CORONAL HOLE BOUNDARIES AND THEIR INTERACTIONS WITH ADJACENT REGIONS

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Abstract. Coronal hole boundaries are the interfaces between regions where the coronal magnetic field contains a significant component which is open into the heliosphere and regions where the field is primarily closed. It is pointed out that there are constraints on the magnetic field which opens into the heliosphere that must be satisfied in the corona: it must come into pressure equilibrium in the high corona, and the component of the field which connects to the polar regions of the Sun must differentially rotate. A model is presented in which satisfying these constraints determines which field lines are open and which are closed, and thus where the polar coronal hole boundaries occur. Some of the consequences of this model are discussed.

Key words: coronal holes, solar wind, Ulysses

1. Introduction

The subject of this paper is coronal hole boundaries and their interactions with adjacent regions. It is perhaps appropriate to begin then by defining a coronal hole boundary. The definition here will be quite simple: a coronal hole boundary is the interface between a region in the corona where the magnetic field contains a significant component which is open into the heliosphere, and a region where the magnetic field is primarily closed. This is not to say that on the side with a significant open field there are no loops and other closed structures—presumably there are—but there is nonetheless a significant open field component. Of course from this open field, the solar wind flows, reduces the coronal density, and thus forms a coronal hole. We will also concentrate here on solar minimum conditions, and in particular on the well developed and somewhat stable polar coronal holes and their extensions.

Wang, Sheeley, and co-workers, in a series of papers (Nash *et al.* 1988; Wang *et al.* 1988; Wang and Sheeley 1993; Wang *et al.* 1996) have argued that the positioning of coronal holes arises from the superposition of an axial symmetric polar magnetic field and a non-axial symmetric equatorial field. It is thus the global magnetic field structure of the Sun that specifies coronal hole boundaries. These models are intrinsically static since the field configuration is determined from a potential field model. However, the evolution of the coronal hole and its boundaries under the influence of differential rotation can be modeled by assuming that the corona is in continuous relaxation to a potential field configuration, presumably due to reconnection. This model provides an explanation for the apparent rigid rotation of the polar coronal holes.

In this paper we argue a somewhat different point of view. Namely, the differential rotation of the photosphere results in motions of the coronal magnetic field.

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However, field lines in the corona which open into the heliosphere must relax to being essentially in pressure equilibrium in the high corona. It is then the motions due to differential rotation combined with the need to relax to pressure equilibrium which determine which field lines are open into the heliosphere and which are closed, and therefore where the coronal hole boundaries occur. The general concepts of this approach and additional details are discussed in Fisk *et al.* (1999).

There are important differences in the consequences of the model presented here and those of, e.g., Wang and Sheeley. In this model no reconnection is required within the polar coronal hole; indeed, differential rotation and the absence of reconnection cause the field line motions described here. Reconnection does determine the coronal hole boundaries, but even here, as we shall discuss, it occurs at low latitudes removed from the photospheric boundary of the polar coronal hole. Moreover, the heliospheric magnetic field which results from the model presented here is fundamentally different from that which results from a traditional potential field model for the corona.

2. Relevant Observations

Lets us begin then by reviewing some of the observations of open field lines, which are summarized in Table I. The Table has been divided into three categories of observations, or of inferences from the observations. The first are heliospheric, of the properties of open field lines and of the solar wind; the second are solar observations, and the third category includes some solar and heliospheric observations which will support the arguments that we will make. The first heliospheric observation is the well known one that at least near solar minimum the polarity of the heliospheric magnetic field is essentially uniform in each hemisphere, and with the polarity of the corresponding solar pole. The regions of uniform polarity are separated by an equatorial current sheet. The current sheet is the expected extension of the streamer belt. It is wavy, but even more important it is tilted relative to the solar rotation axis, and that tilt becomes less as we approach solar minimum (Shultz 1973; Smith *et al.* 1978; Suess *et al.* 1993).

The second observation is that the radial component of the heliospheric magnetic field is essentially uniform with latitude, as has been documented in detail by Smith and Balogh (1995), from Ulysses observations. A uniform field strength with latitude is what should be expected, which is a point that has been made convincingly by Suess (1999). If we extrapolate back the magnetic field strength and the solar wind plasma pressure, we easily conclude that the beta of the plasma—the ratio of thermal to magnetic energy—is very small, 10^{-2} or less in coronal holes, at a few solar radii from the Sun. The radius of curvature of the open field lines is relatively large at this point. The open field lines are essentially radial. A low beta plasma cannot support any net magnetic forces. The only alternative is then no pressure gradients in the magnetic field strength. That is to say the magnetic field becomes uniform in strength in the corona, and thus creates a magnetic field in the

Table I
Observations relevant to this theory

Observations	Comments
Heliospheric	
Magnetic field is divided into two regions of uniform polarity separated by an equatorial current sheet (e.g., Smith *et al.* 1978).	Current sheet is the expected extension of streamer belt; it is wavy and tilted relative to solar rotation axis.
Radial component of magnetic field is uniform with latitude (Smith and Balogh 1995).	
Extrapolation of solar wind parameters—magnetic field strength and plasma pressure—back to high corona yields a plasma with a very small β (Suess 1999).	Implies force-free conditions. Field is essentially radial, which implies magnetic pressure must be essentially constant.
No strong time variations in heliospheric magnetic field near solar minimum (Smith and Balogh 1995).	
Solar wind occurs in two types: fast and steady, and slow and variable (e.g., Phillips *et al.* 1995).	Fast wind from polar coronal holes occurs at higher latitudes; slow wind from band about equatorial current sheet.
Magnetic field lines from polar coronal holes expand non-radially.	Polar coronal holes at base of corona have smaller solid angle than regions of high speed wind in heliosphere.
Fast and slow wind have different origins (Geiss *et al.* 1994).	Slow wind has strong FIP bias; fast wind does not.
Solar	
Photosphere differentially rotates (e.g., Snodgrass 1983).	20–25% slower rotation, or more, at poles.
Characteristic scale size for organization of magnetic field in photosphere is supergranules, or $\lambda \sim 30{,}000$ km; characteristic time scale for reconfiguration of network is $\tau \sim 1$–2 days (Schrijver *et al.* 1997).	Limits rate at which field lines should diffuse in photosphere or corona; effective diffusion coefficient is λ^2/τ.
Supporting	
Corona rotates more rigidly than photosphere (e.g., ref. in Bird and Edenhofer 1990).	
Low energy energetic particles propagate easily in heliographic latitude (e.g., Roelof *et al.* 1997).	

heliosphere which is uniform strength, as is observed. We will make considerable use here of the uniformity of the field strength of open field lines in the corona, at several solar radii.

We should note also that there are no large time variations in the heliospheric magnetic field (Smith and Balogh 1995). At least at this point in the solar cycle, the total magnetic energy in the magnetic field in the heliosphere is relatively constant. Coronal mass ejections do occur, bringing out new magnetic flux, but during solar minimum this is not a large effect, and in general we are dealing with a heliospheric magnetic field strength which is constant in time and a radial component, or equivalently a strength back in the corona, which is constant in latitude and longitude.

The next observation is that the solar wind comes in two types: fast and slow. The fast wind occurs at the higher latitudes, above 30 degrees or so in heliographic latitude. The slow solar wind occurs at low latitudes. The fast wind extends downward in latitude below 30 degrees heliographic latitude, and then as it flows outward it overtakes and interacts with the slow wind. The geometry in a rough sense is simply that the slow wind originates from a band that surrounds the equatorial current sheet which in turn is tilted in heliographic latitude.

The fast wind is considered to originate from the polar coronal holes. The polar coronal holes occupy a much smaller solid angle in the low corona than does the fast solar wind. There must therefore be a considerable nonradial expansion of the open field lines from the polar coronal holes, from a small surface area in the low corona, to the larger surface area in the heliosphere.

The origin of the slow solar wind is less clear, which is a point we will discuss later. However, whatever is the origin of the slow wind it is different from the origin of the fast wind. As has been described in detail by, e.g., Geiss *et al.* (1994), the slow wind is enhanced in elements with low first ionization potential (FIP), whereas in the fast wind, there is little or no such enhancement. Enhancements based on first ionization potential must occur in the chromosphere where the particles can be neutral. Clearly, there is then a difference in the origin in the low corona and chromosphere between the fast and slow wind, and thus between the open field lines on which the fast and slow wind flows.

For solar observations, we will make use first of the well known fact that the photosphere differentially rotates, with the poles, to the extent that the photospheric rotation rate can be determined at high latitudes, rotating 20–25% slower than the solar equator (e.g., Snodgrass 1983). The second solar observation is more of an inference than an observation. The characteristic scale size for the organization of the magnetic field in the photosphere is the size of supergranules, $\lambda \sim 30{,}000$ kilometers. As has been seen by the SOHO MDI observations, this network of supergranules appears to be reconfigured on a time scale of $\tau \sim 1$–2 days, through the continuous emergence of new flux (Schrijver *et al.* 1997). New loops emerge and reconnection occurs. This reconfiguration is somewhat of a random process. And should result in a diffusion of magnetic field lines, with a characteristic diffusion coefficient of λ^2/τ . We will use this diffusion coefficient later to argue that random motions of the field lines must be sufficiently slow so that, for the time scales with which we will be interested, the rotational motions of the Sun are more important than these diffusive motions. The magnetic field lines, in effect, simply remain attached to the differentially rotating photosphere.

Finally, there is a category in Table I called supporting observations, which will support the conclusions that we will draw here, and which we will return to below in more detail. The solar observation that is supporting is that the corona tends to rotate more rigidly than the underlying differentially rotating photosphere. If we look at coronal green lines, prominences, or the boundaries of well defined coronal holes, or particularly their extensions, they tend to rotate more rigidly than the photosphere, at least during the declining activity phase (e.g., ref. in Bird and Edenhofer 1990). Finally there are some heliospheric observations of the configuration of the heliospheric magnetic field and the important Ulysses observation that low energy energetic particles propagate easily in heliographic latitude (Roelof *et al.* 1997).

3. Surface of Constant Pressure

Consider now the following spherical surface which is illustrated in Figure 1. The surface is placed at several solar radii from the Sun. The surface is permeated only by open magnetic field lines. That is, the surface is safely above any closed loop structures. We will also place this surface well inside the Alfvén point, which typically occurs at 10–15 solar radii, in which case the dynamic pressure of the solar wind is not important. From the list of heliospheric observations in Table I, and the inferences from them, the plasma at this surface is a very low beta plasma, i.e., thermal pressure very much less than the magnetic field pressure. The magnetic field, then, must be in a force-free configuration; no thermal pressure forces to balance the magnetic forces. We assume, however, that the radius of curvature of the magnetic field which permeates this surface is large compared to the radius of the surface. That is, the field lines through this surface are essentially radial, in which case the magnetic field strength must be nearly constant.

We marked on the surface several regions. First is the location of the equatorial current sheet, which for simplicity we take to be a plane, that is, no warps, and which is tilted relative to the solar rotation axis. If we define an axis "M" that is normal to this plane, and use M to define a spherical coordinate system, then the equatorial current sheet lies at a polar angle, θ_M, of 90 degrees.

The slow solar wind is considered to come from a band about the equatorial current sheet. Again, for simplicity we take this band to be uniform, and to reach to a polar angle of θ_{M_1} . The fast solar wind comes from the region $\theta_M < \theta_{M_1}$.

The field lines which carry the fast solar wind have a non-radial expansion underneath the surface in Figure 1; they connect to the polar regions of the Sun and form the polar coronal hole. The field lines which carry the slow solar wind have an unspecified origin at this time, to which we will return.

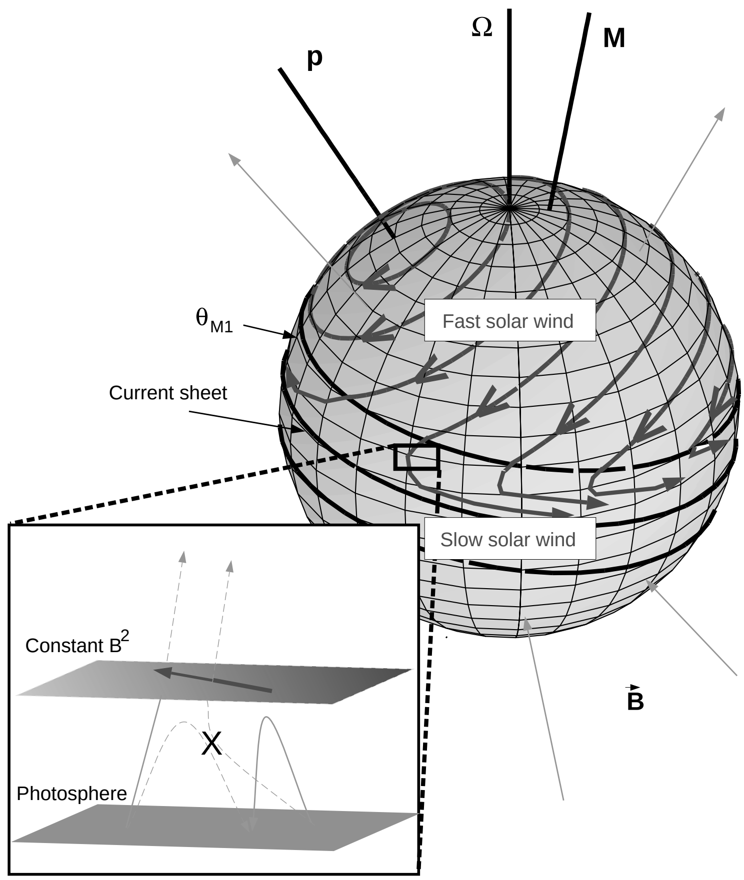

Figure 1. The surface of constant magnetic pressure. The surface is located at several solar radii from the Sun, and is penetrated only by open magnetic field lines. The surface is located in a region of low beta plasma, and the field lines are primarily radial. The location of the equatorial current sheet and the interface between the regions of fast and slow solar wind, θ_{M1} , are marked. The M-axis is normal to the plane defined by the equatorial current sheet, and is offset from the solar rotation axis Ω. The field line located at p connects to the solar heliographic pole. The arrows on the surface are the trajectories of the field lines which penetrate through the surface, and are described in the text.

The Sun is of course not this regular. However, we do know that the boundary between the fast and slow solar wind is tilted relative to the rotation axis; otherwise the two flows would not interact. This tilt of the interface is the important issue.

Consider now any motions of the magnetic field on this surface. There is no reconnection occurring on the surface, and thus the inductance equation is simply:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) \tag{1}$$

This equation can be then be manipulated into the following form:

$$\frac{\partial B^2/2}{\partial t} = -\nabla \cdot (B^2 \mathbf{u}_\perp) - \mathbf{u}_\perp \cdot [(\nabla \times \mathbf{B}) \times \mathbf{B}] \tag{2}$$

where $\mathbf{u}_\perp$ is the velocity normal to the magnetic field direction.

The first assumption is that the magnetic field is essentially constant in time. The flux of open magnetic field near solar minimum is not changing, in which case the time derivative of B^2 is zero. We are also assuming that the magnetic field is essentially force free; it is a low beta plasma. That is, $(\nabla \times \mathbf{B}) \times \mathbf{B}$ must be essentially zero. We also assume that the field is essentially radial, in which case force-free is equivalent to constant field magnitude, and the motions normal to the field must lie on the surface we have just defined.

With these assumptions, then, any motions on the surface of constant magnetic pressure must satisfy

$$\nabla \cdot \mathbf{u}_\perp = 0 \tag{3}$$

This is a rather obvious point. Any motions which result in a divergence would also result in an accumulation of magnetic field strength, which cannot be supported in our force-free field conditions.

At the equatorial current sheet the polar component of $\mathbf{u}_\perp$ must be zero. We are not mixing polarities across the current sheet. We are not annihilating magnetic fields at the current sheet and reducing the field strength in time. We thus have a boundary condition at the current sheet that $\mathbf{u}_\perp$ must be zero, and $\mathbf{u}_\perp = 0$ is a solution to equation 3. It is not unreasonable then to ask whether $\mathbf{u}_\perp$ is zero everywhere. This, however, is unlikely. The surface in Figure 1 should be roughly stationary in the frame co-rotating at the equatorial rotation rate of the Sun. The current sheet is a low latitude structure. Similarly this boundary, θ_{M_1}, between the fast and slow solar wind is at low latitudes, and the axis in this figure, the M axis, is drawn normal to the plane of the current sheet. All these structures, then, are rotating essentially with the equatorial rotation rate. However, the magnetic field lines which penetrate this surface in the fast solar wind region attach back to the polar region of the Sun, which differentially rotates 20 to 25% slower than the equatorial region.

We argued earlier that if we consider the rate at which field lines are likely to diffuse across the solar surface, we are constrained by the fact that the characteristic dimension for the photosphere magnetic field is the size of supergranules, some 30,000 kilometers, and the characteristic time is the observed time during which the supergranule network is reconfigured, which is 1 to 2 days. If we compare the resulting diffusion time with the time during which the field lines differentially rotate, we find that at high latitudes the differential rotation time is much faster. This is not surprising. In general a systematic convection wins over a random diffusion, unless the diffusion is extremely fast. The point is, however, that the field lines which penetrate the surface in Figure 1 in the fast wind region are attached to the photosphere in the polar region. They are thus forced to differentially rotate and move along this surface. That is, $\mathbf{u}_\perp$ will not be zero along this surface.

We can estimate what these velocities are likely to be along the surface in Figure 1, as was done by Fisk (1996) in discussing the heliospheric magnetic field that results from these motions along this surface. The M axis is essentially the axis of symmetry of the expansion of the magnetic field from the polar coronal hole. We have some field strength for open field lines on the solar surface, and they expand non-radially to a uniform field strength on the surface in Figure 1. There is then a simple one-to-one mapping of every open field line on the solar surface to this outer surface. This is best illustrated in Figure 2. The center sphere depicts the solar surface. The outer shell is the surface in Figure 1. The M axis is the same, as is the rotation axis. The field lines expand about M, symmetrically and non-radially from the solar surface to the outer surface. Figure 2 is again in the frame which co-rotates with the equatorial rotation rate. The M axis is fixed because it is normal to the equatorial current sheet. However, the solar surface in the polar region is differentially rotating. And the field lines which are attached to this differentially rotating surface are forced to move along the outer surface on the trajectories shown. This situation is easiest to see if we examine the field line which comes from the solar pole. It of course does not differentially rotate, and in this co-rotating frame, it expands non-radially and comes out at the fixed location marked p on the outer surface. All other field lines differentially rotate about this field line on the solar surface, and about p on the outer surface. Because the M axis is offset from the rotation axis, and the non-radial expansion is considerable, the excursions of the field lines in latitude and longitude on the outer surface are considerable.

We have drawn these trajectories in Figure 2 as circles. In reality they will be more complicated. The expansion is not really symmetric about M, the field strength on the solar surface may be uneven, etc. However, circles are easy to deal with, and they should indicate the general trends of the motions.

The field line trajectories in Figure 2, which are for the magnetic field in the fast solar wind region in the polar coronal hole, are also shown in Figure 1. In the slow solar wind region, there must also be trajectories, because we have a requirement that $\nabla \cdot \mathbf{u}_\perp = 0$ everywhere on the surface. The motion in the θ direction across the interface from fast to slow solar wind must be continuous. The motion in the θ direction at the current sheet must be zero. We are not mixing polarities across the current sheet or eliminating flux here. The solution for $\mathbf{u}_\perp$ in the slow solar wind region is then completely determined, and is discussed in detail in Fisk *et al.* (1999). The solution is shown schematically in Figure 1 with the arrows in the slow solar wind region.

The physics here is fairly simple. In the fast solar wind region, differential rotation drives the motions of the field lines. In the slow solar wind region, our requirement that there is no magnetic pressure buildup drives the motions. In other words, if we did not have the predicted motions, the deposition of magnetic flux at

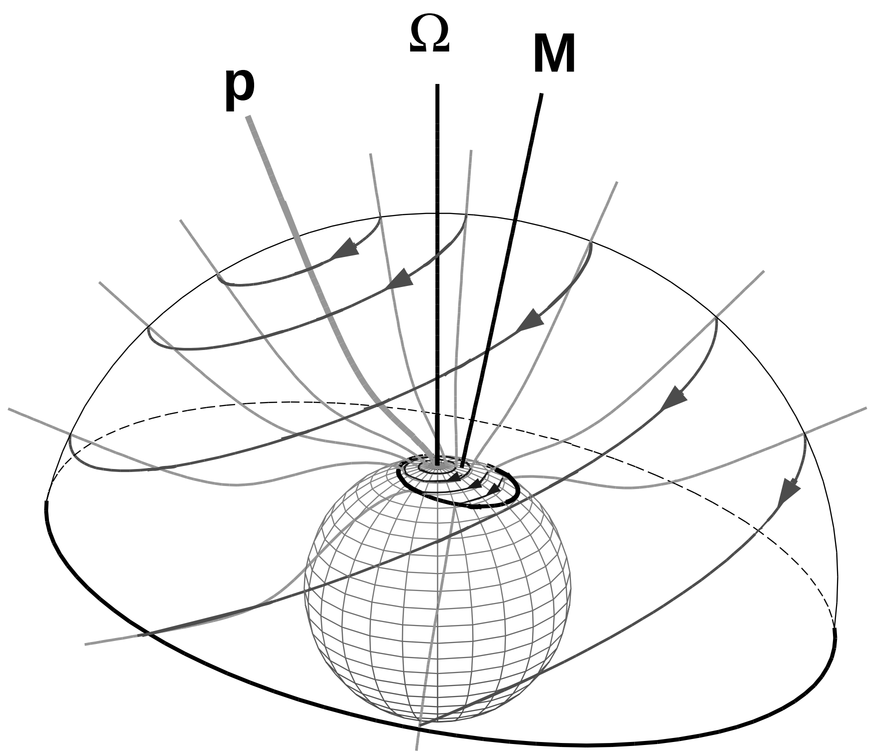

Figure 2. An illustration of the motions of the magnetic field in the corona, in the polar coronal hole, as predicted in the model of Fisk (1996) (after Zurbuchen *et al.* 1997). The outer surface, which is defined in the text, is penetrated only by field lines which open into the heliosphere, and which have essentially constant magnetic pressure. The figure is drawn in the frame co-rotating with the equatorial rotation rate. The M axis is the axis of symmetry for the expansion of the magnetic field from a polar coronal hole. The Ω axis is the solar rotation axis. The open lines are field lines, with p marking the field line that connects to the heliographic pole. The curves with arrows are the trajectories of the field lines, the motions of which are driven by differential rotation of the photosphere.

low latitudes, resulting from the differential rotation, would cause a flux build-up that cannot be supported. Since we are not allowing flux through the current sheet, the only recourse is motion in longitude, back to the other side of the Sun.

Let us return now to the coronal hole boundary problem. The base of an open field line in the polar coronal hole moves by differential rotation. This forces motion of the field lines on the surface in Figure 1. Eventually it reaches low latitudes. No buildup in the magnetic forces is allowed. Thus the field line must turn to make the return trip to the other side of the Sun. It then becomes entangled with other field lines, perhaps with large loops, and presumably reconnects. Failure to perform this reconnection would yield a very unnatural and insupportable bend in the field line. The top end of the field line must move to avoid magnetic pressure buildup.

The bottom end must find a way to follow. As the field line traverses back to the other side of the Sun at low latitudes, it presumably does so through a series of reconnections, which are illustrated schematically in the insert in Figure 1.

Now we are back to the main subject. When the polar field line reconnects, it produces a large scale closed loop. In other words, the polar field line is opened into the heliosphere until it moves to low latitudes, after which it reconnects. We have thus defined the boundary of the coronal hole. It occurs when the non-radial expansion of the polar field brings the upper end of the field line to low latitudes, and it is forced to reconnect in order that it can make the return trip back to the other side of the Sun.

The process on the other side of the Sun is more difficult—the side opposite to the one shown in Figure 1. Field lines at low latitudes are transported in longitude, and then on the back side of Figure 1 they must reconnect to polar field lines to continue the motion across the polar hole. A low latitude field line thus has to find a high latitude field line with which to reconnect. Perhaps this is a multi-step process in which the reconnection occurs with some intermediate latitude loop and then with a polar field line. The point is, however, if such reconnection does not occur, there would be an unacceptable buildup or depletion of magnetic flux and pressure on the surface in Figure 1.

In this model, then, the constraint which determines which field lines are open and which are closed is the requirement that the magnetic pressure is constant on the surface in Figure 1. Differential rotation will drive motions of the field lines on this surface. Field lines are continuous down into the photosphere. Thus, at low latitudes the motions on this surface must be accompanied by corresponding motions at the solar surface which only can be accomplished if polar field lines which were opened become closed, and there is continuous reconnection among low latitude loops as the field lines move in longitude.

4. Some Consequences

Consider now some of the consequences of this model. First of all, there is a clear difference between the origin of the fast solar wind and the slow solar wind. The fast wind originates on a single continuously open field line. The slow wind originates on field lines which are continuously reconnecting, jumping from low latitude loop to low latitude loop. This model for the corona, in which there are clear distinctions between the continuously open field lines from the polar coronal hole and randomly open field lines at low latitude, was proposed by Axford (1977). We should expect in these models, as is observed, that the slow wind is much more variable than the fast wind. It is also possible, as was done by Schwadron *et al.* (1999), to construct a first ionization or FIP enhancement mechanism which takes advantage of the fact that in this model the material which forms the slow solar wind started as material which was stored on closed loops. Recall that the slow wind is FIP enhanced, whereas the fast wind is not (Geiss *et al.* 1994).

This model also suggests that the corona should appear to rigidly rotate. The field lines which are open and those which are closed, and thus where the density is enhanced and where it is not, is determined by the global properties: the need for the open field lines to both move on the surface in Figure 1, to not cross the current sheet, and to be in pressure equilibrium. These flow patterns are fixed in the frame which co-rotates with the equatorial rotation rate. The pattern thus rotates rigidly as will the underlying density structure of the corona implied by this pattern.

The coronal hole boundary, in particular, should tend to rigidly rotate, since it forms when the field lines encounter the low latitude interface in Figure 1, θ_{M1}, which is sufficiently low in latitude to rotate effectively at the equatorial rotation rate.

The configuration of the heliospheric magnetic field is a major consequence of this model. The trajectories on the field lines in Figure 1 are simply the footpoints of the heliospheric magnetic field. Unlike the standard Parker spiral for the heliospheric magnetic field, where the footpoints remain at a single latitude and simply co-rotate rigidly with the Sun, here the footpoints make large excursions in latitude and longitude. This creates a much more complicated field configuration in the heliosphere, as has been discussed in detail by Fisk (1996) and Zurbuchen *et al.* (1997).

The large excursions in latitude do provide a natural explanation for perhaps the most curious observation from Ulysses. It is well known that low energy particles—of order an MeV or less—are accelerated in the stream-stream interaction regions in the solar wind, the Co-rotating Interaction Regions, at low latitudes. These accelerated particles, however, are seen up to the highest latitudes observed by Ulysses, up to 80 degrees or so (Roelof *et al.* 1997). In a Parker spiral, the field lies on cones of constant latitude. It is hard to image how these low energy or low rigidity particles can propagate across the magnetic field in latitude. In the model here, however, the magnetic field in the heliosphere, as a result of the motion of the footpoints, can make a direct connection from low to high latitudes, and provides an easy path for the low energy particles to propagate in latitude.

Finally, we should mention that there has always been evidence in heliospheric observations for the motion of the open field lines in the corona. There are periods of time—over hours, days—when the heliospheric field is essentially radial, that is, when it is substantially underwound. In many cases this is unlikely to be a heliospheric effect caused by solar wind interactions. Rather, the more reasonable explanation is that the footpoints of the heliospheric field are in motion back in the corona.

5. Summary

In summary, we have argued that there are constraints that must be imposed on the field lines which open into the heliosphere: they must be in pressure equilibrium in the high corona, they must be anchored into the differentially rotating photosphere, and they must not cross the tilted equatorial current sheet. The tilt of the current sheet is determined by the underlying photospheric magnetic field. When you satisfy these constraints, there are inferences for when and where field lines must be open and when and where they must be closed, and that process of closing previously open field lines, and vice versa, is what determines the location and properties of coronal hole boundaries.

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