Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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The three-dimensional structure of the magnetic field of a sunspot

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Abstract. Spectro-polarimetric observations in several spectral lines allow to determine the height variation of the magnetic field of a small sunspot throughout the solar photosphere. The full Stokes-vector is measured with high spatial resolution. From these data we derive the magnetic field vector. The magnetic field strength decreases with height everywhere in the spot, even in the outer penumbra where some other authors have reported the opposite. The precise value of this decrease depends on the exact position in the spot. Values vary between 0.5 and 2.2 $\mathrm{G\,km^{-1}}$ when they are determined from an iron and a silicon line in the near infrared. The magnetic field is less inclined in the higher layers where the silicon line is formed. Once the magnetic vector field is known, it is straight forward to determine current densities and helicities. Current densities exhibit a radial structure in the penumbra, although it is still difficult to correlate this with the structure seen in the intensity continuum. In spite of this, current densities have a potential to serve as diagnostic tools to understand the penumbra, at least with the spatial resolution of the upcoming telescopes. The mean infered helicity is negative, as expected for a spot in the northern hemisphere. Nevertheless, there are locations inside the spot with positive helicity.

Keywords. Sun: sunspots – Sun: magnetic fields – polarization

1. Introduction

The magnetic field of sunspots was discovered one hundred years ago by Hale (1908), but up to now, many details of the sunspots' magnetic structure are not well understood. There are controversies how fast the magnetic field decreases with height and by how much the penumbral field is inclined. Twist of the magnetic field might be important to balance the magnetic pressure in the upper layers of the photosphere and above. Electric currents have a potential to distinguish between different penumbra models. To shed more light on these issues, we measured the magnetic vector field of a small sunspot in two different spectral lines, Fe I 1078.3 nm and Si I 1078.6 nm. On May 27, 2006 the spot was very close to the central meridian, and we observed it with the Tenerife Infrared Polarimeter (TIP, see Collados, Lagg, Díaz García, *et al.*, 2007) at the German Vacuum Tower Telescope (VTT) on Tenerife. From the Stokes profiles we determine the magnetic vector field with the SIR-code (Stokes Inversion based on Response functions) of Ruiz Cobo & del Toro Iniesta (1992). More detailed results have already been published by Balthasar & Gömöry (2008).

2. Results

We find that the mangetic field inside the spot is always higher in the deeper layers where the iron line is formed. In the first step, we devide the difference of the magnetic field from the two lines by the height difference. The total magnetic field strength decreases by about 2.2 $\mathrm{G\,km^{-1}}$ in the umbra and by 0.5 $\mathrm{G\,km^{-1}}$ in the penumbra. Our umbral value is smaller than that of Mathew, Lagg, Solanki, *et al.* (1995). Looking at the vertical component B_z, we find only a slightly smaller value in the umbra, while B_z increases in the outer penumbra. The latter is explained by the high inclination to the vertical in the outer penumbra, and this inclination decreases with height, which is in contrast to Mathew, Lagg, Solanki, *et al.* (1995).

The height dependence of B_z can also be calculated from $\mathrm{div}\, B = 0$. We determine the required derivatives from differences of the neighboring pixels. The values of this height dependence of B_z are smaller than those from the quotients of the differences, but they are slightly larger than previous results by Hofmann & Rendtel (1989). Uncertainties of the formation heights of the spectral lines could be one reason, but the solar atmosphere is not extended enough to explain all discrepencies this way. Our main concern is the accuracy of the horizontal derivatives, because the neighboring pixels might represent different fine structures and different geometrical heights.

Despite these inaccuracies, we also determine the vertical component of the electric current density from the horizontal derivatives of the magnetic field strength using

$$(\nabla \times \boldsymbol{B})_z = \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} = \mu J_z. \tag{2.1}$$

We find radial structures of current densities in the penumbra, but they are not correlated with intensity structures. Nevertheless, our result demonstrates the diagnostic power of current densities.

In a similar way we also calculate current helicities

$$H_z = B_z \cdot (\nabla \times \boldsymbol{B})_z. \tag{2.2}$$

Helicity is an indicator of twist in magnetic field lines which might be very important to keep the magnetic field together in the upper photosphere and above. In agreement with the result of Seehafer (1990), we find a dominance of negative helicity as expected for a spot in the northern hemisphere. However, there are some locations inside the spot with positive helicity, as it was reported previously by Socas Navarro (2005) for another spot.

3. Prospects

With a new generation of solar telescopes such as the 1.5 m GREGOR, which will be commissioned in 2010, we will increase the spatial resolution significantly. This is very important to calculate more reliable derivatives of the magnetic field.

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