New Perspectives on Solar Prominences

B. Schmieder

Observatoire de Paris, 92195 Meudon Cedex Principal, France

Abstract.

New observations of solar prominences obtained during multi-wavelength campaigns with the SOHO and Yohkoh space missions bring new insight into the physical conditions of prominences and their environment. The new data provides important constraints for theory. In this framework, 3-D models of the magnetic configuration of filaments have been developed recently. They allow us to consider non-potential configurations and electric current distributions. We will present some new developments of 3-D models of a bipolar magnetic field and twisted flux tube which explains the presence of fine structures in prominences. The models also explains how the feet reach the photosphere and how prominences erupt as a part of a coronal mass ejection (CME). The new models bring valuable information on the global solar magnetic field with direct implications for dynamo theories and on the helicity of the heliosphere.

1. Introduction

This is not an exhaustive review on prominences but a subjective summary of papers presented during the IAU 167 meeting held in Aussois in April 1997. The meeting results are supplemented by some papers appearing recently in the literature. I will draw heavily from some reviews by Berger, Démoulin, Martin & McAllister, Seehafer, Vial, Webb. Brendan Byrne was fascinated by solar prominences and tried in different ways to detect similar prominences on stars (see Byrne et al. 1998 and Cameron this issue). We had long conversations about the similarities of these objects, and we discussed what star prominence studies can bring to solar physics. I will review in the first chapter some general properties of solar prominences. In the second chapter I will present the status of magnetic field observations and theories of prominences. In the last chapter I will draw attention to the now well established rules concerning the chirality of prominence signatures and then conclude with a discussion on how these statements can be interpreted.

2. Structure and Dynamics of Filaments

2.1. General properties

Prominences are thin structures consisting of cold plasma embedded in the hot corona (Figure 1). Their general shape has been known for nearly a century (e.g.
d’Azambuja and d’Azambuja 1948). When observed on the disk, prominences are often referred to as filaments. They form in channels with aligned magnetic flux. Mainly two types of prominences can be considered: the quiescent prominences and the active-region prominences. The latter ones are lower in altitude, and smaller in all their dimensions (see Table 1). The magnetic field of a quiescent prominence is typically 5-40 G and the direction is mainly along the length of the prominence. The field is almost horizontal, but in the horizontal plane it is inclined to the filament axis at an angle of about 15°.

![Images of prominences](image1)

Figure 1. Observations of prominences in Hα (a), Ca II line (b) and (d) with the Meudon spectroheliograph and in UV lines: (c) with EIT He II 304Å and (e) with SUMER C III 977Å.

2.2. Diagnostic of Thermodynamic Parameters

In order to understand the existence of cool material in the corona, it is essential to precisely measure its temperature and the variation of temperature within the structure, especially at the interface regions. Table 1 is a summary of the Hvar reference Atmosphere of Quiescent Prominences (Engvold et al. 1990). Since this publication, new investigations have been completed. I will
quote observations in the He 10830 Å line which allow one to see clearly the corridor of the filament (Harvey & Gaizauskas 1998), the observations obtained in He II 304Å with EIT which has provided many movies of eruptive prominences and allows one to better understand the flow inside prominences. The SOHO/SUMER spectrograph has tracked filaments and prominences using the Lyman series window. Lyman lines show a central reversal in filaments. NLTE computations show that the reversed part of the profile is due to absorption by the filament overlying the chromosphere. The ratio of the peaks gives an indications of the velocities inside the filament. To fit all the Lyman series we need to introduce a prominence-corona transition region in the isothermal model (Schmieder et al. 1998). Using SOHO/CDS spectrometer observations, Kucera et al. (1998a) derived the optical thickness of a prominence from the analysis of the absorption of the coronal emission lines by Hydrogen (H\(^0\) upper bound at λ < 911 Å ) and Helium (He\(^0\) upper bound at λ < 504 Å ) continua.

2.3. Fibrils and Plagettes in the Filament Channel

Filaments are always found above inversion lines of the photospheric magnetic field in regions, called corridors or filament channels, which are nearly free of chromospheric fibrils. They are also characterized on either side by the presence of H\(\alpha\) fibrils, nearly aligned with the inversion line, indicating a high magnetic shear (Foukal 1971, Rompolt 1990). The corridor is nearly free of vertical magnetic field flux except small parasitic polarities (Martin 1990). At the locations of these small polarities we observed the plagettes from which fibrils stream parallel to the filament (Figure 2). Two morphological forms of filament channels and filaments have been identified. They are called dextral and sinistral. An observer standing on the positive polarity side of a dextral/sinistral filament would see the lateral feet pointing to the right/left along the filament channel. These names correspond to right-bearing/left-bearing prominences if the prominence feet bear off to the right/left of the main axis. All dextral filaments are right-bearing. Most quiescent filaments in the northern/southern hemisphere are dextral/sinistral at mid- and high latitudes, regardless of the cycle (Martin et al. 1994). Observations show that there is a good correlation between the direction of the magnetic field along the filament as inferred from the plagettes and as inferred from the lateral prominence feet.

The filament channel is larger in radio wavelength than in optical lines (Nobeyama observations).

2.4. Coronal Arcades

The X-ray observations made by Yohkoh/SXT have told much about the coronal arcades overlying filament channels (McAllister et al. 1998). The skew of the coronal arcades changes according to the hemisphere. Skew was defined as the acute angle between the loops and the polarity inversion or filament axis. If the arcade loops cross over the filament in the sense of threads of a left-hand/right-hand screw they defined the loops as left-skewed/right-skewed. Left skewed arcades overlie dextral filaments (Martin & McAllister et al. 1995).
Figure 2. Observation of a filament in the northern hemisphere with the MSDP spectrograph at Pic du Midi: (top panel) – intensity in Hα. Note that it is a dextral filament with right bearing, note also the plagettes in the filaments channel and the fibrils aligned along the main filament axis. (bottom panel) – Doppler-shifts of the filaments and the chromosphere. Note that the velocities are reduced in the filament channel and small cells of higher up and down velocities are located just at the location of the feet. Note aligned velocity structures parallel to the main filament axis in the filament channel (Schmieder et al. 1991).
Table 1. Identity card of prominences

<table>
<thead>
<tr>
<th></th>
<th>Quiescent Prominence</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>60 - 600 Mm</td>
<td>less for active-region filament</td>
</tr>
<tr>
<td>wide</td>
<td>4 - 15 Mm</td>
<td></td>
</tr>
<tr>
<td>distance</td>
<td>30 Mm</td>
<td>size of the supergranules</td>
</tr>
<tr>
<td>between feet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>density</td>
<td>$10^{10}$ - $10^{11}$ cm$^{-3}$</td>
<td>less in prominence-corona region ($10^8$ - $10^9$ in cavity)</td>
</tr>
<tr>
<td>temperature</td>
<td>5000 - 8000 K</td>
<td>higher T (PCTR) observed in UV lines</td>
</tr>
<tr>
<td>magnetic field</td>
<td>4 - 50 G</td>
<td>100 G in active-region prominence</td>
</tr>
<tr>
<td>angle (axis of prom./B)</td>
<td>15 - 25 degrees</td>
<td>Hanle effect</td>
</tr>
<tr>
<td>configuration</td>
<td>inverse</td>
<td>normal for active region filament</td>
</tr>
<tr>
<td>magnetic flux</td>
<td>$2.5 \times 10^{19}$ Mx</td>
<td>for active-region filament</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$F = 10^{20}$ - $10^{21}$ Mx</td>
</tr>
<tr>
<td>flows</td>
<td>vertical 0.5 -5 km s$^{-1}$, horizontal 10-20 km s$^{-1}$</td>
<td>60 km s$^{-1}$ in active prominences</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>Hydrogen lines (Hα - Lyman lines), Ca II</td>
<td>NLTE radiative transfer physical parameters (Nobeyama Observatory)</td>
</tr>
</tbody>
</table>

2.5. Velocities for Quiescent Prominences

According to Doppler-shift measurements only weak vertical velocities are observed ($< 5$ km s$^{-1}$), higher horizontal velocities are detected reaching 20 to 30 km s$^{-1}$ (Schmieder et al. 1989). In activated filaments even higher velocities are observed, particularly inside the lateral feet (Figure 2b).

2.6. Twisted Ropes in Eruptive prominence

Many observations suggest a helical-like pattern during eruption of prominences (Rompolt 1990, Vršnak et al. 1991, Kucera et al. 1998b). The helical structure of prominences is more obvious at the limb (Figure 3). On the disk Raadu et al. (1988) observed blueshifts and redshifts along disturbed filaments suggesting twisted motion along the axis. Filippov (1994) discovered a pattern typical of a twisted flux rope with fishbone-like structures on both sides of the inversion line in a Hα filament. Twisted configurations are also identified in CMEs with in situ measurements from Ulysses (Bothmer et al. 1996). Finally the emergence of twisted flux ropes is also identified by vector field measurements (Leka et al. 1996). Models of eruptive filaments predict such twist (Figure 4).
3. Magnetic Field

3.1. Observations

Hanle Effect  In prominences the Zeeman effect only allows the measurement of the longitudinal component of the magnetic field (Kim 1990). Radio wavelengths provide information on the field strength (Apushkinskii et al. 1990). The Hanle effect gives the three components of the field and the electron density from the polarization components in two spectral lines (Bommier et al. 1994). The main results of Hanle measurements are the following: the prominence field has the opposite direction to that expected from simple extrapolation of the photospheric field. It is what is called ”Inverse type” (Leroy et al. 1984), the orthogonal component ($B_{per}$) is opposite to the field of a simple arcade and also the field component parallel to the prominence ($B_{//}$) is opposite to that of an arcade sheared by differential rotation.

Prominence Magnetic Field  It is now well accepted that the magnetic field in prominences is nearly horizontal, homogeneous on the scale of a few arc seconds, and increasing with height (Leroy et al. 1983).

Presence of Magnetic Dip  The gravitational scale height of prominence material (≈ 200 – 500 km) is much lower than the typical height of prominences ($10^4 – 10^5$ km). This implies that the plasma pressure cannot provide the mechanism of support. The observed velocities (a few km s$^{-1}$) are much less than the free fall velocities and usually the velocity pattern does not show such flows except in arch filament systems or post-flare loops, structures that we do not classify commonly as quiescent prominences. The cold material should be supported by the magnetic field. If enough mass can be brought into the top of the sheared magnetic arcade in less than one hour, the gravity force can bend the top of the field lines and form a dip (Dere et al. 1990, Fiedler & Hood 1993). The observations of dips are not evident but they could be suggested in some data (Rompolt 1990).

![Eruptive prominence observed in Fe IX 195 Å and He II 304 Å by SOHO/EIT on May 31, 1997. Note the helical structure of the prominence observed in He II (Courtesy of C. Delannée).](image-url)
3.2. Magnetic Configurations supporting Prominences

Since the well known 2D model of Kippenhahn & Schlüter (1957), several models have been proposed in 2 1/2-D and then in 3-D. Two types of models are considered: arcade-like configurations and twisted flux tubes.

Model in 3-D with Overlying Arcade  Arcade models in 2 1/2-D cannot have a dip at the top of the field lines even when the magnetic shear increases (Amari et al. 1991). In 3-D it can occur. The overlying arcade locally compresses the central part of an underlying sheared arcade (Antiochos et al. 1994). The latter model gives an inverse polarity prominence with a magnetic field nearly aligned with the photospheric inversion line.

Quadrupolar configurations  These configurations naturally have a dip. Malherbe & Priest (1983) and later Démoval & Priest (1993), Uchida (1998), developed such models. The presence of a corridor free of significant field is needed to have a prominence extension reaching the chromosphere and converging motions to provide mass supply. These models are perfectly adapted for active region filaments (Tang 1987) or filaments between two active regions (MacKay et al. 1998). The presence of “dual arcades” observed by Yohkoh/SXT is a signature of magnetic reconnection in quadrupolar configurations (Uchida 1998).

Models in 3-D with Twisted Flux Tubes  This class of model provides the needed doped magnetic field and seem to be well supported by recent observations. The twisted configuration can be obtained by photospheric twisting motions (Priest

Figure 4. Sketch of an eruptive filament (Courtesy of R. Moore)
Figure 5. Model of bald patch filament in 3-D: (a) Observations of a Hα filament with the MSDP spectrograph on the VTT at Tenerife, (b) MDI magnetogram and extrapolated magnetic field lines drawn only in the dips, (c) 3-D view, (d) side view (Aulanier et al. 1998 c)
et al. 1989), by converging motions in a sheared arcade with magnetic reconnection at the inversion line (van Ballegooijen & Martens 1989), by resistive instability in a sheared arcade or by relaxation and accumulation of helicity (Démoulin & Priest 1989, Rust & Kumar 1994) or by emergence from the convective zone (Low 1994, 1996). Prominence feet appear as a direct consequence of the parasitic polarities present in the filament channel. Priest et al. (1996) used the emergence of small loops to create feet or “barbs”. The feet would be due to the reconnection occurring between the emerging dipole and the main filament field. Aulanier & Démoulin (1998 a,b) showed that the feet appear naturally above secondary photospheric magnetic inversion lines produced by the parasitic polarities which create local quadrupolar configuration able to support the plasma in the feet.

3-D model of Prominence with a bald patch A recent model has been developed by Aulanier et al. (1998c, 1999) which shows the importance of field topology. They consider a bipolar configuration imposing a twisted flux tube using the equations of linear magnetohydrostatics (lmhs) for the extrapolation (Low 1992). Pressure and gravity are taken into account. They use directly the observed longitudinal fields, taken from magnetograms obtained by SOHO/MDI comparing their field lines with the filament observations obtained on the ground (VTT, Tenerife) and in space (SUMER). The dips of the field lines where material can be supported is examined. In Figure 5 they draw only the portion of the field lines dipped enough (2Mm) finding good agreement between the shape and location of the dipped field lines and the shape of the filament body (Figure 5). The lateral feet are explained by the presence of parasitic polarities close to the filament axis. When you consider low field lines with dips tangent to the photosphere, you can define a region containing all these tangent points where the field is purely horizontal. Such a place is called a “bald patch” (location in the photosphere free of vertical magnetic field lines). The overlay shows that the lateral feet correspond to such locations on each side of the inversion line where material can be readily supported. Many Hα dark chromospheric fibrils correspond to such locations. The magnetic field can be defined by magnetic surfaces. Because of the presence of parasitic polarities in the filament channel, separatrices do exist in many places. When the bald patch corresponds to a part of the intersection of the separatrix with the photosphere, a current layer can exist over the bald patch and the plasma along the field lines can be heated by ohmic dissipation. This explains the presence of the heated plasma observed at UV temperatures along the legs of the arcades overlaying filaments observed with SUMER in Si iv (Kucera et al. 1999a).

4. Magnetic Helicity and Filaments

The observations show specific relationships of chirality between filaments, coronal arcades, active regions, coronal mass ejections and magnetic clouds.

4.1. Chirality of Filaments and Arcades

The chirality relationship of filaments and overlying arcades is in the inverse sense, as shown above. It applies to both quiescent and dynamic arcades that
evolved after filament eruption/coronal mass ejection events. Many of the dynamic arcades evolved such that the later-forming loops showed apparent rotation relative to the earlier-forming loops. This apparent rotation also has a specific sense. Left-skewed/right-skewed arcades turn in the counterclockwise-clockwise sense decreasing the magnetic shear (Martin 1998).

4.2. Shear Angle of Active Regions

Conspicuous fibrils are observed near sunspots penumbrae. Richardson (1941), recognizing a similarity between fibril pattern and the pattern of iron filings around bar magnets, made an extensive study of the orientation of the superpenumbra fibrils and found that the majority are clockwise for sunspots in the southern hemisphere. This was confirmed later by Rust and Martin (1994). On the other hand Seehafer (1990) estimated the electric current helicity in 16 active regions and concluded that the electric current helicity is predominantly positive/negative in the southern/northern hemisphere. This result was confirmed also from a comparison between Mees vector magnetograms and current-free configurations (Pevtsov et al. 1994).

4.3. Chirality of large scale X-ray Structures

Very large scale X-ray structures have been noticed to exhibit a slender S or backward-S shape as a function of hemisphere (Rust &.Kumar 1996, Moore et al. 1997). Reverse S-shaped structures predominate in the northern hemisphere as do S-shaped structures in the southern hemisphere. These S-shape patterns also apply to many filament channels.

4.4. Helical Structure of Magnetic Cloud

Interplanetary clouds are the ejected parts of coronal mass ejections as first concluded by Marubashi (1986). Many such plasma clouds have helical structure detected by magnetometers on board spacecrafts (Burlaga 1991, Webb 1998). Gosling (1990) proposed that helical magnetic fields in interplanetary clouds originate from magnetic reconnection in ascending coronal arcades. Based on the same scenario, Martin & McAllister (1998) anticipate that left-skewed coronal arcades become left-helical CMEs and are detectable later as left-helical interplanetary clouds. Rust (1994) found that the majority of interplanetary clouds with left/right-helical structures come from the northern/southern hemispheres, but he proposed that the helicity of the clouds reflects the helicity of the filaments before they erupt, which in turn reflects the helicity of the solar dynamo generated fields.

4.5. Twisted Configurations

Modelling a filament as an initially untwisted axial magnetic field aligned with the inversion field, Martin & McAllister (1998) claim that dextral filaments develop right-helical twist on the sun and that the corresponding interplanetary clouds have the helicity opposite to the CMEs after they have been detached from the Sun by reconnection. This solution is controversial and another solution of all these laws of chirality is proposed based on the idea that the filament lies in the lower portion of a large-scale helical magnetic field which supports the
filament against gravity (Rust & Kumar 1994, Aulanier et al. 1998 c, 1999). However Martin & McAllister did not support the idea of a twisted flux rope because of fine structure observations and vertical velocities in the barbs.

5. Discussion on Helicity

A natural way to explain how both magnetic field components, parallel and normal to the prominence, are inverse is to use a quadrupolar field sheared by the differential rotation (Priest et al. 1996). However, this gives a magnetic helicity dominance in each hemisphere contrary to observations. Berger (1998) reviewed different statements that are well established to sketch a solution. Helicity is conserved in ideal MHD, and it is probably well conserved on the Sun, so any positive helicity generated by plasma motions, for example, must be offset by negative helicity generation. Berger proposed to explain the sign of the helicity, namely, Northern hemisphere negative, Southern Hemisphere positive by taking into account the transfer of the helicity either into or from the solar wind or across the equator, beneath the surface. His solution to helicity in filaments is based on the emergence of twisted flux tubes. The same approach was advocated by Rust (1994). Reconnection below the solar surface could create twisted flux tubes which emerge due to buoyancy. By transfer and redistribution of the helicity and by using faster rotation at the equator one can reproduce at least the observed global helicity pattern.

Démoulin (1998) explained that the right sign of helicity could be obtained with Coriolis forces acting on diverging supergranular flows (Priest et al. 1989). This process is very efficient and can accumulate helicity in twisted tubes but since localized motions give neutralized currents, it is difficult to reproduce the dominance of one polarity as observed in each hemisphere. If a local dynamo cannot give a good explanation, then global dynamo models should be investigated for their possible helicity-producing qualities.

6. Conclusion

The large amount of data concerning helical features, from filaments to interplanetary clouds, have shown a great organizing principle of nature. We need models that can fit into a unified theory. We have shown the importance of twisted flux tube emergence, the presence of parasitic polarities in the inversion line corridor, the aligned fibrils in the filament corridor and all the chirality laws. Many questions are unsolved and we need further observations with multiwavelength instruments to test the existing different proposed approaches.

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