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ON THE FINE STRUCTURE OF SOLAR FILAMENTS

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ABSTRACT

High-resolution Hα images of solar filaments show a variety of dark fine-structure fibrils, most of them aligned with the magnetic field that is sheared with respect to the filament long axis. Here we demonstrate how such fibrils can be explained in terms of the magnetic field dips produced by realistic mass loading due to plasma condensation along the top of a magnetic prominence arcade. Our interpretation is supported by (2+1)-dimensional radiation-magnetohydrostatic simulations that predict quantitatively the properties of such condensations that are suspended in the dipped magnetic field.

Subject headings: radiative transfer — Sun: prominences

1. INTRODUCTION

Solar prominences, or filaments when observed on the disk, show a rich variety of different types of fine structures. When seen at the limb, the prominences often exhibit rather long vertical threads (see, e.g., Fig. 1.2 in Tandberg-Hanssen 1995). On the disk, recent high-resolution Hα observations show horizontal, fibril-like structures, typically inclined with respect to the filament long axis—see Figure 1, where we show an example from the Dutch Open Telescope (DOT). Other examples from the Swedish Solar Telescope (SST) can be found in Engvold (2005) and Lin (2004).

The width of these horizontal fibrils can be as small as the resolution limit (100–150 km in the case of SST or DOT), while their length is of the order of the filament width, typically a few thousand kilometers. These horizontal fibrils are densely packed along the main body of the filament, giving the impression that this part of the filament is composed of a vertical superposition of many such fine structures. There is the question of how the *vertical* structures (threads) seen on the limb can be reconciled with the *horizontal* fibrils of Hα filaments. Moreover, various measurements of the prominence magnetic fields indicate that the field is predominantly horizontal and thus aligned to the disk fibrils rather than to vertical prominence threads (Leroy 1989). A possible scenario to explain this behavior is based on the fine-structure dipped magnetic topology (see, e.g., Poland & Mariska 1987). Many dips filled with cool plasma can be aligned vertically, producing a configuration that gives the impression of vertical threads. In this Letter, we suggest that each such dip has a rather small vertical extension and its projection against the disk resembles an individual horizontal fibril. In order to support this idea, we perform here approximate computations using two-dimensional thread models of Heinzel & Anzer (2001, hereafter Paper I) and Heinzel et al. (2005, hereafter Paper II).

The physics of prominence magnetohydrostatic (MHS) equilibria that give rise to the expected dips is detailed in Heinzel & Anzer (2005). These models are based on the assumption that the dips are produced entirely by the weight of the prominence material. This requires that the magnetic field of the prominence is sufficiently weak (say, below 10 G) to lead to a high enough value of the plasma β. For the central parts of prominences, Jensen & Wiik (1990) give $p_g = 0.1$–2.0 dyn cm^{-2} and $p_m = 0.6$–20.0 dyn cm^{-2}; therefore, taking $\beta = 0.1$–1.0 seems quite reasonable. But for those cases where the field is much stronger, the magnetic dips can only be the result of the complexity of the field. Such fields will then be essentially force-free. Force-free field extrapolations from the photosphere have been calculated by many groups (e.g., Aulanier & Démoulin 1998, 2003; Lionello et al. 2002). However, the question of what is the realistic value of the field strength in quiescent prominences has not yet been resolved. Bommier et al. (1994) have performed an extensive systematic study and found typical field strengths between 5 and 10 G. Aulanier & Démoulin (2003) extrapolated the observed photospheric fields around prominences and obtained 3 G for a quiescent and 40 G for an active region prominence. There are some recent prominence observations that seem to indicate higher values of the field strength. For example, Casini et al. (2003) give fields between 10 and 20 G for the main body of a prominence and up to 70 G at some localized places. But no systematic study on such higher fields in prominences has been performed so far. Taking these observational facts into account, we study here the MHS equilibria of weak-field dips that are formed by the gravity. In § 2, we briefly describe our two-dimensional models of dips that can form vertically infinite threads. Section 3 shows how we project individual dip structures onto the disk by using an approximate radiative transfer technique. Numerical examples of our models are presented in § 4, and § 5 is devoted to the discussion.

2. TWO-DIMENSIONAL MODELS OF VERTICAL THREADS

Two-dimensional radiation-MHS models of fine-structure threads in prominences were presented in Paper I and Paper II. These two-dimensional models describe self-consistently the variations of the dipped magnetic field and of the gas pressure and density (the temperature structure is prescribed on an empirical basis) in the horizontal plane. The threads are infinite in the vertical direction and are aimed at representing long fine structures that are roughly vertically oriented. This situation is typical for many quiescent prominences, as we have described in § 1. The models naturally explain how vertical threads can form in a horizontal magnetic field. The dips are calculated on the basis of the Kippenhahn-Schlüter model (Kippenhahn &

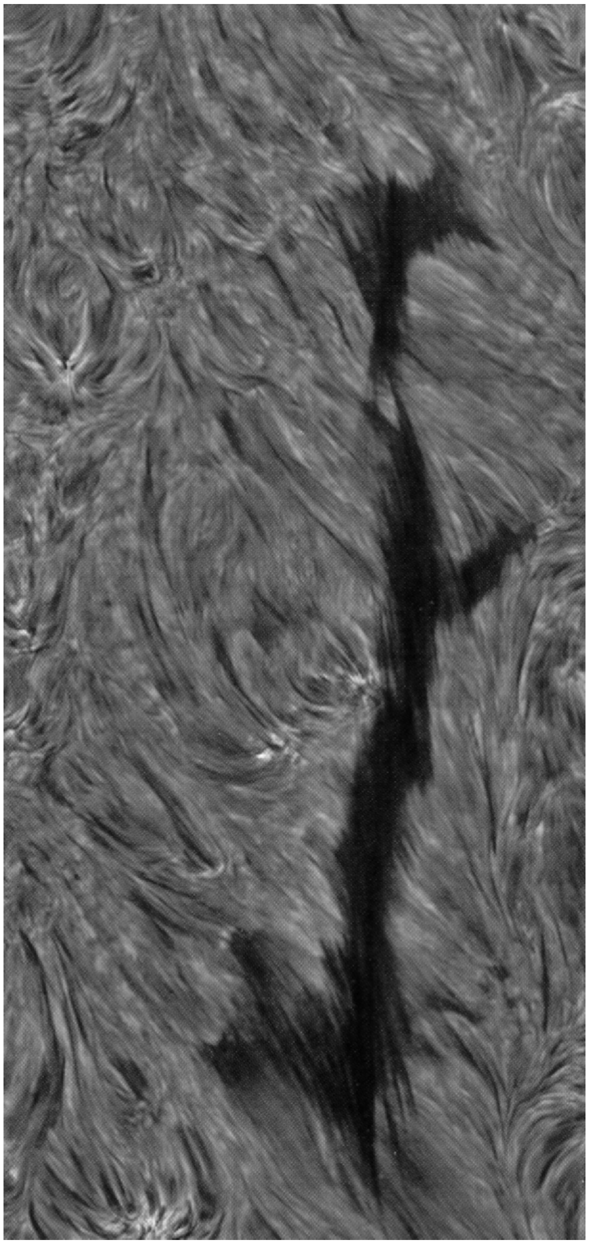

FIG. 1.—High-resolution Hα filtrogram of a filament on the disk. Fine-structure fibrils are clearly visible in this image taken by DOT on La Palma (courtesy of R. J. Rutten).

Schlüter 1957), which has been generalized to two dimensions. In the horizontal plane, the gas pressure is in equilibrium with the magnetic pressure of the dipped field (see Paper I).

For a given temperature structure, the gas density is computed iteratively from the hydrogen ionization structure, which, in turn, is obtained by solving the two-dimensional non-LTE radiative transfer problem in a multilevel hydrogen atom. For further details, see Paper I and Paper II.

In Paper II, we have computed a grid of 18 thread models, varying the magnetic topology, the mass loading, and the temperature structure (see Table 1 of Paper II). A two-dimensional cross section of these threads in the horizontal plane is also displayed there in Fig. 17, which shows that most of these models have structures with the length much larger than the width (large aspect ratios). This suggests that such threads, seen in projection against the solar disk, will be visible as rather long and narrow *horizontal* fibrils. In order to see how such projections will look like when observed in the Hα line, we compute in this Letter a small grid of six models and then perform the formal solution of the transfer equation for the Hα line in the vertical direction. This is described in detail in § 3, and we denote these configurations as (2+1)-dimensional models: two-dimensional transfer modeling of the vertical threads and then one-dimensional formal transfer within a vertically confined element cut out of the infinite thread.

3. (2+1)-DIMENSIONAL MODELS OF HORIZONTAL FIBRILS

The two-dimensional models studied in Paper I and Paper II provide us with the distribution of all relevant parameters in the horizontal plane. This distribution is invariant in the vertical direction. If the threads are supposed to be composed of finite-height elements, they should be modeled as fully three-dimensional structures (possibly with several of these three-dimensional dip configurations aligned vertically). Then viewing them from the top would give us an idea how such three-dimensional elements can look when projected onto the solar disk. The three-dimensional radiative-transfer modeling is a rather straightforward generalization of the two-dimensional case; however, the vertical variations of the magnetic fields and the plasma parameters are difficult to determine; so far, no three-dimensional MHS models of dips caused by gravity exist. Therefore, we restrict our consideration to a simple situation where the vertical distribution is kept homogeneous as in our two-dimensional models, but then the thread is vertically cut with a height H, which we take as a free parameter. Alternatively, we can consider a magnetic flux tube of a given vertical extension H; since B_x is constant along x, the vertical extension of such a flux tube will then be constant along the entire structure. Therefore, the models discussed below will also apply to this type of configuration. The line emissivities, the opacities, and the source function in our approach are determined from the two-dimensional transfer in a vertically infinite thread, and we use them for a formal integration of the transfer equation in the vertical direction along z. Since the source function and the line opacity are constant in this direction, we obtain for the intensity of the vertically outward directed radiation the simple formula

$$I = I_b e^{-\tau} + S(1 - e^{-\tau}), \qquad (1)$$

which corresponds to the well-known cloud model (Beckers 1964). In this equation, I is the line-center intensity of the filament, I_b is the line-center intensity of the background disk radiation, S is the line source function, and τ is the line-center optical thickness of the fibril in the vertical direction for a given height H with

$$\tau = \chi H, \qquad (2)$$

where χ is the absorption coefficient at the line center. The Hα line-center intensity at the disk center is $I_b = 0.17 I_c$, where $I_c = 4.077 \times 10^{-5}$ cgs is the continuum intensity around the Hα line, at the disk center. We call this approach a (2+1)-dimensional transfer model. Using this kind of approximation, one can compute the horizontal distribution of the line intensities, which corresponds to the visibility of the fibrils on the disk.

4. NUMERICAL EXAMPLES

To demonstrate quantitatively how various conditions will affect the appearance of our (2+1)-dimensional fibrils when seen in Hα against the disk, we have computed six models with the

TABLE 1
PARAMETERS OF FIBRIL MODELS

Model	M_0 (g cm^{-2})	B_x (G)	B_{z1} (G)	ψ (deg)	p (dyn cm^{-2})	β	τ	S/I_b	C
1	10^{-5}	4.5	0.4	85	0.04	0.05	0.09	0.45	−0.05
2	3×10^{-5}	4.5	1.2	76	0.08	0.10	0.33	0.46	−0.15
3	10^{-4}	4.5	3.8	50	0.60	0.75	6.53	0.60	−0.40
4	10^{-5}	9.0	0.2	89	0.03	0.01	0.07	0.45	−0.04
5	3×10^{-5}	9.0	0.6	86	0.04	0.01	0.12	0.45	−0.07
6	10^{-4}	9.0	1.9	78	0.17	0.05	0.94	0.48	−0.32

following parameters: central column masses of $M_0 = 10^{-5}$, 3×10^{-5}, and 10^{-4} g cm^{-2} and the horizontal field component at the central field line of $B_x = 4.5$ and 9.0 G. The geometrical thickness across the field lines in the horizontal plane is taken arbitrarily as 1000 km, which is also the horizontal width 2δ of the thread models (see Paper I). All other parameters are the same as for the model presented in Paper I, where their precise meaning is also explained. In particular, the temperature is increasing from $T = 8000$ K in the central parts to 50,000 K at the boundary, where we take the coronal gas pressure $p_0 = 0.03$ dyn cm^{-2}. In Table 1, we summarize the basic parameters of these six models. The z-component of the magnetic field at the prominence boundary (along the central field line) is $B_{z1} = 2\pi g M_0/B_x$, with g being the gravitational acceleration at the solar surface. If we now denote by ψ the angle between the central field line at this boundary and the vertical, by p the gas pressure at the center of the dip, and by β the plasma parameter $\beta = 8\pi p/B_x^2$, we find for $p \gg p_0$ a simple analytical relation between β at the dip center and ψ (Heinzel & Anzer 1999):

$$\beta \simeq ctg^2\psi. \tag{3}$$

Some other useful relations between the various parameters are given in Heinzel & Anzer (2005).

As a characteristic value for H, we take 10^3 km. If one takes substantially larger values for H, then the projection of fine structures onto the solar disk would always give much wider fibrils than actually observed. The observational fact that the total width of filaments may increase toward the limb can be explained by the projection of several narrow fibrils vertically aligned. Note that the horizontal extension of our vertically infinite two-dimensional threads is proportional to the hydrostatic pressure scale height H_s, but it does not depend on the arbitrary value of the vertical extension H. Then the value of H multiplied by the opacity gives the optical thickness, which determines to a great extent the visibility of the fibril when it is projected against the solar disk.

From the intensity given by equation (1), we compute the *contrast*, defined as

$$C = \frac{I - I_b}{I_b}. \tag{4}$$

All our models exhibit a negative contrast, which is quite typical for Hα filaments seen against the disk (filaments are dark). For the scattering source function, we get $S \simeq I_b/2$, which leads (using eq. [4]) to C between 0 and −0.5 for τ between 0 and infinity; see also the discussion in Heinzel & Anzer (2005). Our Figure 2 shows the Hα line-center contrast of individual (2+1)-dimensional fibrils projected onto the disk center. The values of this contrast in the center of the dips are given in Table 1, together with the corresponding values of the line

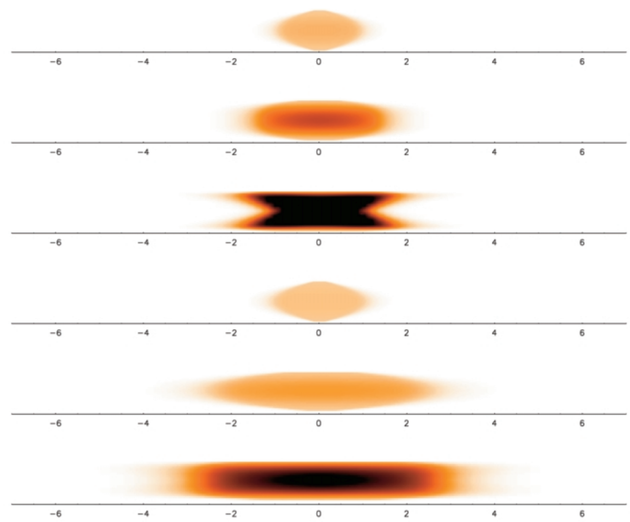

FIG. 2.—Hα line-center contrast relative to the solar disk background shown for six models described in Table 1. The vertical extension is $H = 1000$ km; the horizontal extension along the field is determined by the MHS equilibrium. Perpendicular to this direction, the fibrils have a unique thickness of 1000 km. The scales are given in units of 10^3 km. Darker structures correspond to larger opacity in the Hα line center.

source function (in units of I_b, so it amounts to roughly $\frac{1}{2}$). Note the qualitative correlation between the filament darkness and the line-center optical thickness in Figure 2. Consistently with the Hα observations, it follows that for $\tau < 0.1$ the structure is barely visible, while for $\tau > 1$ it is very dark. Sometimes these model fibrils show a "hornlike" shape (Fig. 2). This always occurs when the column mass in the central parts of the fibril becomes large. In this case, the central parts sag down much more than the surroundings and therefore are squeezed strongly in the field direction. The appearance of the horns thus depends on the mass distribution across the field lines; as in Paper I, we take here a parabolic decrease of the mass loading from the central field line toward the fibril boundary. But these horns will be very difficult to observe even with very high spatial resolution because projection effects will always smear them out.

5. DISCUSSION

Based on two-dimensional prominence fine-structure models, we have demonstrated how the narrow dark fibrils seen in recent high-resolution Hα filament images can be obtained. We were able to reproduce quantitatively the shapes, opacities, and contrasts in good agreement with typical observations. Note that the length of our threads shown in Figure 2 is determined by the MHS equilibrium, while the width is quite arbitrary. For our models, we took a width of 1000 km, but dark filament fibrils seen at the resolution limit might be much narrower and the aspect ratio will thus be larger. From Table 1, one can compare different parameters among all models in order to have an idea how these models behave. For example, it is interesting to note the rather low $\beta = 0.05$ for model 6, which has a spectroscopically reasonable value of the central gas pressure and an acceptable value of B_x. This very shallow dip model resembles the magnetic dips of Aulanier & Démoulin (1998, 2003), where the effect of a mass loading is neglected and the field topology results from the extrapolation of the magnetic field derived from a given photospheric flux distribution. Note that the magnetic dips obtained by these authors (and also others) from extrapolations are visualized in Hα only schematically as uniform black bars, while here we perform detailed transfer calculations to obtain realistic contrasts of the fibrils.

A standard analysis of filaments observed with medium resolution (say, between 0″.5 and 1″), which is based on the one-dimensional cloud model, gives a typical Hα line-center optical thickness around unity (e.g., Molowny-Horas et al. 1999), which corresponds to the observed contrast close to −0.3. However, better resolution automatically leads to even higher contrast and the fine-structure fibrils become darker—see images obtained by DOT or SST. Therefore, the actual τ will be larger than that derived from lower resolution data. If we assume the same vertical extension, the darker fibrils must correspond to a larger mass loading, which in turn may indicate more pronounced dips. On the contrary, if we keep the mass loading, the higher values for C and therefore also for τ can be obtained for the central parts of filaments if several fibrils are lined up along the line of sight.

A more appropriate two-dimensional transfer approach would be such that a horizontal fibril is taken infinite along its long axis and finite in its cross section. This would better reflect the boundary conditions for irradiation from the underlying solar disk. However, such a two-dimensional geometry cannot describe the basic ingredients of our modeling, i.e., the horizontal extensions of the MHS dips. Therefore, we have to sacrifice the details of the non-LTE excitation and ionization in order to get a more or less realistic horizontal distribution of the densities. Nevertheless, the problem is not that critical, since the line excitation by the incident solar radiation will be similar in the centers of thin vertical as well as thin horizontal threads (this is because for the vertical case the boundary irradiation has a dilution factor around $\frac{1}{2}$, while for the horizontal case this factor is 1 at the bottom and 0 at the top, which again gives $\frac{1}{2}$ for the mean value). Note that the value of the Hα source function taken in the center of our fibril (Table 1) is comparable to empirical values obtained by Molowny-Horas et al. (1999)—this also justifies our geometrical simplification. But only a fully three-dimensional radiative transfer can give reliable quantitative results, and we plan to generalize our modeling in this direction.

Our two-dimensional models of vertical threads that are static and infinite in the vertical direction represent a *lower* limit on the horizontal extension along the field lines, for a given mass loading M_0 and magnetic field intensity B_x. More realistic three-dimensional structures with vertically localized condensations will produce, for the same parameters, more extended dips. Moreover, if flows are taken into account along the field lines, the topology of the dips will be also modified. The dynamics of Hα fibrils was observationally studied by Zirker et al. (1998), Engvold (2005), and Lin (2004), but these authors considered only structures without dips. Their interpretation of flows could apply to rather long fibrils located around the barbs of filaments or to some long threads, which are usually observed in active region filaments. Our dip scenario will be more relevant for the case of bundles of dark fibrils that are located around the top of a magnetic arcade.

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