ORIGIN OF THE SOLAR WIND: THEORY

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Abstract. A theory is presented for the origin of the solar wind, which is based on the behavior of the magnetic field of the Sun. The magnetic field of the Sun can be considered as having two distinct components: Open magnetic flux in which the field lines remain attached to the Sun and are dragged outward into the heliosphere with the solar wind. Closed magnetic flux in which the field remains entirely attached to the Sun, and forms loops and active regions in the solar corona. It is argued that the total open flux should tend to be constant in time, since it can be destroyed only if open flux of opposite polarity reconnect, a process that may be unlikely since the open flux is ordered into large-scale regions of uniform polarity. The behavior of open flux is thus governed by its motion on the solar surface. The motion may be due primarily to a diffusive process that results from open field lines reconnecting with randomly oriented closed loops, and also due to the usual convective motions on the solar surface such as differential rotation. The diffusion process needs to be described by a diffusion equation appropriate for transport by an external medium, which is different from the usual diffusion coefficient used in energetic particle transport. The loops required for the diffusion have been identified in recent observations of the Sun, and have properties, both in size and composition, consistent with their use in the model. The diffusive process, in which reconnection occurs between open field lines and loops, is responsible for the input of mass and energy into the solar wind.

1. Introduction

The purpose of this paper is to discuss a theory for the origin of the slow solar wind. At solar minimum, the solar wind consists of two distinct components. At higher heliographic latitudes, fast solar wind with speeds of $\sim$750 km s^{-1} originates from the polar coronal holes. At mid latitudes, surrounding the streamer belt in the corona, the wind is distinctly slower, with speeds $\sim$400 km s^{-1} (Phillips *et al.*, 1995). The differences between fast and slow solar wind at solar minimum are even more revealing in their composition. Slow solar wind is enhanced in elements with low First Ionization Potential, or is said to be FIP enhanced. Fast solar wind shows a much smaller FIP enhancement (Geiss *et al.*, 1995; Zurbuchen *et al.*, 1999). During solar maximum, the solar wind exhibits many of the properties of slow solar wind, both in speed and in composition, at all heliographic latitudes. There are, however, isolated and transient coronal holes that yield fast solar wind (Zurbuchen *et al.*, 2001).

To discuss the origin of the solar wind it is necessary first to discuss the behavior of the magnetic field in the corona, and in particular the open magnetic flux. Open

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flux is defined here as the magnetic flux that has been convected outward with the solar wind; the magnetic field lines remain attached to the photosphere, and effectively extend to infinity. These are the field lines along which the solar wind is expected to flow from the corona. In Fisk and Schwadron (2001) a detailed model is presented for the behavior of the open magnetic flux on the Sun. We repeat aspects of Fisk and Schwadron (2001) here and then apply this model to specify the origin of the solar wind.

2. Behavior of the Open Magnetic Flux of the Sun

The magnetic field of the Sun can be considered as having two distinct components: Open magnetic flux in which the field lines remain attached to the Sun and are dragged outward into the heliosphere with the solar wind. Closed magnetic flux in which the field remains entirely attached to the Sun, and forms loops and active regions in the solar corona.

Open magnetic flux is well ordered and thus exhibits a certain simplicity. Starting with the initial observations of *Pioneer 11* (Smith *et al.*, 1978) and now continuing with the observations of *Ulysses* (Balogh *et al.*, 1995), it has been determined that the open flux in the heliosphere is organized into two hemispheres, each with uniform polarity, separated by a reasonably well-defined current sheet. At solar minimum conditions the current sheet is located near the solar equator, and the polarity in each hemisphere reflects the polarity of the corresponding polar region of the Sun. As solar activity increases, the current sheet becomes more inclined to the solar equator. Recent *Ulysses* observations suggest that even in periods of high solar activity, a single current sheet is consistent with the observations, with corresponding well-ordered polarity for the open flux (Balogh and Smith, 2001). However, exactly how the current sheet behaves at the maximum of solar activity and at very high latitudes remains to be determined.

Open magnetic flux reverses its polarity over the solar cycle. During periods of increasing solar activity, the current sheet becomes more inclined to the solar equator. As solar activity decreases, the current sheet again becomes more aligned with the equator, but now with the opposite polarity for the magnetic field in each hemisphere from that of the previous cycle.

The radial component of open magnetic flux in the heliosphere is observed to be relatively constant with latitude and with time (Smith and Balogh, 1995). The constancy with latitude is expected. The field in the outer solar corona should be both force-free and nearly radial, which requires it to be of near constant magnitude. The constancy in time is an aspect we will exploit. Observations at Earth, e.g., as are discussed in Wang *et al.* (2000a), and observations at *Ulysses* (Smith and Balogh, 1995), do show variations in the radial component of the open flux. However, they appear to be transient and certainly of a much smaller magnitude than variations in the total magnetic flux of the Sun.

Although open magnetic flux is uniform in the outer corona, it is not evenly distributed on the solar surface. During solar minimum conditions the open flux is concentrated at the solar poles, giving the solar magnetic field a strong dipole component. This concentration of open flux results in regions of high-speed solar wind flow, with a resulting depletion of coronal density, i.e., well-established polar coronal holes. In periods of solar activity, there are isolated and transient coronal holes.

2.1. PROPERTIES OF OPEN MAGNETIC FLUX

There are certain basic properties of open magnetic flux that need to be taken into account in any successful model for the coronal magnetic field. To illustrate these properties, consider the simple drawing in Figure 1. Maxwell's equation (the divergence of the magnetic field is zero) places a firm requirement that magnetic field lines must be continuous. In the upper panel, there are two surfaces, each of which is threaded by magnetic field lines of the same polarity, which extend through the surfaces to infinity. We introduce a loop through the left-hand surface, and allow one side of the loop to reconnect with a field line that threads both surfaces. Clearly, this process will change the location on the first surface of the field line that threads both surfaces, but has no impact on the flux through the right-hand surface. If we want to influence the flux through the right-hand surface it is necessary, as in the bottom panel, to introduce a field line that threads both surfaces, but with opposite polarity. This new field line can then reconnect with one of the original field lines that threads through both surfaces. Two loops are formed, and flux can be convected outward through both surfaces.

The analogy with the magnetic field in the corona is straightforward. A basic property of open magnetic flux on the Sun (flux that threads through the photosphere and continues into the heliosphere) is that open flux cannot be destroyed by interacting with closed magnetic flux (the loops in the corona that connect on both ends to the Sun). Open flux can be removed from the Sun only by reconnecting with other open magnetic flux of opposite polarity.

Open magnetic flux on the Sun is well organized into regions of the same polarity, separated by a current sheet (Balogh and Smith, 2001). There is little opportunity, then, for open flux of opposite polarity to be in contact, except at the current sheet. The observation that open magnetic flux on the Sun is relatively constant in time is thus expected.

There are several interesting consequences of the constancy of open flux. The reversal of the polarity of the open magnetic flux over the solar cycle should not be considered as a shedding of old flux and the emission of new flux. There is no process for the removal of old open flux, except reconnection with itself, which is unlikely. Rather, the observations are quite consistent with the reversal occurring as the result of the transport of open flux in the corona. The current sheet appears to rotate. It appears to remain relatively intact as it becomes highly inclined to the

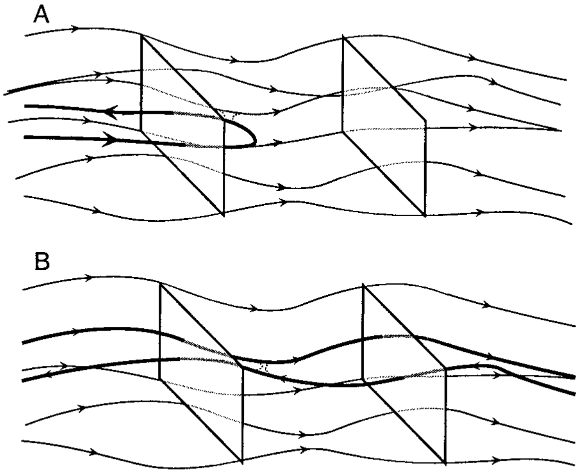

Figure 1. An illustration of the consequences for a open field line that reconnects with a closed field line, and with another open field line. In the upper panel, two surfaces are threaded by field lines of the same polarity (open field lines). Reconnection with a loop (a closed field line) changes the location of the open field line on the left surface, but does not affect the open flux through the right surface. In the bottom panel, an open field line of the opposite polarity is introduced. Now, the open field lines can reconnect, and the resulting loops are convected outward through both surfaces, altering the open flux through the surfaces.

solar equator. It can then complete the rotation to become aligned again with the solar equator. This process implies that it is transport of open flux that accomplishes the field reversal.

2.2. A MODEL FOR THE BEHAVIOR OF OPEN MAGNETIC FLUX

In the approach taken here, we make one basic assumption:

- The open magnetic flux on the Sun is constant in time. This assumption is justified both by observations (e.g., Wang *et al.*, 2000a; Smith *et al.*, 2001) and by acknowledging that open flux can only be removed from the Sun by having it reconnect with other open flux of the opposite polarity, which appears unlikely.

Understanding the behavior of open magnetic flux on the Sun is then reduced to a problem of understanding its transport. It is not readily destroyed, but it can be moved.

We consider that open magnetic flux can diffuse on the solar surface. Diffusion of field lines by convective motions in supergranules has been invoked in the past (Leighton, 1964; Wang *et al.*, 2000b). However, this process is rather slow, and faster processes may be available. As is illustrated in Figures 1 and 2, an open magnetic field line that reconnects with a closed loop moves its location on the Sun. A new smaller loop is formed, and the footpoint of the open field line moves to lie over the end of the original closed loop where the polarity is the same as the open

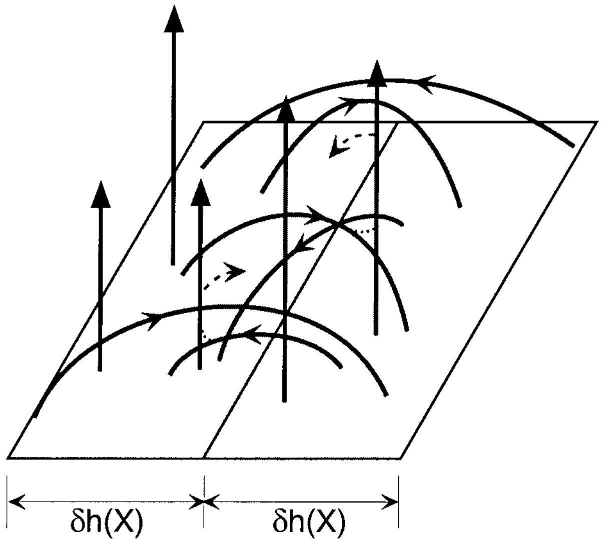

Figure 2. An illustration of the process by which open field lines can diffuse on the solar surface by reconnecting with closed loops. A series of randomly oriented loops are shown, along with open field lines all of the same polarity. The open field lines reconnect with the closed loops and jump randomly in position.

field line. If there are numerous loops in the low corona, and they are randomly oriented, this is a diffusive process, with a diffusive coefficient $\kappa \sim (\delta h)^2/\delta t$. Here, δh is the characteristic distance over which the jump in the location of the footpoint of the open field line occurs, i.e., it is a significant fraction of the characteristic dimension along the solar surface of the closed loops. The characteristic time for the jump is δt, i.e., the characteristic time for reconnection between an open and closed field line.

In Feldman *et al.* (1999) there is an extensive discussion of the morphology of coronal loops, as has been revealed recently by observations from the TRACE and SOHO missions, and which builds upon earlier observations from *Skylab*. These observations reveal a hierarchy of isothermal loop structures, smaller ones with lower temperatures, larger ones with higher temperatures. There is an effective canopy of hotter loops with temperatures of $\sim$ 1.4 × 10^6 K and a range of sizes from 2 × 10^4 km to 4 × 10^5 km overlying the cooler ones. Open magnetic field lines must penetrate this canopy. These hotter loops thus represent ideal candidates for an effective diffusion of open field lines. The open field lines reconnect with the loops, and can execute jumps in their location on the Sun with characteristic dimensions of order a sizeable fraction of the loop size. The loops appear to be sufficiently random to execute a diffusive process.

There are other properties of the $\sim$ 1.4 × 10^6 K loops discussed by Feldman *et al.* (1999) that will be important for us. The loops are not uniformly distributed on the solar surface, but rather are absent in coronal holes. There is thus a clear anti-correlation between the occurrence of these loops and the strong open magnetic flux present in coronal holes. The composition of these loops is also interesting in that it is observed by Feldman and Widing (1993) and Feldman *et al.* (1998) to be enhanced in elements with low first ionization potential. We will return to this point when we discuss the origin of the slow solar wind.

In the approach taken here we make the additional assumption:

- Open magnetic flux is separated into distinct regions separated by a current sheet. Again, this is consistent with heliospheric observations, and also with the first assumption above.

We consider that little reconnection occurs at the current sheet, nor is there mixing of flux of opposite polarity across the current sheet. Open field lines freely diffuse within regions where the open flux is of uniform polarity; however, we assume that they do not diffuse across the current sheet and thus do not mix polarities across this boundary.

The diffusive transport process described here causes open field lines to move. It is difficult to imagine, however, how the open field lines can penetrate a current sheet. A current sheet can be considered as a rotation of the magnetic field, or as a null in the field which for pressure balance requires an increase in particle pressure at the null. In either case, it is unlikely that an open field line can freely penetrate the current sheet. The current sheet, of course, forms only above the solar surface. The restriction that open flux cannot penetrate the current sheet requires that tensional forces introduced in the solar corona restrict the motions of open field lines on the solar surface.

2.3. THE CORRECT DIFFUSION EQUATION

There are two forms for the diffusion equation. One, which is commonly used to describe the propagation of energetic particles, has the diffusion occurring as the result of particles moving among relatively static scattering centers. The second is used to describe diffusion that results from displacements of, e.g., particles, by some external medium such as turbulence flows. The latter form is the one that is appropriate to describe the diffusion of open magnetic field lines as a result of reconnection with closed loops.

In Fisk and Schwadron (2001) several derivations are provided for the diffusion equation for transport of open field lines by reconnection with closed loops. The first derivation is based on Parker's 1963 book on interplanetary dynamical processes (Parker, 1963), where the two forms of the diffusion equation are derived. The second is a quasi-linear derivation. In both cases the correct form for the behavior in time of the radial component of open magnetic flux in the corona, due to diffusion of open field lines by reconnection with closed loops and subsequent random jumps in location, is

$$\frac{\partial B_r}{\partial t} = \nabla_S^2 (\kappa B_r) - \nabla_S \cdot (\mathbf{u}_S B_r) , \tag{1}$$

where $\kappa = (\delta h)^2/2\delta t$. Here, δh is the characteristic jump distance, which should be a sizeable fraction of the loop size, and δt is the characteristic time for reconnection and thus for making a jump in location. We consider that the closed loops in the corona have random orientations, and thus the diffusion coefficient is isotropic (in two dimensions). All of the uniform convective motions along the solar surface, such as differential rotation or meridional flow, or even change in frame of reference, are captured in the flow velocity $\mathbf{u}_S$.

The net transport of magnetic flux in Equation (1),

$$S_B = -\frac{\partial}{\partial x}\left(\kappa B_r\right), \tag{2}$$

should be contrasted with the net transport or streaming that results from particles of density n diffusing among relatively static scattering centers, in which case the streaming of the particles, S_p, is (Parker, 1963)

$$S_p = -\kappa_p \frac{\partial n}{\partial x}, \tag{3}$$

where the particle diffusion coefficient is $\kappa_p = v\lambda/3$, with v the particle speed and λ the mean free path for the scattering of the particles by the static scattering centers. Clearly, in Equation (2) the condition for no net transport or streaming is κB_r is constant. In Equation (3) no streaming occurs only when the density is spatially constant.

To repeat, B_r in Equation (1) includes only open magnetic flux. The interaction between open flux and closed loops is captured by the diffusion coefficient, κ. We consider that the total open flux at the Sun is constant in time, i.e. there is no reconnection of open flux with itself, and that the open flux is confined to regions surrounded by a current sheet, across which there is no diffusion. Equation (1) thus applies to regions where the open flux has a single polarity, and the behavior of the open flux at the current sheet must be treated as a condition on a boundary, across which there is no transport of open flux.

2.4. SOLUTIONS TO THE DIFFUSION EQUATION

In Fisk and Schwadron (2001) various solutions to Equation (1) are presented: a solar minimum solution can be constructed in which there are well established polar coronal holes, in which the principal transport is due to convection by differential rotation. Outside of the polar coronal holes the transport is due primarily to diffusion. A solar maximum solution can also be constructed in which diffusion is the principal transport mechanism everywhere on the sun. This solution has the interesting feature that it appears to require that the current sheet rotates, i.e., the requirement that there is diffusion at all latitudes appears to demand that the current sheet, and the open flux that it separates, rotates. The process can account for and is consistent with observations of the reversal of the polarity of open magnetic flux during the solar cycle.

It should also be noted in Equation (1) that in cases where diffusion is the dominant process, κB_r = constant is a solution. The diffusion coefficient, $\kappa = (\delta h)^2/2\delta t$, depends on the presence of loops, i.e., on the jump distance δh which is related to loop size, and on the probability of and therefore the characteristic time for reconnection with loops, δt. In regions where there is a strong population of loops, κ will be large, and conversely where the population of loops is diminished, κ is smaller. This anti-correlation between the presence of loops and the presence of strong open flux is exactly what is observed (Feldman *et al.*, 1999). Coronal holes, where the open flux is strong, are relatively devoid of the canopy of overlying loops which we are using for reconnection and thus for diffusion of the open field lines.

3. The Origin of the Solar Wind

The origin of the solar wind in the model presented here is straightforward. Closed loops, such as are illustrated in Figure 2, reconnect with open field lines. The loops contain material. The open field lines open into the heliosphere and are effectively at vacuum. As the reconnection occurs the material will drain from the loops, populate the corona, and ultimately form the solar wind.

Fisk *et al.* (1999b) invoke this process to explain the fast solar wind from the well-established polar coronal holes at solar minimum, as is illustrated in Figure 3. Recent SOHO observations have shown that small magnetic loops are continuously emerging within supergranules in the photosphere (Schrijver *et al.*, 1998). Some of the loops, perhaps only a relatively small fraction, expand with the convective flow in the supergranule such that one end of the loop is convected into the concentration of open flux at the edge of the supergranule. Reconnection can occur causing the open field line to be reoriented over the opposite side of the loop, which is then convected into another flux concentration. The consequence of this process is that open field lines jump from one flux concentration to another. The observations show that flux concentrations are enhanced and disappear with a characteristic time scale of ~ 1.5 days (Schrijver *et al.*, 1998).

During solar minimum, the solar wind has two separate and distinct components (e.g., Phillips *et al.*, 1995). There is fast wind from the polar coronal holes, with speeds $\sim$750 km s^{-1}. At low latitudes, in a band that surrounds the equatorial current sheet, there is slow wind, with speeds $\sim$400 km s^{-1}. The argument, then, is that fast wind originates from the small emerging loops in the coronal hole. Slow wind originates from the pre-existing canopy of loops that overlies the solar surface in regions outside of the polar coronal holes. In both cases the material on the loops is released to form the solar wind when reconnection with open field lines occurs.

This process for forming the fast and slow solar wind provides a natural explanation for the compositional differences in the two flows. Slow solar wind is enhanced in elements with low First Ionization Potential, or is said to be FIP enhanced. Fast solar wind shows a much smaller FIP enhancement (Geiss *et al.*,

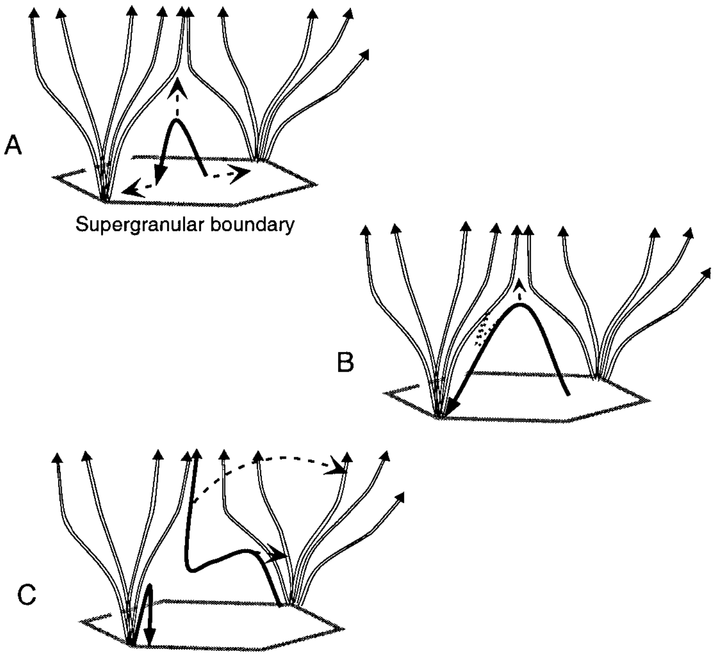

Figure 3. An illustration of the expected behavior of emerging magnetic loops in the photosphere (after Fisk *et al.*, 1999b). In (A) a new loop (shown in black) emerges in the center of a supergranule. In (B) the ends of the loop migrate to the boundaries of the supergranule where there are concentrations of magnetic flux (shown in white); only field lines which open into the corona are shown. The end of the loop with polarity opposite to that of the flux concentration reconnects with a field line that opens into the corona. In (C) the new open field line is transported laterally to be reoriented over the other side of the loop.

1995; Zurbuchen *et al.*, 1999). Fisk *et al.* (1998), Fisk *et al.* (1999a) and Schwadron *et al.* (1999) argue that the differences in FIP enhancements result simply from the fact that slow wind originates from relatively long-lived loops. Schwadron *et al.* (1999) provide a detailed model in which wave heating on the loops preferentially enhances elements with low FIP. The model yields the observed FIP enhancements in the slow wind. Since the wave heating takes time to perform the enhancements, the shorter-lived loops from which fast solar wind originates will be less FIP enhanced. These model calculations are confirmed by the observations of Feldman *et al.* (1998), who find that the canopy loops with temperatures of $\sim 1.4 \times 10^6$, which we use to form the slow solar wind, are FIP enhanced. Smaller, shorter-lived loops in the polar coronal hole are not observed to be FIP enhanced.

Releasing material from large overlying loops to form the slow solar wind will inherently introduce a variability into the slow wind, as observed in both density and speed. The slow wind will reflect the properties of the individual loops, which can vary. For example, coronal electron temperatures can be determined from the charge states of the solar wind ions, which become frozen-in in the low corona. For the fast wind a single electron temperature suffices. For the slow wind, multiple electron temperatures are required (Fisk *et al.*, 1998).

Fisk *et al.* (1999b) also point out that the properties of the emerging loops illustrated in Figure 3 can be used to determine the energy flow and final speed of the fast solar wind. The emerging loop creates an upward Poynting vector into the corona, $\mathbf{S}_p = c\mathbf{E} \times \mathbf{B}/4\pi$, where the electric field $\mathbf{E} = -(\mathbf{u}_l \times \mathbf{B})/c$ and $\mathbf{u}_l$ is the upward velocity of the loop. When the loop reconnects with an open field line, it does not return into the photosphere, and thus this process creates a net upward Poynting vector into the corona. There are other emerging loops that do not reconnect with open field lines, and eventually subduct back into the photosphere. These latter loops create no net upward Poynting vector. There also may be emerging loops that do not expand as in Figure 3, but rather are convected into a single flux concentration. For these loops there is not much displacement of the open field line, and the new loop created by the reconnection process, which can be subducted into the photosphere, will be comparable in size to the original loop. Only loops that perform as in Figure 3 create a significant net upward Poynting vector. The emerging loop in Figure 3 creates a significant upward Poynting vector, which, following reconnection, propagates into the corona. The loop that is created following reconnection is small, and when subducted back into the photosphere has only a small downward Poynting vector.

Fisk *et al.* (1999b) note that the net Poynting vector into the corona determines the final energy flow of the solar wind. In a simple single-fluid MHD model, the Poynting vector into the corona must equal the energy flow out. We can also assume that the process in Figure 3 determines the mass flow of the solar wind. Material is drained from the loops by the reconnection process. Thus the net upward motion of the loop carries material into the corona, which specifies the solar wind mass flux. Fisk *et al.* (1999b) then show that the final speed of the solar wind can be given simply by

$$\frac{u_f^2}{2} = \frac{\displaystyle\int_\sigma \left\langle \frac{c}{4\pi}(\mathbf{E} \times \mathbf{B}) \right\rangle \cdot \mathrm{d}\mathbf{s}}{\displaystyle\int_\sigma \langle \rho \mathbf{u} \rangle \cdot \mathrm{d}\mathbf{S}} - \frac{GM_0}{r_0}. \tag{4}$$

Here, the Poynting vector is integrated over surface area σ, and the brackets denote average quantities. The mass flux of the solar wind is $\int_\sigma \langle \rho \mathbf{u} \rangle \cdot \mathrm{d}\mathbf{s}$; G is the gravitation constant; M_0 is the mass of the Sun; and r_0 is the solar radius.

The final speed of the fast solar wind can also be expressed in terms of quantities observed in the corona. The emerging loop in Figure 3 alters the distribution of open magnetic flux in the polar coronal hole. Following reconnection, an open field line is moved from one flux concentration to another flux concentration. The flux concentrations are observed to be enhanced and diminished with a characteristic time of $\tau \sim 1.5$ days (Schrijver *et al.*, 1998). Thus, the Poynting vector associated with the emergence of new loops and their reconnection with open field lines must be sufficient so that

$$\int_{\sigma} \left\langle \frac{c}{4\pi} (\mathbf{E} \times \mathbf{B}) \right\rangle \cdot \mathrm{d}\mathbf{s} = \frac{1}{\tau} \int_{\mathrm{vol}} \frac{B^2}{8\pi} \mathrm{d(vol)} \equiv \frac{W_B}{\tau}, \tag{5}$$

where W_B is the total magnetic energy in open field lines that connect into surface area σ. The final solar wind speed in Equation (4) can thus be expressed as (Fisk *et al.*, 1999b)

$$\frac{u_f^2}{2} = \frac{W_B}{\rho u \sigma \tau} - \frac{G M_0}{r_0}. \tag{6}$$

The flux of open magnetic field in the polar coronal hole near solar minimum can be determined simply by extrapolating from observations at 1 AU. The radial component of the magnetic field at 1 AU is observed to be $\sim 3.5 \times 10^{-5}$ G (Smith and Balogh, 1995). The radial component varies as heliocentric distance squared, and polar coronal holes undergo a super-radial expansion in the inner corona such that the cross section of the hole decreases by a factor ~5 between the outer corona and the solar surface. The result is that $B_r \sim 8$ G, on average, at the base of the polar coronal hole.

Accounting for the non-radial expansion of the magnetic field from the polar coronal hole, Fisk *et al.* (1999b) determine that $W_B/\sigma \sim 5.9 \times 10^{10}$ G^2 cm. The mass flux of the solar wind is constant in a steady state and can also be extrapolated from observations at 1 AU to be $\rho u \sim 9 \times 10^{-11}$ g cm^{-2} s^{-1} at the base of the corona. The characteristic time for change in the open flux is $\tau \sim 36$ hours. Thus, from Equation (6), the final speed of the fast solar wind from the polar coronal hole near solar minimum is found to be ~ 780 km s^{-1}, as is observed (Phillips *et al.*, 1995).

The characteristic time τ for enhancing and diminishing the concentrations of open flux should be comparable to the characteristic reconnection time, since it is the reconnection process that is altering the open flux, causing open field lines to jump in position. Thus, the characteristic time for reconnection, which determines the diffusion coefficient in the polar coronal holes, is also $\delta t \sim 36$ hours.

The approach applied to fast solar wind can also be used to estimate the characteristic time for reconnection with the overlying canopy of loops at low latitudes. The open flux at low latitudes originates from a band of latitudes that surrounds the equatorial current sheet, from which slow solar wind originates. Again we can determine the open flux in the low corona by extrapolating from 1 AU. The open magnetic field from low latitudes should not undergo a super-radial expansion, in which case $B_r \sim 1.6$ G, on average at the base of the corona, and $W_B/\sigma \sim 7 \times 10^9$ G^{2}cm. The mass flux in the solar wind at 1 AU is observed to be comparable in both the fast and the slow solar wind. Extrapolating back to the base of the corona, $\rho u \sim 1.8 \times 10^{-11}$ g cm^{-2} s^{-1} in the slow wind. The final speed of the slow wind is $\sim$400 km s^{-1}. Thus, from Equation (6), the characteristic time for changes in open flux due to reconnection with loops at low latitudes should be $\delta t \sim 38$ hours, i.e., it is essentially the same as the characteristic time for reconnection in the polar coronal hole.

At solar maximum, the open flux should be more evenly distributed across the Sun, and thus similar to the open magnetic flux at low latitudes at solar minimum. The final speed of the solar wind at solar maximum is also comparable to that of the slow solar at solar minimum, or $\sim$ 400 km s^{-1}. The characteristic time for reconnection must thus also be $\delta t \sim 38$ hours. In transient coronal holes during periods of solar activity, the diffusion coefficient decreases and the open flux increases. The quantity W_B/σ can thus be substantially larger, but so long as δt increases commensurately, the final speed of the solar wind may not vary appreciably, as is observed (Zurbuchen *et al.*, 2001).

4. Concluding Remarks

We have presented a model for the origin of the solar wind which is based on the model of Fisk and Schwadron (2001) for the behavior of the magnetic field of the Sun. In Fisk and Schwadron (2001) it is argued that the total open magnetic flux of the Sun should tend to be constant in time, and that its behavior – its distribution on the solar surface and its reversal in polarity during the solar cycle – is due to its motion on the solar surface. The motion is argued to be a diffusive process, in which open field lines reconnect with closed loops, and jump in location. This reconnection process drains the material on the loops into the corona and creates the solar wind. The reconnection process releases a Poynting vector into the corona, which can be calculated, and the resulting energy and mass flux of the solar wind are reasonable. This process can also account for the compositional differences between fast and slow solar wind, since well-established coronal loops, which are the origin of slow solar wind, are both predicted and observed to be enhanced in elements with low first ionization potential.

Acknowledgements

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