Astron. Astrophys. 339, L53–L56 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Upwelling in a young sunspot

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Received 23 September 1998 / Accepted 5 October 1998

Abstract. An upflow of with a velocity exceeding $0.5\,\mathrm{km{\cdot}s^{-1}}$ is found in the umbra of the preceding spot in a young active region with ongoing flux emergence. A weak downflow is indicated in the corresponding spot of follower polarity. Such a flow pattern is consistent with the counter-rotation flow along a rising magnetic flux loop driven by the Coriolis force as predicted by numerical simulations.

Key words: sunspots – Sun: magnetic fields – Sun: photosphere – Sun: activity

Table 1. Observing parameters (spectrograph and ASP)

Spectral range:	630.1–630.3 nm
Spectral resolution:	225 000 (@ 630 nm)
Dispersion:	1.19 pm/pixel
Spatial scale:	0.37 arcsec/pixel
Slit width:	0.6 arcsec
Step width:	0.375 arcsec/pixel
Integration time:	2.1 sec
Map cycle time:	$\sim$ 17 min/map (144 spectra)
Field of view:	53 x 74 arcsec

1. Introduction

Systematic photospheric flows in the umbrae of mature sunspots are insignificant (Beckers 1977, Schmidt & Balthasar 1993), so that almost hydrostatic equilibrium along magnetic field lines can be assumed. The mass flux due to the inverse Evershed effect in the chromosphere (Maltby 1975) is much too small to give rise to an appreciable photospheric flow. While the emergence of filamentary magnetic flux is generally associated with upward motion of horizontal field (Lites et al. 1998) and a downflow along less inclined magnetic field lines (e.g., Brants 1985), not much is known about the gas flows within young sunspots shortly after their formation. Such flows could possibly still bear the imprint of systematic motions along the rising magnetic flux tube from which the corresponding sunspot group forms. Simulations of flux loops emerging through the convection zone (e.g., Choudhuri 1989, Fan et al. 1993, Schüssler et al. 1994) predict such longitudinal flows arising from a combination of effects, namely, sliding motion associated with the Parker instability, Coriolis forces (angular momentum conservation), and remnants of a longitudinal flow in the original equilibrium of the flux tube (Moreno-Insertis 1997).

2. Observations and data analysis

The active region NOAA 7968 was observed close to disc center ($\cos\theta = 0.98$) at June 5, 1996, two days after its first registration (Solar-Geophysical Data 1996). The observations were carried out with the HAO/NSO Advanced Stokes Polarimeter (ASP; see Elmore et al. 1992, Lites 1996) operated at the VTT of the National Solar Observatory at Sacramento Peak, Sunspot, New Mexico, USA. The four Stokes parameters were measured and five spatial maps covering the active region were obtained consecutively in time between 13:41 UT to 15:04 UT by spatially scanning with the spectrograph. Further details of the observations are given in Table 1. The calibration (corrections for dark current, gain, instrumental polarization, and crosstalk) of the ASP data was carried out according to Skumanich et al. (1997).

Figs. 1 and 2 show the continuum spectroheliogram and the Stokes V amplitude, respectively, for the first map. Ongoing emergence of magnetic flux in this young active region was detected in the region between the main spots, where the magnetic field was found to be mainly horizontal (Sigwarth 1998).

Strength and inclination of the magnetic field were determined from an inversion of the Stokes vectors following Skumanich & Lites (1987). The line-of-sight velocity of the magnetized plasma was derived from the shift of the zero-crossing wavelength of the Stokes V profiles with respect to the rest wavelength of the line center. Only V-profiles of regular shape (no central reversals or mixed polarities within the resolution element) were taken into account. The telluric O_2 lines at 630.2 nm and 630.3 nm were used as wavelength reference in order to remove wavelength shifts due to instrumental effects. Taking into account the gravitational redshift, solar and terrestrial rotation as well as the orbital motion of the Earth, we achieved an absolute calibration of the Stokes V zero-crossing wavelength with respect to laboratory wavelengths for the two

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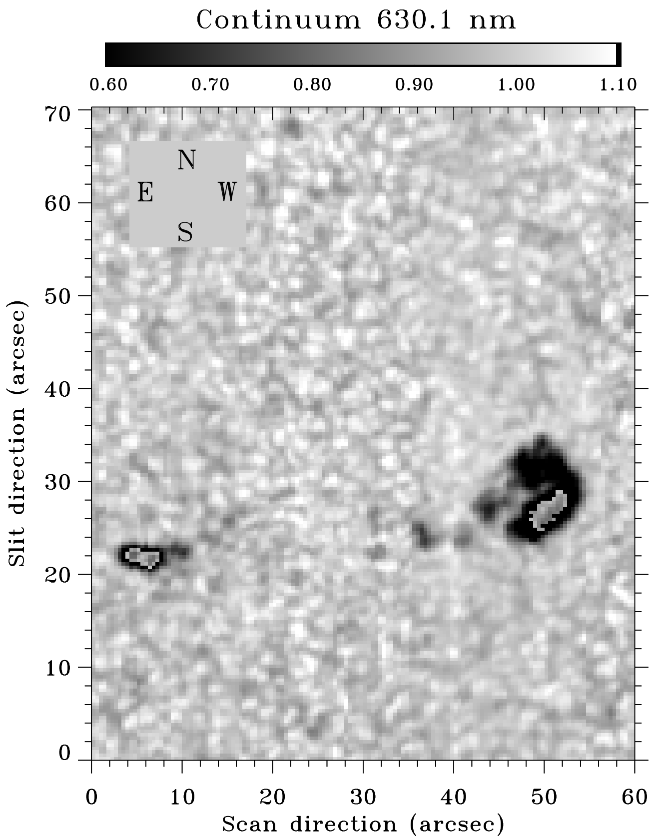

Fig. 1. Continuum spectroheliogram of the emerging flux region observed on June 5, 1996 at 13:41–13:58 UT. The spectroheliogram consist of 144 intensity scans at 630.1 nm. The intensity is normalized to the average intensity excluding the spots. The preceding spot is on the right-hand (west) side. The enhanced areas within the spots mark the location where the flows are observed. Disc center is in the direction of the lower right corner.

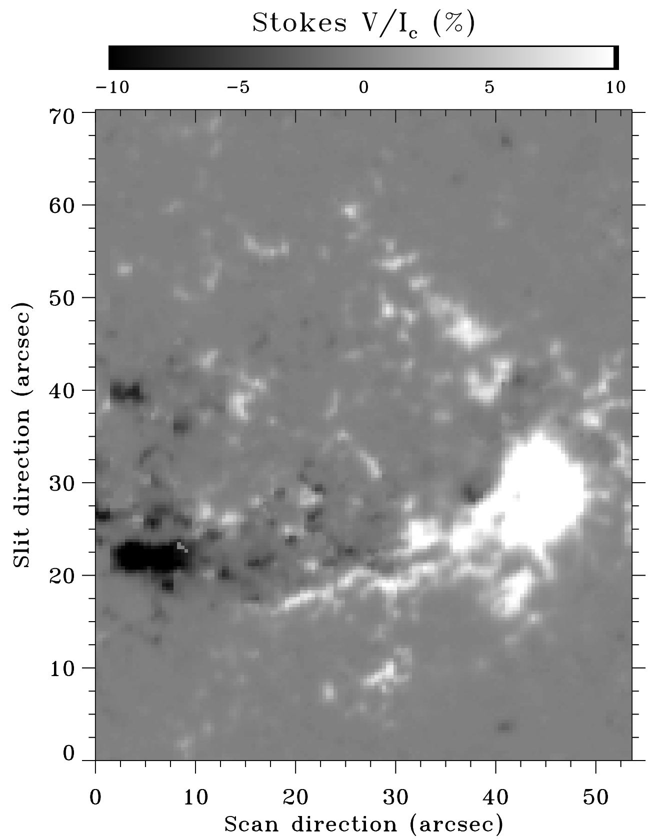

Fig. 2. Stokes-V amplitude map from FeI 630.25 for the observed region. Negative polarity (f-spot) is dark, positive polarity (p-spot) is bright.

Fe lines given by Higgs (1960, 1962). For the O_2 lines we used the wavelengths given by Pierce & Breckinridge (1973). We also made a correction for the slightly asymmetric instrumental profile of the spectrograph. The laboratory wavelengths of the Fe lines are known with an accuracy of $\pm$0.2 pm, equivalent to about $\pm$100 m·s^{-1}, and the wavelength positions of the O_2 lines are slightly dependent on air pressure ($\pm$0.02 pm), so the total systematic error is in the range of $\pm$120 m·s^{-1} . The determination of wavelength positions in the data (Stokes-V zero-crossing position, line core position) has a statistical error of $\pm$100 m·s^{-1} (mainly caused by measuring the location of the cores of the narrow O_2 lines). In the worst case, the error of the absolute velocity can reach a value of $\pm$220 m·s^{-1}.

3. Results

Fig. 3 shows scatter plots of the flow velocity (determined from the zero-crossing shift of Stokes V) vs. field strength for points from the first map with a field strength exceeding 0.1 T. Positive (upper panel) and negative (lower panel) magnetic polarity are shown separately. In our definition, the preceding (p) part is of positive polarity while the following (f) part has negative polarity (cf. Fig. 2). For fields strength below $\simeq 0.15$ T we find a general downflow of about 500 m·s^{-1}. Crosses indicate data points with a field strength exceeding 0.19 T together with a continuum intensity below a threshold of $0.45 I_0$ for the preceding spot and $0.70 I_0$ for the following spot, where I_0 denotes the average intensity outside the spots. In Fig. 1, the corresponding areas are indicated by artificially enhanced intensities. For the umbra of the p-spot we find an average upflow of 720 m·s^{-1}, whereas for the f-spot there is a small downflow of 85 m·s^{-1}. Table 2 gives the mean values and standard deviations for velocity, field strength, and field inclination. The temporal variation of the mean values over the five consecutive maps (covering a time span of about 70 min) is within the range of statistical and systematic errors.

Since the observed active region is very young, the measured line-of-sight velocities in the spot umbrae are probably affected by the ongoing separation of the polarities, i.e. negative polarity moving eastward, positive polarity moving westward. By comparing our five maps we find indeed that the spots move apart with a relative horizontal velocity of 440 m·s^{-1}. Due to the location of the observed region at N 2.6° and E 16.3° (heliocentric coordinates) this corresponds to a line-of-sight velocity of $\simeq 100$ m·s^{-1}. Even if we fully attribute this motion to the p-spot, the upflow in its umbra would clearly remain significant.

Table 2. Flow velocity, v, field strength, B, and field inclination with respect to the local surface normal, γ, averaged over the selected areas within the spots. Standard deviations (1σ) are given in the brackets. The number of data points included is noted in the last column.

	v (m·s^{-1})	B (T)	γ (deg)	# points
p-spot	-720 (107)	0.215 (0.01)	14 (8)	59
f-spot	85 (145)	0.215 (0.01)	11 (6)	34

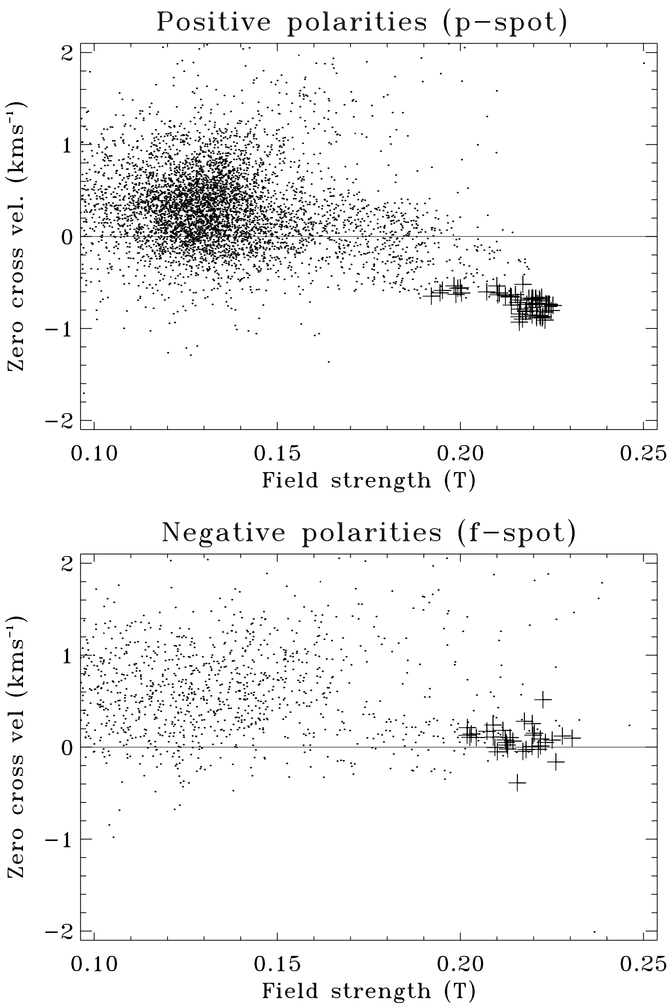

Fig. 3. Scatter plots of the flow velocity vs. magnetic field strength. The two magnetic polarities are considered separately in the upper and lower panel, respectively. Negative velocity corresponds to an upflow. The points marked with crosses are located in the darkest regions within the spots.

On the other hand, it cannot be excluded that the apparent downflow in the f-spot is partly due to the separation motion of the spots. We can rule out the Evershed effect as the cause for the observed velocities because the field inclination in the dark regions of the spots included in our analysis is almost vertical (cf. Table 2), so that we obviously have avoided penumbral regions with possible outflows. Considering the accuracy of the absolute velocity calibration of better than $\pm$220 m·s^{-1} and the standard deviations given in Table 2 we conclude that there is a clear upwelling in the umbra of the p-spot with a velocity exceeding 0.5 km·s^{-1}. On the other hand, there is no strong material motion in the f-spot; at most, a weak downflow is indicated.

4. Discussion

How can we physically interpret the observed flows, particularly the surprising upwelling in the umbra of the preceding spot? We can rule out a siphon flow (Meyer & Schmidt 1968, Montesinos & Thomas 1997): firstly, since p- and f-spot have almost the same field strength and, secondly, because any connection between the p-umbra and weaker magnetic features in the f-part would lead to a *downflow* in the p-spot, opposite to the observed flow direction. We can also exclude the strong upflows predicted by Schlichenmeier et al. (1998) since this mechanism applies only to the inner part of a well-established penumbra, while we consider umbral regions with nearly vertical field.

A possibility that is in accordance with the observed velocities is the counterflow against the direction of rotation (in a rotating frame of reference), which is caused by angular momentum conservation of the plasma carried by a rising magnetic flux loop. Such flows have been found in numerical simulations of flux tubes in the convection zone (Moreno-Insertis et al. 1994, Caligari et al. 1995, Fan et al. 1994). At the solar surface, the counterflow would correspond to upflows in preceding spots and downflows in follower spots. A detailed comparison with results of simulations cannot be made since the latter do not cover the actual flux emergence at the surface and the later evolution of the sunspots. Nevertheless, the flow direction (upflow in the p-part and downflow in the f-part) and also the magnitude of the upflow velocity are in agreement with the results of simulations that best reproduce other observed properties of sunspot groups like emergence latitudes, tilt angles, and geometrical asymmetry. For instance, Moreno-Insertis (1997, his Fig. 8) gives a longitudinal velocity of about 400 m·s^{-1} for the most likely value of the initial field strength of the magnetic tube progenitors of active regions, i.e., $B_0 = 10^5$ G (Schüssler et al. 1994).

On the other hand, we cannot expect the longitudinal counterflow along a flux loop to be maintained as a stationary flow from p-spot to f-spot for a long time after their formation. Soon after emergence, the loop arches high into the tenuous coronal layers, through which the large mass flux of the flow cannot be driven. Therefore, the flows in the p- and in the f-spot become disconnected and develop independently. It is therefore conceivable that the upwelling in the p-spot still continues while the f-spot already approaches hydrostatic equilibrium.

The evolutionary phase caught by the observations appears to provide the best opportunity to detect a possible surface manifestation of a flow along a rising flux loop. In the early phases of flux emergence the rapid ascent of the apex and the downward sliding motions associated with the fast rise in a strongly stratified background dominate. This motion corresponds to a downflow along mainly vertical fields, to which Stokes-V is sensitive. The general downflow of about 500 m·s^{-1} that we find for field strengths below $\simeq 0.15$ T may partly be due to this mechanism working in the region of ongoing emergence of magnetic flux between the spots. On the other hand, downflows are commonly found in high-resolution Stokes-V observations of magnetic fields outside sunspots (e.g., Grossmann-Doerth et al. 1996, Sigwarth et al. 1999). At later times (in mature sunspots) hydrostatic equilibrium along the field lines has established itself. Unfortunately, we do not have high-quality observations of the same spot at a later stage of development to confirm the fading of the upflow. On the other hand, most spectroscopic or polarimetric sunspot observations deal with mature sunspots and these observations invariably show the absence of a systematic flow.

In an earlier attempt to detect longitudinal flows along emerging flux loops, Cauzzi et al. (1996) found a slight asymmetry between the downflow velocities measured in the positive and negative magnetic polarity, respectively, averaged over large regions of flux emergence and decreasing with time. The difference of up to 150 m·s^{-1} was interpreted as an indication for a longitudinal flow along the flux loop in the direction of rotation. Within the flux emergence region contained in our data set we find no indication of such a systematic downflow asymmetry. Note also that Cauzzi et al. used intensity profiles of a spectral line for their velocity determination so that they do not distinguish between magnetic and non-magnetic gas.

5. Conclusion

We have found a strong upflow in the p-spot and an indication for a weak downflow in the f-spot of a young active region with ongoing flux emergence. Horizontal polarity separation, siphon flow, and the Evershed effect can be excluded as explanations of this flow pattern. On the other hand, the observed velocities are consistent with the counterflow along a rising magnetic flux loop due to angular momentum conservation. More observations of young sunspots, preferably located at or very near disc center, are needed in order to examine whether the flow pattern found in this particular case is a general feature.

Acknowledgements. We wish to thank K.S.Balasubramaniam, the observing and programming staff at the NSO/SP VTT, and the ASP-group at HAO/NCAR for their support during the observations and the data reduction. We are grateful to Sami Solanki for thought-provoking suggestions. This work has been supported by the DFG (Deutsche Forschungsgemeinschaft) under grant Schm 1168/1-2.

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