GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.14, PAGES 2649-2652, JULY 15, 1998

Flow shear across solar wind discontinuities: WIND observations

J. De Keyser and M. Roth

Belgian Institute for Space Aeronomy, Brussels, Belgium

A. Söding

Universität zu Köln, Germany

Abstract. We examine the tangential magnetic field and velocity shears across directional discontinuities (DDs) with significant change in magnetic field intensity observed by WIND in slow and fast solar wind streams. The magnetic field rotation sense in fast wind DDs is that predicted by theory for outward propagating rotational discontinuities (RDs), but flow shear magnitude and orientation do not always satisfy RD theory. Alternatively, DDs with small normal magnetic field can be regarded as tangential discontinuities (TDs); the observed shears imply that the length scale over which the proton velocity distribution changes at the discontinuity can be both smaller or larger than that of the electron distribution. The slow wind includes a larger fraction of DDs that disagree with RD theory. It is shown that the flow shear orientations allowed in a TD provide a continuous transition between the opposite orientations for RDs propagating along or against the magnetic field direction.

Introduction and Discontinuity Selection

Satellite observations have established the presence of directional discontinuities (DDs) throughout the solar wind [e.g., *Burlaga et al.*, 1977; *Tsurutani and Smith*, 1979; *Lepping and Behannon*, 1986; *Tsurutani et al.*, 1996]. The apparent decrease of DD occurrence rate with radial distance can be accounted for by selection effects of DD identification criteria; the majority of DDs seems to be formed inside 1 AU [*Burlaga*, 1971; *Tsurutani and Smith*, 1979]. DD occurrence rates are different in solar wind streams, corotating interaction regions, and polar coronal holes [*Tsurutani et al.*, 1996; *Ho et al.*, 1996]. One distinguishes rotational from tangential discontinuities (RDs and TDs). In this paper we study the flow shear across solar wind DDs in fast and slow solar wind streams at 1 AU. We interpret the observations using RD and TD theories.

We have analyzed 60 s averaged WIND magnetic field data over the period April 5–24, 1995 to find isolated DDs that satisfy the *Burlaga* [1969] and/or *Tsurutani and Smith* [1979] criteria. These DDs are further inspected using 3 s average data. DDs labeled "rotational discontinuity" by the selection process are fairly well understood; those labeled "tangential discontinuity" surprisingly resemble the "RD" class in a number of ways [*Neugebauer et al.*, 1984]. We focus on the "TD" class ($\Delta|\boldsymbol{B}|/B_{\max} \geq 0.2$ and $B_n/B_{\max} \leq 0.4$; B_n is the average normal magnetic field, $\Delta|\boldsymbol{B}|$ the field strength change across the DD, and $B_{\max}$ the maximum field strength). The solar wind speed distribution is bimodal during the analysis interval, dividing the DDs into fast and slow wind sets containing 69 and 74 DDs, respectively (solar wind speed threshold 450 km s^{-1}). For each DD we computed the minimum variance frame (MVF); x is the DD normal, with $B_x > 0$. We determined the jumps of the magnetic field $\Delta\boldsymbol{B}_t = \boldsymbol{B}_{t2} - \boldsymbol{B}_{t1}$ and of the tangential proton velocity $\Delta\boldsymbol{V}_t^+ = \boldsymbol{V}_{t2} - \boldsymbol{V}_{t1}$ (where "1" and "2" identify the two sides of the DD) across each DD using 3 s magnetic field data from the MFI magnetometer and 80 s proton data from the SWE plasma instrument. The magnetic field and velocity vectors on either side were obtained as the average over the two data points immediately preceding and following the time interval during which the DD occurs; the variances δV on either side estimate the rms error on the velocity. Since the plasma velocity varies slowly ($\delta V < V_{\rm th}^+$), except across DDs, the uncertainty on $\Delta\boldsymbol{V}_t$ due to the limited time resolution of the plasma data is of the order of δV. From the SWE instrument we also obtained the plasma density, the ion and electron temperatures, and the electron temperature anisotropy; we assumed the proton anisotropy to be the same. We further subselected DDs for which $\delta V < |\Delta\boldsymbol{V}_t^+|$ (that is, insignificantly small jumps are eliminated) and for which the pressure anisotropy is well defined, resulting in 43 fast wind and 58 slow wind DDs. Plasma beta is 2–6 in the fast wind, and 4–10 in the slow wind. Pressure balance is satisfied to within 10% (the error margin on densities and temperatures; alpha particles were ignored), confirming that the DDs are equilibrium structures. The threshold $B_n/B_{\max} \leq 0.4$ is rather high, so that "TD" class DDs can actually be of (anisotropic) RD or TD nature.

Magnetic Field and Flow Shear

The solar wind (bulk density ρ and velocity $\boldsymbol{V}$) consists of not necessarily comoving components (mass density ρ^ν, mean velocity $\boldsymbol{V}^\nu$). In uniform solar wind the streaming velocities $\delta\boldsymbol{V}_\parallel^\nu = \boldsymbol{V}^\nu - \boldsymbol{V}$ are parallel to $\boldsymbol{B}$, and such that the total parallel current is zero. The mass fluxes across a DD are $G^\nu = \rho^\nu(V_n^\nu - U)$, where U is the (unknown) normal velocity of the spacecraft relative to the DD. Conservation of the tangential electric field across a RD [*Hudson*, 1970] predicts the tangential flow shear:

$$\Delta\boldsymbol{V}_{tp}^\nu = \frac{G^\nu}{B_n}\Delta(\boldsymbol{B}_t/\rho^\nu).$$

Paper number 98GL51938.
0094-8534/98/98GL-51938$05.00

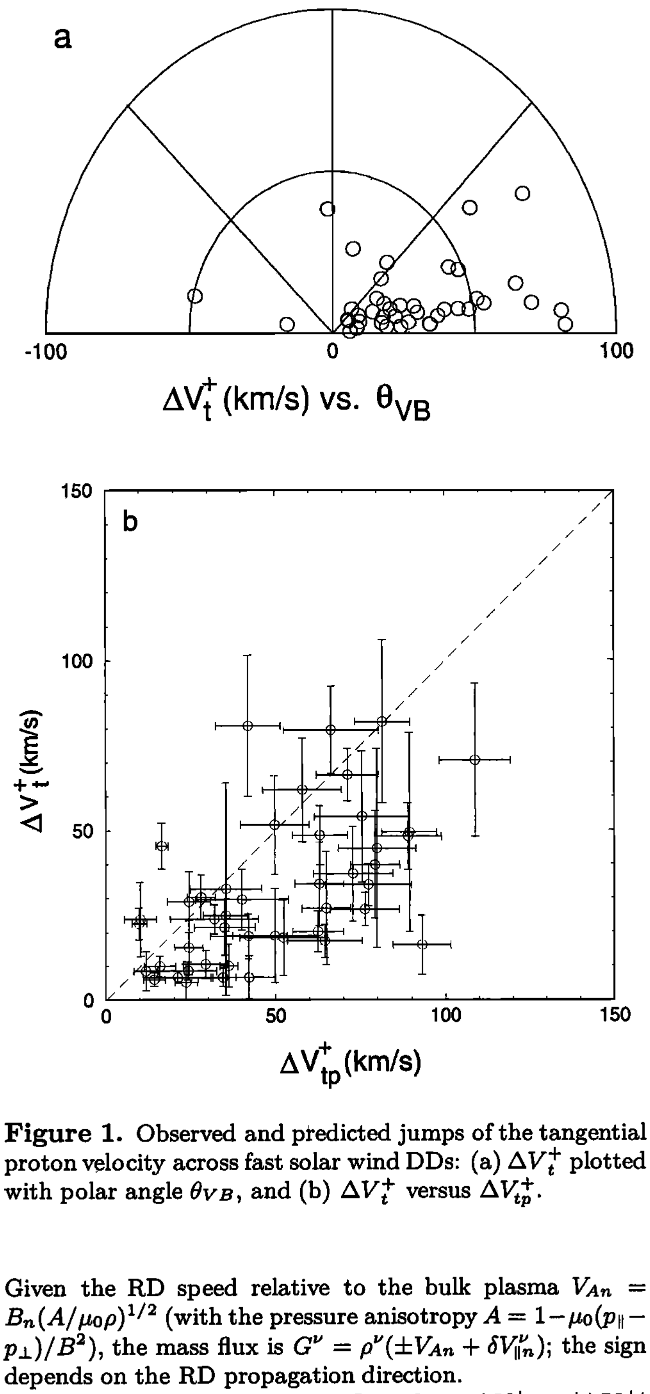

Figure 1. Observed and predicted jumps of the tangential proton velocity across fast solar wind DDs: (a) ΔV_t^+ plotted with polar angle θ_{VB}, and (b) ΔV_t^+ versus ΔV_{tp}^+.

Given the RD speed relative to the bulk plasma $V_{An} = B_n(A/\mu_0\rho)^{1/2}$ (with the pressure anisotropy $A = 1-\mu_0(p_\parallel - p_\perp)/B^2$), the mass flux is $G^\nu = \rho^\nu(\pm V_{An} + \delta V_{\parallel n}^\nu)$; the sign depends on the RD propagation direction.

Figure 1a plots the proton flow shear $\Delta V_t^+ = |\Delta \boldsymbol{V}_t^+|$ versus the angle θ_{VB} between $\Delta \boldsymbol{V}_t^+$ and $\Delta(\boldsymbol{B}_t/\rho^+)$ for the fast wind DDs (the data set covers one fast stream of south polarity). Both vectors tend to be parallel: As the protons essentially comove with the bulk plasma ($\delta V_{\parallel n}^+ < V_{An}$ since they constitute the largest mass fraction), this corresponds to outward propagating RDs in the southern hemisphere (where $\boldsymbol{B}$ points sunward). We have also investigated the correlation between the $\boldsymbol{B}$ and $\boldsymbol{V}$ fluctuations throughout the fast stream (that is, not only the strong jumps at DDs) and similarly found this parallel orientation. This is consistent with earlier studies of Alfvénic fluctuations in the fast solar wind [*Belcher and Davis*, 1971; *Belcher and Solodyna*, 1975; *Smith et al.*, 1995]. For about 1/6 of the DDs $\Delta \boldsymbol{V}_t^+$ deviates more than 45° from the ΔV_{tp}^+ direction. Note that inaccurate knowledge of G^+ does not affect the relative orientation of both vectors. The quantitative comparison between ΔV_t^+ and ΔV_{tp}^+ (Figure 1b) suffers from the absence of proton temperature anisotropy data as well as from the hypothesis that there is only one proton stream comoving with the bulk plasma; the influence of a secondary proton beam and of alpha particles has been discussed by *Neugebauer et al.* [1984]. Error analysis shows that $\delta(\Delta V_{tp})/\Delta V_{tp} \approx \delta A/2A + \delta\rho/2\rho$ with $\delta A \approx \beta[\tau\delta(T_\parallel^+/T_\perp^+) + \delta(T_\parallel^-/T_\perp^-)]/2(\tau+1)$ and $\tau = T^+/T^-$. As the proton anisotropy generally ranges from 1.1 to 1.5, we estimate $\delta(T_\parallel^+/T_\perp^+) \approx 0.2$. With $\delta(T_\parallel^-/T_\perp^-) \approx 0.03$, we find $\delta A/A \approx 0.2$ (slow wind: $\beta = 8$, $\tau = 1/4$; fast wind: $\beta = 5$, $\tau = 1$). With 5% accuracy on the density the uncertainty on ΔV_{tp} is about 15%, which corresponds to the horizontal error bars in the figure. The vertical error bars reflect the observational uncertainty $\delta V = [(\delta V_1)^2 + (\delta V_2)^2]^{1/2}$. Like *Neugebauer et al.* [1984], we find that ΔV_t^+ is on average below ΔV_{tp}^+.

Figure 2 shows similar results for the slow wind. These plots can be interpreted in part as a result of the superposition of sectors of opposite polarity. The slow wind DDs, however, also include sector boundaries, which cannot be regarded as in- or outward propagating waves inside a sector of given polarity. For a quarter of the DDs the $\Delta \boldsymbol{V}_t^+$ and $\Delta \boldsymbol{V}_{tp}^+$ orientations do not match within 45°. In the slow wind the $\Delta V_t^+/\Delta V_{tp}^+$ ratio is even smaller, partly due to the assumption that the proton and electron anisotropies are equal (the proton anisotropy is known to be generally larger in the slow wind).

Alternatively, the TD model developed in [*De Keyser et al.*, 1997; *De Keyser and Roth*, 1997] can be used to interpret low B_n/B DDs. This model treats the solar wind as a proton–electron plasma; hence $\delta V_\parallel^\nu = 0$. It predicts that the $\Delta \boldsymbol{V}_t$–$\Delta(\boldsymbol{B}_t/\rho)$ relation depends on the characteristic lengths $\mathcal{L}^\pm$ over which proton and electron velocity distribution functions change across the layer. The minimum values of $\mathcal{L}^\pm$ are the respective gyroradii $r^\pm$; since $\mathcal{L}^-/\mathcal{L}^+$ must be in the range 0.1–10 in order to avoid excessive polarization electric fields, both values are of the order of or larger than r^+. Figure 3 plots the scaled velocity shear $\Delta V_t^+/V_{\rm th}^+$ (where $V_{\rm th}^+$ is the thermal proton velocity). This plot is obtained by rotating the MVF around x so as to align y with the inner bisector of $\boldsymbol{B}_{t1}$ and $\boldsymbol{B}_{t2}$; as $\boldsymbol{B}$ generally rotates less than 180° this implies that $B_y > 0$, so that the sign of ΔV_z determines the direction of the convection electric field change across the TD. For the fast solar wind (Figure 3a), the positive magnetic field rotation sense ($\theta > 60°$, $\Delta B_z > 0$, marked by a plus) in the upper quadrants and the negative sense ($\theta < -60°$, $\Delta B_z < 0$, marked by a minus) in the lower quadrants correspond to the parallel orientation discussed previously. Small rotations ($|\theta| < 60°$, marked by a circle) correspond to small $|\Delta V_z|$. The slow wind results (Figure 3b) can again be regarded as the consequence of the superposition of sectors of both polarities. Figure 3 confirms that generally $\Delta V_t^+ < V_{\rm th}^+$, consistent with the existence conditions for TD equilibrium [*De Keyser et al.*, 1997]. Comparing Figure 3 with Figure 8 in [*De Keyser et al.*, 1997], the following situations are found to occur: (a) $\mathcal{L}^+ > r^+ \gtrsim \mathcal{L}^-$, $\Delta \boldsymbol{V}_t$ in the lower quadrants, (b) $\mathcal{L}^- > \mathcal{L}^+ \approx r^+$, $\Delta \boldsymbol{V}_t$ in the upper quadrants, (c) $\mathcal{L}^- \approx \mathcal{L}^+ \gtrsim r^+$, $\Delta \boldsymbol{V}_t$ in upper or lower quadrants. This finding is consistent with simulations of internal solar wind TD structure [*De Keyser et al.*, 1997].

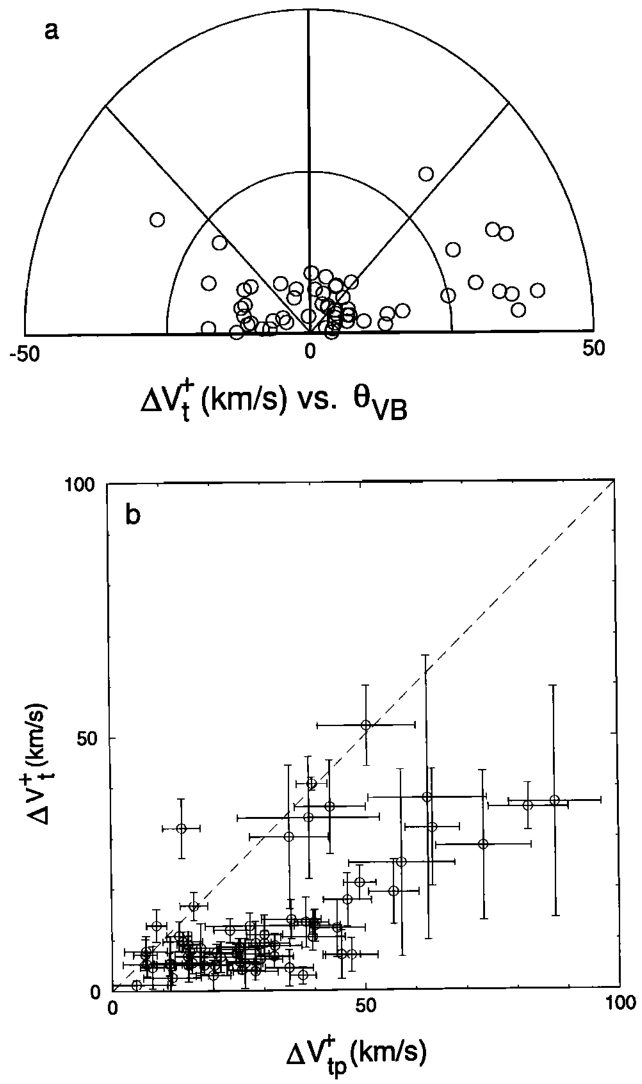

Figure 2. Observed and predicted jumps of the tangential proton velocity across fast solar wind DDs: (a) ΔV_t^+ plotted with polar angle θ_{VB}, and (b) ΔV_t^+ versus ΔV_{tp}^+.

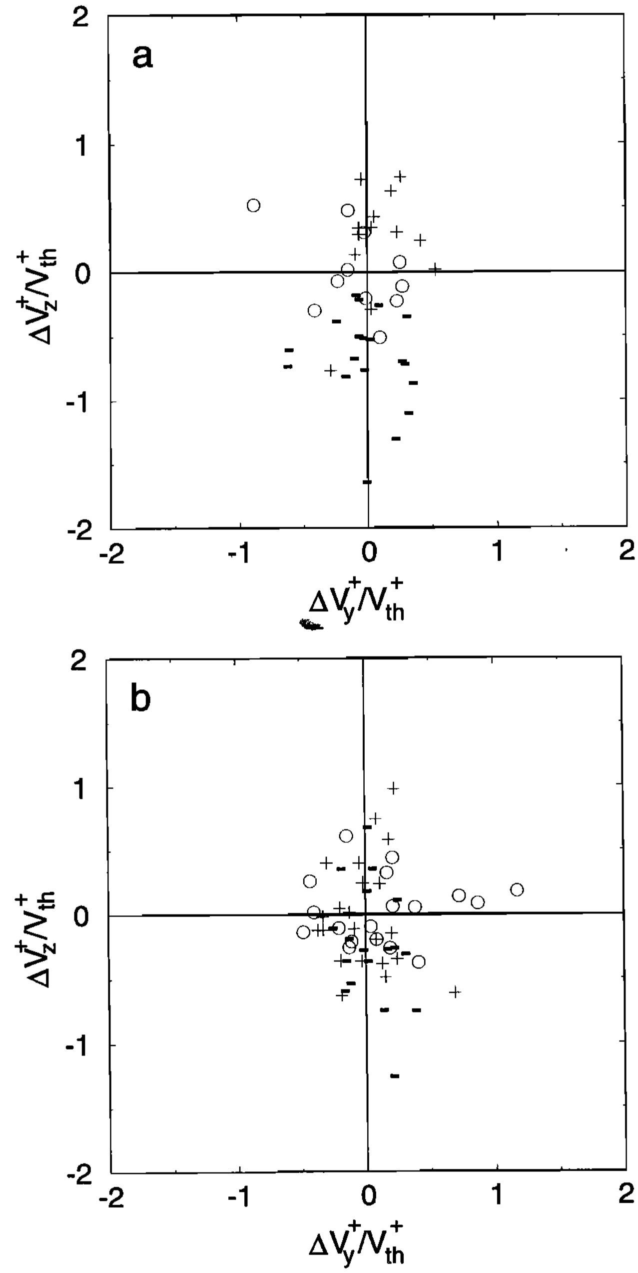

Figure 3. Tangential proton velocity jump normalized to ion thermal velocity in a reference frame where y is the inner bisector of the tangential magnetic field vectors on either side of the DD; pluses, minuses, and circles designate magnetic field rotations $\theta > 60°$, $\theta < -60°$, and $|\theta| < 60°$, respectively. (a) Fast wind. (b) Slow wind.

Discussion

The purpose of this paper was to examine the relation between flow and magnetic shear in a sample of well-defined DDs with $\Delta|B|/B_{\max} \geq 0.2$ and $B_n/B_{\max} \leq 0.4$. The direction of the magnetic field and velocity changes are typical for Alfvénic structures propagating away from the Sun, but the orientation and magnitude of the proton flow shear do not always match RD theory, especially in the slow wind, suggesting a larger fraction of TDs there. Such deviations are also expected when the protons do not comove with the bulk plasma (solar wind proton, electron, and alpha populations generally move at different speeds). A TD interpretation gives indications about the electron and proton velocity distribution transition lengths. The occurrence of the situation $\mathcal{L}^- > \mathcal{L}^+$ implies the existence of a mechanism that broadens electron layers to the proton gyroradius scale or wider, and thus constrains DD formation scenarios.

The RD and TD models are complementary. The TD model used here can be regarded as a limit RD case, as the populations "trapped" inside the layer are fed from the plasmas on either side as in a RD. The flow shear orientations allowed in TD equilibrium provide a continuous transition path between the opposite orientations for RDs propagating along or against the magnetic field direction. For an RD propagating outward while $\boldsymbol{B}$ points inward, $\Delta(\boldsymbol{B}_t/\rho)$ and $\Delta\boldsymbol{V}_t$ are parallel. As the relative inclination of the field and the DD layer changes (B_n/B decreases, slower RD propagation) the structure increasingly resembles a TD, allowing the parallel orientation with a positive ($\mathcal{L}^- > \mathcal{L}^+$) or negative

($\mathcal{L}^- < \mathcal{L}^+$) rotation sense, and the antiparallel orientation with the reverse rotation sense. When the RD propagates along the magnetic field direction, only antiparallel $\Delta(\boldsymbol{B}_t/\rho)$ and $\Delta\boldsymbol{V}_t$ are possible.

Our results confirm the Alfvénic nature of the "TD" class [*Neugebauer et al.*, 1984]. A tentative explanation for this behavior is the following. Particles downstream of an RD originate from the upstream side; their properties are determined by the jump conditions. As the RD propagation speed decreases (smaller B_n/B), particles need more time to drift across the layer and can be affected by other phenomena (deviations from planar geometry, diffusion due to microturbulence ...), resulting in a lower velocity jump magnitude than predicted from the RD relation. Plasma differences observed across a DD reflect source region properties only for small B_n and when one is close to the source. The Alfvénic nature of TDs therefore suggests that most solar wind TDs, at least in the fast wind, are a particular case of RDs, that is, phase-steepened large-amplitude Alfvén waves [*Tsurutani et al.*, 1994] that happen to propagate quite slowly as their wave vector is nearly perpendicular to the magnetic field. The larger fraction of deviations from the RD relation in the slow wind and the larger proportion of small B_n DDs in the slow wind B_n/B histogram (not shown) witness the contribution of a significant number of field-aligned current sheets. This is not surprising as the latter include sector boundaries, a distinct TD population.

Acknowledgments. The authors thank R. Lepping and K. Ogilvie, PIs for the WIND MFI magnetometer and the SWE plasma instrument, as well as the data processing teams. J.D.K. and M.R. acknowledge the support by ESA/PRODEX and by the Belgian Federal Services for Scientific, Technological and Cultural Affairs. The work by A.S. was supported by DARA/DLR.

References

Belcher, J.W., and L. Davis, Jr., Large-amplitude Alfvén waves in the interplanetary medium 2, *J. Geophys. Res., 76*, 3534–3563, 1971.

Belcher, J.W., and C.V. Solodyna, Alfvén waves and directional discontinuities in the interplanetary medium, *J. Geophys. Res., 80*, 181–186, 1975.

Burlaga, L.F., Directional discontinuities in the interplanetary magnetic field, *Solar Phys., 7*, 54, 1969.

Burlaga, L.F., Nature and origin of directional discontinuities in the solar wind, *J. Geophys. Res., 76*, 4360–4365, 1971.

Burlaga, L.F., J.F. Lemaire, and J.M. Turner, Interplanetary current sheets at 1 AU, *J. Geophys. Res., 82*, 3191–3200, 1977.

De Keyser, J., M. Roth, B.T. Tsurutani, C.M. Ho, and J.L. Phillips, Solar wind velocity jumps across tangential discontinuities: Ulysses observations and kinetic interpretation, *Astron. Astrophys., 321*, 945–959, 1997.

De Keyser, J. and M. Roth, Equilibrium conditions for the tangential discontinuity magnetopause, *J. Geophys. Res., 102*, 9513–9530, 1997.

Ho, C.M., B.T. Tsurutani, R. Sakurai, B.E. Goldstein, A. Balogh, and J.L. Phillips, Interplanetary discontinuities in corotating streams and their interaction regions, *Astron. Astrophys., 316*, 346–349, 1996.

Hudson, P.D., Discontinuities in an anisotropic plasma and their identification in the solar wind, *Planet. Space Sci., 18*, 1611–1622, 1970.

Lepping, R.P., and K.W. Behannon, Magnetic field directional discontinuities: characteristics between 0.46 and 1.0 AU, *J. Geophys. Res., 91*, 8725–8741, 1986.

Neugebauer, M., D.R. Clay, B.E. Goldstein, B.T. Tsurutani, and R.D. Zwickl, A reexamination of rotational and tangential discontinuities in the solar wind, *J. Geophys. Res., 89*, 5395–5408, 1984.

Smith, E.J., A. Balogh, M. Neugebauer, and D. McComas, Ulysses observations of Alfvén waves in the southern and northern solar hemispheres, *Geophys. Res. Lett., 22*, 3381–3384, 1995.

Tsurutani, B.T., and E.J. Smith, Interplanetary discontinuities: Temporal variations and the radial gradient from 1 to 8.5 AU, *J. Geophys. Res., 84*, 2773–2787, 1979.

Tsurutani, B.T., C.M. Ho, E.J. Smith, M. Neugebauer, B.E. Goldstein, J.S. Mok, J.K. Arballo, A. Balogh, D.J. Southwood, and W.C. Feldman, The relationship between interplanetary discontinuities and Alfvén waves: Ulysses observations, *Geophys. Res. Lett., 21*, 2267–2270, 1994.

Tsurutani, B.T., C.M. Ho, R. Sakurai, B.E. Goldstein, A. Balogh, and J.L. Phillips, Symmetry in discontinuity properties at the north and south heliographic poles: Ulysses, *Astron. Astrophys., 316*, 342–345, 1996.

J. De Keyser and M. Roth, Belgian Institute for Space Aeronomy, Ringlaan 3, B-1180 Brussels, Belgium. (e-mail: Johan.DeKeyser@oma.be, Michel.Roth@oma.be)

A. Söding, Institut für Geophysik und Meteorologie, Universität zu Köln, Albertus-Magnus-Platz, D-50923 Köln, Germany. (e-mail: soeding@geo.Uni-Koeln.de)

(Received April 8, 1998; revised June 2, 1998; accepted June 5, 1998.)