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Sunspot evolution observed with SST

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Abstract. We report on the evolution of an active region NOAA 11263 observed with SST at extreme high spatial resolution (0.″15). We analyzed spectral and spectropolarimetric data acquired at Fe I 557.6 nm and 630.2 nm spectral ranges, respectively, to study the magnetic field properties and the dynamics of the plasma in the umbral and penumbral region of the sunspot. Interestingly, images acquired in photospheric continuum show twisting motions of the penumbral filaments. Moreover, we investigate if MMFs are present during the evolution of the sunspot. Brightenings in Ca II H line are also noticed, indicating the occurrence of transient phenomena in the chromosphere.

Key words. Sunspots – Sun: surface magnetism – Sun: photosphere – Techniques: high angular resolution

1. Introduction

Sunspots are one of the most remarkable phenomena of the solar magnetic activity and constitute a typical example of the process of interaction between plasma and magnetic fields.

The formation of a sunspot is associated to the emergence of magnetic flux tubes from the convective zone. The presence of strong (10^3 G) magnetic fields in the umbra is thought to inhibit the energy transport from the convection zone, leading to the local cooling of the photosphere. However, this process is not yet completely clear (Borrero & Ichimoto 2011).

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Recent high spatial and temporal resolution observations have revealed the presence of several small spatial scale phenomena occurring during the evolution of sunspots, whose properties still need to be investigated (Ichimoto et al. 2007; Borrero & Ichimoto 2011).

Among them of particular interest are umbral dots (UDs) observed in sunspot umbrae. These structures are transient brightenings with typical size of ∼ 300 km and lifetime of ∼ 10 minutes (Sobotka et al. 1997a,b). The mechanism behind UDs formation seems to be convection that interacts with the strong vertical field of the umbra. In the developed sunspots UDs are smaller and quiescent due to the stronger suppression of convection (Bharti et al. 2010).

Recent measurements carried out with an excellent spatial resolution ($\sim 0\farcs1$, which correspond to $\sim$ 70 km on the Sun's surface) were performed at the Swedish 1-m Solar Telescope (SST; Scharmer et al. 2003) in La Palma (Spain). They show the difference between the most dark component of the penumbra, which has a more inclined and weaker magnetic field, and the bright component, which has a stronger magnetic field and a more vertical inclination of the magnetic field lines. Consequently the penumbral magnetic field has a particular structure called "uncombed". Direct observational evidence supports the magnetoconvection nature of the penumbral structure and of the Evershed flow in presence of strong and inclined magnetic field (Deng et al. 2011).

Observations show horizontal plasma flow (Evershed flow; Evershed 1909) along the penumbral filaments and that the magnetic field inclination increase in the dark penumbral filaments, which carry the Evershed flow (Weiss 2006).

Other interesting features, whose nature is still unclear, are the crossing between penumbral filaments (Shine et al. 1994). This crossover is thought to be more consistent with a tube overlaying the lower penumbra than with a deep structure. Ichimoto et al. (2007) found in Hinode observations a number of penumbral bright filaments that revealed twisting motions around their axes. The twisting motions were observed only in penumbra. However these authors interpreted the twist not as an actual twist or turn of filaments, but as a manifestation of dynamics of penumbral filaments with three-dimensional radiative transfer effects.

Another phenomenon observed in sunspots is the presence of moving magnetic features (MMFs) which are a key element in the dispersal of the magnetic field. MMFs are small magnetic-flux concentrations, which usually appear in the sunspot penumbra. Later they interact with the ambient magnetic field, and then disappear (Zuccarello et al. 2009, and references therein).

In this contribution we will present extremely high resolution observations acquired by SST, showing some preliminary results about (i) the role of UDs inside the umbrae, (ii) Doppler velocity in penumbral filaments and its association with the Evershed flow, (iii) an observation of a twist in penumbral filaments.

2. Observations and data analysis

The datasets were acquired during an Observational Campaign which took place from the 6^{th} to the 19^{th} of August 2011 at the SST, in La Palma, Canary Islands (Spain). The active region NOAA 11263 was observed on August 6^{th} 2011, located at solar coordinates (621″,188″), from 09:53:32 UT to 10:48:43 UT, using the CRisp Imaging Spectropolarimeter (CRISP; Scharmer 2006; Scharmer et al. 2008) mounted on the SST.

Spectroscopic measurements were acquired along the Fe I line at 557.6 nm at 20 line positions in steps of 3 pm, from -27 pm to 27 pm with respect to the line center, and at a point in the continuum at 66 pm, taking 20 frame for each line position.

Full Stokes measurements were taken at 15 line positions in steps of 4.4 pm along the Fe I line at 630.25 nm, from -30.7 pm to 30.7 pm with respect to the line center. The average cadence of each scan is 28 seconds and the total number of scans acquired is 118. Liquid crystals modulated the light cycling through four polarization states, and 20 exposures per polarization state were acquired, resulting in a total of 80 exposures per line position.

Data acquired at the SST on the 6^{th} of August were calibrated using the standard reduction for dark current and flat field. These data were processed using the MOMFBD (Multi-Object Multi-Frame Blind Deconvolution; van Noort et al. 2005) technique in order to achieve the highest spatial resolution in combination with the adaptive optic. Wideband images, acquired simultaneously with the scans, were used as a so-called anchor channel to ensure precise alignment between the sequentially recorded CRISP narrowband images. Thus, we obtained two 3D-datacubes containing restored, aligned data.

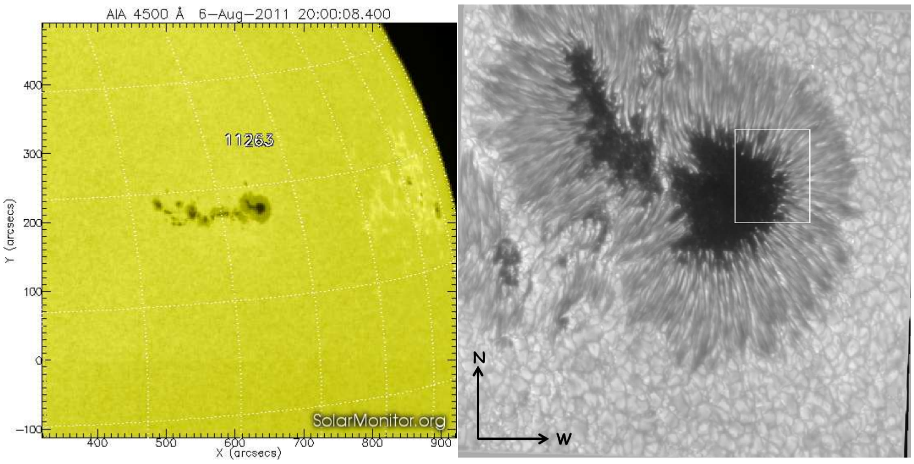

Fig. 1. *Left panel*: Image of the active region NOAA 11263 observed by AIA/SDO at 450 nm. *Right panel*: Image of the western sunspot observed by SST in the continuum of the line Fe I line at 557.6 nm on the 6th of August 2011. The FOV is 57.″5 × 57.″8. The north is at the top of the image and the west is on the right. We indicate with a rectangle a region where a twist of penumbral filaments occurred.

The plasma velocity along the line of sight was deduced using a Gaussian fit of the Fe I line at 557.6 nm extracted from the datacube. We calibrated the velocity by assuming that the global velocity field of the entire field-of-view (FOV) was zero.

Circular and linear polarization signals, derived from the Stokes parameters Q, U and V, were obtained using the innermost 10 spectral points of the Fe I line at 630.25 nm, using the following formulae:

$$V_s = \frac{1}{10 I_c} \sum_{i=1}^{10} \epsilon_i V_i,$$

$$L_s = \frac{1}{10 I_c} \sum_{i=1}^{10} \sqrt{Q_i^2 + U_i^2},$$

where I_c is the mean of the continuum intensity, $\epsilon_i = [1, 1, 1, 1, 1, -1, -1, -1, -1, -1]$, and i refers to the spectral points.

The Dutch Open Telescope (DOT) and the Solar Optical Telescope (SOT; Tsuneta et al. 2008) aboard the Hinode satellite performed joint observations of approximately the same FOV during the SST data acquisition. We used this data to complement SST information.

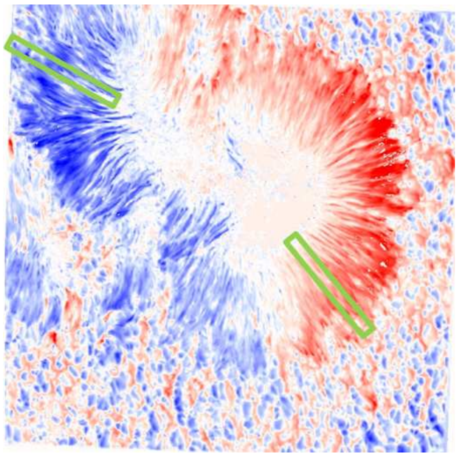

Fig. 2. Dopplergrams of NOAA 11263. Upward and downward motions are scaled respectively between -3 kms^{-1} (blue) and 3 kms^{-1} (red). Green rectangles indicate the two penumbral filaments analyzed in detail.

3. Results

Figure 1 (*left panel*) shows the photospheric configuration of NOAA 11263 as observed by AIA/SDO at 450 nm on the 6th of August 2011. The FOV of SST observations covers only the western part of the active region. We display in

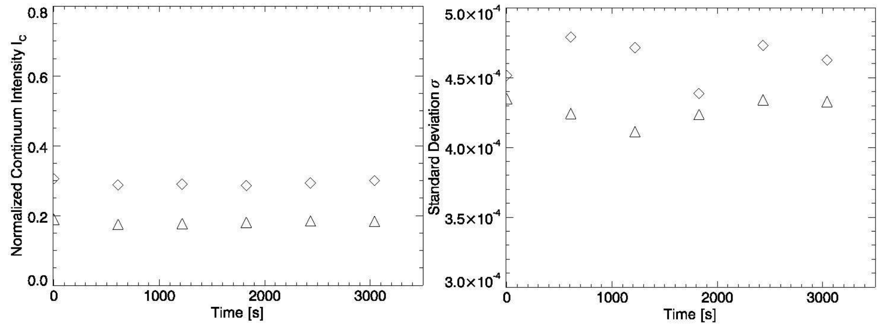

Fig. 3. Normalized continuum intensity of the western and eastern umbra (*left panel*) and standard deviation of the intensity of the western and eastern umbra (*right panel*). Triangles indicate the western penumbra, diamonds the eastern one.

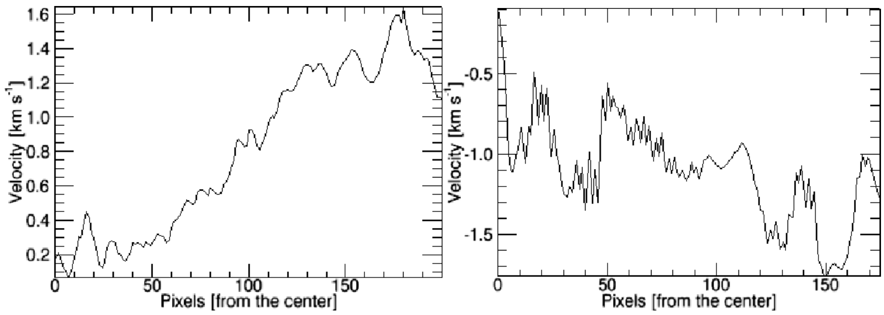

Fig. 4. Trend of the Doppler velocities computed along the western (*left panel*) and the eastern (*right panel*) penumbral filaments indicated in Fig. 2.

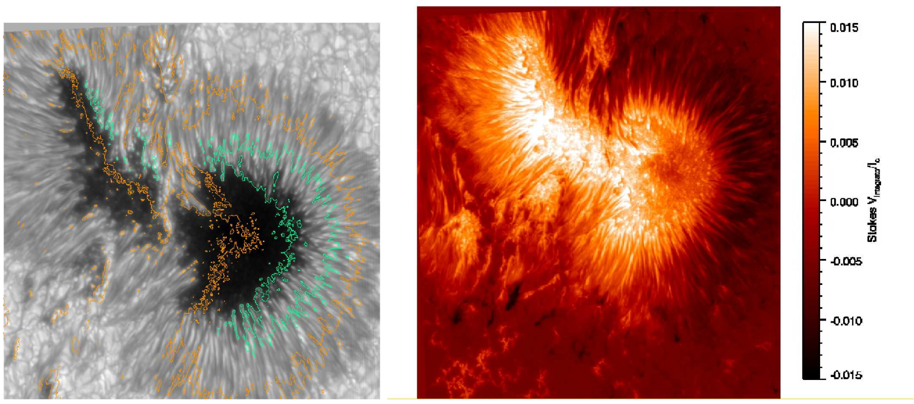

Fig. 5. Left: Contours of the linear polarization over the intensity map of the continuum of the Fe I line at 630.25 nm: green 5%, orange 2.5%. Right: Map of the circular polarization. The FOV is the same of Fig. 1. We can observe the details of the filamentary magnetic structure of the penumbra.

Fig. 1 (*right panel*) a sunspot of NOAA 11263 observed in the continuum of the Fe I line at 557.6 nm by the SST. This sunspot has two umbrae divided by a light bridge and surrounded by the same penumbra. The larger umbra has

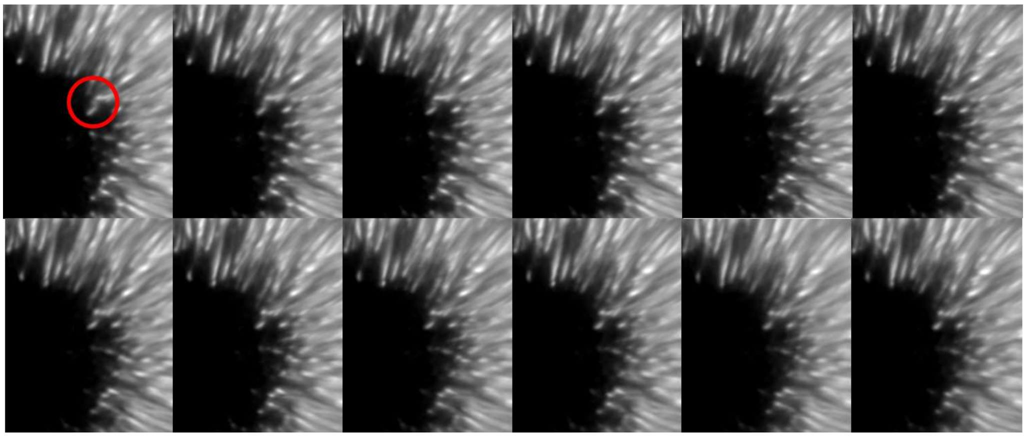

Fig. 6. Evolution of the penumbral filaments crossing each other (cadence of 27 s). The FOV is $9''.5 \times 11''.8$, indicated with the rectangle in Fig. 1 (*right panel*).

an area of 87 Mm^2 and the smaller one of 42 Mm^2.

We studied the evolution of the sunspot by extracting 6 images from each datacube of the observed region, with a cadence of 10 minutes.

The eastern umbra, which is more elongated, has several UDs and appears less homogeneus than the larger one. Figure 3 shows the temporal evolution of average (*left panel*) and standard deviation (*right panel*) of value of intensity contrast in the two umbrae computed in the Fe I 557.6 nm nearby continuum.

The eastern umbra is characterized by an intensity contrast that is almost 50% higher than the western one: this suggests a less efficient mechanism of inhibition of the convection in the eastern structure. Moreover, Hinode measurements of the magnetic field strength give an average intensity of ~ 2500 G in the larger umbra, ~ 2000 G in the smaller umbra.

The map of the Doppler velocity displayed in Fig. 2 clearly shows that the UDs are characterized by upflows, confirming the results obtained by numerical simulations of umbral magneto-convection (Schüssler & Vögler 2006), predicting the existence of upflows at the center of UDs. This dopplergram shows that upward and downward motions are also present in the light bridge, confirming previous findings (Hirzberger et al. 2002; Berger & Berdyugina 2003; Rouppe van der Voort et al. 2010).

In Fig. 2 we can observe a blueshift in the penumbral filaments toward the center of the disk and a redshift in the ones toward the limb of the disk, in agreement with the classical feature of the Evershed flow. We notice that plasma motion is present only in some penumbral filaments, not in the entire penumbra.

We analyzed the Evershed flow along two penumbral filaments, indicated in Fig. 2. Panels in Fig. 4 show the trend of the Doppler velocities computed along a western (*left panel*) and an eastern (*right panel*) filaments. The Doppler velocities in the filaments increase from the center of the sunspot toward the edges, but this increase is not continuous.

We plot the contours of the linear polarization signal over the sunspot, showing that the linear polarization signal is stronger in the penumbra than in the umbra (see Fig. 5, left panel). We also display the map of circular polarization in Fig. 5 (right panel). This shows that the circular polarization signal is stronger in the umbra than in the penumbra. Note that these polarization maps are affected by projection effects: an inversion of the spectropolarimetric data would be necessary to obtain the geometrical information about the vector magnetic field.

Looking at the temporal sequence of the circular polarization maps of the sunspot we observed several MMFs in the penumbral filaments: the MMFs appear and disapper along the penumbral filaments.

We found evidence of twist in the penumbral filaments of the sunspot. We display in Fig. 6 a sequence of 8 minutes of filtergrams in the Fe I 557.6 nm continuum, that shows the evolution of the region around the twist. Two close penumbral filaments cross each other before disappearing into the umbra. The twist is a not common event and it might provide information about the twisting in flux tubes.

We also found in the Ca II H core a plasma jet coming from the edge of the sunspot.

4. Conclusions

We studied the small-scale evolution of a sunspot in active region NOAA 11263 benefiting from extremely high resolution observations with long duration acquired by the SST. The most important results obtained in this analysis can be summarized as follows.

The higher continuum intensity, the larger number of UDs and the lower magnetic field (deduced from Hinode measurements) in the eastern penumbra suggest a less effective mechanism of convective suppression in this structure than in the western one.

The line-of-sight velocity increases along the penumbral filaments but some asymmetries are present between the eastern and western filaments.

The time sequence in the Fe I 557.6 nm continuum shows a clear evidence of a crossing between two filaments. We wonder if it is a real twist. It will be also interesting to study the evolution of MMFs and of the Ca II H jet.

It will be very important to further study these features, since we can better understand several small-scale physical processes thanks to the high quality of the sequence acquired.

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