Axial Fields in Quiescent Prominences

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ABSTRACT

The formation of poleward-migrating coronal magnetic structures associated with high-latitude solar prominences is considered. These structures are observed to have axial fields which are inconsistent in direction with models in which differential rotation acts upon a line-tied, coronal magnetic field along a polarity inversion line running east-west. It has been pointed out that the correct axial fields are produced when the polarity inversion line begins at a large tilt angle ($\gtrsim 90^\circ$) with respect to latitude, but considered this mechanism to be implausible for solar prominences. This paper argues that decaying active regions provide the regions of unipolar flux between which prominences are observed to form, and demonstrates how "Joy's Law" provides the initial tilt angles for axial fields to be formed with the correct orientation.

Subject headings: Sun—Sun: rotation—prominences: quiescent, axial fields

1. Introduction

Solar prominences are coronal magnetic structures in which relatively cool (5000–10,000 K; c.f., Hirayama, Nakagomi, and Okamoto 1979; Heasley and Milkey 1983) and dense ($10^{11}\,\mathrm{e}^-\,\mathrm{cm}^{-3}$; c.f., Landman 1985; Foukal, Hoyt, and Gilliam 1986) plasma is suspended at coronal heights (10^4–10^5 km) above the photosphere. The surrounding corona is about 100 times hotter and more rarefied, so the prominence material must be thermally shielded from the corona by its magnetic field. Prominences are invariably located along segments of polarity inversion lines (PIL) which separate regions of positive and negative flux through the solar surface. Some prominences are associated with the sunspot latitudes. This type is short-lived and migrates equatorwards with the sunspots over the course of the solar activity cycle. Other prominences form poleward of the activity belt and move to higher latitudes. (The polar crowns are comprised of such prominences which have migrated to the boundaries of the polar coronal holes.) This type of prominence may last for days or even weeks and is described as "quiescent".

The magnetic fields of prominences projected above the solar limb can be measured by the Zeeman and Hanle effects (Leroy 1989). The results indicate that these fields are mostly horizontal with components parallel (axial) and perpendicular (transverse) to the long axis of the prominence (Athay et al. 1983; Querfeld et al. 1985). The overall field is close to axial, usually at an angle of 15° to 30° with respect to the prominence axis (e.g., Tandberg-Hanssen and Anzer 1970; Leroy, Bommier, and Sahal-Brechot 1984). Much has been made of the direction of the transverse fields in the discrimination between prominence models. However, Rust (1967) and others later (c.f., Leroy, Bommier, and Sahal-Brechot 1984) point out that the direction of the axial fields also imposes constraints on the nature of prominence formation.

The direction of the axial field $\hat{\mathbf{b}}$ obeys a hemispheric dependence (illustrated in Figure 1*a*) such that $\hat{\mathbf{b}} = \pm\hat{\mathbf{n}} \times \hat{\mathbf{r}}$, where the plus sign applies in the northern hemisphere (and minus in the southern). The vector $\hat{\mathbf{n}}$ points across the PIL from the positive to the negative side, and $\hat{\mathbf{r}}$ points radially outwards from the Sun; the vector $\hat{\mathbf{n}}$ generally alternates with the solar activity cycle.

As a result of the high electrical conductivity of the solar atmosphere, the magnetic field is "tied" to the plasma and at the photosphere the plasma motion dictates the motion of the field. Hence,

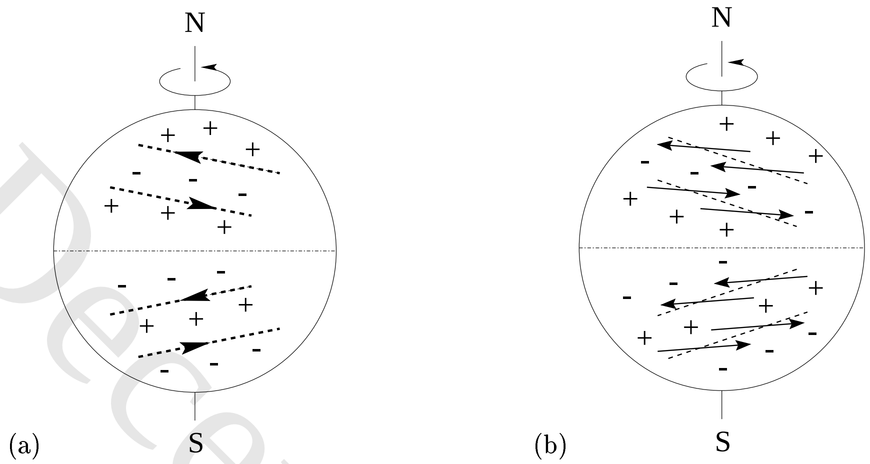

Fig. 1.— Observed axial fields vs. model prediction. (*a*) The *observed* direction of axial fields in quiescent prominences for each hemisphere, and relative to the polarity distribution of the surface flux. (*b*) The sense of shear for arcade lines over a polarity inversion line (PIL) as produced by Model A. Note that the components of sheared field along the polarity inversion lines agree with the sense of the axial fields in (*a*). This figure is based on Figure 1 of van Ballegooijen and Martens (1990), with the notable exception that the pair of PILs in each hemisphere represent young, poleward-migrating prominences, and do *not* describe polar crown prominences.

shearing flows on and below the surface will rotate fields initially transverse to become axial. The solar differential rotation (i.e., the latitudinal gradient of the rotation) produces shear flows at the surface and is a natural candidate for explaining the hemispherical dependence. However, van Ballegooijen and Martens (1990) demonstrated how an arcade, initially constructed of potential fields with the PIL running east-west, which is sheared by differential rotation, will acquire an axial component which has the *opposite* direction to the observed direction of axial fields in solar quiescent prominences.

They proposed two mechanisms which utilize the differential rotation to produce axial fields which match observations. In their first solution (hereafter, Model A), the PIL must be rotated by the shear by more than 90°. They discounted this idea on the grounds that quiescent prominences (and polarity inversion lines) at high latitudes are almost always oriented east-west and are not observed to rotate through large angles. Their second solution (hereafter, Model B) invokes subsurface differential rotation and a complicated process which involves three stages of reconnection and the eruption of a heretofore unobserved helical field.

This paper argues that polarity inversion lines of prominences can indeed be rotated through angles greater than 90° when they are associated with the dispersal of active regions, and hence the simpler Model A applies.

2. Neutral line rotation

The creation of an axial field component via differential rotation is modelled in van Ballegooijen and Martens (1990); their case for initial angle $\beta_0 > 90°$ is illustrated in Figure 2. In this description, the field lines are initially potential in an arcade formation at right angles to the PIL (Figure 2*a*). The field is "line-tied" to the motion of the photosphere. The rotational shear in the local frame of reference is given with the surface velocity:

$$v_x = -\omega y, \qquad v_y = 0, \tag{1}$$

where the x-axis runs east-west and the y-axis runs north-south, and ω is the radially outward component of vorticity associated with the differential rotation ($\omega > 0$ in the northern hemisphere).

The PIL begins at an angle β_0 with respect to a line of constant latitude and as time advances

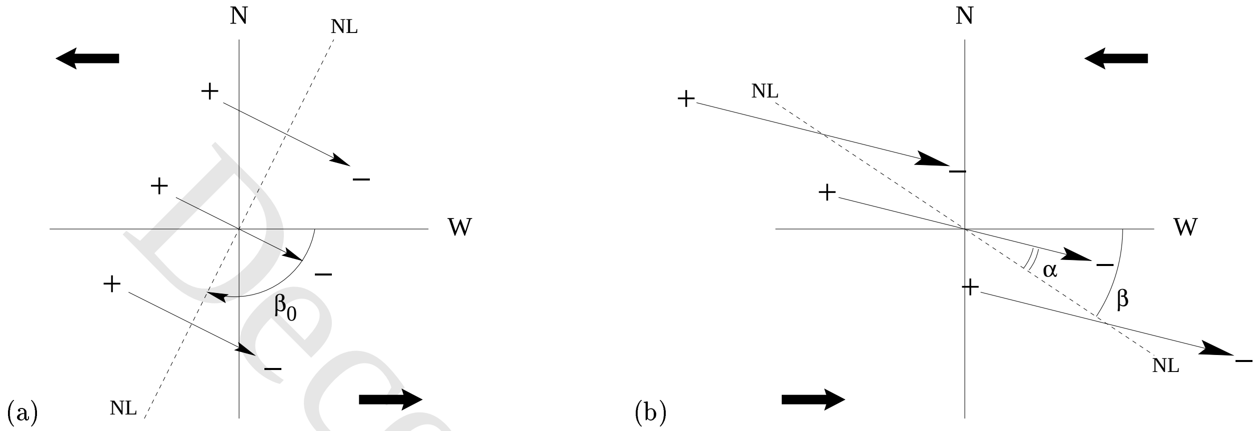

Fig. 2.— Arcade shear by differential rotation. (a) Initial configuration of a potential field arcade over a polarity inversion line (PIL) with symmetry along the axis. The thick arrows indicate the direction of a shear appropriate to the northern solar hemisphere. The angle β_0 between the PIL and a line of constant latitude begins at a value greater than 90°. (b) The arcade at a later time where the fields have moved according to a linear surface shear. The PIL has rotated, and the angle α between the PIL and the fields is no longer equal to 90°, which indicates there is an axial component. This figure is based on Figure 3 of van Ballegooijen and Martens (1990).

$\beta(t) \rightarrow 0$. The angle α between the field lines and the PIL begins at 90° and also becomes more acute with the passage of time, i.e., the initially transverse fields are sheared such that they gain an axial component (Figure 2b). Figure 1b indicates the direction of the sheared fields in each hemisphere. A comparison with Figure 1a confirms that this mechanism produces the observed direction of axial fields *for young, poleward-migrating prominences.* This mechanism of neutral line rotation is not argued here to produce the correct axial fields for the older population of prominences which form the polar crowns. The pair of PILs in each hemisphere of Figure 1 is intended to indicate the arrangements for alternate advancing fronts of quiescent prominences.

This result is mathematically described in van Ballegooijen and Martens (1990) as a function of the initial angle β_0 and time. For the case where $0° < \beta_0 < 45°$, neutral line rotation gives the *incorrect* orientation of the axial component. For the intermediate range of initial angles where $45° < \beta_0 < 90°$, the arcade shear gives the correct axial orientation at early times $t < t_1$, and the incorrect orientation at later times $t > t_1$. The reversal time t_1 is given in their Equation (7):

$$t_1 = \omega^{-1}(\tan\beta_0 - \cot\beta_0). \qquad (2)$$

They point out that for β_0 just under 90°, t_1 might be long enough for a prominence to form while the axial fields still have the correct direction. Once the prominence forms, the axial "correctness" would be frozen in, so for short prominence formation time scales, the range of favorable initial angles may extend below 90°.

This mechanism (Model A) was deemed implausible by van Ballegooijen and Martens (1990) since they believed that such large initial tilts of the PIL were not observed. In fact, there is a large population of polarity inversion lines which starts with this magnitude of tilt. Active regions arise as two concentrations of oppositely-polarized magnetic flux. Described as "Joy's Law" (Hale et al. 1919), the long axis of this bipole is, on average, tilted with respect to latitude such that the leading polarity is closer to the equator than the following polarity (for a statistical treatment, see Fisher, Fan, and Howard 1995). The PIL begins as the perpendicular bisector of the long axis and thus must be at an angle $\beta_0 > 90°$. Figure 3 displays the dispersal of flux from a bipole according to a flux-transport model which includes a parabolic rotation profile and diffusion. The center of the bipole begins at 15° N with an initial tilt angle of 10° towards the equator. This pat-

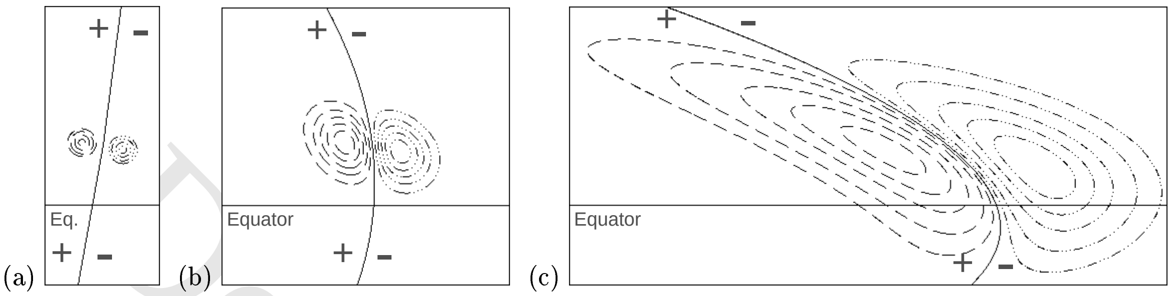

Fig. 3.— Evolution of a flux bipole from two point sources of opposite polarity according to diffusion and parabolic shear across latitudes. The positive (+) polarity is marked by long dashes, the negative (−) by dash-dot-dot-dot. The curved solid line indicates the polarity inversion line (PIL). The horizontal solid line indicates the solar equator. Parameters are fit to solar values of differential rotation and diffusion and the solution models the decay of an active region at (*a*) 0.1, (*b*) 1.0, and (*c*) 5.0 solar rotations (see Weber and Longcope 2000). Contour levels are shown to indicate shape and are not similarly scaled between figures. Note the rotation of the PIL.

tern is regularly observed in magnetograms, and was modelled early on by Leighton (1964). The PIL is observed to rotate over time. Statistically, most of the large regions of leading polarity at high latitudes will arrive through this configuration. Insofar as the fields retain their topological connectivity to the following region of opposite polarity, the correct axial fields should be formed in the conceptual manner of Model A.

3. Discussion

The second solution of van Ballegooijen and Martens (1990) for the formation of axial fields with the observed direction was based on the observation that for small β_0, the *subsurface* sections of the arcade are sheared to have the correct axial component. Models such as that of Priest, van Ballegooijen, and MacKay (1996) are based on this mechanism. In the preparation phase of their model, the sheared arcades would be expected to show axial components with the incorrect orientation; however, they argue that the coronal fields intermittently relax to a potential configuration on a timescale of days according to the tearing mode instability.

In contrast, Model A of van Ballegooijen and Martens (1990) produces the correct axial fields almost immediately, although in reality the initial field configuration of active regions is not that of a uniform arcade with symmetry along the axis. The argument that the shear of active regions produces the correct axial fields requires further investigation into the efficiency with which the initially concentrated flux diffuses outward along the polarity inversion line to form the sorts of unipolar regions between which prominences are found. The assumption that the fields are "line-tied" may also need deeper consideration. It is apparent that magnetic reconnection takes place in the photosphere, and is probably a key mechanism in the evolution of the largest coronal structures (c.f., Wang and Sheeley 1993, on the rigid rotation of coronal holes). This reconnection can allow sheared fields to relax, which would greatly impact upon the progression of Model A. On the other hand, reconnection is probably necessary to construct a prominence in the inverse topology (Pneuman 1983; van Ballegooijen and Martens 1989). The question is not whether reconnection takes place, but whether it allows the coronal fields to relax to their potential state on the timescales associated with the formation of filament channels. Active region structures are observed to resist complete relaxation, sometimes for several solar rotations (i.e., months), so it appears possible that the axial fields can be maintained in Model A under solar conditions.

Joy's Law states that there is a statistical tendency for active regions to have tilt angles such that the leading polarity is closer to the equator than the following one. However, there is a lot of scatter in the distribution of observed tilt angles, and a non-negligible part of the population corresponds to initial angles $\beta_0 < 90°$. As mentioned earlier, angles β_0 just under $90°$ can still lead to correctly oriented axial fields if the prominences form early enough to freeze the axial direction. The small number of quiescent prominences which are observed to violate the hemispheric rule for axial direction are predicted to correspond to the small population of active regions which go against Joy's Law, i.e., which supply initial angles β_0 too much less than $90°$. A statistical comparison of these two populations could be made to test this hypothesis. Conversely, an assumption of correlation could be used to estimate t_1, the prominence formation time.

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