and Landolfi & Landi Degl’Innocenti (1996)
and consider that those asymmetries are caused by the simultaneous effect of gradients in the line-of-sight velocity $V_{\text{LOS}}$ and in the line-of-sight component of the magnetic field vector $B_\parallel = B \cos \gamma$. The large number of nodes allowed in $V_{\text{LOS}}(\tau_5)$ (see Section 4) is a direct consequence of the need to fit these extremely asymmetric Stokes V profiles.

Gradients in $B_\parallel$ have been included by, as already mentioned, allowing two nodes in $\gamma(\tau_5)$ and one node in $B(\tau_5)$. This combination is more general than allowing two nodes for $B(\tau_5)$ and only one for $\gamma(\tau_5)$. This is a consequence of the modulus of the magnetic field vector being defined as a positive quantity which, unlike the former case, makes the inversion with only one node in $\gamma(\tau_5)$ unable to yield solutions where $B_\parallel$ changes sign with optical depth. The possibility of obtaining solutions where $B_\parallel$ changes sign does not imply that all inferred stratification will actually have it (i.e., $\text{family 3}$; see Section 5.3 and Figure 6).

Since our discussion in the next section will rely heavily on the presence of a reversal in the polarity of the magnetic field, it is crucial to establish whether this feature is really needed to reproduce the observed profiles. To this end we once more repeated our inversions (as described in Section 4) but this time employing one node in $\gamma(\tau_5)$ and two in $B(\tau_5)$. In this case, all retrieved stratifications in $B(\tau_5)$ show the same sign at all optical depths (as in $\text{family 3}$). Interestingly, the quality of the fits worsens significantly. The average value of the merit function, $\chi^2$, doubles in those pixels that belong to $\text{families 1 and 2}$. Meanwhile, $\bar{\chi}^2$ also increases in those pixels that belong to $\text{family 3}$, but comparatively less ($<50\%$). These results suggest that allowing two nodes in $\gamma(\tau_5)$ is necessary to successfully fit the observed Stokes profiles, and therefore also that, the inferred reversal in the polarity of the magnetic field $B_\parallel$ (in $\text{families 1 and 2}$) is not an artifact imposed by our choice of model, but rather a characteristic feature of these events.

Finally, as previously discussed, a model that contains only one component assumes that the solar photosphere is laterally homogeneous within each observed pixel, or at least, assumes that the vertical variations in the physical parameters play a more important role than the horizontal ones in the formation of the observed spectral line. While there is no guarantee that this is indeed the case, the high spatial resolution achieved by SUNRISE/IMaX makes this approximation a reasonable first step in the study of these events.

7. DISCUSSION AND CONCLUSIONS

The results presented here confirm our initial conclusions in our previous studies (Borrero et al. 2010, 2012) on these extremely shifted polarization signals. Namely that, (1) they occur mostly at the center or edges of granular cells, (2) they are characterized by supersonic upward velocities, (3) they involve magnetized plasma, and (4) magnetic fields of opposite polarities are often ($\gtrsim70\%$ of the cases) seen in their proximity ($\gtrsim2''$). In addition to this, the inversion of the Stokes profiles reveals that these events seem to belong to three distinct families. These families frequently present features such as: (5) temperature enhancement of a few hundred Kelvins in the mid-photosphere, (6) shift from supersonic upflows to supersonic downflows at some height in the photosphere, and (7) the presence of a reversal in the polarity of the magnetic field vector also at some height in the photosphere at the exact location where the event occurs.

Owing to their common features, and under the assumption that only one physical mechanism is responsible for all the observed events, it would be almost straightforward to consider magnetic reconnection as their probable cause: magnetic field lines of opposite polarity coalesce and the energy stored in the magnetic field is released into kinetic and thermal energy. The two different polarities would channel the plasma in different directions giving rise to both positive and negative line-of-sight velocities (Rezaei et al. 2007; Cameron et al. 2011). Unfortunately, not all investigated pixels share the aforementioned properties. For instance, only some cases ($\text{families 1 and 3}$) show both positive and negative supersonic line-of-sight velocities $V_{\text{LOS}}$, while $\text{family 2}$ possesses only $V_{\text{LOS}} < 0$ (upflows). In addition, the reversal in the polarity of the magnetic field vector is not always present (e.g., $\text{family 3}$; see Figure 6), and only in the case of $\text{family 1}$ ($14.3\%$ of the cases) does the reversal in $B_\parallel$ occur at the same location as the change in the sign of $V_{\text{LOS}}$.

On the one hand, taking into account that the interaction between magnetic fields and granular convection leads to a rich variety of phenomena, it is conceivable that the differences between the inferred families are caused by the underlying physical mechanism being different in each case. Although there are many possible candidates, a search across the available literature (Steiner et al. 1998; Cheung et al. 2008 and references therein) does not reveal any mechanism that reproduces the observational features, either in general or in the individual families, of the events studied in this work. For instance, the supersonic flows predicted by Cattaneo et al. (1990) and later observed by Rybáek et al. (2004) and Bellot Rubio (2009) occur above granules and involve supersonic flows, but they are mostly horizontal and therefore their contribution to $V_{\text{LOS}}$ is unlikely to be large. Flux-emergence processes described in Cheung et al. (2008) also take place in granules, but they do not seem to involve very large upflows. Swaying motions in flux tubes (Steiner et al. 1998) excite upward propagating shock fronts, but they occur mainly above intergranular lanes. Finally, vortex tubes that were originally found in granules (Steiner et al. 2010) have been recently associated with fast upflows but on nearby dark lanes (Yurchyshyn et al. 2011) and, therefore, they probably correspond to a different kind of event.

On the other hand, one could attempt to salvage the hypothesis of reconnection by adopting different views. For instance, we could argue that one cannot expect all families to be fully consistent with the classic picture of magnetic reconnection because they might correspond to different stages in the temporal evolution of the events (see Cameron et al. 2011). In order to rule out or to confirm this possibility, one would need an uninterrupted, and possibly longer, time series of L12-2 data. Hopefully, this will be possible in the upcoming second flight of SUNRISE/IMaX that is scheduled to take place in the summer of 2013. It can also be argued that, even if events belonging to $\text{family 3}$ do not show a polarity reversal in the magnetic field, this reversal can indeed take place in the upper photosphere ($\log \tau_5 < -3$; see Section 5.3). Moreover, even if the polarity reversal is not present on the same pixel, in Borrero et al. (2010) we had already detected opposite polarities within $2''$ in $70\%$ of the events. In the future, it would be very interesting to combine IMaX observations with data from the upcoming IRIS mission, to study a possible relationship between these reconnection events and the presence of mostly unipolar regions (coronal holes) and/or type II spicules in the chromosphere (McIntosh et al. 2011).

Comments from Oskar Steiner and Rolf Schlichenmaier are gratefully acknowledged. Thanks to Fatima Rubio for providing the heliocentric angle of the observations, and to Tino Riethmüller for pointing out an error in the identification of the
Co line spectral line in Figure 1. The German contribution to *SUNRISE* is funded by the Bundesministerium für Wirtschaft und Technologie through Deutsches Zentrum für Luft-und Raumfahrt e.V. (DLR), Grant No. 50 OU 0401, and by the Innovationsfond of the President of the Max Planck Society (MPG). The Spanish contribution has been funded by the Spanish MICINN under projects ESP2006-13030-C06 and AYA2009-14105-C06 (including European FEDER funds).

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