Distribution and properties of open magnetic flux outside of coronal holes

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[1] The open magnetic flux of the Sun, the component of the solar magnetic field that forms the heliospheric magnetic field, is known to be concentrated into coronal holes, regions of low plasma density where the solar wind escapes easily. There also is evidence for concentrations of open flux in the vicinity of active regions. In this paper we explore the possibility that there is an additional component of open flux. We argue that open magnetic flux will reconnect with closed magnetic loops and that this process will distribute a small fraction of the open flux into a uniform, radial component in regions that do not underlie the overexpansion of the magnetic field from coronal holes. This additional component of open flux will facilitate the escape of energetic particles from solar flares and also the escape of plasma to form the slow solar wind.

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1. Introduction

[2] The magnetic field on the surface of the Sun can be divided into two components: open magnetic flux, which opens into the heliosphere and forms the heliospheric magnetic field; and closed magnetic flux, in the form of loops attached at both ends to the Sun. The open flux is known to be concentrated into coronal holes, regions of low density where the solar wind escapes easily [*Mitchell et al.*, 1981; *Kohl et al.*, 1999; *Miralles et al.*, 2001]. This is particularly true at solar minimum, when two large coronal holes form near the poles of the Sun and give rise to fast solar wind that dominates the heliosphere everywhere outside of the region surrounding the solar equatorial plane. There are also transitory coronal holes during solar maximum conditions that give rise to solar wind flows, which are generally not as fast as at solar minimum. Small coronal holes can also form near active regions, again giving rise to open flux and escaping solar wind [*Kahler and Hudson*, 2001; *Neugebauer et al.*, 2002; *Luhmann et al.*, 2002; *Neugebauer and Liewer*, 2003; *Schrijver and DeRosa*, 2003].

[3] The issue that we will explore in this paper is whether there is additional open magnetic flux distributed more broadly on the Sun, beyond the known concentrations in coronal holes. The reason to explore such an option has several motivations.

1.1. Easy Escape of Energetic Particles

[4] It is apparent in many different solar observations that energetic particles escape relatively easily from the Sun. Since the gyroradii of these particles are small compared to any relevant dimension, we should assume that the particles require easy access to open field lines. Yet if the open flux is concentrated into coronal holes, to the exclusion of other regions, it is unclear that the open flux required for easy escape is present [*Pan et al.*, 1984].

[5] Consider, for example, type III radio bursts. Suprathermal electrons from the Sun streaming along open magnetic field lines produce Langmuir waves that yield type III radio emissions. The spatial distribution of type III radio bursts should thus be a good indication of the location of the open magnetic field [*Paesold et al.*, 2001, and references therein]. The spatial resolution of these measurements is currently not high; yet there is certainly no indication that the type III radio emission is concentrated in coronal holes. It is probably concentrated in active regions, which give rise to the accelerated electrons. Not every active region, however, has an accompanying concentration of open flux, and even when one is present, there is no indication that the electrons find their way across the complicated magnetic field structures of active regions and escape preferentially from the accompanying coronal hole.

[6] There are also many small solar flares on the Sun ($\sim$1000 per year during solar maximum conditions), which result in the impulsive emission of energetic particles into the heliosphere [*Dulk et al.*, 1998]. The observed intensities of ions and electrons rise and decay relatively abruptly, and the escape of the particles is generally confined to a relatively narrow range of longitudes. These events are believed to originate on coronal loops, where preferential heating of certain ions occurs, and thus there is a dramatic alteration of the elemental and isotopic composition; e.g., ^{3}He can be enhanced by a factor of $\sim 10^4$ [*Reames*, 1999, and references therein]. The abrupt nature of the intensity increases seen in the heliosphere suggests that the particles escape easily from the loops on which they are accelerated, onto open field lines. The loops, however, are not prefer-

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entially located in the immediate vicinity of concentrations of open flux. Nor should we expect that the particles, which have small gyroradii in the corona, can easily be transported across the coronal magnetic field. All this suggests that open flux is distributed broadly on the Sun and present in the vicinity of the loops where the flare occurs. In fact, *Reames* [2002] argues that the interaction of the loop with open flux is essential for an impulsive solar particle event, triggering the disruption of the magnetic field in the loop and the escape of energetic particles.

1.2. Slow Solar Wind

[7] There are marked differences in the elemental and ionic charge composition of the solar wind, generally distinguished by the plasma flow speed [*Schwenn*, 1990, and references therein]. Slow solar wind ($\sim$400 km s^{-1}) is enhanced in elements with low first ionization potential (FIP); fast wind is much less FIP enhanced. Slow solar wind has ionic charge states corresponding to coronal electron temperatures (where the charge states are frozen-in) of 1.4–1.85 $\times$ 10^6 K; fast wind has charge states formed at temperatures of <1.4 $\times$ 10^6 K. As discussed by *Feldman et al.* [2005], comparison of the composition of the solar wind with the composition at the Sun reveals that the origin of the fast wind is clearly coronal holes, which are observed to have little if any FIP enhancements and cool electron temperatures. The slow solar wind most closely matches large coronal loops on the quiet Sun, which have electron temperatures in the same range as the electron temperatures that yield the solar wind charge states [*Zurbuchen et al.*, 2000]. Most important, the large loops are observed to have FIP enhancements similar to the slow wind. The solar wind, as with energetic particles, must escape along open field lines, indicating that the open flux must be present in close vicinity to the large coronal loops on the quiet Sun.

1.3. Radio Occultation Observations

[8] *Woo and Habbal* [2000] have argued that the traditionally strict interpretation that the fast solar wind with open magnetic flux is concentrated into coronal holes is not correct. Using radio occultation observations and white light measurements of path-integrated density, combined with Doppler dimming measurements, they conclude that the fast wind originates from both the quiet Sun and the polar coronal hole, again requiring open flux present outside of the coronal holes. This additional component of open flux appears in the observations to be radial.

1.4. Potential Field Source Surface Models

[9] The standard method for determining the configuration of the coronal magnetic field is a potential field model, which was pioneered by *Altschuler and Newkirk* [1969] and *Schatten et al.* [1969]. The magnetic field is assumed to be current free and thus can be described as the gradient of a scalar potential, which is a solution to Laplace's equation. The inner boundary condition is the observed magnetic field on the solar surface. On the outer boundary the magnetic field is assumed to be radial on the so-called source surface of the solar wind, which is placed typically at 2.5 solar radii. This method is widely used by the community and is the basis for many studies of the evolution of the magnetic field of the Sun, in particular by Y.-M. Wang, N. R. Sheeley, and colleagues [e.g., *Wang and Sheeley*, 1992; *Wang et al.*, 1989, 2000a, 2000b].

[10] Potential field models appear to provide an adequate description of the locations of concentrations of open flux, which in a potential field model is that flux which crosses the source surface. In that sense, the gross features of the distribution of open flux are captured in such models. However, a potential field model, by definition, cannot capture or predict a distribution of open flux that results from open flux undergoing frequent reconnection and becoming embedded into regions with closed magnetic flux. Such interactions, and the resulting complex magnetic field structures, inherently involve currents. There is then a region above the solar surface, the inner boundary condition of a potential field model, where currents are present and the basic assumption of a potential field model fails.

[11] It is thus not surprising that a potential field, source surface model does not contain a broadly distributed component of open magnetic flux. Equivalently, if we want to search for a broadly distributed component, we need to include as a central feature of our model the interactions of open flux with closed coronal loops.

[12] In this paper we assume that the open magnetic field and the closed magnetic field are continuously interacting with each other through reconnections. The open flux relaxes to an equilibrium configuration, the solutions for which can reveal how much open flux lies outside of concentrations of open flux, where it is located, and how it is behaving. We find that there should be a component of open flux outside of coronal holes and active regions that is uniform and radial. This component of open flux will be concentrated in regions that do not underlie the overexpansion of the open flux from coronal holes. The amount of open flux in this additional component will vary during the solar cycle, and we describe a method for determining this additional component.

[13] We begin by considering the various means by which open and closed magnetic flux can interact and their consequences. We conclude that open magnetic field lines will diffuse throughout the solar corona, driven by reconnection between open flux and closed coronal loops. We derive a three-dimensional diffusion equation, which describes this diffusive behavior, and show that the equilibrium solution is a uniform, radial component of open flux in certain regions of the Sun. We conclude by discussing how these results can be incorporated into models for the coronal magnetic field, and discuss the motions of the open flux outside of coronal holes and their influence on the heliospheric magnetic field.

2. Interactions Between Open Magnetic Flux and Closed Coronal Loops

[14] There are two principal means by which we anticipate that open magnetic flux and closed magnetic loops can interact: interactions at the base of coronal loops and interactions in the canopy of loops.

2.1. Interactions at the Base of Coronal Loops

[15] Magnetic fields are in continuous motion on the solar surface, convected by the random motions of the photosphere. The result is a diffusive transport, first noted by

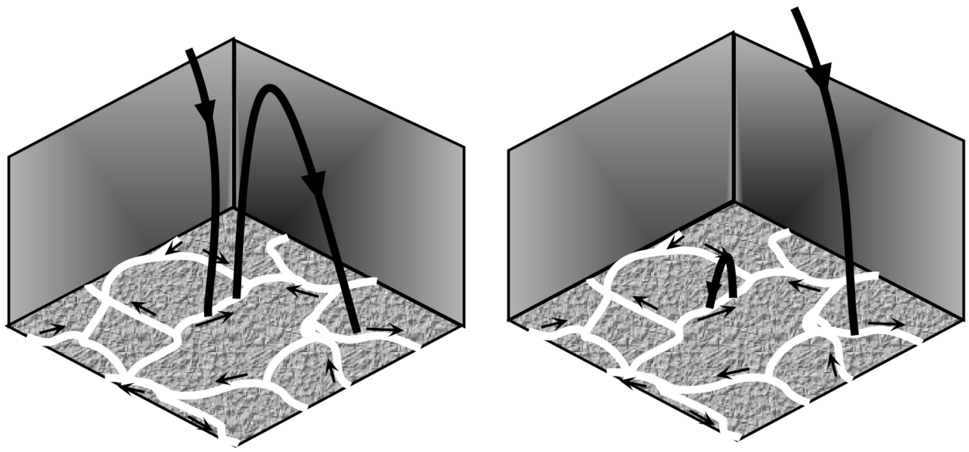

Figure 1. Illustration of the interaction between open magnetic field lines and small coronal loops. (left) Foot points of an open field line and the foot points of a coronal loop are in motion due to the random convective velocities on the solar surface. (right) Open field line has reconnected with the loop, near the base of the foot point of opposite polarity to the open field line, and is being displaced to lie over the location of the other foot point. A small secondary loop is also formed.

Leighton [1964] and the basis for many models for the behavior of the magnetic field of the Sun [e.g., *Wang and Sheeley*, 1991; *Wang et al.*, 1989, 2000a, 2000b; *Schrijver*, 2001; *Schrijver and Title*, 2001; *Schrijver et al.*, 2002; *Schrijver and DeRosa*, 2003]. When concentrations of magnetic flux of opposite polarity encounter each other, as a result of these random motions, they are observed to annihilate each other, i.e., to reconnect and subduct below the solar surface [*Schrijver et al.*, 1997, 1998; *Handy and Schrijver*, 2001; *Simon et al.*, 2001].

[16] Consider the interaction between an open magnetic field line and a coronal loop, illustrated in Figure 1. The foot points of both the open field line and the base of the loop execute random motions in the network lanes of the photosphere. When the open field line encounters the base of a coronal loop of opposite polarity it will reconnect and be displaced to lie over the other foot point of the loop. There will also be a small secondary loop formed at the reconnection site, but we assume it subducts away since observations show that interacting flux concentrations of opposite polarity annihilate each other and disappear [e.g., *Handy and Schrijver*, 2001].

[17] Small loops on the quiet Sun are randomly oriented [*Handy and Schrijver*, 2001]. Thus the displacement of the open field line as a result of reconnection with the small coronal loop is random and can be considered to be a diffusive process. Open field lines on the surface of the Sun thus execute two statistically independent diffusive processes. They are randomly convected with photospheric motions, as is all magnetic flux, and they are randomly displaced by reconnecting with small coronal loops at their base. The latter process can be more important for open flux, since the separation of the foot points of loops, and thus the displacement of the open flux, should be larger than the linear displacement of open field lines executing random convective motions in the photosphere. The diffusive coefficient of this combined diffusive process can be related to basic solar parameters, such as the rate of emergence of new magnetic flux on the Sun [*Fisk*, 2005].

2.2. Interactions in the Canopy of Loops

[18] We should also expect that open magnetic field lines interact with and reconnect in the canopy of loops present on the Sun. There is a hierarchy of loops present on the quiet Sun, outside of active regions, roughly ordered by loop temperature [*Feldman et al.*, 1999]. Even in coronal holes, small cool loops are present. Outside of coronal holes, there is a canopy of loops present, with temperatures around $1.4-1.6 \times 10^6$ K and sizes of 2×10^4 to 4×10^5 km, overlying cooler loops.

[19] There are two basic arguments for why open flux will become embedded into closed field regions and thus penetrate through and reconnect in the canopy of loops.

[20] 1. The reconnection of open field lines at the base of coronal loops, described previously, will displace open field lines by the separation of the foot points of the loop and will naturally tend to embed the open field lines deeper into closed field regions.

[21] 2. Open field lines from concentrations of open flux such as coronal holes will overexpand in the overlying corona and overlie the canopy of loops. The open flux from the polar coronal holes at solar minimum is in motion, driven by differential rotation, and thus in motion relative to the low-latitude coronal loops that it overlies. These motions of the overexpanded open flux alter the configuration of the heliospheric magnetic field [*Fisk*, 1996]. As pointed out by *Fisk et al.* [1999], the systematic motions of open flux driven by differential rotation cannot continue indefinitely to low latitudes without violating the observation that there is a single current sheet separating the open magnetic flux of the Sun. Rather, the open flux from the polar coronal hole needs to reconnect in the canopy of loops at low latitudes and execute diffusive motions, resulting in a continuous flow pattern of open flux: convection by differential rotation at the higher latitudes and diffusion by reconnection in the canopy of loops at low latitudes.

[22] We have then an additional, statistically independent diffusion process for open magnetic flux, diffusion by reconnection in the canopy of loops present outside of

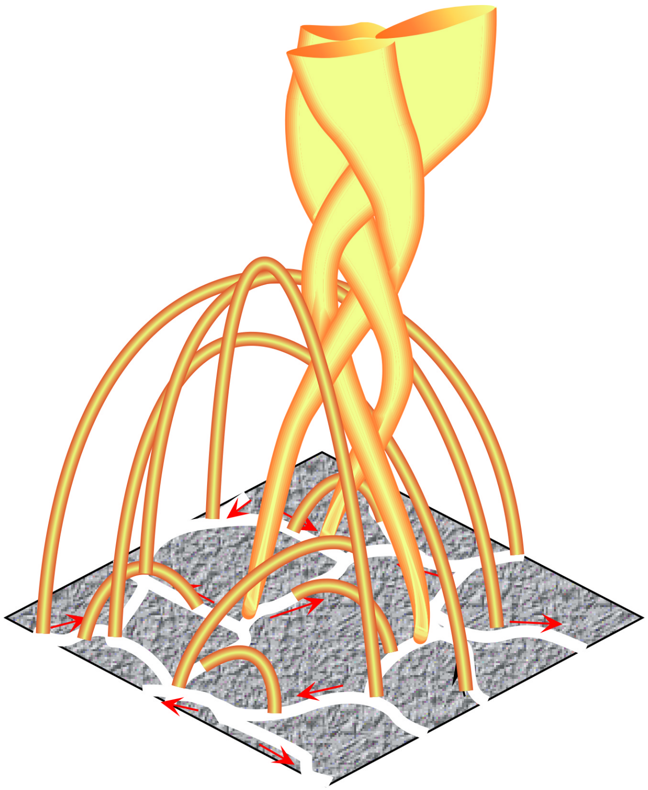

Figure 2. Illustration of a region of closed magnetic loops and interpenetrating open magnetic field lines. Small loops spanning supergranules are shown, as are larger loops that form an overlying canopy. Open field lines penetrate through the loops. The foot points of the open field lines and the loops move with the random convective motions on the solar surface. The open field lines can reconnect with the loops at their base, as is illustrated in Figure 1, or in the canopy. The random motions and reconnections cause the open field lines to become intertwined and braided in the overlying corona.

coronal holes, which we call canopy diffusion. Unlike the diffusion coefficient for random convective motions, or for reconnection at the base of coronal loops, which we can relate to basic solar parameters [*Fisk*, 2005], the diffusion coefficient for canopy diffusion is intrinsically harder to determine. Open field lines are in motion in the overlying corona and being dragged through the canopy of loops. The purpose of this canopy diffusion is to produce a continuous flow pattern of open flux. Thus the canopy diffusion coefficient cannot be determined independently from observations near the solar surface, but rather must be determined self-consistently with the systematic motions of open flux in the corona overlying the canopy of loops. Fortunately, for the problem we consider here of determining the distribution of open flux outside of coronal holes, detailed information on the canopy diffusion coefficient is not necessary.

[23] The diffusion process for open flux that results from reconnection with coronal loops requires, of course, the presence of loops. In coronal holes, there are only small loops present, and thus the only diffusion process of significance should be diffusion by random convective motions. In the case of the polar coronal holes, the dominant transport mechanism for open flux will be convection by differential rotation. Outside of coronal holes, however, where there is a full canopy of loops present, the primary diffusive process for open flux should be reconnection with coronal loops at their base and in the canopy, with the latter more likely to be important since the reconnection is with the largest loops present, those that comprise the canopy, and thus the largest displacements are possible. Thus outside of coronal holes, canopy diffusion should be the dominant transport process, exceeding other diffusive processes or any convective transport.

2.3. Diffusion Above the Canopy of Loops

[24] We should also note that the random motions resulting from reconnection with loops will produce a braiding and twisting of open field lines throughout the corona above, as is illustrated in Figure 2. The magnetic field provides the dominant force throughout the corona within the Alfvén point of the solar wind at about 10 solar radii. We should expect then that the sharp bends in the open magnetic field introduced by reconnection will be translated into the corona above by the large tensional force of the field. The overlying field will attempt to move in concert with the random motions at the base, and thus random motions will be driven throughout the corona. In fact, the imparted braiding and twisting of the open field lines is observed in the heliospheric magnetic field and is considered to be responsible for the cross-field diffusion of energetic particles [e.g., *Jokipii and Parker*, 1969]. The diffusion coefficient for random motions of open magnetic fields in the overlying corona is an extension of the diffusion coefficient due to reconnections with loops, again with the expectation that canopy diffusion is dominant in regions outside of coronal holes.

[25] Thus, for regions outside of concentrations of open flux such as coronal holes, where there is a canopy of loops present, we expect that open magnetic flux interacts with the loops through reconnection, both at the base and in the canopy, and that such reconnections and the resulting displacements of the flux cause the open field lines to diffuse throughout the corona above the canopy. If we have a diffusion equation, which we derive next, which describes this three-dimensional diffusion, we can then seek solutions to this equation that will reveal how much open flux is outside of the open flux concentrations and how it behaves.

3. Three-Dimensional Diffusion Equation

[26] We can derive a diffusion equation for the diffusion of magnetic field in the corona using a standard quasi-linear approach. In the appendix of *Fisk and Schwadron* [2001], this technique is used to derive the appropriate equation for diffusion on the solar surface (two-dimensional diffusion). It is straightforward to extend this derivation into three dimensions, which we provide in Appendix A. We make the assumption that diffusion governs the transport and behavior of the open field lines and we ignore any effects associated with a mean convection velocity of the plasma.

[27] The approach is to start from the standard inductance equation

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

which assumes that the vector magnetic field $\mathbf{B}$ is frozen into the plasma, which is moving with velocity $\mathbf{u}$. We take the magnetic field to have a mean component, $\mathbf{B}_o$, and a random component, $\delta\mathbf{B}$, which has an ensemble average, $\langle\delta\mathbf{B}\rangle = 0$. We take the plasma velocity to have no mean component, $\mathbf{u}_0$, normal to the mean magnetic field, and a random component, $\delta\mathbf{u}$. We ignore the effects of convective transport normal to the mean magnetic field; the flow of the solar wind will also not enter into our analysis since it is parallel to $\mathbf{B}_o$.

[28] As is discussed by *Fisk and Schwadron* [2001] and in Appendix A, care must be taken in describing the statistical properties of $\delta\mathbf{u}$. We will allow for spatial variations in the properties of the turbulence, and thus sitting at one location and receiving parcels of plasma from surrounding regions, we should expect that the local ensemble average of $\langle\delta\mathbf{u}\rangle \neq 0$. Rather, we will assume that a volume average of $\delta\mathbf{u}$, or $\langle\delta\mathbf{u}(\mathbf{r} + \delta\mathbf{r})\rangle$ is zero, where $\delta\mathbf{r}$ is a random distance, larger than the correlation length of the turbulence, about a location $\mathbf{r}$. A similar issue arises in deriving the expressions for Eddy diffusion of trace gases in an atmosphere. This subtlety of the statistical properties of compressible turbulence ultimately gives rise to the diffusion coefficient being inside the del operator and results in the nonstandard form of the equation for diffusion driven by an external medium, which is discussed in detail by *Fisk and Schwadron* [2001].

[29] We then take an ensemble average of equation (1), or

$$\frac{\partial \mathbf{B}_o}{\partial t} = \nabla \times \langle\delta\mathbf{u} \times \delta\mathbf{B}\rangle, \tag{2}$$

and use a quasi-linear approach, as described in Appendix A, to determine the correlation term, $\langle\delta\mathbf{u} \times \delta\mathbf{B}\rangle$. We assume that the turbulent velocities are normal to $\mathbf{B}_o$ and have no preferred direction about $\mathbf{B}_o$, in which case the components of the diffusion tensor are

$$\kappa = \left\langle \delta u_i(\mathbf{r}, t) \int_{-\infty}^{t} \delta u_i(\mathbf{r}', t')dt' \right\rangle. \tag{3}$$

The subscript i denotes a component of $\delta\mathbf{u}$. The quantities marked with the prime are streamed variables, integrated over the past trajectory of the parcels of plasma moving with $\delta\mathbf{u}$. Clearly, κ is simply of the form $\lambda^2/2\delta t$, where λ^2 is the mean square distance over which the plasma executes coherent motion.

[30] After much algebra, we find that equation (2) becomes

$$\frac{\partial \mathbf{B}_o}{\partial t} = \nabla \times [-\kappa\nabla \times \mathbf{B}_o - \nabla\kappa \times \mathbf{B}_o]. \tag{4}$$

Note that $-\nabla\kappa$ has the same role as would a mean convection velocity $\mathbf{u}_0$. This result is a consequence of our assumption about the statistical properties of the turbulence. Even in cases where the mean convection velocity is zero, as we are assuming here, a spatially varying κ results in an apparent mean convection.

[31] Equation (4) has aspects that arise in mean-field dynamo theory, which makes similar assumptions about the interaction and thus the correlation of small-scale turbulence with small-scale magnetic field variations [e.g., *Biskamp*, 1993]. However, in dynamo theory, there is a preferred orientation for the random motions, the so-called alpha effect, which gives rise to the amplification of the magnetic field. We are assuming that there is no preferred orientation and thus have only the diffusive effects. We are also very careful with the treatment of the statistical properties of the turbulence that gives rise to the mean convective velocity, $-\nabla\kappa$ in equation (4).

[32] Equation (4) can be shown to reduce to a standard equation for diffusion on the solar surface. Recalling the vector identity,

$$\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2\mathbf{A}, \tag{5}$$

and assuming that $-\nabla\kappa$ is normal to $\mathbf{B}_o$ (the turbulent motions are normal to $\mathbf{B}_o$), then in the case when $\mathbf{B}_o$ is radial, equation (4) readily reduces to

$$\frac{\partial B_o}{\partial t} = \nabla^2(\kappa B_o), \tag{6}$$

which is the form found by *Fisk and Schwadron* [2001], with the diffusion coefficient inside the del operators.

[33] It is important to note the separation of scale lengths. We assumed in deriving equation (4) that $\mathbf{B}_o$ and $\nabla \times \mathbf{B}_o$ vary only on scales large compared to the correlation length of the turbulence. A clear separation of scale lengths between those of the mean field and those of the turbulent motions is required. Equation (4), then, is not applicable for reconnection processes, since such processes, e.g., at X-type neutral points, invariably contain large curls. Rather, the diffusion process should be applied in essentially unipolar regions of the corona, in which there is a mean field lying in one general direction, with a slowly varying curl, and a set of random motions, driven, e.g., by motions at the coronal base, which occur on scales small compared to the variations in the mean magnetic field. Thus equation (4) can be applied only above the canopy of loops, since in the canopy reconnection is occurring. Indeed, above the canopy is an ideal location for equation (4), since this region contains unipolar regions, turbulent motions driven from below, and a clear separation of scale lengths.

4. Solutions for the Distribution of Open Flux

[34] Open magnetic flux interacting with the canopy of loops outside of coronal holes and diffusing throughout the overlying corona behaves according to equation (4), and thus solutions to equation (4) determine the distribution and behavior of open flux in these regions. We begin by searching for steady state solutions, $\partial\mathbf{B}_o/\partial t = 0$, which will describe the average behavior of the open flux.

[35] There is another constraint on the behavior of the open flux. We note in equation (4) that diffusion of the fieldlines requires the presence of $\nabla \times \mathbf{B}_o$. However, if $\nabla \times \mathbf{B}_o$ contains a component perpendicular to $\mathbf{B}_o$, the field

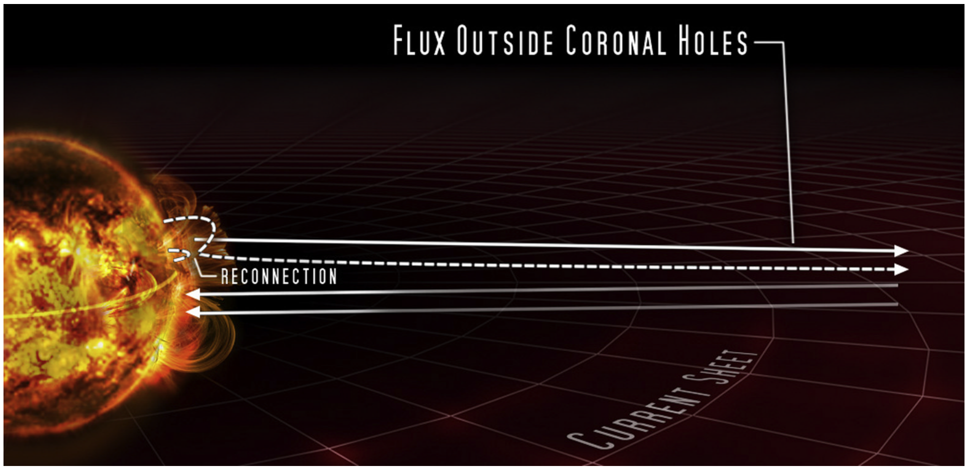

Figure 3. Illustration of open field lines relaxing to equilibrium by reconnecting in the canopy of loops. The open field lines relax to being uniform and radial in certain regions of the Sun by reconnecting in the canopy, as indicated by the dashed field line.

exerts a force on the coronal plasma, which given the strength of the field should result in motions of the plasma. We should expect then in a steady state the solutions for $\mathbf{B}_o$ will also be force free, or

$$\nabla \times \mathbf{B}_o = \alpha \mathbf{B}_o, \tag{7}$$

where α is constant along a magnetic field line.

[36] We require then that $\mathbf{B}_o$ satisfies both the steady state version of equation (4) and equation (7), or

$$\frac{\partial \mathbf{B}_o}{\partial t} = 0 = -\alpha^2 \kappa \mathbf{B}_o - \nabla(\alpha\kappa) \times \mathbf{B}_o - \nabla \times (\nabla\kappa \times \mathbf{B}_o). \tag{8}$$

It is clear from equation (8) that the only steady state solution is $\alpha = 0$, the current-free or potential field solution. The diffusion process should cause the open field to relax to a state of minimum energy, which is a potential field. There is also a requirement that the third term on the right of equation (8) is zero. This places a condition on $\nabla\kappa$ and on the motions of the open flux, which are convected with an effective velocity of $-\nabla\kappa$, which we consider in section 5.

[37] We argue then that outside of coronal holes, the open flux above the canopy of loops, where the open field lines are reconnecting and diffusing, should be a potential field, and that this conclusion should hold wherever the field is strong and thus diffusing, even out to the Alfvén point.

[38] It is important to note that this is not the potential field solution of a standard potential field source surface model. In a standard potential field model, the magnetic field is assumed to be known on the solar surface, at least its radial component, and this defines the inner boundary condition. The potential is a solution to Laplace's equation, which is second order, and thus an outer boundary condition is also required. The usual simplifying assumption is that the field is radial on the outer boundary, the so-called source surface, where the solar wind drags the field radially outward [e.g., *Altschuler and Newkirk*, 1969; *Schatten et al.*, 1969].

[39] The outer boundary condition in a potential field source surface model, however, is problematic. The field may be radial, but by definition it is not uniform; there are higher harmonics present, resulting from the inner boundary condition, and they introduce nonuniformity. However, if the field is radial but not uniform, it is not force free. The boundary condition is inconsistent with the solution. It is to be hoped that this inconsistency is not too debilitating and that the solution must relax to uniformity somewhere beyond the source surface.

[40] For the potential field solution presented here we do not have the option of treating the outer boundary condition casually. We concluded that so long as the open flux is diffusing it will relax to a state of minimum energy, a potential field everywhere in the corona, and if we require a radial field on the outer boundary it must be a potential radial field. However, there is only one solution to Laplace's equation, one potential field that is radial on the outer boundary, and that is a field that is radial and uniform everywhere.

[41] Unlike a standard potential field source surface model, we are not required to match the observed magnetic field on the inner boundary. We are dealing here only with open magnetic flux, not the total flux. Equation (4) applies only above the canopy of loops, not in the canopy or near the solar surface, where the reconnection is occurring. We are then free to choose the inner boundary condition. We have in effect a slippery surface on the inner boundary, the canopy of loops, as is illustrated in Figure 3. Open field lines are free to reconnect, diffuse, and relax to a radial, potential field. We require only that there is enough closed flux present with which to reconnect, which is never a problem, and that the additional component of open flux can also be radial on the outer boundary. As we argue in section 6, this latter condition requires that the uniform radial distribution is limited to regions that do not underlie the overexpansion of the open magnetic flux from coronal holes.

5. Motions of the Open Magnetic Flux

[42] We also have a requirement that a steady state solution to equation (8) demands that

$$\nabla \times (\nabla\kappa \times \mathbf{B}_o) = 0. \tag{9}$$

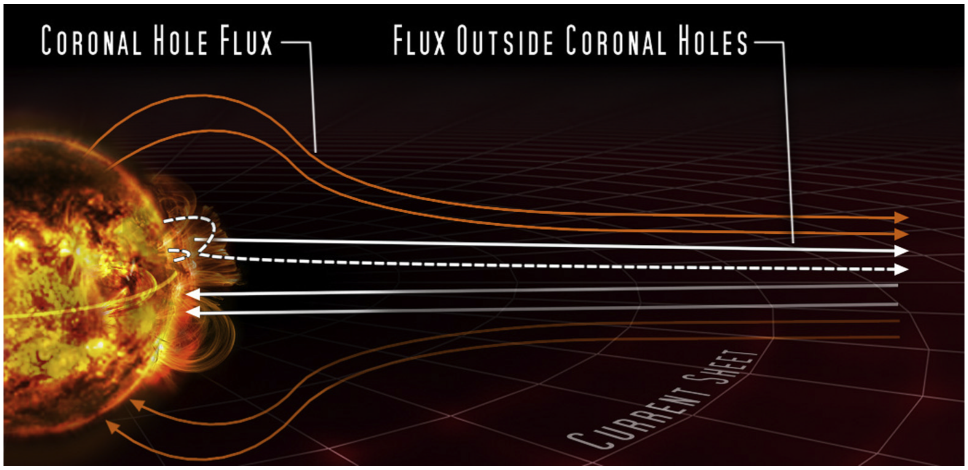

Figure 4. Illustration of the final configuration of the open magnetic flux at solar minimum. Open magnetic flux from the polar coronal hole over expands and overlies the canopy of loops. An additional component of open flux that reconnects with the canopy of loops relaxes to being radial and uniform in the region that does not underlie the open flux from the coronal hole. There is a region between the polar coronal hole and the region containing the additional component of radial open flux where open flux is limited. Open flux is transported through the region where it is limited, and the amount of open flux present depends on how rapidly the transport occurs.

Thus, at the top of the loops, where the open flux is radial and essentially uniform, we have the additional requirement on the diffusion coefficient that

$$\nabla^2 \kappa = 0. \tag{10}$$

The diffusion coefficient results from random convective motions, from reconnections at the base of coronal loops, and primarily from canopy diffusion. The canopy diffusion coefficient adjusts so as to satisfy equation (10), or equivalently, we can solve equation (10) for at least $-\nabla\kappa$, which is the effective mean convection of the open field lines due to the diffusion.

[43] Possible solutions for $-\nabla\kappa$ are presented by *Fisk and Schwadron* [2001]. For solar minimum conditions, the open magnetic flux is assumed to be convected across the polar coronal holes by differential rotation and to diffuse outside of the polar coronal holes. Thus at the edge of the polar coronal holes the boundary condition for equation (10) is continuity of streaming, or transport of open flux. There is another boundary condition at the current sheet, which at solar minimum lies near the equatorial plane of the Sun. Fisk and Schwadron argue that open magnetic flux does not reconnect at the current sheet, and thus at the current sheet the normal component of $\nabla_\perp\kappa = 0$. The resulting solution to equation (10) is a flow pattern of open field lines in the diffusing region. These flow patterns influence the configuration of the heliospheric magnetic field, just as differential rotation across the polar coronal holes influences the configuration of the heliospheric magnetic field [*Fisk*, 1996].

[44] *Fisk and Schwadron* [2001] also present solutions to equation (10) appropriate for solar maximum conditions. In this case there are no well-established polar coronal holes, and the resulting solutions are consistent with a current sheet that rotates about an axis that lies near the equatorial plane. This rotation can accomplish the reversal in polarity of the open magnetic flux during the solar cycle.

6. Distribution and Magnitude of Open Flux Outside of Coronal Holes

[45] A necessary condition for the additional component to be present is that there are ample coronal loops for the open magnetic flux to interact and reconnect with. This process distributes open flux into predominantly closed field regions. We expect, however, that the additional process of relaxing to a radial magnetic field will concentrate the additional component into a subset of the regions with ample coronal loops that is determined by the need for the total open flux in the outer corona to relax to pressure equilibrium.

[46] The configuration of the coronal magnetic field should appear as in Figure 4. There will be coronal holes, where the open flux is strong and it overexpands to overlie the surrounding closed field structures. There will be radial open flux outside of coronal holes. The overexpansion of the field from the coronal hole will be limited, since in the high corona the open field must come into pressure equilibrium. Conversely, the additional component of open flux outside of coronal holes will be limited to those regions that do not lie under the overexpansion of the magnetic field from coronal holes.

[47] A radial component of open magnetic flux will decrease as $1/r^2$, from the solar surface to 1 AU, where it can be determined from the observed radial component of the heliospheric magnetic field of $\sim 3.5 \times 10^{-5}$ G. We thus expect that the magnitude of the additional component of open flux in regions not underlying the overexpansion of the open flux from coronal holes will be ~ 1.6 G on the solar surface.

[48] There are then regions, under the overexpanding field from coronal holes, where open flux that connects

to the solar surface is absent or at least limited, consistent with *Axford* [1977]. At solar minimum, then, the additional component of open flux is concentrated in and near the streamer belt. The open flux, of course, arrives in this low-latitude region, in this model, by being transported into and out of the polar coronal holes. Some open flux will thus be present in the intermediate region between the polar holes and at low latitudes, as shown in Figure 4. However, it may be limited if the speed at which the open flux is transported through the intermediate region is high. As in any flow problem, the density varies inversely as the speed, and thus if the open flux is transported across the intermediate region through rapid reconnections and large displacements, the density of open field lines in this region will be low.

[49] It should be noted that this configuration of open magnetic flux outside of coronal holes is different from that proposed by *Woo and Habbal* [2000]. In their model, open flux is distributed broadly across the entire Sun. Here, open flux is concentrated in coronal holes, as is commonly believed, and also in regions that do not underlie the over expansion of open flux from coronal holes. The concentrations of open flux near the equatorial current sheet, illustrated in Figure 4 for solar minimum, have similarities to the extended halo around the streamer belt and its extension into the heliosphere, the so-called heliospheric plasma sheet, discussed by *Bavassano et al.* [1997].

[50] The fast solar wind clearly originates in coronal holes and can be identified from both its observed speed and its composition [*Geiss et al.*, 1995; *Raymond et al.*, 1998]. We expect that the slow solar wind originates along the additional radial component of open flux outside of coronal holes. This additional component connects the heliosphere with the large coronal loops on the quiet Sun that most resemble slow solar wind in both their elemental and ionic charge composition [*Feldman et al.*, 2005]. Conversely, we can use the observed latitude and longitude distribution of the slow solar wind to identify those regions that should contain the additional component of radial open flux.

[51] Gilbert et al. (A new technique for mapping open magnetic flux from the solar surface into the heliosphere, submitted to *Astrophysical Journal*, 2006) have recently developed a mapping technique for the open magnetic field in the corona that is ideally suited to determining the distribution of open magnetic flux outside of coronal holes. Gilbert et al. use the requirement that open flux, which is nonuniformly distributed on the solar surface, must relax to being uniform and radial on some outer surface in the corona. The mapping from the solar surface to this outer surface can thus be done by a simple mathematical relaxation technique. Gilbert et al. use observations of the magnetic field on the solar surface and a potential field source surface model to determine both the location of the heliospheric current sheet and the open flux present in coronal holes on the solar surface. They then use their relaxation technique to map to the outer surface (effectively the solar wind source surface). If they add open flux outside of coronal holes, the relaxation of the coronal hole magnetic flux is limited as in Figure 4. They can adjust the open flux outside of coronal holes and get various locations for boundaries between the coronal hole magnetic flux and the additional component. This is a pressure equilibrium calculation and the boundary locations are dependent only on the total amount of additional open flux outside of coronal holes. If we assume that fast solar wind is confined to coronal holes, Gilbert et al. need to locate and specify the location of one boundary between the coronal hole magnetic field (fast wind) and the additional component (slow wind) to specify all aspects: the mapping of the open magnetic flux in coronal holes from the solar surface into the heliosphere and the distribution of the additional radial component of open flux outside of coronal holes.

[52] During solar minimum conditions, the slow solar wind is confined to a narrow latitude range surrounding the near-equatorial current sheet. The additional, radial component of open flux is also confined to this region and is small compared to the open flux from the polar coronal holes. For example, if the slow solar wind extends $\pm$ 15° from the current sheet, the additional component of open flux is 25% of the total open flux of the Sun. During solar maximum, when coronal holes are more transitory, the additional component of open flux can be a larger fraction of the total open flux.

[53] The open flux in the heliosphere can be determined by potential field source surface models based on solar observations. Reasonable agreement between the predictions of these models and the observed heliospheric field is obtained [*Wang et al.*, 2000b], even though the models do not include the additional component of open flux. However, there is uncertainty in the solar observations [e.g., *Wang and Sheeley*, 1995] and, in particular, observations of the magnetic field are limited in the polar regions of the Sun. It does not seem unreasonable that there is an uncertainty of 20–30% in the total open flux obtained by potential field source surface models, which would allow for the prediction of an additional component of open flux outside of coronal holes obtained here.

7. Concluding Remarks

[54] We have argued that there is a component of open magnetic flux in addition to the open flux in coronal holes. The additional component is the result of the interaction and reconnection between open flux and coronal loops that distributes open magnetic flux outside of coronal holes. This same process will cause the additional component to relax to a uniform, radial configuration, in regions that do not underlie the overexpansion of the open flux from coronal holes. The magnitude of the additional component of open flux on the solar surface is $\sim$1.6 G, inferred from heliospheric observations; the distribution in latitude and longitude should be the same as that of the slow solar wind. The presence of this open flux on the Sun is consistent with observations of energetic particle release into the heliosphere, observations of electromagnetic emissions of escaping electrons (so-called type III radiation), the compositional measurements of the slow solar wind, and occultation measurements near the solar corona, as discussed in the Introduction.

[55] The solutions on which we based our conclusion were steady state, and thus it is worthwhile to ask whether this approach is adequate. The Sun, after all, is quite

dynamic and contains many transients such as coronal mass ejections or the emergence of active regions that alter the configuration of the coronal magnetic field. There are two timescales appropriate during which time-dependent solutions should relax to a steady state equilibrium. First, we required that the large-scale field relaxes to being force free. This should occur on a timescale of the Alfvén speed transit time, since this is the speed at which waves propagate in the corona. If we take an Alfvén speed of $\sim$500 km s^{-1} and a characteristic distance of $\sim$1 solar radius (7×10^5 km), this is a timescale of only a fraction of an hour. The longer, and thus dominant relaxation time should be the diffusive timescale $\sim\lambda^2/\kappa$.

[56] The canopy diffusion coefficient at solar minimum can be estimated from the solutions of *Fisk and Schwadron* [2001] to be $\kappa \sim 1.6 \times 10^5$ km^2 s^{-1}. At solar minimum there are also well-established global structures in the coronal magnetic field, in which case we take λ to equal approximately one solar radius, and the resulting diffusive timescale is about one solar rotation period. This is of course the same timescale during which potential field source surface models, which are based on synoptic observations, are considered to be valid, and do provide the overall configuration of the open flux when it is dominated by concentrations of open flux. It is probably reasonable then to assume that at solar minimum the overall structure of the coronal field is steady on this timescale, and our solutions are valid.

[57] At solar maximum, conditions are more dynamic. We expect then that our solutions are valid only in smaller regions, which are steady on the appropriate timescale. For example, again using timescales of $\sim\lambda^2/\kappa$, and the same value of $\kappa \sim 1.6 \times 10^5$ km^2 s^{-1}, we conclude that our solutions should be valid in a region of dimension $\sim$0.5 solar radii that is steady on the scale of 1 week. It is also possible that the canopy diffusion coefficient at solar maximum is much larger than this value, when many large loops are present, and the solutions hold over larger regions.

Appendix A

[58] To derive equation (4), we follow the derivation for the surface diffusion equation in the appendix of *Fisk and Schwadron* [2001] and extend it into three dimensions.

[59] Consider first some of the properties of the turbulence. We assume that there are random velocities in the plasma, $\delta\mathbf{u}$. We note, as did *Fisk and Schwadron* [2001], that care must be taken in defining the statistical properties of $\delta\mathbf{u}$. We assume that the volume average of $\delta\mathbf{u}$, not the local average, is zero, i.e., $\langle\delta\mathbf{u}(\mathbf{r}+\delta\mathbf{r})\rangle = 0$, where $\delta\mathbf{r}$ is a random distance, larger than the correlation length of the turbulence, about a location $\mathbf{r}$, and angle brackets denote ensemble average. Since we will allow for spatial variations in $\delta\mathbf{u}$, sitting in one location and receiving parcels of plasma from surrounding regions, we should expect that $\langle\delta\mathbf{u}\rangle \neq 0$.

[60] Indeed, the importance of specifying the technique for determining the average value of $\delta\mathbf{u}$ is revealed by expanding $\langle\delta\mathbf{u}(\mathbf{r}+\delta\mathbf{r})\rangle$ in a Taylor series, or

$$\langle\delta\mathbf{u}(\mathbf{r}+\delta\mathbf{r})\rangle = \langle\delta\mathbf{u}(\mathbf{r})\rangle + \langle(\delta\mathbf{r}\cdot\nabla)\delta\mathbf{u}\rangle. \tag{A1}$$

This expansion is allowed provided the spatial variations in δu^2 are small on the scale of $\delta\mathbf{r}$, i.e., $\delta u^2 \gg \delta\mathbf{r}\cdot\nabla\delta u^2/2$. The expansion in equation (A1) reveals that both $\langle\delta\mathbf{u}\rangle$ and $\langle\delta\mathbf{u}(\mathbf{r}+\delta\mathbf{r})\rangle$ cannot be zero if $\nabla\delta\mathbf{u}$ is not zero.

[61] We assume that the plasma includes a mean magnetic field, $\mathbf{B}_o$, and variations in the magnetic field $\delta\mathbf{B}$ (which will be correlated with $\delta\mathbf{u}$). We assume that $\langle\delta\mathbf{B}\rangle = 0$.

[62] For simplicity, we assume that $\delta\mathbf{u}$ is normal to $\mathbf{B}_o$, and that the turbulent motions have no preferred direction about $\mathbf{B}_o$. This latter assumption has the consequence of reducing the diffusion tensor we will derive to a scaler.

[63] Finally, we assume that the plasma has no mean velocity other than $\langle\delta\mathbf{u}\rangle$. We can add the effects of an additional mean convection velocity, $\mathbf{u}_0$, later.

[64] Consider now the inductance equation for convective motions,

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}), \tag{A2}$$

and thus, with $\mathbf{u} = \delta\mathbf{u}$ and $\mathbf{B} = \mathbf{B}_o + \delta\mathbf{B}$, the ensemble average of equation (A2) becomes

$$\frac{\partial\mathbf{B}_o}{\partial t} = \nabla\times\langle\delta\mathbf{u}\times\delta\mathbf{B}\rangle + \nabla\times(\langle\delta\mathbf{u}\rangle\times B_o), \tag{A3}$$

where $\langle\delta\mathbf{u}\rangle$ obeys equation (A1).

[65] Subtracting equation (A3) from equation (A2) yields

$$\frac{\partial\delta\mathbf{B}}{\partial t} = \nabla\times(\delta\mathbf{u}\times\mathbf{B}_o), \tag{A4}$$

where we have made the usual quasi-linear approximation and retained only first-order terms. Equation (A4) can then be integrated to yield

$$\delta\mathbf{B}(\mathbf{r},t) = \int_{-\infty}^{t} dt'\nabla\times(\delta\mathbf{u}'\times\mathbf{B}_o), \tag{A5}$$

where the time integral is over the past trajectory of the plasma, $\delta\mathbf{u}'$. We denote the past trajectory position of the plasma to be

$$\delta\mathbf{r} = \int_{-\infty}^{t} dt'\delta\mathbf{u}'. \tag{A6}$$

[66] Thus, substituting equation (A5) and equation (A6) into equation (A3), we find that

$$\frac{\partial\mathbf{B}_o}{\partial t} = \nabla\times\langle\delta\mathbf{u}\times\nabla\times(\delta\mathbf{r}\times\mathbf{B}_o)\rangle + \nabla\times(\langle\delta\mathbf{u}\rangle\times\mathbf{B}_o). \tag{A7}$$

[67] By using vector identities, by noting that $\nabla\cdot\mathbf{B}_o = 0$, and with our assumption that the turbulent motions are normal to $\mathbf{B}_o$, i.e., $\delta\mathbf{r}\cdot\mathbf{B}_o = 0$, we can show that

$$\begin{aligned}\langle\delta\mathbf{u}\times\nabla\times(\delta\mathbf{r}\times\mathbf{B}_0)\rangle = &-\langle\delta\mathbf{u}\nabla\cdot\delta\mathbf{r}\rangle\times\mathbf{B}_0 \\ &+\langle\delta\mathbf{u}\times(\delta\mathbf{r}\times\nabla\times\mathbf{B}_0)\rangle \\ &+\langle 2\delta\mathbf{u}\times(\mathbf{B}_0\cdot\nabla)\delta\mathbf{r}\rangle \\ &+\langle\delta\mathbf{u}\times(\mathbf{B}_0\times\nabla\times\delta\mathbf{r})\rangle.\end{aligned} \tag{A8}$$

[68] The first term in equation (A8) can be written

$$\langle \delta \mathbf{u} \nabla \cdot \delta \mathbf{r} \rangle = \nabla \cdot \langle \delta \mathbf{r} \delta \mathbf{u} \rangle - \langle \delta \mathbf{r} \cdot \nabla \delta \mathbf{u} \rangle. \quad \text{(A9)}$$

By our assumption that the turbulence has no preferred direction about $\mathbf{B}_o$, the first term in equation (A9) then reduces to $\nabla\kappa$, where κ is the diffusion coefficient in equation (4). The second term in equation (A9) is $-\langle \delta \mathbf{u} \rangle$ by equation (A1).

[69] The second term in equation (A8) can be written

$$\langle \delta \mathbf{u} \times (\delta \mathbf{r} \times \nabla \times \mathbf{B}_o) \rangle = -\kappa \nabla \times \mathbf{B}_o. \quad \text{(A10)}$$

[70] The third and fourth terms in equation (A8) can be argued to be zero since the components of the turbulent velocities, and their derivatives, are uncorrelated with orthogonal components.

[71] Thus, substituting equation (A9) and equation (A10) into equation (A8), equation (A7) becomes equation (4) or

$$\frac{\partial \mathbf{B}_o}{\partial t} = -\nabla \times \nabla \times (\kappa \mathbf{B}_o). \quad \text{(A11)}$$

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