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Some properties of an isolated sunspot

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Abstract. We present an investigation of a single sunspot observed in the neutral Fe line at 1089.6 nm with the Tenerife Infrared Polarimeter at the Vacuum Tower Telescope on Tenerife. Using the SIR code, we obtain maps of the magnetic field strength, inclination and azimuth, and Doppler velocities. The magnetic field strength drops from 2800 G in the umbra to about 700 G at the outer penumbral boundary, where we encounter an average magnetic inclination of 72°.
Comparing the magnetic flux passing through different areas, we conclude that the inner penumbra must be deep, while the outer penumbra could be shallow. Assuming that the magnetic field strength encountered at the outer penumbral boundary forms a smooth surface through which the total flux of the spot passes, it would be approximately an ellipsoidal cap with a top height of 5250 km. This scenario leads to an average vertical magnetic gradient of 0.4 G km^{-1}.
Evershed Doppler velocities are about 2 km s^{-1}. Two penumbral locations related to dark intensity features exhibit a steeper and slightly stronger magnetic field than elsewhere in the penumbra, and one of them is connected to an interruption of the Evershed effect.

Key words. sunspots – Sun: magnetic fields

1. Introduction

Sunspots with their strong magnetic field are an important topic for solar physics as described in the review of Solanki (2003). The availability of new polarimeters like the Advanced Stokes Polarimeter (ASP, Elmore et al. 1992) and the Tenerife Infrared Polarimeter (TIP, Martínez Pillet et al. 1997) gave important impetus to the investigation of the magnetic field in sunspots. Because the Zeeman splitting increases with wavelength, the infrared observations are extremely sensitive to the magnetic field. With these tools and sophisticated inversion codes the magnetic structure of sunspots was investigated by Lites et al. (1993), Westendorp Plaza et al (2001), del Toro Iniesta et al. (2001), Balthasar et al. (2001), Schlichenmaier & Collados (2002), Bellot Rubio (2003), Bellot Rubio et al. (2003), Mathew et al. (2003), and Bellot Rubio et al. (2004). The investigators observing in the infrared use iron lines in the 1500–1600 nm range which are very sensitive to the magnetic field, but with their high excitation potentials these lines become weak in the dark umbra. An important question for such investigations is the height dependence of the magnetic field strength. Mathew et al. (2003) found a very high value of 4 G km^{-1} for the decrease with height, while previous observations of photospheric lines in the visible yielded 2–3 G km^{-1} (Balthasar & Schmidt 1993) or 1.5–2 G km^{-1} (Westendorp Plaza et al. 2001). Values between 0.5 and 1 G km^{-1} were obtained from chromospheric lines by Rüedi et al. (1995) and Eibe et al. (2002). Investigations by Hofmann & Rendtel (1989) yielded even smaller values of 0.32 G km^{-1}. Hagyard et al. (1983) ascribed longitudinal field strengths of slightly above 1000 G, derived from the C IV line at 154.8 nm to a height range of 4000–6000 km.

An important question is whether the penumbra is deep or shallow. This has consequences for how to explain the penumbral structure, e.g. the interchange convection in the model of Jahn & Schmidt (1994) works only in a deep penumbra. Solanki & Schmidt (1993) followed an idea of Schmidt (1991) and compared the magnetic flux rising through the umbra with that passing through a hemisphere having the radius of the spot and the field strength measured in the outer penumbra. They found a significantly higher value for the hemisphere and concluded that at least half of the flux is rising through the penumbra, and therefore, the penumbra must be deep. Solanki et al. (1994) confirmed this result. From our observations we can determine the total magnetic flux passing through the visible layer of the sunspot. This amount turns out to be smaller than the flux passing through a sphere. Taking into account that the vertical component of the magnetic gradient differs from the horizontal one, we replace the sphere by a rotational ellipsoid and we will show that the outer penumbra might be shallow. The height of such an ellipsoid allows us to estimate the mean vertical magnetic gradient over several thousand kilometers.

2. Observations and data reduction

The isolated spot was observed on May 23, 2002 with TIP attached to the spectrograph of the German Vacuum Tower Telescope (VTT), located at the Observatorio del Teide, Tenerife. The spot was numbered AR 9958, and at the time of the observations it was 24° away from the center of the solar disk. It had a radius of 9480 km and did not change its size significantly compared to the day before. During the following days it became somewhat smaller before it disappeared behind the solar limb. TIP recorded the full Stokes vector of the neutral iron line at 1089.63 nm. With an excitation potential of 3.06 eV it does not change its strength very much from the quiet sun to the umbra, and there are no indications for blends in the umbra. It exhibits a Zeeman-triplet with a splitting factor of 1.5, so this line is well suited for sunspot investigations. At this wavelength, a splitting factor of 1.5 causes a wider separation of the Zeeman components than the frequently used lines Fe 525.02 nm (g = 3.0) and Fe 630.25 (g = 2.5).

The total exposure time to obtain the full *I, Q, U*, and *V* spectral images was 0.5 s each. A number of ten images were added up to increase the signal-to-noise ratio to a value of about 200 in the *Q, U, V* continuum. The pixel size corresponds to 0.″38 in the spatial and 2.26 pm in the spectral direction, respectively. The scanning perpendicular to the slit was performed with steps of 0.″4, obtaining the full map in 11.5 min.

The re-composed image of the spot is shown in Fig. 1. The achieved spatial resolution was slightly better than 1.″0. We would like to point to two dark patches in the penumbra indicated in the figure. Patch 1 is obviously connected to the umbra and is probably a part of it. For patch 2 there is only a narrow dark filament connecting it to the umbra. These patches disturb the symmetry assumed in Sect. 4, therefore we have to consider them. Time series of this spot obtained for central slit positions were investigated by Balthasar (2003).

The Stokes parameters are inverted using the SIR-code of Ruiz Cobo & del Toro Iniesta (1992) in the same way as Balthasar (2003). For the purpose of this paper we use only one atmospheric component (with a constant amount of 10% for the straylight coming from the quiet sun), in contrast to Bellot Rubio et al. (2004), where a two-component inversion is done. The code yields a temperature stratification and height independent values for the magnetic field strength, inclination and azimuth with respect to the line-of-sight (LOS), and the Doppler shift. Because only the iron line is included in the inversion, we kept the microturbulence fixed to 1800 m s^{-1} and the macroturbulence to 600 m s^{-1}. Since the line is coming from a narrow atmospheric layer as demonstrated by the response functions for the magnetic field in Fig. 2, height gradients would be doubtful. A comparison of observed and fitted line profiles is given in Fig. 3.

The azimuthal ambiguity of the magnetic field is resolved assuming a more or less radial structure inside the spot. If needed, the obtained azimuth is changed by 180° to fulfill this requirement. From the total field strength and the magnetic angles we calculate the Cartesian coordinates of the magnetic vector with respect to the LOS and rotate this vector to a frame with respect to the solar surface normal. From these values we obtain the final magnetic inclination and azimuth.

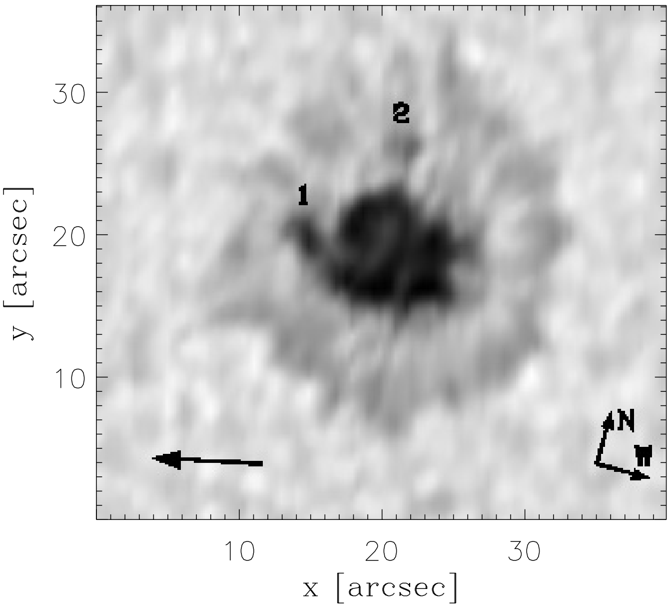

Fig. 1. Infrared intensity map of the spot, composed from the local continuum next to 1098 nm. The arrow points to disk center. Two dark penumbral patches discussed in the text are marked by digits.

3. Results of the inversion

The results of the SIR-inversion are shown in Fig. 4. A small but significant polarization is detectable outside the continuum boundary of the spot. If the integrated absolute circular and linear polarization both drop below 0.125%, we consider them to be noise and we suppress the corresponding areas in the following maps.

We obtain a maximum total field strength of 2800 G close in the center of the umbra, but not exactly there, and the field strength decreases to 720 G at the outer penumbral boundary. The mean radial dependence of the magnetic field strength corresponds to a horizontal gradient of −0.18 G km^{-1}. The two dark patches embedded in the penumbra in the North and East of the spot (indicated in 1) coincide with an enhanced magnetic field strength.

The magnetic field lines in the center of the umbra are almost perpendicular to the solar surface, while those at the southern penumbral boundary are almost horizontal; here we encounter values above 80°. The azimuthal average increases from less than 10° in the umbra to 73° at the outer boundary. The lowest inclination coincides much better with the center of the spot than the magnetic field strength. In the outer penumbra we do not find flux reversals. To the North and to the East there are two ridges with a smaller inclination (by about 20°) compared to the azimuthal average. The mentioned dark penumbral features fall onto these ridges. Another but less pronounced inclination ridge is detectable in the West. We do not find conspicuous variations of the inclination for the faint light bridges seen in Fig. 1.

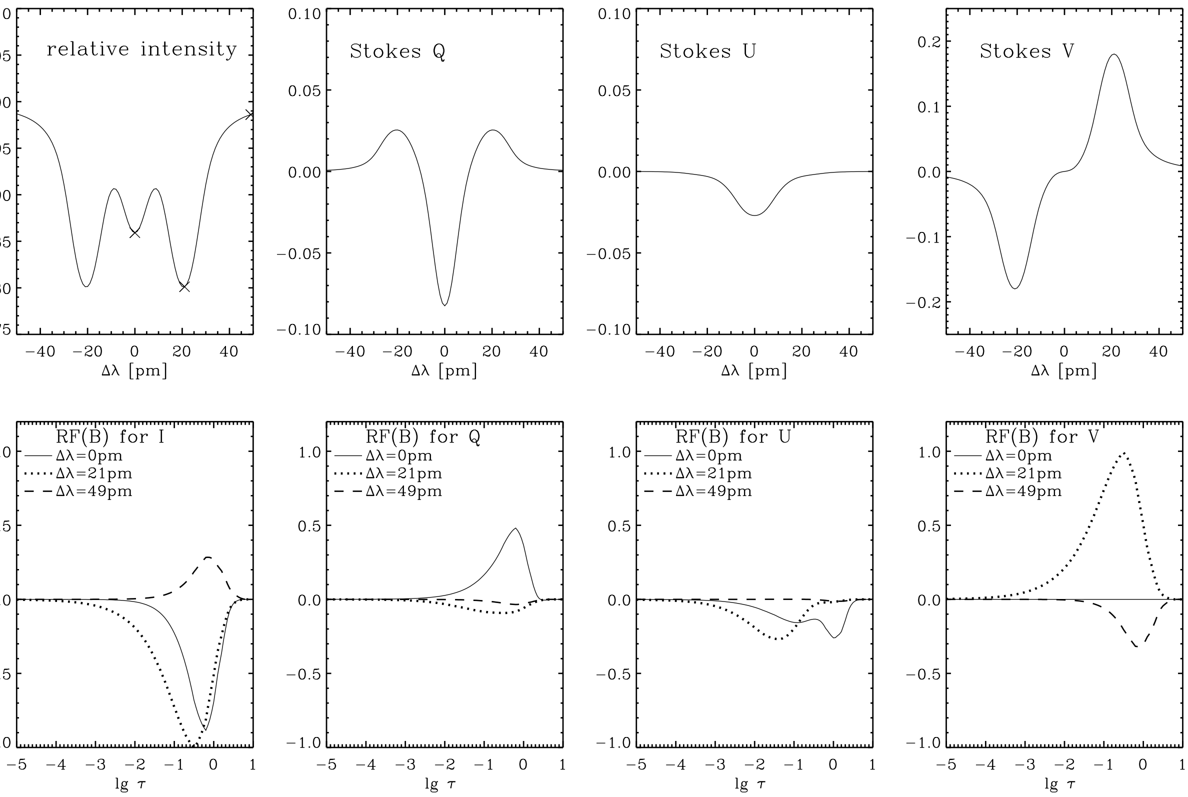

Fig. 2. Stokes profiles calculated with the DMG-code of Grossmann-Doerth (1994) for a magnetic field strength of 2500 G and an inclination of 30° in the umbral model M4 of Kollatschny et al. (1980). The U-profile is due to the magneto-optical effect. The lower row shows response functions of *I, Q, U*, and *V* to the magnetic field strength for the positions marked in the intensity profile. The response functions are normalized to the maximum absolute value of all plotted ones.

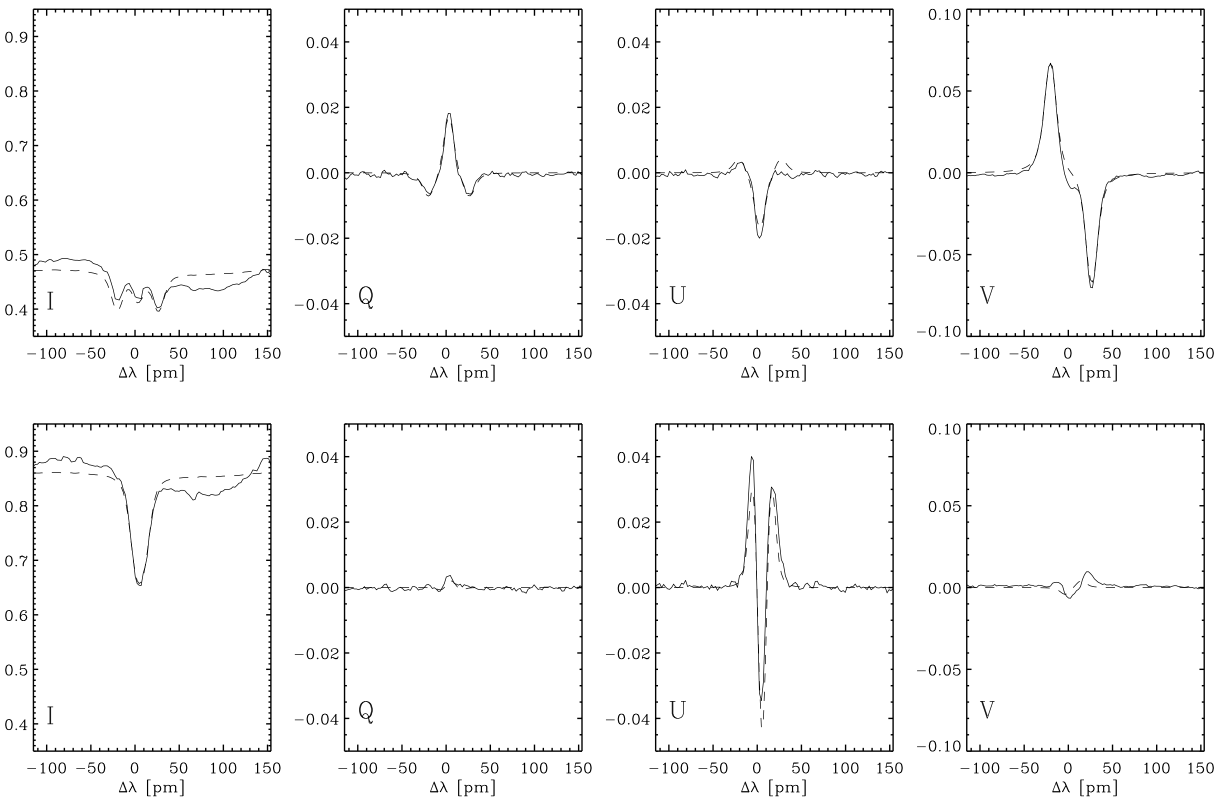

Fig. 3. Comparison of observed Stokes profiles (solid lines) and the corresponding SIR-results (dashed lines) for umbra (upper row) and penumbra (lower row). Intensity profiles are normalized to the continuum of the quiet sun. The observed intensity profiles are influenced by an interference pattern which did not disappear completely during the flatfield procedure.

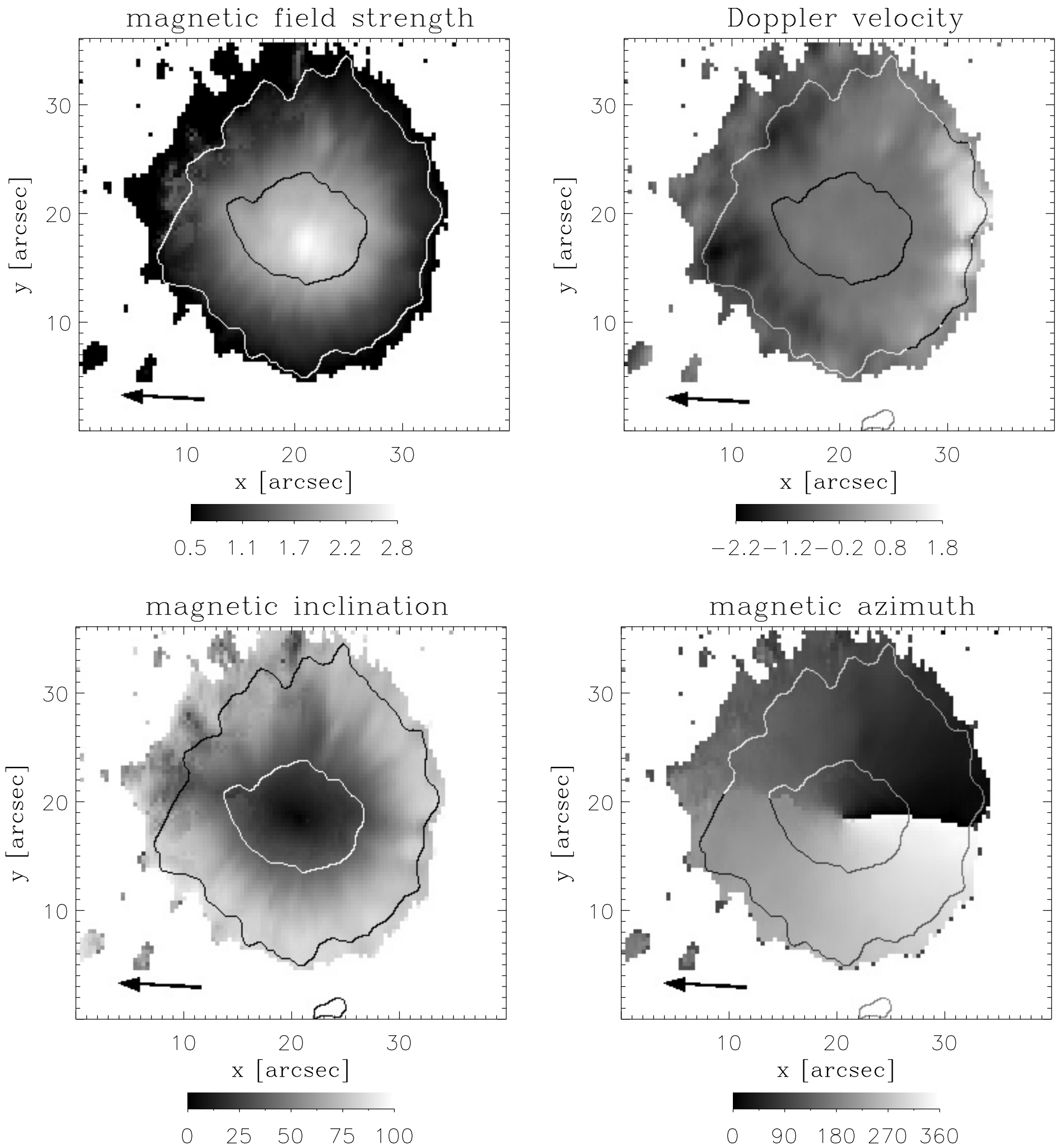

Fig. 4. *Upper left*: total magnetic field strength of the spot. The scale bar gives the magnetic field strength in kilogauss. *Upper right*: Doppler velocities, negative values are blueshifts. *Lower left*: inclination of the magnetic field in degrees. *Lower right*: azimuth of the magnetic field in degrees. The contours mark the boundaries of umbra and penumbra. Values at positions outside the spot where the polarization signal is very weak are suppressed. The arrow points to disk center.

For the magnetic azimuth no strong deviations from a radial structure are detectable, for most pixels these deviations are below 10 degrees. Exceptions are the penumbral ridges; there the magnetic field points away from the crest of the ridge with angles up to 20 degrees while the crest itself follows the radial direction. However, because we do not have a fixed common zero point for the geometrical height scale, the azimuth still might be slightly influenced by projection effects.

Doppler velocities connected with the Evershed effect vary between -2.1 and $1.75\ \mathrm{km\,s^{-1}}$, blueshifts correspond to negative velocities. Although the velocity reference is taken in an area of the quiet sun close to the spot, we detect higher velocities in the center side penumbra. High Evershed velocities coincide with more inclined magnetic field lines, in agreement with sophisticated two-component inversions, e.g. by Bellot Rubio et al. (2003). On the other hand, especially in the center-side magnetic ridge, we encounter low velocities for locations with a steep magnetic field. The highest blueshifts are found in two locations on both sides of this ridge, but not coinciding with the direction toward disk center. Another narrow gap is detectable in the limb-side penumbra.

4. Depth of the penumbra and the magnetic gradient

In this section we use the idea of Schmidt (1991) and Solanki & Schmidt (1993) to compare the magnetic flux passing through a certain area at the solar surface with that passing through

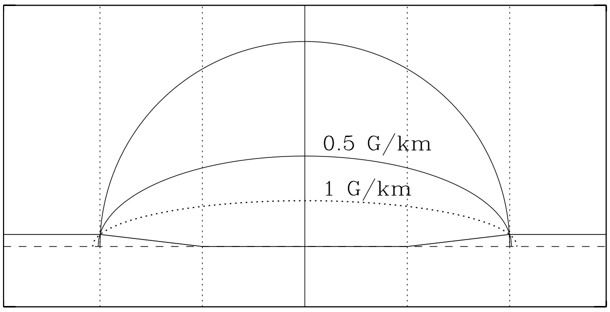

Fig. 5. Scheme for comparison of hemisphere and semi-ellipsoids for different vertical gradients of the magnetic field. The hemisphere corresponds to a gradient of 0.18 G km^{-1}. The dashed horizontal line indicates the geometrical height of the umbra, the solid line above stands for $\tau = 1$ assuming a Wilson depression of 800 km. The surfaces are semi-ellipsoids with respect to the dashed horizontal line. The solid vertical line is the axis of symmetry and the dotted lines indicate the boundaries of umbra and penumbra.

an isomagnetic hemisphere with the field strength at the outer penumbral boundary. In contrast to them we use a rotation ellipsoid. The surface area S of such a semi-ellipsoid is given by the equation

$$S = \pi b^2 + \pi ba \frac{a}{\sqrt{b^2 - a^2}} \cdot \operatorname{arsinh}\left(\frac{\sqrt{b^2 - a^2}}{\mathrm{a}}\right)$$

where b is the radius of the spot and a is the short axis perpendicular to the solar surface (the symmetry axis). The reason to use an ellipsoid is the fact that the magnetic field decreases much faster with height than with distance from the center of the spot. A vertical gradient of 2.5 G km^{-1} is found by Balthasar & Schmidt (1993), while the horizontal gradient of this spot amounts to 0.18 G km^{-1}. If the vertical gradient of Balthasar & Schmidt is constant with height, it would cause that a is only 850 km assuming a field strength of 3000 G at height zero. Figure 5 gives a scheme of a comparison of the hemisphere with ellipsoids for different height gradients of the magnetic field strength. A reasonable Wilson depression of 800 km (see Prokakis 1974; Balthasar & Wöhl 1983; and Solanki 2003) is assumed. The consequence of this is that we have to consider caps instead of full hemispheres or semi-ellipsoids. For all these considerations one implicitly assumes that the field lines pass the surface perpendicularly. We cannot give an argument that this is really the case, however the observed height dependence of the vertical gradient of the magnetic field suggests a goblet like structure of the magnetic field rather than the shaving brush like structure often shown, e.g. by Schmidt (1991). Such a configuration could fulfill the requirement of perpendicularity. Values for the magnetic flux are given in Table 1.

Assuming the surface of $\tau = 1$ as a plane (because we do not know its correct shape which is corrugated), only 41% of the magnetic flux rises through the umbra, in agreement with the statement of Solanki & Schmidt (1993). When we assume a Wilson depression of 800 km, the penumbral surface would be funnel-like with a tilt of 8$\stackrel{\circ}{.}$2, (as it is indicated in Fig. 5) the total flux reduces by about 13%, and the umbral contribution would be 48%. If we increase the tilt to 20°, we would obtain a reduction of the total flux by 34%, but that would lead to a Wilson depression of 2020 km which is rather improbable. However, following a field line with the mean radially dependent inclination from half the spot radius to the outer boundary, one would gain a height of 2890 km. Therefore we conclude that we measure real additional flux in the penumbra.

Table 1. Magnetic flux through different areas. Caps are reduced areas assuming a Wilson depression of 800 km. Top heights are calculated for a difference of 2100 G (difference between central umbra and outer penumbral boundary). The funnel-like penumbra has a surface tilted by 8$\stackrel{\circ}{.}$2 corresponding to the assumed Wilson depression.

Area of	$\Phi[10^{21}$ Mx]	Top height[km]
Umbra	1.10	0
Umbra and inner penumbra	1.92	0
Whole spot	2.67	0
Umbra plus funnel-like penumbra	2.31	0
Hemisphere	4.09	9480
Sphere cap	3.76	9480
Semi-ellipsoid 2.5 G km^{-1}	2.10	840
Ellipsoid cap	2.04	840
Semi-ellipsoid 1.0 G km^{-1}	2.27	2100
Cap	2.09	2100
Semi-ellipsoid 0.5 G km^{-1}	2.70	4200
Cap	2.41	4200
Semi-ellipsoid 0.4 G km^{-1}	2.95	5250
Cap	2.64	5250

Taking into account the result of Bellot Rubio (2003) from a two-component inversion, which yields one component with a steep magnetic field in the inner penumbra, we divide our penumbra in an inner and outer part defining the boundary somewhat arbitrary at a vertical field component of 1000 G. This value corresponds roughly to the vertical field strength at the location where Bellot Rubio et al. (2004) find the sharp transition from a steep to a more horizontal magnetic field in the second atmospheric component of their calculations. The area of the inner penumbra is shown in Fig. 6. We find that 72% of the magnetic flux rises through umbra and inner penumbra. Therefore we agree with Solanki and Schmidt that the inner penumbra must be deep, but the outer penumbra might be shallow.

From these values it becomes obvious that a hemisphere with a constant field strength is not a realistic assumption because more flux is going out than coming up through the area of the whole spot, and that would violate flux conservation. For a similar reason a magnetic decrease of 2.5 G km^{-1} must be restricted to photospheric layers. We find a good agreement for the flux through the whole spot at the solar surface and an ellipsoid cap assuming an average magnetic decrease of 0.4 G per kilometer of height. If there is a smooth surface with the constant field strength of the outer boundary of the penumbra (about 700 G), we expect to encounter this field strength at a height of 5250 km above the center of the umbra.

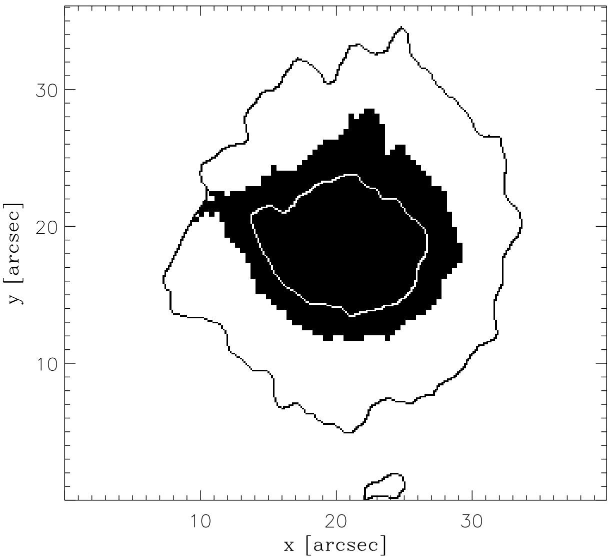

Fig. 6. Area of umbra and inner penumbra where the vertical component of the magnetic field strength is larger than 1000 G. The contours indicate the umbral and the outer penumbral boundary.

5. Discussion and conclusions

The general properties of this spot are in good agreement with various previous results, see e.g. Lites et al. (1993), Westendorp Plaza et al. (2001) and Mathew et al. (2003), i.e. a central field strength of about 2800 G declines to about 700 G at the outer penumbral boundary. The field lines are more inclined close to the outer boundary of the spot, but in the present investigation we do not find angles of more than 90 degrees, in contrast to Mathew et al. (2003). This might be a question of size of the spot; the spot observed by them was larger than the one of our investigation. In some cases downward field lines are found for one of two atmospheric components derived from an inversion (see del Toro Iniesta et al. 2001; Bellot Rubio 2003; or Bellot Rubio et al. 2004).

The special results are summarized here:

1. From a comparison of the magnetic flux through umbra, umbra plus inner penumbra and whole spot we conclude that the inner penumbra is deep while the outer might be shallow. The umbral contribution of 41% is rather small compared to the total flux, therefore more magnetic flux is needed. The contribution of the outer penumbra is also significant, but because of its extended area (72% of the total area of the spot) and the high inclination of the magnetic field one is not forced to assume a deep outer penumbra.
2. Calculating the flux through different ellipsoidal caps, we conclude that the average decrease of the magnetic field strength with height amounts to 0.4 G km^{-1} over a height range of 5250 km. We expect the magnetic field strength at the outer penumbral boundary of about 700 G to occur again in this height above the central umbra.
3. We find two or perhaps three magnetic ridges in the penumbra with a higher field strength than elsewhere in the penumbra; the field lines here are less inclined and point away from the crest of the ridge. Extraordinary dark penumbral features coincide with these ridges. We observe a gap of the high Evershed velocities on the center-side ridge and take this as an indication that the Evershed flow is concentrated in the more inclined filaments.

At the outer boundary of the penumbra, the magnetic field strength is of the order of 700 G. The corresponding magnetic pressure $B^2/8\pi \approx 2 \times 10^3$ Pa is of the same order as the dynamic pressure of granules rising with about 2 km s^{-1} and a density of 5×10^{-7} g cm^{-3} (1×10^3 Pa). Such granular velocities occur, see e.g. Balthasar (1998). Granules with a higher velocity would penetrate the magnetic field. Therefore it is rather probable that the outer boundary is determined by this equality. These considerations are in agreement with those of Wiehr (1996).

The vertical field gradient of 0.4 G km^{-1} is rather low compared to values of 2–3 G km^{-1} found by Balthasar & Schmidt (1993) or the 4 G km^{-1} recently obtained by Mathew et al. (2003) from an inversion technique. Both results are based on different photospheric lines. Our present investigation shows that such high values can be valid only for a narrow photospheric layer, otherwise flux conservation would be violated. Eibe et al. (2002) investigated the Na D_1 line and found vertical gradients of the order of 1 G km^{-1}. Rüedi et al. (1995) obtained 0.5 G km^{-1} comparing the He line at 1083 nm with the neighboring Si line. The He line originates 1500–2000 km above the photosphere. All these results would be in agreement if the magnetic field strength decreases rapidly with height in photospheric layers but much less so in the chromosphere. Nevertheless all these values are larger than those obtained from investigations by Hagyard et al. (1983) or Hofmann & Rendtel (1989). The lower limit of 4000 km for the longitudinal field of above 1000 G in the transition region given by Hagyard et al. might be in agreement with our result for the total field strength, but their upper limit of 6000 km appears too high.

Our considerations depend on the choice of 800 km for the Wilson depression. The Wilson depression is not a well determined quantity. Assuming smaller values, the differences between semi-ellipsoids and caps become smaller, and a stronger vertical gradient of the magnetic field is needed, otherwise the question would arise where all the outgoing flux comes from. On the other hand, assuming a larger Wilson depression, the gradient could be smaller, but as discussed in Sect. 4, the incoming flux would be smaller due to surface tilts. Altogether, the assumed Wilson depression of 800 km and the resulting vertical magnetic gradient of 0.4 G km^{-1} over a height range of 5250 km appear reasonable to us.

When we conclude that the outer penumbra might be shallow it does not mean that the magnetopause must fall together with the optical surface of $\tau = 1$, but the vertical extent would be much smaller than the radius of the spot. Thus our results are not in severe contradiction to the model of Jahn & Schmidt (1994), but note that the total magnetic flux of 2.67×10^{21} Mx we find is smaller than the minimum value Jahn & Schmidt need to balance the heat flux.

We do not want to discuss the penumbral structures in detail because the present investigation is based only on a one-component inversion. Investigations by Sütterlin (2001), Balthasar et al. (2001) or the first results from the new Swedish telescope on La Palma by Rouppe van der Voort et al. (2004) show that penumbral structures are smaller than the resolution of the VTT in the near infrared. Therefore an inversion with two or more atmospheric components is justified, but that will be the topic of a future paper.

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References

Balthasar, H. 1998, Astron. Nachr., 319, 387
Balthasar, H. 2003, Sol. Phys., 218, 85
Balthasar, H., & Schmidt, W. 1993, A&A, 279, 243
Balthasar, H., & Wöhl, H. 1983, Sol. Phys., 88, 71
Balthasar, H., Sütterlin, P., & Collados, M. 2001, Astron. Nachr., 322, 367
Bellot Rubio, L. R. 2003, in ASP Conf. Ser., 307, Solar polarization 3, ed. J. Trujillo Bueno, & J. Sánchez Almeida, 301
Bellot Rubio, L. R., Balthasar, H., Collados, M., & Schlichenmaier, R. 2003, A&A, 403, L47
Bellot Rubio, L. R., Balthasar, H., & Collados, M. 2004, A&A, in press
Eibe, M. T., Aulanier, G., Faurobert, M., Mein, P., & Malherbe, J. M. 2002, A&A, 381, 290
Elmore, D. F., Lites, B. W., Tomczyk, S., et al. 1992, Proc. SPIE, 1746, 22
Grossmann-Doerth, U. 1994, A&A, 285, 1012
Hagyard, M. J., Teuber, D., West, E. A., et al. 1986, Sol. Phys., 84, 13
Hofmann, A., & Rendtel, J. 1989, Astron. Nachr., 310, 61
Jahn, K., & Schmidt, H. U. 1994, A&A, 290, 295
Kollatschny, W., Stellmacher, G., Wiehr, E., & Falipou, M. A. 1980, A&A, 86, 245
Lites, B. W., Elmore, D. F., Seagraves, P., & Skumanich, A. P. 1993, ApJ, 418, 928
Mathew, S. K., Lagg, A., Solanki, S. K., et al. 2003, A&A, 410, 695
Martínez Pillet, V., Collados, M., Sánchez Almeida, et al. 1999, in ASP Conf. Ser., 183, High resolution Solar Physics: Theory, Observations and Techniques, ed. T. R. Rimmele, K. S. Balasubramaniam, & R. R. Radick, 264
Prokakis, Th. 1974, Sol. Phys., 35, 105
Rouppe v.d. Voort, L. H. M., Löfdahl, M. G., Kiselman, D., & Scharmer, G. B. 2004, A&A, 414, 717
Rüedi, I., Solanki, S. K., Balthasar, H., Livingston, W., & Schmidt, W. 1995, in 15thNSO/Sacramento Peak summer workshop, Infrared tools for solar observations – what's next?, ed. J. R. Kuhn, & M. J. Penn, 431
Ruiz Cobo, B., & del Toro Iniesta, J. C. 1992, ApJ, 398, 375
Schlichenmaier, R., & Collados, M. 2002, A&A, 381, 668
Schmidt, H. U. 1991, Geophys. Astrophys. Fluid Dyn., 62, 249
Solanki, S. K. 2003, A&A Rev., 11, 153
Solanki, S. K., & Schmidt, H. U. 1993, A&A, 267, 287
Solanki, S. K., Rüedi, I., Livingston, W., & Schmidt, H. U. 1994, in Infrared Solar Physics, ed. D. Rabin, J. Jeffries, & C. A. Lindsey, Kluwer, Dordrecht, IAU Symp., 154, 471
Sütterlin, P., 2001, A&A, 374, L21
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. 2001, ApJ, 547, 1130
Wiehr, E. 1996, A&A, 309, L4