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MEASUREMENTS OF MAGNETIC FIELDS IN SOLAR PROMINENCES

Egidio Landi Degl'Innocenti
Istituto di Astronomia, Università di Firenze, Firenze, Italy

INTRODUCTION

It is well known that the magnetic field vector plays a fundamental role in the physics of solar prominences, being the main agent in determining their geometrical forms, their motions, and, eventually, their existence itself. For this reason, any attempt of measuring magnetic field vectors in prominences has to be considered as an extremely important contribution to the understanding of the physical picture of these structures.

Magnetic fields can be measured, in solar prominences, by means of two different basic mechanisms that are responsible for the introduction (or the reduction) of a given amount of polarization in spectral lines: these are the Zeeman effect and the Hanle effect.

Through the splitting of the magnetic components of a spectral line, the Zeeman effect is able of introducing a certain amount of circular polarization across the line profile. This circular polarization results in being of the order of

$$\bar{g}\ \nu_L \cos\psi \ / \ \Delta\nu$$

where $\bar{g}$ is the effective Landé factor of the line, ν_L is the Larmor frequency that is proportional to the magnetic field, ψ is the angle between the magnetic field and the line of sight and $\Delta\nu$ is the line-broadening in frequency units. For typical magnetic fields that are believed to be present in prominences ($\cong$ 10-20 G), the circular polarization results in being of the order of few tenths of a percent or lower, and can then be measured by means of high-sensitivity magnetographs or spectropolarimeters. With this technique, however, only the longitudinal component of the field can be obtained and the real structure of the vector magnetic field configuration remains highly undetermined.

The Hanle effect consist in a modification of the linear polarization that is induced in spectral lines by the anisotropic illumination of the prominence plasma by the photospheric radiation field. In the absence of magnetic fields, emission lines from prominences are, in general, linearly polarized along the solar limb direction, with polarization values typically of the order of a fraction of a percent. The presence of a magnetic field acts through the combination of a depolarization mechanism and a rotation of the direction of maximum polarization that both depend on the intensity and direction of the field. As a result, the magnetic field vector can be conveniently recovered through the measurement of linear polarization in suitable emission lines from prominences, although a twofold degeneracy, typical of the Hanle effect, avoids an unambiguous determination of $\vec{B}$ from optically thin lines. The aim of this paper is to present an updated review of the work that has been done on this subject and to point out some of the perspectives that are still open for future work.

MEASUREMENTS OF MAGNETIC FIELDS THROUGH THE ZEEMAN EFFECT

The first quantitative observations based on this technique were obtained in the late 60's by means of standard solar magnetographs. The main results, due to Rust (1966, 1967), Harvey (1969), and Tandberg-Hanssen (1970) were obtained with the Climax magnetograph of HAO and are reviewed in Tandberg-Hanssen (1974). They show a distribution of the longitudinal component of the magnetic field vector, as observed in Hα for 135 quiescent prominences, ranging from 0 to 26 G, with a peak value at approximately 5 G, and an overall mean of 7.3 G. It was also shown by these investigators that, even if the measured field strength may vary from point to point (with a slight trend for $B_{\parallel}$ to increase with height), the polarity of the field does not change for a given prominence. Similar observations have been reported more recently by Kim et al. (1982) and by Nikolsky et al. (1984). These observations, obtained with the spectrally scanning magnetograph installed at the 53 cm coronograph of the Kislovodsk Station, show a broad distribution of observed field strengths with two peaks for $B_{\parallel}$ close to 8 and 20 G. Moreover, it has been found by these authors, from a statistical analysis of the behavior of the observed field strength with the angle beween the line of sight and the prominence long axis, that the magnetic field vector is inclined of approximately 25° with respect to the prominence long-axis itself.

In spite of the good results that have been obtained through the Zeeman-effect method, it has to be pointed out here that, according to theoretical calculations (Landi Degl'Innocenti, 1982) and to observations (Athay et al., 1983, Nikolsky et al., 1984), the V-profile of a typical emission line from prominences (like HeI D_3, H_α, or H_β) has a characteristic signature that results from the superposition of a symmetric component (due to atomic polarization) and an antisymmetric component (due to the Zeeman effect). The determination of the longitudinal component of the field requires the separation of the antisymmetric component from the observed profile. This procedure has been actually followed in the reduction of the observations by Nikolsky et al., whose results can then be considered as fully reliable.

MEASUREMENTS OF MAGNETIC FIELDS THROUGH THE HANLE EFFECT

In recent years, extensive series of linear polarization observations in prominence emission lines have been obtained through the Pic-du-Midi coronograph polarimeter (Leroy et al., 1977, 1984; Leroy, 1981) and through the HAO Stokes polarimeter (House and Smartt, 1982; Athay et al., 1983; Querfeld et al., 1985). At the same time, our theoretical understanding of the physical mechanisms underlying the appearance of polarization in prominence emission lines has grown considerably. While Landi Degl'Innocenti (1983) has attacked in full generality the problem of the generation and transfer of polarized radiation in spectral lines, more specific contributions have been brought by several authors. Bommier and Sahal-Brechot (1978) have developed a formalism of the quantum theory of the Hanle effect to obtain the theoretical expectations for the integrated linear polarization of the HeI D_3 line in optically thin prominences in the presence of weak magnetic fields ($B < 10$ G).

This formalism has been subsequently generalized by Bommier (1980) to allow for larger values of the magnetic field and by Landi Degl'Innocenti (1982) to interpret the fine structure of the D_3 line not only in linear but also in circular polarization. Further theoretical progress has been achieved by Landolfi and Landi Degl'Innocenti (1985) who have computed the expected polarization of the NaI D lines in optically thin prominences for arbitrary values of the magnetic field vector, by Bommier et al. (1986 a,b) who have performed analogous computations on H_β taking properly into account the depolarizing effect of electron collisions, and, finally, by Landi Degl'Innocenti et al. (1986) who have attacked the more involved problem of H_α polarization in optically thick prominences.

The theory developed in the papers quoted above have been successfully applied to a conspicuous set of data with the aim of determining the configuration of the magnetic field vector in prominences. Athay et al. (1983) report on the interpretation of the D_3 polarization observed in 13 prominences with the HAO Stokes-polarimeter. The main result of this investigation concerns the inclination of the magnetic field vector with respect to the solar radius that shows a pronounced preference to be close to 90°; in other words, the field appears to be horizontal. The values obtained for B range from 6 to 27 G while the azimuth angle α with respect to the prominence long-axis does not show any sistematic trend. It must be emphasized at this point that, due to the fact that it is impossible to discriminate (for optically thin lines) between two magnetic fields symmetric with respect to the plane containing the line of sight and the solar radius, the azimuth angle determination has an intrinsic ambiguity. In the observations of Athay et al. (1983) it was impossible to ascertain, in most cases, whether the field was crossing the prominence in the same sense of the underlying photospheric field or in the opposite sense. More recently, Leroy et al. have presented very interesting results on the interpretation of the (unresolved) D_3 line observed with the Pic-du-Midi coronograph polarimeter in 120 prominences of the polar crown (Leroy et al., 1983) and in 256 quiescent prominences of medium and low latitude (Leroy et al., 1984). In these investigations, that complete previous results obtained by Leroy (1977, 1978), the azimuth α of the magnetic field vector is retrieved by means of a detailed statistical analysis that is based, however, on the assumption of the horizontality of the field itself. The main results of the analysis by Leroy et al. are summarized in the following: a) for polar crown prominences a mean value of 6 G is obtained at the beginning of solar cycle XXI, and a mean value of 12 G is reached just before maximum; b) the azimuth of the magnetic field vector, α, makes a small angle (25°) with the long axis of the prominence and shows a marked preference to be directed from the negative to positive photospheric polarity, thus supporting the Kuperus-Raadu (KR) family of models (Kuperus and Raadu, 1974) and contraddicting the Kippenham-Schlüter (KS) one (Kippenham and Schlüter, 1957); c) for quiescent prominences of medium and low latitude, there is strong evidence that they can be grouped in two different types, those having maximum height smaller than 3×10^4 km, and those having maximum height larger than 3×10^4 km; d) prominences of the first type are found to have a magnetic structure consistent with the KS type of models with $\alpha \sim 20°$ and $B \sim 20$ G; e) prominences of the second type are found to have a magnetic structure consistent with the KR type of model with $\alpha \sim 25°$ and $B \sim 5$ to 10 G.

Finally, some new results have been published by Bommier et al. (1986a) on the magnetic field vector determination in a reduced number of quiescent prominences observed quasi-simultaneously in D_3 and H_β at Pic-du-Midi. Apart from the independent determination of electron densities (a subject that is not covered in this paper), the use of two different lines allows, in principle, to obtain the inclination of the field with respect to the solar radius. (Similarly to the case where the two fine-structure components of D_3 are observed, as in Athay et al., 1983). The results obtained from the joint D_3 and H_β observations are found to be in general good agreement with previous diagnostics based solely on D_3 observations, although the field inclination appears to scatter significantly from the 90° value, being in the range between 70° and 110°. These tilt angles with respect to the horizontal are interpreted by Bommier et al. assuming a V-shaped depression of the lines of force in the prominence material.

PERSPECTIVES FOR FUTURE WORK

The results that have been summarized in the former sections clearly show the potentiality of polarimetric observations as diagnostic tools for our understanding of the magnetic configuration of solar prominences. A further point where some progress can be achieved in the near future concerns the resolution of the ambiguity intrinsic to circular and linear polarization observations. Indeed, from circular polarization observations only the projection of the magnetic field along the line of sight can be determined (once the antisymmetric component is extracted from the V-profile), while, from linear polarization observations of optically thin lines, a twofold ambiguity remains between a magnetic field determination and its specularly symmetric image with respect to a plane containing the line of sight and the local solar radius (for prominences observed in the plane of the sky). For optically thick lines like H_α, the situation changes dramatically, as the possibility of multiple scattering inside the prominence body introduces a further physical direction into the problem and changes the simple specular symmetry previously outlined. Polarization diagrams for the expected polarization in H_α from optically thick prominences have been obtained by Landi Degl'Innocenti et al. (1986). Their results show that an ambiguity is still present in the field determination, but this ambiguity doesn't have the simple behavior of the specular symmetry typical of the optically-thin case. Simultaneous observations in optically thin and optically thick lines are then able, in principle, of solving the azimuth ambiguity. In concluding we want to stress the fact that the theory of the Hanle effect is nowadays established to such a degree of sophistication that it could provide the actual determination of the magnetic configuration of prominences with improved accuracy with respect to the present situation. To this aim simutaneous observations of the circular and linear polarization in several spectral lines (HeI D_3, NaI D, H_α, H_β) are needed. We hope that a new instrument, capable of performing similar observations with high spatial resolution, will be soon available to the solar scientific community in order to unravel in further details one of the most puzzling problems in the physics of solar prominences, namely the problem of their magnetic configuration.

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