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A MODEL FOR DEXTRAL AND SINISTRAL PROMINENCES

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ABSTRACT

In a recent paper Martin and coworkers have discussed several striking facts about the structure of solar prominences and the filament channels in which they lie. They form two classes, called dextral and sinistral. In a dextral (sinistral) prominence, an observer viewing a prominence or filament channel from the positive-polarity side would see the magnetic field point to the right (left) along the axis of the filament channel, whereas an observer viewing from above would see the prominence feet bear off the axis to the right (left). Furthermore, dextral prominences dominate the northern hemisphere and sinistral the southern hemisphere, regardless of the cycle. Fibrils in the filament channels do not cross the prominence but usually stream from or to plagettes parallel to the prominence axis.

These pioneering observations suggest that there is a coherent organizational principle orchestrating the global nature of prominences, and they have led us to reexamine the standard paradigms of contemporary prominence theory, such as that (1) prominences form in a sheared force-free arcade, (2) formation is by radiative instability, (3) the prominence material is static, and (4) eruption occurs when the shear or twist is too great. We propose a new model which accounts for the above new observational features in a natural way, replaces many of the above paradigms, and explains the previously puzzling feet of a prominence. It is a dynamic model in which a prominence is maintained by the continual input of mass and magnetic flux. The correct global dextral and sinistral patterns for high-latitude east-west prominences (such as those in the polar crown) are created by an organizational principle that includes the combined effects of differential rotation on subphotospheric flux, its subsequent emergence by magnetic buoyancy, and its rearrangement by flux reconnection to form a filament channel with magnetic flux oriented along its axis. Continual emergence and reconnection creates a prominence as a flux tube along the filament channel axis and filled with cool plasma which is lifted up from the photosphere and chromosphere by the reconnection process. Prominences at low latitudes are in this model formed in a similar way, except that it is a general subphotospheric flow (rather than differential rotation) which acts and so may produce either dextral or sinistral structures, depending on the sense of the flow. The effect of neighboring plagettes in avoiding the prominence and making it snake its way along the filament channel is modeled. It is suggested that feet are short-lived structures caused by the interaction of nearby magnetic fragments with the prominence field and may represent either the addition or the extraction of mass from the prominence.

Subject headings: MHD—Sun: prominences

1. INTRODUCTION

Solar prominences are beautiful and mysterious creatures whose basic properties are at present far from understood (Tandberg-Hanssen 1974; Jensen, Maltby, & Orrall 1979; Ballester & Priest 1988; Priest 1989; Ruždjak & Tandberg-Hanssen 1990). Fundamental questions (such as how they form, what their overall structure is, why they possess feet, what the cause of their fibril nature is, and why they erupt) have not yet been convincingly answered, although substantial progress has been made over the past 10 years.

The lack of convincing answers is surprising, since prominences are of profound importance for solar physics and astrophysics. In solar physics, as well as being of great interest in their own right, prominences have an intimate connection with two-ribbon solar flares and coronal mass ejections. Furthermore, in an astrophysical perspective they offer an ideal opportunity to study the bifurcation of plasma into cool and hot states, as well as the subtle and nonlinear effects of gravitational, magnetic, and pressure forces on the equilibrium and stability of plasma.

The main observational features of prominences are well established. A typical large quiescent prominence is 60–600 Mm long, 10–100 Mm high, and 4–15 Mm wide, with a density of 10^{16}–10^{17} m^3 and a temperature of 5000–8000 K. It lies above a polarity inversion line, where the normal component of the magnetic field reverses sign. When observed on the disk, prominences are often referred to as filaments, which form in channels with aligned magnetic flux (Martin 1986). Active-region prominences are lower in altitude, smaller in all their dimensions, and have higher field strengths (up to 100 G). The magnetic field of a quiescent prominence is typically 5–40 G and is directed mainly along the length of the prominence: it is almost horizontal and inclined to the axis at an angle of about 15°. Important studies by Leroy (1989) and Leroy, Bommier, & Sahal-Bréchot (1983) concluded that the magnetic field of most quiescent prominences is directed oppositely to what would be expected for a normal arcade based on the photospheric polarities. This led Priest (1989) to classify prominences and prominence models as either *inverse* or *normal.* Active-region prominences are much more difficult to observe on the limb, but they are thought to be mainly normal, although, in a sample of lower-lying ones than those of Leroy, Kim et al. (1988) finds that some are normal and some inverse.

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The early prominence theories focused on the transverse structure; they include the Kippenhahn-Schlüter (1957) model for a normal polarity prominence and the Kuperus-Raadu (1974) model for one of inverse polarity. Other inverse-polarity models include that of Démoulin & Priest (1993) and Hundhausen & Low (1994) for a prominence in a quadrupolar field, and that of Cartledge & Priest (1994) for a polar-crown prominence. Recently, Priest, Hood, & Anzer (1989) focused on the longitudinal structure and suggested that a prominence is located in a large twisted flux tube (see also Hood & Priest 1979; Low 1993), whose twist is acquired by reconnection of flux (see also van Ballegooijen & Martens 1989, 1990). This twisted flux tube model has many positive features which agree with the observations, including the fact that when a prominence erupts it does indeed look like a tube. In their model, the twist is necessary to provide support. Rust & Kumar (1995) have followed Priest et al. (1989) in suggesting that a prominence is a twisted flux tube, and they have made the novel suggestion that the plasma in a prominence is lifted up by the flux tube as it emerges. They also suggest that prominence feet represent plasma that is supported in the concave-upward part of the flux tube. Since feet are observed at the limb to be reaching down toward the surface, we prefer an alternative explanation (§ 6).

An important feature which Rust (1967) observed and which has lain unnoticed by theorists for many years is that all polar-crown prominences have the same longitudinal component in the northern hemisphere in one cycle. The startling fact is that the sign of this component is exactly the opposite of what one would expect from differential rotation acting on an initially potential coronal arcade. However, van Ballegooijen & Martens (1989, 1990) suggested an appealing solution, namely, that the field could be sheared in the correct sense by differential rotation below the photosphere before it emerges. This is a feature which we are adopting and modifying here.

We first of all (§ 2) summarize some new observations in the paper by Martin, Bilimoria, & Tracadas (1994), which are not accounted for by most of the previous theories. Then we detail a new model which explains both the local and the global features in a natural way. It complements a very recent and most elegant paper by Low & Hundhausen (1995), which is in the same spirit as our work and presents a global model for an inverse-polarity prominence sheet embedded in a flux tube and surrounded by an overlying cavity. The qualitative features of our model are described in § 3 and are followed by details on the structure of the filament channel and filament (§ 4), and the process of mass and flux capture (§ 5), and for the first time the previously puzzling feet of a prominence are modeled theoretically.

2. SUMMARY OF NEW OBSERVATIONS

Martin et al. (1994) have discovered several general properties from a detailed examination of 154 prominences. Their main findings are as follows:

1. Two classes of magnetic configuration exist for filament channels and for the filaments lying in them. They are called *dextral* and *sinistral*. An observer standing on the positive-polarity side of a dextral filament or filament channel would see the magnetic field point to the right along the axis of the filament channel (Fig. 1*a*), whereas for a sinistral filament it would point to the left (Fig. 1*b*). The direction of the field is indicated most easily from the direction of the fibrils in the channel combined with knowledge of the line-of-sight component, but it may also be found from direct measurement of the magnetic field at the limb or by knowing the polarity of the fields at the ends of the filament; the first of these methods has been shown to give correctly the direction of the local horizontal component assuming the simplest overall magnetic configuration. The magnetic field is directed essentially along a filament channel and a filament within it. An example of a dextral prominence is shown in Figure 2.

2. Two classes of structure exist for prominences. They are called *right-bearing* if the prominence feet (appendages, barbs, or legs) bear off to the right of the main axis of the

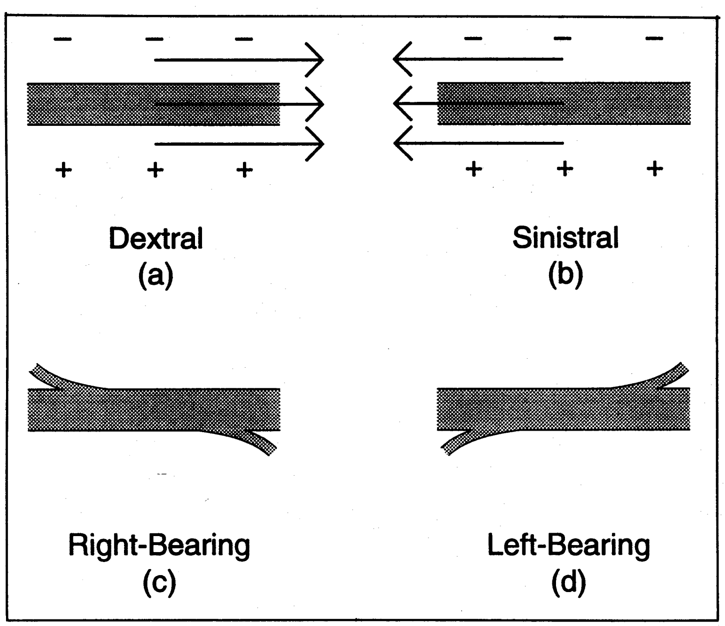

FIG. 1.—Structures of prominences seen from above. Dextral prominences are right-bearing, and sinistral ones are left-bearing.

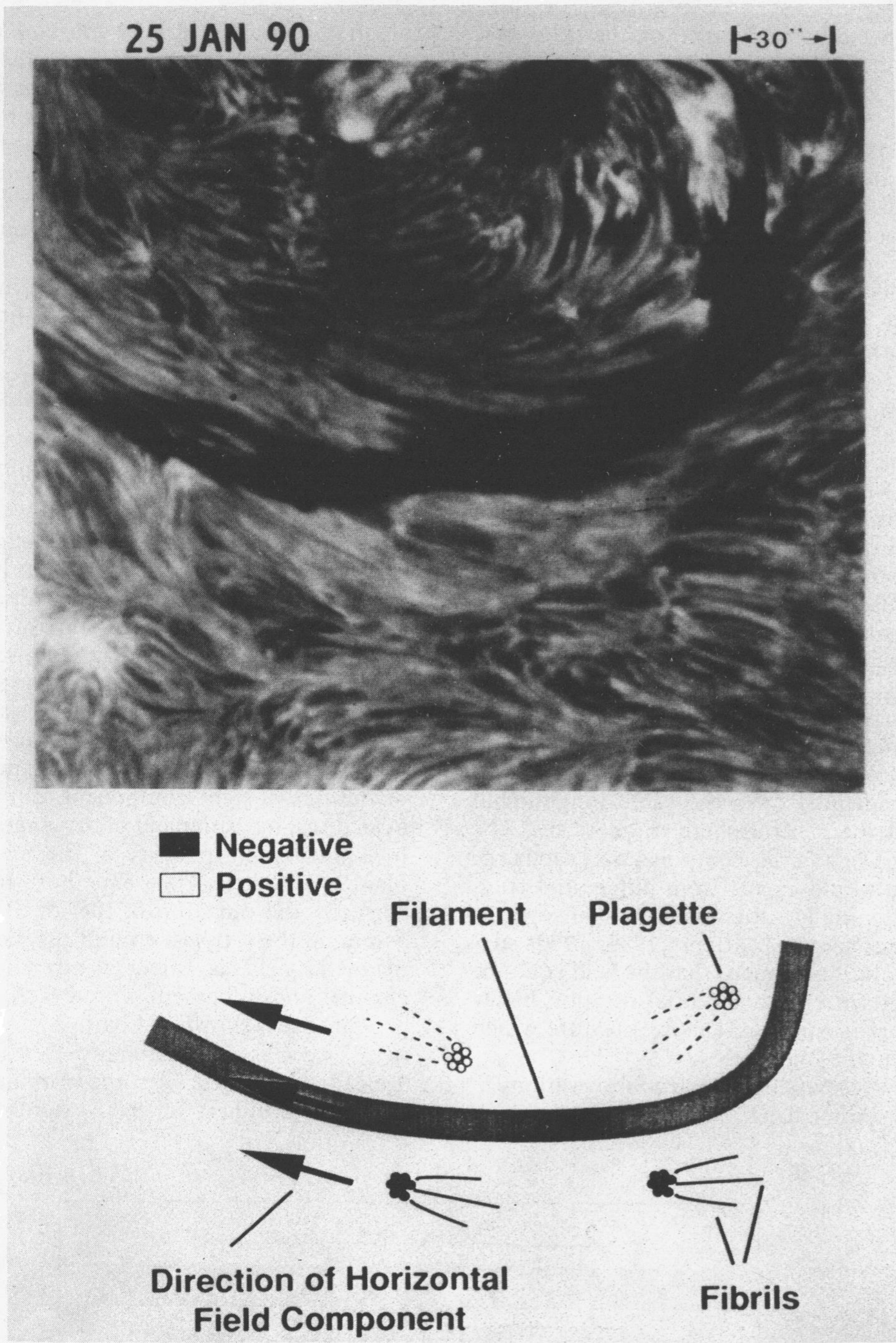

FIG. 2.—An active-region dextral filament. (Courtesy S. Martin, Big Bear Solar Observatory.)

prominence (Fig. 1*c*) and *left-bearing* if they bear off to the left. Examples are shown in Figure 3*a*.

3. All dextral filaments are right-bearing, and all sinistral filaments are left-bearing.

4. Most quiescent filaments in the northern hemisphere are dextral, regardless of cycle, and most of those in the southern hemisphere are sinistral.

5. As previously found by Foukal (1971), plagettes in the filament channel consist of fibrils which stream parallel to the filament to or from a network element having the usual polarity on that particular side of the polarity inversion line (e.g., Fig. 2).

Martin et al. (1994) put forward the hypothesis that the intermediate barbs of a prominence are rooted in weak magnetic fields inside a supergranule cell and having the opposite polarity to the network field on that side of the prominence; in Martin & Echols (1994) they give a qualitative model for the prominence structure. Other points that they stress about the observations include the fact that filament channels are longer than filaments and develop before them. Also, when the magnetic flux density in and adjacent to a prominence increases, the prominence and filament channel narrows and the prominence fills more of the channel. Plagettes correspond to network patches of normal polarity, and, from the overall structure of the fibrils in a channel, Martin et al. (1994) follow Foukal (1971) in inferring that the field lines related to the antiparallel fibrils of plagettes close to filaments have their opposite-polarity ends either on the same side of the filament channel or

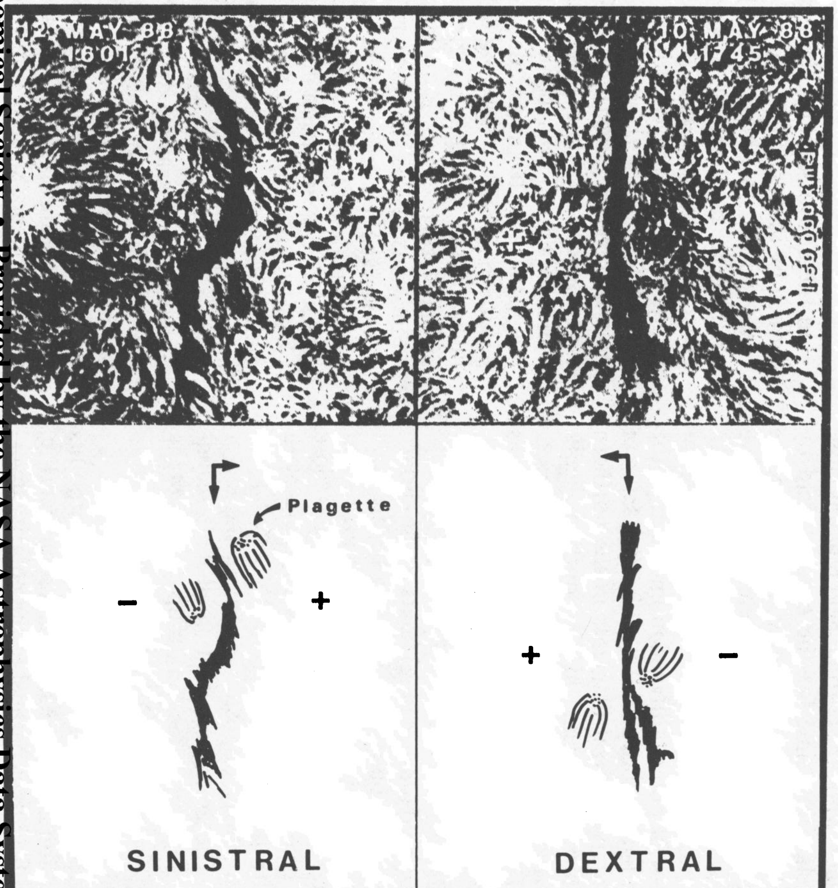

FIG. 3*a*

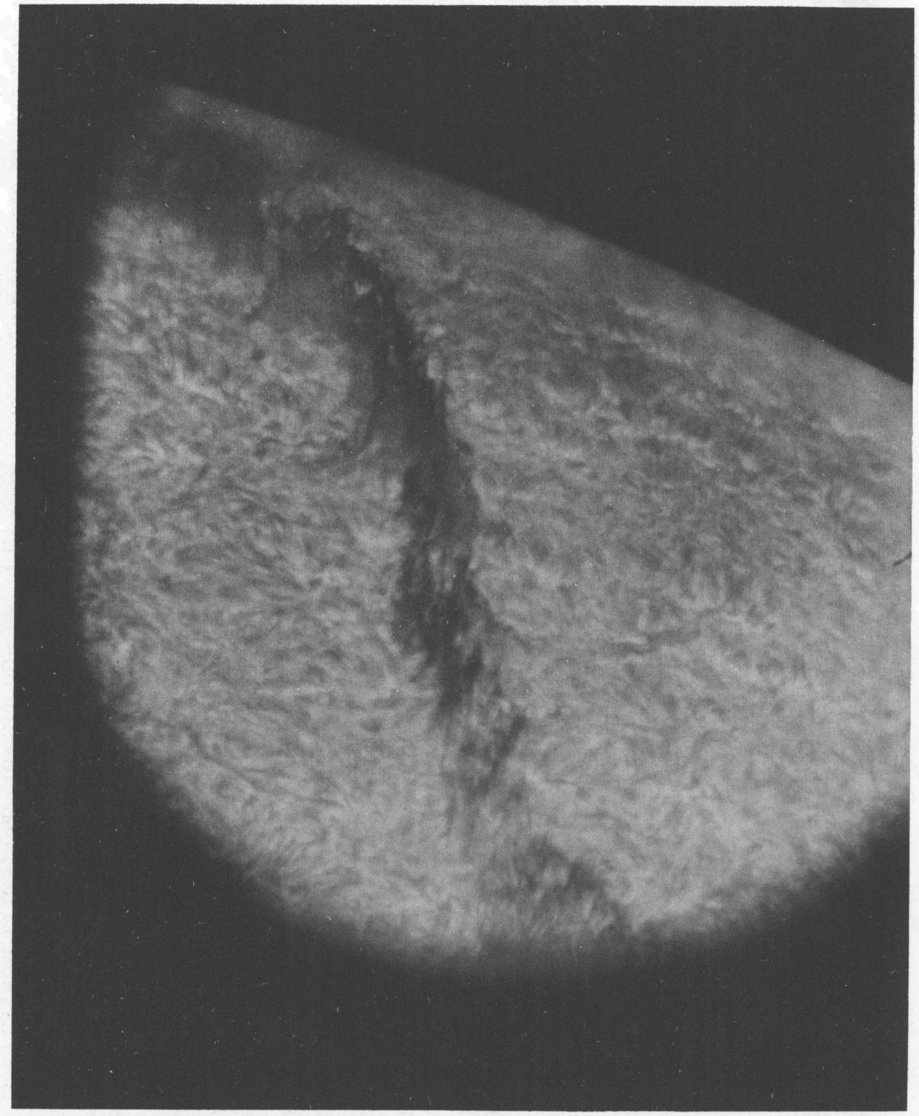

FIG. 3*b*

FIG. 3.—(*a*) Examples of quiescent prominences that are sinistral and **dextral**, with left-bearing and right-bearing feet, respectively. (Courtesy S. Martin, Big Bear Solar Observatory.) (*b*) Filament showing inclined fibril structure. (Courtesy O. Engvold.)

beyond the end of the channel. Quiescent filaments often divide the opposite polarities of active regions or remnants of successive active regions. Border filaments on the edges of active regions have properties intermediate between active-region and quiescent prominences. The end of a filament can be high in the corona and barbs lie between plagettes rather than in plagettes or network. Intermediate barbs are rooted inside supergranulation cells and may be associated with ephemeral regions or weak opposite-polarity fragments.

Most quiescent filaments are of inverse polarity, so this is consistent with the hypothesis that the legs are connected to opposite-polarity fragments: the observed inverse polarity would then refer to the polarity of the feet. (It would also predict that active-region filaments, whose polarity is extremely difficult to measure accurately, are generally inverse.)

Rust & Kumar (1995) have inferred, in agreement with the Martin et al. (1994) discovery of dextral and sinistral filaments, that the twist in prominences is preferentially left-handed in the northern hemisphere and right-handed in the south. This is also consistent with observations of sunspots, which show that anticlockwise whorls are three times as common in the north, and clockwise ones in the south (Richardson 1941; Yang, Hong, & Ding 1988). Furthermore, anticlockwise whorls are consistently related to dextral filaments, and clockwise ones to sinistral filaments (Rust & Martin 1994).

3. QUALITATIVE AND GLOBAL FEATURES OF THE MODEL

The global aspects of our model for high-latitude east-west prominences (such as those in the polar crown) follow four phases as follows:

3.1. *Preparation Phase*

We suppose that differential rotation acts on the field below the solar surface, while the coronal field remains close to potential: the relaxation time for the coronal field by tearing mode instability is typically a few days. Figure 4*a* shows the resulting field in the northern hemisphere above and below a rectangular section of the photosphere. It can be seen from Figures 4*a* and 4*e* that the field component parallel to the east-west polarity inversion line such as the polar-crown region (shown dotted [P.I.L.] in Fig. 4*a*) is of the correct sense to give dextral filaments in the northern hemisphere and sinistral filaments in the southern hemisphere. It is also correct when the field direction is reversed, as in Figure 4*d*; in Figure 4*a* the subphotospheric plane has been lowered in order to show the structure better.

3.2. *Filament Channel Formation*

Next, the magnetic field (*dashed lines*) floats to the surface by convection of magnetic buoyancy: it would be stretched out by differential rotation deep in the convection zone and would rise and be taken up by supergranulation cells close to the surface. The field emerges as a series of bipoles with the orientation of the underlying field (Fig. 4*b*). The bipoles have the magnetic polarity opposite to that of the large-scale environment. The emergence and small-scale reconnection to produce longer field lines builds up the flux of the filament channel parallel to the polarity inversion line.

3.3. *Filament Formation*

Supergranular flow then carries the magnetic footpoints to the polarity inversion line where they can reconnect (Fig. 4*c*). This forms long field lines parallel to the polarity inversion line: the new field lines are long enough to lift mass up into the corona to prominence heights. A filament is then made up of many such tubes inclined very slightly to the polarity inversion line, as observed in the fibril structure of a filament at the highest resolution (Fig. 3*b*). The smaller scale reconnections in the previous phase only lift cool material up to the chromosphere. The properties of flux cancellation, and in particular its prevalence at prominence sites, have been studied in a series of papers by Martin (1986, 1988, 1990, 1992) and Martin, Livi, & Wang (1985) (see also Zwaan 1987); such observations and the suggestion of Martin (1992) of reconnection as an additional way to introduce mass into a filament have stimulated this model. Livi, Wang, & Martin (1985) define flux cancellation as "the mutual loss of magnetic flux in closely spaced features of opposite magnetic polarity" in photospheric magnetograms, and we shall here adopt as a working hypothesis that reconnection is taking place in the chromosphere or corona above such flux elements or in the photosphere between them (Priest 1987).

3.4. *Eruption*

The prominence and its overlying arcade may erupt either when the twist in the prominence makes it lose MHD equilibrium or stability (Hood & Priest 1980; Priest & Forbes 1990; Mikic et al. 1990) or when essentially all of the underlying (*dashed*) field lines have emerged, so that the coronal field lines are no longer anchored to subphotospheric flux. When it erupts, the prominence and its overlying arcade form a coronal mass ejection, and in discussion of interplanetary space this is referred to as a *magnetic cloud*. The resulting structure has left-handed twist in the northern hemisphere (Fig. 4*f*) and right-handed in the southern hemisphere, in agreement with the observations of Bothmer & Schwenn (1994) for magnetic clouds (see also Rust 1994).

In the above scenario the long filament field lines were formed by reconnection of bipoles at the polarity inversion line. Another possibility (Fig. 5) is that after bipoles have emerged in neighboring supergranule cells (Fig. 5*a*), the effect of the supergranule flow is to sweep one set of footpoints out to reconnect with the surrounding network (Fig. 5*b*), while the other set is carried in to reconnect at the polarity inversion line (Fig. 5*c*). It does not matter which of the two reconnection events occurs first: the net effect is the same. In Figure 5*b* reconnection with the network adds magnetic shear to the arcade, and then in Figure 5*c* reconnection of footpoints of long field lines across the polarity inversion line lifts mass high into the corona. The net result of many such events is to create a weakly twisted, left-handed flux tube in the northern hemisphere (Fig. 5*d*).

We have been describing here a basic mechanism for east-west oriented filaments on a polar-crown or sub–polar-crown polarity inversion line, namely, those that are known to possess the global dextral and sinistral patterns. So the question arises, what is the formation mechanism for filaments at intermediate and low latitudes which are in general not oriented east-west? There are several possibilities, which may produce either dextral or sinistral configurations, in agreement with observations at such latitudes. Whereas the only mechanism we have found to work at high latitudes is subphotospheric differential rotation, at intermediate and low latitudes the filament-channel and prominence structure may be built up either by general

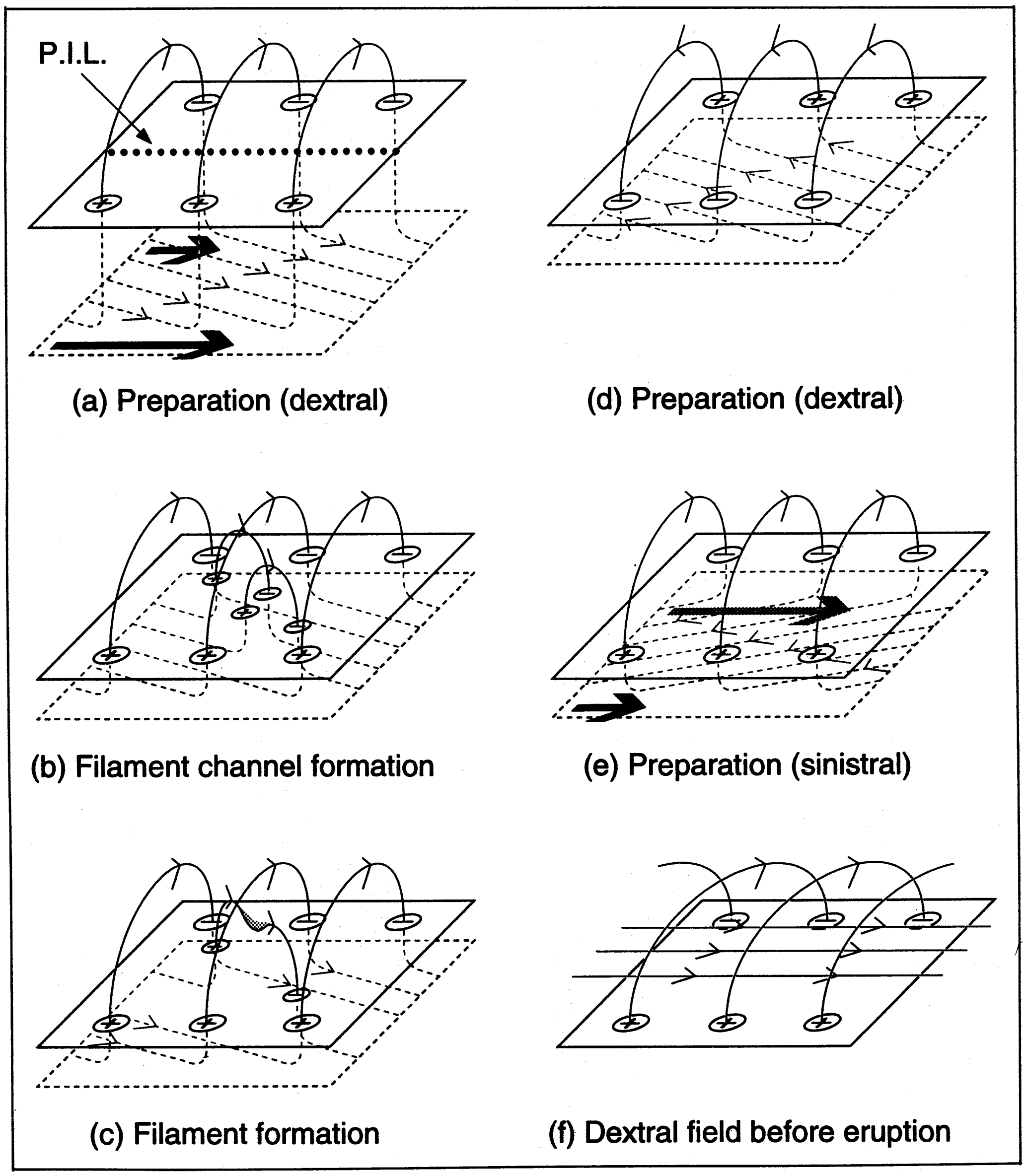

FIG. 4.—Subphotospheric (*dashed*) and coronal (*solid*) field lines in the phases of (*a*) preparation, (*b*) filament channel formation, and (*c*) filament formation. Also shown are preparation phases (*d*) for a configuration with reversed field direction but the same subphotospheric flow, showing that it still produces a dextral configuration, and (*e*) for a flow with the opposite shear giving a sinistral structure. (*f*) A dextral field before eruption.

subphotospheric motions or by surface shear as magnetic sources move past one another. In addition, for those polarity inversion lines that have started in a north-south direction with no filament and possess an overlying arcade with loops in an east-west direction, there is an extra possibility (van Ballegooijen & Martens 1990), namely, that differential rotation acts on the inversion line while the loops remain oriented east-west and so become sheared relative to the inversion line. As such prominences drift to the poles and the inversion line becomes stretched out in an east-west direction, the prominences may erupt, and so we are left with subphotospheric differential rotation as the only mechanism for subsequent re-formations of a prominence.

4. STRUCTURE OF A FILAMENT CHANNEL AND PLAGETTES

The observations of Martin et al. (1994) show clearly that plagette structures in a filament channel tend to run parallel to the channel and to avoid the filament. We may build on these observations and model simply the effect of plagettes on a filament in a filament channel by regarding the filament field as uniform and of strength B_0 in the x-direction and by representing two plagettes as point sources of strength $-f$ at a distance along the y-axis and strength $+f$ at a similar position on the negative y-axis. Thus

$$\boldsymbol{B} = B_0\,\hat{x} + f\left(-\frac{\hat{\boldsymbol{r}}_1}{r_1^3} + \frac{\hat{\boldsymbol{r}}_2}{r_2^3}\right), \tag{1}$$

where

$$\boldsymbol{r}_1 = x\hat{x} + (y - a)\hat{y} + z\hat{z}\,, \tag{2}$$

$$\boldsymbol{r}_2 = x\hat{x} + (y + a)\hat{y} + z\hat{z}\,. \tag{3}$$

Figure 6 shows a sample of the resulting magnetic field lines viewed from different directions in the case when $a = 1.3$ units and $f/B_0 = 2\pi/5$. Three field lines come from each plagette, and seven field lines are also shown which pass through points located at a height of 0.5 in the y-z

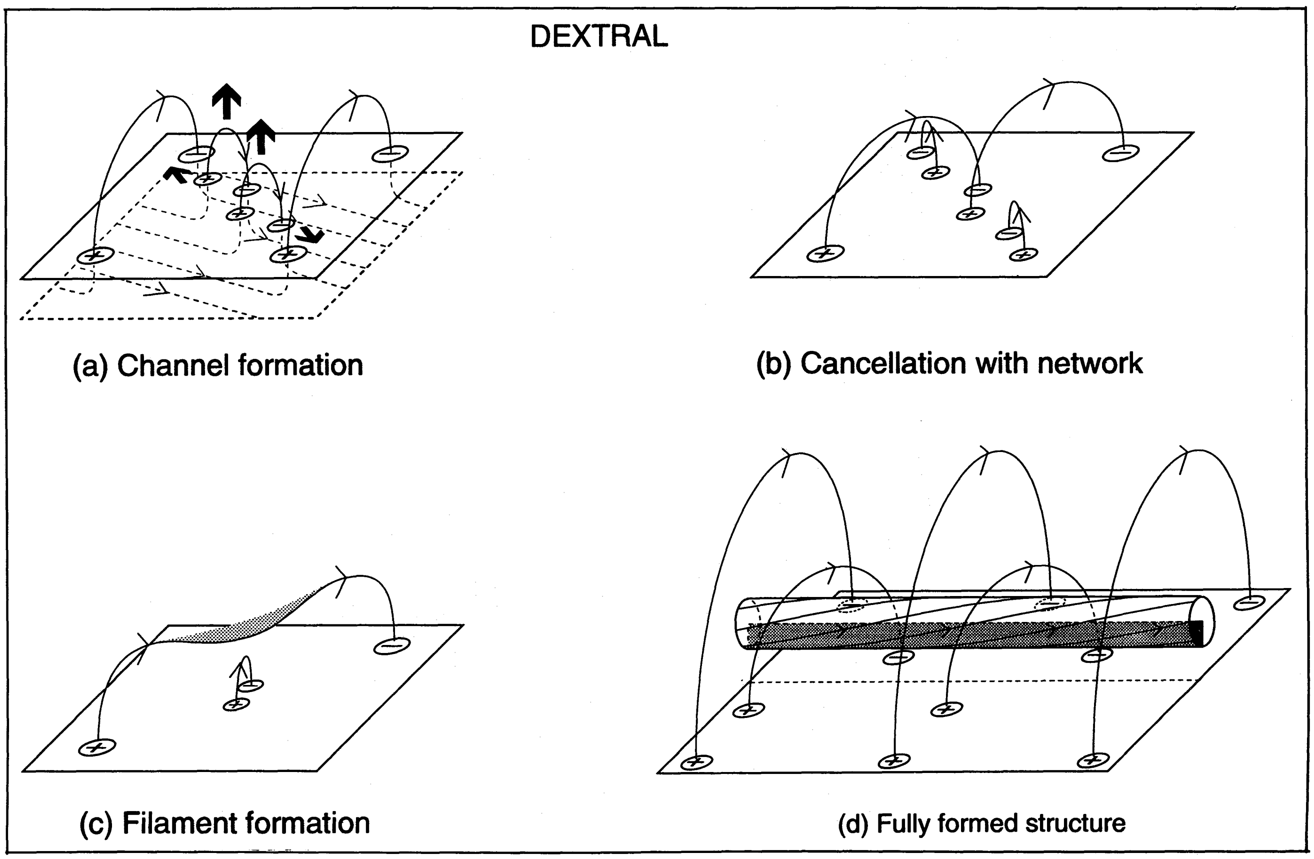

FIG. 5.—Alternative scenario for fillament formation

plane. It can be seen how the plagettes make field lines closest to them rise in height to avoid the plagettes. Each of the plagettes is surrounded by a "plagette magnetosphere" with the magnetopause (*dashed line*) acting as a separatrix, separating the field of the plagette from the field of the prominence.

An important effect, often observed in filaments, is that the plagettes cause the filament to kink and be displaced by an amount *d*, say, so that it avoids the plagettes. The path of the filament and the dimensions of the plagette magnetopause depend on the ratio $f/(B_0 a^2)$ of flux in a plagette to flux in the prominence. Figure 6*d* shows the way the displacement *d* increases with this dimensionless flux ratio.

Another important effect of plagettes on prominences is to make the prominence width (w) decrease, as shown in Figure 6*e*. When $f/(B_0 a^2)$ exceeds a critical value of about 0.41, the plagette flux disrupts the filament and the two plagettes become connected magnetically. A beautiful example of such behavior has recently been observed by O. Engvold (1995, private communication) at the Canary Islands.

5. PROCESS OF MASS AND FLUX CAPTURE

How can we model the way mass and flux may be captured by magnetic reconnection in the photosphere, chromosphere, and corona and raised up to prominence heights (Martin 1992)? Consider a bipolar pair of magnetic fragments with fluxes $\pm f$ located at distances a and b along the x-axis and immersed in a uniform ambient field. Suppose that there is another, similar bipolar pair situated at the symmetric positions $-a$ and $-b$ on the negative y-axis (Fig. 7*a*). The resulting field is

$$\boldsymbol{B} = B_0 \hat{\boldsymbol{x}} + f\left(\frac{\boldsymbol{r}_1}{r_1^3} - \frac{\boldsymbol{r}_2}{r_2^3} - \frac{\boldsymbol{r}_3}{r_3^3} + \frac{\boldsymbol{r}_4}{r_4^3}\right), \tag{4}$$

where

$$\boldsymbol{r}_1 = \boldsymbol{r} - a\hat{\boldsymbol{x}}\ , \quad \boldsymbol{r}_2 = \boldsymbol{r} + a\hat{\boldsymbol{x}}\ , \tag{5}$$

$$\boldsymbol{r}_3 = \boldsymbol{r} - b\hat{\boldsymbol{x}}\ , \quad \boldsymbol{r}_4 = \boldsymbol{r} + b\hat{\boldsymbol{x}}\ . \tag{6}$$

Now suppose the outer source and sink are held fixed while the inner source and sink slowly approach one another, with the overlying field evolving through a series of potential equilibria, as shown schematically in Figure 7. Initially, the two bipoles are not connected magnetically (Fig. 7*b*) but are separated by a magnetic channel. Eventually, as the magnetic fragments approach one another, the fields come into contact (Fig. 7*c*) and reconnect (Fig. 7*d*). In the process, the initial field line that reconnected rises in the atmosphere, and, as it does so, it carries mass (*shaded area*) upward to prominence heights. As the mass rises, it spreads out along the field line. Some of the mass may be spread beyond the field line maxima and spill down to the ends of the field lines and so produce the redshifts (e.g., Schmieder et al. 1994) that are often observed over magnetic fragments. (Such a feature may also be present in a foot formation mechanism [§ 6].) The height (h) of the field line that captures the mass in this way can be calculated and the spread of mass along the field line estimated. Redshifted material at up to 15 km s^{-1} is often seen, especially at prominence feet (Schmieder, Raadu, & Wiik 1991). Also, the reconnection below the prominence could explain the bright rim that is

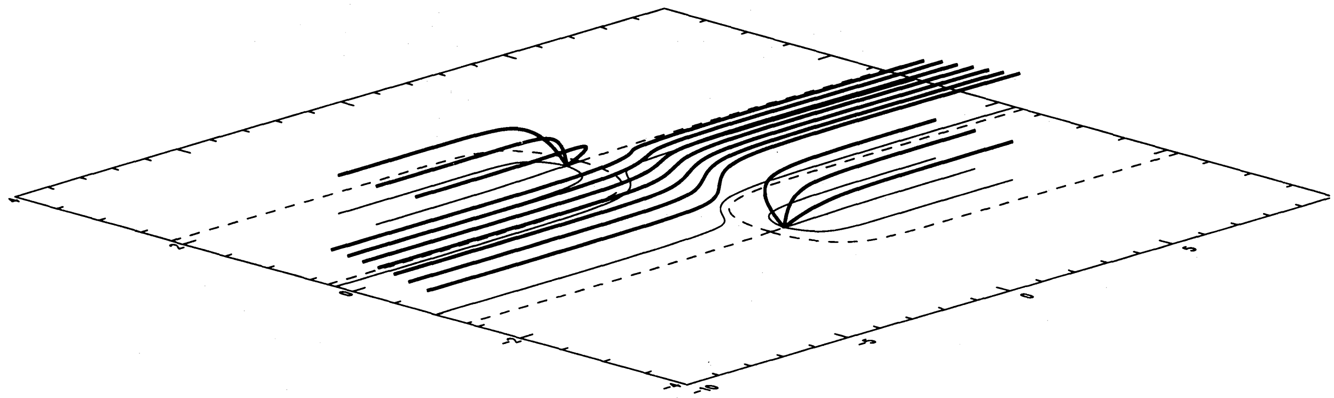

FIG. 6a

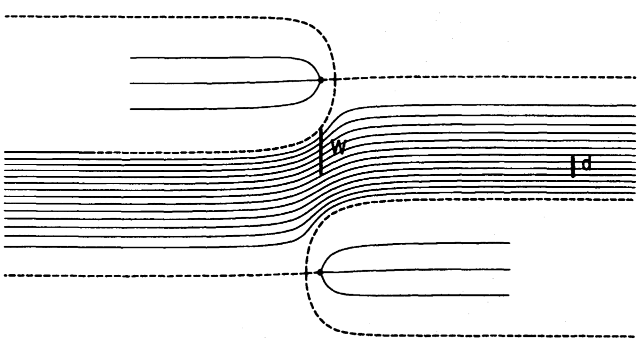

FIG. 6b

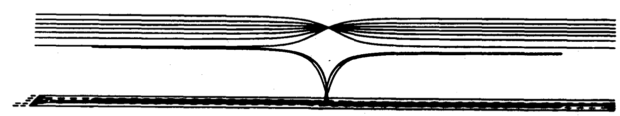

FIG. 6c

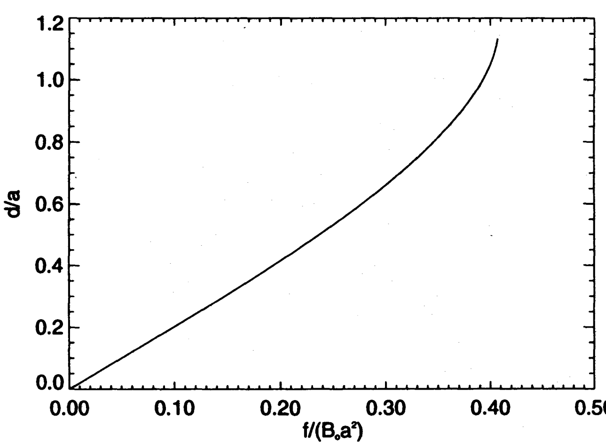

FIG. 6d

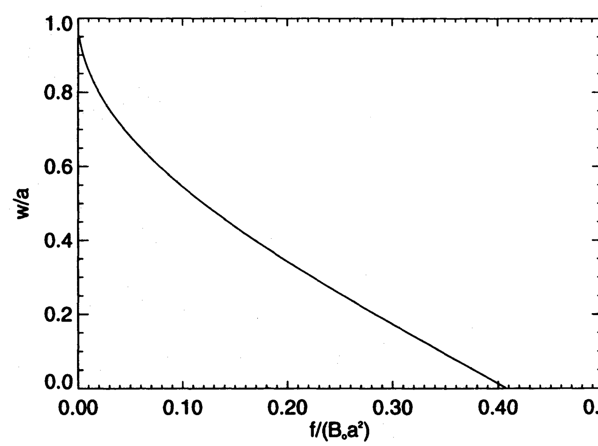

FIG. 6e

FIG. 6.—Model of a plagette in filament channel, showing the effect of a pair of plagettes on the magnetic field lines in a prominence viewed from (*a*) an oblique angle, (*b*) above, and (*c*) the side. (*d*) Lateral displacement *d* of a prominence of field strength B_0 caused by a pair of plagettes of fluxes $\pm f$ at distances $\pm a$ from the origin. (*e*) The corresponding prominence width.

often observed on the underside of prominences: such rims tend not to be observed in polar-crown or active-region prominences, perhaps because the energy release is too weak in the low magnetic fields of the former and because the ambient plage obscures them in the latter; they are more common in prominences of the sub–polar crown or of remnant active regions, where the fields are stronger than the polar crown.

From equation (4) it can be seen that on the z-axis ($x = y = 0$) the magnetic field has by symmetry only an x-component, namely,

$$B_x(0, z, 0) = B_0 - \frac{2af}{(z^2 + a^2)^{3/2}} + \frac{2bf}{(z^2 + b^2)^{3/2}} . \quad (7)$$

Thus the X-type neutral point first forms (at the origin, Fig. 7*c*) when $B_x(0, 0, 0)$ vanishes, namely, at a critical value (a_c) of a, where

$$a_c^2 = \frac{2f}{B_0 + 2f/b^2} ,$$

or, in terms of a dimensionless distance $\bar{a}_c = a_c/b$ and flux $f^* = 2f/(b^2 B_0)$,

$$\bar{a}_c^2 = \frac{f^*}{1 + f^*} . \quad (8)$$

As the flux ratio f^* increases from 0 to infinity, so $\bar{a}_c$ increases from 0 to 1.

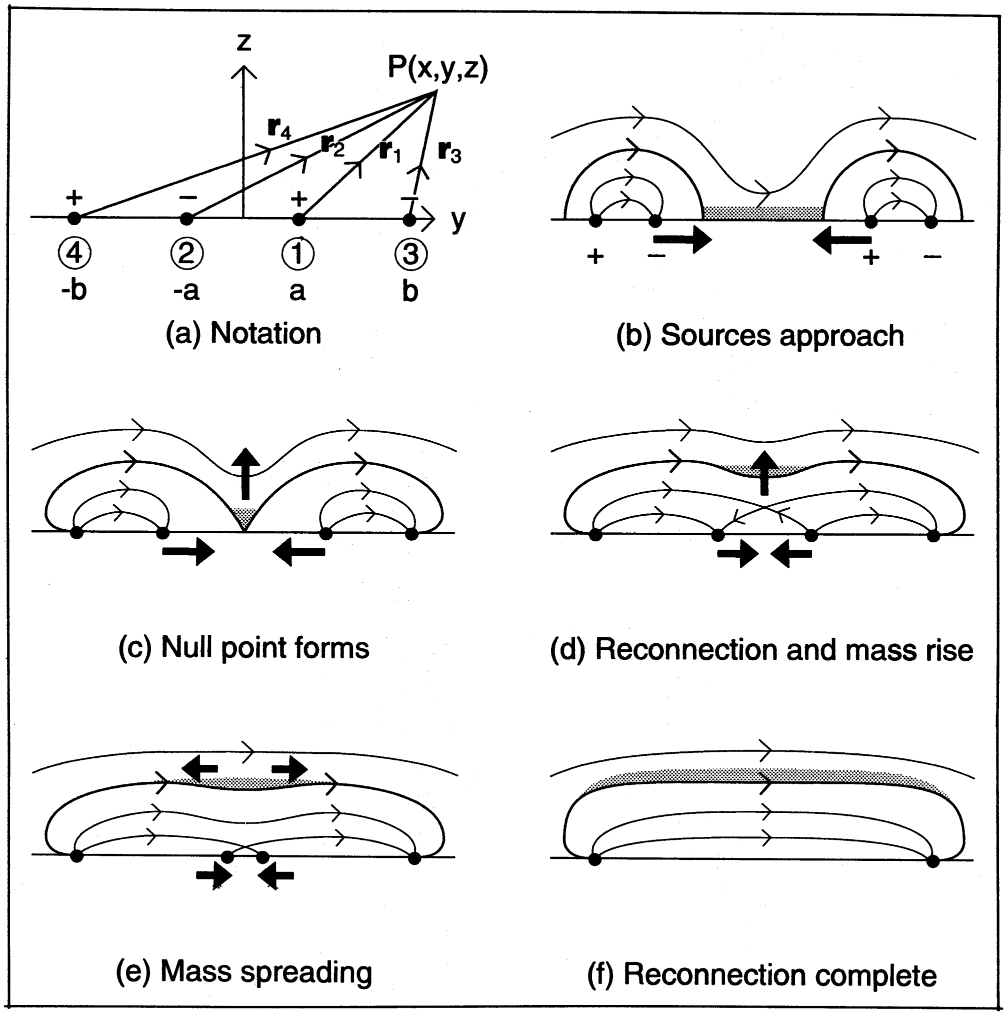

FIG. 7.—Reconnection and mass capture as magnetic sources cancel

As the flux sources at $\pm a$ approach each other, a decreases from a_c to zero and the neutral point rises up the z-axis: its height $[z_N = z_N(a, b, f, B_0)]$ is given by setting B_x equal to zero in equation (7); in terms of dimensionless coordinates $\bar{z}_N = \bar{z}_N/b$, $\bar{a} = a/b$, it becomes a function of only two variables $[\bar{z}_N = \bar{z}_N(a, f^*)]$ given by

$$1 - \frac{f^* \bar{a}}{(\bar{z}_N^2 + \bar{a}^2)^{3/2}} + \frac{f^*}{(\bar{z}_N^2 + 1)^{3/2}} = 0 . \quad (9)$$

It can be seen from Figure 8*a* that, as the flux sources at $\pm a$ approach each other, the neutral point rises to a maximum height and then falls to zero. The maximum height increases with f^*.

Consider the field line that first reconnects and then rises as the sources approach. It crosses the z-axis at a height h which may be calculated from the condition that the magnetic flux up to that height vanish. Thus, setting to zero the integral of $2\pi z B_x(0, z, 0)$ from 0 to h yields the following equation for h in dimensionless form (where $\bar{h} = h/b$)

$$\frac{\bar{h}^2}{2f^*} - \frac{1}{(1 + \bar{h}^2)^{1/2}} + \frac{\bar{a}}{(\bar{a}^2 + \bar{h}^2)^{1/2}} = 0 . \quad (10)$$

A graph of $\bar{h}(\bar{a}, f^*)$ in Figure 8*b* shows how the height increases as a decreases for a fixed flux f.

When the two sources at $\pm a$ meet and reconnect at the origin, the field line reaches its maximum height h_m given by setting $\bar{a} = 0$ in equation (10), so that

$$\frac{\bar{h}_m^2}{f^*} = \frac{2}{(1 + \bar{h}_m^2)^{1/2}} . \quad (11)$$

The graph of $\bar{h}_m = \bar{h}_m(f^*)$ is shown in Figure 8*c*, where (for $f^* \ll 1$) $\bar{h}_m$ increases with f^* as $(\frac{1}{2}f^*)^{1/2}$, whereas for $f^* \gg 1$ it increases as $(\frac{1}{2}f^*)^{1/3}$. This gives the maximum height which plasma can reach, and it can be seen that it depends on the flux (f), the source separation ($2b$), and the ambient field strength (B_0). For typical values of $f^* \simeq 1$ the maximum height is typically equal to or greater than the source distance (b). Thus closely separated sources a distance of, say, 5 Mm apart will lead to mass rise only through a height of about 5 Mm, but widely separated sources of, say 50 Mm will produce a mass rise to 50 Mm altitude. Finally, the distance (L) that mass spreads along a field line may be estimated by supposing that it spreads from the dip at the z-axis until it has risen a vertical distance equal to a scale height (Λ). The result for one particular case is shown in Figure 8*d*, where L increases to about $0.5b$ as a decreases.

The magnetic flux balance may be estimated as follows. The typical rate of flux emergence and cancellation is 10^{18} Mx h^{-1} per supergranule (Livi et al. 1985) or 2×10^{19} Mx day^{-1} per supergranule. This is equivalent to one ephemeral region, and the fact that it is a reasonable figure may be

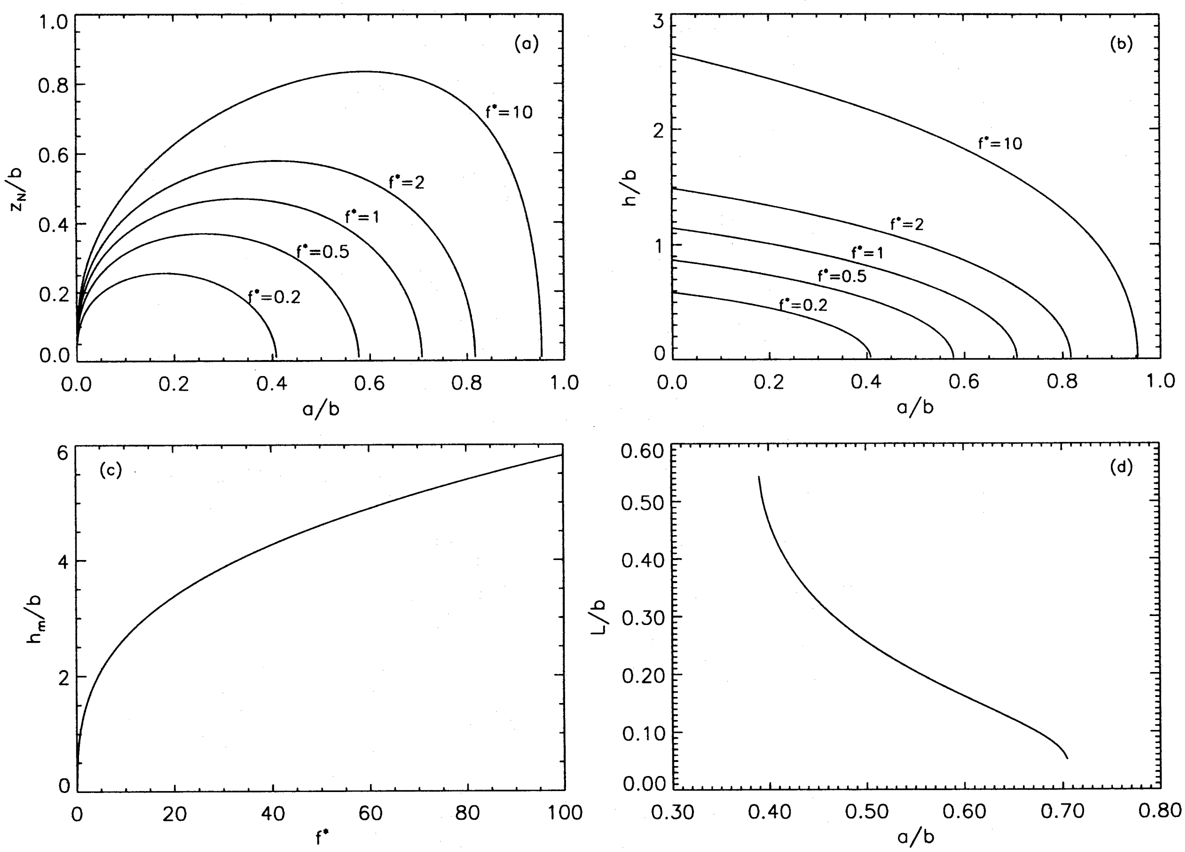

FIG. 8.—Properties of mass rise for four sources of strengths f, $-f$, f, $-f$ at distances $-b$, $-a$, a, b, respectively, along the x-axis in an ambient field of strength B_0. (*a*) Neutral point height z_n as a function of a/b for various values of $f^* = 2f/(B_0 b^2)$. (*b*) Height h of the first field line to reconnect. (*c*) Maximum height h_m of such a field line. (*d*) Distance L that mass spreads along a field line for $f^* = 1$ and $\Lambda/b = 0.05$.

confirmed by noting that in 10^5 s magnetic flux emerges in a typical supergranule at a speed 0.1 km s^{-1} from a depth of 10 Mm: therefore, if the field strength is 10 G across the width 30 Mm of a supergranule, this would imply that 3×10^{19} Mx emerges in a day in each supergranule. By comparison, the flux in a filament channel of cross-sectional area 60 Mm × 30 Mm and with a 10 G field is 2×10^{20} Mx. This implies, therefore, that it would take 5 days to build up such a flux or to regenerate it if it all erupted (although perhaps only part of it erupts in practice).

Now let us turn to the mass balance. Let us assume conservatively that mass is picked up from a patch having an area

$$A = 2 \text{ Mm} \times 1 \text{ Mm} .$$

Furthermore, suppose it is picked up from the canopy with a plasma pressure which is in balance with the magnetic pressure of a 10 G field:

$$p = \frac{(10 \text{ G})^2}{8\pi} = 4 \text{ dynes cm}^{-2} .$$

This corresponds to a canopy height of about 1200 km above $\tau = 1$ and again may be a conservative estimate. If the plasma beta is about unity and the plasma is in hydrostatic equilibrium above the canopy, the column mass above this height is

$$m = \frac{p}{g} = \frac{4 \text{ dynes cm}^{-2}}{2.7 \times 10^4 \text{ cm s}^{-2}} = 1.5 \times 10^{-4} \text{ g cm}^{-2} .$$

Therefore, the total mass picked up is

$$M = mA = (1.5 \times 10^{-4})(2 \times 10^{16}) \text{ g} = 3 \times 10^{12} \text{ g} .$$

When lifted up, this mass spreads over a volume (V), say 10 Mm long, 1 Mm wide, and 1 Mm high, so the mass density becomes

$$\rho = \frac{M}{V} = \frac{3 \times 10^{12} \text{ g}}{10^{25} \text{ cm}^3} = 3 \times 10^{-13} \text{ g cm}^{-3} .$$

This corresponds to a hydrogen particle density of

$$n = \frac{\rho}{m_{\rm H}} = 2 \times 10^{11} \text{ cm}^{-3} ,$$

which is about the observed density of filaments, as required.

Indeed, the density could not be more than a factor of, say, 10 bigger than this, for otherwise the plasma beta would be very large, and so the magnetic field would be dominated by the plasma and would not be able to lift up the plasma. This points to a real difficulty with the suggestion of Rust & Kumar (1995) that the prominence plasma is lifted up in a U-shaped section of a flux tube from below the photosphere: if it came from a depth of only 5 Mm, say, the plasma density would be a million times greater than the above estimates; also the magnetic field would be completely dominated by the plasma and so would not be able to raise the plasma.

6. STRUCTURE AND ROLE OF FEET

6.1. *Flux Emergence*

Suppose new bipoles emerge below or close to a prominence and interact with the prominence magnetic field (Martin et al. 1994; Martin & Echols 1994). In Figure 9 we

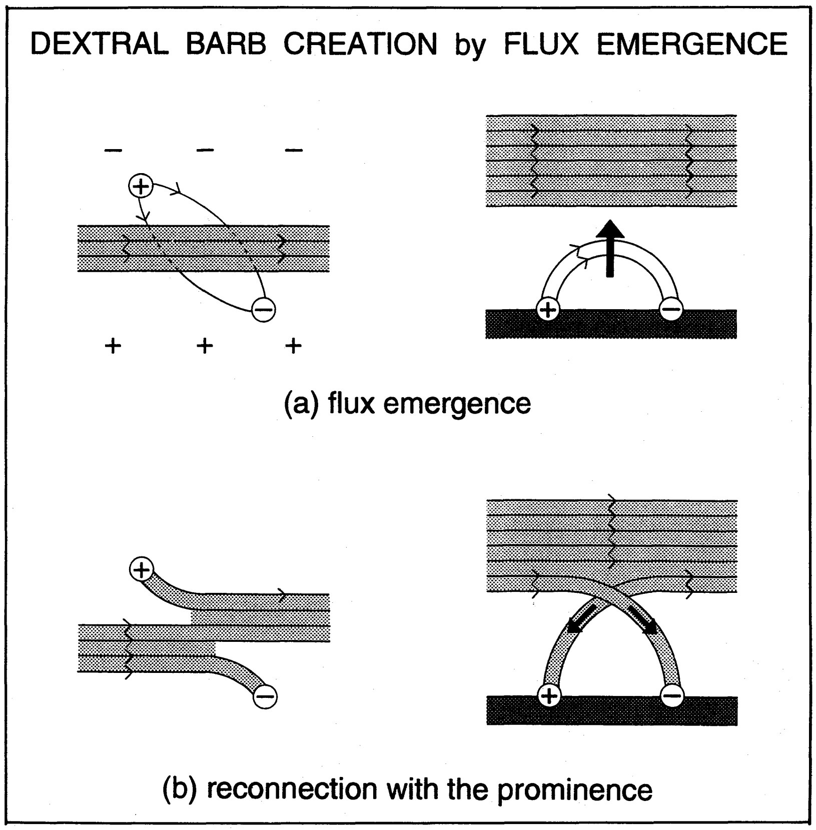

FIG. 9.—Creation of dextral feet (or barbs) in the northern hemisphere by the emergence of new magnetic flux from below the solar surface, as seen from above (*left*) and from the side (*right*). (*a*) New flux emerges below a prominence (*shaded area*). (*b*) It reconnects with the prominence field and creates feet with downflowing plasma. Because the subphotospheric flux has a particular orientation due to the subphotospheric shear, only feet with the required orientation are produced.

can see from above and from the side a dextral filament and a bipole emerging with the preferred orientation that corresponds to the underlying field. When the bipole reconnects with the filament field (Fig. 9*b*), it naturally produces right-bearing feet (barbs or legs), as required. This is directly due to the preferred orientation of emergence, which is a key feature of our model.

Two important consequences are as follows. First of all, the effect of the feet is to extract flux and also mass from the filament, since the emergence has created a magnetic link to the photosphere along which gravity makes the plasma drain. Superimposed on that downflow there is the rising of the emerging loop and also the possibility of jets ejected by the reconnection process, so the net flow signature may be rather complex, as observed by Schmieder et al. (1991). Second, the feet are anchored in magnetic features with a polarity opposite to the dominant magnetic polarity on each side of the filament, a property which was proposed by S. F. Martin (1993, private communication) and has been observationally verified for specific data sets (Martin 1994).

6.2. *Flux Reconnection*

Next, consider the reconnection of underlying flux. Figures 10*a* and 10*b* show what happens if two bipoles with the preferred orientation undergo reconnection of their nearest poles at the polarity inversion line, being forced together by supergranule flow. A long flux tube is formed, inclined to the prominence underneath it and lifting captured mass up to the underside of the prominence. The net effect therefore is that both mass and flux are added to the prominence. The feet that are formed in this case contain plasma that is basically rising, although some may spill downward near the ends of the flux tube. A key feature is that the feet plasma in this model is supported against gravity. (Subsequently, it may reconnect with the main body, as in the previous scenario in § 6.1.) Thus we are suggesting that many feet are locations where plasma is being lifted up after flux reconnection. Indeed, in some cases a series of feet may be observed without the joining prominence body; in such cases, we suggest that there is insufficient reconnection for the rising plasma to spread very far, or, alternatively, the reconnection may have ceased so that the plasma has drained down to the foot regions. (Again, this is a prediction which could be checked observationally.)

The reconnection of overlying coronal flux is also a possibility on theoretical grounds, as indicated in Figures 10*c* and 10*d*, although it is less likely observationally. Again, this process adds mass and flux to the prominence, but it also adds magnetic helicity and is more efficient than the underlying flux reconnection mechanism at adding mass, in the sense that none is lost by spillage along the ends of the tube. The overlying loops are filled with coronal plasma and so do not show up in chromospheric pictures, in which there are no chromospheric structures crossing the prominence from the plagettes. The extensions of the new tube on either side of the prominence as it wraps around the prominence may represent feet, although they are likely to be less pointed than those produced by emerging flux or underlying reconnection, since the "feet" are in this case far from the ends of the flux tube where the feet field lines eventually converge into the photosphere. As in the previous example, this also provides a mechanism for supporting plasma in a

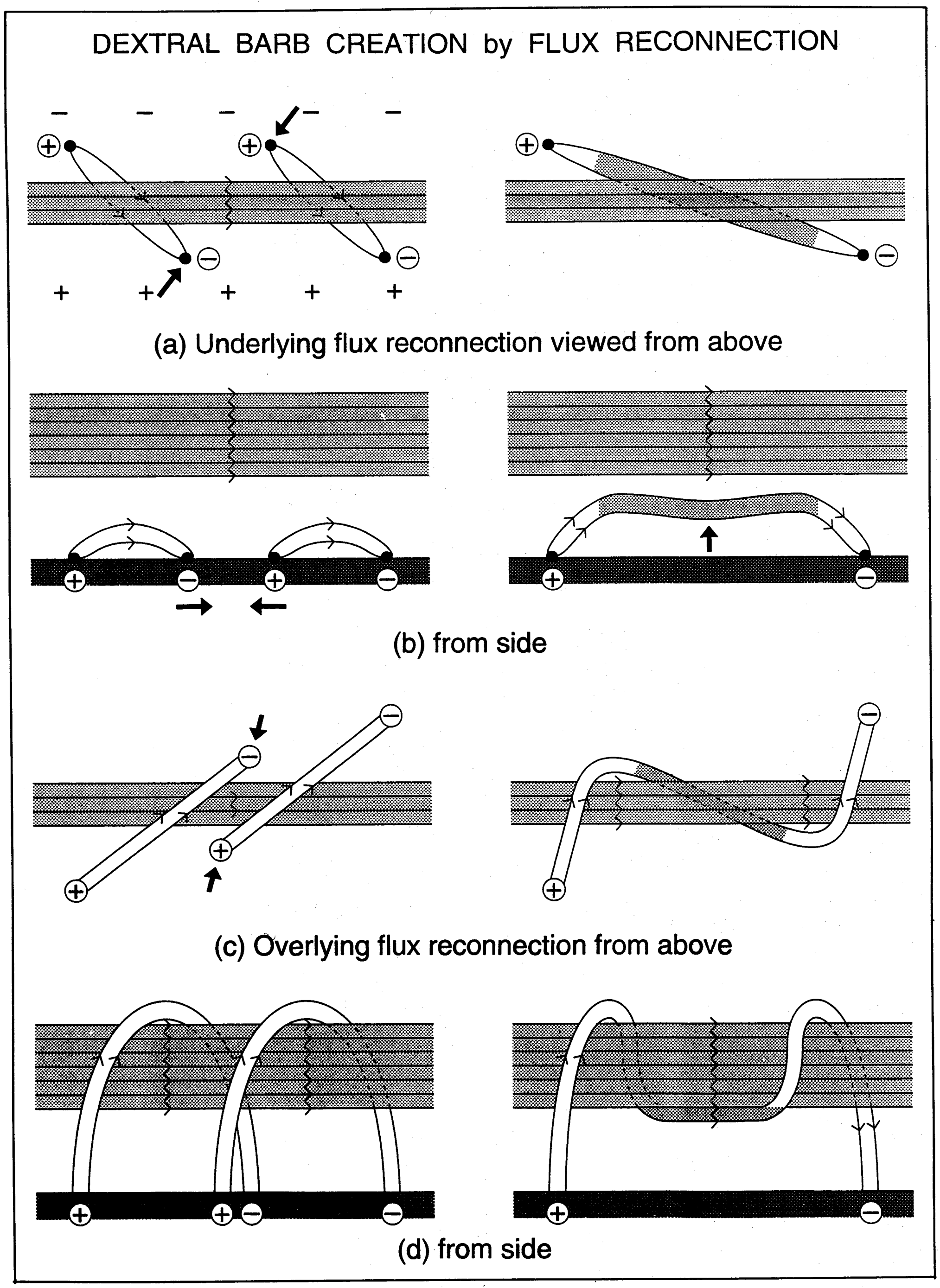

FIG. 10.—Reconnection of (*a*), (*b*) underlying flux or (*c*), (*d*) overlying flux to create dextral feet (barbs)

foot. Furthermore, it is possible that the bright rim often seen below prominence at line center in narrowband filters (d'Azambuja & d'Azambuja 1948) may be caused by the heat that would be generated during the reconnection that takes place in any of the three scenarios for the formation of feet that we are suggesting here in Figures 9 and 10.

7. CONCLUSION

The main paradigms of classical (i.e., most previous standard) prominence theory are the following:

A. Formation is by radiative instability when the length of a flux tube exceeds a critical value such that the conduction time exceeds the radiation time.

B. The basic structure of the magnetic field around a prominence is that of a highly sheared force-free arcade with the field lines crossing the axis at a small angle and so being highly nonpotential; the shear is produced by photospheric motions parallel to the prominence; in a plane normal to the prominence axis, it may be of normal or inverse polarity.

C. Prominence material is essentially static or slowly evolving, with most of it remaining in the prominence for its lifetime.

D. Eruption occurs when the twist in a prominence is too great.

Several of these paradigms are being seriously challenged by recent observations and advances in theory. Theoretical studies of the onset of thermal instability and nonequilibrium (Van Hoven, Sparks, & Tachi 1986; Steele & Priest 1990) have shown that the development of cool structures is a complex question and that the criterion for onset is not the simple one expected in paradigm A. It now appears that, as the length of a hot coronal loop increases, there is no onset of radiative instability or lack of a hot equilibrium: rather, the hot equilibrium remains in stable existence, and it is rather difficult to transfer it to a cool equilibrium.

Paradigm B has been seriously challenged by the observations of Martin (1990) and Martin et al. (1994): some filaments form without evidence of appreciable shear flow; also, the fact that there is a strong field component along the filament does not imply that the field has to be non-potential, since the distribution of flux sources along the filament channel could produce such a strong component. Furthermore, some theoretical papers have suggested that prominences form in large flux tubes (Hood & Priest 1979; Priest et al. 1989).

In addition, many complex motions have been observed in and around prominences (Schmieder 1988; Schmieder et al. 1991), contradicting paradigm C. Finally, although twist and twisting motions are observed in some prominences (e.g., Vrsnak 1990; Vrsnak et al. 1988; Vrsnak, Rušdjak, & Rompolt 1991; Gigolashvili 1978; Liggett & Zirin 1984), and there are theoretical grounds for believing paradigm D (Hood & Priest 1980; Mikic et al. 1990), it has not yet been carefully shown from observations.

The observations by Martin et al. (1994) have confirmed and established three key facts:

I. Filaments lie along polarity inversion lines, with fibrils from plagettes (Foukal 1971) in the filament channel running parallel to the filament rather than crossing it (as would have been expected in paradigm B).

II. There is a near-perfect correlation between the direction of the magnetic field along the filament (right- or left-directed, as inferred from the plagettes in the filament channel) and the orientation of the prominence barbs or feet (right- or left-bearing when seen from above); filaments are either dextral with right-directed magnetic fields and right-bearing feet or sinistral with left parity.

III. Most filaments in the northern hemisphere are dextral, while most of those in the southern hemisphere are sinistral; this is consistent with Hyder (1965), Rust (1967), Leroy et al. (1983), Rust & Kumar (1995), who showed that there is a systematic pattern in the direction of the axial field in mid- and high-latitude prominences.

These are supplemented by a fourth fact established by Bothmer & Schwenn (1994):

IV. Magnetic clouds (Burlaga 1988; Burlaga & Behannon 1982) in interplanetary space have left-handed twist in the northern hemisphere and right-handed twist in the southern hemisphere (see also Rust 1994).

The new theory we are presenting here for the formation and structure of a filament channel and prominence builds on previous ideas, as mentioned in the text. It has seven key features which explain observations I–IV in a natural way and replace most of paradigms A–D:

1. It suggests that cool mass may be added to a prominence by a second mechanism in addition to the radiative condensation referred to in paradigm A, namely, the lifting up of the photospheric and chromospheric mass in response to flux reconnections; to determine which of the two mechanisms dominates will require further observations and theory.

2. The basic structure of the prominence magnetic field is a flux tube, which may be untwisted or twisted, but (in contrast to the twisted flux tube model [Priest et al. 1989]) the twist is not an essential ingredient; a model is proposed for a filament and its filament channel, including the effect of plagettes, which accounts for observation I; this replaces paradigm B.

3. For the first time several local models are proposed for prominence feet which account for their dextral or sinistral structure (observation II); these models naturally explain why filaments with right-directed magnetic fields have right-bearing fine magnetic structures and filaments with left-directed fields have left-bearing structures.

4. The hemispheric patterns in observations III and IV are explained by a global model including the combined effects of subsurface velocity shear, flux emergence, and flux reconnection.

5. In contradiction to paradigm C, the model is dynamic, with a continual input and output of mass and magnetic flux, driven by flux reconnection; emergence of flux builds up a filament channel with flux parallel to the polarity inversion line, and then flux reconnection forms and maintains a prominence in the filament channel.

6. If the reconnection ceases, the filament simply fades away, since it is no longer maintained (such an example on 1980 June 25 has been observed by V. Gaizauskas 1995, private communication); the process of flux reconnection tends to add magnetic helicity to a prominence and therefore build up the prominence twist, so that, if the twist becomes too great, the prominence will erupt, in agreement with paradigm D (however, an alternative possibility is that the global flux which is connected below the photosphere emerges, and so the coronal field lines are no longer anchored and erupt by magnetic buoyancy).

7. At middle and high latitudes the subsurface velocity shear is mostly due to solar differential rotation, which explains observations III and IV; the lack of a correlation between dextral/sinistral and hemisphere at low latitudes suggests that the horizontal velocity shear in this region is more variable (sometimes in the same sense as the average differential rotation, sometimes in the opposite sense).

The key organizational principles in the new model are the following: the differential rotation of subphotospheric flux continually producing flux parallel to the polarity inversion line; the relaxation of the overlying coronal field to a minimum energy state (which will be a linear force-free field that conserves global magnetic helicity—i.e., close to a potential state when such magnetic helicity is small); the emergence of subphotospheric flux in small bipoles oriented along the polarity inversion line; and the reconnection of such flux to form long field lines lifting cool material to prominence heights. These produce a coherent picture which explains many diverse observations in a natural way.

The theoretical ideas we have been putting forward stress the importance of a detailed program of prominence observations to answer new questions and deepen our understanding of the prominence phenomenon. In this program it is crucial to have coordinated observations of photospheric magnetograms, Hα and He λ10830 features, and coronal X-ray structures. In particular, more observations are urgently required to try to answer the following key questions:

a) How is the parallel field of a filament channel built up? What is the flux imbalance along a channel, and how did it originate? Is there a preferred orientation in the emergence of flux? What are the structure and evolution of a filament channel? Where are the main sources and sinks of flux? What flux cancellations are taking place? How are the changes in the Hα and He λ10830 structure from day to day related to changes in the magnetic sources?

b) What evidence is there for or against particular formation mechanisms of filaments? How does the mechanism vary with latitude? We are suggesting that the mechanism may be subphotospheric (differential rotation at east-west polarity inversion lines at high latitude or general shearing motions parallel to inclined inversion lines at intermediate and low latitudes), or it may be photospheric (differential rotation of north-south lines at intermediate latitudes or general shearing motions at intermediate and low latitudes).

c) What are the origin and evolution of plagettes and their influence on the filament? Do they form by intrusion of network flux that is initially connected elsewhere or by the emergence of flux parallel to the polarity inversion line?

d) Do feet or barbs end in opposite-polarity fragments? How do such fragments originate and evolve? Are the feet formed by flux emergence or flux reconnection? How do feet change in time in relation to the evolution of the neighboring magnetic fragments? What is the difference between fine short-lived barbs and thicker longer-lived feet?

e) Finally, do filaments fade when reconnection stops? Are they disrupted and broken when the plagettes are too strong? Do they erupt when the twist is too great?

Several other properties of prominences may be understood in a natural way in the light of the theory we are proposing. First, why are prominences in active regions of either dextral or sinistral parity? Why is there a hemispheric pattern for quiescent filaments but not for active-region ones? Outside active regions the subphotospheric flows are dominated by differential rotation in the systematic way we have described and so naturally produce dextral filaments in the northern hemisphere and sinistral ones in the southern hemisphere. However, in the active-region belts the subphotospheric flows are much more complex and so can lead to flux emergence with a much greater variety of inclinations, thereby giving either dextral or sinistral prominences. Then, second, what makes only the dextral filaments survive in the northern hemisphere? As filaments migrate away from active regions, they move from a relatively mixed and random medium into a quieter and more systematic one. The necessity for prominences to be continually fed in our scenario with mass and flux by flux reconnection means that, when a filament leaves an active-region zone, it will continue to exist only if it is of the right parity for that hemisphere, since its "food" (in the form of new flux emerging from below and growing by reconnection) will be of only one parity in a given hemisphere. Finally, why do some parts of a quiescent filament channel, and not others, contain filaments? According to the theory, this should depend on the amount and duration of flux reconnection—which in principle could be tested observationally.

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