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Structure of a simple sunspot from the inversion of IR spectral data

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Abstract. Analysis of spectral data of two neighboring infrared lines, Fe I 15648.5 Å ($g = 3$) and Fe I 15652.9 Å ($g_{\rm eff}$ = 1.53) are carried out for a simple sunspot when it was near the solar disk center ($\mu = 0.92$), to understand the basic structure of sunspot magnetic field. Inversions of Stokes profiles are carried out to derive different atmospheric parameters both as a function of location within the sunspot and height in the atmosphere. As a result of the inversion we have obtained maps of magnetic field strength, temperature, line-of-sight velocity, field inclination and azimuth for different optical depth layers between $\log(\tau_5) = 0$ and $\log(\tau_5) = -2.0$. In this paper we present few results from our inversion for a layer averaged between $\log(\tau_5)$ from 0.0 to -0.5.

Key words: Sun: spots – Sun: magnetic structures

1. Introduction

Even though sunspots are the most widely observed magnetic features, only recently a coherent picture of the sunspot magnetic structure started to emerge (eg. Westendorp Plaza et al. 2001). Observations in infrared wavelength has its merits because of the squared wavelength dependence of Zeeman splitting, and also the effect of stray light is smaller in infrared. The potential of the Fe I 15648.5 Å and Fe I 15652.9 Å lines in the IR H-band to diagnose the properties of solar magnetic features are described by Solanki et al. (1992). Using this combination of Landé $g = 3$ and $g_{eff} = 1.53$ lines it is possible to measure the field strength in solar magnetic features simply and with great accuracy. By forming the line ratio between the V profiles of these lines it is in principle possible to measure field strengths as low as 100 G. Using an inversion technique it is possible to determine the stratification of physical quantities in the solar photosphere from the spectral line profiles (Ruiz Cobo & del Toro Iniesta 1992, Frutiger 2000, Frutiger et al. 2000, Westendorp Plaza et al. 2001). We have inverted a two dimensional spectropolarimetric map of a sunspot near the disc center observed in the above two lines, some of the results are discussed in the following sections.

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2. Data and analysis

We use TIP (Tenerife Infra-red Polarimeter, Collados 1999) spectropolarimetric data, simultaneously recorded on 27 September 1999, in two IR Fe I lines (15648.5 Å, $g = 3$ and 15652.9 Å, $g_{\rm eff} = 1.53$), of a fairly round sunspot, when it was near the disk center (μ = 0.92). The spot belongs to region NOAA 8706 and has a size of around 31″.

The data were fitted using the code ‘INVERT’ described by Frutiger et al. (2000). The Stokes profiles were calculated in LTE through a two-component model atmosphere composed of a magnetic and non-magnetic part. In every pixel two atmospheric components are allowed for, one magnetic (with filling factor α) and one field-free (with filling factor $1 - \alpha$). In sunspot the field free component describes stray light. The synthetic profiles were iteratively fitted with observed data using response functions (RFs) and the Levenberg-Marquardt algorithm that minimizes the merit function χ^2 (Ruiz Cobo & del Toro Iniesta 1992, Frutiger 2000). The use of RFs considerably accelerates the iterative scheme, making it fully automatic. The relevant free parameters for the inversion are (depth dependent) magnetic field strength, the field inclination, line-of-sight velocity, field azimuth and the filling factor. Telluric and molecular blends associated with the above lines introduced inaccuracies in the inversions if left unattended. We have removed the telluric blend from

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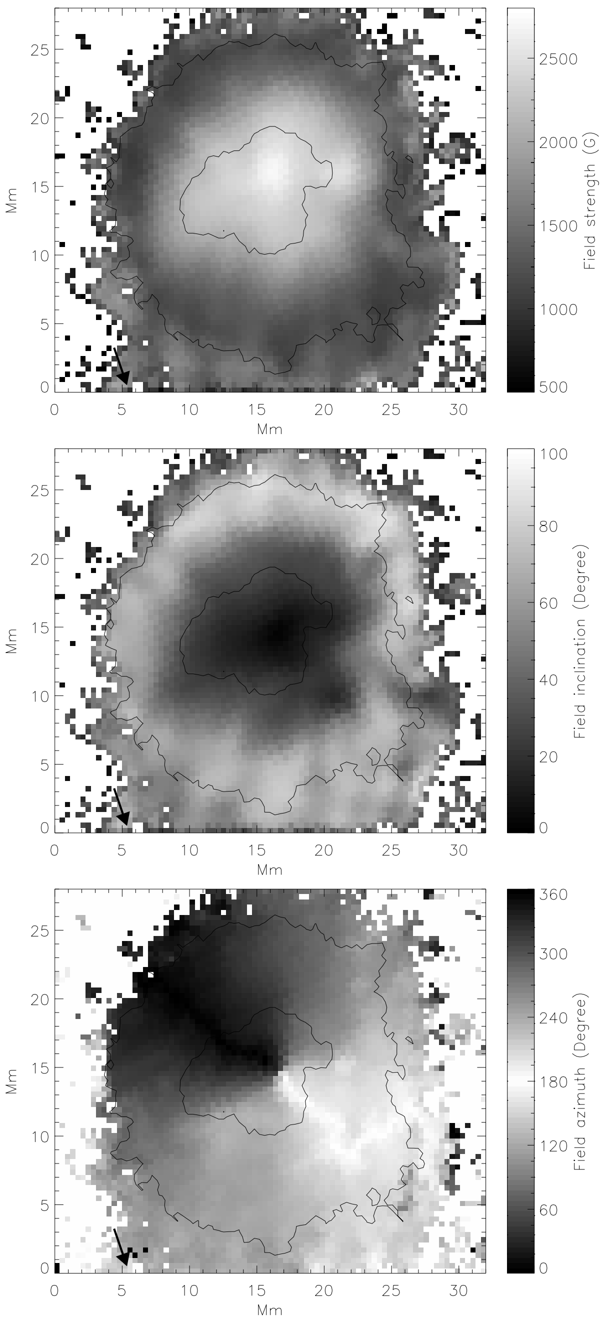

Fig. 1. The field strength (B), field inclination (γ), and the azimuth (χ) maps for the analyzed sunspot. The contour show the umbral and penumbral boundary derived from the continuum intensity. The arrow points towards the Sun center.

the Fe I 15648.5 Å line by fitting the averaged quiet Sun profile with a computed profile. The two molecular OH blends present in Fe I 15652.9 Å line are also inverted, which improved the reliability of the deduced atmospheric parameters, in particular in the umbra where these blends are strong (Berdyugina et al. 2001). In the following sections, we mainly concentrate on the structure of the sunspot for deep atmospheric layers, specifically we consider the layer averaged over $\log(\tau_5)$ values ranging from 0.0 to -0.5.

3. Results

In Fig. 1 we show the maps for field strength (B), field inclination (γ), and azimuth (χ) for the observed sunspot. In B map the strongest fields concentrate in locations closer to the center umbra. The maximum field strength found in this spot is around 2800 G near center of the umbra, which coincide with the darkest region in the umbra. The field strength smoothly decreases in the radial direction, and reaches a value of around 1000 - 1200 G near the penumbral boundary. We found a vertical gradient of around -4 G/km, in the umbra and slightly higher in penumbra in these layers. The umbral field is found to be relatively diffused, whereas in the penumbra, radial structures identified as "spines", with field strength greater than surrounding are evident. These structures are of enhanced magnetic field, and are of more vertical than the surroundings.

The middle panel in Fig. 1 shows γ with respect to the surface vertical. The inclination is almost zero in the umbral core, and smoothly increases outward. It reaches an average value of 70 - 80 degrees near outer penumbra. At few locations in the outer penumbra γ runs beyond 90°. These locations coincide with the strongest downflows in the velocity map. In the penumbra the "spine" structures are characterised by low values of inclination. χ shows a smooth variation azimuthally, without showing considerable twist.

4. Conclusions

We have inverted a two dimensional infrared spectropolarimetric map of a simple sunspot near the disc center. In the magnetic field map, we found clear signature of spine structures in the penumbra which have more vertical field than the surroundings. We found locations in the outer penumbrae, where the field inclination runs beyond 90°, implying a return flux. The strongest downflows in the velocity maps coincide with these locations. Comparing the velocity and B maps we also found that the Evershed channels are mostly located in the spaces between the spines.

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