

On the need of high-resolution spectropolarimetric observations of 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 coronagraphs, 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 β 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 brief 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 coronagraph (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 (Sahal-Br  chet et al. 1977; Bommier & Sahal-Br  chet 1978).

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. 1983, 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 coronagraph 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).

The landmark results obtained from those studies can be summarized as :

- the magnetic field derived from inversions has strength in the 3–15 G range for quiescent prominences;
- it is mostly horizontal, making a small angle $\langle\theta\rangle \sim 25^\circ$ with the long axis of the structure;
- 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);
- a (very) large majority of prominences are of the *inverse polarity* (IP) type (Bommier and Leroy 1998);
- the “Rust–Leroy rule” on *chirality* which relates prominence magnetic fields with the global solar magnetism (Leroy et al. 1983).

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.

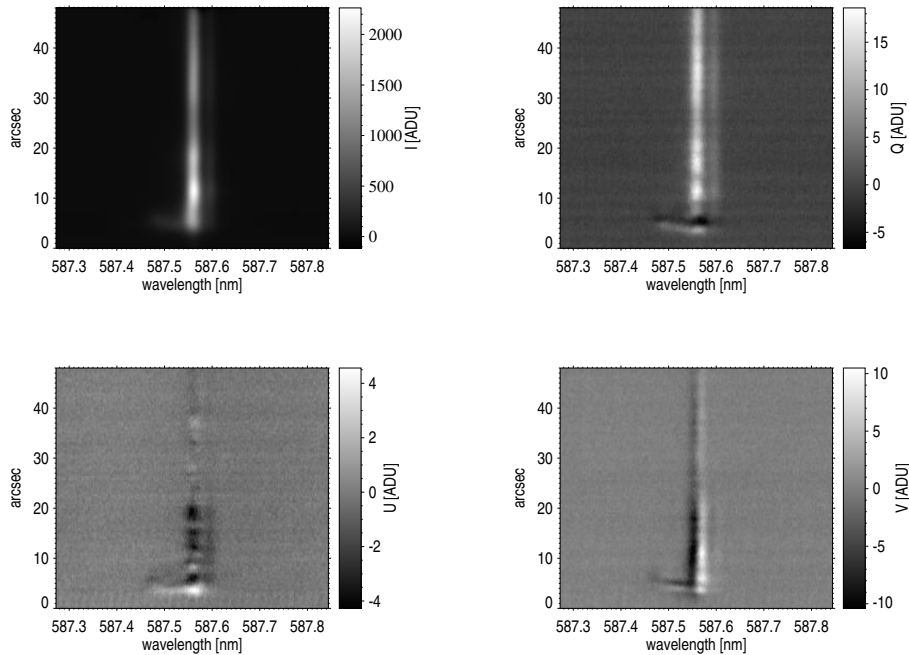


Figure 1. Maps of the time-averaged Stokes parameters I , Q , U and V from He I D_3 observations (taken from Paletou et al. 2001).

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 “seen” 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 to limb measurements, manifestations of the so-called *lower level atomic polarization* even in the presence of a few gauss strength and almost horizontal magnetic fields.

4. Issues from MHD modelling

4.1. 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 (see e.g. Antiochos et al. 1994; van Ballegoijen & Martens 1989; Amari et al. 1999; DeVore & Antiochos 2000; van Ballegoijen 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.

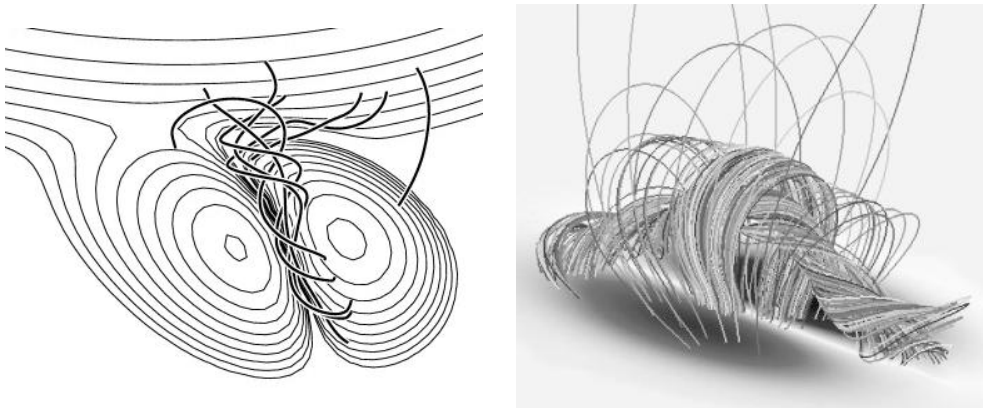


Figure 2. Examples of homogeneous strongly twisted flux rope models. (*Left*) van Ballegoijen et al. (2000). (*Right*) Amari et al. (1999).

4.2. 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

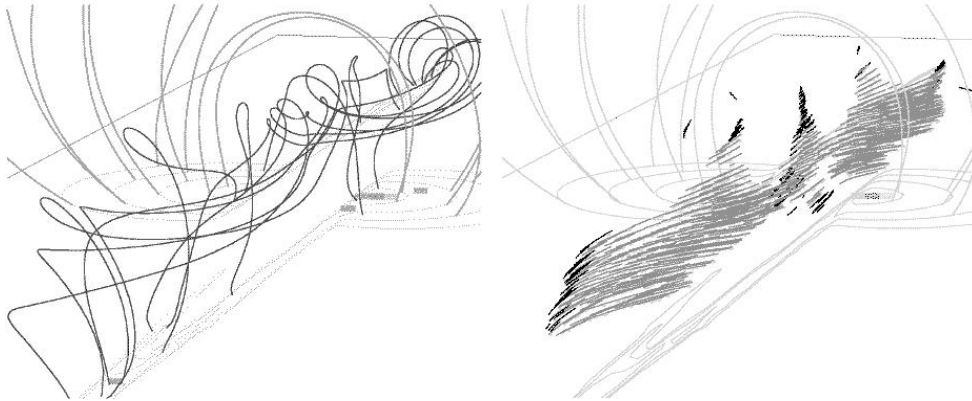


Figure 3. Sheared arcade model. (*Left*) field lines forming an inhomogeneous weakly twisted flux rope (DeVore & Antiochos 2000). (*Right*) corresponding distribution of inverse (resp. normal) polarity prominence dips drawn in grey (resp. black) (Aulanier et al. 2002).

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 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 (see e.g. van Ballegoijen 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 shearing motions *parallel* to the polarity inversion line of the magnetic field (see 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).

4.3. 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 $H\alpha$ 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.

So 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.

5. 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:

1. 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_{perp} to B_{axis} and its spatial variations.
2. Is an inverse polarity pattern *always* seen across the prominence body, or can mixtures of inverse and normal polarities be observed?
3. 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*”.
4. 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?
5. What is the relationship between the *horizontal* magnetic field and the observed *vertical* fine structure? Their lifetime is of the order of 10 mn and their typical size is about 0.2 arcsec i.e. comparable to the diffraction limit of most of the solar telescopes operated so far.

The significant step forward proposed by the ATST in term of spatial resolution will bring new light upon the latter problem, whereas the combination of high-sensitivity polarimetric measurements of very fine scale structures within timescales of the order of 10 mn still appears quite challenging!

6. Towards future observations

A 4-m aperture solar telescope such as the ATST can play a crucial role in order to achieve the relevant spectropolarimetric measurements needed for answering the above-mentioned questions.

The ideal capabilities required would be: *(i)* to benefit from a low diffused-light level for off-limb observations; *(ii)* to be able to do simultaneously *full-Stokes* spectropolarimetry in the visible range and in the near IR range; typical wavelengths should be 587.6 nm (D_3) and 1083 nm of He I, H α and H β of H I although one should also consider to use the fainter D lines of Na I (see Landolfi & Landi Degl'Innocenti 1985); *(iii)* make complementary observations of the *surrounding corona* using, for instance, the Fe XIII lines at 1074.7 and 1079.8 nm (see Lin et al. 2000).

High polarimetric sensitivity is required, on one hand, in order to be able to extract reliable estimates of the *gradients* of the magnetic field within the prominence body. On the other hand, the ability to study carefully the *temporal evolution* of the magnetic topology is of crucial importance in order to investigate the kind of instabilities leading to a prominence eruption and, ultimately, to the triggering of CMEs.

Therefore, we believe that a comprehensive programme of *direct* measurements of the magnetic field in prominences *and* filaments is absolutely necessary and will definitely bring a wealth of exciting new results.

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