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Formation of the Penumbra and Start of the Evershed Flow

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Abstract. We analyze high-resolution observations of Active Region NOAA 11490, acquired on 2012 May 28 and 29. Spectropolarimetric measurements of the photospheric lines of Fe I at 617.3 nm and 630.25 nm were taken with the Interferometric BIdimensional Spectrometer (IBIS), mounted on NSO/DST, during about 30 minutes for each day. To study the evolution of continuum intensity, LOS velocity, inclination and strength of the magnetic field during the entire time interval, we also used data taken by SDO/HMI. We used the SIR code to invert the Stokes profiles observed with IBIS, using different initial models to take into account the physical conditions of the plasma in the region of umbra, penumbra, and quiet Sun. From the analysis of the SIR results, we found that, before the formation of the penumbra, the annular zone is characterized by downflows in the inner part. Furthermore, we observed that the onset of the classical Evershed flow occurs on a short time scale, 1–3 hours, while the penumbra is forming. In order to investigate the conditions that lead to the establishment of the classical Evershed flow, we analyzed the evolution of the continuum intensity, LOS velocity, inclination and strength of the magnetic field in a segment in the north-western part of the leading spot. In about 1 hour, we noted a clear evolution from redshift to blueshift in the penumbral filaments along the selected segment. We propose a scenario in which the penumbra is formed by magnetic flux dragged down from the canopy surrounding the initial pore: the Evershed flow starts when the sinking magnetic field dips below the solar surface and magnetoconvection sets in.

1. Introduction

The mechanisms responsible for penumbra formation remain unclear because their study requires time series observations of sunspots with high temporal, spatial, and spectral resolution carried out from their first appearance as pores (Thomas & Weiss 2004). We know that this process starts when some parameters, such as magnetic field strength or inclination angle, reach critical values. Leka & Skumanich (1998) found a critical value of magnetic field of $1–1.5 \times 10^{20}$ Mx above which a pore can develop a penumbra. Instead, Rezaei et al. (2012) proposed a critical magnetic field strength $B_{\rm crit} \leq 1.6$ kG and a critical inclination angle of the magnetic field $\alpha \geq 60°$ with respect to the normal to the photosphere, above which the penumbra begins to form. Recently, Schlichenmaier et al. (2010) found that the penumbra starts to develop on the side opposite the following polarity and it grows in sectors. For the first time they also observed, before the formation of the penumbra, a line of sight (LOS) velocity at some azimuths of opposite sign with respect to that displayed by the typical Evershed flow. In this contribution we report the analysis of the penumbra formation in the Active Region NOAA 11490, focusing the attention on the LOS velocity and magnetic field changes that occur during this formation process.

2. Observations and data analysis

The NOAA 11490 was analyzed using NSO/DST IBIS (Cavallini 2006) and SDO/HMI (Scherrer et al. 2012) during May 28–29, 2012.

The IBIS observations were carried out on 2012 May 28 from 13:39 UT to 14:12 UT, and on May 29 from 13:49 UT to 14:32 UT. For both days, the data set consists of 30 scans of the Fe I 630.25 nm line, with 67 s cadence. The line profile was sampled in spectro-polarimetric mode using 30 spectral points. To determine the evolution of the magnetic field strength, inclination, and azimuth, we performed a single-component inversion of the Stokes profiles for all the available scans of the Fe I 630.25 nm line using the SIR code (Ruiz Cobo & del Toro Iniesta 1992). The spectra were normalized to the quiet Sun continuum intensity, I_c. More precisely, we divided the FOV into three regions, identified by different thresholds in I_c to account for the different physical conditions: quiet Sun ($I_c > 0.9$), penumbra ($0.7 < I_c < 0.9$), and umbra ($I_c < 0.7$). For each of these regions we chose a different model of atmosphere for the inversion. After we obtained the magnetic field strength, inclination, and azimuth, we resolved the 180° azimuthal ambiguity using the non-potential field calculation approach of Georgoulis (2005), and transformed the components of the magnetic field vector into the local solar frame. We also estimated the plasma velocity along the LOS using Gaussian fits of the line profiles. The Doppler shift of the centroid of the line profiles in each spatial point was measured with an estimated relative error of about ±0.2 km s^{-1}. The velocity was calibrated by imposing that the plasma in a quiet Sun region has on average a convective blueshift (Dravins et al. 1981), while was set to zero in the umbra.

We analyzed Space weather HMI AR Patches (SHARPs, Bobra et al. 2014) continuum filtergrams and Dopplergrams in the Fe I 617.3 nm line, taken by SDO/HMI over the same period, in order to study the evolution of the LOS velocity field in the forming penumbra. These data cover one day of observation, from 2012 May 28 at 14:58:25 UT to May 29 at 14:58:25 UT. The cadence of these data is 12 minutes and their angular resolution is 1″. We also analyzed the components B_r, B_θ, B_ϕ of the magnetic field vector deduced from SDO/HMI SHARPs data.

The IBIS and SDO/HMI observations were co-aligned using the first spectral image in the continuum of the Fe I 630.25 nm line acquired by IBIS on May 28 at 13:39 UT and on May 29 at 13:59 UT, and the SDO/HMI continuum image closest in time (13:36 UT and 13:58 UT, respectively). We used the IDL SolarSoft mapping routines to take into account the different pixel sizes. To analyze the evolution of the plasma flow in the forming penumbra, we aligned the SDO/HMI images from 19:00 UT to 24:00 UT taking as reference image the first of these images.

3. Results

The pore shown in Fig. 1 forms its penumbra in about 24 hr (see top left and bottom left panels). In this time the pore changes its initial shape. In particular, the penum-

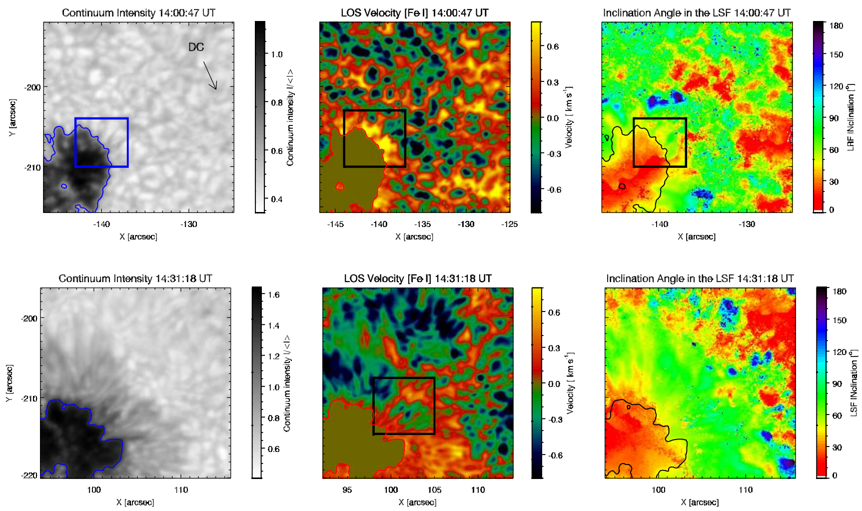

Figure 1. Maps of intensity (left), LOS velocity (middle), and inclination angle of the magnetic field (right) before (upper row) and after (lower row) penumbra formation. The maps of intensity and magnetic field inclination are obtained from the SIR inversion of the Stokes profile of the Fe I 630.25 nm acquired by IBIS. (Adapted from Murabito et al. 2016)

bra initially develops only in the north and south part of the pore, later it develops in the western part, and only at 23:58 UT it also develops in the part toward the opposite polarity. The right panels of Fig. 1 show the inclination maps of the magnetic field as obtained using the SIR code. These maps reveal that around the pore, before the penumbra formation (right top panel), the inclination is not constant but there are a number of sectors with different magnetic inclination. We called this kind of configuration (upside down) ballerina skirt structure of the magnetic field. There are also patches, characterized by an inclination of about 180°, corresponding to the polarity opposite to that of the sunspot. After the penumbra has formed (right bottom panel), the inclination angle increases gradually from about 40°–50° in the inner most penumbra to about 80°–90° at its boundary. The middle panels show the LOS velocity as deduced by the Doppler shift of the centroid of the Fe I 630.25 nm line. The area around the pore before the formation of the penumbra is characterized by downflows larger than 1 km s^{-1}. This is particularly evident in the region marked by a black square in the velocity map in the top middle panel of Fig. 1. This region is also characterized by elongated cells in the photosphere (marked by blue square in the continuum intensity maps of Fig. 1). The flow pattern after the penumbra formation is similar to the classic Evershed flow.

3.1. Evolution of the plasma flow in the forming penumbra

To follow the evolution of the forming penumbra and of the plasma flow we analyzed the SDO/HMI data. In particular, Fig. 2 shows the formation of the penumbra in the northwestern part of the pore from 21:12 UT to 21:58 UT on May 28. To further study the evolution of the flow parameters, i.e. continuum intensity, magnetic field strength, inclination angle of the magnetic field and LOS velocity, we analyzed them in the 2 pixel wide (and 25 pixel long) segment A overplotted in the maps of Fig. 2. During that

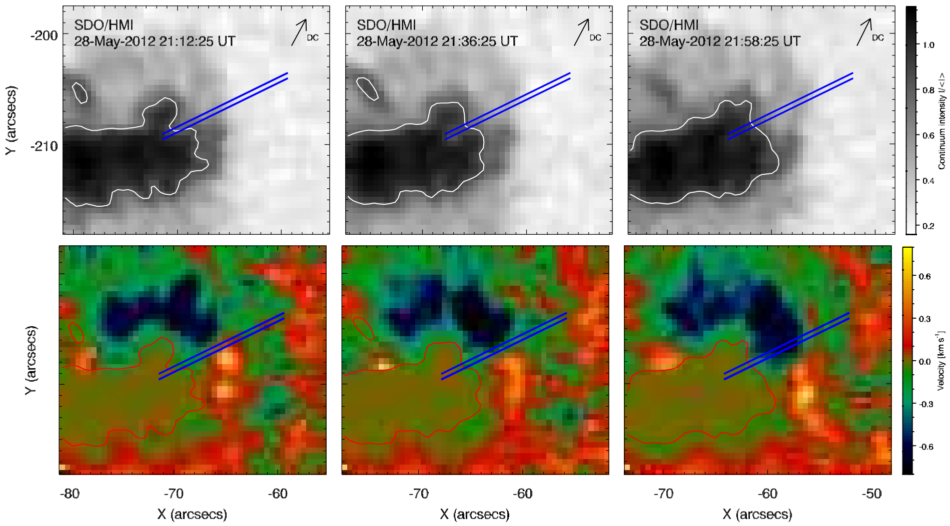

Figure 2. Maps of the continuum intensity (upper panels) and LOS velocity (bottom panels) from 2012 May 28 at 21:12 UT to 2012 May 28 at 21:58 UT as deduced by SDO/HMI. The arrows point to the disk center. (Adapted from Murabito et al. 2016)

time interval we can see that the blushifted region covers a larger range of azimuths around the growing spot in the top right area, while the area characterized by redshift decreases. In Figs. 5 and 6 in Murabito et al. (2016) we showed the evolution of the LOS velocity and the magnetic field strength along the segment on May 28 from 19:00 UT to 24:00 UT. These figures showed that in the inner part of the selected segment there is a clear evolution from redshift (see the curves in the bottom right panel of Fig. 5 in Murabito et al. (2016), at 19:00, 20:00 and 21:00 UT) to blueshift. This transition occurs between 21:00 UT and 22:00 UT. The bottom panels of Fig. 6 in Murabito et al. (2016) show the evolution for the magnetic field strength. We note that the magnetic field strength changes significantly (about 400 G) between 6″and 13″from the inner edge of the segment. Another important result is that the magnetic field strength increased only some minutes after the Evershed-like flow had already been established. In Fig. 7 in Murabito et al. (2016) we showed the differences between the values of physical parameters on May 28 at 24:00 UT and at 19:00 UT. This figure displayed that the continuum intensity decreases of about 20% in 5 hr between 6″and 11″ from the inner edge of the segment, and it increases by about 27% between 2″ and 6″. The increase can be due to the shrinking of the pore along this segment. This increase in the continuum intensity can be associated with the decrease that we saw in the magnetic field between 4″and 6″. Finally, a variation of about 20° can be detected for the inclination angle.

4. Conclusion

The most important result of this observations is that the velocity field changed sign in 1–3 hr along a cut starting from the pore into the nearby quiet Sun while the Evershed flow was established. The field strength increased only some minutes after the

Evershed-flow had already been established. In fact, the velocity had already changed sign (at 21:24 UT) while the magnetic field had still a very low value in the penumbral region (it increased to a higher value at 22:00 UT). To explain these results we propose the following scenario, described in more detail in Murabito et al. (2016). In the initial phase the canopy field of the pore gets weaker far from the boundary of the pore. Due to the weak field, the convective flows can drag down into the photosphere forming small U-loops where the inner footpoint has the opposite magnetic polarity to the pore. At the same time, this footpoint is the outer footpoint of an inverted U-loop that connects it to the pore. This configuration could explain the observed inverse Evershed flow because the external footpoint is brighter (hotter) than the pore, has little magnetic flux and has a comparatively weak field. In this situation, a siphon flow directed toward the pore is established. With time, more and more flux is dragged down, increasing the flux in the external footpoint of the inverted U-loop, at some point the field lines reach the solar surface. As a consequence, the region darkens as the magnetic field inhibits convection, but when the brightness reaches a new equilibrium at a lower value the darkening stops and the magnetoconvection starts. The process of the magnetoconvection has as a consequence the establishment of the Evershed flow.

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