ROLE OF HELICITY IN THE FORMATION OF INTERMEDIATE FILAMENTS

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Abstract. In the last few years new observations have shown that solar filaments and filament channels have a surprising hemispheric pattern. To explain this pattern, a new theory for filament channel and filament formation is put forward. The theory describes the formation of a specific type of filament, namely the ‘intermediate filament’ which forms either between active regions or at the boundary of an active region. It describes the formation in terms of the emergence of a sheared activity complex. The complex then interacts with remnant flux and, after convergence and flux cancellation, the filament forms in the channel. A key feature of the model is the net magnetic helicity of the complex. With the correct sign a filament channel can form, but with the opposite sign no filament channel forms after convergence. It is shown how the hemispheric pattern of helicity in emerging flux regions produces the observed hemispheric pattern for filaments.

1. Introduction

Filaments are one of the most interesting but mysterious of all solar phenomena. In a key paper Martin, Bilimoria, and Tracadas (1994) have shown that these objects and their birth grounds (filament channels) have a surprising hemispheric pattern. In the northern hemisphere most quiescent filaments are dextral, and in the southern hemisphere most are sinistral. This refers to the direction of the magnetic field when standing on the positive polarity side and gives the two possible orientations for the axial field (namely to the right for a dextral structure and to the left for a sinistral one). No pattern was found for low-latitude active-region filaments. These results have also been confirmed in more recent surveys by Bommier and Leroy (1997) and Leroy, Zirker, and Gaizauskas (1997). Such a pattern for quiescent filaments shows that there is an organisational principle of some kind behind the global nature of filaments and so this needs to be identified. The idea of a global organisational principle was reinforced by observations of X-ray arcades seen above filaments by Martin and McAllister (1995). They found that stationary arcades above dextral filaments are always left-bearing, while those above sinistral filaments are always right-bearing (as seen from above). The arcade orientation and filament channel orientation have a one-to-one correspondence. All post-eruption arcades that reform at successive heights above dextral filaments do so with a counterclockwise rotation with height and above sinistral filaments with a clockwise

rotation with height. A full description of these hemispheric patterns and others can be found in Zirker et al. (1997).

In response to these observations new theories of filament formation have been put forward by Rust and Kumar (1995), Kuperus (1996), Priest, van Ballegooijen, and Mackay (1996), and Zirker et al. (1997). Each of these authors recognized that surface differential rotation alone would give the wrong axial component in each hemisphere (a fact reinforced by van Ballegooijen, Cartledge, and Priest (1997)) and so put forward a different scenario for the origin of the hemispheric pattern. Priest et al. (1996) explain it by the combined effects of differential rotation acting on subphotospheric flux, its subsequent emergence by magnetic buoyancy and then the rearrangement of the emerged elements by magnetic reconnection to give the correct axial component (see also van Ballegooijen and Martins, 1990). On the other hand Rust and Kumar (1995) considered the filament as a twisted (helical) flux rope. This helical flux rope is organized by sub-photospheric differential rotation to give the correct axial component and then emerges into the solar atmosphere as a twisted magnetic field. The filament mass then rests in the bottom of the helix in static support. Kuperus (1996) and Zirker et al. (1997) explain the hemispheric pattern by surface flows acting on surface fields along with magnetic reconnections to give the correct axial component. Kuperus (1996) considers the coronal magnetic field as a collection of discrete elements and separatrix surfaces. Differential rotation acts on these elements and magnetic reconnections driven by photospheric shear and converging motions creates a filament with the correct axial component in each hemisphere. Alternatively, Zirker et al. (1997) consider a mid-to high-latitude bipolar magnetic region which has been acted upon by differential rotation. Diffusion of flux towards the polarity inversion line and reconnections then give the correct axial component. Zirker et al. (1997) do not use shear flows parallel or anti-parallel to the polarity inversion line to obtain the axial component (see Antiochos, Dahlburg, and Klimchuk, 1994). Both Kuperus (1996) and Zirker et al. (1997) prefer not to ascribe the patterns to unobservable subsurface flows which cannot be tested. All of the authors above give reasonable theoretical and observational arguments to support their models. The readers are left to consider the validity of the respective arguments for themselves.

Filaments form in a wide variety of sizes and locations on the Sun. They range from the small active-region filaments which form in regions of strong magnetic field at low latitudes, to the large quiescent filaments which form in quiet background regions of the polar crown. Although there are many theories for the formation of filaments, very few examples of formation have ever been observed. Since there is such a wide variety of filaments forming in different physical locations, this suggests that there may be several different mechanisms producing the various types (Priest, 1997). This paper will focus on the formation mechanism of a specific type of filament, namely the ‘intermediate’ filament. Another major class of filament is the ‘polar crown’ filament, but the mechanism described here is inappropriate to describe its formation, since the process here involves the large-
scale emergence of new flux, which does not occur at the high latitudes of the polar crown. Polar-crown filaments are more appropriately described by other theories such as Kuperus (1996), Priest, van Ballegooijen, and Mackay (1996), or Zirker et al. (1997).

The observations behind the model discussed here were made by Gaizauskas et al. (1997) and then modelled by Mackay et al. (1997). The observations and models showed the development of the filament channel with the emergence of an activity complex and then formation of a filament in the channel. An important feature in creating the channel with the correct chirality was the net magnetic helicity of the complex. In this paper we will consider how the net magnetic helicity (positive or negative) of activity complexes is related to the formation and hemispheric patterns of intermediate filaments, a feature which none of the above authors have included in their models. To begin with, the process of filament channel and filament formation will be described and the role of helicity in the formation discussed. Next a hemispheric pattern will be deduced from the models and finally a comparison between the model described here and those of Priest et al. (1996) and Rust and Kumar (1995) will be given.

2. Process of Filament Channel and Filament Formation

On the Sun there are many different classes of filament. Each of these classes form at different locations and have different scaling properties. The process outlined below describes the formation of an ‘intermediate’ or ‘boundary’ filament, which forms between single bipolar regions of flux or activity complexes and unipolar background fields. In general they circle the periphery of the main flux concentrations but have one end rooted in one of the flux polarities. In a survey carried out by Tang (1987) it was found that the majority of filaments (63%) form above polarity inversion lines between adjacent regions of flux rather than above polarity inversion lines contained in a single bipolar. The formation process is deduced from the observations of Gaizauskas et al. (1997) and the modelling of Mackay et al. (1997) which described the magnetic field of the observed structures by force-free fields. In terms of the hemispheric pattern of Martin, Bilimoria, and Tracadas (1994), the intermediate filaments have been included with quiescent filaments, but so far no individual study has been undertaken solely for them.

To begin with, a new region of flux emerges in the form of an activity complex (or a bipolar region). In a recent survey of 152 active regions by Gaizauskas and Zwaan (1997) it was found that the majority of ‘active-region’ filaments form either inside or around activity complexes rather than inside single bipolar regions. An activity complex will therefore be considered from now on, although the details of the model are the same for both types of region. The complex must emerge close enough to a remnant region so that the two can interact. Not only convergence but also cancellation of flux has to take place so the neighbouring magnetic polarities
of the new region and remnant region must have the opposite sign. The activity complex must therefore emerge, either to the east or west of the remnant region (see Figure 1(a), where a complex emerges on the west side in the southern hemisphere). The remnant region will have previously been acted on by differential rotation, meridional flows and supergranular diffusion and therefore will be more elongated and extend to higher latitudes than the activity complex. The effect of the remnant region on the field of the complex is small at the initial stages of development (i.e. both regions are independent from each other). This is supported by the observations of Gaizauskas et al. (1983), who found that most emerging activity complexes are in good flux balance. The flux of the activity complex is also often in a sheared state. This gives a dominant direction and horizontal field component at the level of the chromosphere and lower corona between the two regions and therefore helps the formation of a filament channel. It is the sheared nature of the field that gives the sinistral/dextral nature of the channel (see Figure 1(b), where the force-free alpha is positive giving rise to a sinistral channel).

Convergence of flux now occurs between the two topologically distinct regions as the component bipoles inside the activity complex expand and some of their flux is transported outwards as Moving Magnetic Features (MMF, Harvey and Harvey, 1973) into the surrounding network. Due to the convergence the two regions interact and reconnection takes place. The remnant region forms a boundary on one side of the channel and allows flux to connect down along the polarity inversion line between the two regions. Flux from the trailing positive polarity of the activity complex is transported into the filament channel as MMF towards the polarity inversion line. Elements of flux from the negative region also move into the channel (Figure 1(c)). At the point of maximum convergence, flux elements from the two regions cancel and the filament forms. It links excess flux from the convergence to other flux down the channel but not to the large remnant region (Figure 1(d)). The arrows give the direction of the axial component of field on either side of the filament structure. As can be seen, the axial component points in the same direction on both sides of the filament, which is consistent with the observations of Martin, Bilimoria, and Tracadas (1994). This is due to the type of twisting (the sign of alpha) which turns more flux to connect along the channel, parallel to the polarity inversion line rather than across it. However, with increasing distance from the polarity inversion line on either side the field vectors becomes less aligned with the polarity inversion line. This is again consistent with the observations of Martin, Bilimoria, and Tracadas (1994). A more detailed plot showing the field connectivity at the height and location of the filament observed by Gaizauskas et al. (1997) can be seen in Mackay et al. (1997), Figure 7. Since the flux that connects down the channel is small compared with the neighbouring regions, it takes the form of a thin vertical sheet (Mackay et al. (1997), Figure 8). The filament therefore forms in the field due to an imbalance of flux along the channel but with a sheared field rather than a potential field as previously suggested by Mackay and Priest (1996). Although the field is sheared, the filament structure does not necessarily
have helical twist. It is suggested that the mass is fed into the filament by the convergence and cancellation of flux (Priest, van Ballegooijen, and Mackay, 1996).

For the magnetic field of the filament to connect down the channel so that it lies along the polarity inversion line, the activity complex must have the correct sign of alpha with respect to the remnant region. Consider now what happens for the opposite (−ve) sign of alpha. In Figure 1(b) the fibrils would point in a S–N direction and the field direction would be reversed. After convergence and
reconnection the field configuration of the channel shown in Figure 1(e) is produced. In this case transverse structures across the polarity inversion line are formed rather than a dominant field along it. In other words, the configuration required for the formation of a filament channel and filament is not set up (Mackay et al., 1997, Figure 8).

The most important feature of this scenario is that a channel with sinistral or dextral nature is created when the complex emerges with the correct sign of alpha. The correct sign with respect to the neighbouring region (in this example +ve) gives a dominant horizontal component along the polarity inversion line between the two regions (i.e., a filament channel), while the opposite sign gives transverse structure and no filament channel after convergence.

The following questions naturally arise. First, how common is this method of formation? For this process to occur, the emergence of new flux in a sheared state and then its interaction with existing remnant flux is required. This will best occur during a phase of the solar cycle when there is much old flux lying around. It is not the only method that forms a filament but it may be a predominant one at low latitudes during the ascending phase of the solar cycle. As we approach solar maximum this hypotheses could easily be tested using SoHO and ground-based instruments. The second question is, how is the mass introduced into the filament and what keeps it there? This question is more difficult and presently a matter of debate, so a definite answer cannot be given. One possibility is that mass is introduced when the flux elements cancel. The cancellation of topologically distinct flux elements may create a current sheet which ‘shoots’ mass down the channel along the field lines that represent the filament. The mass then lies on field lines that are sufficiently long and flat to support it for a period of time. However, since the mass is not held in static support it will need to be continually replenished. Thus a process of continual small-scale flux convergence and reconnection below the filament (as suggested by Priest, van Ballegooijen, and Mackay (1996) and observed by Martin (1990)) would be required. Another possible means of mass supply is that flux is picked up from the chromosphere as the two regions converge. Recent simulations by Galsgaard and Longbottom (1997) have shown that it is possible to have density enhancement between regions of opposite polarity flux as they converge and reconnect. The full details of this are as yet unknown and more observations and theoretical work will be required to answer the question fully. The method described above only considers the evolution of the magnetic topology of the filament channel and filament. There is not enough information at present to describe in detail the plasma process involved. However, the model does show that magnetic helicity can be important for the formation of filaments.

Since magnetic helicity is important for the formation of filaments it needs to be shown that active regions can indeed supply the required amount of helicity to account for the helicities observed in filaments. As an order of magnitude estimate consider an active region as a closed uniform flux tube. The total helicity of the active region is then \( H = T \Phi^2 \), where \( T \) is the number of twists and \( \Phi \) the
magnetic flux (Berger and Field, 1984). If, for example, the active region has one complete turn and a flux of between $10^{21}$–$10^{22}$ Mx then its helicity lies between $10^{42}$–$10^{44}$ Mx$^2$. Now for a typical filament of height 50000 km, width 5000 km and magnetic field 10 G, the flux threading through it is $2.5 \times 10^{19}$ Mx. If it also has one turn (a filament may be unstable if it has much more than one turn, Priest, 1989) its helicity is then $6.25 \times 10^{38}$ Mx$^2$. From this simple order-of-magnitude calculation it can be seen that there is enough helicity in emerging active regions to account for the helicity in filaments.

A more detailed calculation of helicities can be carried out using the filament channel observed by Gaizauskas et al. (1997). The helicity per unit volume of the old remnant region and new region after they interact to form the filament is $1.9 \times 10^{13}$ Mx$^2$ m$^{-3}$. This value is calculated under the linear force-free approximation and is consistent with the results of Wang (1996). The self-helicity per unit volume of the filament structure in the channel is $7.5 \times 10^{8}$ Mx$^2$ m$^{-3}$. From this it can be seen that the filament structure only contains a small fraction of the total helicity of the flux regions. In Wang (1996) it was also found that the rate of change of helicity per unit volume per unit time in a typical active region is $2.64 \times 10^{10}$ Mx$^2$ m$^{-3}$ s$^{-1}$. This in itself is much higher than the computed self-helicity of the filament and again shows that the amount of helicity in emerging active regions can easily account for the helicity of filaments. Finally, critical values of the force-free alpha can be found such that there is enough twisting to allow flux to connect down the channel rather than across it. Again for the channel observed by Gaizauskas et al. (1997) it is found that a filament-type structure can exist down the channel for alpha values in the range $1.66 \times 10^{-9}$ m$^{-1}$ to $1.79 \times 10^{-8}$ m$^{-1}$. All of these alpha values are well within the observed range of values found in Pevtsov, Canfield, and Metcalf (1995) and give a wide range of possible values for which the correct connections can occur.

3. Hemispheric Patterns

In a recent paper by Pevtsov, Canfield, and Metcalf (1995) it was found that there is a hemispheric pattern for the net helicity of active regions. In the northern hemisphere 76% of active regions have negative helicity (alpha $-ve$) and in the southern hemisphere 69% have positive helicity (alpha $+ve$). The dominant values of alpha in each hemisphere do not change with the solar cycle or with class of flux region (unipolar, active region, activity complex). These results have also been confirmed by an independent study (Abramenko, 1996). In the present model the net helicity of the activity complex plays an important role in determining the chirality of the channel. The correct sign of helicity gives connections down the channel along the P.I.L. and the wrong sign gives connections across the channel. Can a hemispheric pattern for this type of filament formation be explained by the hemispheric pattern of helicity?
To see if this is the case we construct force-free models of the channel analysed before, which formed on 25 July 1979, but consider also the effects of flux emerging on both the east and west side of the remnant region and in each hemisphere according to the polarity emergence law for both cycles 21 and 22. The sign and value of alpha is deduced that produces connectivity down the channel rather than across it so that a filament-type structure can be obtained as before. The results are presented in Table I for different solar cycles, hemispheres, and sides of emergence of the new flux relative to the old flux.

If the flux regions emerge to the west of the activity complex in cycle 21 a positive value of alpha is required to give the correct connectivity in the southern hemisphere and a negative value of alpha is required in the northern hemisphere. With this, sinistral channels are produced in the southern hemisphere and dextral channels in the northern hemisphere (Figure 2(a)), which is consistent with the results of Martin, Bilimoria, and Tracadas (1994). If the opposite value of alpha is used in each case, a transverse structure is obtained across the channel and no flux connects down the channel to produce a filament-type structure (Figure 2(b)). In Figure 2 the filament channel is elongated compared to the newly emerged activity complex since the old remnant region, which forms a boundary on one side, has been acted upon by supergranular diffusion and meridional flows. These effects occur over long periods of time and push flux towards the poles. In general they have not had time to act on the activity complex and this allows the flux of the activity complex to connect to much higher latitudes along the length of the polarity inversion line. Alternatively, if the flux emerges on the east side of the remnant region the opposite occurs. A negative value of alpha is required in the southern hemisphere and gives a dextral channel and a positive value is required in the northern hemisphere to give a sinistral channel (Figure 3(a)). Again if the opposite sign of alpha is used in each case flux connects across the channel and not down it (Figure 3(b)). Emergence on the west side needs the dominant sign of alpha in each hemisphere to obtain the correct magnetic structure while emergence on the east side needs the minority sign

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<td>22</td>
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of alpha. The minority values of alpha in each hemisphere give the wrong chirality, while the dominant values give the correct chirality. Thus statistically there is a much higher chance of having dextral filaments in the northern hemisphere and sinistral filaments in the southern hemisphere. However, both can be produced by this mechanism in each hemisphere. The same pattern is found for the next cycle (22) with the polarity of the flux regions reversed accordingly; thus the results are independent of the solar cycle as Martin, Bilimoria, and Tracadas (1994) found. This shows the significance of helicity in the hemispheric patterns of filaments, a feature not considered until recently. In this paper a hemispheric pattern known from observations has been used along with theory to explain a hemispheric pattern for intermediate filaments.

The models constructed are also consistent with the results of Martin and McAlister (1995) for the overlying arcades. The axial component of field in the channel is created from the type of twisting due to the sign of alpha in the complex. The arcades overlying the filament channel must have the same direction of axial field as the filament channel lying below them or there would be a field reversal with height. Thus all stable arcades lying above dextral filament channels should be left-bearing and all arcades above sinistral filament channels correspondingly right-bearing (Figure 1(f)).

The filament channel in this model is represented by a sheared force-free field. As we go higher up into the corona we would expect the field to relax more to a potential field with height. Thus the higher up, the more transverse the field should be across the P.I.L. The relaxation time for the coronal field through a tearing mode instability would be typically a few days. When eruptions occur some energy will be lost but not all of it. The field that closes down is then seen as a dynamical loop system and loops that were not seen before are now lit up. If the field is relaxing towards a potential field with height (as Schmieder et al. (1996) found) then a clockwise rotation of the loops with height would occur for sinistral filament channels and a counter-clockwise rotation for dextral filament channels (Figure 1(f)). This is indeed what is seen in the observations. The arcade orientation must be consistent with the axial component of field in each channel and that is why there is a one-to-one correspondence between them.

4. Comparison with Previous Models

It is now useful to compare the method of formation described above with the models of Rust and Kumar (1995) and Priest, van Ballegooijen and Mackay (1996) to show how well the previous theoretical models compare with the present one deduced from observations.
Figure 2. Emergence west of the remnant region for cycle 21, showing (a) filament channel formation for dominant values of $\alpha$ in each hemisphere. Arrows give the direction of the horizontal component of field on either side of channel. (b) Transverse structure across the P.I.L. for minority values of alpha in each hemisphere. In each case the flux regions are not drawn to scale for each hemisphere.


In their model the authors describe the formation of a filament as the emergence of a horizontal, twisted flux rope. The flux ropes are produced by a global, subsurface velocity that twists the field. Subsurface differential rotation then acts on the flux
rope to give the correct axial component in each hemisphere. To support this they describe the barbs of pre-eruptive filaments as a filled helix and interpret the cancelling magnetic features seen during formation as the emergence of a U-shaped loop that lifts mass up into the corona. With each new U-loop emergence the total length of the emerged flux rope increases and helicity and mass are added to the filament. The model does not use shearing motions of surface fields or magnetic reconnections to form the filament.
While their scenario is appealing due to its simplicity, it does not fit the picture deduced from the observations. First of all, it does not include the role of the filament channel in the formation of the filament. For the type of filament considered in this paper, the filament channel is observed to be created by the emergence of a new region of flux in a sheared state. It is then the shear of this region that produces the sinistral/dextral nature and a dominant horizontal component of field in the channel long before the actual filament forms. The fibrils of the channel represent arches that connect regions of positive and negative flux, they do not represent emerging horizontal flux ropes. Secondly, cancellation of flux does occur in our model but it is interpreted differently. The cancellation is observed to occur between elements of the new and remnant regions. If it represented the emergence of a U-shaped loop that connected the cancelling fragments below the surface, the emergence of the loop would give a flux rope that stretched across the polarity inversion line and not along it. The emerging structure would be at a large angle to the dominant direction of field in the channel. In our opinion the cancellation is of two topologically distinct structures that are not necessarily connected below the surface because one structure had emerged many months before the other. These elements cancel out and in the process inject mass down the channel to form the filament. Reconnections also play an important role in the changing topology of the channel as the two flux systems converge. In our opinion the Rust and Kumar scenario does not fit well the method of formation seen here. However, our mechanism is for a specific type of filament formation so it does not rule out their process for other types of filament.

4.2. Priest, van Ballegooijen, and Mackay (1996)

The above authors put forward a dynamical model for the formation of filaments where the filament is maintained by the continual input of mass and magnetic flux from cancelling magnetic fragments. Subsurface differential rotation is used to give the correct axial component in each hemisphere. However, the build-up of this component in the chromosphere and corona is described in terms of small-scale emergences and reconnections along the polarity inversion line. These emergences and reconnections create the filament as a flux tube along the filament channel with cool plasma lifted up from the photosphere and chromosphere by each reconnection. The flux tube may have twist but it is not an essential ingredient. Continual reconnections are required to maintain the filament channel and filament.

This scenario also differs greatly from the one described in Section 2. To begin with, it describes the filament channel formation through the systematic alignment of small-scale fields that have emerged once subsurface differential rotation has acted upon them. In contrast, the mechanism of the present paper forms the channel by the emergence of a sheared region. The formation of the channel occurs with one large-scale emergence, rather than with a series of small-scale emergences as Priest, van Ballegooijen, and Mackay (1996) suggest. To form the filament, reconnections are required in both scenarios. In our model the new and remnant regions interact
with the remnant region forming a boundary on one side of the channel. The filament then forms after there is a large-scale cancellation of flux at the top of the channel. Thus the filament is formed by one large cancellation building up the mass and flux rather than by many small-scale cancellations. However, a process of many small-scale cancellations below the filament would be required to maintain it after it has formed. The method of Priest, van Ballegooijen, and Mackay (1996) may be more suitable for high-latitude filaments, such as those of the polar crown, where there are no clear large-scale emergences of flux. At high latitudes where the fields are weaker, small-scale emergences and reconnections may more easily orient the field to the sinistral/dextral direction in each hemisphere. However, at lower latitudes where the fields are stronger the process is less likely. This again emphasizes the point that several formation mechanisms may be operating on the Sun for the different classes of filament, rather than one method of formation for all of them.

5. Conclusion

In this paper a new scenario has been put forward for the formation of filament channels and filaments. It involves the emergence of new flux and its interaction with remnant flux. The key ingredient in the model is the net helicity of the new region that emerges. With the correct sign of helicity a filament channel and filament can form between the two regions; with the incorrect sign, transverse structure is obtained across the polarity inversion line and no filament can form. The observed hemispheric pattern of helicity then naturally leads to a hemispheric pattern for this type of filament, with dextral filaments dominating in the northern hemisphere and sinistral filaments in the southern hemisphere. This method, however, is appropriate for one specific type of filament, namely the intermediate or boundary filament. The formation of polar crown filaments is more likely to be caused by one of the alternative methods described in the introduction. However, the present model stresses that magnetic helicity can have an important effect on the hemispheric patterns of filaments a feature that should be included in future modelling.

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