THERMAL-MAGNETIC RELATION OF A SUNSPOT AS INFERRED FROM THE INVERSION OF $1.5\mu M$ SPECTRAL DATA

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ABSTRACT

We present the thermal-magnetic relation in a simple, isolated sunspot deduced from the inversion of 1.56 μm spectropolarimetric data. Due to the high Zeeman sensitivity of the $g = 3$, Fe I 1.5648 μm line, we can study this relationship in the entire sunspot. An inversion technique based on response functions is used to derive various parameters, both as a function of location within the sunspot and of height in the atmosphere. In this paper we attempt to relate field strength, vertical and radial field components and the field inclination with temperature.

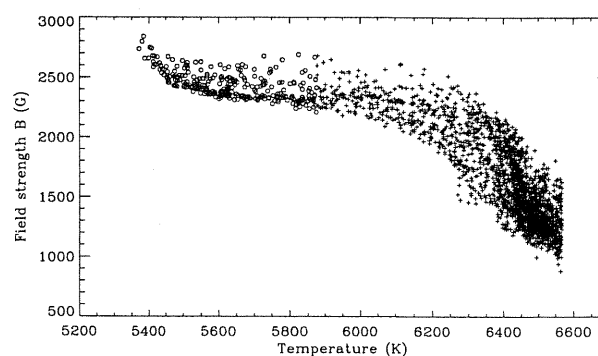Key words: Sunspots: magnetic field; spectropolarimetry: infra-red.

Figure 1. Magnetic field strength B versus continuum brightness temperature T. The circles denote the umbral points whereas the plus signs represent penumbral points.

1. INTRODUCTION

The temperature distribution within a sunspot is related to its magnetic field structure (e.g., Kopp & Rabin 1992, Solanki et al. 1993, Martínez Pillet & Vázquez 1993, Balthasar & Schmidt 1994, Stanchfield et al. 1997, Westendorp et al. 2001). Due to the superior Zeeman sensitivity of 1.56 μm lines it is possible to investigate this relationship in the whole sunspot (Solanki et al. 1992). Also, the effect of stray light is smaller in the infrared, which otherwise could contaminate the intensity profiles (Kopp & Rabin 1992). We have carried out an investigation of the thermal-magnetic relation in a simple sunspot by inverting a set of spectral data obtained in two adjacent 1.56 μm lines.

2. DATA AND ANALYSIS

We use TIP (Tenerife Infra-red Polarimeter, Collados 1999) spectropolarimetric data, simultaneously recorded on 27th Sep 1999, in two IR Fe I lines (15648.5 Å, $g = 3$ and 15652.9 Å, $g_{\text{eff}} = 1.53$), of a fairly round sunspot, when it was near the disk center ($\mu = 0.92$). The spot belongs to region NOAA 8706 and has a size of around 31″. The inversion of the data is carried out using the code described by Frutiger (2000, cf. Frutiger et al. 2000) to obtain the depth dependent atmospheric stratification of various parameters.

For this investigation the continuum temperature, obtained by converting continuum intensity into temperature using the Planck function, is employed. In the following sections, we mainly concentrate on the thermal-magnetic relation for deep atmospheric layers, specifically we consider the layer averaged over $log(\tau_{.5})$ values ranging from 0.0 to −0.5.

3. OBSERVED RELATIONSHIPS

Figure 1 shows the B vs T relationship for optical depths averaged over $log(\tau_{.5})$ from 0.0 to −0.5. Our

results are similar to the results obtained by earlier investigators. It differs in the fact that for the first time 1.56 μm data of a whole sunspot have been analyzed (and not just a few slices across a sunspot) and in addition we can present what are probably the most reliable results, at least in the penumbra, for the deepest observable layers. In the umbra, the magnetic field strength decreases with increasing temperature and the distribution is distinctly nonlinear. The relatively small increase of B in the umbra is at least partly related to the fact that the observed sunspot was small compared with, e.g., that observed by Solanki et al. (1993). The penumbral distribution of B versus T also shows an overall steep decrease of B with increasing T. Stray light might effect this gradient. Figure 2 shows a field inclination γ versus T diagram averaged over the same layers. As in the case of B, γ also displays a similar nonlinear relationship with T. Note the points with $\gamma > 90°$ (i. e. those lying above the dotted line in Fig. 2), implying return flux. This coincides with down flows in the outer penumbra.

In Fig. 3 we plot the vertical (B_z) and radial (B_r) field components versus T. B_z shows a similar trend as the total field, except that it drops almost to zero at the highest temperatures. It actually drops slightly below zero at locations where γ runs beyond 90° near the penumbral boundary. B_r, on the other hand increases almost linearly with temperature.

Figure 4 show scatter plots of field strength (B) versus core intensity in the Fe I 15648 and 15652 Å lines. We obtain a result similar to that found by Stanchfield et al. (1997), except a doubling in Fe I 15648 Å core intensity plot in the penumbra. The two branches correspond to two different sets of line-of-sight field inclination for disk side and limb side penumbral points. For larger field inclinations (as is the case of limb side penumbral points), the Zeeman π to σ peak ratio becomes larger, which results in a reduction of the line core intensity. This effect is more prominent in a completely Zeeman split line. A noticeable difference in core intensity is seen in the disk side ($\gamma \sim 27°$) and limb side ($\gamma \sim 87°$) penum-

Figure 3. Magnetic field components B_z and B_r versus T. The symbols have the same meaning as in Fig. 1.
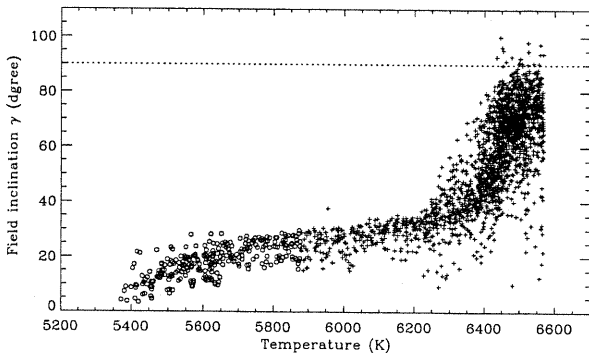

Figure 2. Magnetic field inclination γ versus continuum brightness temperature T. The symbols have the same meaning as in Fig. 1.
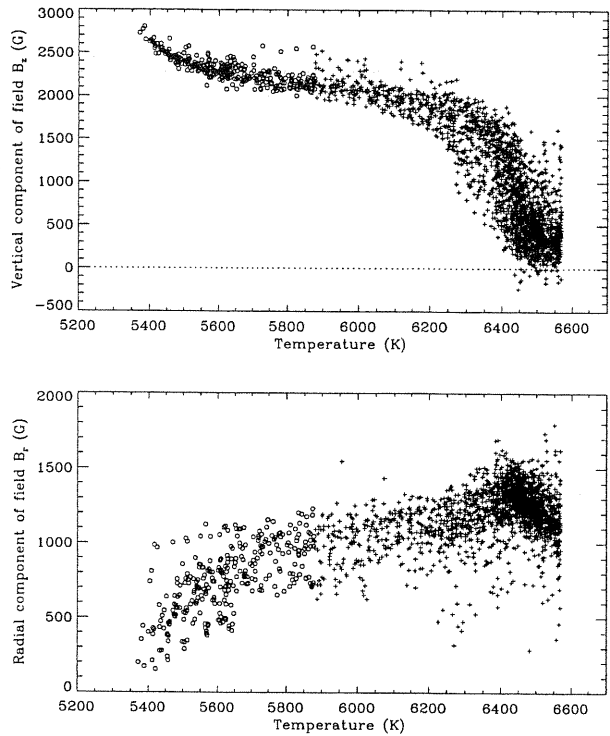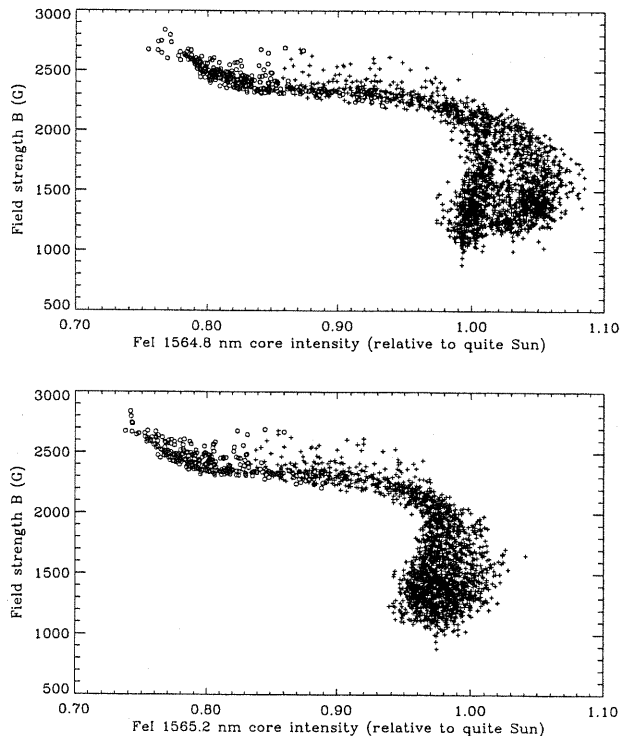

Figure 4. Magnetic field strength B versus Fe I 1564.8 (top) and 1565.2 nm (bottom) core intensity. The symbols have the same meaning as in Fig. 1.
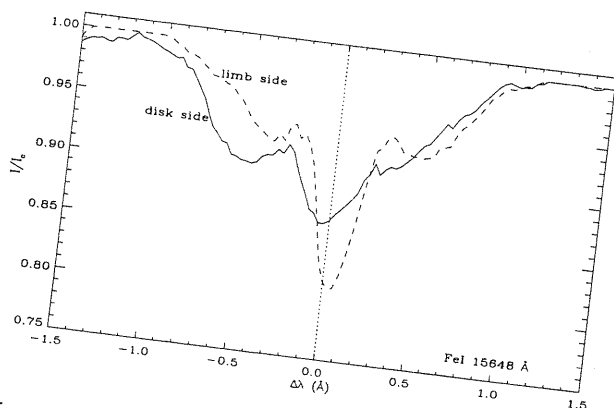
Figure 5. Sample profiles of the g = 3 line from the disk side and limb side penumbra showing the change in line core intensity for two different field inclinations.
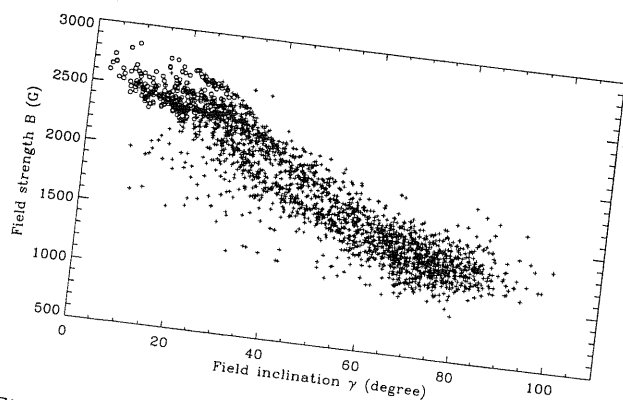

Figure 6. Magnetic field strength B versus field inclination γ. The symbols have the same meaning as in Fig. 1.

found a nonlinear relationship between the field inclination and temperature. A linear relationship is found between the magnetic field strength and field inclination.

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bral Fe I 15648 Å intensity profiles shown in Figure 5.

In addition to the thermal-magnetic relation, we also obtained a plot for field inclination γ versus B which is shown in Fig. 6. The results are similar to the one obtained by Stanchfield et al. (1997). Here the relationship is almost linear, with a bifurcation visible around γ = 40°, which includes mostly penumbral points. The two branches are due to the distinct spine structures seen in the penumbra.

4. CONCLUSIONS

We have investigated the relationship between the temperature and the magnetic field vector by inverting a set of IR spectropolarimetric data for a simple sunspot. We found a nonlinear relationship between the field strength and temperature, which confirms the results obtained by earlier investigators. The relationship found between magnetic field strength and core intensity differs from the above especially for the penumbral points, where two distinct values of field strength is found at the same core intensity in the inner and outer penumbral regions. We also