

Acceleration of the solar wind as a result of the reconnection of open magnetic flux with coronal loops

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[1] There are compelling observations of a clear anticorrelation between solar wind flow speed and coronal electron temperature, as determined from solar wind ionic charge states. A simple theory is presented which can account for these observations, including the functional form of the correlation: Solar wind flow speed squared varies essentially linearly as the inverse of the coronal electron temperature. In this theory, magnetic field lines in the corona that open into the heliosphere reconnect with coronal loops near their base. This process displaces the open field line and disturbs and imparts energy into the overlying corona, thereby determining the Poynting vector into the corona. This process releases mass from the loop into the corona and determines the mass flux of the solar wind. The Poynting vector and mass flux into the corona determine the final speed of the solar wind and yield a relationship that provides an excellent fit to observations. The reconnection of open field lines with coronal loops, and their subsequent displacements, also results in a diffusive transport of open field lines, which influences the configuration of the heliospheric magnetic field. *INDEX TERMS*: 2164 Interplanetary Physics: Solar wind plasma; 2169 Interplanetary Physics: Sources of the solar wind; 7509 Solar Physics, Astrophysics, and Astronomy: Corona; 7835 Space Plasma Physics: Magnetic reconnection; *KEYWORDS*: solar wind, coronal loops, reconnection, solar wind charge states

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1. Introduction

[2] In a companion paper, *Gloeckler et al.* [2003] present observations from Ulysses of a clear anticorrelation between the solar wind flow speed and the coronal electron temperature, as determined from solar wind ionic charge states. The anticorrelation is consistent with a specific curve, motivated by the theory that is presented in this paper: Solar wind flow speed squared varies essentially linearly as the inverse of the coronal electron temperature. There is, of course, scatter in the points owing to variations on the Sun and stream-stream interactions in the solar wind. Moreover, as would be expected, the specific curve, solar wind speed squared versus the inverse of the electron temperature, is most readily discernible when a broad range of solar wind speeds and coronal electron temperatures are considered. Such conditions are most prevalent at solar minimum, when both high- and low-speed flows occur. When a simple average is formed in these conditions, the specific curve holds for both fast solar wind from coronal holes and slower wind from elsewhere on the Sun. The only exception is solar wind plasma associated with coronal mass ejections (CMEs), and even here it can be argued that the relationship holds with different choices for solar parameters [*Gloeckler et al.*, 2003].

[3] In many ways the relationship between solar wind speed and coronal electron temperature observed by *Gloeckler et al.* [2003] is a surprise. There is no expectation that electrons in the corona have a major, direct role in the acceleration of the solar wind, particularly the fast solar wind. The temperatures and densities of the electrons, and the resulting pressure, are insufficient to accelerate the solar wind to the observed speeds of up to ~ 800 km/s. This has led to numerous models for the acceleration of the solar wind in which the protons must obtain the required large pressures [e.g., *Hansteen et al.*, 1999]. It is perhaps equally surprising that the solar wind speed is anticorrelated with the coronal electron temperature. In models where there is both proton and electron heating, and yet the electrons remain cooler owing to heat conduction into the chromosphere [e.g., *Hansteen et al.*, 1999], we might expect that higher proton temperatures, and thus high flow speeds, were directly correlated with the coronal electron temperature. Rather, the observations of *Gloeckler et al.* [2003] that flow speed and coronal electron temperature are anticorrelated are providing us with unique information on conditions and processes occurring in the corona, which are, in turn, responsible for the final speed of the solar wind.

[4] In this paper, we present a simple theory to explain the compelling observations of *Gloeckler et al.* [2003]. The theory is an outgrowth of our work on the transport of open magnetic flux on the Sun [e.g., *Fisk*, 1996; *Fisk et al.*, 1999a; *Fisk and Schwadron*, 2001] and on the current

understanding of the behavior of the coronal magnetic field and the development of coronal loops [e.g., *Schrijver et al.*, 1997; *Handy and Schrijver*, 2001; *Simon et al.*, 2001]. There is considerable evidence that open magnetic field lines on the Sun (those that open into the heliosphere) readily reconnect with closed magnetic loops. This results in a diffusive transport of the open flux that can account for the configuration of the heliospheric magnetic field and offers an explanation for the formation of coronal holes and the apparent rotation of the large-scale current sheet that separates opposite polarities of the heliospheric magnetic field during the solar cycle [*Fisk and Schwadron*, 2001]. Processes similar to this are invoked to explain the evolution of the polar magnetic field of the Sun [*Schrijver et al.*, 2002] and to explain the apparent ease with which the magnetic fields in CMEs become detached from the Sun and do not result in a buildup of the magnetic field in the heliosphere [*Crooker et al.*, 2002].

[5] The theory for the solar wind presented here is based on this simple process. An open field line reconnects with a closed magnetic loop and is displaced in its location. This displacement disturbs the overlying coronal magnetic field and deposits energy into the corona. The reconnection permits the mass originally stored on the coronal loop to be released onto the open field line. As we shall demonstrate with a set of remarkably simple assumptions and calculations, it is possible to derive a formula that exactly accounts for the observations of *Gloeckler et al.* [2003].

[6] There are, of course, many solar wind theories more complicated than the one presented here [e.g., *Parker*, 1958; *Isenberg*, 1991, and references therein; *Marsch*, 1994, and references therein; *Hansteen and Leer*, 1995; *Axford and McKenzie*, 1997; *McKenzie et al.*, 1997]. No doubt, in time, some of these complexities will have to be added to our simple theory, and more completeness will be achieved. Nonetheless, the simple points made here do account for the observations, and, indeed, the challenge, perhaps, is to other theories. The clear anticorrelation between solar wind speed and coronal electron temperature of *Gloeckler et al.* [2003], and the apparent simple relationship between these two quantities, represents a critical test against which all solar wind theories should be judged.

[7] We begin by reviewing the current understanding of the behavior of the solar magnetic field in the photosphere and the implications of this understanding for the formation and evolution of coronal loops. We then describe the role that open magnetic flux should play in this process and how the behavior of the open flux should lead to the input of energy and mass into the solar corona and the formation of the solar wind. The result is a simple formula consistent with the observations of *Gloeckler et al.* [2003].

2. Behavior of the Solar Magnetic Field in the Photosphere

[8] Observations from the Michaelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory (SOHO) have revealed a very straightforward process for the formation of coronal loops on the quiet Sun [e.g., *Schrijver et al.*, 1997; *Handy and Schrijver*, 2001; *Simon et al.*, 2001]. Concentrations of magnetic flux with different polarities are

observed to be in continuous motion along the network of lanes between granules and supergranules. The flux concentrations rise through the solar surface as small bipolar loops on granular scales. The two ends of the loops in the photosphere, which are what is observed, then separate, enter the lanes, and move with the convective flows along the lanes.

[9] When a flux concentration of one polarity encounters a flux concentration of opposite polarity, they are observed to cancel and disappear. It needs to be remembered, of course, that this is a three-dimensional process. It was a loop that emerged; what are observed by MDI are the foot points. As is depicted in Figures 1a and 1b, when foot points of opposite polarity encounter each other, they reconnect, forming a new loop that bridges the other endpoints of the original two loops. A small secondary loop is also formed at the site of reconnection, which presumably subducts into the photosphere since the flux concentrations at this location are observed to disappear.

[10] *Handy and Schrijver* [2001] follow the evolution of small, emerging bipolar loops using combined observations from MDI and the Extreme Ultraviolet Imaging Telescope on SOHO. They find that emerging bipoles in the quiet Sun reach a typical length of $\sim 1.4 \times 10^9$ cm before reconnecting with other flux concentrations in a time period of ~ 5 –12 hours. They argue that this is the basic mechanism by which large coronal loops are formed on the quiet Sun, through the coalescence of smaller loops rather than through the emergence of a single large loop.

[11] The coalescence process appears to result in loops of various sizes everywhere on the solar surface. *Feldman et al.* [1999] report on a systematic study of the morphology of coronal loops on the quiet Sun. Loop size varies with temperature, with hotter loops overlying cooler ones. Loops are present everywhere, including in coronal holes. In the case of coronal holes the loops are cooler and smaller, with temperatures $< 800,000$ K, and separation of foot points of less than or of the order of the size of supergranules, $\sim 30,000$ km, and corresponding heights of $\leq 15,000$ km. Outside of coronal holes the loops are hotter and larger, with typical temperatures of $\sim 1.5 \times 10^6$ K and heights from 40,000 to 400,000 km.

[12] Consider that some of the flux concentrations observed by MDI are the foot points in the photosphere of open field lines, field lines that open into the heliosphere. Certainly, there are such concentrations in coronal holes, where the open magnetic flux is strong. We will argue that open flux also occurs in lesser amounts throughout the quiet Sun. In this case, as is depicted in Figures 1c and 1d, the emerging loop expands and enters the network of lanes and can encounter a concentration of open magnetic flux of opposite polarity. Reconnection occurs. The small secondary loop forms again and presumably subducts back into the photosphere; the flux concentrations at the reconnection site disappear. Moreover, the original emerging loop also disappears. The open field line is displaced to lie over the side of the original loop with the same polarity.

[13] This reconnection of loops with open field lines may also be the process that limits the size of coronal loops on the quiet Sun. All other processes (the random motions of foot points in the network lanes and the coalescence of loops) tend to form bigger loops. The reconnection of loops

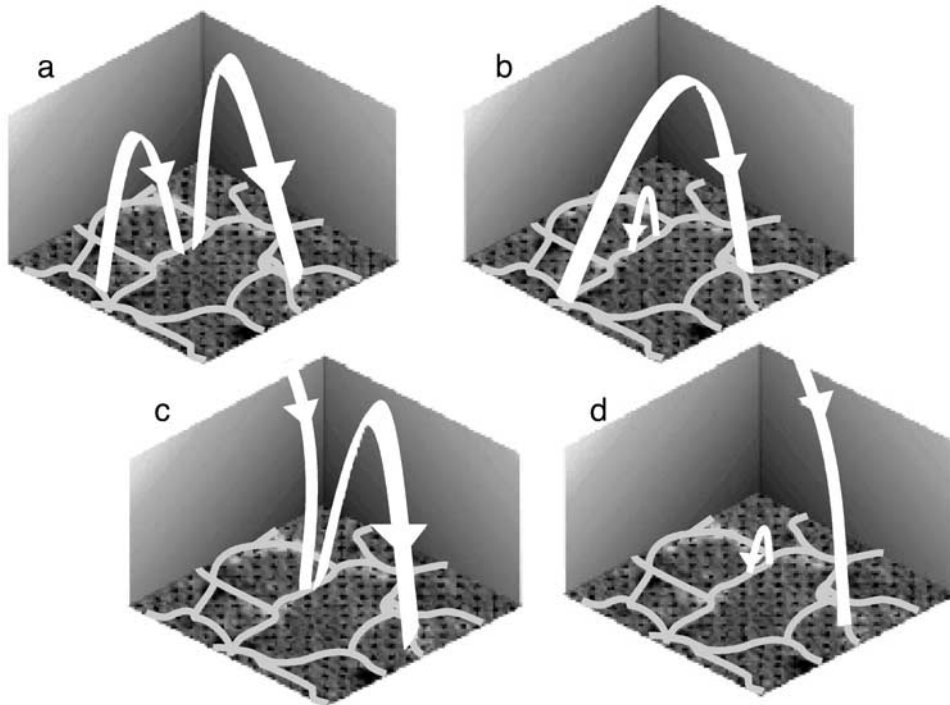


Figure 1. An illustration of the reconnection of loops and open field lines. (a) The foot points of two loops move with convective velocities along the lanes separating the granular and supergranular cells on the solar surface. (b) Two of the foot points of the loops have reconnected to form a new larger loop and a small secondary loop that will subduct back into the photosphere. (c) The foot points of a loop and an open field line move along the lanes. (d) A foot point of the loop and the open field line have reconnected, the open field is displaced to lie over the location of another foot point of the loop, and a small secondary loop is again formed that should subduct back into the photosphere.

with open field lines terminates this growth. In a steady state these processes should balance.

[14] The solar wind is expected to originate from relatively quiet regions on the Sun: coronal holes for fast solar wind and regions with primarily closed magnetic flux, removed from active regions, for the slow solar wind [e.g., *Axford, 1977*]. The coronal loops that we consider here, with heights from 15,000 to 400,000 km and temperatures from $\leq 800,000$ K to $\sim 1.5 \times 10^6$ K, are thus the appropriate ones for interactions between open field lines and loops. There are other loops on the Sun as well. The initial emerging loops are quite small, perhaps ~ 1000 km. *Axford and McKenzie [1997]* consider that these small loops are convected into the network of open field lines on the Sun, and this is the source of energy to the solar wind. We relate the energy input to the corona to the large-scale displacement of open field lines that results from reconnection with larger loops, and thus we are concerned only with the larger loops. Active regions contain strong magnetic fields and large loops. The temperatures of the material in active regions, however, are relatively hot (e.g., $> 2 \times 10^6$ K) and unlikely to form the solar wind. Particles that form the solar wind exhibit charge states that correspond to electron temperatures of $< 2 \times 10^6$ K [e.g., *Bürgi and Geiss, 1986*].

[15] The displacements of open field lines, resulting from reconnections with loops, can be fairly large. Outside of coronal holes the separation of foot points of loops is easily

in excess of 100,000 km. The displacements, at least for the smaller loops, should also be randomly oriented since the loops themselves are observed to have random orientation, presumably owing to the random convective motions and the coalescence process [*Handy and Schrijver, 2001*]. These random displacements can be described by a diffusive process, considered in detail by *Fisk and Schwadron [2001]*. The coupling between open magnetic flux and loops, through this diffusive process, can also contribute to the accumulation of open magnetic flux to form coronal holes [*Fisk and Swadron, 2001*]. The diffusive process will distribute open magnetic flux throughout the quiet Sun but at a lesser strength than in coronal holes. The diffusive motions, coupled with large-scale convective motions driven by differential rotation, contribute to the determination of the configuration of the heliospheric magnetic field [*Fisk, 1996; Fisk et al., 1999a*].

3. A Model for the Formation of the Solar Wind

[16] The issue for the present paper is whether these same displacements of open field lines, resulting from reconnections with coronal loops, can provide the energy and mass needed to form the solar wind.

3.1. Deposition of Energy Into the Corona

[17] There are many means, similar to the processes involving loops described in section 2, by which reconnection

tion can release energy into the solar atmosphere. For example, *Tarbell et al.* [1999] and *Rytova et al.* [1999] describe a mechanism whereby loops reconnect, and the resulting motions of the reconnected loops excite shocks and waves that transmit energy upward into the atmosphere. The reconnection process itself should also impart some heat to the material on the loops, a point to which we will return later in section 3.4.

[18] For our purposes here, we require (1) a heating mechanism that readily deposits energy into the upper corona, at the solar wind critical point (several solar radii) and beyond, to form the solar wind with typical temperature and velocity profiles and, even more importantly, (2) a heating mechanism that is naturally coupled to the mass flow of the solar wind. We demonstrate below that with such coupling the required formula for the solar wind speed will result. For these purposes the more interesting events are the relatively large-scale displacements of the open field lines, resulting from the reconnection with loops. We argue that such displacements will impart energy throughout the corona; the reconnection process will release material from the loops onto the open field lines. Fortunately for our model, the details of the reconnection process are not critical. It is observed to occur, and, as we shall see, not even the timescale for its occurrence enters into the final answer.

[19] There is a very simple principle at work here. If you add magnetic flux to a volume by displacing a field line into a volume of the corona, you increase the energy density in the volume and the magnetic pressure. The volume will expand, doing work on the surrounding plasma. This process is equivalent to exciting magnetosonic waves in the corona, which are readily damped.

[20] We note first that random displacements of field lines owing to reconnections with loops at the base of the corona must result in equivalent displacements throughout the corona. The field lines, when they are first displaced, should oscillate about their new position but in time should come into equilibrium at their new location. Open field lines are relatively “stiff” since the Alfvén speed in the corona is large. Moreover, random motions at the base of the corona must be accompanied by equivalent motions higher in the corona; otherwise, unupportable bends in the open field lines will result.

[21] Consider, then, a simple calculation for the amount of energy deposited into the corona per time. Imagine that you have a surface element in the photosphere, ds , which contains the foot points of both a coronal loop and an open field line, each with the same polarity and magnetic flux. Suppose that the other end of the loop reconnects with an open field line, and thus now there are two open field lines threading ds . The new open field line, created by reconnection of an open field line with the loop, will in time be displaced to lie along the path through the corona of the original open field line. This process thus doubles the amount of open magnetic flux passing through ds , and when the magnetic field returns to equilibrium, it will do work on the overlying corona.

[22] The open magnetic field strength along the path of the open field line in equilibrium will increase from \mathbf{B}_{open} to $2\mathbf{B}_{\text{open}}$, where \mathbf{B}_{open} is the magnetic field strength of the original open field line and is equal to the average open

magnetic field strength in this region of the corona. The total magnetic energy along the path of the open field line in equilibrium thus becomes

$$E_{\text{magnetic}} = \frac{4}{8\pi} (B_{\text{open},i} ds) \int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}. \quad (1)$$

Along \mathbf{B}_{open} , $2\mathbf{B}_{\text{open}} \cdot d\mathbf{n}$ is constant and equal to $2B_{\text{open},i} ds$, where $d\mathbf{n}$ is a surface element normal to \mathbf{B}_{open} . The integral $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ is along the open field line in its equilibrium position.

[23] When the open flux returns again to equilibrium, $2B_{\text{open},i} ds$ remains constant; the volume occupied by $2\mathbf{B}_{\text{open}}$ in the corona will increase but the magnetic flux through this volume remains unchanged. However, in this expansion $2 \int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ goes to $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$. The magnetic field energy released by this process is deposited in the corona and accelerates the solar wind. We take the characteristic time for open field lines to execute their random displacements to be δt . We assume that the relaxation to equilibrium occurs on a short timescale compared to δt . Thus, for open field lines that pass through a surface S_i the rate of deposition of energy into the overlying corona by the displacements of open field lines and their return to equilibrium is

$$\frac{dE}{dt} = \frac{1}{4\pi\delta t} (B_{\text{open},i} S_i) \int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}. \quad (2)$$

[24] Equation (2) can also be derived simply by determining how much work is performed through the displacement of a field line. The field line exerts a force that is proportional to $\nabla \times \mathbf{B} \times \mathbf{B}$; force times displacement is the work performed. With each field line displaced with a characteristic time δt and integrating over the volume of the overlying corona, the rate of energy deposition in equation (2) results.

[25] The characteristic time for reconnections δt can be determined from the probability that the concentrations of open magnetic flux and loop magnetic flux will interact, which, in turn, depends on the shape and size of the network lanes and the convection speeds along these lanes. Values of δt of ~ 10 – 40 hours seem to be typical. For example, *Handy and Schrijver* [2001] find that emerging bipolar loops make their first reconnection within 5–12 hours. *Schrijver et al.* [1998] find that as much flux emerges as is present on the quiet Sun within ~ 40 hours; that is, this is a typical timescale for the interaction of emerging flux with existing flux, including open flux. We find in section 3.3 that, for our purposes here, δt will cancel out in our final formula and need not be considered further.

[26] The integral $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ in equation (2) is interesting in that it can be determined for all open field lines, provided that we are willing to approximate the coronal magnetic field as a potential field, or $\nabla \times \mathbf{B}_{\text{open}} = 0$. Thus, for any closed surface in the corona with surface area element $d\mathbf{m}$,

$$\int \nabla \times \mathbf{B}_{\text{open}} \cdot d\mathbf{m} = \oint \mathbf{B}_{\text{open}} \cdot d\mathbf{l} = 0, \quad (3)$$

where the contour integral is around the perimeter of the surface. We take \mathbf{B}_{open} to lie in the heliocentric radial

direction at the base of the corona, and also at several solar radii, where the solar wind begins to drag the field radially outward. Consider, then, a closed contour that lies along the solar surface and along a spherical surface in the outer corona. There is no contribution to the contour integral in equation (3) for either of these sections because $\mathbf{B}_{\text{open}} \cdot d\mathbf{l} = 0$. The contour is completed along any two open field lines. Since $\oint \mathbf{B}_{\text{open}} \cdot d\mathbf{l} = 0$, the integral $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ must be the same for each open field regardless of the geometry by which the open field line expands in the corona, e.g., either a radial or superradial expansion (provided it can be approximated as a potential field). If there is an open field line in the corona that undergoes a radial expansion, $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h} = B_{\text{open},i} r_o$. The radial component of the heliospheric magnetic field at 1 AU is observed to be $\sim 3 \times 10^{-5} G$; it varies inversely as heliocentric distance squared, and it is reasonably constant in latitude and during the solar cycle [Smith and Balogh, 1995]. From the observed open magnetic field then, $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ for all open field lines will be $\sim 9.6 \times 10^{10} G \text{ cm}$.

[27] It is important to note in equation (2) that we make no assumptions concerning the mechanisms by which the deposited energy, resulting from the displacement of open field lines, ultimately heats the corona and accelerates the solar wind. For our purposes, we require only the rate of energy deposition, and we assume that the energy is converted into heat and that, in particular, the protons are heated. Electrons in the corona do not have temperatures sufficient to have a major role in the acceleration of the solar wind; rather, it is the protons that must be heated to accelerate the solar wind [e.g., Hansteen et al., 1999]. Numerous mechanisms have been developed to preferentially heat ions in the corona [e.g., Marsch, 1994, and references therein; Hollweg, 2000], and these would need to be invoked.

3.2. Deposition of Mass Into the Corona

[28] There is mass on the closed loops in the corona, which should be released when open field lines reconnect with the loops. We consider that the reconnection occurs very low on the loop; the small secondary loop that is formed by the reconnection readily subducts back into the photosphere. On the side of the loop that reconnects, all material above the reconnection point must thus be elevated into the corona and projected outward along the open field line. Some of this material may fall back onto the photosphere. However, the strength of the magnetic field in the loop should exceed the open field strength, which will expand into the surrounding corona, and thus there is a mirroring force that should restrict the material from returning to the photosphere.

[29] Quiet-time loops in the corona have been observed by Feldman et al. [1999] to be relatively isothermal. Temperatures range from below $1 \times 10^6 \text{ K}$ in coronal holes to $\sim 1.5 \times 10^6 \text{ K}$ in the quiet Sun outside coronal holes. We make the simplifying assumption that the loops are uniform cylinders and semicircular in shape. The mass density profile along the loop will then be

$$\rho_{\text{loop}}(z) = \rho_{\text{loop},i} \exp[-z(GM_{\odot}m_p/2r_0^2kT)], \quad (4)$$

where $\rho_{\text{loop},i}$ is the mass density at the point of reconnection at the base of the loop, z is vertical height above the base

point, G is the gravitational constant, M_{\odot} is the mass of the Sun, r_0 is the solar radius, m_p is the mass of the proton, the dominant species, T is the isothermal temperature, and k is the Boltzmann constant.

[30] The total mass on the loop can be found by integrating over the semicircular loop. We assume only the mass from one side, the side on which there is reconnection, will be released. When performing this integration numerically, we find that to a reasonable approximation, in the typical temperature range of coronal loops of $\leq 1-2 \times 10^6 \text{ K}$ and in the typical height range of 15,000–100,000 km, the total mass can be expressed as

$$M_{\text{loop}} = \rho_{\text{loop},i} S_{\text{loop}} \left(\frac{2r_0^2 kT}{GM_{\odot}m_p} \right) \cdot [1 - \exp(-1.75h_{\text{loop}}GM_{\odot}m_p/2r_0^2kT)], \quad (5)$$

where S_{loop} is the cross-sectional area of an individual loop.

[31] In order for open field lines to reconnect with closed loops, the magnetic flux must be the same for each. That is, if the amount of open flux that reconnects in time δt is $B_{\text{open},i} S_i$, then the corresponding cross-sectional area of loops that are undergoing reconnection must be $S_{\text{loop}} = S_i (B_{\text{open},i}/B_{\text{loop},i})$, where $B_{\text{loop},i}$ is the magnetic field strength in the loops, which is constant since the loops are assumed to be cylindrical.

[32] The total mass that is released from loops into the corona per unit time, by reconnection with the open field lines that pass through S_i , is then

$$\frac{dM}{dt} = \left(\frac{\rho_{\text{loop},i}}{B_{\text{loop},i}} \right) \left(\frac{B_{\text{open},i} S_i}{\delta t} \right) \left(\frac{2r_0^2 kT}{GM_{\odot}m_p} \right) \cdot \left[1 - \exp\left(-\frac{1.75h_{\text{loop}}GM_{\odot}m_p}{2r_0^2kT} \right) \right]. \quad (6)$$

Mass does not accumulate through time in the corona, and thus the increase in mass per unit time in equation (6) must be balanced by the mass flux of the solar wind:

$$\rho_i u_i = \left(\frac{\rho_{\text{loop},i}}{B_{\text{loop},i}} \right) \left(\frac{B_{\text{open},i}}{\delta t} \right) \left(\frac{2r_0^2 kT}{GM_{\odot}m_p} \right) \cdot \left[1 - \exp\left(-\frac{1.75h_{\text{loop}}GM_{\odot}m_p}{2r_0^2kT} \right) \right]. \quad (7)$$

3.3. A Formula for Solar Wind Speed

[33] Consider a volume in the corona through which the solar wind flows. The volume is bounded at the very base of the corona, where mass is first injected, by surface S_i ; at its sides by a cylindrical surface that lies parallel to the open magnetic field; and by an outer surface S_o , where the solar wind has obtained its full flow speed, e.g., near the Alfvén point where the solar wind speed is equal to the Alfvén speed at ~ 10 solar radii. We take the inner surface S_i to be sufficiently large to include the loops with which the open magnetic field is reconnecting. Thus the displacements of open field lines that result from these reconnections are contained within the volume. We assume that both S_i and S_o are sufficiently small so that solar wind flow parameters, at

least in an average sense, can be considered to be uniform across the surfaces.

[34] We then invoke a standard MHD energy balance equation to determine the final speed of the solar wind. This approach was used by, for example, *Fisk et al.* [1999b] for a model of the fast solar wind. We assume that the solar wind can be described as a single MHD fluid, with density ρ and flow velocity \mathbf{u} . We consider that there is no net increase in mass, magnetic field strength, or thermal energy in the corona over time, and thus, in a time-averaged sense, the solar wind flow is in a steady state. For these conditions and with the above assumptions about the volume through which the solar wind is flowing in the corona,

$$\left\langle \rho \mathbf{u} \frac{u^2}{2} \right\rangle \cdot \mathbf{S}_o = \langle \mathbf{P} \rangle \cdot \mathbf{S}_i - \frac{GM_O}{r_0} \langle \rho \mathbf{u} \rangle \cdot \mathbf{S}_i, \quad (8)$$

$$\langle \rho \mathbf{u} \rangle \cdot \mathbf{S}_o = \langle \rho \mathbf{u} \rangle \cdot \mathbf{S}_i, \quad (9)$$

where angle brackets denote time average. The term on the left of equation (8) is the energy flux through the outer surface (S_o), whose normal is parallel to the open magnetic field. The first term on the right is the Poynting vector \mathbf{P} into the corona through an inner surface (S_i). The second term on the right of equation (8) is the loss in energy flux due to the gravitational field of the Sun.

[35] Equation (8) is simply a statement that, in a time-averaged sense, the energy flow out of the corona equals the energy flow into it. We assume in equation (8) that the energy flow through the outer surface is due primarily to the flow energy of the solar wind; the solar wind has a high Mach number flow on the outer surface. We further assume that the Poynting vector dominates on the inner surface. The energy flux due to the flow energy of the solar wind will be small on the inner surface since the solar wind is only beginning to be accelerated. Also, the energy flux due to convection of thermal energy is neglected since the heating of the corona, due to dissipation of the Poynting vector, occurs beyond the inner surface. Equation (9) is simply a statement that, in the time-averaged sense, the mass flux of the solar wind is constant.

[36] The mass flux will lie parallel to the magnetic field. The solar wind flows along the field where the magnetic energy density is large compared to the ram pressure of the solar wind. We also assume that the Poynting vector is parallel to the magnetic field in the corona. This does not have to be the case since electromagnetic energy could flow normal to the field. However, we assume that the displacements are all contained in the volume defined by S_i and S_o and that the dissipation of energy that is generated by the displacements is similarly contained in this volume.

[37] Combining equations (8) and (9) thus yields the simple relationship for the final speed of the solar wind u_f [*Fisk et al.*, 1999b]:

$$\frac{u_f^2}{2} = \frac{P_i}{\rho_i u_i} - \frac{GM_O}{r_0}. \quad (10)$$

The final speed of the solar wind depends only on the ratio of the magnitude of the Poynting vector P_i to the mass flux per unit area $\rho_i u_i$ at the base of the corona.

[38] The rate of energy deposited into the corona, given in equation (2), which results from the displacement and subsequent relaxation to equilibrium of the open field lines, must be provided by P_i . The mass flux into the corona, which results from material released from the loops by reconnection with open field lines, is given in equation (7). Thus, substituting equations (2) and (7) into equation (10), we find a formula for the final speed of the solar wind

$$\frac{u_f^2}{2} = \left(\frac{B_{\text{loop},i}}{\rho_{\text{loop},i}} \right) \left(\frac{\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}}{4\pi r_o} \right) \left(\frac{GM_O m_p}{2r_0 kT} \right) \beta(h_{\text{loop}}, T) - \frac{GM_O}{r_0}, \quad (11)$$

where $\beta(h_{\text{loop}}, T) = \{1 - \exp[-(1.75 h_{\text{loop}} GM_O m_p)/(2r_0^2 kT)]\}^{-1}$. Note that the term $B_{\text{open},i} \delta t$ cancels when we take the ratio of P_i to $\rho_i u_i$.

3.4. Comparison With Observations

[39] As noted above in equation (3), the quantity $\int \mathbf{B}_{\text{open}} \cdot d\mathbf{h}$ should be approximately constant and $\sim 9.6 \times 10^{10} G \text{ cm}$, provided that the open magnetic field can be described as a potential field. For loops on the quiet Sun, *Feldman et al.* [1999] find that the height of loops h_{loop} increases with increasing temperature of the material in the loops; hotter loops overlie cooler ones. Thus $\beta(h_{\text{loop}}, T)$ should be primarily a function of temperature T , and since loop height enters as h_{loop}/T , it should not be a particularly strong function of temperature.

[40] Thus, provided that the quantity $B_{\text{loop},i}/\rho_{\text{loop},i}$ is relatively constant on the Sun, this theory for the acceleration of the solar wind makes the interesting prediction that the final speed of the solar wind depends on only one parameter, the temperature of the material in the originating loops, and that the final speed squared over 2 varies essentially linearly as $1/T$. The quantity $B_{\text{loop},i}/\rho_{\text{loop},i}$ could, in fact, be relatively constant if loops expand such that the density and magnetic field strength expand in proportion to each other.

[41] The dependence on loop temperature in equation (11) arises simply because the mass available, and thus the mass flux, is proportional to the scale height, which, in turn, is proportional to temperature. The final speed squared of the solar wind in equation (10) varies inversely with the mass flux.

[42] Equation (11) should hold in all forms of the solar wind: fast solar wind from coronal holes, where the loops involved are smaller and cooler, and slow solar wind from elsewhere on the Sun, where the loops are larger and hotter.

[43] In the companion paper, *Gloeckler et al.* [2003] find that equation (11) does indeed provide an excellent fit to observations for both fast and slow solar wind, including the unadjustable intercept of the linear curve in $1/T$, the gravitational potential energy per unit mass of the Sun, GM_O/r_0 . Generally, loop height is taken to be proportional to loop temperature, and the quantity $B_{\text{loop},i}/\rho_{\text{loop},i}$ is adjusted to provide a detailed fit to the observations. In fact, the detailed fit to the observations can be used to specify difficult to determine solar parameters, such as loop height and loop magnetic field strength.

[44] There is, of course, a leap of faith here. *Gloeckler et al.* [2003] measure solar wind charge states, from which

they determine coronal electron temperatures. Equation (11) requires the actual loop temperature. It is not unreasonable that these will be nearly identical. First of all, the loops that are used are observed to have temperatures comparable to those inferred from solar wind charge states. A typical, relatively large coronal loop on the quiet Sun, which should be responsible for the slow solar wind, is observed to have temperatures of $\sim 1.5 \times 10^6$ K [e.g., *Feldman et al.*, 1999], whereas the coronal electron temperature inferred from charge states is $\sim 1.8 \times 10^6$ K. Similarly, in fast solar wind the loops have temperatures of $\sim 800,000$ K, whereas the charge state inferred temperature is $\sim 1.1 \times 10^6$ K. These apparent systematic differences could result from the reconnection process itself, when the open field line reconnects with the loop. A small amount of heat could be imparted to the loop. The actual release process itself, in which there is a sudden drop in density, could facilitate the freeze-in of ionic charge states at the point of release. Conversely, the free flow of electrons along the open field lines could preserve the electron temperature near the loop value, and the freeze-in occurs at the more traditional several solar radii [e.g., *Birgi and Geiss*, 1986]. In the detailed numerical model of N. A. Schwadron (A model for acceleration of the solar wind due to the emergence of magnetic flux, submitted to *Journal of Geophysical Research*, 2002) the solar wind charge states are calculated and found to be representative of the electron temperatures in the loops. The protons, in contrast, need to be heated in the corona by the dissipation of the energy imparted by the displaced open field lines in order to form the solar wind.

[45] All that is required by *Gloeckler et al.* [2003] is that there is a one-to-one relationship between the coronal electron temperature inferred from charge state measurements and the temperature of the loop responsible for the electrons. For example, if these two temperatures are proportional to each other, there is no change in the use of equation (11) to relate observed solar speed to observed charge states other than some small adjustment to the inferred loop heights and magnetic field strength.

4. Concluding Remarks

[46] We argue in this paper that the energy and mass that create the solar wind result from the reconnection of open magnetic field lines with closed magnetic loops. This model for the acceleration of the solar wind has several unique features that distinguish it from conventional models. The solar wind plasma is preheated in the coronal loops and released by reconnection with open magnetic field lines. The mass that is on the loops and the rate of reconnection and release determine the mass flux of the solar wind. The displacement of open field lines due to their reconnection with closed loops and their relaxation to equilibrium determine the Poynting vector into the corona. The mass flux and Poynting vector determine the final speed of the solar wind and relate it to the temperature in the originating loop. Most significantly, the resulting relationship for the final speed of the solar wind appears to provide an excellent fit to the observations of *Gloeckler et al.* [2003].

[47] This approach to solar wind acceleration can be contrasted with the more conventional approach in which a deposition of energy and/or momentum in the outer

corona is assumed [e.g., *Parker*, 1958; *Isenberg*, 1991, and references therein; *Hansteen and Leer*, 1995; *Axford and McKenzie*, 1997; *McKenzie et al.*, 1997]. In these models the source of the energy and momentum is usually identified in a qualitative sense, and the profile for the deposition of the energy or momentum is typically modeled by an exponential in radial distance. The inner boundary condition at the base of the corona is a fixed density or pressure, and the more sophisticated models heat the chromosphere through downward heat conduction from the corona. The solar wind then establishes a critical point solution, passing uniquely from subsonic to supersonic flow and satisfying the boundary condition of zero pressure at infinity [*Parker*, 1958]. The mass and energy flux is then an output of the model.

[48] In the approach taken here, we assume that we can specify the mass flux and the energy flux, the Poynting vector, into the base of the corona. Rather than assume that an energy source is present in the corona, as in more conventional models, we identify the source of this energy with processes occurring at the base of the corona. The solar wind still needs to establish a critical point solution, and the initial Mach number must be chosen such that the solution passes through the critical point. As is evident in equation (10), specifying the mass flux and Poynting vector at the base of the corona determines the final speed of the solar wind provided that the net energy input into the corona is given by the Poynting vector (i.e., heat flux out through the base can be ignored), and provided that a supersonic flow is achieved (i.e., given that the output from the corona is primarily flow energy). The profile for the deposition of energy or momentum is immaterial in determining this final speed.

[49] It is also interesting to note that the final speed determined by equation (10) is independent of the expansion of the cross section of the solar wind flow in the corona. It depends only on conditions at the coronal base. In more conventional solar wind models the deposition of energy per unit volume in the corona is a function of radius. A solar wind that overexpands in the corona, e.g., the nonradial expansion of fast solar wind from the polar coronal holes, has an increasing cross section and occupies a relatively larger volume in the corona. The total energy deposited in the flow, i.e., the deposition per volume integrated over the volume, thus depends on the expansion, as does the final flow speed. In the model presented here the energy provided to the flow enters at the base of the corona and the Poynting vector is assumed to lie along the magnetic field. The total energy deposited in the flow is thus fixed by the Poynting vector at the base, independent of the expansion. This model accounts naturally for the near constancy of the solar wind speed in the polar coronal holes at solar minimum, even though the expansion of the solar wind should vary across the holes [*Fisk et al.*, 1999b].

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