DETERMINATION OF THE MAGNETIC FIELD VECTOR IN A POLAR CROWN PROMINENCE VIA THE HANLE AND ZEEMAN EFFECTS IN THE HE I 10830 Å MULTIPLET.

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ABSTRACT

The spectropolarimetric observations of a polar crown prominence reported here were obtained using the Tenerife Infrared Polarimeter attached to the Vacuum Tower Telescope at the Teide observatory. The slitjaw Hα image shows that this prominence was made of several nearly vertical threads of plasma. We show that the observed polarization in the He I 10830 Å multiplet is sensitive to magnetic fields via the Hanle and Zeeman effects and that the magnetic field vector, inferred via the theoretical modelling of our spectropolarimetric observations, results to be inclined by about 25° with respect to the solar local vertical.

Key words: prominences; polarimetry.

1. INTRODUCTION

The magnetic field is the most important physical quantity for understanding the formation, stability and evolution of solar prominences. The most reliable strategy we have available for inferring the magnetic field vector is via the measurement and theoretical interpretation of Stokes profiles in suitably chosen spectral lines. The quantum theory of the Hanle and Zeeman effects for the interpretation of spectropolarimetric observations started to be developed many years ago (e.g., Bommier, 1976; 1980; Landi Degl’Innocenti 1982). Most of the modern work concerning the diagnostics of prominence magnetic fields has been carried out via the He I D3 multiplet at 5876 Å (e.g., the reviews by Leroy 1989; Landi Degl’Innocenti 1990 and Paletou & Aulanier 2003, and references therein). Our work is based, however, on spectropolarimetry of the He I 10830 Å multiplet. As in the case of the D3 line, the interpretation of the spectropolarimetric observations in the 10830 Å multiplet have to be done applying the quantum theory of the Hanle and Zeeman effects as done by Trujillo Bueno et al. (2002).

2. SPECTROPOLARIMETRIC OBSERVATIONS

The observations reported here were carried out on May 27, 2001 with the Tenerife Infrared Polarimeter (TIP; see Martínez Pillet et al. 1999) mounted on the German Vacuum Tower Telescope (VTT) at the Observatorio del Teide (Spain). TIP uses ferro-electric liquid crystal retarders as polarization modulators. After the light beam is temporally modulated it goes through a double birefringent plate that divides it into two orthogonal polarization beams, which are then imaged on a single detector array. In order to measure I, Q, U and V, TIP takes four consecutive images with independent analyzer configurations, that result in linear combinations of the four Stokes parameters. The information obtained independently from each polarization beam is combined only at the end of the data reduction procedure in order to correct for the seeing-induced crosstalk from I to Q, U and V.

The spectrograph’s slit was located at about 20 arcsec off the South solar visible limb and parallel to it. Fig. 1 shows the observed Stokes parameters of the He I A10830 multiplet at one point along the direction of the spectrograph’s slit. We point out that the presence of a non-zero Stokes U profile indicates a rotation of the direction of linear polarization with respect to the direction parallel to the solar limb. According to the theory of the Hanle effect this is the observational signature of the presence of a magnetic field inclined with respect to the solar local vertical. Note also that at the plasma temperatures of prominences this multiplet shows only two spectral lines, one to the blue at 10829.09 Å and one to the red at 10830.3 Å, and that only the “red” line shows linear polarization. This can be explained in terms of atomic level polarization (cf. Trujillo Bueno et al. 2002). An atomic level is said to be polarized when there exist population imbalances and quantum coherences among its magnetic sublevels. For the weak magnetic field of solar prominences the presence of atomic level polarization in the upper level of the transition is the main cause of the emitted linear polarization, since the contribution of the transverse Zeeman
Figure 1. Example of the observed Stokes profiles of the He I 10830 Å multiplet corresponding to a point along the slit. The positive reference direction for Stokes Q is the parallel to the nearest solar limb. The zero of the wavelength axis is set to the center of the ‘blue’ line (see text).

The effect is normally negligible. The reason of the presence of linear polarization only in the ‘red’ line is a consequence of the structure of the 10830 Å multiplet. The upper term of this multiplet has three levels, with angular momentum $J_u$ equal to 2, 1 and 0 in order of increasing energy. The ‘blue’ line is due to emissions from the upper level with $J_u = 0$, which is intrinsically unpolarizable, and for this reason we do not observe emitted linear polarization in this line. The ‘red’ line is the result of the superposition of two blended lines (one having $J_u = 1$ and the other $J_u = 2$). The fact that these two levels cannot be polarized is the reason that explains why we observe linear polarization in the ‘red’ line, since we then have selective emission processes. In the case of solar prominences the unpolarized and anisotropic photospheric illumination that produces atomic level polarization in the upper levels of the ‘red’ line. The presence of a magnetic field reduces and modifies the atomic level polarization and the emitted linear polarization (Hanle effect).

Note also in Fig. 1 that Stokes V shows the typically antisymmetric profile of the longitudinal Zeeman effect.

3. THEORETICAL MODELING

To infer the magnetic field vector in solar prominences from the observed Stokes profiles in the He I λ10830 Å multiplet, we apply the theory of the Hanle and Zeeman effects as described in detail in Landi Degl’Innocenti & Landolfi (2004). The main assumptions of our analysis are that the prominence plasma is optically thin and that collisions play a negligible role on the atomic excitation. We quantify the atomic level polarization by means of the multipole components, $\rho^S_{QQ}(J,J')$, of the atomic density matrix. Such $\rho^S_{QQ}(J,J')$ elements allow us to quantify the overall population of each $J$-level. As well as the population imbalances between the magnetic sublevels pertaining to each $J$-level and the quantum coherences between pairs of magnetic substates, even between substates pertaining to different $J$-levels of the same term. We solve the statistical equilibrium equations for the multipole components ($\rho^S_{QQ}(J,J')$) of the atomic density matrix (see Section 7.6.a in Landi Degl’Innocenti & Landolfi (2004) for the five lower terms of the triplet system of helium (namely 23$S, 23^3P, 33^3S, 33^3P$ and 33$D$). These statistical equilibrium equations take fully into account the Hanle and Zeeman effects produced by a static magnetic field of given strength $B$, inclination $\theta_B$, and azimuth $\chi_B$ (see Fig. 2).

From the calculated $\rho^S_{QQ}(J,J')$ elements it is then possible to compute the emission coefficients $\epsilon_i$ (with $i = I, Q, U, V$), for the line transition under consideration (see the equations of Section 7.6.b in Landi Degl’Innocenti & Landolfi (2004)). It is then straightforward to calculate the emergent Stokes parameters because, for an optically thin medium, they are simply proportional to the corresponding components of the emission vector.

4. DETERMINATION OF THE MAGNETIC FIELD VECTOR

In order to infer the magnetic field vector we compare the observed Stokes profiles at each point along the slit with the theoretical Stokes parameters we have included in a suitable database. In Fig. 3 the solid line shows the results of our theoretical modelling of the observed Stokes profile shown in Fig. 1, for a magnetic field of 31 gauss, with inclination $\theta_B = 25^\circ$ and with azimuth $\chi_B = 160.5^\circ$. The final result of this investigation is contained in Fig. 4, which shows that the inferred magnetic field vector is rotating around a fixed direction in space (given by $\theta_B \approx 25^\circ$ and $\chi_B \approx 168^\circ$) as one considers consecutive spatial points along the direction specified by the spectrograph’s slit.
ACKNOWLEDGEMENTS

This work has been partly supported by the Spanish Ministerio de Ciencia y Tecnología through project AYA2004-05792 and by the European Commission via the Solar Magnetism Network.

REFERENCES

Bommier, V., 1976, Thèse de 3ème Cycle, Université de Paris VI
Landi Degl’Innocenti, E. 1990, in Dynamics of Quiescent Prominences, ed. V. Ruzdjak & E. Tandberg-Hanssen (Berlin: Springer), 206

Figure 3. Example of theoretical fit (solid line) to the observed Stokes profiles of Fig. 2 (open circles). The theoretical Stokes profile corresponds to \( B = 31 \) gauss, \( \theta B = 25^\circ \) and \( \chi B = 160.5^\circ \).

Figure 4. Variation along the spectrograph slit of the inclination (\( \theta B \)), azimuth (\( \chi B \)), and intensity (in gauss see the numbers close to each point) of the inferred magnetic field vector.

5. CONCLUSIONS

We have reported spectropolarimetric observations of a polar crown prominence in the He I 10830 Å multiplet, including our physical interpretation of the observed Stokes profiles based on the quantum theory of the Hanle and Zeeman effects. We find magnetic fields with a mean inclination \( \theta B \approx 25^\circ \) and a mean azimuth \( \chi B \approx 168^\circ \). Moreover, as shown in Fig. 4, we find that in the central part of the observed polar crown prominence the magnetic field vector is rotating around a fixed direction in space specified by such \( \theta B \) and \( \chi B \) values. Our results suggest that the widespread belief that prominence magnetic fields are mainly horizontal might be valid only for quiescent prominences located far away from the solar magnetic poles.