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Magnetic Vector Field Above a Sunspot

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Abstract. We present an analysis of the spectro-polarimetric measurements of the active region NOAA 10886 taken with the Tenerife Infrared Polarimeter in the Fe I 10783 Å spectral line. The magnetic field strength and the magnetic inclination and azimuth were inferred from the data using the inversion code SIR. The vertical current densities and the vertical derivative of the vertical component of the magnetic field were then calculated for the leading spot of the AR 10886. We revealed that typical values of the vertical current densities vary in the range $\pm 40\,\mathrm{mA\,m^{-2}}$ inside the spot. Moreover, we found an extended area of enhanced vertical current densities in the umbra (values up to $-80\,\mathrm{mA\,m^{-2}}$). Our analysis also showed that the vertical component of the magnetic field strength decreases by $0.6 - 1.6\,\mathrm{G\,km^{-1}}$ and $0.5 - 0.8\,\mathrm{G\,km^{-1}}$ in the umbra and inner penumbra, respectively. On the other hand, we found an increase of the vertical component of the magnetic field in the outer penumbra (typical values vary between $0.1 - 0.5\,\mathrm{G\,km^{-1}}$).

1 Introduction

The low value of the plasma β in the corona implies that the processes in the outer solar atmosphere are driven by magnetic field (Walsh & Ireland 2003). But with the present instruments it is almost impossible to measure coronal magnetic fields directly. Therefore, extrapolations of the photospheric magnetic fields are commonly used for a better description of the coronal structures. The most recent extrapolation methods assume a force-free magnetic field (Régnier et al. 2002; Valori et al. 2005). A good knowledge of the full magnetic vector $\mathbf{B}$ and/or the electric current densities $\mathbf{j}$ is crucial for such extrapolations. Moreover, better determinations of the electric current densities can help to understand the fine structure of sunspots (e.g. penumbral filaments). Another important and still not fully solved question is how fast the magnetic field strength decreases with height.

Following these points we investigate the magnetic vector field of a sunspot in order to determine the vertical component of the electric current densities and the vertical derivative of the vertical component of the magnetic field strength. For the calculation of these parameters we used the method described in the paper of Balthasar (2006).

2 Data and data reduction

The data discussed here were taken on May 27, 2006 with the Tenerife Infrared Polarimeter (Martínez Pillet et al. 1999) attached to the spectrograph of the German Vacuum Tower Telescope. In addition, the KAOS system (Kiepenheuer Adaptive Optic System) was used

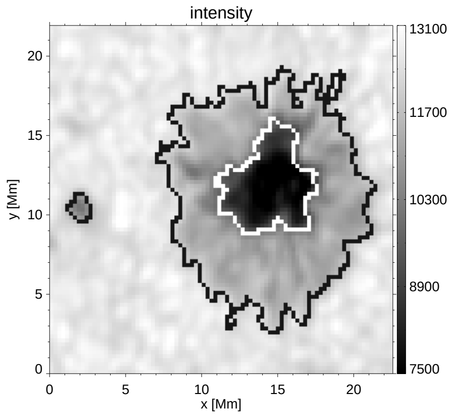

Figure 1. Infrared intensity map of the leading spot of the active region NOAA 10886 composed of the local continuum near the observed spectral line. Scanning was done from left to right. The contour lines mark the outer boundaries of umbra and penumbra.

to ensure stable conditions during the whole observing sequence. The full Stokes vector measurements of the active region NOAA 10886 were performed near disk center in the Fe I 10783 Å spectral line. To obtain the final components of the Stokes vector (i.e. *I, Q, U,* and *V*), ten sets of single exposures at 200 ms were added up to increase the signal-to-noise ratio. Therefore, the exposure time was 2 s for each Stokes parameter. The observed AR was scanned with a step width 0.34 arcsec. The pixel size along the slit corresponded to 0.35 arcsec. Totally 3 scans, each with 360 steps, were performed to cover the whole AR. Note, that in this paper we will focus only at results which were determined for the leading spot of the AR 10886 (Fig. 1).

The standard photometric reduction (i.e. removing of the dark currents, applications of the flat-fields etc.) of the raw measurements was performed and the instrumental crosstalk was removed from the data. The data were then corrected for geometrical foreshortening and interpolated so that a pixel size corresponds to 0.34 arcsec in both spatial directions.

3 Results and Discussion

The components of the magnetic vector **B** (magnetic field strength and magnetic angles) were determined through an inversion of the Stokes parameters. The inversion was performed using the SIR code (Ruiz Cobo & del Toro Iniesta 1992) in the same way as it is described in Balthasar & Collados (2005). Vertical components of the electric current densities j_z were then calculated using following formula

$$\mu j_z = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}, \tag{1}$$

where μ is the magnetic permeability. The partial derivatives were determined from the difference of the two neighboring pixels. The obtained values of the j_z are shown in Fig. 2 (left). Typical values of the vertical current densities vary between $\pm\, 40\,\mathrm{mA\,m^{-2}}$ in the umbra. The

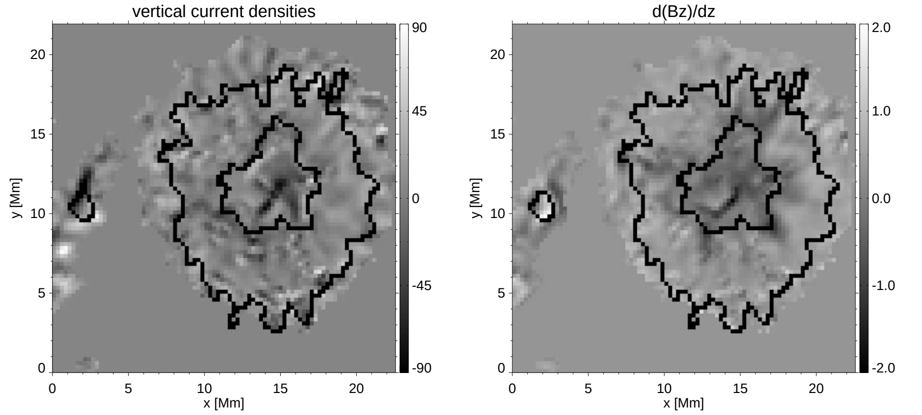

Figure 2. *Left:* Vertical current densities calculated for the leading spot of the AR 10886. The displayed values are given in $\mathrm{mA\,m^{-2}}$. *Right:* Vertical derivative of the vertical component of the magnetic field strength for the leading spot of the AR 10886. The displayed values are given in $\mathrm{G\,km^{-1}}$. Note that if the integrated absolute circular and linear polarization both drop below a treshold value, the remaining polarization signal is regarded to be noise and the corresponding areas are suppressed in the figures. The contour lines indicate outer and inner penumbral boundary.

values of the j_z in the penumbra are somewhat smaller and vary in the range $\pm 30\,\mathrm{mA\,m^{-2}}$. Note that the estimated errors of the values mentioned above are of the same order. These findings are in good agreement with results of Balthasar (2006). He analyzed a set of eight sunspots and came to the conclusion that the typical values of the vertical current densities vary between $\pm 40\,\mathrm{mA\,m^{-2}}$ inside the sunspots. Beside of this we found also areas with enhanced values of the vertical current densities extending up to -75 $\mathrm{mA\,m^{-2}}$ in the umbra and up to -60 $\mathrm{mA\,m^{-2}}$ in the penumbra. Unfortunately, limited spatial resolution of the VTT did not allow us to associate the position of the enhanced vertical current densities with the fine structures of the sunspot. On the other hand, relatively high values of the j_z detected near the outer penumbral boundary are rather unrealistic as only a very weak polarization signal was detected in that area.

As the Fe I 10783 Å spectral line comes from a rather narrow atmospheric layer, the vertical stratification of the magnetic field strength obtained directly from the inversion code could be unreliable. Therefore, we calculated only the vertical derivative of the vertical component of the magnetic field strength using partial derivatives of the horizontal magnetic components, i.e.

$$\frac{\partial B_z}{\partial z} = -\left(\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y}\right) \Longleftrightarrow div\boldsymbol{B} = 0. \tag{2}$$

The same method was used by Hofmann & Rendtel (1989) and Balthasar (2006). The determined gradients of the B_z are shown in Fig. 2 (right). We revealed that the magnetic field strength decreases with height by $0.6-1.6\,\mathrm{G\,km^{-1}}$ in the umbra. These values are higher than the $0.3-0.4\,\mathrm{G\,km^{-1}}$ obtained by Hofmann & Rendtel (1989) but comparable with the findings of Balthasar (2006). We found negative gradients of the vertical component of the magnetic field strength also in the inner penumbra. But the decrease of the B_z with height is slower in the inner penumbra then in the umbra (typical values vary between -0.5 G km^{-1} and -0.8 G km^{-1}). In contrast, we found an increase of the magnetic field strength with height in the outer penumbra and outside the spot. The typical values are in the range between 0.1 G km^{-1} and 0.5 G km^{-1}. The increase of the magnetic field strength with height can be explained if the magnetic field is less inclined in higher layers as reported by Westendorp Plaza et al. (2001). But recently Borrero et al. (2004) found an increase of the inclination with height while results of Sánchez Cuberes et al. (2005) reveal that the inclination is independent of height.

4 Conclusions

We examined the vertical current densities and the height dependence of the vertical component of the magnetic field strength in a sunspot. Our analysis showed that the typical values of the j_z vary between $\pm$ 40 mA m^{-2} inside the spot. We also revealed a decrease of the vertical component of the magnetic field strength with height in the umbra and inner penumbra and positive height gradients of the B_z in the outer penumbra and outside the spot. But we should remind here that the results presented in this paper depend on two assumptions: *(i)* the neighboring magnetic components belong to the same height layer, and *(ii)* they belong to the same magnetic finestructure. If this is not true then the obtained values become meaningless as the determined partial derivatives (see eq. 1 and 2) were not calculated for the same structure of the spot. Data with much higher spatial resolution (as they will be provided with new solar telescopes like GREGOR or ATST) are therefore necessary for the future verification of our results.

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