ON THE COMPARISON OF FILAMENT CHIRALITY AND AXIAL MAGNETIC FIELDS DEDUCED FROM A FLUX TRANSPORT MODEL

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ABSTRACT

In this paper a comparison between the observed chirality of filaments and the axial component of magnetic field obtained from a flux transport model is carried out. The flux transport model considers the effects of differential rotation, meridional flows and diffusion acting on both photospheric and coronal fields. From this it is determined whether the hemispheric pattern of filaments originates from flux transport effects. The filaments considered formed over a four month period during CR 1724-1727 when there was little or no flux emergence. Along with the comparison a detailed analysis of a special case in which dipped inverse polarity field lines formed within a quadrupolar region during CR1724 is also described.

Key words: magnetic fields; filaments.

1. INTRODUCTION

The main observational properties of solar prominences have been known for many years. However, recently Martin et al. (1994) found a surprising hemispheric pattern. It was found that filaments are predominately dextral in the northern hemisphere and sinistral in the southern. A dextral/sinistral filament is one in which the axial magnetic field component points to the right/left when viewed from the positive polarity side. The organisational principle behind this orientation needs to be identified. In light of this van Ballegooijen et al. (1997) considered in detail whether the surface effects of differential rotation, meridional flows and diffusion could in fact create the correct axial component in each hemisphere. Using observed magnetic field distributions, they simulated the evolution of photospheric and coronal field under these effects, and predicted where filament channels would form. They found that equal numbers of dextral and sinistral filament channels were formed in each hemisphere in conflict with filament observations. However, the results of van Ballegooijen et al. (1997) are somewhat inconclusive because they only considered statistical relationships, and did not make detailed comparisons with observations of specific filaments. The aim of this paper is to go a stage further and use an observed magnetic surface distribution to consider the correlation of the model with the chirality of observed filaments at the precise observed location along the P.I.L. that the filament was observed. For this to be carried out a flux region in which there is little or no flux emergence is required as the model only considers the effects of surface flux transport. The model therefore assumes that the magnetic field of the filament originates from the surrounding corona. Such a flux distribution with little flux emergence along with a number of well defined filaments was found during the period of CR 1724-1727 in the Northern Hemisphere (Gaizauskas et al. 1999). In section 2 the flux transport model is applied to the observed magnetograms and the coronal axial field deduced from the model is compared with the chirality of the filaments. In Section 3 a detailed analysis of the formation of dipped inverse polarity field lines within a quadrupolar region in CR 1724 is given. The conclusions are given in Section 4.

2. COMPARISON OF MODEL AND OBSERVATIONS

During the period of CR 1724-1727 six filaments with well defined chirality were observed in ORSO Hα filtergrams during the development of a large switchback in the Northern Hemisphere. In the months previous to CR 1724 there was a large amount of flux emergence within the switchback however from CR 1724 onwards there was very little visible emergence. During this period flux transport at the surface extends the switchback in the east-west direction and pushes the flux from the active latitudes poleward. Over this period the evolution of the surface field of the switchback was well described by the surface flux transport model of van Ballegooijen et al. (1997) and by detailed account of the evolution of the flux can be found in Gaizauskas et al. (1999).

The observed chirality of the filaments is now compared with the axial component of field generated in the corona by the surface flux transport model. The model which is described in the paper by van Ballegooijen et al. (1997) includes the effects of differential rotation, meridional flows and diffusion acting

on both the photospheric and coronal fields. In order to carry out the comparison the corresponding synoptic chart magnetograms for each rotation are obtained from the NSO archive and used as the initial surface configuration. Since the maps only give the photospheric field the initial coronal field is assumed to be potential with a source surface at 2.5R⊙ where the field becomes radial. From the synoptic chart magnetograms the comparison is carried out in two distinct ways. In the first method the surface and coronal fields for each rotation are evolved for 15 days under the above effects and the axial field in the corona at the observed location of the filament is computed. After the field has been evolved the map is then reset to the next months synoptic chart, again with an initial potential field in the corona. By resetting the surface field each month a very accurate account of the surface distribution is obtained, but no memory of the previous evolution proceeds from one month to the next in the corona. Alternatively, in the second method the initial rotation of CR 1724 is taken with it’s assumed potential field. The surface and coronal fields are then evolved for the entire period of CR 1724-1728 (108 days) without resetting the surface or coronal fields. As the number of days proceeds beyond 27 discrepancies do occur between the evolved surface field and the observed surface field however the main large scale features of the switchback remain throughout the evolution. Again the skew along the appropriate part of the P.L.L. is calculated on the 15th day of each month but this time the measurements contain a memory of what occurred in previous rotations. Although the surface configuration is not as accurate as before the main features do still exist and the measurements give an indication of how the initial chosen coronal configuration used in method 1 can effect the result.

The results of the comparison for both of the methods can be seen in Table 1. The skew is calculated at a height of 10,000 km with the P.L.L. also calculated at this height. This height is chosen as it lies in the low corona where significant skew of the field must exist if surface effects are to create a filament channel (Schmieder et al., 1985). Also by calculating the skew at the same height as the P.L.L. it can be determined whether the field lines are dipped or not. Normal Polarity field lines denote arcades and inverse polarity field lines dips. However should be noted that in the present code the field is not evolved in a state of mechanical equilibrium. This unfortunately tends to lead to the diffusion of axial fields away from the P.L.L. and as a result it is unlikely that I.P. fields will be formed and maintained along the P.L.L. A more in depth study is presently being carried out which includes the feature of mechanical equilibrium as the flux is evolved. The fact that the field is not in a state of mechanical equilibrium may effect whether NP or IP polarity fields are obtained however it should not in any way effect the chirality of the field produced.

From Table 1 it can be seen that as well as calculating the skew for the evolved field the nature of the field (normal polarity - NP, inverse polarity - IP) is also given. For method 1 the correct chirality with inverse polarity dipped field lines was obtained for CR 1724, while CR 1726 gave the correct chirality with normal polarity field lines. The other four cases gave a skew opposite to what was observed. For the second method of comparison it can be seen that different results are obtained for some of the comparisons. For the second type of evolution, two out of the four filaments considered gave the same chirality as the observations, again one with inverse polarity field lines and the other with normal polarity field lines. Only four filaments are considered in this case since the polarity inversion line around which the filaments form in CR 1725 was too small to accurately calculate the skew. The results from both comparisons however show in principle that surface flux transport could explain the chirality of some of the filaments observed however not all of them. From that it therefore seems that the effects of differential rotation, meridional flows and supergranular diffusion cannot explain the hemispheric patterns of filaments alone.

One point that stands out from the table is that the initial chosen coronal configuration is very important in determining the skew of the field lines along the switchback. This can be seen by the difference in the results in the third and fourth columns in Table 1. Since there is therefore an uncertainty in the initial configuration this leads to an uncertainty to which comparisons are correct and which are not. Finally it is interesting to note that for CR 1724 the correct chirality of the field is obtained along with inverse polarity dipped field lines even though the model tends to diffuse inverse polarity fields away. The reason why CR 1724 gives the correct chirality with inverse polarity dipped field lines and is now considered.

### Table 1. Comparison between the flux transport model and the observed chirality of the filaments.

<table>
<thead>
<tr>
<th>CR</th>
<th>Observed Chirality</th>
<th>Evolved Method 1</th>
<th>Evolved Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1724</td>
<td>Dextral</td>
<td>Dextral (IP)</td>
<td>Dextral (IP)</td>
</tr>
<tr>
<td>1725</td>
<td>Sinistral</td>
<td>Dextral (IP)</td>
<td>N/A</td>
</tr>
<tr>
<td>1726</td>
<td>Sinistral</td>
<td>Sinistral (NP)</td>
<td>Weak (NP)</td>
</tr>
<tr>
<td>1727</td>
<td>Dextral</td>
<td>Dextral/</td>
<td>Sinistral (NP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sinistral (NP)</td>
<td>Sinistral (NP)</td>
</tr>
</tbody>
</table>

3. FILAMENT CHANNEL FORMATION IN CR 1724

In Section 2 a comparison between the observed chirality of filaments and the axial field component produced in the corona by a surface flux transport model was carried out. In all of the cases considered only one gave dipped inverse polarity field lines along with the correct observed chirality of the filament. This case is now considered in more detail to see why, it gives the correct skew with inverse polarity field lines when inverse polarity field lines are unlikely to form with this model.

3.1. EVOLUTION OF FLUX

The evolution of the surface flux distribution in the region of the switchback is now considered for CR
Figure 1. Evolution of surface flux and field vectors at a height of 10,000 km for the switchback in CR 1724. The evolution is shown at 6-day intervals where intensity level saturates at 20 G.
Throughout the period of evolution most of the flux cancellation in the field of view occurs between the two positive areas and the negative area in between them. This can be seen by the reduced intensity of the negative flux in Figure 1(g) compared to Figure 1(a). With this the two positive flux areas move closer together and become more apparent to one other.

The rotation of the field vectors at a height of 10,000 km as the surface and coronal fields are evolved can be seen in Figure 1(b), (d), (f) and (h) with the P.I.L. again plotted at a height of 10,000 km. The plots show a close up view of the location along the P.I.L. that the filament was observed. On day 6 (Figure 1(b)) the field vectors have no definite skew. By day 12 (Figure 1(d)), at the location of closest approach of the two positive areas a region of significant skew can be seen. The field vectors are of normal polarity and the skew is dextral. The skew of the field vectors is a result of the flux from the two positive regions countering each other and turning the field both northwards and southwards along the P.I.L.. The amount of skew continues to increase as more negative flux is canceled. On day 18 (Figure 1(f)) a region of strong dextral skew can be seen. Field vectors of normal polarity, inverse polarity and parallel to the P.I.L. can be seen. The field vectors that are of inverse polarity denote the dips and on either side of the dips there is a strong dextral axial component. By day 24 (Figure 3(h)) even more of the flux along the P.I.L. is of inverse polarity. However this time there is a mixture of both dextral and sinistral inverse polarity. The region of dextral skew exists at higher latitudes along the P.I.L. and the region of sinistral polarity at lower latitudes.

From this it can be seen that the formation of the region of dips is mainly a result of the type of quadrupolar flux configuration and not a result of the features considered in the model. However, filaments are commonly associated with this type of flux region (Tang 1987). Without the quadrupolar flux configuration the skew seen here with inverse polarity field lines could not be produced. Significant skew can only form after enough of the negative flux that lies between the two positive areas has been eaten away so that the two positive areas can interact with each other. This has the effect of turning the flux both north and south along the P.I.L. and gives the inverse polarity dipped field lines. Most of the flux is turned north along the P.I.L. to weaker fields and this creates the strong dextral skew. This type of flux interaction can only occur within a quadrupolar distribution where similar flux regions lie close enough together that interaction between them is possible. In the evolution the surface effects of differential rotation, meridional flows and diffusion act as the driver for the interaction of the flux regions. These effects drive the cancellation of flux and the subsequent interaction and reconnection of the flux that gives the inverse polarity. However these surface effects by themselves in this model could not produce the inverse polarity dipped field lines without the quadrupolar flux distribution. In the other cases considered in Section 2 the quadrupolar nature along the diagonal arm of the switchback disappeared after CR 1725 when the switchback became strongly extended in the east-west direction. When this happened flux areas of like polarity could no longer interact with each other to turn flux along the P.I.L. to produce dips. This is why dipped in-

Figure 2. Structure of field lines around the region of dips for Day 24.
of inverse polarity field lines. In Figure 2 the structure of the field lines can be seen in the dipped region for day 24. In the first plot Figure 2(a) the field lines can be seen at a height of 10,000km. The heights represent the height at which the field lines cut through the P.I.L. at the minimum of the dip. The field lines are all of inverse polarity and therefore dipped. All of the field lines that are dipped originate in the interior positive region and none come from the large positive region. There are roughly equal numbers of sinistral skewed field lines and dextral skewed field lines as the flux is turned both directions along the P.I.L.. By 60,000km (Figure 2(b)) the picture has changed by a large amount. The field lines that are dipped now connect from the large positive region to the large negative region, therefore the connectivity of the field has changed with height. The field lines now have the distinctive "S" type shape and with the increased height the skew of the field lines has decreased. The shape of the field lines is very similar to those found in Mackay et al. (1999). The length of the dipped region is similar to before but this time all of the field lines are of dextral type. Since the location and extent of the dipped region is similar to before again there are dextral field lines lying above sinistral ones. At a height of 120,000km (Figure 2(c)) no field lines pass over the P.I.L. in the inverse polarity direction. Most of them cut the P.I.L. in the normal direction but some have a strong left-bearing axial component. With further increase of height the shear of the field lines becomes less and more normal to the P.I.L.. In Figure 2(d) a side view of the field lines can be seen plotted at the heights given above. The lowest field lines have the deepest dips and the dips become shallower with height. Although the field lines shown in Figure 2 are not in force balance a very similar form for the dips at exactly the same location is found when linear force-free field (lfff) models are constructed from the surface distribution. In the lfff models the dips form for a negative value of alpha (\(\nabla \times B = \alpha B\)) and have the same two types of connectivity as shown above. This indicates that the formation of the dips at that location is not a result of the field not being in a state of mechanical equilibrium but a result of the type of flux pattern considered.

During the period of evolution, the structure and connectivity of the field lines changes by a large amount. Initially all of the field lines are normal to the P.I.L.. When enough of the negative flux is eaten up dipped field lines can form along the P.I.L. at the location of closest approach of the two positive regions. In general there are two separate types of connectivity for the dips. The first type is from the positive region on the right to the large negative region on the left and the second type is from the small positive region in the center to the same negative region. The formation of both types of dips can be seen in Figure 3. In Figure 3(a) the initial unconnected field lines for the first type of dips can be seen. Both are arch-like structures (bold field lines in Figure 3(c)). As the negative flux is eaten up along the P.I.L. these field lines reconnected with each other to give the "S" shaped structures seen in Figure 3(b), which clearly has a dip (light field line in Figure 3(c)). As further reconnections take place along the P.I.L. this field line is then lifted up. This type of reconnection dominates at the early stages until much of the flux that comes from the large positive region and

3.2. CONNECTIVITY AND STRUCTURE OF THE FIELD LINES

The connectivity and structure of the field lines at the location of the dips is now considered. From the initial stage of evolution to around day 12 the field lines were very transverse across the P.I.L. and showed little skew. From day 12 onwards skew along the P.I.L. begins to develop (Figure 1) and steadily increased until day 15 when the first inverse polarity field lines were found. By day 18 there was a significant amount

Figure 3. Diagram showing the two types of connectivity of the field lines that reconnected.
connects to the negative region gets eaten up. After most of it has been eaten up the second type of reconnection then takes over and that is why there is a changing connectivity of the field with height and time. The initial unconnected field lines for the second type can be seen in Figure 3(d). Again as more negative flux along the P.I.L. gets eaten up, reconnections take place to produce the field line shown in Figure 3(e). The vertical structure of both sets of field lines can be seen in Figure 3(f) where again the bold field lines are the unconnected ones and the dips in the reconnected field lines can be clearly seen.

The vertical structure of the dips is such that low down there are strongly skewed inverse polarity field lines. As height increases the magnitude of the skew decreases and with this the dips become shallower. The dips then translate onto very flat field lines that lie axially along the P.I.L. above the dips and then onto normal polarity arcades that have little skew. The connectivity of the dips also changes with height as a result of the different types of reconnections taking place. The structure of the dips is very similar to that found in Mackay et al. (1999) for a linear force-free field.

4. DISCUSSION

In this paper the origin of the hemispheric patterns of filaments has been considered. A comparison between the chirality of filaments and the axial magnetic field component created in the corona by a surface flux transport model has been carried out. The model considers the effects of differential rotation, meridional flows and diffusion on both surface and coronal fields. It was found that the model could only explain the chirality of a few of the filaments but not the majority of them. Since it could only explain the chirality of a few of the filaments this suggested that effects other than those of surface flux transport resulted in the origin of the filaments axial field.

One feature which is not included in the present model which could strongly effect the comparison is the helicity with which flux regions emerge. Petrov et al. 1995 showed that in the northern/southern hemisphere active regions have predominately negative/positive helicity. Since this provides a preferential turning of the field in each hemisphere if this was included in the initial configuration the results of the comparison could be significantly altered. However due to the simplicity of the model, such a feature could not be included here. It will however be important to include such a feature in future modeling. This is now being investigated using a more detailed model which is described in the paper by van Ballegooijen (1999). However from the results above it can be seen that magnetic flux transport by itself probably cannot explain the chirality of filaments even though it describes well the movement of the surface flux. Therefore the hemispheric pattern of filaments may be a result of a complex interaction between the surface effects and the initial helicity of the corona field.

From the above discussion it can be seen that if the origins of the hemispheric pattern of filaments is to be identified then much more detailed and complicat-

ed models need to be constructed. The simple model above does show in principle how dipped inverse polarity field lines can be produced within a quadrupolar flux distribution as a result of interactions within it. In a quadrupolar flux distribution like polarity flux regions lie close enough together so that there is a strong interaction between them. Magnetic flux transport can then act as a driver for cancellation of flux between the regions. The cancellation, strong interaction and subsequent reconnection of the field can then produce inverse polarity dipped field lines even when the model tends to diffuse these fields away. It is very interesting to note that the dipped inverse polarity field lines formed at the exact location of the filament and it was well observed surface motions that lead to their formation. Thus a possible mechanism for producing inverse polarity dipped field lines within a quadrupolar flux region from well observed surface flows has been identified (see Antiochos et al. 1994). On the sun it is possible that a number of different mechanism act at different locations to produce all of the different types of filaments. This may be one of these methods. However filaments that form outside a quadrupolar region would have to form by another method since this method is particular to the quadrupolar region. The process described above may however occur naturally within quadrupolar flux regions. It shows how realistic surface motions could lead to the formation of dipped inverse polarity field lines within a specific flux configuration.

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REFERENCES

van Ballegooijen, A.A. 1999, Geophysical Monograph 111, 213