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Diagnostic of prominence magnetic fields through spectropolarimetric observations(*)

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Summary. — In recent times there has been a strong revival of interest in spectropolarimetric observations of solar prominences. This is due to the fact that new instruments, with unprecedented spectral resolution and polarimetric accuracy, are now available to solar physicists. These instruments open for the first time the possibility of unveiling the fine structure of magnetic fields and its correlation with velocity fields and density inhomogeneities in these fascinating objects. The interpretation of spectropolarimetric observations of solar prominences still stands, however, as one of the most challenging problems of what is nowadays known as *atomic astrophysics*, or, in other words, modern atomic physics applied to the diagnostic of astronomical objects. In this brief review, a hystorical account of the measurements of magnetic fields in prominences is given, and the present status of the theory, which stands at the basis of the interpretation of the observations, is dicussed. Some perspectives for future investigations are also presented.

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1. – Hystorical overview

The first quantitative measurements of magnetic fields in solar prominences were obtained through the traditional magnetograph technique. By observing the difference between right and left circular polarization in a small wavelength interval centered on the wing of a spectral line, it is possible to obtain, through a calibration procedure, the value of the component of the magnetic field along the line of sight. Thanks to the work by Rust, Harvey, and Tandberg-Hanssen [1-4], important results were obtained in the late sixties and in the early seventies with the Climax Magnetograph of the High Altitude

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Observatory working on Hα. These observations, performed on 135 prominences in total, showed a distribution of the magnetic-field component, $B_{\|}$, ranging—in absolute value—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 magnetic-field component may vary from point to point in a single prominence (with a slight trend to increase with height), the polarity of the field does not change and remains as a characteristic of the full prominence. After more than a decade, further observations were reported by Kim *et al.* [5], and by Nikolsky *et al.* [6]. These observations, obtained with the spectrally scanning magnetograph installed at the 53 cm coronograph of the Kislovdsk station, showed a broad distribution of observed field components with two peaks for $B_{\|}$ close to 8 and 20 G. Moreover, it was found by these authors, by means of a statistical analysis, that the magnetic-field vector is inclined of approximately 25° with respect to the long axis of the prominence.

Substantial progress in the investigation of the magnetic field in prominences was made possible by the observation of linear polarization in emission lines and by its interpretation in terms of the Hanle effect. Due to the low density typically met in prominences, a relatively large amount of linear polarization has to be expected in spectral lines. The atoms, irradiated by the anisotropic radiation field of the photosphere, become "aligned" and thus produce, in the de-excitation process, linearly polarized radiation (resonance polarization). In the absence of magnetic fields, such polarization is directed along the tangent to the solar limb. When a magnetic field is present, the amount and the direction of linear polarization are modified by the Hanle effect. This phenomenon provides a powerful diagnostic tool for inferring the intensity and direction of the magnetic field from observations.

An extensive series of linear polarization observations in prominence emission lines was obtained, in the late seventies and early eighties, through the Pic du Midi coronograph polarimeter (Leroy and collaborators [7-9]) and through the High Altitude Observatory Stokesmeter [10-12]. Approximately in the same period, the theoretical understanding of the pysical mechanisms underlying the phenomena of resonance polarization and the Hanle effect grew considerably, thanks to the work of Bommier and collaborators [13-15], and of Landi Degl'Innocenti [16]. The work of Bommier and collaborators was principally directed to the interpretation of the polarization signals observed in prominence lines by a broad-band instrument, like the Pic du Midi coronograph, whereas the work of Landi Degl'Innocenti made possible the interpretation of the Stokes parameters profiles (in linear and circular polarization) and, consequently, of the fine structure typically observed in He lines. In this respect, it has to be kept in mind that the line which is mostly used for the diagnostic of magnetic fields in prominences is the HeI D_3 line at 5876 Å, and that this line has two fine-structure components which are separated by approximately 350 mÅ.

Thanks to this theoretical and observational effort, a clear scenario has emerged about the large-scale configuration of the magnetic field in prominences. Introducing a reference system with its z-axis directed along the vertical and the x-axis directed along the prominence long axis, it turns out that the largest component of the magnetic-field vector is B_x, which implies that the magnetic field is mostly horizontal. Moreover, the field lines wrap around the prominence according to the so-called Kuperus and Raadu model [17]. Since prominences generally form above neutral lines separating large photospheric bipolar regions, it follows that the transverse component of the magnetic field, B_y, is generally directed from the negative to the positive polarity, a result that was considered at the time rather surprising but that nowadays appears to be clearly established.

Concerning the magnetic-field intensity, the typical values obtained thorough the Hanle effect diagnostic range from 6 to 20 G without no particular trend to increase or decrease with height.

2. – Modern perspectives

Thanks to the results obtained through the Pic du Midi coronograph and through the High Altitude Observatory Stokesmeter, a general picture of the magnetic structure of prominences has emerged. But many questions about such a structure have not yet been answered because of the limited resolution (spatial and temporal) of the old observations. It has to be kept in mind that both for the Pic du Midi and the High Altitude Observatory instruments, the typical spatial resolution was of the order of 5 arcsec, which hampered any attempt of investigating the fine structure of magnetic fields in the delicate and spectacular threads that are commonly seen in prominences. Moreover, the analysis of the old data was generally performed by compressing all the spectral information contained in the Stokes profiles in a small number of parameters, without any attempt of fitting consistently the full profiles.

This was an intrinsic limitation of the broad-band observations performed with the Pic du Midi coronograph polarimeter. In this case, the observations consisted of only two quantities, namely the fractional linear polarization observed in the HeI D_3 line (or in other lines, like those of the hydrogen Balmer series) through a filter having a width larger than the line profile. In formulae, denoting by $I(\lambda)$, $Q(\lambda)$, $U(\lambda)$, and $V(\lambda)$ the Stokes profiles of the radiation coming from the prominence, all the information was contained in the two quantities p_Q and p_U defined by

$$p_Q = \frac{\int Q(\lambda)\,p(\lambda)\,\mathrm{d}\lambda}{\int I(\lambda)\,p(\lambda)\,\mathrm{d}\lambda}\,, \qquad p_U = \frac{\int U(\lambda)\,p(\lambda)\,\mathrm{d}\lambda}{\int I(\lambda)\,p(\lambda)\,\mathrm{d}\lambda}\,,$$

$p(\lambda)$ being the profile of the filter centered on the line under investigation. On the contrary, the HAO Stokesmeter was indeed capable of measuring the full Stokes profiles of the prominence radiation, but, due to the considerable noise present in the observations, the interpretation was generally performed by disregarding the circular polarization profile and by fitting the Stokes parameters $I(\lambda)$, $Q(\lambda)$, and $U(\lambda)$, to Gaussian-shaped profiles whose parameters were subsequently compared with theoretical expectations. For the HeI D_3 line, for instance, the fit was of the form

$$S_i(\lambda) = \sum_{j=1,2} a_{ij} \exp\left[-\left(\frac{\lambda-\lambda_j}{\Delta\lambda_{\mathrm{D}}}\right)^2\right] \qquad (i=0,1,2)\,,$$

where $S_i(\lambda)$ is the i-th Stokes parameter ($i = 0,1,2$, corresponding to I, Q, and U, respectively), λ_j is the central wavelength of the j-th component of the line ($j = 1,2$), and where a_{ij} and $\Delta\lambda_{\mathrm{D}}$ are the free parameters of the fit. Whereas the parameter $\Delta\lambda_{\mathrm{D}}$ was used to determine the kinetic temperature of the HeI atoms in prominences, the diagnostic of the magnetic field was performed by comparing the four ratios

$$r_1 = a_{11}/a_{01}\,, \qquad r_2 = a_{21}/a_{01}\,, \qquad r_3 = a_{12}/a_{02}\,, \qquad r_4 = a_{22}/a_{02}\,,$$

with a table containing the corresponding values of the theoretical results obtained for different configurations of the magnetic-field vector and for the particular height of the obseved point in the prominence.

The modern polarimeters that are presently in operation raise the possibility of obtaining cleaner spectropolarimetric profiles, less affected by noise in comparison with those available in the past. Moreover, the reduced amount of stray light present in the telescopes also allows the observation of polarimetric profiles in filaments, not only in prominences. This entails the possibility of observing the same object under considerably different angles and reduces the ambiguities that are often met when measuring the magnetic field from off-limb obesrvations.

Concerning the theory, it can be stated that the old algorithms, developed in the late seventies, and based on the density-matrix approach, still stand as the state-of-the-art techniques for interpreting the observations. These algorithms are based on the solution of the statistical equilibrium equations for the atomic density matrix. For instance, for interpreting the observations in the HeI D_3 line, or in the infrared HeI line λ10830, it is necessary to introduce an atomic model which is composed of five fine-structured terms which are split into eleven fine-structure J-levels. This implies the solution of an algebraic system of 405 equations in 405 unknowns. Once the solution is found, the (polarized) emission coefficient in a given line can be found from the values of the density matrix elements of the upper level of the transition. Similarly, the absorption coefficient, which in the "polarized case" generalizes into a 4×4 matrix, is found from the values of the density matrix elements of the lower level.

In the case of a prominence observed off the limb, and supposing the prominence plasma to be optically thin, the observed Stokes parameters are simply proportional to the emission coefficient. On the contrary, for a prominence observed (as a filament) over the solar disk, still keeping the hypothesis of the optical thinness of the prominence plasma, the observed Stokes parameters result from two contributions (plus a zeroth-order contribution—the photospheric radiation field—in the case of the intensity). One contribution is proportional to the emission coefficient and the other, generally of opposite sign, is proportional to the absorption coefficient (the so-called dichroic term).

There is another important aspect of prominence spectropolarimetry that is worth to be discussed in some detail. This concerns the possibility of diagnosing velocity fields through polarimetric observations and, at the same time, the contamination that can be induced on the Hanle effect by the presence of velocity fields. Consider an atom that is located in a prominence, and suppose that this atom is moving with a certain velocity with respect to the average solar atmosphere. Due to the Doppler effect, the radiation field experienced by the atom is, in general, velocity dependent. This happens when the photospheric radiation field contains an absorption (or an emission) line around any transition frequency that is contributing to pump the atom to its upper levels. We have here a typical phenomenon of Doppler brightening (or of Doppler dimming) which may have a deep effect on the polarization of the radiation scattered by the atom by inducing a rotation of the plane of polarization that mimics the Hanle effect (see, for instance, ref. [18]).

For the diagnostic of magnetic fields, one should try to avoid as much as possible this type of phenomena induced by the Doppler effect on polarization. To this aim, it is advisable to use spectral lines such as the HeI D_3 or λ10830, because the HeI lines are not present in the photospheric spectrum and, consequently, Doppler brightening (or Doppler dimming) phenomena do not affect the overall excitation of neutral helium atoms in prominences. On the other hand, the simultaneous (or quasi-simultaneous) observation of the polarization in a line that is sensitive to these phenomena (like, *e.g.*, the NaI D_1 or D_2) may be used, in principle, for the diagnostic of velocity fields.

In concluding we like to stress that spectropolarimetry of solar prominences is nowadays enriched with novel possibilities of investigation. It is hoped that this new type of observations would become soon available to the solar community in order to get further insight into the physics of these fascinating and misterious objects.

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