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On the nature of extended EUV filaments

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Abstract. This paper describes the properties of extended EUV filaments and the theoretical modelling of them. We summarise the general aspects of the depression of EUV-line emission and give an interpretation of recent filament observations in transition-region and coronal lines. The EUV filament was found to be located relatively high in the corona (at least 20 000 km above the solar surface) and this requires an MHD scenario alternative to the parasitic-polarity model of Aulanier & Schmieder (2002). Here we present a new idea for the support of cool gas in the magnetic arcade of a prominence which is capable of explaining both wide and vertically extended EUV filaments. Our mechanism is based upon the twisting of individual flux tubes, similar to the one which was suggested by Priest et al. (1989). Finally, the consequences of this new model are discussed.

Key words. Sun: filaments – Sun: magnetic fields – Sun: UV radiation

1. Introduction

Recent coordinated observations by SOHO and THEMIS have allowed a detailed study of the relation between EUV and Hα filaments (Heinzel et al. 2001; Schmieder et al. 2003). These authors have analysed one filament in great detail. Their main result is that the Hα filament and the EUV filament are well aligned with each other, but the EUV filament is considerably wider. The Hα filament has a width of 10–20 arcsec, while the EUV counterpart has a width of 50–100 arcsec. Schmahl & Orrall (1979) suggested that one can interpret the dark EUV filament as being due to Lyman continuum absorption of the transition-region or coronal lines by overlying cool neutral hydrogen gas. This interpretation is further supported by the observations of Chiuderi Drago et al. (2001) who found that the filaments are dark for lines below 912 Å and almost invisible for lines above 912 Å.

Therefore, extended dark EUV filaments require that there exists a region of extremely large width containing cool neutral hydrogen. The fact that very large areas are filled with cool material represents a great challenge for any theoretical modelling attempt since the typical pressure scale heights of this cool material are only 100–300 km. Therefore, all individual cool structures can only have horizontal extensions along field lines amounting to typically less than 2000 km. This then implies that one needs a large number of such small structures to cover the entire area. One also has the constraint that the vertical column density of all the cool material in the extended EUV region has to be on one hand small enough that the region is transparent in Hα but on the other hand sufficiently large that it is opaque in the Lyman continuum (see Heinzel et al. 2001).

In this paper we shall discuss several new aspects of theoretical modelling of extended EUV filaments. In Sect. 2 we describe the EUV absorption and blocking model, Sect. 3 discusses the interpretations of the EUV observations and summarises the properties of the parasitic polarity model developed by Aulanier & Schmieder (2002). In Sect. 4 we present our idea how a collection of twisted flux tubes located in a magnetic arcade can also produce extended regions of EUV absorption. Finally, in Sect. 5 we discuss the consequences of this modelling approach.

2. Depression of EUV-line emission

Extended structures around prominences (filaments) have been observed in EUV lines shortward of the Lyman continuum (912 Å), both on the solar limb and the disk. In the present study we concentrate on disk observations. In this case we have to distinguish between two principally different kinds of EUV lines, namely coronal lines (formed at coronal temperatures above 10^6 K) and lines of species at lower ionisation stages emitted mainly in the transition region. These lines which are emitted below the cool filament are simply absorbed by the Lyman continuum and thus one can fully apply the absorption model to explain the EUV-line depression. However, in the case of hot coronal lines we have to take into account the coronal heights at which they are emitted and the heights at which the cool filament plasma can absorb and/or block the coronal radiation. In the following we will consider EUV lines studied by Heinzel et al. (2001) and Schmieder et al. (2003).

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2.1. OV transition-region line

We assume that the brightness depression observed in the OV transition-region line is entirely due to absorption by Lyman continuum. The Lyman continuum optical thickness at the wavelength of a EUV line is given by

$$\tau_\lambda = -\ln\left(\frac{I_{\rm fil} - I_{\rm fg}}{I_{\rm bg}}\right), \qquad (1)$$

where $I_{\rm fil}$ is the intensity of the EUV filament, $I_{\rm bg}$ the intensity of the background under the filament (taken to be the quiet-Sun intensity $I_{\rm QS}$ for OV) and $I_{\rm fg}$ is the intensity of the foreground, here assumed to originate in the prominence-corona transition region (it is measured at the darkest central parts of the filament where the background radiation is fully absorbed). To convert τ_λ determined at the position of an EUV line to that at 912 Å (Lyman continuum head), we use the well-known λ^3-dependence for hydrogen continua opacity and get factors 0.322 for MgX, 0.329 for OV and 0.186 for SiXII. For one particular filament Heinzel et al. (2001) and Schmieder et al. (2003) obtained values between about 3 and 10 for τ_{912}. We shall discuss this filament in the next subsection.

2.2. MgX and SiXII coronal lines

There are three possibilities how to interpret the brightness depression in the coronal lines: (i) by presence of a void around the filament, i.e. the missing hot plasma, (ii) if the filament is located relatively high in the corona compared to the scale-height of the coronal line emission then a large fraction of coronal radiation emitted below it can be absorbed by the Lyman continuum, and (iii) the filament is rather extended in height and its volume effectively blocks the coronal radiation. A combination of these three effects can take place. In order to explain quantitatively the MgX and SiXII measurements, one has to construct a model which takes into account all these mechanisms. The situation can be simplified by assuming that even if there is any kind of a void, this void (or coronal cavity) extends over an area much larger than the EUV filament. Actually the observed filament has a remarkably similar shape in both transition-region as well as in coronal lines which indicates that the depression can not be due to a void which would hardly outline the EUV filament in detail. Under such conditions, our so-called "quiet-Sun" intensity $I_{\rm QS}$ is just the mean intensity in the observed field-of-view outside the filament and represents the intensity of the corona surrounding the filament. In the case of this particular filament the measured values of $I_{\rm QS}$ are larger than those reported by Brooks et al. (1999) for the quiet Sun and therefore they in fact rule out the presence of any coronal void (here we keep the notation of $I_{\rm QS}$ for this intensity in order to be consistent with the earlier papers).

In what follows we will use the results of a complex modelling approach which is worked out in Heinzel et al. (2003). The basic idea is to use the value of τ_{912} derived from the OV line and compute the absorption and blocking consistently in the two coronal lines of MgX and SiXII which have different scale-heights. For each line we use Eq. (1), where now $I_{\rm fg} = [1 - f(h'')]I_{\rm QS}$ and $I_{\rm bg} = f(h')I_{\rm QS}$. The function $f(h)$ describes the variation of the coronal emissivity with height and it has the approximate form $f(h) = 1 - \exp(-h/H)$, where h is the height in the corona and H is the scale-height of the coronal emission. From Eq. (1) applied to the two lines, it is poissible to obtain values for h' (bottom of EUV filament) and h'' (top of EUV filament), by using an iterative method proposed in Heinzel et al. (2003). In the case of a quiet-Sun corona the scale-heights for MgX and SiXII lines can be obtained from the observations of Fludra et al. (1999) (their Fig. 2), by using the Abel transform.

Applying this procedure to MgX and SiXII intensities observed by Schmieder et al. (2003) (for typical line intensities see their Table 1), we have arrived at following conclusions: The data can not be interpreted in terms of quiet-Sun scale-heights for both the MgX and SiXII line, no solution is obtained with the iterative method. This is because the filament is located in an active region (see Aulanier & Schmieder 2002) where the scale-heights can be quite different from those of the quiet Sun. In such a case one can use the results of Sterling et al. (1999) which show that in an active region, the MgIX scale-height is similar to the quiet-Sun scale-height of MgIX derived from Fludra et al. (1999), but for hotter lines the emission is much more concentrated towards the limb. Therefore, we took in our analysis H for MgX from Fludra et al. (1999) (about 30 000 km) and using $f(h)$ we computed the height at which $I_{\rm fg}$ can be obtained. Then using this height (about 45 000 km) and $I_{\rm fg}$ for SiXII, we computed the scale-height H for this line. It is considerably reduced compared to the quiet-Sun value (about 42 000 km compared to 85 000 km), which is consistent with the findings of Sterling et al. (1999). Now using this new H for SiXII, we were able to obtain a plausible solution for heights h' and h'' within the EUV filament extension. For τ_{912} in the abovementioned range one gets h' between approximately 25 000 and 40 000 km, while h'' varies from 30 000 to about 60 000 km. The heights are generally lower for larger τ and the difference between the two heights (i.e. the geometrical thickness of the EUV structure) also decreases for higher values of τ.

These structures extended in height must have temperatures and gas pressures (densities) which will lead to a relatively small τ_{912} as determined in Schmieder et al. (2003). Typical values are T around 10 000 K and p around 10^{-2} dyn cm^{-2} (Heinzel et al. 2003).

The finding that the EUV absorbing structures are located at relatively large heights above at least 20 000 km posses the question what is the origin of such structures. Aulanier & Schmieder (2002) used the same filament observations as Heinzel et al. (2001) and Schmieder et al. (2003), but they concentrated on dark EUV features seen in the transition-region line OV "because it displayed mostly the same dark features as in other recorded lines ..., but with a better contrast". On one side, using only the OV line, one can fully apply the absorption model even to rather low-lying dips of Aulanier and Schmieder. However, the observed coronal lines require a cool plasma much more extended vertically. This problem has led us to consider an MHD model which is alternative, or complementary, to that of Aulanier & Schmieder (2002).

3. Extended EUV filaments and their interpretation

These new observations present a great challenge for the theoretical modelling of quiescent prominences. The width of the Hα filament is only around 10–20 arcsec, and this already includes all possible projection effects which can amount to 5–10 arcsec! Therefore, Hα prominences are in general rather narrow as is suggested by the theoretical magneto-hydrostatic models. The same projection effect as seen in Hα can also somewhat widen filaments observed in EUV lines, but such an effect is by far too small to explain the new observations.

The EUV observations require the existence of extended low temperature regions of moderate column density. The optical depth in the Lyman continuum is considerably larger than that in Hα. According to Heinzel et al. (2001) one has for a given column density and taking a typical temperature of $T = 8000$ K

$$\frac{\tau_{912}}{\tau_{\mathrm{H}\alpha}} \approx 60\text{–}100, \tag{2}$$

where $\tau_{\mathrm{H}\alpha}$ and τ_{912} are the optical thicknesses in Hα and in the Lyman continuum, respectively. This means that the column density which produces an optical depth one in the Lyman continuum can be a factor 60–100 smaller than that which produces the same depth in Hα. For the EUV lines considered, Heinzel et al. (2001) give for the optical depths ratios $\tau_{\mathrm{l}}/\tau_{912} = 0.2\text{–}0.3$, where τ_{l} is the Lyman continuum optical thickness at the wavelength of the EUV line. This will lead to $\tau_{\mathrm{l}}/\tau_{\mathrm{H}\alpha}$ in the range of say 10–30.

This then means that the column densities which are responsible for the EUV absorption can be by this factor smaller than those in the Hα filament. Therefore, for inclined magnetic field lines the EUV filament can be several pressure scale heights wider than the Hα filament. But for typical field line inclinations this widening effect will be less than 10 arcsec and therefore can also not explain the large width of the EUV filament (see also the discussion given in Aulanier & Schmieder 2002).

For these reasons Aulanier & Schmieder (2002) have developped a model which is based upon the presence of parasitic polarities inside an otherwise rather uniform bipolar region. Such fields can have many low-lying (below 4000 km) magnetic dips which extend to large distances from the central filament and they can therefore produce extended EUV-absorption features.

4. Twisting of magnetic flux tubes

In the following we shall present a possible alternative to the model described above by which extended cool structures located higher in the corona can be explained. In our approach the EUV filament is directly connected with the magnetic arcade of the prominence. We base our modelling on the 2D thread configuration discussed in Heinzel & Anzer (2001). First we shall briefly summarise the relevant properties of this thread model.

The basic idea of the thread model is that the prominence has very pronounced fine structures. In our previous paper we have modelled this by assuming that there are many vertical threads of high density. These threads are kept in magnetohydrostatic equilibrium. In the vertical direction magnetic tension balances gravity and in horizontal direction along the prominence axis magnetic and gas pressure are in equilibrium. For the present modelling the details of this equilibrium are not important and we shall therefore not discuss them here. But we want to point out that for simplicity we only consider here configurations without magnetic shear.

The model of Heinzel & Anzer (2001) describes the prominence itself and its immediate neighbourhood. At larger distances the magnetic field has to connect to that of the coronal arcade which actually produces the prominence as a whole. Therefore, the field has to bend over to reach the solar surface. This then has interesting consequences for the topology of the magnetic field: field lines which go through the threads will have very pronounced dips (depending on the amount of mass loading) in each thread and two peaks at both sides of the prominence. The field lines which penetrate the inter-thread region are flat near the prominence and gradually bend downward, having only one peak in the prominence plane. All these peaks have horizontal parts where cool material could be supported. But these configurations are unstable w.r.t. horizontal perturbations. Therefore, these simple configurations cannot supply any additional cool mass outside of the Hα filament.

But there is the possibility of field line twisting to achieve additional dips. This mechanism was first proposed by Priest et al. (1989). They considered one single gigantic magnetic flux tube of diameter 60 000–100 000 km and a total length around 200 000 km. If this entire flux tube is now twisted then magnetic dips will be formed in a large part of the region (basically in most of the lower half of the flux tube). In their model this region was considered as the place of the prominence formation and its support. Here we shall consider a somewhat different situation: we take the arcade as the sum of many individual narrow flux tubes. Then each of these flux tubes will be twisted by the rotational motion occurring in the photosphere. Depending on the amount of twist and the curvature of the flux tubes more or less extended regions with dips will develop. In the following we shall describe this aspect more quantitatively.

For simplicity we consider the case of the inter-thread field which has only one peak first. We assume for this that the flux tube is described by a part of a circle with radius R and a height of its apex above the photosphere h; then the width of the arcade is given by

$$D_{\mathrm{a}} = 2\sqrt{h(2R - h)}, \tag{3}$$

and the length of the tube is

$$l = 2R \arccos\left(\frac{R-h}{R}\right)\cdot \tag{4}$$

For the cross-section of the flux tube we take a circle with radius r. The field of the twisted flux tube is given by the components $B_{\|}$ which is along the tube and B_{ϕ} which is the azimuthal component.

The condition that there exists a dip is the vanishing of the total vertical field component. This then implies

$$B_{\|} \sin\psi = B_{\phi} \sin\phi \cos\psi, \tag{5}$$

where ψ is the inclination of the flux tube with the horizontal plane and ϕ is the azimuthal coordinate measured from the vertical downward direction. This gives us the condition for the existence of a dip

$$B_\phi \geq B_{||} \tan\psi. \tag{6}$$

We denote by x_1 the distance of the dip position from the symmetry plane of the arcade. This distance can be related to the inclination angle ψ by

$$\tan\psi = \frac{x_1}{\sqrt{R^2 - x_1^2}}, \tag{7}$$

which then leads to

$$B_\phi \geq B_{||} \frac{x_1}{\sqrt{R^2 - x_1^2}}\cdot \tag{8}$$

This condition specifies the amount of twist (i.e. the ratio $B_\phi/B_{||}$) which is necessary in order to produce a dip at the position x_1. To obtain this amount of field line twist one has to turn the foot points of the tube n times around, where n is given by the relation

$$n = \frac{lB_\phi}{2\pi r B_{||}}\cdot \tag{9}$$

With Eqs. (4), (8) and (9) one obtains the condition

$$n \geq \frac{x_1}{\sqrt{R^2 - x_1^2}} \frac{R}{\pi r} \arccos\left(\frac{R-h}{R}\right)\cdot \tag{10}$$

Therefore, the extension of the observed dark EUV region directly determines the number of turns of the flux tube which are required in this particular type of model.

We shall now select one specific set of parameters to describe our model which seems reasonable with respect to the observations. For this we take $R = 100\,000$ km, $h = 30\,000$ km, $r = 2000$ km. This gives us $D_a = 140\,000$ km and implies

$$n \geq 13 \frac{x_1}{\sqrt{R^2 - x_1^2}}\cdot \tag{11}$$

From this relation we obtain the values $n \geq 1.3$ for $x_1 = 10\,000$ km, $n \geq 2.6$ for $x_1 = 20\,000$ km, $n \geq 4.1$ for $x_1 = 30\,000$ km and $n \geq 5.7$ for $x_1 = 40\,000$ km. This result has direct consequences for our modelling: if the EUV filament were only 20 000 km wide, one full turn of the flux tube would be sufficient, but if it is 60 000 km wide one needs around 4 full turns.

This aspect is very important for the stability of these twisted tubes. Such thin flux tubes with a large amount of twist are usually kink unstable. The only possible stabilising mechanism is flux freezing at the end points of the flux tubes. It has been found recently by Mikic et al. (1990) that a maximum amount of twist of 2.4 rotations can be stabilised in this way. From these estimates we conclude that a rather large fraction (but not the full region) of the observed EUV filament could be explained in this way.

We shall now turn to those flux tubes which pass through the prominence threads. In this case one has two peaks located symmetrically w.r.t. the prominence and displaced by the distance Δx from the Hα filament. One can now apply the same analysis as above to this new geometry, but with different values for the length of the flux tubes, the radius of curvature and the position of the peaks. All these quantities are theoretically not well determined. To obtain them one would in principle have to solve the full prominence-corona arcade equilibrium problem. Here we shall instead only give some simple estimates which are rather plausible. We suggest the following values: displacement of the peaks 20 000 km, a flux tube length of 2/3 of the previous case and radius of curvature 50 000 km. Taking these values and $n' = 4.0$ we can calculate a new distance $x_1 = 15\,000$ km. Therefore in this case the maximum distance of the dips from the prominence amounts to $\Delta x + x_1 = 35\,000$ km and thus gives a total EUV filament of 70 000 km, which is similar to the observed value.

Taking the two results together we conclude that nearer parts of the EUV filament are produced by flux tubes passing through inter-thread regions and the more distant ones are due to flux tubes which go through the threads. Therefore an area of total width 70 000 km can be covered by these dips and thus allows the formation of extended cool condensations.

5. Discussion

The configuration presented in the previous section is based upon a magnetic arcade which consists of an ensemble of many twisted flux tubes. Such a configuration will be necessarily quite complex and it is at present impossible to compute the resulting equilibrium explicitely. For this reason we only want to point out here that as long as the twisting is sufficiently small all the twisted flux tubes should be able to relax to a neighbouring equilibrium. The amount of twist required in such models leads to ratios $B_\phi/B_{||}$ of typically less than 0.2. This now implies that the additional magnetic energy associated with the twisting will be less than 10% of the total energy. Therefore, on energetic grounds one will expect the existence of such equilibria. In the present paper we have studied the stability of the model only for the idealisation of straight cylindrical flux tubes without mutual interaction. Assuming photospheric line – tying the stability of these tubes can be specified. Curved flux tubes with varying cross section will not exactly be represented by such an approach. But for sufficiently large aspect ratios the stability Eq. (11) should give a reliable estimate of the maximum twist of these flux tubes.

The modelling will be further complicated by the fact that the observations often show strong shear in prominences and that the field of many prominences is of inverse (I) polarity. The shearing of field lines has several consequences: it stretches them and also makes them expanding in the vertical direction. Both effects will therefore lead to an increase of the length of the flux tubes and therefore make the configuration less stable for any given ratio of $B_\phi/B_{||}$. On the other hand, if the shearing is concentrated as was assumed by DeVore & Antiochos (2000) then a rather large portion of the field will be very flat and a smaller amount of twist will be sufficient to produce the dips. From these considerations we conjecture that even strongly sheared arcades can have large enough regions of dips to explain the observations.

The consequences for inverse polarity configurations are strongly model dependent. We shall discuss this aspect on the basis of two different classes of models. The first one is that of an arcade which is produced by a quadrupolar photospheric flux distribution. The simplest configuration of this type was given by Anzer (1990). Then the field with inverse direction lies above a neutral point and the field lines have one central dip and two neighbouring peaks. Such a field is very flat over a large area and therefore a small amount of twist can produce the required effect. This means that such a model will work even better than a simple arcade.

The situation, however, is less favourable if one uses a giant twisted flux rope for the basic configuration (Priest et al. 1989; van Ballegooijen & Martens 1990). In this case one will have a hierarchical structure with many small twisted flux tubes which generate the giant rope. Then all these flux tubes will be considerably longer than in a simple arcade; the increase in length will typically be of the order of a factor 3–5. This reduces the stability of the configuration tremendously and therefore magnetic dips may only exist near the mid-plane of the large rope. In this case it seems doubtful whether or not the twisting mechanism can produce sufficiently extended EUV filaments.

Both the configurations of Aulanier & Schmieder (2002) and the ones considered here can reproduce the observed extended EUV filaments. But the two models give different predictions which could be tested by observations:
The most pronounced difference is the height of the absorbing dips. In our model the twisted flux tubes are present over the entire height of the magnetic arcade. They are distributed randomly over this whole region and fill only a small fraction of the volume. Such a situation can be simulated by assuming that all the absorbing material is concentrated in a layer which is placed at mid-height in the arcade. This mean height is then typically between 15 000 km and 30 000 km. This is also consistent with the observational results presented in Sect. 2. On the other hand, all parasitic polarity dips in the model of Aulanier & Schmieder (2002) are located below 4000 km. This will have very important consequences for the absorption model: (i) All lines which are emitted in the transition region will be absorbed in the same way in both models, because their emission occurs always below the absorber, no matter how low this layer is located; (ii) All the coronal lines will behave completely differently. In our model a sizeable fraction of the coronal radiation is emitted in a region below the absorber and therefore a large amount of radiation can be absorbed, or blocked. On the other hand, in the Aulanier and Schmieder model there is no room for a corona below the absorber, the entire corona is above it. This means that no darkening should occur in this model for hot lines, unless some peculiar depletion of coronal-line emissivity occurs almost exactly above the OV filament region. Under these circumstances one would have to assume the existence of a coronal void around the prominence which would be responsible for the darkening of the coronal lines. Such coronal voids (or cavities) overlying quiescent prominences have actually been observed during solar eclipses (Koutchmy et al. 1994; November & Koutchmy 1996) and their dimensions are of the right order (50 000–100 000 km). But at present there is no general information how common these voids are in typical prominence-corona configurations. Moreover, the corona around the filament used for this study was much brighter than the quiet-Sun corona and this is due to the presence of an active region. One way to decide the question about voids would be to observe EUV filaments in coronal lines both below 912 Å and above it. In the case of a void all the lines should behave in the same way; but if a cool absorber is mainly responsible for the filament then the lines below 912 Å should show the dark filament, whereas those above 912 Å will be affected only by the weaker blocking effect.

The interpretation of the filament in terms of a coronal void also faces the following problem: It has been noted by Aulanier & Schmieder (2002) that the morphology of the dark structures observed is strikingly similar in the lines emitted in the transition region and in the corona. This fact strongly suggests the same absorption mechanism (together with some additional blocking of the coronal lines) for the formation of the dark features in all these lines, as actually found by Heinzel et al. (2001) and Schmieder et al. (2003). If this conclusion is correct one inevitably has to assume that the cool material has to be located high enough in the corona.

There will be also a geometric effect resulting from the different heights of the absorber. If the top of the absorber is lower than the height of the Hα prominence then parts of the limbward region of the EUV filament will be obscured by the Hα filament. Therefore a systematic asymmetry w.r.t. the Hα filament should be observed when the filament is sufficiently close to the limb. This effect will be very pronounced for the model of Aulanier & Schmieder and rather weak in the case of our model.

There is yet another difference in the two models but its observational consequences are less clear: in our model the EUV filament is directly connected with the magnetic arcade of the prominence. In the model of Aulanier & Schmieder the dips result from parasitic polarities which are embedded in a rather uniform background field. In this case the association with the prominence is not so obvious. On this basis one would expect that the relation between the Hα filament and the EUV filament will be more pronounced in our model than in that of Aulanier & Schmieder. But it seems difficult to quantify this prediction under the given conditions.

An important point of interest has also been mentioned by Heinzel et al. (2001) and Aulanier & Schmieder (2002). It has been suggested that the material which is present in the EUV-absorption region might contribute to the high density part of coronal mass ejections (CME). Since in our model this gas is distributed over the entire arcade it can be easily ejected together with the erupting prominence.

In order to obtain a better idea which of the two models is more appropriate, and under which conditions, we will need more systematic studies of several different Hα–EUV filament complexes; this should be an interesting task for future ground based and space observations. The filament should be traced until it reaches the limb and then complementary diagnostics will become possible by using various emission lines covering a wide range of opacities. However, a common problem with all such limb observations is the presence of projection effects.

Finally, we want to point out again that due to the complexity of all such configurations it is not possible to construct full magnetic equilibrium models and it is even more difficult to find any exact stability conditions for these configurations. But nevertheless we think that the simple physical arguments given above indicate that the proposed configurations can exist. For this reason we have suggested the twisting mechanism as a plausible alternative to the parasitic polarity dip model of Aulanier & Schmieder (2002) for the explanation of extended filaments observed in EUV lines.

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