MAGNETIC DIPS AND THE PHYSICS OF QUIESCENT PROMINENCES

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ABSTRACT

This paper discusses the recent developments of prominence modelling. The basic aspect of our discussion is the presence of magnetic dips in all the models. We first show that "initial" dips are needed for prominence formation and stability. We then give some typical examples for different field configurations with dips. Next we discuss those dips which are required for prominence support. We present both 1D (slab) and 2D (thread) models. In addition the problem with the theoretical modelling of extended EUV filaments is described. Then we explain the difficulties with the observational confirmation of dipped structures. We also comment on a model which suggests that equilibria can be obtained for configurations without dips and finally we summarise the most relevant aspects.

Key words: solar prominences: theoretical models, magnetic configurations.

1. INTRODUCTION

This review is based upon the idea that quiescent prominences are supported by magnetic fields. Other, more exotic support mechanisms, as for example Alfven waves, will not be considered here. The paper is not intended to be a review article in the classical sense. Instead I try to focus the view on some of the more recent developments in prominence modelling. The discussion of the different theoretical aspects will be given by selecting the typical representatives for each class of models and for this reason my presentation will not be exhaustive. Therefore I have to appologise to all those authors who are not mentioned here.

Let me first give some general physical properties of quiescent promineces. They can be considered as cool, geometrically thin sheets of high density which stand approximately vertical on the solar surface. The typical parameters can be characterised by: length around 100000 km, height around 50000 km, thickness around 1000 km, central temperature 6000 K, central density 3 10^{-13} g/cm^3 and a magnetic field around 3 G. All these numbers give only some mean values and there is a large scatter in all of them, both from prominence to prominence and also in each individual prominence. Here the value for the thickness is based upon theoretical estimates because the much larger values derived from filament observations will in most cases be due to projection effects. In addition prominences are not really uniform sheets, they are actually composed of many fine-structures of different types: extended threads which can have different orientations, and also blob-like features.

Prominences are usually located along a polarity inversion line of the magnetic field where the vertical component of the photospheric field changes sign. For shortness - but somewhat misleading - this line is often called "neutral line". An interesting feature of quiescent prominences is their field topology in particular the relation between photospheric and prominence field directions. In some cases the field emerges on one side of the prominence, penetrates it and enters the photosphere on the other side. This configuration represents a simple arcade and the field is of "normal" or N- polarity. If it has opposite orientation one calls it "inverse" or I- polarity. Prominences of I-polarity were first discovered by Leroy et al. (1984). A detailed statistical analysis by Bommier & Leroy (1998) showed that a large majority of quiescent prominences have actually I-polarity.

It is widely accepted that this magnetic field provides the support for the prominence. The supporting Lorentz force is given by

$$\mathbf{f}_L = \mathbf{j} \times \mathbf{B}, \qquad (1)$$

with

$$\mathbf{j} = \frac{1}{4\pi}\, curl\, \mathbf{B}. \qquad (2)$$

The geometry of the magnetic field is of great importance for the modelling of prominence equilibria. In particular the question whether the field has dips or not is crucial for all prominence models. In the following I shall therefore discuss the existing models in terms of their magnetic dips.

2. MAGNETIC FIELD CONFIGURATIONS

The magnetic field in the central parts of prominences has to be horizontal in order to produce a purely vertical Lorentz force. This implies that the field in the neighbourhood will be either curved upward - have a dip - or curved downward - have a peak (the more hypothetical case that the field has an inflection point, i. e. is curved upward on one side and downward on the other, will be discarded here).

Any curved magnetic field produces a tension force which is given by

$$f_t = \frac{B^2}{4\pi R}, \tag{3}$$

where B is the magnetic field strength and R the radius of curvature of the field lines. In the case of equilibrium this tension has to be balanced by some other force. As a next step we shall discuss the two extreme cases for such an equilibrium.

2.1. Dips in coronal fields

The corona is in general a low-β plasma, where β denotes the ratio of gas pressure to magnetic pressure. Since also the gravitational force of the tenuous corona is negligible the magnetic field has to be approximately force free. Therefore under these circumstances the tension has to be balanced by a gradient of the magnetic pressure. Then one has

$$\frac{B^2}{4\pi R} = \frac{B^2}{8\pi \Delta z}, \tag{4}$$

or

$$R = 2\,\Delta z, \tag{5}$$

where Δz is the typical vertical scale for changes in B^2. In coronal arcades one can take $\Delta z = 50000$ km as a typical value, which leads to $R = 100000$ km. From this result one can draw the conclusion that these "initial" dips are extremely shallow.

2.2. Dips resulting from the weight of the prominence

Once a prominence is fully developed the weight of it can distort the original force free coronal field considerably. In this case the equilibrium will be given by the following equation:

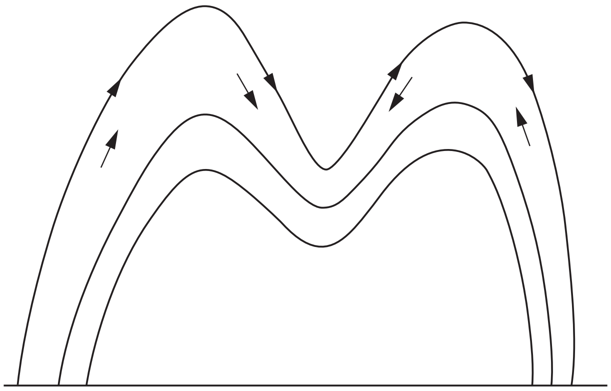

Figure 1. Sketch of a magnetic field configuration with dips, arrows indicate the associated syphon flow. After Pikel'ner (1971).

$$\frac{B^2}{4\pi R} = \rho g. \tag{6}$$

Note that under these circumstances the effects of the magnetic pressure can be neglected. If we take $\rho = 3\,10^{-13}$ g/cm^3 and $B = 3$ G we obtain for the radius of curvature $R = 900$ km. This value is two orders of magnitude smaller than the one which we had derived for the "initial" dips. Therefore one can conclude that the final dips are in general much more pronounced than the initial ones.

3. MODELLING OF MAGNETIC DIPS

3.1. "Initial" dips: motivation

The theoretical modelling of prominences requires the presence of these "initial" dips for the following two reasons: for the formation of prominences and also for their stability.

Several different mechanisms for the formation of prominences have been proposed.They can be classified as follows:

I. Syphon flows

This idea was first suggested by Pikel'ner (1971). He considered a magnetic flux tube with a dip at its top. If there is a large enough positive pressure difference between the chromosphere and the center of the dip then a syphon flow will drive material into the dip where it can accumulate. A schematic picture of this kind of flow is shown in Fig. 1.

II. Injection

A different mechanism for prominence formation has been studied by Poland & Mariska (1986). They assumed that chromospheric material will be shot upward along magnetic field lines. If this field has sufficiently deep dips the gas can be trapped in this potential well and thus lead to a prominence.

III. Condensation

Antiochos et al. (1999) have developed a numerical model which is based upon the existence of thermal condensations in the corona. They considered one very long flux tube which has a shallow dip at the top. They also assumed a heating function which is strongly concentrated towards the foot points of the loop. They found that under these circumstances a condensation will appear after a certain time near the center of the dip. Although they did not follow their calculations over a sufficiently long time they suggested that this represents the initial phase of prominence formation.

All these mechaisms have in common that the basic field configuration has to have dips. Dependindg on the mechanism these dips have to be more or less deep.

The other reason why dips are needed in the initial field is the stability of these configurations. Stability against horizontal displacements of the plasma can only be obtained if the field is locally curved upward. This aspect has been noted first by Kippenhahn & Schlüter (1957). Later it was confirmed by Anzer (1969) on the basis of a detailed MHD stability analysis obtained from the energy principle.

3.2. Theoretical models for "initial" dips

I. Quadrupolar field configurations

A simple two-dimensional field configuration was proposed by Anzer (1990). The configuration is based upon a potential magnetic field which is produced by four lines of hypothetical monopoles which are placed at the solar surface, see Fig. 2. As one can see there exists a region above the separatrix of the configuration where the field lines have dips. For this model the dip region lies rather high in the corona; its height is comparable to the half-width of the arcade. For this reason only high lying prominences can be represented by such a model. There is yet another problem with the model: it is not applicable to polar crown prominences which arise from bipolar photospheric fields. The configurations considered are of I-polarity type if one relates the prominence field to the photosheric field in the immediate neighbourhood of the "neutral line"; but it is of N-polarity w.r.t. the more distant field. This behaviour is a common feature of all quadrupolar configurations.

II. Twisted flux ropes

There is a different mechanism to produce dips which relies on the twisting of flux ropes. One can consider a very large magnetic flux rope (diameter ≈ 100000 km) which straddles the photospheric "neutral line". If this tube is twisted by a sufficient amount then a large region with dips will be generated (Priest et al., 1989), see Fig. 3. The dips occur in the lower half of the flux tube. In this part a prominence can develop. It is important to point out that only the bottoms of the dips will be filled with cool material and therefore the prominence still is a narrow vertical sheet, despite the fact that the flux tube itself has a circular cross section. Since twisted flux tubes will always contain electric current this configuration has to be of genuine force free type. Such models can produce both N- and I-polarity prominences depending on the sense of the twisting. An alternative to this twisting scenario has been proposed by van Ballegooijen & Martens (1989). They start from a simple magnetic arcade which is subsequently sheared by a large amount. This new field is then allowed to undergo reconnection. The final field configuration resembles the one of Priest et al. (1989).

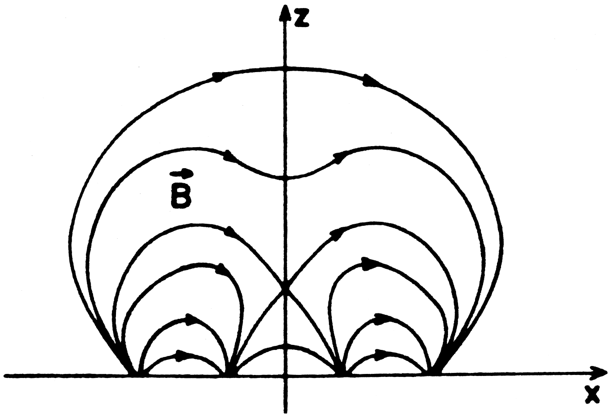

Figure 2. Potential field configuration resulting from a quadrupolar photospheric flux distribution. Magnetic dips are present in a finite range of heights above the separatrix. After Anzer (1990).

III. Force free fields with mixed polarities

This kind of models was studied by Aulanier & Démoulin (1998). They considered linear force free fields. In general force free fields can be described by the relation

$$curl\, \mathbf{B} = \alpha \mathbf{B}, \tag{7}$$

where the scalar function α has to be constant along each individual field line. A special case which is mathematically simpler is the one where α is constant in the entire region (linear force free field). Aulanier & Démoulin calculated periodic three dimensional fields of this type. They included several higher harmonics to allow for a mixture of photospheric polarities. They found from these calculations that if α is very large then dips can be formed in many parts of the arcade considered. A typical result of their calculations is shown in Fig. 4. Only the lower parts of the magnetic dips are drawn in this figure. One common aspect of these linear force

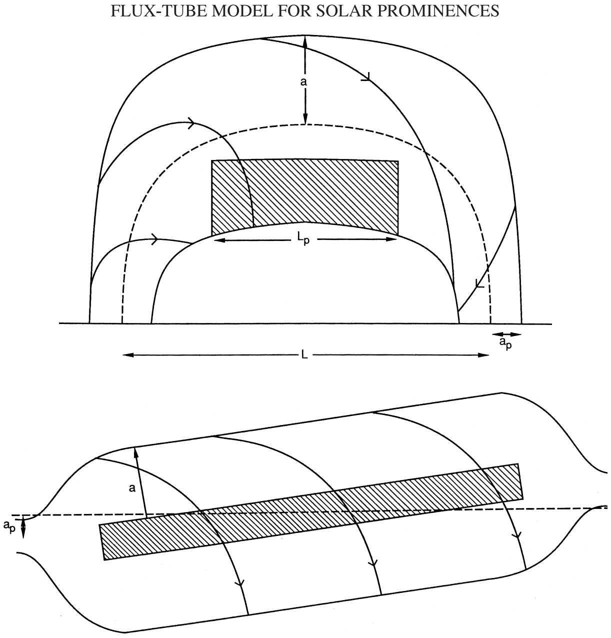

Figure 3. Sketch of a giant flux rope with twisted field lines seen from the side (upper panel) and from the top (lower panel). The position of the prominence is also indicated. From Priest et al. (1989).

free models is the fact that they give the desired type of configuration only if one assumes $\alpha \approx 0.99\,\alpha_{crit}$, where α_{crit} is the maximum value of α allowed for an arcade with prescribed dimensions. This requirement represents a strong restriction for the models used. At present it is not clear whether a physical mechanism exists which could explain the predominance of fields in the solar atmosphere which have $\alpha = \alpha_{crit}$ within less than 1 %.

IV. Sheared magnetic arcades

A numerical three-dimensional model for sheared magnetic configurations has been developed by DeVore & Antiochos (2000). They considered a simple bipolar initial configuration without currents. This

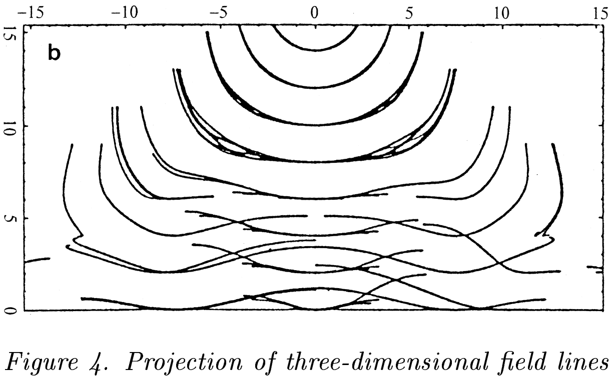

Figure 4. Projection of three-dimensional field lines into a plane perpendicular to the prominence axis. Only the bottom parts of magnetic dips are shown. From Aulanier & Démoulin (1998).

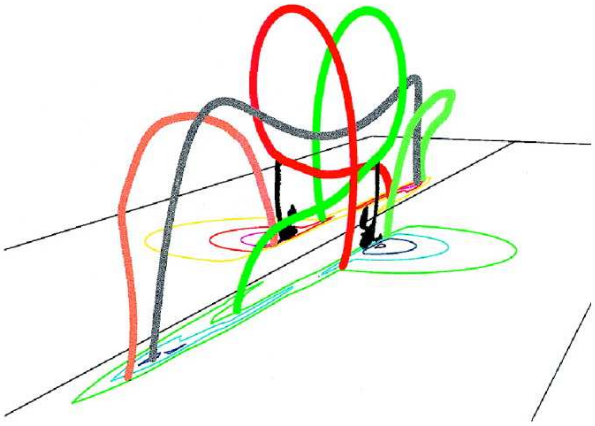

Figure 5. Representation of a three-dimensional magnetic field resulting from a highly concentrated very strong shear flow. From DeVore & Antiochos (2000).

field was then stretched by a prescribed photospheric shear flow. This shearing motion is strongly concentrated towards the "neutral line". The width of the shear region is taken to be w, where $2w$ represents the characteristic dimension of the initial field. The motion was slow enough that the field could always relax to a force free equilibrium. The shear motion was maintained until a maximum displacement of $\pm 16w$ was reached. An intermediate configuration obtained in this process is shown in Fig.5. This figure indicates that such a mechanism can actually produce some magnetic field lines with dips. The physical reason for these dips is the strong tension of the unsheared overlying field lines which pull down the stretched field lines below them.

There are, however, some questions concerning this model:

a. The assumed shear flows seem rather extreme. On one hand they have to be very concentrated towards the "neutral line", on the other hand the required displacements are enormous. If we take for example w = 25000 km, which seems quite reasonable, then one finds for the maximum displacements assumed in this model $w = \pm$ 400000 km, which is more than half a solar radius.

b. Also the efficiency of the process is not really clear. From the figures given in DeVore & Antiochos (2000) one gets the impression that only a few of the field lines exhibit dips. If this were actually true then the model will not be very useful. But this question will need further studies.

3.3. Deformation of dips due to prominence weight

The initial dips which were described in the last section are needed for the prominence formation. But once a prominence has grown from this initial phase to a mature size the weight of the cool prominence material can deform the associated magnetic field considerably and the dips are no longer determined by Eqn (4). Instead now a strong Lorentz force will be induced which supports the mass of the prominence against the gravitational downward force. As a consequence of this mechanism pronounced dips will be formed.

For the case of one-dimensional slab models there is a simple relation between the field geometry and the prominence weight. One has

$$\frac{B_x B_{z1}}{2\pi} = gM, \tag{8}$$

where B_x is the horizontal field component perpendicular to the prominence axis, B_{z1} the vertical field on one side of the slab (note: the vertical field on the opposite side will be $-B_{z1}$ because of symmetry) and M is the column mass in x - direction (Anzer & Heinzel, 1998). Eqn (8) describes the global equilibrium of all such 1D prominence sheets. The internal structure of the slab will be determined by the choice of the functions $T(x)$, $i(x)$ and the value of the coronal gas pressure, p_0; here T is the temperature and i the degree of ionisation.

One can obtain a simple relation between the value of the plasma β ($=8\pi p/B^2$) and the magnitude of the dips (Heinzel & Anzer,1999). If one neglects the small contribution due to the outside coronal pressure one finds

$$\frac{B_{z1}}{B_x} = \sqrt{\beta_c}, \tag{9}$$

where β_c is the plasma β in the center of the prominence ($= 8\pi p_c/B_x^2$), and p_c the central gas pressure. This mathematical relation can either be used to determine the field geometry if the value for β_c is known from observations, or alternatively to derive β_c for a given magnetic field configuration.

Under certain circumstances one can also determine the field geometry for 2D prominence fine structures. For 2D vertical prominence threads Heinzel & Anzer (2001) have developed such an equilibrium model. In their model all physical quantities are allowed to vary along the prominence axis (i.e. in the y-direction). In this case one obtains rather simple equilibria because the force balance in y-direction is achieved by taking the total pressure (magnetic pressure plus gas pressure) as being constant. The new aspect of these models is that one can now prescribe the variation of the column mass M as a function of y. Under these circumstances also the geometry of the magnetic dips will change along the prominence axis. Such a varying field geometry obtained for one specific model is presented in Fig. 6.

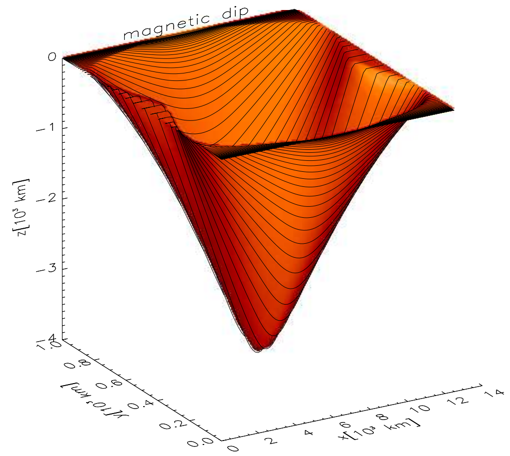

Figure 6. Magnetic dips in a two-dimensional vertical thread model. The prominence axis is in the y - direction and the coordinate x is perpendicular to the prominence. The configuration is similar to the one used in the paper of Heinzel & Anzer (2001).

4. MODELLING OF EXTENDED EUV FILAMENTS

Recent SOHO/CDS observations have shown that filaments are much more extended in EUV lines than their associated Hα filament. One particular filament has been studied in great detail by Heinzel et al. (2001) and Schmieder et al. (2002). In this case it was found that the width of the EUV filament is around 35000 – 70000 km, whereas the Hα filament is only about 10000 km wide. The true width of the Hα filament could in principle be smaller because of the presence of projection effects. These projection effects can also affect the EUV filament in the same way. But because of the large absolute width of the EUV filament the relative correction will be rather small in this case. The presently accepted interpretation of these dark EUV filaments is that they are caused by the absorption of the EUV lines by the Lyman continuum of overlying neutral hydrogen. This then implies the pressence of cool material in the corona. Since the absorption in the Lyman continuum is much more efficient than the one in the line of Hα a rather small amount of neutral hydrogen along the line of sight will be sufficient to reproduce the observations. The observed EUV line absorptions described by Heinzel et al. can be explained by assuming a typical vertical particle column density of neutral hydrogen of 10^{18} /cm^2. This cool material has to be spread out over a very large area away from the Hα filament in order to be consistent with these observations. Since the support of this cool material requires the presence of magnetic dips one has to conclude from this fact that the dips are distributed over a very extended region. The immediate question then is how such a dip region can be formed. At present two different suggestions have been proposed for the formation of these dips.

I. Dips resulting from "parasitic magnetic polarities"

The magnetic field measurements of the particular region under consideration show a very complex structure: the basic bipolar field distribution contains a large number of opposite "parasitic polarities". Aulanier & Schmieder (2002) have taken the measured photospheric fields and calculated on this basis force free magnetic fields with a constant value for α. Their results are illustrated in Fig. 7 where a representative sample of those field lines which have dips is shown. The authors found that all dips with the exception of the ones which are reponsible for the Hα filament are at very low coronal heights; typically less than 4000 km. The low lying dips extend to large distances away from the Hα filament comparable to the size of the entire EUV region. Therefore if a large number of these dips is filled with a sufficient amount of cool gas this mechanism can explain the extended EUV filament. One problem with this model is however the extremely low height of these dips. This means that such a type of model cannot explain the presence of the filament in hot coronal EUV lines which are emitted at rather large heights. Therefore one would have to invoke a different mechanism operating for those lines.

II. Twisted flux tubes

A different approach has been taken by Anzer & Heinzel (2002). They assumed that the magnetic arcade which produces the Hα filament consists of a collection of individual twisted flux tubes. In such a configuration the twisting can lead to dips where otherwise the flux tube without twist would be curved downward. This is a modification of the model developed by Priest et al. (1989). In our new model the horizontal extension of the region with dips now depends upon the amount of twist which is present in each flux tube. The twisting process will be limited by the occurence of kink instabilities. But even when one takes this limit into account one finds that for typical prominence arcades the dip region can become comparable to the width of the EUV filament. If one assumes that as in the model of Aulanier & Schmieder the dips are filled with cool material one can explain the observations. This model has also the advantage that dips are possible over the entire height of the arcade. It therefore allows the explanation of those observations which were made in the coronal EUV lines.

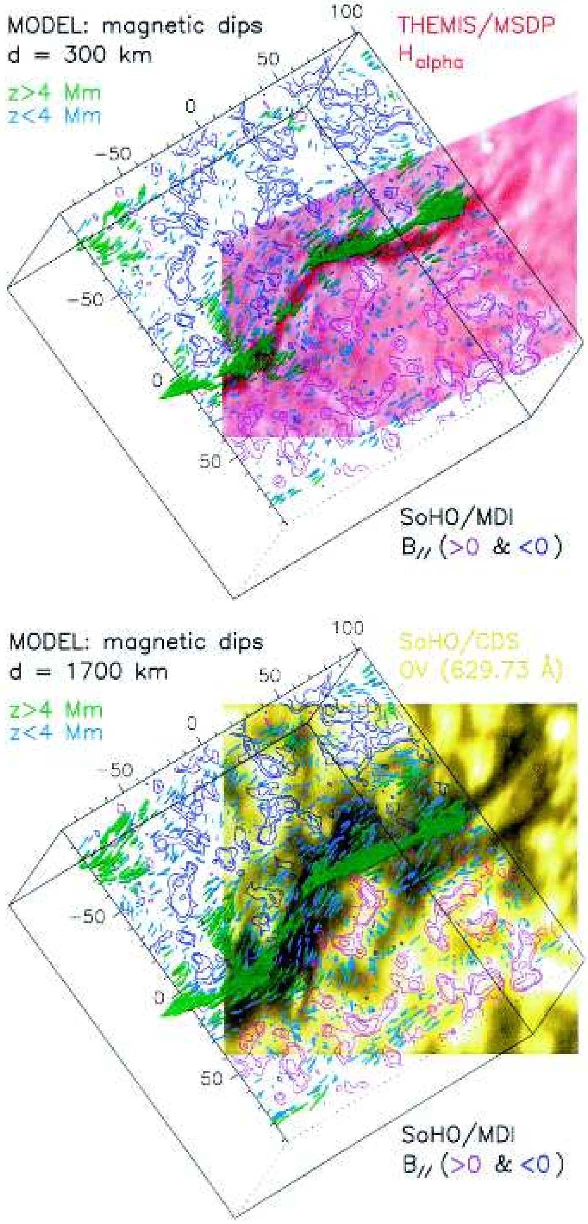

Figure 7. Locations of magnetic dips in an extended EUV filament as calculated by Aulanier & Schmieder (2002). The field lines can be seen as weak grey lines and the EUV filament is black. In the upper panel all dips are only filled to a height of 300 km, in the lower one to a height of 1700 km which makes the structures better visible. The details of this model can only be appreciated by looking at the original color presentation of Fig. 3 in Aulanier & Schmieder.

5. OBSERVATIONAL EVIDENCE FOR MAGNETIC DIPS

The presence of magnetic dips in quiescent prominences is a common feature of almost all theoretical models. Therefore it is of great importance to confirm this property by observations.

5.1. Direct evidence

If only some fraction of all flux tubes which penetrate a prominence is filled with cool material - as is actually suggested by the presence of prominence fine structure - then one would expect to see these curved flux tubes in optical images of prominences. In particular they should be visible in lines with high contrast and good spatial resolution, as for example Hα. But the fundamental problem with such observations will be the extremely small pressure scale heights at these temperatures, which are of the order of only 150 km. This value has to be compared with the spatial resolution of the observations. A typical presently achievable resolution amounts to 300 km. Under these conditions one can imagine the following possibilities:

I. A flux tube has a very large radius of curvature. Then one can resolve the horizontal dimension of the Hα structure. But in this case one will only see a horizontal straight flux tube without a dip.

II. A flux tube has a small radius of curvature. In this case the flux tube has a horizontal extension of only a few scale heights and therefore the structure is unresolved and one will only see a blob-like fearure.

This means that in both cases one will not find any signature of magnetic dips. But since the actual difference between the maximum resolution and the scale height is not very large one can hope that in the near future the spatial resolution can be improved enough to make at least some of these dips visible.

5.2. Indirect evidences

5.2.1. Magnetic field measurements

If one were able to measure the full magnetic field vector at the near-side surface of any prominence then one could infer the total field geometry, assuming that the field is symmetric w.r.t. the midplane of the prominence sheet. Bommier et al. (1994) found that in some cases the vertical field component at the surface is quite large. Inclination angles as large as 45 deg where sometimes found (note: this value of the inclination angle will imply a plasma β of unity). But the authors were not able to determine the sign of this vertical component. For this reason one can only concude that the field has either a dip or a peak. Since peaks cannot provide a magnetic equilibrium these observations are a strong indication for magnetic dips. Sonmetimes it has been argued that if one finds magnetic fields in prominences which increase with height then this result will prove the existence of magnetic dips. Such a conclusion is a direct consequence of our Eqn (4). But one has to realise that this equation is only valid in the case of a force free solar corona. Therefore it cannot be applied to the final prominence configuration and this then means that any conclusion derived for the prominence geometry on this basis can be quite misleading.

5.2.2. Oscillations

Yun et al. (2002) have observed displacements of an individual blob of material relative to the position of the associated Hα filament. This blob moved from one side of the filament to the other and then turned back again. The authors interpreted this behaviour as an oscillatory motion of cool gas in the potential well of a magnetic configuration with a dip. If the field lines have constant curvature the period of oscillation is given by

$$P = 2\pi\sqrt{\frac{R}{g}}. \tag{10}$$

From the observed oscillation period $P \approx 45$ min one can derive a curvature radius of $R \approx 50000$ km. This means that in this case the inferred dips are rather shallow.

6. PROMINENCE EQUILIBRIA WITHOUT DIPS

In a recent numerical study Karpen et al. (2001) found that cool material can also exist under special circumstances in a coronal loop without a dip. These authors considered a magnetic flux tube which is curved downward everywhere. They then took a special type of heating function which allowed the formation of a thermal condensation near the top of the loop. After this cool blob was formed it started to oscillate around some equilibrium position. The physical mechanism for this kind of oscillation is the following: when the blob starts to move in one direction of the flux tube the gas on this side will be compressed and on the opposite side it will be diluted. Therefore a pressure difference will be generated. If the pressure difference becomes large enough to overcome the gravitational force the blob will be driven back to the equilibrium. The situation is similar to the one of a solid pipe with closed ends which is filled with gas. If a massive plug is put inside of the tube one can also generate the same oscillatory motions. But for this mechanism to work two extremely special conditions have to be fulfilled:

I. The gas pressure inside the flux tube has to be enormous. Karpen et al. took a value of 1.5 dyn/cm^2 for their model. This implies a particle density $n = 10^{10}$ /cm^3 for a coronal temperature $T = 10^6$ K.

II. The two surfaces at both ends of the flux tube have to behave like solid walls, this means that any motion across the solar chromosphere will be forbidden in this model.

Both these assumptions seem to be very unrealistic for the case of the solar atmosphere. For this reason I think that it is rather doubtful that this can be the general support mechanism for quiescent prominences. It only might work in some singular special cases. Therefore one has to conclude that magnetic dips are basically always necessary for prominence equilibria.

7. SUMMARY

Magnetic dips are required in nearly all theoretical models of solar prominences. These dips are needed for two different physical reasons:

I. They will provide the location where prominences can form. They also give rise to the stability of the prominence.

II. Only dips can produce the required upward directed Lorentz force which has to counteract gravity in order to give an equilibrium.

Although magnetic dips are such a universal ingredient of all theoretical prominence models they are very difficult to confirm observationally. In particular the direct evidence is very hard to achieve. The reason for this is the fact that due to the small pressure scale heights the dimension of such dips is below the best presently available spatial resolutions. But with a slightly higher resolution and with a systematic search programme one should be able to detect at least some dip structures. This seems to be a very interesting observational project for the near future.

ACKNOWLEDGEMENT

The author would like to thank ESA for financial support.

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