An explanation for strongly underwound magnetic field in co-rotating rarefaction regions and its relationship to footpoint motion on the the sun

N. A. Schwadron[1]
Southwest Research Institute, San Antonio, Texas, USA

Received 2 March 2002; revised 28 March 2002; accepted 24 April 2002; publisehd 18 July 2002.

[1] Strongly underwound magnetic field is observed to be correlated with the occurrence of co-rotating rarefaction regions (CRRs). We demonstrate that the phenomenon is likely caused by the combined action of (1) the motion of footpoints of open magnetic field lines on the Sun from within to outside coronal hole boundaries; and (2) the effect of solar wind shearing in rarefaction regions. We provide formulas that may be used to relate the observed underwinding of magnetic field lines in CRRs to infer the velocities of footpoints through coronal hole boundaries. The observations of strong field underwinding in CRRs generally confirms the hypothesis that the footpoints of open magnetic field lines move on the Sun through coronal holes, the sources of fast solar wind. *INDEX TERMS:* 2134 Interplanetary Physics: Interplanetary magnetic fields; 2102 Interplanetary Physics: Corotating streams; 2169 Interplanetary Physics: Sources of the solar wind; 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields

1. Introduction

[2] *Parker* [1963] derived the heliospheric magnetic field pattern, a so-called Parker Spiral, based on the concept that magnetic field lines are rooted at the Sun which rotates bodily and are frozen into the supersonic flow of the steady, radially directed solar wind. The basic prediction of the theory is that the magnetic field lines form a spiral on cones of constant latitude, with the magnetic field given by $\mathbf{B}_p = B_B\left(\frac{R_B}{r}\right)^2\left(\hat{\mathbf{e}}_r - \frac{\Omega_\odot r\ \sin\theta}{V}\hat{\mathbf{e}}_\phi\right)$ where B_B is the radial magnetic field strength of open magnetic flux on the Sun on a surface where the magnetic field first achieves a uniform magnetic pressure, R_B is the radial location of the surface, $\Omega_\odot$ is the bodily rotation rate of the Sun, $\hat{\mathbf{e}}_r$ is the unit vector in the radial direction, $\hat{\mathbf{e}}_\phi$ is the unit vector in the azimuthal direction, the radial solar wind speed is given by V, the heliocentric radius is given by r, and θ is the co-latitude. The spiral angle, the angle relative to the radial direction, is readily computed and is about 45° near 1 AU in the ecliptic, beyond which the field becomes more strongly azimuthal.

[3] It is well known that magnetic field measurements by spacecraft generally agree with the predictions of *Parker* [1963] as reviewed by *Ness and Burlaga* [2001] and discussed by many other authors [e.g., *Thomas and Smith*, 1980; *Burlaga et al.*, 1982; *Forsyth et al.*, 1996a, 1996b; *Bruno and Bavassano*, 1997]. It is less well known, however, that the mean spiral angle deviates strongly in the radial direction inside large scale Corotating Rarefaction Regions (CRRs) [*Smith et al.*, 2000; *Murphy et al.*, 2002] which co-rotate with the Sun, are characterized by a monotonic decrease in solar wind speed, and map back to regions of small longitudinal extent on the Sun, termed "dwells" [*Schwenn*, 1990]. *Posner* [1999] attributed this effect to the combined action of footpoint motion and super-expansion of the wind from coronal holes. *Jones et al.* [1998], for example, report on extreme cases in which heliospheric magnetic fields detected by Ulysses are nearly radial and finds that a significant number of the cases were accompanied by a monotonic decrease in solar wind speed (i.e., rarefaction regions) which map back to dwells.

[4] These observations call for a revision to the Parker field model. It is the purpose of this paper to provide a simple model that shows that magnetic fields may strongly deviate from a standard Parker magnetic field due to the combined effects of (1) footpoint motion of open magnetic fields on the Sun from within to beyond coronal hole boundaries, and (2) the shearing of the solar wind flow in rarefaction regions.

2. Theory

[5] There are a number of ways to cause deviations of the field from a standard Parker spiral and it may be worthwhile to rule some out of these possibilities. First of all, consider the case that footpoints of the open magnetic field are rooted on the Sun and rotate bodily with the Sun at the rotation rate, $\Omega_\odot \approx 2\pi/26\ \text{day}^{-1}$. There exists a frame of reference that rotates with the Sun in which the magnetic footpoints of the open magnetic field remain stationary. If we denote the flow velocity of the solar wind in an inertial reference frame by $\mathbf{V}$, then the solar wind velocity in the co-rotating reference frame is, $\mathbf{V}' = \mathbf{V} - \Omega_\odot r\ \sin(\theta)\hat{\mathbf{e}}_\phi$, where r is the heliocentric radius, θ is the co-latitude, and $\hat{\mathbf{e}}_\phi$ is the unit vector directed in the azimuthal direction. Assuming the magnetic field is parallel to the flow velocity near the Sun, it must be parallel to the flow velocity $\mathbf{V}'$ throughout the heliosphere. Since the magnetic field does not change upon transformation from the co-rotating frame to the inertial frame, the vector $\mathbf{V}'$ defines the direction of the magnetic field in both frames. Since the local velocity $\mathbf{V}$ can be directly

[1]Also at Department of Atmospheric, Oceanic and Space Science, The University of Michigan, Ann Arbor, USA.

0094-8276/02/2002GL015028

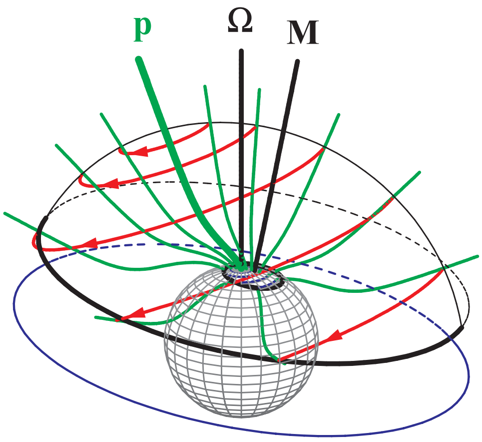

Figure 1. An illustration of the motions of the open magnetic field in the solar corona, *Fisk et al.* [1999]; *Schwadron et al.* [1999]. The figure is drawn in the frame corotating with the equatorial rotation rate. The "M" axis is the axis of symmetry for the expansion of the magnetic field from the polar hole. The "Ω" axis is the solar rotation axis. The green lines are open field lines, with "p" the field line that connects to the heliographic pole. The red curves are the trajectories of the field lines, the motion of which is driven by differential rotation of the photosphere, which takes footpoints beyond coronal hole boundaries (shown here by the thick black curves). The blue curve on the outer surface shows the current sheet location.

measured, the direction for the magnetic field can be unambiguously predicted. The essential point is that the observations indicate strong deviations of the local magnetic field direction from the direction indicated by $\mathbf{V}'$. Since the locally measured solar wind velocity $\mathbf{V}$ can be used in the analysis of the data, the analysis may implicitly takes into account the possibility of variations in the speed and velocity from the point of origin to the point of observation. The analysis then if properly conducted rules out the possibility that magnetic footpoints rotate rigidly with the Sun [*Murphy et al.*, 2002].

[6] The next possibility to consider is the effect of motions of magnetic footpoints on the Sun. In particular consider the case in which the solar wind velocity is uniform and radial in the inertial frame, and the magnetic footpoints move on a surface where the magnetic field first achieves magnetic pressure balance. This effect was first considered by *Fisk* [1996], as illustrated in Figure 1. The essential assumption made here is that coronal holes rotate rigidly, while the underlying open magnetic field footpoints undergo differential rotation. As shown in the figure, when the coronal hole's symmetry axis is offset from the rotation axis (or, more generally, if the coronal hole boundary does not exist at a unique solar latitude), then the footpoints of open magnetic field lines move beyond the coronal hole boundary at its trailing edge.

[7] We will then take velocities of magnetic footpoints, $\mathbf{u}_\perp = \omega_\theta R_B \hat{\mathbf{e}}_\theta + \omega_\phi R_B \sin\theta \hat{\mathbf{e}}_\phi$, on a surface where the magnetic field has achieved a uniform magnetic pressure with radial field strength B_B at radial location $R_B \sim 10\ R_\odot$. The footpoints move under the influence of this velocity field $(\mathbf{u}_\perp)$ within the spherical surface as is illustrated by the red curves on the outer surface in Figure 1. The resulting field configuration in the heliosphere is given by

$$\mathbf{B}_F = B_B\left(\frac{R_B}{r}\right)^2\left[\hat{\mathbf{e}}_r - \frac{(\Omega_\odot + \omega_\phi)r\sin\theta}{V}\hat{\mathbf{e}}_\phi - \frac{\omega_\theta r}{V}\hat{\mathbf{e}}_\theta\right] \quad (1)$$

Note that the effect of the motions on the surface at $r = R_B$ is to cause systematic deviations of the field from the radial solar wind flow velocity. Equivalently, it may be argued that deviations of the magnetic field from the solar wind direction would cause deviations of the magnetic field throughout the heliosphere. These points of view are in fact equivalent: deviations of the field from the radial flow direction necessitate footpoint motions on a surface at fixed radius.

[8] Consider then a specific example that is comparable to the observations reported by *Murphy et al.* [2002]. We will take a solar wind speed V = 600 km/s and a 20° latitude (co-latitude of 70°). Differential rotation within the polar coronal hole yields a rotation rate $\omega \approx \Omega_\odot/5$. Consider an open flux tube that originates near the trailing edge of a coronal hole and has a footpoint velocity on the outer surface consistent with rotation rates $\omega_\theta = \Omega_\odot/10$ and $\omega_\phi = -\sqrt{3}\Omega_\odot/10$. These resulting footpoint motions are comparable to those that would arise on the trailing edge of the coronal hole boundary (on the outer surface) shown in Figure 1. Deviations of the magnetic field due to these footpoint motions alone would cause a departure of the magnetic field from a standard Parker spiral (computed with the rotation rate $\Omega_\odot$) of about 3° if we take a radial distance at 5 AU. To make matters even worse, the departure angles of the field diminish at larger distances from the Sun. In order to explain the large deviations of the magnetic field, of order 10°, we would require very large footpoint rotation rates $\omega_\phi \sim -0.4\ \Omega_\odot$. It has been pointed out by *Fisk et al.* [1999] that footpoints may in fact move rapidly in the slow wind region when the current sheet is strongly tilted. Although, these effects cannot be completely ruled out as the cause of the strong field deviations, we suggest that it is not a likely explanation, particularly considering the frequent concurrence of rarefaction regions and strong field departures.

[9] The final case to be considered here is the effect of the sheared solar wind flow in the rarefaction region combined with the effect of footpoint motion on the Sun. Consider then a boundary between fast and slow solar wind near the trailing edge of a polar coronal hole that occurs at a position (θ_0, ϕ_0) in co-latitude and azimuth on the outer surface where the field first achieves pressure balance. We consider that a magnetic footpoint moves from coordinates $(\theta_0 - \delta\theta_0/2, \phi_0 + \delta\phi_0/2)$ inside the coronal hole associated with faster solar wind to the coordinates $(\theta_0 + \delta\theta_0/2, \phi_0 - \delta\phi_0/2)$ outside the coronal hole boundary where the wind is slower. Hence the magnetic footpoints move across the coronal hole boundary from fast solar wind with speed $V + \delta V/2$ to slow solar wind with speed $V - \delta V/2$ over a time interval δt (the quantities $\delta\phi_0$, $\delta\theta_0$ may be taken to be arbitrarily small so as to bound a specific region with a speed gradient and an average speed V; for purposes of clarity we take this region to bound the coronal hole boundary). Note here that the angular separations of the rarefaction regions are readily related to the footpoint angular rotation rates:

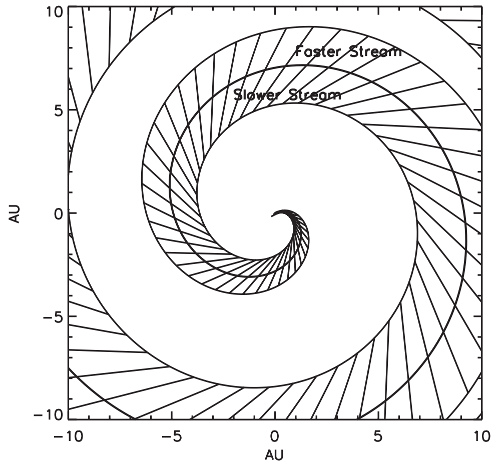

Figure 2. The orientation of the magnetic field in rarefaction regions. Streamlines are shown by the solid spirals segments show the field orientation.

$\delta\phi_0 = -\omega_\phi \delta t; \delta\theta_0 = \omega_\theta \delta t$. Since the speed is observed to monotonically decrease in CRRs, the plasma in the rarefaction region can be taken to propagate ballistically. Hence the streamlines from the rarefaction region straddling the coronal hole boundary are readily computed. In the reference frame that co-rotates bodily with the Sun at the equatorial rotation rate, the azimuthal angle of the plasma parcel from inside the coronal hole boundary is given by $\phi_f(t) = \phi_0 - \delta\phi_0/2 - \frac{\Omega_\odot r_f(t)}{V+\delta V/2}$, where $r_f(t)$ is the heliocentric radius of the ballistically propagating plasma parcel, $r_f(t) = R_B + (V + \delta V/2)(t + \delta t/2)$. Similar relations are easily written down for the plasma parcel emitted from the position beyond the coronal hole boundary. The co-latitude of the parcels inside and beyond the coronal hole boundary remain fixed as the parcels propagate outwards. The angular separations and radial separation of the emitted plasma parcels are then readily computed and provide the direction of the heliospheric magnetic field, $\mathbf{B}_1$, in the rarefaction region:

$$\mathbf{B}_1 = A_1(r)\left[\left(I - \frac{r\,\omega_\phi}{V^2}\frac{\delta V}{\delta \phi_0}\right)\hat{\mathbf{e}}_r - \frac{r\,\omega_\theta}{V}\hat{\mathbf{e}}_\theta - \frac{(\Omega_\odot - \omega_\phi)r\sin\theta}{V}\hat{\mathbf{e}}_\phi\right] \tag{2}$$

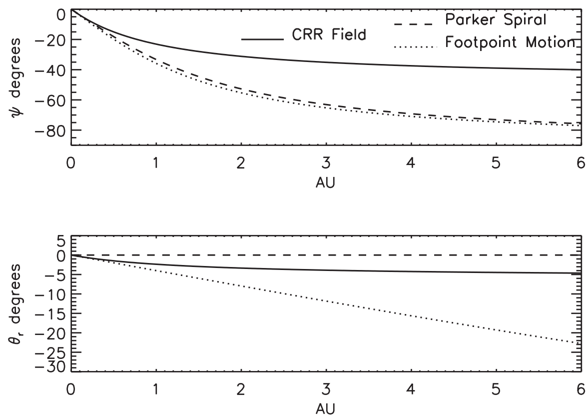

Figure 3. The field angles relative to the radial direction. For details see Section 2.

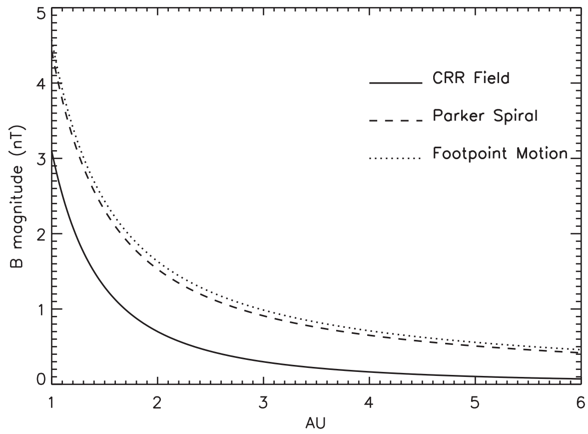

Figure 4. The solid curve is the field magnitude in a rarefaction region. Also shown are the field magnitudes in the case of a Parker spirals and of pure footpoint motion (4).

where $A_1(r)$ is an amplitude factor of the field in the rarefaction region. Note that in this equation, the solar wind velocity shearing term may be given by $\omega_\phi \frac{\delta V}{\delta\phi_0} = -\omega_\theta \frac{\delta V}{\delta\theta_0} = \frac{-\delta V}{\delta r} = \mathbf{u}_\perp \cdot \nabla_B V$ where $\nabla_B V$ indicates the gradient of the solar wind velocity in the outer surface where the field achieves magnetic pressure balance.

[10] The field angles are readily computed from (2). Consider a specific example for the parameters listed above with a net decrease in speed of 300 km/s across a region of 5° longitudinal extent, so that the speed gradient in the rarefaction region is given approximately by $\delta V/\delta\phi_0 = -60$ km/(s-deg). In Figure 2, we show equatorial projections of the streamlines and field line segments in the CRR out to 10 AU. In Figure 3 we show the field angles relative to the radial direction as a function of radial distance. The angle ψ is the field direction relative to the radial direction in the $\phi - r$ plane and can be related by

$$\tan\psi = \frac{B_\phi}{B_r} = -\frac{(\Omega_\odot + \omega_\phi)r\,\sin\theta}{V - (r/V)\mathbf{u}_\perp \cdot \nabla_B V}. \tag{3}$$

Similarly, θ_r is the field angle relative to the radial direction in the $\theta - r$ plane. Hence, $\tan\theta_r = \frac{B_\theta}{B_r} = -\frac{\omega_\theta r}{(r/V)\mathbf{u}_\perp \cdot \nabla_B V + V}$. Note that these angles approach fixed values for radial distances, $r > V^2/(\mathbf{u}_\perp \cdot \nabla_B V)$. Note also that the phase of the field is fixed in the $\theta - \phi$ plane, with the angle relative to the azimuthal direction given by $\tan\theta_\phi = \frac{B_\theta}{B_\phi} = \frac{\omega_\theta}{(\Omega_\odot + \omega_\phi)\sin\theta.}$ The simple expression in (2) provides us with a means to utilize observations of magnetic field in CRRs to determine the precise nature – magnitude and direction – of footpoint motions across coronal hole boundaries.

[11] The amplitude factor $A_1(r)$ may be solved for by insisting conservation of open magnetic flux. The magnetic field, $\mathbf{B}_{ch}$, in the region of fast solar wind can be solved for is consistent with equation (3) with a fast solar wind speed (V + δV/2). Given the direction of $\mathbf{B}_1$ from equation (2), the conservation of open magnetic flux requires that the magnetic field is continuous in the direction perpendicular to the interface that separates ambient fast solar wind and solar wind in the rarefaction region. So denoting $\hat{\mathbf{e}}_{I\perp}$ the unit vector perpendicular to

the interface, our requirement of magnetic flux conservation may be expressed, $\mathbf{B}_1 \cdot \hat{\mathbf{e}}_{I\perp} = \mathbf{B}_{ch} \cdot \hat{\mathbf{e}}_{I\perp}$. Our problem then is reduced to solving for the unit vector perpendicular to the interface. On the surface where the field has achieved magnetic pressure balance at $r = R_B$, we take an orientation of the interface to be inclined by an angle Ψ_I relative to the azimuthal direction: $\hat{\mathbf{e}}_I = \hat{\mathbf{e}}_\theta \sin\Psi_I + \hat{\mathbf{e}}_\phi \cos\Psi_I$. The interface is then defined by a vector in the direction of the fast solar wind streamline and $\hat{\mathbf{e}}_I$. The unit vector perpendicular to the interface is given by

$$\hat{\mathbf{e}}_{I\perp} = \frac{\Omega_\odot r \sin\theta \sin\Psi_I \hat{\mathbf{e}}_r - (V + \delta V/2)\cos\Psi_I \hat{\mathbf{e}}_\theta}{\sqrt{(V + \delta V/2)^2 + (\Omega_\odot r \sin\theta \sin\Psi_I)^2}} + \frac{(V + \delta V/2)\sin_I \hat{\mathbf{e}}_\phi}{\sqrt{(V + \delta V/2)^2 + (_\odot r \sin\theta \sin_I)^2}}. \quad (4)$$

Applying conservation of magnetic flux, we may then solve for $A_1(r)$:

$$A_1(r) = B_B \left(\frac{R_B}{r}\right)^2 \omega_\perp \cdot \left[\left(1 + \frac{\delta V}{2V}\right)\omega_\perp + \left(\frac{r}{V^2}\mathbf{u}_\perp \cdot \nabla_B V + \frac{\delta V}{2V}\right)_\odot \sin\theta \sin\Psi_I\right]^{-1} \quad (5)$$

where $\omega_\perp = -\omega_\theta \cos\Psi_I + \omega_\phi \sin\theta \sin\Psi_I$ is the rotation rate on the surface at $r = R_B$ perpendicular to the interface in the direction $\hat{\mathbf{e}}_I$. Note that this defines the amplitude of the field only at the interface. Within the rarefaction region, a differential equation requiring a divergence-free magnetic field is solved to determine the field strength. Generally however, the magnitude of the field at the interface is representative of the field magnitude at a given radial location inside the rarefaction region. Figure 4 shows the field magnitude at the interface for the physical scenario described previously with $\Psi_I = 20°$. Also shown are the field magnitudes in the case of a Parker spiral, and of pure footpoint motion (equation 3).

3. Conclusions

[12] We have shown that footpoint motion on the Sun from inside to beyond coronal hole boundaries causes magnetic fields in co-rotating rarefaction regions in the heliosphere to become stretched due to connection of the field lines across shearing solar wind streams. The consequence is strongly underwound magnetic field in co-rotating rarefaction regions. We have shown that observed properties of the magnetic field in rarefaction regions may be related in a simple way to the motions of magnetic footpoints on a surface close to the Sun where the field first achieves magnetic pressure balance. We have then the opportunity to utilize in-situ observations of the heliospheric magnetic field to infer the motions of open magnetic footpoints from within to beyond coronal hole boundaries [*Murphy et al.*, 2002], and thereby test concepts outline by *Fisk and Schwadron* [2001]. The observational concurrence of strongly underwound magnetic field in rarefaction regions generally supports these concepts.

[13] An assertion has often been made that the differences between solar wind stream types occurs purely due to an expansion effect: fast solar wind is formed on flux tubes that undergo stronger flux tube expansion, whereas slow solar wind also is formed from within coronal holes, but the expansion is weaker [e.g., *Wang and Sheeley*, 1994]. The motion of footpoints across coronal hole boundaries described here implies that open magnetic flux is not restricted to coronal holes, and therefore is not consistent with the view that flux tube expansion alone accounts for the differences between solar wind streams.

[14] Another consequence of the concepts put forth here is the prediction that magnetic field should be strongly underwound in the outer heliosphere at the latitudinal boundaries separating fast and slow solar wind. This may have important implications in particular for cosmic ray drifts and the propagation of energetic particles.

[15] **Acknowledgments.** This work was supported by DoD MURI grant F49620-01-1-0359, NSF grant ATM 0096664 and NSF grant ATM 9714070. I would like to thank Neil Murphy, Ed Smith, and Bruce Goldstein for a valuable week at JPL.

References

Bruno, R., and B. Bavassano, On the winding of the imf spiral for slow and fast wind within the inner heliosphere, *Geophys. Res.Lett.*, *24*, 2267, 1997.

Burlaga, L. F., R. P. Lepping, K. W. Behannon, L. W. Klein, and F. M. Neubauer, Large-scale variations of the interplanetary magnetic field: Voyager 1 and 2 observations between 1–5 au, *J. Geophys. Res.*, *87*, 4345, 1982.

Fisk, L. A., Motion of the footpoints of heliospheric magnetic field lines at the Sun: Implications for recurrent energetic particle events at high heliographic lattitudes, *J. Geophys. Res.*, *101*(A7), 15,547–15,553, 1996.

Fisk, L. A., and N. A. Schwadron, The behavior of open magnetic on the Sun, *Astrophys. J.*, *560*, 425, 2001.

Fisk, L. A., T. H. Zurbuchen, and N. A. Schwadron, On the coronal magnetic field: Consequences of large-scale motions, *Astrophys. J.*, *521*, 868, 1999.

Forsyth, R. J., A. Balogh, T. S. Horbury, G. Erdos, E. J. Smith, and M. E. Burton, The heliospheric magnetic field at solar minimum: Ulysses observations from pole to pole, *Astron. Astrophys.*, *316*, 287, 1996a.

Forsyth, R. J., A. Balogh, E. J. Smith, G. Erdös, and D. J. McComas, The underlying Parker spiral structure in the Ulysses magnetic field observations, 1990–1994, *J. Geophys. Res.*, *1*(101), 395–403, 1996b.

Jones, G. H., A. Balogh, and R. J. Forsyth, Radial heliospheric magnetic fields detected by ulysses, *Geophys. Res. Lett.*, *25*(16), 3109, 1998.

Murphy, N., E. J. Smith, and N. A. Schwadron, Observations and implications of strongly underwound magnetic fields in co-rotating rarefaction regions, *J. Geophys. Res.*, *In Preparation*, 2002.

Ness, N. F., and L. F. Burlaga, Spacecraft studies of the interplanetary magnetic field, *J. Geophys. Res.*, *106*(A8), 15,803, 2001.

Parker, E. N., *Interplanetary Dynamical Processes*, Interscience, New York, 1963.

Posner, A., Spuren quassi-stationaerer heliosphaerischer struktur des solaren minimums: Schorcosiep- und ulysses/cospin-messungen cir-assoziierter energiereicher protonen, Ph.D. Thesis, University of Kiel, 1999.

Schwadron, N. A., L. A. Fisk, and T. H. Zurbuchen, Elemental fractionation in the slow solar wind, *Astrophys. J.*, *521*, 859, 1999.

Schwenn, R., Large-scale structure of the interplanetary medium, in *Physics of the Inner Heliosphere*, edited by R. Schwenn and E. Marsch, vol. 1, chap. 3, pp. 99–181, Springer-Verlag, Berlin, 1990.

Smith, E. J., A. Balogh, R. F. Forsyth, B. T. Tsurutani, and R. P. Lepping, Recent Observations of the Heliospheric Magnetic Field at Ulysses: Return to Low Latitude, *Advances in Space Research*, *26*, 823, 2000.

Thomas, B. T., and E. J. Smith, The Parker spiral configuration of the interplanetary magnetic field between 1 and 8.5 AU, *J. Geophys. Res.*, *85*, 6861, 1980.

Wang, Y.-M., and N. R. Sheeley Jr., Global evolution of the interplanetary sector structure, coronal holes, and solar wind streams during 1976–1993: Stackplot displays based on magnetic observations, *J. Geophys. Res.*, *99*, 6597–6608, 1994.

N. Schwadron, Southwest Research Institute, 6220 Culebra Road, Post Office Drawer 28510, San Antonio, Texas, 78228-0510, USA.