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The three-dimensional structure of sunspots

I. The height dependence of the magnetic field

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ABSTRACT

Aims. We investigate the height dependence of the magnetic field of a sunspot, which has been until now a controversial issue.

Methods. Full-Stokes profiles of a sunspot, derived from infrared spectro-polarimetric measurements, were investigated. The magnetic field strength, inclination and azimuth were obtained using an inversion code. The results from two different spectral lines deliver the height dependence of the magnetic vector field. Vertical current densities and helicities as well as the vertical derivative of the vertical component of the magnetic field strength are calculated using Maxwell's equations.

Results. Inside the spot, the total magnetic field strength decreases with height, even in the outer penumbra, where the opposite trend was reported by other investigators. Outside the spot, the field strength increases with height apart from at a few small locations. This result is interpreted in terms of magnetic canopies. Magnetic field lines are less inclined in higher layers everywhere in the field of view. In the umbra, the vertical component of the magnetic field decreases by values in the range 0.5–2.2 G km^{-1}, depending on the applied method. Mean values in the inner penumbra are smaller than in the umbra. In the outer penumbra, the vertical magnetic component increases independently of the local intensity distribution. A pore close to the spot exhibits a more rapid decrease with height than the spot itself. The electric current densities and helicities depend on the fine structure of the sunspots. Typical values of the current densities vary in the range $\pm$40 mA m^{-2}. The mean values are -11 mA m^{-1} for the umbra and -2 mA m^{-1} for the penumbra, respectively, but the propagated errors are of the same order as the mean values. There are indications that the radial structure of the penumbra is related to enhanced current densities, but at the present resolution we are unable to establish a correlation with local intensity fluctuations.

Conclusions. If the spatial resolution is sufficiently high, electric current densities and helicities could be applied as reliable diagnostic tools for understanding penumbral fine structure.

Key words. Sun: sunspots – Sun: magnetic fields

1. Introduction

An important but so far unresolved topic in solar physics is the precise height dependence of the magnetic vector field in sunspots and their surroundings. Results differ depending on the applied method, as discussed in the following. One approach to deriving the solution is to compare results obtained independently from different spectral lines. Values of between 1.5 and 3 G km^{-1} were found by Wittmann (1974) and by Balthasar & Schmidt (1993). Moran et al. (2000) reported a gradient of 2 G km^{-1} close to the umbra and about 1 G km^{-1} in the outer penumbra. Leka & Metcalf (2003) compared data taken in a chromospheric line (Na D_1) with data from photospheric lines and arrived at a similar result. Their gradient for the penumbra is even smaller than that of Moran (2000). From a comparison of photospheric and transition region measurements (C IV), Hagyard et al. (1983) concluded that the gradient of the vertical component of the magnetic field is only approximately 0.1–0.2 G km^{-1}.

The second approach is to determine the atmospheric stratification from the inversion of one individual spectral line or a combination of two or more spectral lines. Mathew et al. (2003) found a value of 4 G km^{-1} using infrared lines originating deep in the photosphere, while Westendorp Plaza et al. (2001) measured 2.0 G km^{-1} and Sánchez Cuberes et al. (2005) derived 1.5 G km^{-1} from lines formed in the mid layers of the photosphere. Sánchez Cuberes et al. (2005) found that the gradient is almost independent of position inside the spot. Borrero et al. (2004) measured a rather large difference of about 800 G over a scale height of the optical depth in the inner penumbra. This difference decreases towards the outer penumbra. Extremely strong gradients of up to 6.5 G km^{-1} in the penumbra were also found by Moran et al. (2007) from observations of the Mg I-line at 12 μm. Westendorp Plaza et al. (2001) and Orozco Suarez et al. (2005) reported an increasing magnetic field strength with height in photospheric layers for the outer penumbra.

The height dependence of the z-component of the magnetic field strength can be determined also from the condition that the magnetic field is divergence-free. Hofmann & Rendtel (1989) obtained values of about 0.32 G km^{-1}, which are lower than values derived directly from the atmospheric stratification. For data sets of higher spatial resolution, Balthasar (2006) found a decrease of approximately 1 G km^{-1} with the same method.

A different method was presented by Brosius & White (2006), who observed the gyro-resonance emission above a large sunspot almost at the solar limb with the Very Large Array (VLA). From these observations at 8 and 15 Ghz, they inferred a magnetic scale height of 6900 km, which implies that the

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magnetic field strength is 960 G in a height of 12 000 km. The corresponding magnetic gradient agrees with that of the line comparison of Hagyard et al. (1983). Another estimate was presented by Balthasar & Collados (2005). They assumed that there was a smooth surface covering the entire spot of a constant magnetic field strength of 700 G, as observed at the outer penumbral boundary. The magnetic flux through such a surface must be the same as through the photospheric layer, where it can be measured directly for a certain spot. Balthasar & Collados (2005) found that these two conditions are fulfilled by a cap of an ellipsoid reaching a top height of 5250 km. The magnetic field strength decreases with height with an average value of 0.4 G km^{-1} over this height difference.

To derive information about the magnetic field in even higher layers of the Sun, one has to extrapolate the photospheric magnetic field. Methods to achieve this depend crucially on the correct knowledge of the vertical component of electric current densities. Current densities have also a high diagnostic potential to probe model calculations of the fine structure of sunspots. Title et al. (1993) investigated electric currents occurring in the model of a fluted penumbra. Electric current sheets play also an important role in the models of Schmidt (1991) and Jahn & Schmidt (1994). Investigations of vertical component of current densities were performed by DeLoach et al. (1984), Ding et al. (1987) and Hagyard (1988) based on vector-magnetographic measurements, as well as by Hofmann et al. (1988) and Hofmann et al. (1989). All of these investigations suffer from the low spatial resolution of the observations. Balthasar (2006) presented results from eight sunspots observed with improved but still insufficient spatial resolution, and found indications that the radial penumbral structure is related to electric currents. Jurčák et al. (2006) investigated vertical current densities close to light bridges and find high current densities along the light bridges.

Another important question to understand the physical nature of sunspots is whether the magnetic field is twisted. The current helicity is a direct indicator of the twist. Seehafer (1990) found that sunspots in the northern hemisphere have a negative current helicity and a positive one in the southern hemisphere. In an extended study, Pevtsov et al. (1995) confirmed this result as a general tendency. Socas Navarro (2005a) found that flux ropes of opposite helicity do coexist in one sunspot.

Until now, the measurements of the magnetic field are obtained either at low spatial resolution or are restricted to small areas such as that of a sunspot. In many cases, only the circular polarization is measured. In the present paper, we investigate the magnetic vector field of a sunspot and determine the vertical components of its electric current density and its current helicity at a high spatial resolution, i.e. of higher accuracy than 1 arcsec using a full Stokes spectro-polarimetry. For this purpose, we use two different spectral lines that originate in different atmospheric layers. Inversions are performed independently for the two lines because deriving the height dependence from the resulting stratification might be misleading if discontinuities occur (see Martínez Pillet 2000). Such discontinuities are present in the model of Schlichenmaier et al. (1998), where a fluxtube is embedded in a magnetic background. From spectropolarimetric observations, Jurčák & Sobotka (2007) derived atmospheric stratifications that have such embedded flux tubes.

2. Observations and data reduction

We observed the sunspot and its surroundings with the Tenerife Infrared Polarimeter (TIP 2, Collados et al. 2007) attached to the spectrograph of the German Vacuum Tower Telescope (VTT), located at the Observatorio del Teide, Tenerife. Measurements of the full Stokes vector were obtained on May 27, 2006 in a spectral range with two different spectral lines Fe I 1078.3 nm and Si I 1078.6 nm. Both lines are Zeeman triplets with a Landé-factor of $g = 1.5$. With an excitation potential of 3.06 eV, the iron line does not change its strength significantly from the quiet sun to the umbra. There are no indications of blends in the umbra. Therefore, this line is well suited for sunspot investigations. The silicon line has an excitation potential of 4.93 eV and is diminished in the cold atmosphere of the umbra.

To obtain the final Stokes-images *I, Q, U*, and *V*, ten sets of single exposures (50 ms) were coadded to increase the signal-to-noise ratio to a value of about 200 in the *Q, U*, and *V* continuum. The total exposure time was then 0.5 s for each Stokes-parameter. The area including the sunspot was scanned with a step width of 0.″35. The pixel size corresponded roughly to 0.″34 along the slit (after binning two pixels). A full scan took about one hour. Three scans at different positions in the *y*-direction had to be combined to cover the range shown in Fig. 1.

The recomposed images of the spot were corrected for geometrical foreshortening and interpolated so that a pixel corresponds to about 260 km in both spatial directions. The final image is shown in Fig. 1. With the adaptive optics system of the VTT (see Berkefeld 2007), the spatial resolution achieved in the 1100 nm range was clearly below 700 km, as the visual inspection of the recomposed image shows. The power spectrum reaches the noise level at a value corresponding to 610 km. The Stokes parameters were inverted using the SIR-code (Stokes Inversion based on Response functions) of Ruiz Cobo & del Toro Iniesta (1992) in the same way as in Balthasar & Collados (2005). The code delivers a temperature stratification and height-independent values for the magnetic field strength, inclination and azimuth with respect to the line-of-sight (LOS), and Doppler shift. The lines under study originate in narrow atmospheric layers so that the height gradients obtained from the inversion of a single line are not very meaningful. We attempted to derive linear gradients from inversions of both lines together, but the results differed strongly from pixel to pixel, even in sign. Therefore we consider that these results were not reliable. The SIR-code also provides error estimates for the derived quantities calculated from the differences in observed and fitted Stokes-profiles.

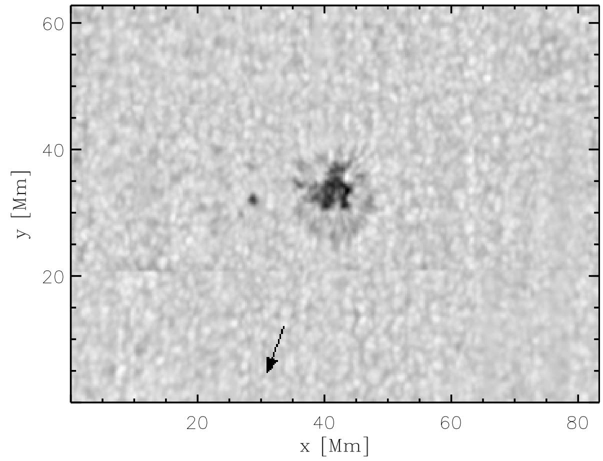

Fig. 1. Infrared intensity map of the spot composed of the local continuum close to the spectral lines. The intensity contrast is enhanced using an unsharp mask. The arrow points towards disk center.

The azimuthal ambiguity of the magnetic field is an old problem in solar polarimetry and several methods have been presented to resolve it. A comparison of these methods was presented by Metcalf et al. (2006). In this comparison, the most reliable result was obtained by an interactive method (AZAM). Since we have two spectral lines from different heights, we attempted to apply the third method of Li et al. (2007) to real data, but the method failed too often. In our case the ambiguity was resolved by assuming a radial structure inside the spot. If needed, the obtained azimuth was altered by 180° to fulfill this requirement. The Cartesian coordinates of the magnetic vector with respect to the LOS were calculated from the total field strength and the magnetic angles. Then, this vector was rotated to the local reference frame with respect to the solar surface normal. The final magnetic inclination and azimuth were obtained from these values. Finally, the geometrical foreshortening was removed for the Cartesian components of the magnetic field. The values obtained in this way are used in the following study. The final errors were derived by error propagation from the calculated errors of the SIR-code.

The magnetic parameters were kept constant during the inversion. Therefore, we ascribed these values to the layer corresponding to the maximum of the contribution function. We determined line depression contribution functions with the DMG-code (Grossmann-Doerth et al. 1988) for two model atmospheres: a quiet sun model (Holweger & Müller 1975) and an umbral model (M4, Kollatschny et al. 1980). The temperature map at $\tau = 1$ obtained from the inversion was used to interpolate pixel by pixel between the geometrical heights corresponding to the maxima of the contribution functions. The resulting maps for the two lines are displayed in Fig. 2. The silicon line originates higher in the atmosphere than the iron line: about 150 km in the quiet sun but less than 100 km in the umbra.

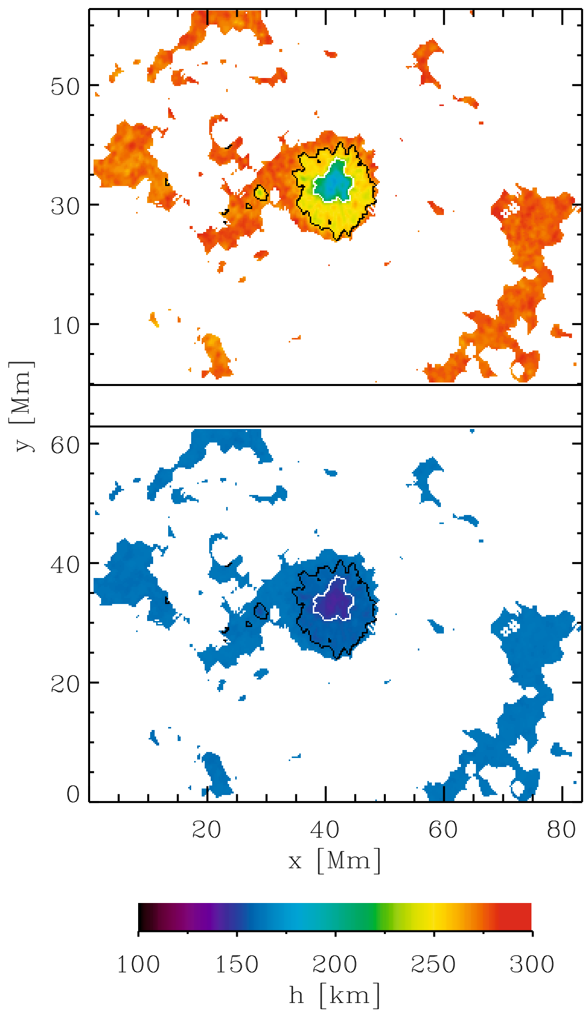

Fig. 2. Formation heights of the two spectral lines, Si 1078.6 nm (*top*) and Fe 1078.3 nm (*bottom*). The scale bar indicates the height in kilometers above lg τ = 0. The black and white contour lines show the inner and outer boundary of the penumbra and the outer boundary of some pores.

3. The magnetic field of the sunspot

The total magnetic field strength and its Cartesian components are displayed in Fig. 3. Values are not displayed in the maps if the integrated absolute circular polarization drops below 1.5×10^{-3} and the linear polarization below 2.3×10^{-3}, which correspond to the noise levels. The spot exhibits positive polarity with a maximum field strength of 2310 G. A radial structure in the penumbra is very pronounced for the vertical magnetic component, while structures in the horizontal components are far less related to the radial direction (see Fig. 3).

The magnetic inclination for the two lines is shown in Fig. 4. The spot has a positive polarity and the field lines are directed upward. Towards the outer boundary of the penumbra, the magnetic field becomes more and more inclined but the angle remains below 90°. Magnetic features westwards of the spot exhibit the opposite polarity. Their inclination is higher than 90°. In all cases the magnetic field is more vertical in the higher layer of the silicon line. For the penumbra, such a result was reported before by Westendorp Plaza et al. (2001), but our result is in contrast to Mathew et al. (2003) and Borrero et al. (2004) who measured an increase in the inclination with height, while Sánchez Cuberes et al. (2005) found that the inclination is independent of height.

4. The height dependence of the magnetic field strength

The difference in the total magnetic field strengths derived from the two lines was divided by the height difference to determine the height dependence of the magnetic field. The result is shown in Fig. 5. Inside the spot, all values are negative and the magnetic field decreases with height. The precise values depend strongly on the position in the spot. The mean value for the gradient of the magnetic field in the umbra is -2.60 ± 0.05 G km^{-1} and the extreme value is -7.2 G km^{-1}. Penumbral values vary between -1 and -2 G km^{-1}. A strong decrease in the magnetic field is found in the small pore close to to the sunspot, where the peak value is -8.2 G km^{-1}.

Outside the spot and the pore, we measure an increase in the magnetic field strength with height for most locations for which significant polarization is found. Embedded in these areas however, there are locations that experience instead a decrease in the field strength. As already visible in Fig. 3, the areas of magnetic field are more extended for the silicon line. This implies that the magnetic field is concentrated into small areas of high field strength in deep layers and expands as a canopy in higher layers.

We now consider the vertical component of the magnetic field. Its height dependence is shown in Fig. 6. Taking into account that parts of the magnetic areas outside the spot have the opposite polarity compared to that of the spot, this result looks at first glance similar to that of the total field strength. However, an important difference is found for the outer penumbra: the vertical

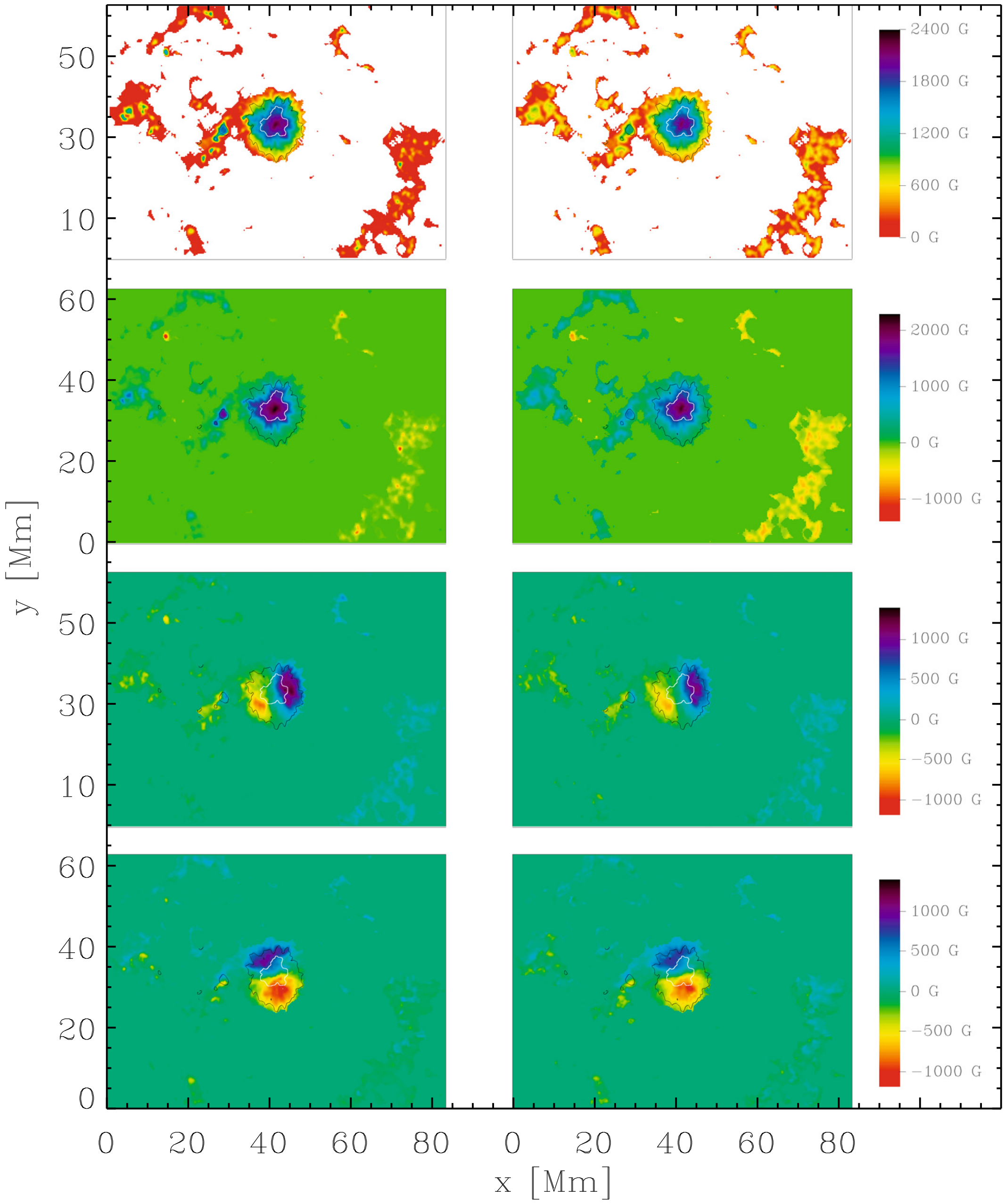

Fig. 3. Magnetic field strength (left for Fe 1078.3 nm, and right for Si 1078.6 nm). *The top row* shows the total field strength, the second row shows the vertical component, the third one the horizontal component in the East-West direction and *the bottom row* the North-South component. The corresponding scales indicate the field strength in G. Contour lines show the intensity boundaries as in Fig. 2.

component increases with height by 1–2 G km^{-1}. This is probably due to variations in inclination, since the magnetic field is less inclined in higher layers. Therefore, the vertical component increases, although the total field strength decreases. The mean value for the umbra is -2.15 ± 0.06 G km^{-1}. The vertical component decreases more slowly than the total field strength because of the smaller inclination of the magnetic field in higher layers.

The vertical dependence of the vertical magnetic component can also be derived using div $\boldsymbol{B} = 0$

$$\frac{\partial B_z}{\partial z} = -\left(\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y}\right).$$

In this application, we follow Hofmann & Rendtel (1989) and Balthasar (2006). The results for the vertical derivatives of the vertical magnetic component are displayed in Fig. 7. In the umbra and inner penumbra, we measure a decrease with height in the vertical component of the magnetic field strength. The mean value in the umbra is -0.56 ± 0.01 G km^{-1} for the iron line and -0.51 ± 0.01 G km^{-1} for the silicon line. The extreme values are -1.35 G km^{-1} and -1.21 G km^{-1}, respectively. For both lines, this method yields a slower decrease with height than the difference method. On the other hand, these values are higher than the 0.3–0.4 G km^{-1} obtained by Hofmann & Rendtel (1989). In the outer penumbra, we find an increase in the vertical magnetic component with height also using this method, in agreement with Hofmann & Rendtel (1989). This finding can be explained by the above result that the magnetic field is less inclined in higher layers.

The pore close to the spot exhibits a decrease in B_z with height. We measure -1.0 G km^{-1} from the iron line and

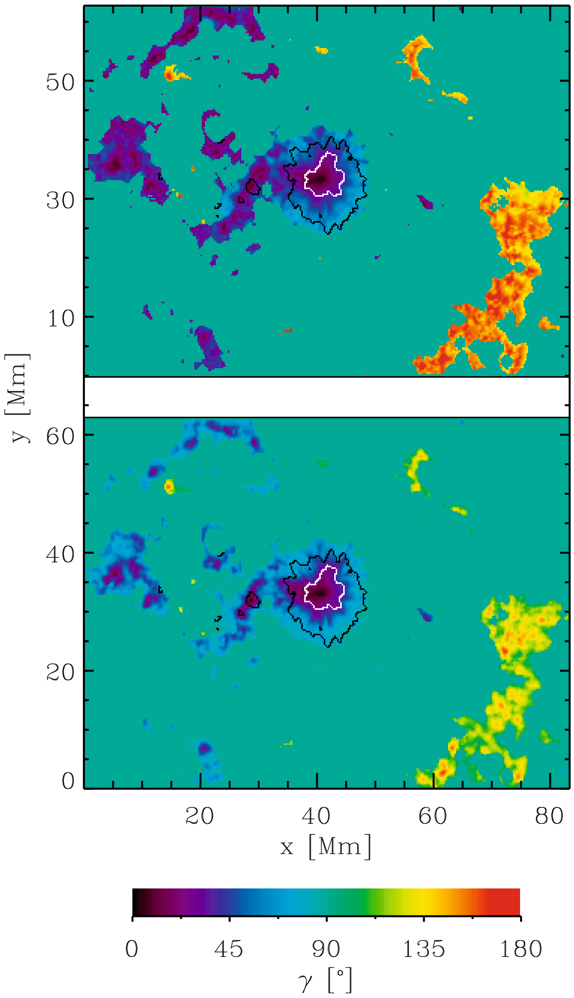

Fig. 4. Inclination of the magnetic field in degrees with respect to the solar surface for Si 1078.6 nm (*top*) and for Fe 1078.3 nm (*bottom*).

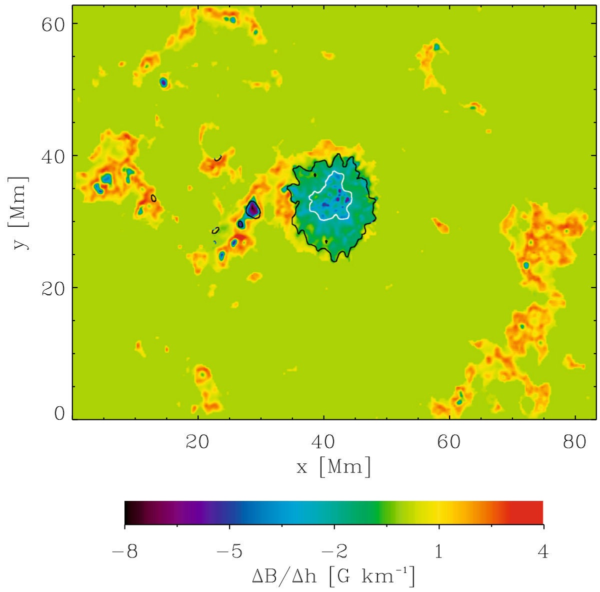

Fig. 5. Difference of the total magnetic field strengths from the two lines divided by the height difference in units of G km^{-1}.

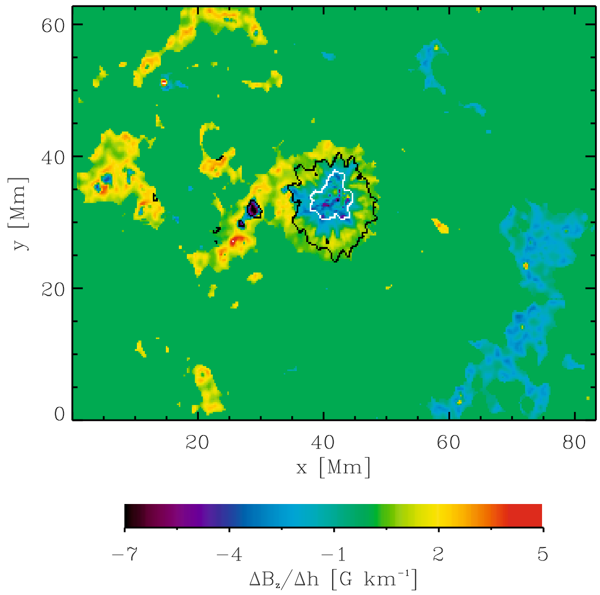

Fig. 6. Same as Fig. 5 but for the vertical component of the magnetic field.

-0.7 G km^{-1} from the silicon line. As for the spot, these values are lower than that derived from the difference method, which is -5.9 G km^{-1} for the pore.

The reason for the remarkable discrepancy between the two methods remains unclear. Some possible explanations are considered in the general discussion at the end of this paper.

5. Vertical current density and helicity

To determine the full vector of the current density, the vertical stratification of the magnetic field must be known. With only two layers, we can determine two layers of the horizontal derivatives of the magnetic field that provide the vertical component of curl $\boldsymbol{B}$

$$(\nabla \times \boldsymbol{B})_z = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = \mu J_z,$$

where $\boldsymbol{J}$ is the electric current density and μ is the magnetic permeability. The partial derivatives were determined from the difference of the two neighboring pixels. This method was applied by DeLoach et al. (1984), Hofmann et al. (1988, 1989), Balthasar (2006), and Jurčák et al. (2006). A preliminary investigation of this spot was published by Gömöry & Balthasar (2007). Now, we present results derived from two spectral lines following an improved data reduction. Maps for the vertical current densities are displayed in Fig. 8.

The umbral mean values are -11 mA m^{-1} for both lines. The values vary between -63 mA m^{-1} and $+34$ mA m^{-1} for the iron line and between -53 mA m^{-1} and $+15$ mA m^{-1} for the silicon line. Because the propagated errors are rather large, on the order of 30 mA m^{-1}, the values cannot be regarded to be significant.

Current helicities are derived from curl $\boldsymbol{B}$ in a way similar to the method of Zhang (2006). Again, we must restrict ourselves to the vertical component

$$H_z = B_z \cdot (\nabla \times \boldsymbol{B})_z.$$

The results are shown in Fig. 9. We calculate mean values of -0.25 $\mathrm{G}^2\,\mathrm{m}^{-1}$ for the iron line and -0.24 $\mathrm{G}^2\,\mathrm{m}^{-1}$ for the silicon line in the umbra in agreement with the general tendency that sunspots in the northern hemisphere exhibit a negative helicity (Seehafer 1990; Pevtsov et al. 1995, 2008; Sokoloff et al. 2008). In the penumbra, the mean value is far lower. We

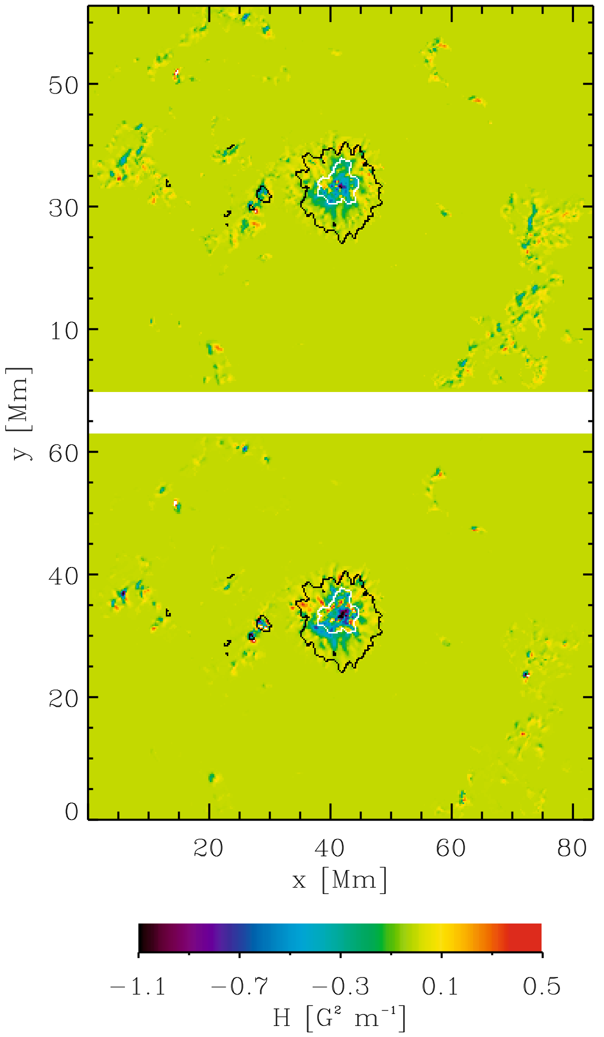

Fig. 7. Vertical derivative of the vertical component of the magnetic field strength, for the silicon line (*top*) and for the iron line (*bottom*). Values of more than +1.0 G km^{-1} and less than −2.0 G km^{-1} are clipped to enhance the visibility of small scale variations.

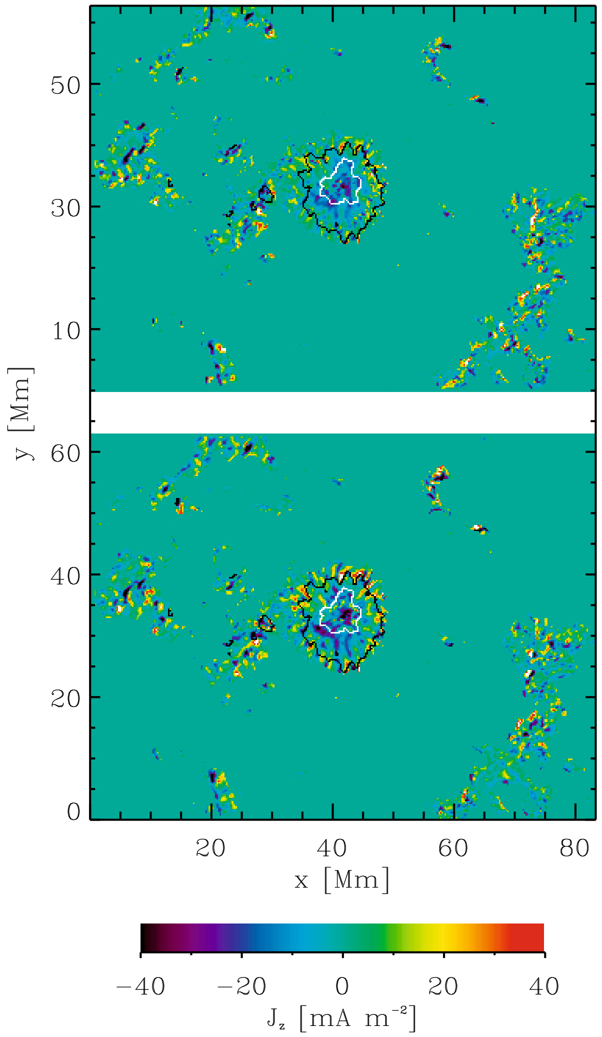

Fig. 8. Vertical current densities for the silicon line (*top*) and for the iron line (*bottom*). Absolute values of more than 40 mA m^{-2} are clipped to enhance the visibility of small scale variations.

measure −0.043 ± 0.003 G^2 m^{-1} for the iron line and −0.033 ± 0.002 G^2 m^{-1} for the silicon line. Although in general the current helicities are negative, there are some locations with positive values, which is in agreement with the findings of Socas Navarro (2005a).

6. The magnetic flux

Integrating over the entire area investigated, we measure a total magnetic flux of $(1.7 \pm 0.5) \times 10^{13}$ Wb for both lines. Looking at the spot only, the values are $(1.4 \pm 0.1) \times 10^{13}$ Wb for the iron line and $(1.3 \pm 0.1) \times 10^{13}$ Wb for the silicon line. This difference is within the error limits. Additionally, it could be explained if part of the magnetic flux escapes through the lateral boundaries of the spot. Outside the spot, we find more flux in the silicon line. In areas of positive polarity, the total amount is $(1.2 \pm 0.2) \times 10^{13}$ Wb for the silicon line and $(0.6 \pm 0.3) \times 10^{13}$ Wb for the iron line. In areas of negative polarity, the values are $(-0.9 \pm 0.2) \times 10^{13}$ Wb and $(-0.3 \pm 0.2) \times 10^{13}$ Wb, respectively. This difference is larger than that for the spot, but it is insignificant at the 2σ-confidence level.

Using the conservation of the magnetic flux, Balthasar & Collados (2005) derive an estimate of the height at which the magnetic field strength decreases to the value measured at the outer boundary of the penumbra. For this purpose, the magnetic flux in the photospheric layer is measured. It is then assumed that there is a simple smooth surface with the same field strength as at the edge of the penumbra. This idea goes back to Schmidt (1991) who proposed a hemisphere of a constant field strength. At that time, reliable spatially and spectrally resolved measurements of the magnetic field strength were only available for locally restricted positions such as a single position of the spectrograph slit. The aim of Schmidt (1991) was to assess whether the penumbra is either deep or shallow from a comparison of the umbral flux with that through the hemisphere. Solanki & Schmidt (1993) concluded consequently that the penumbra must be deep. Balthasar & Collados (2005) measured the photospheric flux of a sunspot and found that it is lower than the amount expected to be transmitted through a hemisphere. Therefore, they replaced the hemisphere by an ellipsoidal cap. For that spot with a radius of about 9500 km they calculated the top height of the ellipsoid to be 5250 km. The presently investigated sunspot has a radius of 6690 km. At the outer penumbra, we measure 720 G in the iron line and 680 G in the silicon line. The corresponding top heights are 4060 km and 4180 km, respectively. The mean decrease in the magnetic field strength over this height range is

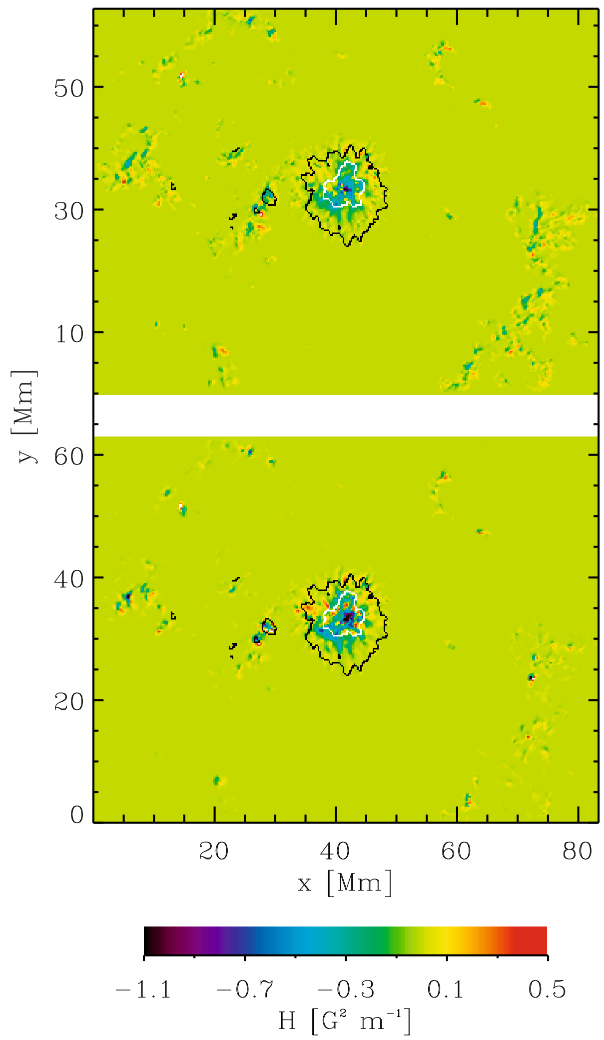

Fig. 9. Current helicities for the silicon line (*top*) and for the iron line (*bottom*). Values of more than 0.5 G^2 m^{-1} and less than −1.5 G^2 m^{-1} are clipped to enhance the visibility of small scale variations.

0.39 G km^{-1} for the iron line and 0.36 G km^{-1} for the silicon line. Since this spot is small, these values are neither in contradiction to the results of Balthasar & Collados (2005) nor to those of Brosius & White (2006) who estimated a magnetic scale height of 6900 km above a large sunspot close to the solar limb from gyro-resonance measurements at the VLA.

7. Discussion and conclusions

We have investigated the magnetic vector field of a sunspot, and we have derived its height dependency, the current density and its current helicity. Our main conclusions can be summarized as follows:

1. The magnetic field is less inclined in the layers of the upper photosphere, independently of the location.
2. The total magnetic field strength decreases with height inside the sunspot.
3. Outside the spot, there are many locations at which the magnetic field strength increases with height, which can be understood as canopies around small features with a high magnetic field strength in deep layers.
4. The vertical magnetic component B_z decreases with height in the umbra and inner penumbra, while it increases with height in the outer penumbra. This is explained by magnetic field lines, which are almost horizontal in deeper layers and less inclined in upper layers. Therefore, B_z increases, although the total field strength is smaller in higher layers.
5. The decrease in the magnetic field strength with height is stronger in a pore close to the main spot.
6. Spatial resolution is crucial for the determination of the partial derivatives, which are needed in calculating electric current density and current helicity.
7. The present data have implied a relation between current density and the penumbral fine structure, although we are unable to quantify this relation because of uncertainties in the partial derivatives.

Within the inversions with one atmospheric component, we do not find a return flux in the outer penumbra as predicted by the model of Osherovic & Garcia (1989). Previous inversions with two atmospheric components, performed for different observations, deliver such a return flux for one of the two components (see del Toro et al. 2001; Bellot Rubio et al. 2003, 2004; Borrero et al. 2004; Sánchez Almeida 2005; Langhans et al. 2005 and Beck 2008). For this case, B_z would also increase with height, even if the horizontal field was located in the higher layer.

The increase in the magnetic field strength with height in the active areas outside the spot is probably an indication of magnetic canopies. We observe many small elements in the field strength derived from the iron line, sometimes of high field strength in very small locations. In the silicon line, the magnetic field expands into their surroundings where no polarization signal is detected in the iron line. Nevertheless, we find a lower magnetic field inclination in the silicon line indicating that most of the expansion occurs in layers below that in which this line is formed.

The horizontal derivatives of the magnetic field are required to determine the vertical derivative of the z-component of the magnetic field by means of div $\boldsymbol{B} = 0$; the current density; and the current helicity. To determine these derivatives properly, it is required that neighboring pixels represent the same height layer. This is not necessarily the case. Socas Navarro (2005a) finds that such a difference might be up to 500 km in a sunspot. They must belong to the same magnetic fine structure. High resolution observations with the new Swedish solar telescope identify many structures smaller than 200 km (see Rouppe van der Voort et al. 2004). This implies that within one pixel at least two atmospheric components could exist. Corresponding inversions (see aforementioned list of references) confirm that the penumbra consists of at least two unresolved magnetic components, which originate not necessarily at the same geometrical height. For such a case, the determination of the partial derivatives would become meaningless, as discussed also by Socas Navarro (2005b) and Balthasar (2006). These uncertainties are probably the explanation for the discrepancies in the height dependence of B_z derived by the two methods. An indication for this is that the present high resolution data deliver a faster decrease than older investigations of lower resolution. On the other hand, one could argue that the height determined from the formation of a spectral line reflects an extended height range and depends on the applied contribution or response function. This might be the solution for the umbra, where the formation heights of the two used lines are close to each other. However, outside the umbra such a large height difference would be required that the theory of stellar atmospheres would be questioned.

However, the maps of the current densities do not resemble pure noise. There is an indication of radial structure in the penumbra. The dominance of negative vertical current densities in the spot, if real, would not be in agreement with the predictions of Title et al. (1993) for the model of the fluted penumbra nor with the field-free gappy penumbra presented by both, Spruit & Scharmer (2006) and Scharmer & Spruit (2006). For both models, one would expect both directions of the vertical current to be next to each other.

In a future paper, we shall investigate several spectral lines sensitive to different heights, which were observed simultaneously with two telescopes. This comparison will allow us to determine the vertical structure of the magnetic field in a more accurate way than with only two spectral lines. However, the unresolved fine structure in the present data causes severe uncertainties. Much higher spatial resolution is required for future observations, which will be provided by a new generation of telescopes such as GREGOR (e.g. Volkmer et al. 2007) or the Advanced Technology Solar Telescope (e.g. Keil et al. 2004).

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