PHOTOSPHERIC AND CHROMOSPHERIC MAGNETIC STRUCTURE OF A SUNSPOT

D. Orozco Suarez[1], **A. Lagg**[2], **and S.K. Solanki**[2]
[1]Instituto de Astrofísica de Andalucía, IAA, CSIC, Granada, Spain
[2]Max-Planck-Institut für Sonnensystemforschung, MPS, 37191 Katlenburg-Lindau, Germany

ABSTRACT

The magnetic field of sunspots has been well studied in their photospheric layers, but is poorly known in the upper chromosphere. Here we present state-of-the-art inversions of the stokes vectors of the He I triplet at 1083 nm and of a photospheric Si I line which give us a map of the magnetic vector in the upper chromosphere, as well as in the photosphere. These maps are analyzed to discuss the differences between the photospheric and the chromospheric upper magnetic structure of sunspots.

Key words: Sunspots; inversion.

1. INTRODUCTION

The magnetic structure of sunspots has been discussed in photospheric layers using visible and infrared lines, via the Zeeman splitting of absorption lines. Observations in the chromosphere are much rarer, although various diagnostics have been used to study the chromospheric structure, ranging from the lower chromosphere (Na I D lines), to the lower corona (radio observations). Most of the spectral lines that have been proposed for this aim suffer from the need for complex radiative transfer or due to the need for satellite observations or poor temporal and spatial resolution. A particularly suitable spectral region to study the magnetic structure of sunspots the 1083 nm spectral region in the infrared, which contains a photospheric Silicon line and a chromospheric Helium triplet, and consequently samples two different layers on the solar surface (e.g. Rüedi et al. 1995). The Helium line has a complex formation, but for purposes of magnetic vector and LOS velocity diagnostics can be treated relatively simply because it is nearly optically thin.

In the present paper, we discuss the sunspots magnetic field structure retrieved from the analysis of the observations.

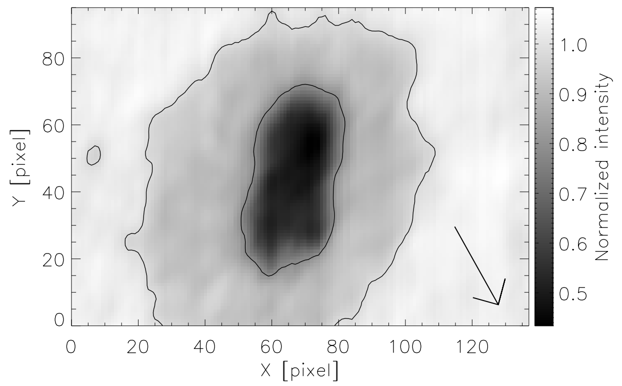

Figure 1. Continuum intensity image of the observed sunspot normalized to the quite Sun continuum intensity. The black contour lines mark the umbral-penumbral and penumbral-quiet Sun boundaries. The arrow points to the solar limb.

2. OBSERVATIONS AND ANALYSIS

An isolated sunspot (see figure 1) at μ=0.88 was observed on September 28, 2002 with the Tenerife Infrared Polarimeter on the Vacuum Tower Telescope at the Teide observatory on Tenerife. The observed sunspot belonged to the region NOAA 0130, located at the solar position 27.4 W, 7.84 N. The wavelength range observed contains one photospheric line, Si 1082.7 nm, and the chromospheric He I triplet at around 1083 nm. These two spectral lines allow us to analyze two different layers at the same time and therefore lead to a better understanding of the magnetic field topology of Sunspots.

Besides the analysis of line profile parameters such as area asymmetry of the Stokes V profile, we carry out an inversion of the Stokes vector following Lagg et al. (2004) for the He I line and Frutiger (2000) for the Si I line, and compare the magnetic field vector, gradients and LOS velocities inferred by applying these

Proceedings of the International Scientific Conference on Chromospheric and Coronal Magnetic Fields, 30 August – 2 September 2005 (ESA SP-596, November 2005)

inversion techniques to both lines.

2.1. Area asymmetry

We analyze the Stokes V area asymmetry of the circular polarization, defined as $\delta A = \frac{\int V(\lambda) d\lambda}{\int |V(\lambda)| d\lambda}$, for Silicon and Helium. In Figure 2 we show the δA for both lines. The Silicon and Helium lines clearly show the position of the neutral line in the sunspot. At both photospheric and chromospheric layers the neutral line appears near the outer penumbral boundary. The Silicon line is sensitive to strong gradients in B present in the penumbra (e.g. Borrero et al. 2005), and shows strong net polarization near the neutral line. Surprisingly the Helium line, formed in the upper chromosphere, also shows broad-band polarization, suggesting the presence of strong variations of the magnetic field vector and LOS velocity also at these layers. It may be speculated that uncombed magnetic fields (e.g. as proposed by Solanki & Montavon 1993) are present even at chromospheric heights. A detailed analysis of both neutral lines indicates that the neutral line seen in Helium is slightly shifted outward from the sunspot. The neutral line appears due to projection effects and indicates the region where the magnetic field lines change their polarity relative to the LOS. The fact that the Helium neutral line is shifted outward indicates that the field lines that we see in the chromosphere are slightly more vertical than in the photosphere.

In Figure 3 we show an example of asymmetric Stokes V profiles and an average over 15 profiles around the Helium neutral line. The upper panel shows clearly anomalous Silicon Stokes V profile, while the Helium line still shows positive polarity, but is also quite asymmetric. The lower panel shows a negative field in Silicon while the Helium shows a mainly positive and highly asymmetric profile.

2.2. Inversion results

In order to compare the sunspot structure in the photosphere and the chromosphere we have to obtain from the observed Stokes spectra various parameters like the full magnetic field vector and the velocity. We achieve this by applying inversion techniques to both lines separately. In particular, the Helium line triplet has been inverted under the assumption of a Milne-Eddington atmosphere model (Lagg et al. 2003), using the fact that the Helium line is in general optically thin and does not need a complicated radiative transfer treatment in order to measure the magnetic field. Zeeman splitting in the incomplete Paschen-Back regime (Socas-Navarro et al. 2004) has been taken into account for this line (c.f. Sasso et al., these proceedings). The Silicon

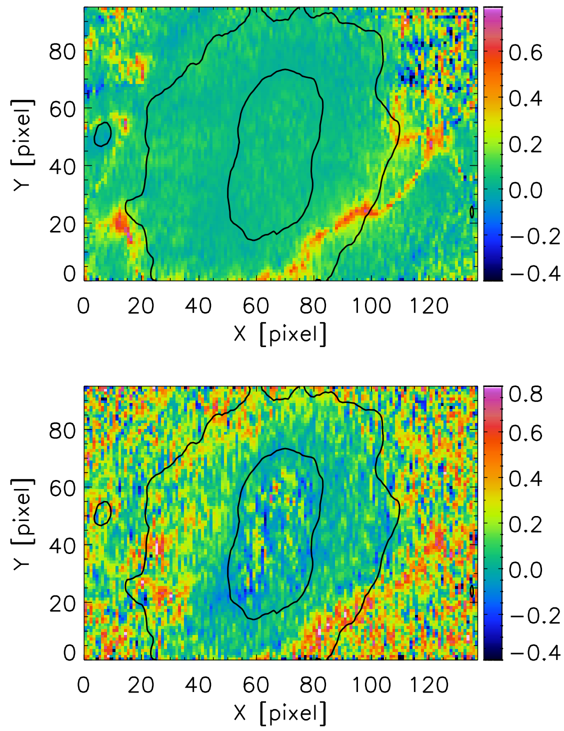

Figure 2. Stokes V area asymmetry maps of the observed sunspot for the Silicon line (top) and for the Helium triplet (bottom). The black contour lines mark the umbral-penumbral and penumbral-quiet Sun boundaries.

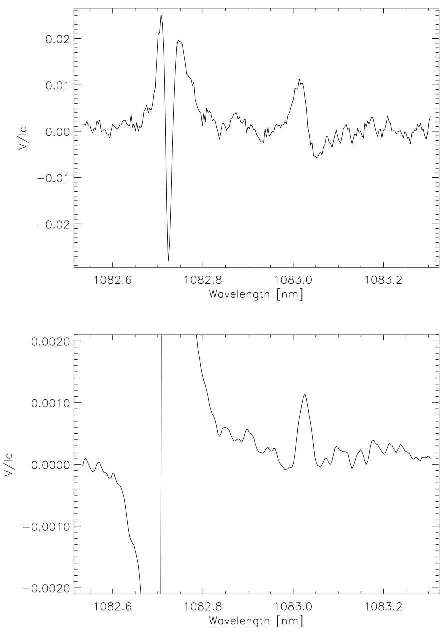

Figure 3. Asymmetric Stokes V profiles for the Silicon and Helium lines. The upper panel shows a pixel for which both lines are strongly asymmetric (pixel x=98 y=24). The lower panel shows an average of 15 Stokes V profiles over the neutral line as seen in Helium.

line has been analyzed using a full model atmosphere in local thermodynamic equilibrium (Frutiger 2000). The model atmosphere contained a gradient in the magnetic field strength and five nodes in line of sight velocity and temperature, the other atmospheric parameters like the field inclination and azimuth have been forced to be constant with height.

Figures 4 and 5 show the field strength, inclination and azimuth angles, as well as the LoS velocity retrieved from the inversions of the Helium and Silicon lines respectively. The Silicon maps correspond to $\log(\tau) = -0.5$. The field configuration reveals differences in the two layers, especially in the field strength which is much weaker in the chromosphere. The velocity in Helium shows the inverse Evershed flow, which is typical of lines formed in chromospheric layers. The velocity also shows umbral oscillations in the chromosphere. The complex pattern of velocities seen in the umbra is a product of the combination of finite sized oscillation cells and the scan of the spectrograph slit from left to right. The results reveal the presence of a high velocity region (left side on the fourth panel in Figure 4) which has been analyzed using a two components model atmosphere. In a detailed analysis of such components we obtain values for the down flow velocity of up to 25 km/s in one component and a field strength in the order of 500 Gauss, while the other component is at rest and has a field strength of 1500 G.

The polarimetric signals in Helium are much weaker than in the Silicon line. This introduces higher uncertainties in the determination of the magnetic field and velocity, which is clearly seen in Figures 4 and 5 as the heightened noise in the recovered parameters.

In the inversion procedure no stray light has been taken into account in any of the models. The Helium line has a large Doppler width and therefore the magnetic splitting of the line lies in the weak field regime, which means that we are mainly measuring magnetic flux. Since the stray light in both lines is the same due to the fact that they belong to the same spectral region, and that the Silicon line has an effective landé factor of 1.5, we estimated the effect of the stray light to be the same in both line. Therefore we can compare the results neglecting the stray light, although we obtain an underestimate of the magnetic field strength, the relative field strengths should be o.k.

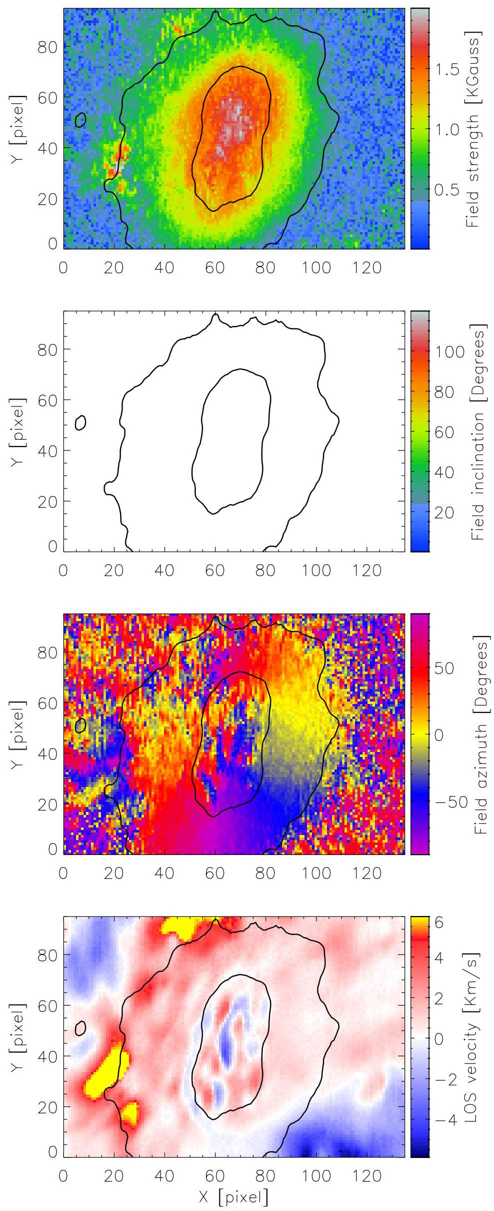

Figure 4. Maps retrieved from the one component inversion of the Helium triplet. The velocity oscillations in the Sunspot's umbra are clearly present in the velocity map.

2.3. Azimuthal averages

In order to compare the magnetic field vector retrieved in both spectral lines, the results have been projected to the local reference frame with respect to the center of the image. In figure 6 we present the azimuthal averages vs. the normalized radial distance for the longitudinal and transversal magnetic field,

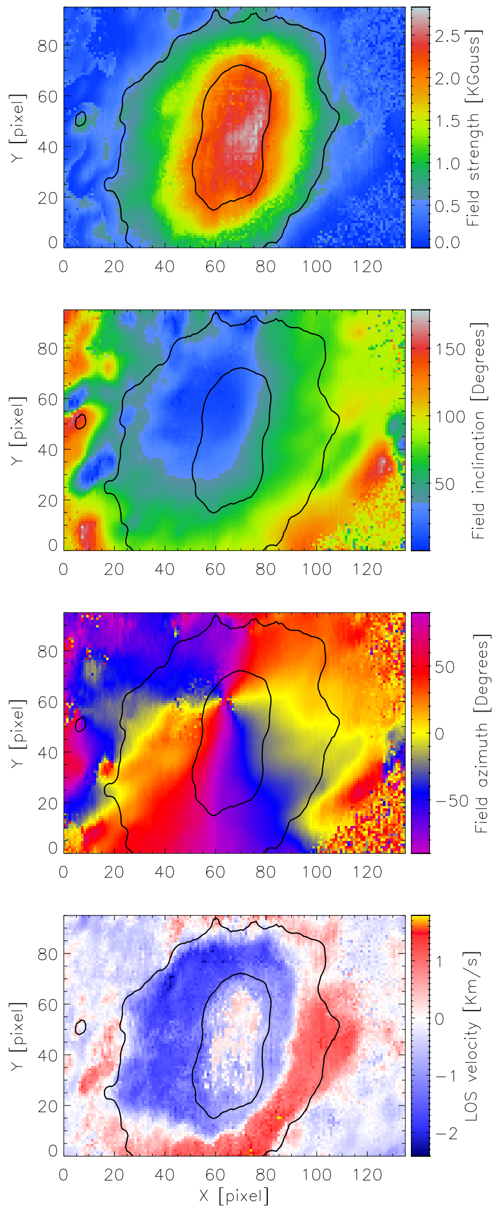

Figure 5. Maps retrieved from the inversion of the Silicon line at $\log(\tau) = -0.5$.

the field zenith angle and the field strength for both layers. It is clear that the magnetic field strength is lower for Helium than for Silicon, which is consistent with the typical magnetic structure of sunspots deduced from, e.g., radio observations (White, these proceedings) or O IV measurements (Hagyard et al.). At the beyond the penumbral boundary the field strength obtained from Helium is higher than Silicon, indicative for the canopy-like structure of the chromosphere overlying a weaker photospheric field. In the sunspot center, the field vector retrieved by the Helium line is affected by the oscillations. Therefore the inferred values have a significant standard deviation, clearly visible in the maps of the zenith angle and the transversal field in the umbral region in figure 6. The zenith angle increases as the magnetic field decreases. We found for the Silicon and Helium lines that the zenith angle depends linearly on r/rp, and that it is very similar for both lines. At the penumbral boundary the uncertainty in determining the zenith angle is evident.

In figure 7 we show the field strength gradient in the photosphere calculated with two different approaches: The field gradient in the photosphere is retrieved directly from the inversions. In addition, the gradient averaged over the height of formation of the He I triplet and the Si I line is plotted. In order to determine this quantity we need to assume some height of formation of the He I triplet. In plane parallel atmospheres Avrett et al. (1994) find a formation height lying within 1600 and 2200 km above the quite solar surface. Thus we assume a mean formation height of 2000 km in order to compute the gradients. The magnetic field gradient averaged over the photosphere reaches values of -1 G/km at the umbral / penumbral boundary. At $r/rp \approx 0.6$ the chromospheric and photospheric field strengths are comparable. At the outer penumbra the gradient is positive and reaches values of 1 G/km. The gradient determined by the He I triplet only shows smaller variations, from -0.5 G/km in the center of the spot to slightly positive values outside the penumbra. The Si I gradient agrees with the result from Westendorp Plaza (2001) for visible lines.

REFERENCES

Avrett, E. H., Fontenla, J. M., & Loeser, R. 1994, IAU Symp. 154: Infrared Solar Physics, 154, 35

Borrero, J. M., Lagg, A., Solanki, S. K., & Collados, M. 2005, A&A, 436, 333

Frutiger, C. 2000, PhD thesis, ETH Zürich, Switzerland, Diss ETH No. 13896

Hagyard, M. J., et al. 1983, SoPh, 84, 13

Lagg, A., Woch, J., Krupp, N., & Solanki, S. K. 2004, A&A, 414, 1109

Ruëdi, I., Solanki, S. K., & Livingston, W. C. 1995, A&A, 293, 252

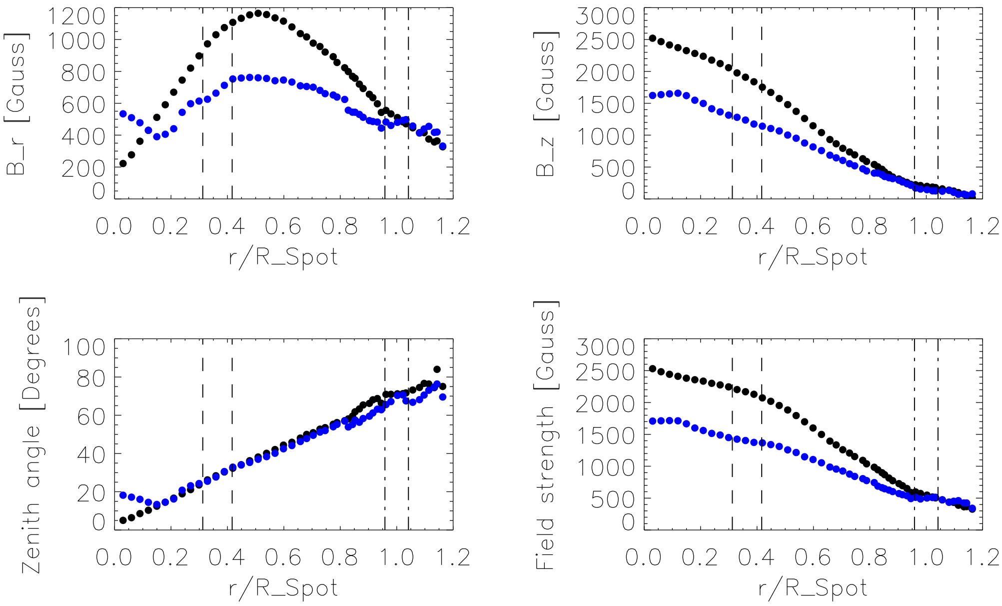

Figure 6. Azimuthal averages vs. normalized radial distance for the longitudinal and transversal magnetic field, the field zenith angle and the field strength . The vertical lines represent the umbral and penumbral boundaries. Two lines are plotted since the observed sunspot was not entirely symmetric. The black points refer to the photosphere (Silicon), the blue points to the chromosphere (Helium).

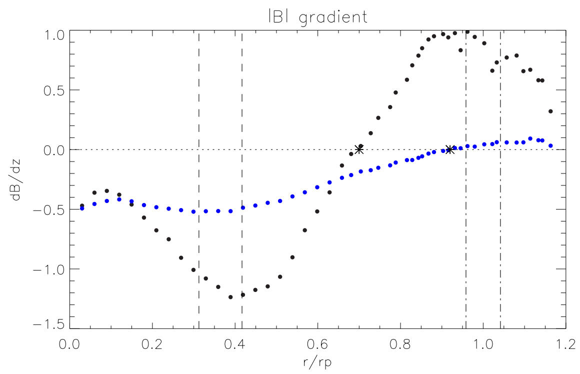

Figure 7. Field strength gradient, [G/km], in the photosphere (black), and gradient between the photosphere and chromosphere assuming a formation height of the He I triplet of 2000 km.

Socas-Navarro, H., Trujillo Bueno, J., & Landi DeglInnocenti., E.2004, ApJ, 612, 1175

Solanki, S. K., & Montavon, C. A. P. 1993, A&A, 275, 283

Westerdorp Plaza, C., del Toro Iniesta, J.C., Ruiz Cobo, B., et al. 2001, ApJ, 547, 1130