N87-20902

MAGNETIC FIELD VECTOR AND ELECTRON DENSITY DIAGNOSTICS
FROM LINEAR POLARIZATION MEASUREMENTS
IN 14 SOLAR PROMINENCES

V. Bommier
Laboratoire de Physique Atomique et Moléculaire
et d'Instrumentation en Astrophysique
DAPHE, Observatoire de Paris-Meudon
92195 Meudon Principal Cédex

ABSTRACT

The Hanle effect is the modification of the linear polarization parameters of a spectral line due to the effect of the magnetic field. It has been successfully applied to the magnetic field vector diagnostic in solar prominences. The magnetic field vector is determined by comparing the measured polarization to the polarization computed, taking into account all the polarizing and depolarizing processus in line formation and the depolarizing effect of the magnetic field. The method has been applied to simultaneous polarization measurements in the Helium D_3 line (5876 Å, $3d\,^3D \rightarrow 2p\,^3P$) and in the Hydrogen Hβ line in 14 prominences. Four polarization parameters are measured (two polarization degrees and two polarization directions), which lead to the determination of the three coordinates of the magnetic field vector and the electron density, owing to the sensitivity of the Hβ line to the non-negligible effect of depolarizing collisions with electrons and protons of the medium. A mean value of 1.3×10^{10} cm^{-3} is derived in 14 prominences.

1. INTRODUCTION

The prominences emission lines observed at the solar limb with a coronagraph are linearly polarized by Rayleigh scattering of the underlying anisotropic photospheric radiation. In zero magnetic field the polarization direction would be parallel to the solar limb. The magnetic field modifies the linear polarization of the emitted line, leading to a depolarization and to a rotation of the polarization direction : these are the two main features of the Hanle effect. This effect has been successfully used for determining the prominence magnetic field from polarization measurements of the Helium D_3 line (5876 Å, $3d\,^3D \rightarrow 2p\,^3P$) (Leroy et al., 1983, 1984; Athay et al., 1983; Querfeld et al., 1985). The diagnostic is achieved by matching the observed polarization parameters and the computed ones. The computation of the polarization of the Helium D_3 line has been achieved using a quantum formalism of matter radiation interaction (Bommier and Sahal-Bréchot, 1978; Bommier, 1980; Landi Degl'Innocenti, 1982), and leaning on the recent works on Helium line formation in prominences (Heasley et al., 1974).

The Hydrogen Hα and Hβ line polarization in prominences has been measured at the Pic-du-Midi (Leroy, 1981). The interpretation of polarization measurements requires further investigation because, owing to the large dipole interaction between the Hydrogen atom and the surrounding electrons and protons, the depolarizing effect of collisions between fine structure levels (n, ℓ, j) and (n, 1, j') cannot be ne-

PRECEDING PAGE BLANK NOT FILMED

glected. This lead to a new method of diagnostic of the electron density, which has been applied to 14 prominences observed in Helium D_3 and Hydrogen $H\beta$ simultaneously (Bommier et al., 1986). By measuring the polarization parameters of two lines, one gets four measured quantities, because two parameters are measured for each line, which are the polarization degree and direction. Four quantities can be determined from interpretation, which are the three coordinates of the magnetic field vector and the electron density in the case of D_3 and $H\beta$. The radiative transfer problem is avoided because these lines are optically thin in prominences; this is not the case of $H\alpha$ which is not optically thin and for which the radiative transfer problem for polarized radiation in the presence of a magnetic field has to be solved before interpreting the observations (Landi Degl'Innocenti, these proceedings).

In Section 2 we present the main steps and physical hypothesis of the $H\beta$ polarization computation; the results of interpretation of polarization measurements are given in Section 3.

2. CALCULATION OF THE LINEAR POLARIZATION OF THE $H\beta$ EMISSION LINE OF SOLAR PROMINENCES

The computation of the linear polarization of prominences Helium and Hydrogen Balmer lines requires firstly a quantum formalism of matter-radiation interaction : the master equation for the atomic density matrix, which describes the evolution of the atom coupled to the bath of photons and perturbers, is solved at the stationary state. The emitted photons density matrix and the polarization parameters of the emitted line are derived straightly from the atomic populations and coherences computed at the stationary state. (Bommier and Sahal-Bréchot, 1978; Bommier, 1980).

The atomic density matrix has been expanded over a basis which diagonalizes the fine-structure and the magnetic field interaction. The validity of the computation is then extended up to field strengths of 100 Gauss. In the case of Hydrogen, the hyperfine structure also has been taken into account in a preliminary calculation, but turns out to be negligible with respect to the measurement inaccuracies.

The resolution of the master equation at the stationary state requires the knowledge of the line formation processes. These are known from the work of Heasley et al. (1974) for Helium lines, Heasley and Mihalas (1976), Heasley and Milkey (1976, 1978) for Hydrogen lines, by solving the coupled problem of radiative transfer and statistical equilibrium. In the case of Hydrogen lines, the first atomic model (Heasley and Mihalas, 1976) assumed five bound levels and a continuum for statistical equilibrium computations. Heasley and Mihalas (1978) have shown that radiative cascades from upper levels up to n = 20 must be included in the statistical equilibrium equations for obtaining correct Balmer line intensities. In fact that effect, together with that of radiative recombinations, is much less important for the atomic polarization. Owing to measurements inaccuracies, it can be neglected in the present problem : thus statistical equilibrium equations have been solved for the levels n = 1 to 4 for the computation of the $H\beta$ polarization.

The alignment of the Zeeman sublevels is due to the absorption of the anisotropic incident photospheric and chromospheric radiation field. However, radiative transfer and statistical equilibrium should be solved consistently for optically thick transitions. In fact very high optical thickness for the Lyman lines are derived in Heasley's series of models ($\tau_{Ly\alpha} \sim 10^6$). Thus, owing to the trapping of the Lyman radiation in the prominence material, we have considered that their anisotropy is completely lost, and we have used the local intensities at the bottom of the pro-

minence, taken from recent quiet sun intensity measurements at the center of the disk. For the Balmer lines, their optical thickness has been obtained by Landman and Mongillo (1979) from line profile measurements : $\tau_{H\alpha} \sim 2.2$; $\tau_{H\beta} \sim 0.3$. Nevertheless, in our computations, the prominence has been assumed to be optically thin in the Balmer lines (Hα and Hβ) and in the Paschen line Pα. With the exception of the Hα line, our model is thus consistent with that of Heasley and Milkey (1978), where the Lyman lines and Hα are optically thick and the Balmer, Paschen and all other lines between excited levels are optically thin.

The computation of line polarization must also take into account the non-magnetic polarizing or depolarizing effects. In the case of Hydrogen lines, the statistical equilibrium results from radiative transitions and also from transitions between fine structure levels n, ℓ, j and n, $\ell\pm1$, j' due to collisions, owing to the large dipole interaction between the Hydrogen atom and the surrounding electrons and protons. The corresponding collisional rates are of the same order of magnitude as the radiative rates, for typical electronic densities of prominences. We have computed the collisional transition probabilities using a semi-classical description of the collision and assuming the impact approximation, which means that the collision duration is very small with respect to the mean time between collisions, or, in other words, that collisions are well-separated in time. The impact approximation is valid at typical electron densities in prominences. The effect of collisions with protons has been found to be 10 times larger than the effect of collisions with electrons. Owing to the isotropic distribution of electrons and protons, the effect of collisions is to decrease the anisotropy of the Zeeman sublevels which is responsible for the polarization of the emitted radiation.

3. DIAGNOSTIC OF THE MAGNETIC FIELD VECTOR AND OF THE ELECTRON DENSITY

The diagnostic of the magnetic field vector and of the electron density is achieved by matching the observed polarization parameters and the computed ones for each observed line. This leads to the determination of a series of field vector solutions and density values for which the computed polarization parameters are equal to the observed ones for each line. The final determination is achieved by looking at the common field vector solutions in the two series.

In fact, in most of cases, multiple solutions are obtained, which are grouped two by two owing to the fundamental degeneracy of the solutions : two field vector symmetrical with respect to the line of sight have the same effect on the line polarization and cannot be distinguished.

In the multiple solutions (up to 8), a selection has been done based on several criteria determined from results obtained in previous works on the prominence magnetic field vector determination from polarization measurements in the D$_3$ line resolved in two components (Athay et al., 1983; Querfeld et al., 1985) or unresolved (Leroy et al., 1984) :
1 - Though rather vertical solutions should be valuable a priori, they can be discarded on account of the statistical analysis of the polarization degree and the direction of polarization observed in the Helium D$_3$ line, for which the depolarization is of magnetic origin only : the observed average depolarization is too large to be consistent with rather vertical fields (Sahal-Bréchot et al., 1977; Leroy, 1978).
2 - Field strengths higher than 30 Gauss are highly improbable in quiescent prominences : such derived field strengths are very probably parasitic solutions due to level-crossings effects in the D$_3$ line (Bommier, 1980).
3 - The angle between the magnetic field vector and the prominence long axis is clo-

se to 25° (Leroy et al., 1983, 1984).
4 - The field component that is along the long axis of the filament shows a general organization which forms over the Sun's Surface a regular pattern well defined and consistent. (Fig. 13 of Leroy et al., 1984).
5 - For the high prominences (h > 30 000 km), which show filamentary or curtain-like structures, the lines of force cross the prominence in the opposite direction with respect to the polarity of the adjacent photospheric field (Leroy et al., 1984) as in the Kuperus-Raadu model type. This is the case of all the prominences of our sample, with the exception of prominence n° 12.

All these criteria have been used for solving the ambiguities of the diagnostic. It is very interesting and important to notice that all these criteria do not contradict one another : it has been possible in all cases to select one field vector and only one, among the multiple solutions of our sample, which agrees with all the above criteria.

However, if we compare our sample to that analyzed by Athay et al. (1983), it contains a greater number of cases where the field lines of force are not exactly horizontal, but somewhat aslant. The angle of deviation of the lines of force from the horizontal plane is more than 25° in seven prominences of our sample. Therefore one must consider that the magnetic field in quiescent prominences should be less horizontal than currently admitted. Such a geometry is difficult to admit in quiescent prominences where the cold material is observed hanging on the support made by the lines of force, either motionless, or hardly moving; a 30° slope of the

Fig. 2 - Histograms of the magnetic field vector and electron density determined in 14 prominences observed at the Pic-du-Midi. The three coordinates of the field vector are : the field strength B, the inclination angle with respect to the horizontal plane $\Delta\psi$, the angle α between the field vector projected on the horizontal plane and the prominence long axis.
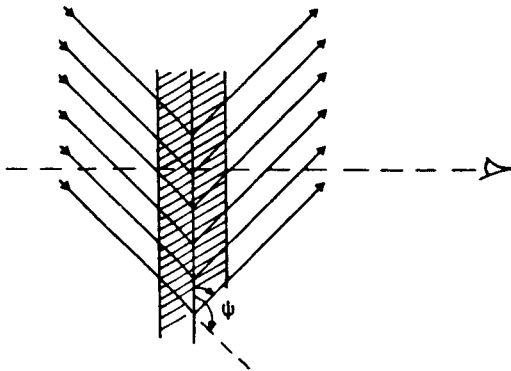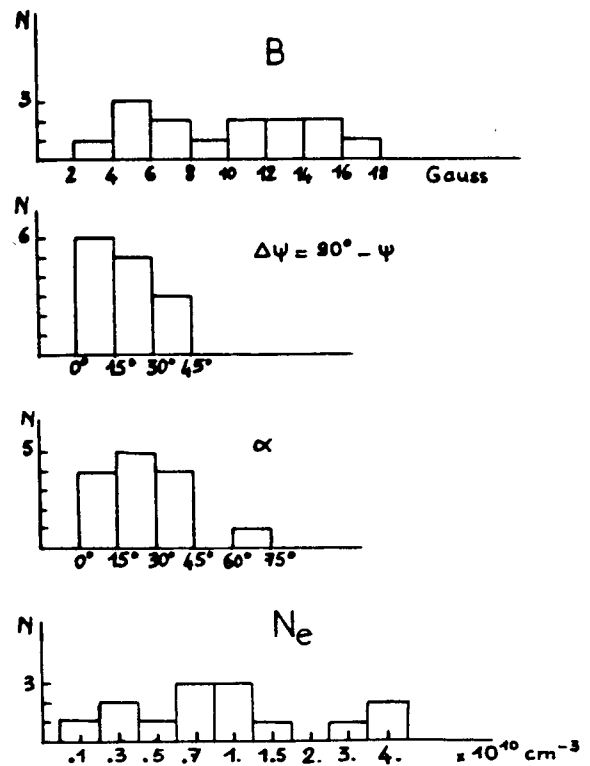
Fig. 1 - the simple geometry of field lines used in this work : the polarization degree and direction of the Hβ line have been computed assuming that two field works with inclination ψ and 180°-ψ, and the same azimuth θ, are present along the line-of-sight.

lines of force would lead to fast drifts downwards of the prominence matter. The interpretation of polarization measurements has been undertaken again, assuming V shaped lines of force (see Fig. 1), in order to schematize by this mean the shape of lines of force in the prominence models (Kippenhahn and Schluter, 1957; Kuperus and Raadu, 1974), in which a magnetic through is assumed, where the cold material can be supported against gravity.

The result on the magnetic field vector and electron density determination is given on the histograms of Fig. 2, which give the three coordinates of the magnetic field vector (field strength, angle of inclination of the lines of force with respect to the horizontal plane, angle between the field vector projected on the horizontal plane and the prominence long axis) and the electron density in the 14 prominences. The mean value of the determined elctron density is $1.3 \times 10^{10} \mathrm{cm}^{-3}$ in the 14 prominences.

The sensitivity of the Hβ polarization to electron and proton collisions is in the range $10^9 - 10^{11} \mathrm{cm}^{-3}$: this is very favourable for using this density diagnostic method in quiescent prominences. For densities larger than $10^{11} \mathrm{cm}^{-3}$ the collisional depolarization becomes very effective, and the polarization degree of Hβ becomes too small to be measured (less than 10^{-3}). Densities higher than $10^{11} \mathrm{cm}^{-3}$ in prominences are therefore not compatible with the observed polarization of the Hβ line.

4. CONCLUSION

The collisional depolarization of Hydrogen lines provides a method for determining the electron density in a density range where the Stark broadening becomes too small to be interpreted, these two methods being therefore complementary.

The method has been applied to magnetic field vector and electron density diagnostic in 14 prominences and has led to a mean value of $1.3 \times 10^{10} \mathrm{cm}^{-3}$ for electron density.

RÉFÉRENCES

Athay, R.G., Querfeld, C.W., Smartt, R.N., Landi Degl'Innocenti, E. and Bommier, V.: 1983, Solar Phys. 89, 3.
Bommier, V., and Sahal-Bréchot, S.: 1978, Astron. Astrophys. 69, 57.
Bommier, V.: 1980, Astron. Astrophys. 87, 109.
Bommier, V., Leroy, J.L., and Sahal-Bréchot, S.: 1986, Astron. Astrophys. 156, 79 and 90.
Heasley, J.N., Mihalas, D., and Poland, A.I.: 1974, Astrophys. J. 192, 181.
Heasley, J.N., Milkey, R.W.: 1976, Astrophys. J 210, 827.
Heasley, J.N., Milkey, R.W.: 1978, Astrophys. J. 221, 677.
Heasley, J.N., Mihalas, D.: 1976, Astrophys. J. 205, 273.
Kippenhahn, R., and Schlüter, A.: 1957, Z. Astrophys. 43, 36.
Kuperus, M., and Raadu, M.A., 1974, , Astron. Astrophys. 31, 189.
Landi Degl'Innocenti, E.: 1982, Solar Phys. 79, 291.
Landman, D.A., and Mongillo, M.: 1979, Astrophys. J. 230, 581.
Leroy, J.L.: 1978, in Physics of Solar Prominences, IAU Coll. 44, eds. E. Jensen, P. Maltby, F.Q. Orrall, p. 56.
Leroy, J.L.: 1981, Solar Phys. 71, 285.
Leroy, J.L., Bommier, V., Sahal-Bréchot, S.: 1983, Solar Phys. 83, 135.
Leroy, J.L., Bommier, V., Sahal-Bréchot, S.: 1984, Astron. Astrophys. 131, 33.
Querfeld, C.W., Smartt, R.N., Bommier, V., Landi Degl'Innocenti, E., and House, L.L.: 1985, Solar Phys. 96, 277.
Sahal-Bréchot, S., Bommier, V., Leroy, J.L.: 1977, Astron. Astrophys. 59, 223.