Spectropolarimetry of solar prominences

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Abstract. The magnetic field is the most important physical parameter that drives the formation, the structuration and the eruption of solar prominences. Consequently, magnetic field measurements within prominences are fundamental for understanding the physics of these fascinating objects. Surprisingly however, very few of such measurements have been performed since old systematic observations made from the 70s up to the mid 80s! Even though these measurements brought landmark results, a lot still remains to be done concerning the temporal and spatial variations of the prominence magnetic field and its relationship with the fine structures of the plasma (e.g. feet/barbs and vertical threads). In this context, we discuss some properties of various empirical and MHD models that could be tested observationally in the near future with (very) large aperture telescopes and coronographs, associated with modern visible and IR spectropolarimetric instrumentation.

1. Introduction

Prominences are cool and dense structures hanging in the hot and diluted solar corona. Being low $\beta$ structures, the channeling of plasma motions and of thermal conduction are controlled by the magnetic field, which also provides support to the prominence material against gravity (see the reviews of Leroy 1989, Landi Degl’Innocenti 1990, Tandberg-Hanssen 1995 and Démoulin 1998). Prominences are important for space weather due to the $\sim 40\%$ association found between eruptive prominences and the spectacular CME phenomena (e.g., Subramanian & Dere 2001 and references therein), which significantly affect the solar-terrestrial environment (e.g., Webb et al. 2000).

Direct magnetic fields measurements were made quite systematically from the 60’s up to the mid-80’s. However, we have been dramatically lacking of new data during the last 15 years, while unleashed MHD theorists could develop state-of-the-art 3D models of prominences. It is now urgent to accumulate new measurements in order to constrain further and to discriminate between the numerous theoretical models.
2. A review of past results

Up to now, the most comprehensive observational work on the determination of magnetic fields in solar prominences was led by J.L. Leroy using the facilities of the Pic du Midi Observatory (France). First measurements, using the D$_3$ line of He I, were done in 1973–1976 with a photo-electric polarimeter attached to a 26-cm diameter coronograph (Leroy et al. 1977, Leroy 1977, 1978). This instrumentation offered a rather high polarimetric sensitivity (better than $10^{-3}$) at the price of a poor spatial resolution ($\sim 3''$) and, no spectral resolution. However, the measured linear polarization signals could be interpreted further in terms of magnetic field strength and orientation by use of the Hanle effect theory (Bommier 1980).

Shortly after, Bommier et al. (1981) pointed-out the possibility of a complete determination of the prominence magnetic field from two simultaneous (linear) polarization measurements made at two different wavelengths. One solution is indeed to observe two different spectral lines, such as D$_3$ and the H$\alpha$ or H$\beta$ Balmer lines of H I, for instance. This approach was successfully applied to diagnose new data collected during the 1974–1982 period (Leroy et al. 1984).

Another possibility comes from the use of the two components of D$_3$ itself, namely the $3d^3D_{3/2,1} \rightarrow 2p^3P_{1,2}$ and $3d^3D_1 \rightarrow 2p^3P_0$ groups of atomic transitions. However it requires to spectrally resolve those two components distant of some 34 pm. First profiles of the D$_3$ line observed in solar prominences were recorded in September 1977 with the HAO Stokes polarimeter available at the 40-cm coronograph of the NSO Evans Solar Facility at Sacramento Peak (Baur et al. 1981). Those new measurements allowed for a complete determination of the magnetic fields in quiescent prominences (Landi Degl’Innocenti 1982, Athay et al. 1983, Querfeld et al. 1985).

We can therefore summarize the landmark results obtained from those studies by the following:

- The magnetic field derived from inversions has strength in the 3–15 G range for quiescent prominences; Zeeman and Hanle measurements are in agreement on this point (e.g., Leroy 1989, Tandberg-Hansen 1995).
- It is mostly horizontal, making a small angle $\langle \theta \rangle \sim 25^\circ$ with the long axis of the structure; arguments leading, statistically, to this important result are developed in the famous article of Leroy et al. (1984).
- The magnetic field strength increases slightly with height (which is compatible with the presence of dipped field lines supporting the cool prominence plasma against gravity); Rust (1967) and Leroy et al. (1983) both report magnetic field gradients of the order of $10^{-4}$ G km$^{-1}$.
- A (very) large majority of prominences are of the inverse polarity (IP) type (Bommier & Leroy 1998); it is hereby important to mention that elements concerning the resolution of the problem of the ambiguity on the direction of the magnetic field can be found in Bommier et al. (1994).
- The so-called “chirality rules”: prominence axial fields are always opposite to what differential rotation predicts (e.g., Leroy et al. 1983, Bommier &
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Figure 1. Maps of the time-averaged Stokes parameters $I$, $Q$, $U$ and $V$ from He I D$_3$ observations (taken from Paletou et al. 2001).

Leroy 1998), and they have a dominant dextral (resp. sinistral) orientation with respect to the large-scale photospheric polarities in the northern (resp. southern) hemisphere (as deduced by Martin et al. 1994 from morphological observations combined with photospheric magnetograms).

However, after this very rich and fruitful period of observations and advances, we just went through 15 years of “sleep” with almost no direct magnetic field measurements at the era of the CCDs! Fortunately, nowadays instruments provide for high spatial and spectral resolution observations together with a $\sim 10^{-3}$ (or better) polarimetric sensitivity.

3. Modern observations

While most of the direct measurements of the magnetic field were done from observations at the limb, Lin et al. (1998) made the first successful full-Stokes spectropolarimetric observations of a filament at the He I 1083 nm wavelength. They demonstrated the great interest of this new spectral window since prominences passing on the disk cannot be easily observed in the D$_3$ line.

Paletou et al. (2001) reported full-Stokes observations in the He I D$_3$ spectral line clearly showing variations in strength and orientation of the prominence magnetic field. As can be seen in Fig. 1, besides linear polarization signals due to the Hanle effect, very conspicuous Zeeman-like signals were also detected
throughout the field of view; and from circular polarization measurements, magnetic field strengths in the 30–45 G range were derived in what seemed to be an “active lobe” in the prominence.

This revival can also be noticed with the work of Trujillo Bueno et al. (2002) who described both prominence and filament spectropolarimetric observations at 1083 nm with the IAC/TIP infrared polarimeter mounted at the German VTT (Observatorio del Teide, Tenerife). These new observations strongly demonstrate, by comparing on-disk with limb measurements, manifestations of so-called lower level atomic polarization even in the presence of a few gauss strength and almost horizontal magnetic fields. Taking into account those subtle atomic physics effects, they could also derive, by fitting observed profiles with theoretical ones, magnetic field strength and possible orientations.

4. Radiative modelling

Historically, the problem of determining the nature of the magnetic field in solar prominences constitutes the first successful application of the Hanle effect in astrophysics. The interpretation of the D$_3$ linear polarization observations of Leroy was made using a suitable theory taking advantage of the density matrix formalism. Details about theoretical aspects can be found in Bommier (1980) and Landi degl’Innocenti (1982), assuming that D$_3$ is optically thin.

Recent progress concern the fast and reliable inversion of full-Stokes spectropolarimetric data such as the one displayed in Fig. 1. From Paletou et al. (2001) measurements, a new PCA-based inversion code suitable for observations made in the D$_3$ line was indeed developed (López Ariste & Casini 2002 and these proceedings). In particular, it was then very convincingly demonstrated how taking into account all the Stokes parameters (and not only linear polarization measurements) affects the reliability of the inversion process$^1$.

However, it is well known that D$_3$ is not always optically thin in prominences. This can be easily checked from well-resolved spectroscopic measurements by the evaluation of the $I_{\text{blue}}/I_{\text{red}}$ ratio which betrays transfer effects once its value gets below 8 (House & Smartt 1982, Landi Degl’Innocenti 1982). Therefore the future development of a “multi-term” polarized radiation transfer code considering a detailed Helium atom model would represent a very significant step forward.

5. Issues from MHD modelling

5.1. Prominence formation

The process of formation of prominences has a lot to do with the study and observations of photospheric flows and flux emergence. Indeed, most of the existing MHD models invoke either converging or shear flows for which observational evidences are required (e.g., Antiochos et al. 1994, van Ballegooijen & Martens

$^1$See the scatter plots in Fig. (8) in López Ariste & Casini (2002) obtained by the inversion of synthetic data.
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1989, Amari et al., 1999, DeVore & Antiochos 2000, van Ballegooijen et al. 2000). Converging flows have been reported by Martin (1998) and, in a recent study, Chae et al. (2001) put in evidence shear motions and the convergence of magnetic concentrations towards the polarity inversion line from SoHO/MDI magnetograms.

Another scenario of formation is based on the direct emergence of (already) twisted flux ropes from the convection zone (Rust & Kumar 1994), but this process seems to be difficult to occur since the weight of material trapped in magnetic dips typically prevents the emergence of the lower parts of the flux rope (Fan 2001).

In any case, from the standpoint of observations, high-resolution (i.e., angular resolution and high polarimetric sensitivity) vector magnetograms are required, as well as long temporal sequences on the disk in order to be able to study the nature of the flows and the evolution with time of the magnetic field configuration in the filament channel.

5.2. Global magnetostatic models

One could roughly classify the MHD models of solar prominences that are the most consistent with observations in two major classes: twisted flux rope models (TFR) and sheared magnetic arcade models (SMA). Even though we are facing different scenarios of formation, all those models yield magnetic properties which match observational and theoretical constraints such as
(i) inverse polarity patterns,
(ii) the mean magnetic field orientation vs. the long axis of the prominence,
(iii) magnetic dips supporting the cool prominence material against gravity, and
(iv) strong nearly field-aligned electric currents.

TFR models consist in building-up a prominence from a collection of already weakly sheared field lines pushed together by converging photospheric flows towards the polarity inversion line. Then reconnection processes can take place, leading to the generation of helical field lines (e.g., van Ballegooijen et al. 2000, Amari et al. 1999). It naturally follows that magnetic dips within TFR models all have the inverse polarity.

SMA models consider field lines whose footpoints experience large shearing motions parallel to the polarity inversion line of the magnetic field (e.g., Antiochos et al. 1994, DeVore & Antiochos 2000). Reconnection is also at work for this class of models which, however, seem to have a tendency to produce less homogeneous twist distributions than what comes out from TFR models. A key property of SMA models is the prediction of very specific mixtures of inverse/normal polarity dips within one same prominence (Aulanier et al. 2002).

5.3. Prominence feet

Prominence feet (also called “barbs”) are also a characteristic feature of most prominences. They typically appear periodically below the prominence body, and they often have lateral extensions pointing away from the prominence axis.

On one hand, Martin et al. (1994) and Zirker et al. (1998) claim that Hα observations of flows prove the occurrence of vertical fields in the feet, which seems to be consistent with the 1D hydro-thermodynamical models of Karpen et al. (2001). On the other hand, Aulanier et al. (1999, 2000) have shown through direct comparison of magnetohydrostatic models to observed filaments that the
feet are formed in horizontal magnetic fields, in a complex 3D distribution of magnetic dips which are due to the presence of photospheric parasitic polarities; they interpret the results of Martin and Zirker as projection effects which can lead true horizontal fields to appear nearly vertical as projected onto the plane of the sky.

Since the continuity of plasma flows over large distances has not yet been clearly proved or disproved, and due to the absence of clear vector field measurements within the feet, the magnetic topology of the feet and the nature of their connection to the prominence is still a hot debate in the field. Solving this issue through direct measurements of their magnetic fields should bring many new constraints to the formation and the global magnetic field configuration of prominences.

6. Some outstanding questions

Regarding the magnetic topologies of prominences and their feet, we need to identify which class of models is the most appropriate. This could be, for instance, of considerable importance regarding our knowledge of the mechanism(s) responsible for the triggering of CMEs, since the free magnetic energy which permits to open the field is believed to be confined in highly stressed fields such as those present in prominences (see the review of CME models by Klimchuk 2001)

It is obvious that high resolution observations are already desperately needed in order to propose additional constraints and/or give answers to the following questions:

- What is the degree of twist of the prominence field lines? And therefore, how homogeneous (“coherent”) is the twist across the prominence body?
This requires high polarimetric sensitivity measurements in order to be able to determine further the ratio $B_{\text{perp}}$ to $B_{\text{axis}}$ and its spatial variations.

- Is an inverse polarity pattern always seen across the prominence body, or can mixtures of inverse and normal polarities be observed? If so, can they only be interpreted in the frame of SMA models as proposed by Aulanier et al. (2002), or could there be other physical mechanisms which could create normal polarities?

- Can we, at last, get direct observational evidences for the presence of magnetic dips? If yes, high angular resolution should provide additional information upon the spatial distribution of those features. Even though most prominence models are based on the presence of magnetic dips, Martin et al. (1994), Zirker et al. (1998) and Karpen et al. (2001) still claim that dips are not necessary “as long as a prominence is a dynamic entity”.

- What is the magnetic topology of the prominence feet? Are they formed in magnetic dips or are they simply due to flows of cool material within classical arcades?

- What is the relationship between the horizontal magnetic field and the observed vertical fine structure? Their lifetime is of the order of 10 min and their typical size is about 0.2 arcsec i.e. comparable with the diffraction limit of most of the solar telescopes operated so far.

However the combination of high-sensitivity polarimetric measurements of very fine scale structures within timescales of the order of 10 min still appears quite challenging.

7. Conclusion

The magnetic fields of prominences/filaments (or more generally, filament channels) are widely believed to play the determining role in eruptive flares and CMEs (Klimchuk 2001). Prominence magnetic fields are also likely to provide key insights into understanding coronal heating and the helicity budget of the Sun. Consequently, determining the magnetic structure of prominences still is one of the most outstanding problems in solar physics (Tandberg-Hanssen 1995).

However this topic has been poorly addressed in the last decade with polarimetric observations. This is mostly due to the fact that this approach is very demanding in terms of the quality of observations, and also very challenging regarding the complexity of polarized radiative transfer modelling, which is unavoidable to achieve the interpretation of data. These issues have only recently begun to be further developed by a few groups, and they seem to provide promising results (e.g., Paletou et al. 2001, López Ariste & Casini 2002 and Trujillo Bueno et al. 2002).

And we guess that only the advent of very large solar facilities of aperture going beyond 1 m, both for spatial resolution and photon collection performances, may provide an opportunity to do so...
In our view, one of the most important issue to address is the increase of polarimetric sensitivity combined with some spatial resolution, even of a few arcsec. Both will be required to extract reliable measurements of the gradients of the magnetic field throughout prominence bodies and feet, at every altitude, down to the photosphere. Such measurements constitute the missing link to achieve a direct coupling with the further development of MHD models, since several models based on different physical hypotheses can nowadays reproduce the past observational results.

This should naturally provide results of great interest for the improvement of the MHD modelling of CMEs even considering that a majority of the latter are not associated with prominence eruptions (Subramanian & Dere 2001). In fact, prominences can be considered as the only probe where highly stressed coronal magnetic fields can be measured. Such measurements are mandatory for understanding the triggering of CMEs, since MHD requires that (regardless of the presence/absence of a prominence) the energy that drives CMEs is contained in stressed magnetic fields.

No doubt that the renaissance of prominence spectropolarimetry will bring a wealth of new exciting results in the years to come, and will also contribute to our understanding of the global magnetic activity of the Sun.

References


Discussion

A. TITLE: There are other observations of filaments and filament dynamics that give clues to the magnetic topology; see for instance TRACE movies of filaments.
M. FAUROBERT: My question regards the observation of filaments. In order to interpret the linear polarization, it is necessary to know the height of the filament. How do you determine it?

F. PALETOU: This is indeed an important parameter to determine in order to estimate with some confidence the amount of Hanle depolarization vs. the (maximum) linear polarization rate given by assuming a \textit{non-magnetic} scattering polarization regime. And indeed a reliable estimate of this height constitutes one of the main difficulties coming along with the analysis of filament spectropolarimetric observations. To the best of my knowledge, the best thing to do would be to carefully track any observed filament from/to its passage at the solar limb and then, assuming that its morphology and geometry “did not change much”, do such a measurement (note that on-disk tracking before/after limb observations also provides a way to evaluate the orientation of the prominence long axis vs. the local meridian).

A. GANDORFER: Can you please comment on the spatial resolution of the THÉMIS data you showed, and about the seeing conditions when the data were taken?

F. PALETOU: THÉMIS intrinsic image quality is so far limited to some 0.4 arcsec spatial resolution with fluctuations depending on the elevation of the telescope; it is primarily due to static aberrations at the level of the entrance window and to mechanical constraints on the primary mirror (G. Molodij, private communication). Up to June 2001, a scintillometer getting light at the level of the entrance window was implemented and properly calibrated, giving a real-time seeing estimate. From this device, I can remember of a \textasciitilde 0.6 arcsec seeing and very stable conditions throughout the whole observing sequence that last some 2.5 hours; sky’s transparency was also excellent.

A. LÓPEZ ARISTE: Refering to the quoted results of magnetograph observations of prominences in the 60’s, when one realizes that the Kemp mechanism (i.e. alignment-to-orientation mechanism; Kemp et al. 1984) is the main responsible for Stokes $V$ and not the Zeeman effect, one wonders about what those measurements were giving as a result... In fact, you can apply the weak field formula to these profiles and you would obtain a perfect ball of scattering around 0, meaning that for any input magnetic field, the result of such a formula is completely uncorrelated though the average is still OK.

E. LANDI DEGL’INNOCENTI: The measurements of the longitudinal component of the magnetic field in prominences in the early 70’s were mainly performed through magnetographic techniques in the H$\alpha$ line, not in D$_3$.

F. PALETOU: Indeed, a well-known article such as the one of Rust (1967) reports of numerous H$\alpha$ measurements, using the Climax station facilities of the HAO. However, longitudinal magnetic field measurements from observations of H$\beta$ of H$\alpha$ and of D$_3$ of HeI (as well as of a few other spectral lines of NaI and MgI) were equally perfomed at the same time using the same facilities; see for instance Harvey & Tandberg-Hanssen 1968, and Tandberg-Hanssen 1970 in which article statistics upon the modulus of the magnetic field as derived from such observations are given.