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THE MAGNETIC FIELD OF SOLAR PROMINENCES.

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Abstract. In his famous monographs, Einar Tandberg-Hanssen writes that "the single, physically most important parameter to study in prominences may be the magnetic field. Shapes, motions, and in fact the very existence of prominences depend on the nature of the magnetic field threading the prominence plasma". Hereafter we sumarize recent contributions and advances in our knowledge about the magnetic field of solar prominences. It mostly relies on high resolution and high sensitivity spectropolarimetry made both in the visible and in the near infrared.

1 Introduction

Solar prominences (filaments) are made-up of dense and cool chromospheric plasma hanging in the hot and low density corona (Tandberg-Hanssen 1995). Besides its intrinsic interest, as a natural laboratory for plasma physics, the study of these structures is also of a more general interest in the frame of space weather studies. Indeed, among other closed magnetic regions such as active regions, eruptive prominences are often associated with coronal mass ejections, or CMEs, that is huge plasma "bubbles" ejected from the solar corona and able to strongly affect Sun-Earth relationships, by their interactions with the terrestrial magnetosphere (see e.g., Gopalswamy et al. 2006, for a recent review upon the various precursors of CMEs).

Despite systematic observations made since the nineteenth century and decades of study, prominence formation mechanisms are still not well understood. In particular, yet no theory can fully explain their remarkable stability in a hotter and less dense medium. However, since the plasma β is low in prominences, the magnetic field is very likely to play a major role in the physical scenarios which could explain prominences formation, stability and, finally, the triggering of these instabilities leading to CMEs (see Fig. 1).

However, the 3D magnetic field topology of solar prominences is not *directly* measureable in the corona. Even though indirect methods are available, the best possible determination of prominences magnetic fields comes from the inversion of spectropolarimetric data, which collection still remains a difficult task. He I multiplets such as λ10830 Å in the near-infrared, and the Fraunhofer "yellow line" D_3 at λ5876 Å are the best tools, so far, to study prominence magnetic fields. Indeed, only a few spectral lines are intense enough for ground-based observations in the optical spectrum of solar prominences i.e., at these wavelength at which spectropolarimetry is usually done. These helium multiplets provide, even if they are fainter than Hα for instance, the most suitable information necessary for the purpose of determining the magnetic field pervading the prominence plasma. Indeed, Hα is generally optically thick in prominences which, together with its hyperfine atomic structure, makes this spectral line still much more difficult to deal with, as compared to the above-mentioned helium multiplets. First spectropolarimetric observations of prominences and associated results about the magnetic field properties have been recently reviewed by Paletou & Aulanier (2003).

2 Recent advances

After very fruitful years of observations made mostly in the 80's, mainly at the *Pic du Midi* in France and at Sacramento Peak by NSO and HAO groups in the USA, spectropolarimetry of prominences seems to resume after the pionnering work of Lin et al. (1998) and the full-Stokes observations of a filament (i.e., a prominence as seen on the disk) in the λ10830 Å multiplet.

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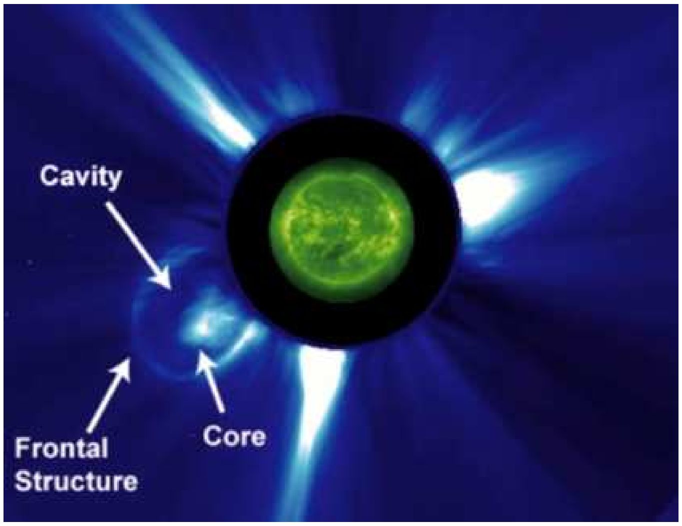

Fig. 1. A view of the standard three-part structure of a coronal mass ejection, as observed on December 20, 2001 with the LASCO coronagraph on-board SoHO. The so-called bright core is the remains of an eruptive prominence (from Gopalswamy et al. 2006).

A few years after, the first *full-Stokes* and high spectral resolution observation of a prominence in the He I D_3 multiplet is made at THéMIS (Paletou et al. 2001). These observations revealed a mixture of Hanle and Zeeman effects signatures. And the direct analysis, under the weak-field approximation, of the measured Stokes V signals pointed at a longitudinal magnetic field value of the order of 40 G, i.e. quite larger than what was usually measured in quiescent prominences (Leroy 1989, Leroy et al. 1984). Magnetic field strengths of the order of 50 G were also reported by Wiehr & Bianda (2003).

The new THéMIS observations have also led to a revision of magnetic field inversion tools (López Ariste & Casini 2002). In particular, these authors demonstrated how taking into account *all* Stokes parameters, and not only linear polarization signals, can increase the reliability of the inversion process.

Shortly after, Casini et al. (2003) published the first *maps* of the vector magnetic field i.e., its modulus, azimuth and inclination, as inferred from *Advanced Stokes Polarimeter* observations made at D_3 of He I, at the Dunn Solar Tower (DST, NSO/SP, USA). Even stronger field measurements were confirmed, up to 70 G, and variations of the orientation of the magnetic field across the prominence body were revealed.

2.1 Indirect methods

Long sequences of observations, more likely provided by spaceborne observatories, offer the possibility, to a certain extent, for an indirect diagnosis of the mean magnetic field in a filament/prominence. Using a 7h30 observing sequence made with the CDS EUV spectrometer on-board SoHO, and from the identification of certain oscillation modes associated to Alfvén and magnetoacoustic waves, Régnier et al. (2001) could infer the angle between the mean magnetic field and the filament long axis, and the magnetic field strength vs. the electronic density (although the latter remained undetermined).

Some important properties of the magnetic field of prominences can also be deduced from vector magnetic maps made at the *photospheric* level, in association with Hα imagery of the area below were stands the prominence. The latter images have to be used *simultaneously* with the photospheric vector magnetograms, and analysed taking into account the so-called *chirality rules* which were established by Martin (1998).

Taking advantage of the multi-line capabilities of THéMIS, and after a delicate analysis of several sets of data, López Ariste et al. (2006) could indeed identify the presence of photospheric magnetic field dips, also known as *bald patches* (see Fig. 2). According to these authors, this observed magnetic field topology in the photosphere tends to support MHD models of prominences based on magnetic dips located within weakly twisted flux tubes.

2.2 Near-infrared observations

The λ10830 Å multiplet of He I is routinely observed at the German VTT with the TIP polarimeter developed at the IAC (Mártinez Pillet et al. 1999, Collados et al. 2007). Filaments and prominences observations made with such instruments have recently conducted to very interesting results.

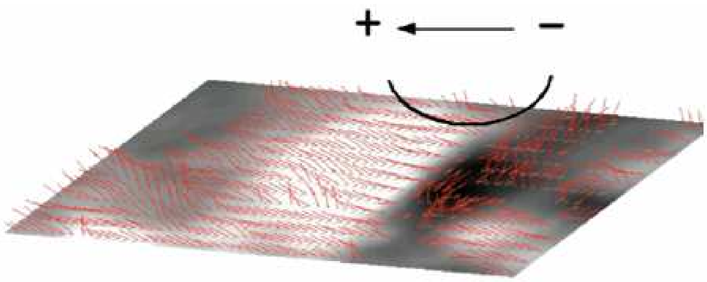

Fig. 2. The presence of magnetic dips supporting the prominence plasma against gravity can be inferred from a careful analysis of both (photospheric) vector magnetic field maps and simultaneous Hα images of the filament and its environment (from López Ariste et al. 2006, using THéMIS multi-wavelength observations).

From observations of a filament at disk center, Trujillo Bueno et al. (2002) could show, from the analysis of linear polarization signals observed in the two well-separated components of the λ10830 Å multiplet, and taking advantage of the forward-scattering geometry of this observation, that the effect of selective absorption from the ground-level of the triplet system of He I is at work. This implies the presence of magnetic fields of the order of a few gauss that are highly inclined with respect to the solar radius vector.

More recently, Merenda et al. (2006) published a quite surprising result concerning the orientation of the magnetic field deduced from the observation of a *polar crown* prominence. A magnetic field of 30 G strength inclined by about 25^o with respect to the local solar vertical direction was inferred. These authors could also deduce from their analysis that, this nearly vertical magnetic field appeared to be slightly rotating around a fixed direction in space as one proceeds along the direction of the spectrograph's slit (which was, in that case, parallel to the local limb).

3 THéMIS on the front line

Nowadays, the 1-m aperture class THéMIS solar telescope installed at the *Observatorio del Teide* in Izaña (Tenerife, Spain) is the tool of choice for observing programmes dedicated to the spectropolarimetry of solar prominences. Since 2006, and the rejuvenation of the pool of detectors for the MTR observing mode (see e.g., Paletou & Molodij 2001), it provides indeed a *unique* capability of high spectral resolution, multi-line spectropolarimetric observations *simultaneously* in the visible and in the near-infrared spectral domains.

On Fig. 3, we display Stokes profiles extracted from data taken on June 2007. With our MTR setup, observations of D_3, Hα and λ10830 Å spectral domains are made simultaneously. For these observations, a polarimetric sensitivity better than 10^{-4} was reached. Such a combination of measurements with high spectral resolution and polarimetric sensitivity is, so far, a unique capability which is fully relevant for the deeper study of prominences magnetic fields in the coming years.

In the frame of our programme of spectropolarimetric observation of prominences, we could also put in evidence "enigmatic" circular polarization signals in Hα, both symmetric and having amplitudes which can be comparable to linear polarization signals, unlike what is predicted by the theory of the Hanle effect (see e.g., Landi Degl'Innocenti 1982). This was confirmed by observations made at the DST with the ASP spectropolarimeter (López Ariste et al. 2005). Even though other groups, such as Stenflo's (ETH, Zürich) using the 45-cm aperture Gregory-Coudé telescope at Locarno with the ZImPol spectropolarimeter could not yet confirm our findings (Ramelli et al. 2006), the analysis of data collected during our 2007 and 2008 observing campaigns do confirm the existence of such V signals. Our present study of this set of data aims at understanding under which conditions such circular polarization signals appear and, which are the physical implications of their presence or absence.

There are several physical processes capable of generating the observed net circular polarization (hereafter NCP) at Hα and, it is still unclear which one, or which combination of effects, is indeed at work in prominences. This may result from the presence of *electric* fields in the prominence plasma (see e.g., Casini & Manso Sainz 2006). However, some authors have also shown that collisional effects, either anisotropic (Derouich 2007) or isotropic (Štěpán & Sahal-Bréchot, these proceedings), can also generate NCP.

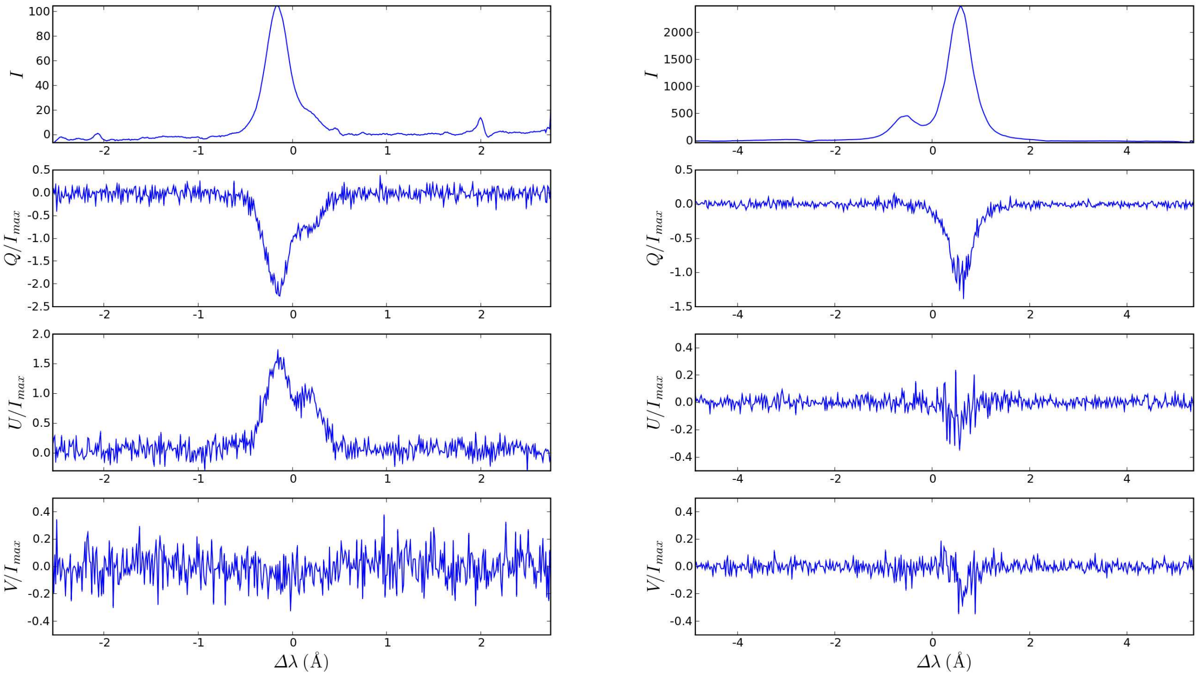

Fig. 3. Full-Stokes measurements of polarized signals formed in a solar prominence observed simultaneously with THéMIS on June 2007, at 5876 Å (left) and at 10830 Å (right). The Stokes profiles Q, U and V are normalized to the maximum of I after removal of the scattered light. Hα was also observed simultaneously with our MTR set-up. Polarization signals displayed here have been obtained with a sensitivity better than 10^{-3}.

4 The need for complex radiative modelling

It happens that measurements of the ratio between the amplitude of the two components of Stokes I, resulting from the atomic fine structure, for the He I λ10830 Å and D_3 multiplets (see e.g., Fig. 11 in López Ariste & Casini 2002) are often in contradiction with the commonly used hypothesis of *optically thin* multiplets (see e.g., Bommier 1977).

Besides, up to now the most recent radiative models (Labrosse & Gouttebroze 2001, 2004) still assume mono-dimensional (1D) static slabs and *no* atomic fine structure for the He I model-atom, which lead to the synthesis of unrealistic Gaussian profiles. Given the high spectral resolution of actual observations, it is therefore important to use the best numerical radiative modelling tools in 2D geometry, as a first step, and a more detailed He I atomic model in order to improve our spectral diagnosis capability.

As a first application of the new 2D radiative transfer code developed by us (Paletou & Léger 2007, Léger et al. 2007), we have shown how *multi-thread* models, for which one considers the emission resulting from a bunch of cool small-scale structures distributed along the line of sight, could explain the measured intensity ratios (Léger & Paletou 2008).

Such a forward complex radiative modelling now have to be exploited and developed further. It should also be used for the generation of synthetic polarization signals, possibly combined with recently developed numerical tools such as HAZEL (Asensio Ramos et al. 2008).

5 Conclusions

The spectropolarimetry of solar prominences have been renewed during the last decade with the advent of both new telescopes, new spectropolarimeters and detectors. Even though the data collection has not been huge so far, most of the measurements of quality have led to new and surprising results.

In that field, the solar telescope THéMIS with its unique multi-line spectropolarimetric capability is definitely, at the present time, the instrument of choice for such studies. In a near-future, only the dedicated ProMag spectropolarimeter currently developed at HAO/NCAR, and to be deployed at the Evans Solar Facility (NSO/SP, USA), will provide almost comparable sets of data.

It is finally expected that the future 4-m aperture solar telescope EST will allow too, at the 2020 horizon, for the collection of the most suitable combination of spectropolarimetric data necessary for ever more precise determinations of the magnetic fields of solar prominences.

Arturo López Ariste (THéMIS, CNRS), Roberto Casini (HAO, NCAR, Boulder), Reza Rezai (KIS, Freiburg) and Ludovick Léger (LATT, U. Toulouse, CNRS) are the main collaborators of our observing programme related to the spectropolarimetry of solar prominences. THéMIS is operated on the Island of Tenerife by CNRS-CNR in the Spanish *Observatorio del Teide* of the *Instituto de Astrofísica de Canarias*.

References

Asensio Ramos, A., Trujillo Bueno, J., & Landi Degl'Innocenti, E. 2008, ApJ, 683, 542

Bommier, V. 1977, Thèse de Doctorat de 3ème cycle, Univ. de Paris VI

Casini, R., & Manso Sainz, R. 2006, J. Phys. B: At. Mol. Opt. Phys., 39, 3241

Casini, R., López Ariste, A., Tomczyk, S., & Lites, B.W. 2003, ApJ, 598, 67

Collados, M., Lagg, A., Díaz García, J.J. et al. 2007, in ASP Conf. Ser. 368, The Physics of Chromospheric Plasmas, eds. P. Heinzel, I. Dorotovič & R.J. Rutten (San Francisco: Astronomical Society of the Pacific), 611

Derouich, M. 2007, A&A, 466, 687

Gopalswamy, N., Mikić, Z., Maia, D. et al. 2006, Space Science Reviews, 123, 303

Labrosse, N., & Gouttebroze, P. 2001, A&A, 380, 323

Labrosse, N., & Gouttebroze, P. 2004, ApJ, 617, 614

Landi Degl'Innocenti, E. 1982, Solar Phys., 79, 291

Léger, L., & Paletou, F. 2008, A&A (in press)

Léger, L., Chevallier, L., & Paletou, F. 2007, A&A, 470, 1

Leroy, J.-L. 1989, in Dynamics and Structure of Quiescent Solar Prominences, ed. E.R. Priest (Dordrecht: Kluwer)

Leroy, J.-L., Bommier, V., & Sahal-Bréchot, S. 1984, A&A, 131, 33

Lin, H., Penn, M.J., & Kuhn, J.R. 1998, ApJ, 493, 978

López Ariste, A., & Casini, R. 2002, ApJ, 575, 529

López Ariste, A., Aulanier, G., Schmieder, B., & Sainz Dalda, A. 2006, A&A, 456, 725

López Ariste, A., Casini, R., Paletou, F. et al. 2005, ApJ, 621, L145

Martin, S.F. 1998, Solar Phys., 182, 107

Mártinez Pillet, V., Collados, M., Sánchez Almeida, J. et al. 1999, in ASP Conf. Ser. 183, High Resolution Solar Physics: Theory, Observations, and Techniques, eds. T.R. Rimmele, K.S. Balasubramaniam & R.R. Radick (San Francisco: Astronomical Society of the Pacific), 264

Merenda, L., Trujillo Bueno, J., Landi Degl'Innocenti, E., & Collados, M. 2006, ApJ, 642, 544

Paletou, F., & Aulanier, G. 2003, in ASP Conf. Ser. 307, Solar Polarization Workshop 3, eds. J.Trujillo Bueno & J. Sánchez Almeida (San Francisco: Astronomical Society of the Pacific), 458

Paletou, F., & Léger, L. 2007, JQSRT, 103, 57

Paletou, F., & Molodij, G. 2001, in ASP Conf. Ser. 236, Advanced Solar Polarimetry – Theory, Observation, and Instrumentation, ed. M. Sigwarth (San Francisco: Astronomical Society of the Pacific), 9

Paletou, F., López Ariste, A., Bommier, V., & Semel, M. 2001, A&A, 375, L39

Ramelli, R., Bianda, M., Trujillo Bueno, J. et al. 2006, in ASP Conf. Ser. 358, Solar Polarization 4, eds. R. Casini & B.W. Lites (San Francisco: Astronomical Society of the Pacific), 471

Régnier, S., Solomon, J., & Vial, J.-C. 2001, A&A, 376, 292

Tandberg-Hanssen, E. 1995, The Nature of Solar Prominences (Dordrecht: Kluwer)

Trujillo Bueno, J., Landi Degl'Innocenti, E., Collados, M., Merenda, L., & Manso Sainz, R. 2002, Nature, 415, 403

Wiehr, E., & Bianda, M. 2003, A&A, 404, L25