MAGNETIC HELICITY AND SOLAR PROMINENCE FORMATION

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Abstract. Simple laws have long-since been put forward from the chirality of observed features to derive the direction of the axial magnetic field inside solar filaments. These are the so-called "filament chirality rules". Here, we report on two uses of these rules applied to THEMIS and SVST observations and to MHD simulations. Being the first to apply these rules to the 180° disambiguation of the direction of the photospheric transverse magnetic field around filaments, we found the unprecedented evidence of magnetic support in filament feet, as predicted by former magnetostatic and recent MHD models. By combining these rules with 3D weakly twisted flux tube models, we identified the sign of the magnetic helicity in several filaments. Following their interactions with one another over a few days, we found that the observational condition for two filaments to merge is that their flux tubes must have the same helicity sign. We theoretically recovered these results, by conducting a parametric study of 3D numerical MHD simulations of sheared bipoles. This study also provided new conditions for filament merging, in yet-unobserved configurations in which sheared bipoles are oppositely oriented.

1 Introduction

Solar filaments and prominences are key-phenomena for the study of high-stressed current-carrying magnetic fields in the solar corona. They can be used to understand how magnetic helicity slowly accumulates in the Sun's corona, and is then later ejected in the heliosphere in the form of coronal mass ejections, which are known to be the main drivers of extreme space weather. In spite of impressive progress with ASP for the 2D measurement of the internal magnetic field in prominences (Casini et al. 2003), building a 3D picture still requires to combine multi-wavelength observations and magnetic models (e.g. Dudik et al. 2008).

In this context, observational laws have been put forward from the chirality of observed features to derive the direction of the axial magnetic field inside solar filaments. These are the so-called "filament chirality rules". They state that a dominant fraction of filaments located in the northern (resp. southern) solar hemisphere have right- (resp. left-) bearing feet and fibrils, left (resp. right) skewed arcades, and dextral (resp. sinistral) internal axial fields, which point rightward (resp. leftward) as the filaments are viewed from the main positive polarity field on the side of the photospheric inversion line above which they are located (Martin 1998).

The most successful filament magnetic models make use of a 3D differentially sheared arcade or a weakly twisted flux tube topology. The good applicability of these models to observations has first been proven through the comparison of plasma-supporting magnetic dips calculated in a linear force-free field model with observed filament material (Aulanier & Démoulin, 1998). Since then, this "magnetic dip filling" procedure has been applied by various groups to to analyze real observations with linear magnetohydrostatic, non-linear magnetofrictional and fully MHD models (Aulanier & Schmieder 2002, Lionello et al. 2002, van Ballegooijen 2004, Bobra et al. 2008). These topologies have also recently been found to be consistent with the evolution of the photospheric vector magnetic field during a filament formation resulting from flux emergence, as observed by Hinode/SOT (Okamoto et al. 2008). When combined with the chirality rules, these models predict that dextral (resp. sinistral) filaments correspond to left- (resp. right) hand magnetic twists, hence to negative (resp. positive) magnetic helicities.

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2 Disambiguation of THEMIS magnetograms and discovery of magnetic dips in a filament foot

A debate is raging in the solar physics community about the magnetic nature of filament feet, which are common underlaying and lateral extensions observed in absorption on the solar disc in Hα and in the EUV. Are these feet formed by continuously injected plasma condensation in magnetic arcades, as hinted by some observations and conceptual models (Martin 1998), or do they consist of quasi-static condensations that are maintained against free-fall by the Lorentz force in a low-lying continuous distribution of magnetic hammocks, from the feet ends to up to the filament bodies, as first predicted by linear force-free field and magnetohydrostatic models (Aulanier & Démoulin 1998, Aulanier & Schmieder 2002, Dudik et al. 2008) ? This issue is important since the former interpretation, if it were true, could put in jeopardy the family of models mentioned in Sec. 1. This debate had been lacking of new discriminators for about ten years, until this issue was recently addressed through new direct measurements of the photospheric magnetic field vector $\vec{B}$ in a filament channel located far from the center of the solar disc, resulting from the PCA-based inversion of high-precision spectropolarimetric observations with the MTR instrument of the THEMIS telescope (López Ariste et al. 2006).

A major problem with these measurements is that they still give the direction of the component of the magnetic field vector on the plane of the sky at $\pm 180°$. This fundamental ambiguity does not allow the observations, taken alone, to state whether an arcade or a dip is measured at a given place. So as to solve this paradigm, chirality rules can be applied to the disambiguation of the measured transverse magnetic fields, before deprojecting them to obtain the three components of the magnetic field vector in the reference frame of the solar surface. This procedure was proposed and applied in López Ariste et al. (2006), and rephrased by Martin et al. (2008). The studied filament was identified to be sinistral, hence with a magnetic field vector globally pointing toward the left, as viewed from the dominant positive magnetic polarity in the photosphere (Fig. 1, top). Interestingly, it was found that, for almost every area analyzed in details within the observed filament channel (indicated by rectangles in Fig. 1), only the sinistral solution that matched the chirality rule on the plane of the sky remained sinistral in the reference frame of the solar surface. Using the chirality-consistent solution to calculate the curvature $B^2/(\vec{B} \cdot \vec{\nabla})\vec{B}$ of the magnetic field at various places within the channel, the first-ever 3D magnetic dip topology was found in the photosphere below a filament foot from observations (Fig. 1, bottom). This is consistent with early linear force-free models for filament feet (Aulanier & Démoulin 1998) and with recently recovered in MHD simulations of prominence formation by twisted magnetic flux tube emergence through the photosphere (Magara 2007).

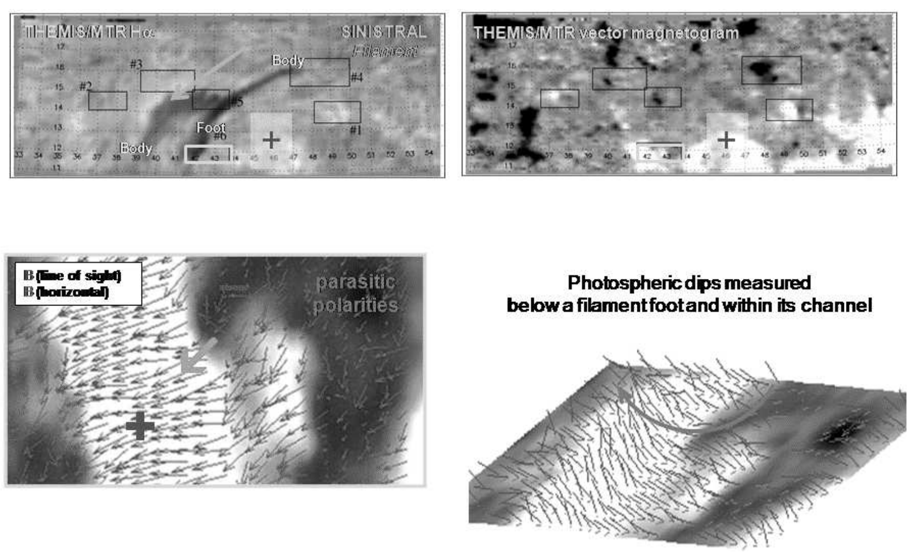

Fig. 1. First-ever dentification of a magnetic dip at the footpointof a filament foot. The vector magnetic field was measured with THEMIS/MTR and the 180° ambiguity was solved using usually observed filament chirality rules. The transverse fields which have an inverse orientation from a $-$ toward a $+$ polarity indicate the presence of magnetic dips above the associated inversion line. (adapted from López Ariste et al. 2006).

3 Hα/EUV observations and MHD simulations of merging/flaring filament sections

Even though a careful reader can hint from previous papers that filaments can only merge if their chirality is the same (see e.g. Malherbe 1989, Martin 1998, Rust 2001, van Ballegooijen 2004), this condition had never been tested with dedicated observational and theoretical studies until recently.

The recent multi-wavelength analyzis of three interacting filament sections F1, F2 and F3 (Fig. 2) observed during a "Joint Observing Programme" between ground-based instruments in the Canary Islands (the SVST and the MSDP on the VTT) the TRACE satellite, was the first dedicated observational study of this issue. Following their evolution over several days, it was shown that F1 and F2 gently merged into a single structure, as observed by a gradual filling in Hα of the gap R1 between both of them. This merging was associated with mild EUV brightenings and with slow Hα Dopplershifts at the merging point (Schmieder et al. 2004). While EUV brightenings are a good indicator of magnetic reconnection, the flows revealed that the merging first took place by dynamic exchanges between the two progenitors, until they formed a single long quiet filament. Two days later F2 and F3 produced a confined flare, as seen with EUV post-flare loops, as they got into contact at the point R2 (Deng et al. 2002). So as to adress the role of helicity in these two events, Schmieder et al. (2004) used the chirality laws for chromospheric fibrils and magnetic field polarity, overlaying coronal arcades and handedness of sunspots. The direction of the axial fields in the three filaments was then identified (see the arrows in the upper-middle panel of Fig. 2). It was then confirmed that when two filaments interact, magnetic reconnection takes place and leads to a merging (resp. a flare) when their helicity signs are of the same (resp. opposite) sign. It was also shown that magnetic helicity must slowly accumulate prior to filament merging, as seen by the rotation of a small twisted sunspot close to the merging point. Finally, it was suggested that magnetic reconnection first accelerates plasma between both progenitor filaments, and that it may later result in a change of topology which can sustain stable plasma all along the new filament.

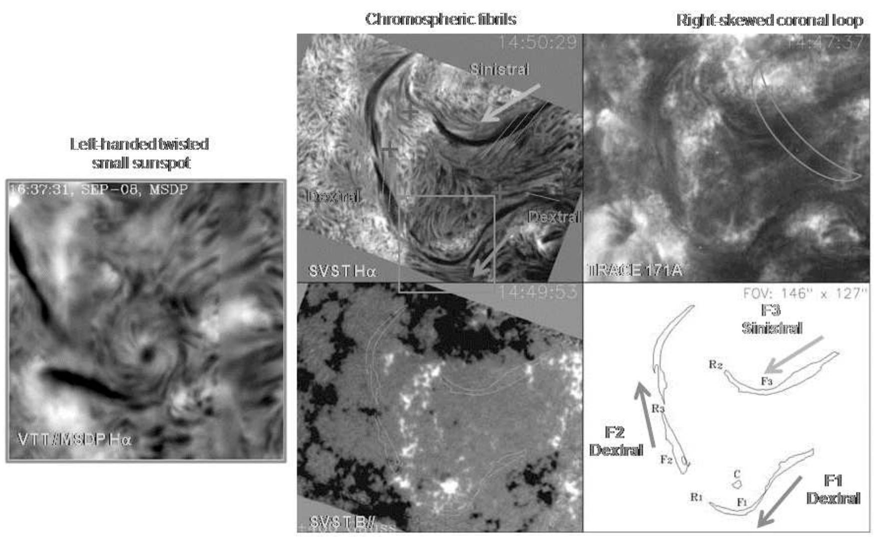

Fig. 2. Identification of the chiralities of three interacting filaments F1,2,3, using various observed features. F1 and F2 were observed to merge in the R1 area, whereas a flare took place between F2 and F3 one day later, as they interacted but did not merge (adapted from Deng et al. 2002 and Schmieder et al. 2004).

Numerical MHD simulations of the formation and interaction between pairs of solar filaments have then been conducted. Line-tied sub-Alfvénic shearing boundary motions were applied to adjacent and initially current-free magnetic dipoles. The simulations were performed in a low-β adiabatic regime, using $500 \times 190 \times 190$ mesh points in a non-uniformed grid. Four possible combinations of chiralities (identical or opposite) and axial magnetic fields (aligned or opposed) between the participating filaments were considered (DeVore et al. 2005). It was found that, when the topology of the global flux system comprising the prominences and arcades is bipolar, so that a single polarity inversion line is shared by the two structures, then identical chiralities necessarily imply identical magnetic helicity signs and aligned axial fields. In this case, finite-B slipping magnetic reconnection formed new field lines linking the two initial prominences (see Fig. 3, left). At early times, shear Alfvén waves

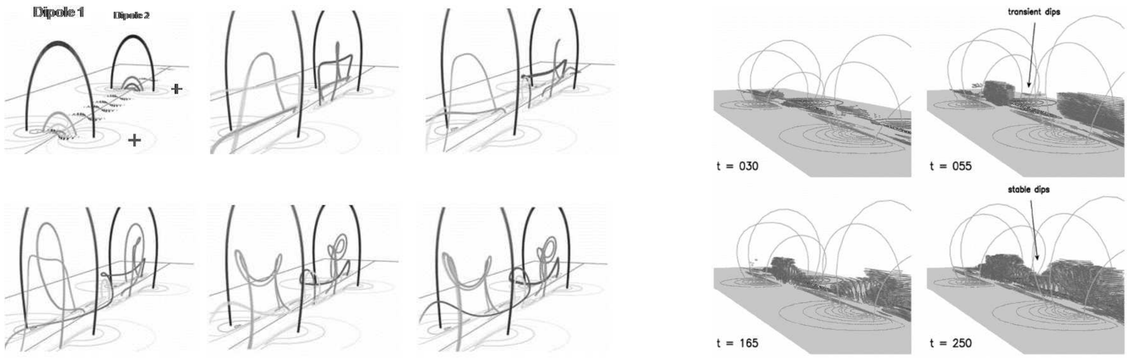

Fig. 3. 3D MHD simulation of prominence merging, resulting from finite-B magnetic reconnection between two dipoles that share a common photospheric inversion line, and whose shear result in the same magnetic helicity sign. *(Left:)* Reconnecting field lines. *(Right:)* Resulting distribution of plasma-supporting magnetic dips, simulating the prominence material (adapted from DeVore et al. 2005 and Aulanier et al. 2006).

propagated through these newly reconnected field lines, which can accelerate plasma condensations from one progenitor to another. As the shear increases, a new distribution of magnetic dips formed and increasingly filled the volume between both progenitors, so that they gradually merged into a single filament. We identified the multistep mechanism, consisting of a complex coupling between photospheric shear, slipping magnetic reconnection in the corona, and formation of quasi bald patches, that is responsible for stable filament merging through dip creation (Aulanier et al. 2006). This first model successfully reproduced the observations of filament merging by Schmieder et al. (2004). The second model, which also made use of a large-scale bipolar field, but which induced opposite helicities and axial fields between the two prominences, hardly resulted in any magnetic reconnection. The resulting lack of merging is consistent with the observations of Deng et al. (2002), although no flare reconnection occured in the model. When the topology instead is quadrupolar, so that a second polarity inversion line crossing the first lies between the prominences, then the converse relation holds between chirality and axial-field alignment. Reconnections that form new linking field lines now occur between prominences with opposite chiralities. They also occur, but only result in footpoint exchanges, between prominences with identical chiralities. These findings do not conflict with the observational rules, since the latter have yet to be derived for non-bipolar filament interactions; they provide new predictions to be tested against future observational campaigns.

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