PHOTOSPHERIC PLASMA FLOWS AROUND A SOLAR SPOT

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Abstract. We study photospheric plasma flows in an active region NOAA 8375, by using uninterrupted high-resolution SOHO/MDI observations (137 intensity images, 44 hours of observations). The active region consists of a stable large spot and many small spots and pores. Analyzing horizontal flow maps, obtained with local correlation tracking technique, we found a system of stable persistent plasma flows existing in the active region. The flows start on either side of the sunspot and extend over $100''$ to the east. Our measurements show that the speed of small sunspots and pores, averaged over 44 hours, was about 100 m s^{-1} , which corresponds to root-mean-square longitudinal drifts of sunspots of $0.67° - 0.76°$ day^{-1}. We conclude that these large-scale flows are due to faster proper motion of the large sunspot relative to the ambient photospheric plasma. We suggest that the flows may be a good carrier to transport magnetic flux from eroding sunspots into the outer part of an active region.

1. Introduction

Distribution of observed magnetic and intensity structures on the surface of the Sun and in its chromosphere and corona depends on the nature of both large scale (super and mesogranules) and small-scale (granules) subsurface flows (Leighton, 1964; Simon and Leighton, 1964). Coupling of the photospheric plasma flows and the magnetic field distribution, as well as the fact that the footpoints of chromospheric and coronal loops are located in the photosphere, means that the plasma flows lead to continuous restructuring of the photospheric magnetic fields and strongly affect the formation and evolution of the coronal field. Interaction of the magnetic fields with the granulation and supergranulation flows causes the photospheric magnetic flux of an active region to be dispersed over the solar surface on a time scale of days to months. It is also clear that the magnetic fields, in turn, have a great effect on the flow pattern. Inspections of flow maps showed that the size of network cells in plages is significantly smaller than that in the quiet Sun (Zwaan, 1978). The variety of observed flows around sunspots and pores (Simon *et al.*, 1988; Wang and Zirin, 1992) suggests that magnetic structures affect the flow of the photospheric plasma. Schrijver *et al.* (1996) showed that mobility of the magnetic elements (pores, small and large sunspots) depends on the net flux in them. Decrease of mobility with increasing flux then would imply that stronger magnetic fluxes should modify surrounding flow pattern. However, little is known on how a strong sunspot would

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affect the photospheric flow. The high-quality long-duration SOHO/MDI intensity image sequences are well suited to detect large-scale surface flows by direct displacement measurements of the local intensity pattern.

This paper is arranged as follows. In Section 2 we describe the observations and the data processing. In Section 3 the observational data were used to study the interaction between small-scale magnetic elements and the photospheric flows. We present a short summary in Section 4.

2. Data and Reductions

The data set contains observations of a large fast evolving sunspot with an extended plage region. Active region NOAA 8375 (Figure 1) appeared as a single sunspot on the visible part of the solar disk on 28 October 1998. Uninterrupted SOHO/MDI observations in the Ni I photospheric absorption line at 6767.8 Å continued for about 3 successive days (3–6 November 1998) with a time cadence of 1 min and a pixel size of $0.605'' \times 0.605''$. The first image was taken when the active region was located at N19 E17 and the last one at N19 W33. More details about this active region can be found in Wang *et al.* (2000) and Yurchyshyn *et al.* (2000) and Yurchyshyn, Wang, and Goode (2001).

We used here the data acquired at the time when the active region was near the central meridian, which includes observations starting on 3 November at 20:00 UT until 5 November 17:15 UT. First, the MDI images were accurately co-aligned with accuracy better than $1''$. To remove motion of the entire group due to the solar rotation we use the large sunspot, A (Figure 1(a)) as a reference object and we only consider here horizontal motions relative to the sunspot A. We used a local correlation tracking method to make the required measurements. The FWHM of the Gaussian window (tracking window) was $6'' \times 6''$. This characterizes the spatial resolution of a flow map and is sufficient to reveal large-scale photospheric motions. A flow map was calculated for each pair of successive images in the data set and is based upon a ~ 20 min correlation interval. November and Simon (1988) performed an extensive analysis of possible errors in the local cross-correlation measurements introduced by atmospheric seeing and evolution of the intensity field under study (solar noise). Since space-based observations are not affected by varying seeing conditions, this source of error is not critical in our case. By tracking the MDI intensity structures with a ~ 20 min time interval we primarily measure displacements of pores and small spots and reduce contributions from the motions of shorter lived granules. Compared to the granulation, pores and sunspots are large and high contrast features, which makes them easier to track. Bogart *et al.* (1988) showed that good results can be obtained on large-scale surface flows using the local correlation technique with a spatial resolution better than $1.5''$. MDI data have a resolution of $1.2''$, which is good enough for flow computation. Our error estimate is based on spatial and temporal consistency of the flow maps. Using a

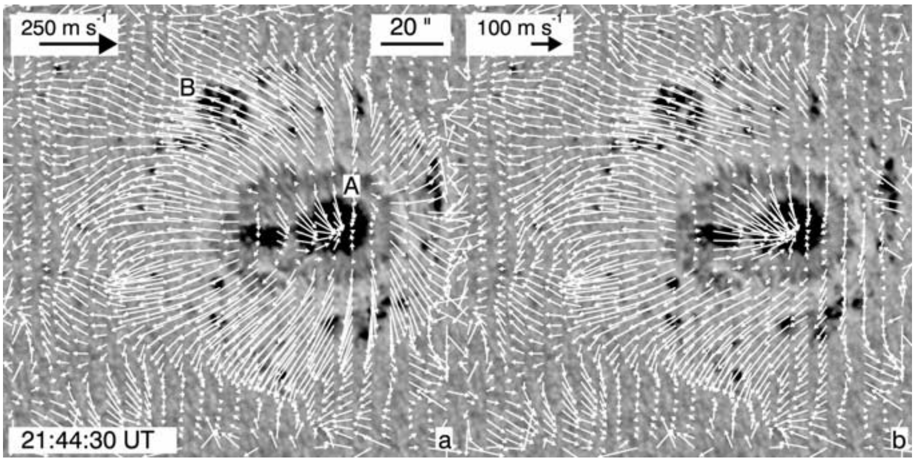

Figure 1. (a) A grey-scale SOHO/MDI Ni I 6767.8 Å intensity image is overlaid by an averaged horizontal flow map; (b) the same image overlaid by the horizontal velocity map with the moat outflow subtracted. North is up and west to the right.

44-hour intensity movie, we selected an extended area which showed a stable flow pattern. The error is defined as the minimum velocity value for which the velocity vector is guaranteed to be in the correct quadrant. Our estimation is that the solar noise is less than 30 m s^{-1}. The final map was derived from the 44-hour average (136 flow maps) of the local cross correlation, which eliminated all short-term oscillations in the horizontal velocity field as well as reducing noise.

3. Results and Discussion

One remarkable phenomenon which drew our attention is the existence of large-scale flows northeast and southeast from the sunspot *A* (Figure 1(a)). The horizontal flow map is a superposition of horizontal flows in the active region and the radial moat outflow around the sunspot. We subtracted the radial moat outflow velocity of 100 m s^{-1} and show the resulting flow map in Figure 1(b).

The flows start on either side of the sunspot and extend over 100″ to the east. The general picture of the flows resembles the pattern of a hydrodynamic flow around an solid obstacle. The role of an obstacle is played by the large sunspot *A*. A similar flow pattern has been found in the penumbras of δ-spots (Kálmán, 1997). The intensity movie shows that the small sunspots and pores, that have been formed along the moat boundary, flow around the sunspot in northeast or southeast directions, depending on their starting position. This can be seen in the right (western) part of Figure 1(a), where arrows create a fan-like pattern. The flow map suggests that these large-scale streams seem to occur due to the faster proper motion of the main sunspot relative to the ambient photospheric plasma. Because of the significant difference in mobility of different magnetic structures (see, e.g., the discussion by Schrijver *et al.*, 1996), the fast moving sunspot can resist the push of the oncoming photospheric plasma, while weaker objects are swept away by the flow. Our measurements show that the speed of small sunspots and pores, averaged over 44 hours, is about 100 m s^{-1}. It has been known for a long time that sunspots rotate faster than the surrounding photosphere (Waldmeier, 1939; Leka *et al.*, 1994; Strous *et al.*, 1996; Herdiwijaya, Makita, and Anwar, 1997). According to Herdiwijaya, Makita, and Anwar (1997) the root-mean-square longitudinal drifts of sunspots are $0.67°-0.76°$ d^{-1}, which corresponds to about 100 m s^{-1}. Strous *et al.* (1996) also found the speed of small spots and pores relative to the major sunspot in an emerging active region to be very close to the above value of about 100 m s^{-1}.

Our observations suggest that the large-scale flows may be an important and missing link in the transport of the magnetic fields. The moat outflow carries away a magnetic flux taken off the sunspot and transports it to the moat boundary. In fast evolving active regions the cell structure is very irregular and an evident supergranular pattern may only be found in the outskirts of active regions (Zwaan, 1978). Therefore, there should be a mechanism to dispose of the removed sunspot's magnetic flux into the outer part of an active region. Such an 'artificial sink' was indeed found in a numerical study of turbulent erosion of sunspots (Petrovay and Moreno-Insertis, 1997). The large-scale flows may be a good carrier to transport and to disperse the field. As we have already mentioned, large spots move faster than the ambient photosphere, while the rotational rate of the network fields well outside an active region does not significantly differ from the photospheric rotational rate (van Tend and Zwaan, 1976). A fast moving sunspot leaves the removed magnetic flux behind, hence the removed fields will tend to be dragged laterally eastward by the flow and will thereby become displaced to supergranular cells. Magnetic elements, being picked up then by the supergranular flows and displaced to the cell boundaries, continue to move along the boundaries and slow down at accumulation sinks and coalesce into a small sunspot (Title, Tarbell, and Topka, 1987; Schrijver *et al.*, 1996). Figure 2 demonstrates this. We show 36 hours of evolution of sunspot *B*, which was formed by 05:00 UT on 4 November. The sunspot was collected from the magnetic fields of the sunspot *A* brought by the large-scale flows, indicated by the arrows in the top-left image. There were many small dark pores traveling to sunspot *B* and the ring-shaped moat boundary. The sunspot umbra consisted of several pores which were pushed together, but they did not merge into one umbra as bright umbral bridges, which marked boundaries between the pores, were seen (image taken at 05:00:30 UT on 5 November). It is worth noting that the evolution of sunspot *B* was a competition between two parties: concentration of the magnetic flux by converging motions and destruction of an accumulation sink. The sunspot destruction was possibly connected with a rapid change of the sunspot velocity, which made the accumulation sink unstable. The mean velocity of the sunspot between 3 November, 03:00 UT and 4 November, 23:15 UT was about 0.08 km s^{-1}. However, after 23:15 UT its velocity suddenly increased up to 0.28 km s^{-1}. The

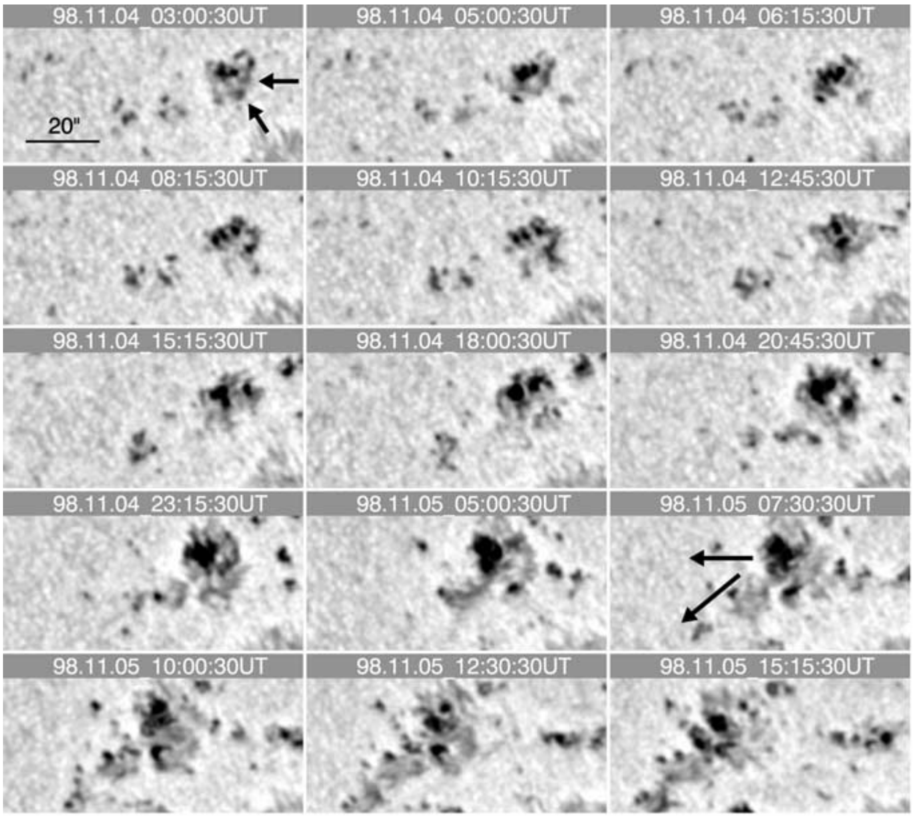

Figure 2. White-light images of 36 hours of evolution of sunspot *B*. The *arrows* show directions of the flows which bring pores to (03:00:30 UT image) and take them from (07:30:30 UT image) sunspot *B*.

sunspot was completely ruined by 15:00 UT on 5 November. The arrows in the 07:30:30 UT image (Figure 2) show the directions in which pores moved after the sunspot was destroyed. Several hours later on 5 November, at 19:45 UT a two-ribbon flare occurred in the active region. Our previous study shows that the flare was a result of interaction of two closed magnetic loops that have a small spatial angle (Yurchyshyn *et al.*, 2000). Taking into account the flow pattern, found in the current study, we suggest that the flare was a consequence of the rapid changes in the photospheric flow. Sudden and persisting dislocations of footpoints of magnetic loops forced a global re-organization of the coronal field which led to a solar flare.

Proper motion of the sunspot may also give rise to the specific moat structure. The moat boundary (a semi-circular chain of small pores in the SOHO/MDI image) is clearly seen only at the western part of sunspot *A* (Figure 1(a), see also Figure 3 in Yurchyshyn, Wang, and Goode, 2001). The boundary might be a result of converging motions of the westward directed moat outflow and the quiet-Sun photospheric plasma creeping eastward up the sunspot as it moves westward. This does not produce sink points but rather a converging line. This line becomes a locus where the magnetic fields merge and cancel continuously forming pores and small sunspots (Leka *et al.*, 1994).

In summary, we present new observations which indicate that faster proper motions of the main sunspot may cause a large-scale plasma flow in an active region. The general picture of the flows resembles the pattern of a hydrodynamic flow around a solid obstacle. We found that the flow significantly modifies distribution of the photospheric magnetic field in an active region. We suggest that the flows may be a good carrier to transport and to disperse the magnetic field of an eroding sunspot. We also propose that the flow may be at the origin of the ring-shaped moat boundary existing around the solar spot.

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