A&A 403, L47–L50 (2003)
DOI: 10.1051/0004-6361:20030576

Astronomy
&
Astrophysics

Field-aligned Evershed flows in the photosphere of a sunspot penumbra

L. R. Bellot Rubio[1], H. Balthasar[2], M. Collados[3], and R. Schlichenmaier[1]

[1] Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany
[2] Astrophysikalisches Institut Potsdam, Telegrafenberg, 14473 Potsdam, Germany
[3] Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Spain

Received 18 March 2003/ Accepted 16 April 2003

Abstract. We determine the inclinations of the vector magnetic field and flow velocity in a sunspot penumbra by interpreting full Stokes profiles of three infrared lines observed with the Tenerife Infrared Polarimeter. It is shown that analyses based on one-component atmospheres deliver flow velocities which are more horizontal than the average magnetic field by up to 10 deg. This apparent violation of the concept of frozen-in magnetic fields is solved as soon as two magnetic atmospheres are allowed to coexist in the resolution element. The magnetic field and velocity in the atmospheric component carrying the Evershed flow are found to be aligned to within ±2 deg all the way from the inner to the outer penumbra. This is the first observational confirmation of magnetic fields being frozen into the plasma in sunspots. Our results indicate that sunspot penumbrae can be understood in terms of inclined flux tubes embedded in a more vertical background field. The flux tubes carry most of the Evershed flows and return to the solar surface in the middle penumbra and beyond. The background atmosphere is essentially at rest in the inner penumbra, and harbors small flows in the outer penumbra.

Key words. MHD – plasmas – Sun: magnetic fields – Sun: photosphere – line: profiles

1. Introduction

In the limit of infinite magnetic Reynolds numbers, the magnetic flux across any surface moving with the plasma remains constant with time (e.g., Priest 1984; Stix 2002). The magnetic field is then said to be frozen into the plasma. In this situation, two plasma elements lying initially on the same field line will do so at all subsequent times. Mass can flow freely along the field lines, whereas transverse motions push and drag them.

The magnetic Reynolds number is defined as $R_{\rm m} = v\ell/\eta$, where v represents the velocity of the plasma, ℓ the typical length of magnetic field variations, and $\eta = 1/(\mu\sigma)$ the magnetic diffusivity, with σ the electrical conductivity, and μ the magnetic permeability. Adopting $v \sim 1$ km s^{-1}, $\ell \sim 200$ km, and $\sigma \sim 1$ A V^{-1} m^{-1} (Kovitya & Cram 1983), the magnetic Reynolds number can be estimated to be $R_{\rm m} \sim 250$ in the photospheric layers of the penumbra. This high value implies that material motions should occur along the lines of magnetic force if the field is static.

The fundamental concept of frozen-in fields has been invoked repeatedly in the context of sunspot penumbrae, both theoretically (Montesinos & Thomas 1997; Schlichenmaier et al. 1998) and observationally (e.g., Bumba 1963; Stanchfield et al. 1997; Westendorp Plaza et al. 1997; del Toro Iniesta et al. 2001; Thomas 2001), but it has never been confirmed by observations. In the penumbra, highly localized mass motions are known to exist. Flow velocities of several km s^{-1} (Bumba 1960; Wiehr 1995; Schlichenmaier & Schmidt 2000) and even supersonic values (del Toro Iniesta et al. 2001) have been reported in connection with the Evershed effect. These flows are generally recognized to be more horizontal than the average vector magnetic field (Adam & Petford 1991; see also the introduction of Title et al. 1993 and the review by Solanki 2003, Sect. 7.3.2). The apparent violation of the frozen-in condition indicated by the observations is often disregarded alleging that the Evershed flows occur only in the dark penumbral filaments, where the magnetic field is more horizontal than the average (Title et al. 1993). No simultaneous measurements of the field inclination and the flow angle allowing for the fine structure of the penumbra have ever been carried out, so this conjecture remains to be proved.

Here we demonstrate that the Evershed flow is indeed aligned with the magnetic field in the penumbra of a sunspot, confirming the theoretical expectation that the field is frozen in the plasma. Our analysis is based on the interpretation of polarization profiles of infrared lines in terms of two magnetic atmospheres filling the resolution element. The need for such a complex modeling is illustrated by carrying out a more classical one-component analysis of the same data. We find maximum average speeds of 6.5 km s^{-1} for the Evershed flows in the outer penumbra. This mean velocity is only slightly smaller than the local sound speed of about 7 km s^{-1}.

Send offprint requests to: L.R. Bellot Rubio,
e-mail: `lbellot@kis.uni-freiburg.de`

2. Observations and data analysis

Active region 8704 was observed on September 20, 1999 with the Tenerife Infrared Polarimeter (TIP) at the Vacuum Tower Telescope of Teide Observatory (Spain). This rather symmetrical sunspot was located 40 degrees off disk center. Large heliocentric distances are important to maximize the Doppler shifts induced by the almost horizontal Evershed flows. TIP was used to measure the four Stokes profiles of the Fe I lines at 15647.3, 15648.5, and 15652.5 Å emerging from the spot. The three lines sample very deep and narrow photospheric layers. Figure 1 shows a map of the spot as seen in continuum intensity. During the observations, the image was stabilized by means of a correlation tracker. We estimate the spatial resolution to be about 1 arcsec. Further details of the observations are given by Balthasar et al. (2001).

The observed Stokes profiles have been corrected for instrumental polarization and then inverted with the help of the SIR code (Stokes Inversion based on Response functions; Ruiz Cobo & del Toro Iniesta 1992). Here we discuss results obtained under the assumption that the polarization profiles can be explained in terms of either one or two magnetic atmospheres filling the resolution element. Details of these inversions are given by Bellot Rubio (2003), who also compares the magnetic structure of AR 8704 resulting from four different physical models.

With a pixel size of 0.4×0.4 arcsec^2, the spatial map of Fig. 1 contains about 10 000 resolution elements. The inversion is run for each pixel independently. This yields the parameters of the various atmospheres filling the resolution element: the three components of the vector magnetic field, the line-of-sight (LOS) velocity, the macroturbulence, the temperature, the fraction of area occupied by each atmospheric component (if appropriate), and the amount of stray light. All these atmospheric parameters are taken to be constant with optical depth except for the temperature (whose stratification is allowed to vary with depth by means of two nodes). This is a reasonable assumption because the lines we consider are formed in photospheric layers not thicker than one or two decades in $\log \tau_5$, where τ_5 is the continuum optical depth at 5000 Å. Electron pressures and densities are computed from the inferred temperatures assuming hydrostatic equilibrium and the equation of state of an ideal gas with variable mean molecular weight to account for the partial ionization of the various atomic species.

The azimuth and inclination of the vector magnetic field returned by the inversion code are expressed in the LOS reference frame. We have transformed these values to the local reference frame by taking into account the position of the spot on the solar disk and the direction of positive Stokes Q defined by the polarimeter. In this paper, inclinations range from 0 to 180 deg and are measured with respect to the solar local vertical.

Details of the calculation of the magnetic field and velocity zenith angles are given below:

Magnetic field inclination. This free parameter of the inversion is essentially determined from the relative amount of linear and circular polarization. Since we are interested in general trends rather than in local fluctuations, we consider the variation of the mean zenith angle with distance from sunspot center. To this end, radial profiles are constructed by averaging the zenith angles of individual pixels along azimuthal paths centered on the spot.

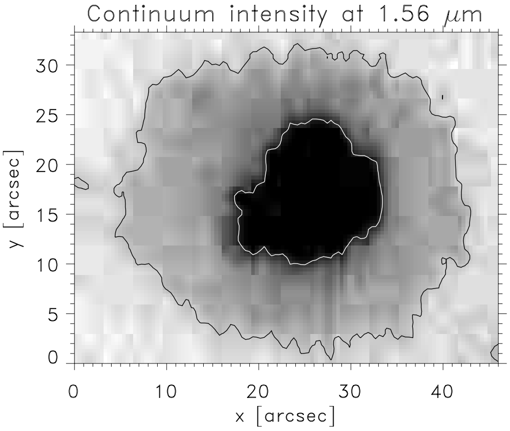

Fig. 1. Continuum intensity map of AR 8704 as observed with TIP on September 20, 1999. The line of symmetry connecting the sunspot's center with the center of the solar disk coincides with the y-axis. The limb-side penumbra is at the bottom.

Velocity inclination. The vector velocity cannot be inferred directly from the observations, because only the LOS component induces a Doppler shift in the Stokes profiles. However, it is possible to determine the inclination of the flow from the azimuthal variation of the LOS velocity by assuming that the flow speed depends only on radial distance, and that the vector velocity has no azimuthal component. These assumptions seem to be justified in view of the symmetry of the spot. Only two disturbances (obvious in the maps of physical quantities but not in Fig. 1) are present in our penumbra at $(x, y) \sim (13, 27)$ and $(34, 27)$ arcsec.

The local reference frame is defined by the z-axis coinciding with the local vertical and the x-axis pointing to disk center along the symmetry line. Let v_z and v_r represent the vertical and radial components of the vector velocity in this reference frame. v_z and v_r are positive upwards and outwards, respectively. The projection of the flow velocity to the LOS is

$$v_\mathrm{LOS}(r, \varphi) = v_\mathrm{r}(r) \sin\theta \, \cos\varphi + v_\mathrm{z}(r) \cos\theta, \qquad (1)$$

where r represents radial distance, θ the heliocentric angle of the observations, and φ the azimuthal angle around the spot center measured counterclockwise with respect to the x-axis (e.g., Kinman 1952; Maltby 1964; Schlichenmaier & Schmidt 2000). From the inversion we know v_LOS as a function of r and φ for the various atmospheric components. A least-squares fit of the inferred LOS velocities to Eq. (1) is done *separately* for each atmospheric component in order to determine the vertical and radial components of the corresponding velocity fields. From these values, the flow angles are computed as $\gamma = \arctan v_\mathrm{r}/v_\mathrm{z}$, and the flow speeds as $v = (v_\mathrm{r}^2 + v_\mathrm{z}^2)^{1/2}$. Figure 2 presents an example of one such fit. As can be seen, the azimuthal variation of the LOS velocity is well described by a cosine function, implying that the assumptions leading to

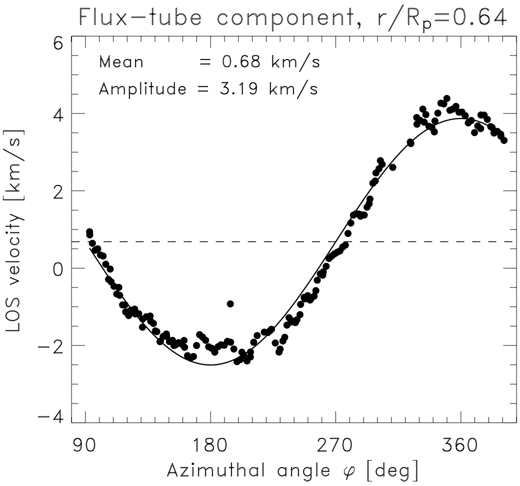

Fig. 2. Azimuthal dependence of the LOS velocity in the atmospheric component describing penumbral flux tubes at $r/R_{\rm P} = 0.64$ (dots) and best-fit sinusoidal curve of the form of Eq. (1) (solid line). The disturbance at $(x, y) \sim (13, 27)$ arcsec has been avoided. The horizontal dashed line represents the azimuthally averaged LOS velocity determined from the fit. Positive LOS velocities indicate blueshifts.

Eq. (1) are appropriate. The reliability of the flow angles depends critically on the absolute velocity calibration of the observations. In the absence of telluric lines or other means to define an absolute velocity scale, we use the central wavelength of the average quiet sun intensity profile as the position of zero velocities. All LOS velocities returned by the inversion code have been corrected for the convective blueshift of the lines before being analyzed. The convective blueshift is estimated to be 445 m s^{-1} according to the two-component model of the quiet sun of Borrero & Bellot Rubio (2002) and the results of Balthasar (1985). The absolute velocity scale of the observations should be correct to within ±100 m s^{-1}.

3. Results

Bellot Rubio (2003) points out that the structure of AR 8704 revealed by the two-component inversions used here is consistent with the notion of penumbral flux tubes embedded in a magnetic background atmosphere, as proposed by Solanki & Montavon (1993). The background component is characterized by rather vertical magnetic fields and does not harbor large flows. The atmosphere representing the penumbral tubes is characterized by nearly horizontal fields and carries most of the Evershed flow. Maximum LOS velocities in the flux tube component were found to be 6 km s^{-1}. A simple one-component inversion of the same data yields results that cannot be associated easily with either the background or the penumbral flux tubes (Bellot Rubio 2003).

The upper panels of Fig. 3 give the inclination of the flow velocity and magnetic field resulting from the one-component (left) and the two-component inversions (middle and right panels correspond to the background and flux-tube atmospheres, respectively). Error bars for the magnetic field zenith angle represent the standard deviation of the values entering the mean. Error bars for the flow angle have been computed through error propagation of the uncertainties in the best-fit coefficients. The lower panels of Fig. 3 show the flow speed as a function of radial distance.

Our one-component analysis is representative of many others based on the assumption than one atmosphere is able to describe the structure of the penumbra. With such an assumption, the *flow is found to be more horizontal than the magnetic field by 10 deg* (Fig. 3, upper left panel). Let us discuss now the more realistic two-component inversions. By considering two atmospheric components in the resolution element we make explicit allowance for the fine structure of the penumbra. This results in much better fits to the observed Stokes profiles (Bellot Rubio 2003). The inferred background atmosphere is characterized by very small flows in the inner penumbra, the flow speed never exceeding 0.4 km s^{-1} (Fig. 3, lower central panel). Under these conditions, the determination of $v_{\rm r}$ from the observed azimuthal variation of $v_{\rm LOS}$ is unreliable and we refrain from computing the flow angle in this part of the penumbra. In the outer penumbra (beyond $r/R_{\rm p} = 0.7$) the velocities are larger, and the flow is found to be more horizontal than the magnetic field. By analogy with the one-component inversions, this suggests that our background atmosphere is a mixture of several magnetic components. In the outer penumbra, the first atmospheric component returned by the inversion code probably represents a combination of background and some penumbral tubes that continue upwards through the canopy, as sketched by del Toro Iniesta (2001).

Because of the much larger flow speeds (up to 6.5 km s^{-1}), the magnetic component representing the penumbral tubes is responsible for the largest fraction of the total mass flux. The upper right panel of Fig. 3 demonstrates that the Evershed flow in this atmosphere is perfectly aligned with the magnetic field. This is a solid result: a *systematic* error of 100 m s^{-1} in the LOS velocities (due to uncertainties in the correction of convective blueshift) would change the flow angles by a mere ±1.5 deg. The *maximum* inclination difference is about 2 deg, well within the error bars. Only in the very outer penumbra does the flow become more horizontal than the magnetic field as a consequence of a fast decrease of the vertical velocity. The less redshifted vertical velocities found near the outer boundary are probably due to quiet sun granulation intrusions encountered by the more external azimuthal paths.

4. Conclusions

Semiempirical models of the penumbra obtained from the inversion of Stokes profiles have achieved a reasonable degree of realism. Analyses based on two magnetic components allow us to confirm important aspects of magnetohydrodynamics in the solar photosphere. In this Letter we have demonstrated that the Evershed flows are aligned with the vector magnetic field in the penumbra. The concept of frozen-in fields (taken for granted by solar physicists without real proof) is then confirmed observationally. This result has important implications for our understanding of sunspot penumbrae. We now have solid observational evidence of Evershed flows being channeled by penumbral flux tubes. Our analysis confirms and

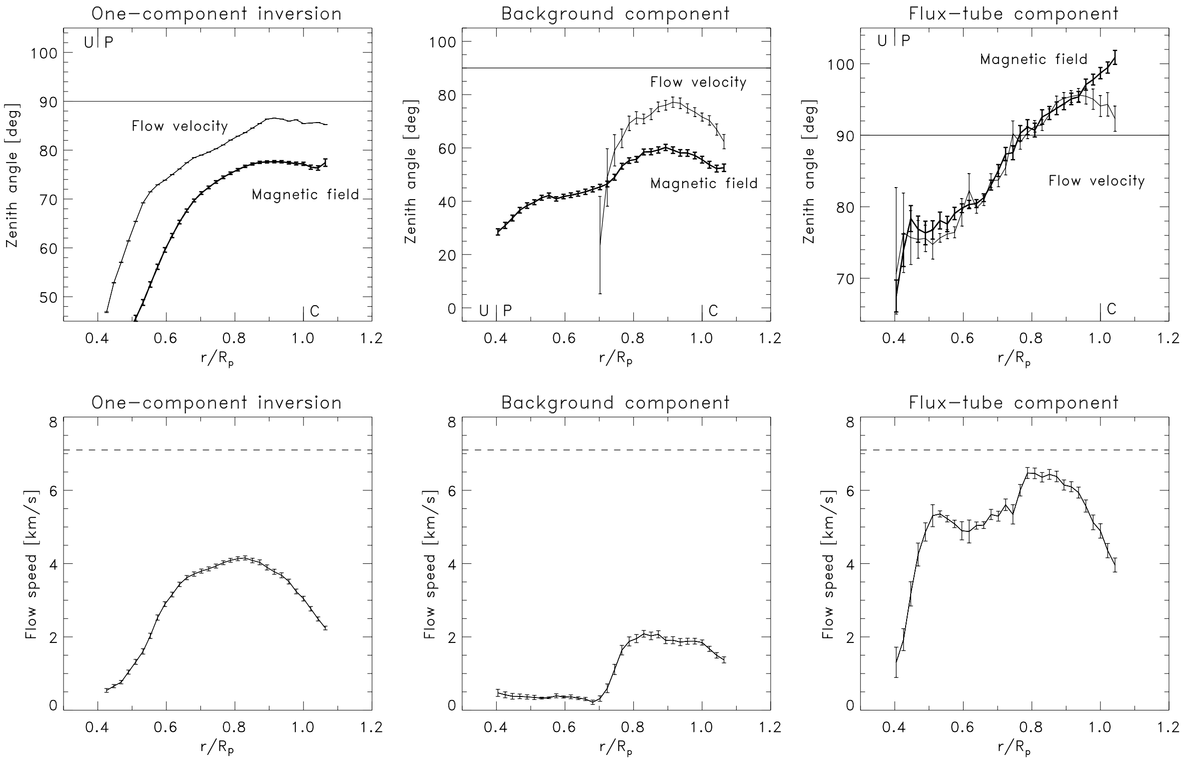

Fig. 3. *Top:* Radial dependence of the magnetic field (thick lines) and velocity (thin lines) zenith angles in AR 8704 as inferred from one-component (left) and two-component inversions (center, right). Central panels correspond to the background atmosphere and right panels to the fluxtube component carrying most of the Evershed flow. *Bottom:* Variation with radial distance of the flow speed as deduced from the analysis of the observed LOS velocities. The horizontal dashed lines represent an estimation of the local sound speed. The umbra/penumbra boundary is at $r/R_{\rm p} = 0.4$, and the outer penumbral boundary at $r/R_{\rm p} = 1.0$.

substantiates earlier conjectures that a sunspot penumbra is essentially a two-component structure with strongly inclined tubes harboring the Evershed flow and a more vertical background where plasma motions are almost absent. Apparently, there is no need to invoke smaller substructures to describe the main features of the penumbra.

The excellent agreement between the flow angle and the magnetic field inclination indicated by Fig. 3 suggests that proper motions of the flux tubes in the vertical direction (i.e., motions transverse to the field lines) cannot be very large, otherwise the flow would be more vertical or more horizontal than the magnetic field. Except perhaps in the very outer penumbra, we do not observe such differences.

Acknowledgements. Discussions with V. Martínez Pillet, B. Ruiz Cobo, O. Steiner, M. Stix, and J.C. del Toro Iniesta are gratefully acknowledged. We thank the referee for valuable suggestions. This work has been supported by the Deutsche Forschungsgemeinschaft under project SCHL 514/2–1 and by the Spanish Ministerio de Ciencia y Tecnología under project AYA2001-1649.

References

Adam, M. G., & Petford, A. D. 1991, Sol. Phys., 135, 319
Balthasar, H. 1985, Sol. Phys., 99, 31
Balthasar, H., Sütterlin, P., & Collados, M. 2001, Astron. Nachr., 322, 367
Bellot Rubio, L. R. 2003, in Third International Workshop on Solar Polarization, ed. J. Trujillo Bueno & J. Sánchez Almeida, ASP Conf. Ser., in press
Borrero, J. M., & Bellot Rubio, L. R. 2002, A&A, 385, 1056
Bumba, V. 1960, Izv. Crim. Astrophys. Obs., 23, 253
Bumba, V. 1963, BAICz, 14, 137
Kinman, T. D. 1952, MNRAS, 112, 425
Kovitya, P., & Cram, L. 1983, Sol. Phys., 84, 45
Maltby, P. 1964, Astrophys. Norveg., 8, 205
Montesinos, B., & Thomas, J. H. 1997, Nature, 390, 485
Priest, E. R. 1984, Solar Magnetohydrodynamics (Dordrecht: Reidel)
Ruiz Cobo, B., & del Toro Iniesta, J. C. 1992, ApJ, 398, 375
Schlichenmaier, R., & Schmidt, W. 2000, A&A, 358, 1122
Schlichenmaier, R., Jahn, K., & Schmidt, H. U. 1998, A&A, 337, 897
Solanki, S. K. 2003, A&ARv, 11, 153
Solanki, S. K., & Montavon, C. A. P. 1993, A&A, 275, 283
Stanchfield, D. C. H., Thomas, J. H., & Lites, B. W. 1997, ApJ, 477, 485
Stix, M. 2002, The sun: an introduction (Berlin: Springer)
Thomas, J. H. 2001, in Encyclopedia of Astronomy and Astrophysics, (London: Nature Publishing Group, and Bristol: Institute of Physics Publishing), 3191
Title, A. M., Frank, Z. A., Shine, R. A., et al. 1993, ApJ, 403, 780
del Toro Iniesta, J. C. 2001, ASP Conf. Ser., 248, 35
del Toro Iniesta, J. C., Bellot Rubio, L. R., & Collados, M. 2001, ApJ, 549, L139
Westendorp Plaza, C., del Toro Iniesta, J. C., Ruiz Cobo, B., et al. 1997, Nature, 389, 47
Wiehr, E. 1995, A&A, 298, L17