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Nature of fluctuations on directional discontinuities inside a solar ejection: Wind and IMP 8 observations

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Abstract. A solar ejection passed the Wind spacecraft between December 23 and 26, 1996. On closer examination, we find a sequence of ejecta material, as identified by abnormally low proton temperatures, separated by plasmas with typical solar wind temperatures at 1 AU. Large and abrupt changes in field and plasma properties occurred near the separation boundaries of these regions. At the one boundary we examine here, a series of directional discontinuities was observed. We argue that Alfvénic fluctuations in the immediate vicinity of these discontinuities distort minimum variance normals, introducing uncertainty into the identification of the discontinuities as either rotational or tangential. Carrying out a series of tests on plasma and field data including minimum variance, velocity and magnetic field correlations, and jump conditions, we conclude that the discontinuities are tangential. Furthermore, we find waves superposed on these tangential discontinuities (TDs). The presence of discontinuities allows the existence of both surface waves and ducted body waves. Both probably form in the solar atmosphere where many transverse nonuniformities exist and where theoretically they have been expected. We add to prior speculation that waves on discontinuities may in fact be a common occurrence. In the solar wind, these waves can attain large amplitudes and low frequencies. We argue that such waves can generate dynamical changes at TDs through advection or forced reconnection. The dynamics might so extensively alter the internal structure that the discontinuity would no longer be identified as tangential. Such processes could help explain why the occurrence frequency of TDs observed throughout the solar wind falls off with increasing heliocentric distance. The presence of waves may also alter the nature of the interactions of TDs with the Earth's bow shock in so-called hot flow anomalies.

1. Introduction

Solar ejecta observed in the interplanetary medium can be produced by flares and coronal mass ejections (CMEs) [e.g., *Gosling*, 1990; *Forbes*, 2000], and they form in close association with the heliospheric current sheet or streamer belt [e.g., *Mulligan et al.*, 1998]. A subset of ejecta contain magnetic clouds characterized by enhanced magnetic intensity, low proton temperatures, and relatively smooth magnetic field rotation [e.g., *Burlaga et al.*, 1981]. Magnetic clouds have been successfully modeled as flux ropes [e.g., *Marubashi*, 1986; *Burlaga*, 1988; *Burlaga et al.*, 1990; *Gosling*, 1990; *Lepping et al.*, 1990, *Farrugia et al.*, 1993].

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Examination of magnetic clouds seen by the Wind spacecraft often shows that sharp gradients in physical parameters can exist both at the edges and within the cloud. For example, *Janoo et al.* [1998] analyzed a number of directional discontinuities (DDs) inside a cloud observed by Wind on October 18–20, 1995, and determined that they had minimum variance normals nearly along the background magnetic field. They concluded that these DDs were rotational discontinuities (RDs), which are abrupt field rotations with nonzero normal magnetic field components. Plasma density and magnetic field strength changed little across these RDs although there were changes in temperature. On the basis of these jump conditions, they concluded that the RDs formed in an almost isotropic plasma. They did not obtain measurements of the plasma anisotropy and did not directly verify that the observed jump conditions matched those expected of a RD. Within the same cloud, a number of true disconnections of the field lines from the Sun were observed by *Larson et al.* [1997] based on complete flux dropouts of electrons across a wide energy range measured by the three-dimensional (3-D) plasma analyzer [*Lin et al.*, 1995]. Janoo et al. correlated some DDs with these disconnections.

In solar ejecta, RDs can evolve from reconnection. Additionally, tangential discontinuities (TDs), which have no normal magnetic field components, can exist, separating flux tubes constituting the ejection, but the latter possibility has received little attention (but see *Fainberg et al.* [1996]). Considerable interest is directed toward the identification of the DDs to advance our knowledge of the internal structure of ejecta and to obtain clues as to the origin and evolution of this structure in the solar atmosphere and interplanetary medium. Moreover, interactions of DDs with geospace depend upon the exact nature of the DD.

The identification of DDs by minimum variance analysis can be impaired by the presence of surface waves. This possibility has not, so far, been considered in association with ejecta. *Hollweg* [1982] was the first to consider the theoretical import of surface wave solutions within the interplanetary medium. He computed solutions for TDs where only changes of field direction occurred. Solutions without density or parallel magnetic field fluctuations exist which would be expected to survive Landau and transit time damping best. These had circular polarization and a minimum variance direction which was directed 90° away from the TD normal. As inferred from minimum variance analysis, a TD with superposed surface waves could have a normal magnetic field component which is significantly different from zero. This could lead to the mistaken conclusion that the discontinuity is rotational. These waves could also give TDs an Alfvénic appearance based on magnetic field and velocity correlations [e.g., *Neugebauer et al.*, 1984; *De Keyser et al.*, 1998].

Horbury et al. [2001] examined 33 DDs in mostly slow solar wind correlating observations from three spacecraft. Minimum variance and the small jump of field intensity at each spacecraft indicated that most were rotational. However, the normal determined from the correlated measurements was mostly consistent with TDs and was turned approximately 90° from the minimum variance normal directions. They interpreted this result to be an observation of fluctuations on the TDs and possibly of the incompressible surface waves predicted by Hollweg. These fluctuations are not observed to be confined to the vicinity of the TDs and so do not have the visual appearance of surface waves in field time series plots. Instead, the magnetic field and velocity correlations of the Alfvénic fluctuations extend through a large region. As we argue below, if these are surface waves, then their properties are presumably determined by a number of TDs with typical cross-field spacing of $\sim 10^6$ km. An additional possibility to be discussed in this paper concerns the role of body waves which can be ducted through flux tubes bounded by TDs or are affected by smoother background gradients.

On December 24 and 25, 1996, the Wind and IMP 8 spacecraft observed the passage of a magnetic cloud. *Farrugia et al.* [2000] gave an overview of the magnetic cloud's varied properties. The purpose of this paper is to follow up on their observations of DDs and associated fluctuations. These DDs differ significantly from those described by *Horbury et al.* [2001] because they have significant jumps in plasma and field parameters which provide strong constraints on RDs and because the fluctuations are confined to the vicinity of the DDs. In addition, the DDs discussed in this paper occur in a solar ejection.

The outline of this paper is as follows: In section 2, we analyze the properties of the DDs in the December 1996 cloud and examine their surroundings. After applying a series of tests, we interpret the discontinuities to be tangential surfaces supporting surface-like waves. In section 3, we discuss what is currently known about waves on TDs and how they can form and evolve in the solar wind. We further explore the implications of having discontinuities within ejecta and clouds and the geoeffects which can result. In section 4, we summarize our results and give our conclusions.

2. Observations and Analysis

An overview of the structure of the December ejecta and cloud observed by Wind is provided by Figure 1. The panels show from top to bottom the proton number density N_p, bulk proton speed V_p, proton temperature (T_p, solid line) and the expected proton temperature ($T_{\rm exp}$, dotted line) for normal solar wind expansion obtained from the statistical studies of *Lopez* [1987], electron temperature (T_e), the ratio T_e/T_p, magnetic field components (B_x, B_y, B_z) in GSE coordinates, magnetic intensity B, and the Alfvén speed c_A from December 23 to 26, 1996. The data are from the Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995], 3-D plasma [*Lin et al.*, 1995], and Magnetic Fields Investigation (MFI) [*Lepping et al.*, 1995] instruments on Wind. Wind was positioned near (80, 19, -8)R_E (in GSE coordinates) and (45, 37, -8)R_E at the start and end of the interval shown, respectively.

In Figure 1, the magnetic cloud interval is delineated by two vertical dashed lines and includes most of December 24 and a part of December 25. The quantity N_p varies over a wide range, and regions of highest density between 15 and 26 cm^{-3} are bounded by sharp gradi-

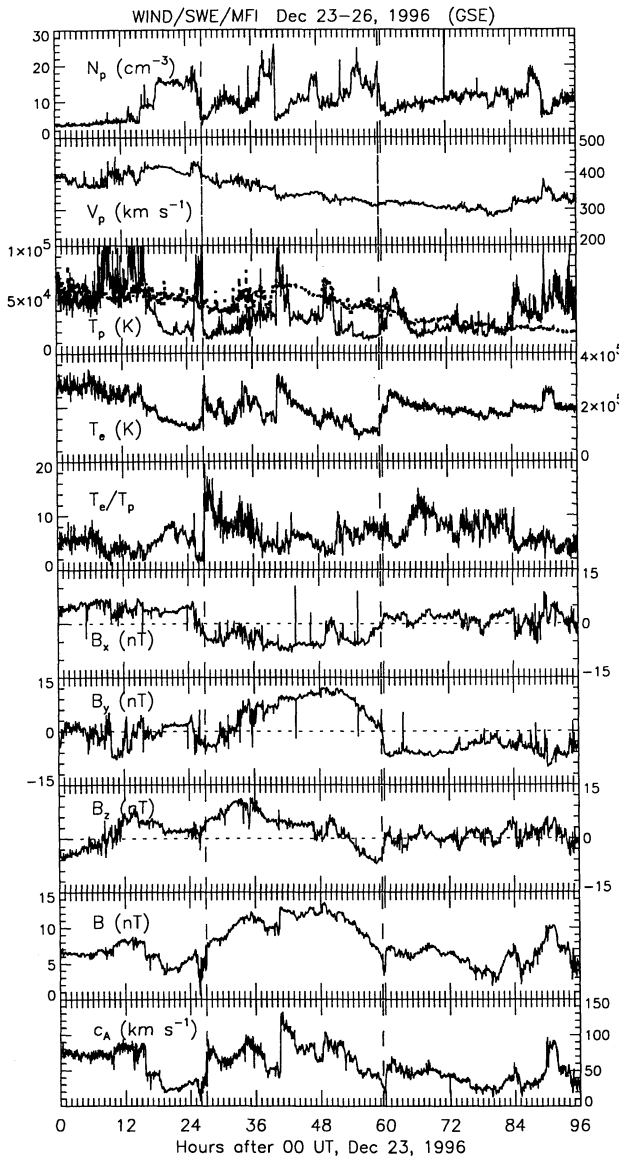

Figure 1. Magnetic field, proton, and electron measurements from the Wind spacecraft for a 4-day period showing the December ejecta [*Farrugia et al.*, 2000].

ents. The value of V_p declines from the front to the back of the cloud, indicating that the cloud is expanding in the radial direction. The value of T_p averages near 3×10^4K (~ 2.6 eV) and is less than the electron temperature T_e inside the cloud by factors of 2 to 10. Between hours 16 and 60 (preceding, and throughout the magnetic cloud interval), T_p is below the expected temperature, consistent with the presence of ejecta material, except in three incursions of warmer than average plasma near hours 26, 41, and 50.

The magnetic intensity B reaches a maximum of around 12 nT in the magnetic cloud interval and is nearly twice the average seen outside the cloud. A magnetic field depression located near hour 25 and just ahead of the cloud is associated with a RD and slow shock which is interpreted as a reconnection layer [*Farrugia et al.*, 2001]. Another magnetic decrease is positioned at the sunward end of the cloud near hour 60. The magnetic field in GSE coordinates (B_x, B_y, and B_z) rotates in direction through the cloud. The value of c_A varies from 30 to 130 km s^{-1} throughout the ejecta and cloud with several abrupt changes.

Figure 2 shows energetic particle data in three channels from the Goddard medium energy experiment on IMP 8 [*McGuire et al.*, 1986]. The count rate of the most energetic ($>$ 60 MeV) particles, dominated by galactic cosmic rays, reaches an approximate and broad relative minimum between the region bounded by vertical lines at 19 hours and 40.5 hours. The line at 19 hours corresponds to the beginning of the ejecta based on low T_p. Hence the cosmic ray flux is depressed on arrival of the ejecta, as is typical [*Richardson,* 1997, and references therein]. The line at 40.5 hours is the sunward boundary of a plasma density enhancement evident in Figure 1 and separates the density enhancement from plasma with $T_p > T_{\rm exp}$. This boundary could be topological, separating different regions of plasma and fields. The cosmic ray count rate increases to a higher level near 38 hours and may correspond to the energetic particles diffusing into the cloud. A further increase of flux is seen near 48 hours in association with another density enhancement. The rate finally steeply drops at 60 hours near the sunward boundary of the cloud. The middle energy particle data (24-29 MeV) show a flux increase near 38 hours and a decease near 60 hours. The $\sim$ 1 MeV particles show an increase in flux not at 38 hours but after 40.5 hours, suggesting that these particles arrive later from the Sun than higher-energy particles due to time of flight.

We now examine in detail fine-scale structure in the form of DDs which is located on the sunward edge of the density enhancement and between 40 and 41 hours (1600 UT and 1700 UT, December 24). Figure 3 shows the N_p, T_p, $T_{p\perp}/T_{p\parallel}$, pairwise components of magnetic field and proton bulk velocity in GSE coordinates, and sum of proton plasma and magnetic field pressures P_t for the interval 1615–1635 UT, December 24. Between 1619 UT and 1632 UT, there is a transition between a region of denser and cooler plasma with smaller B to a more rarefied and hotter plasma with larger B. The nonuniformity is substantial: N changes by a factor of 5, B by 1.4, T_p by 2, and the Alfvén speed by 3. The quantity P_t remains nearly constant across the boundary, indicating that the feature is near equilibrium. The magnitude of the velocity decreases from 370 to 340 km s^{-1} across the boundary. We assume that everything is being convected out at a mean speed with the remaining velocity providing a shear across the transition. The magnitude of shear does not satisfy the criterion of a Kelvin-Helmholtz instability [e.g., *Sen*, 1964], estimated at $\sim$ 60km s^{-1} for a shear parallel to the magnetic field. We cannot rule out the possibility that the instability, although not active when observed, occurred earlier and smoothed out the velocity gradient.

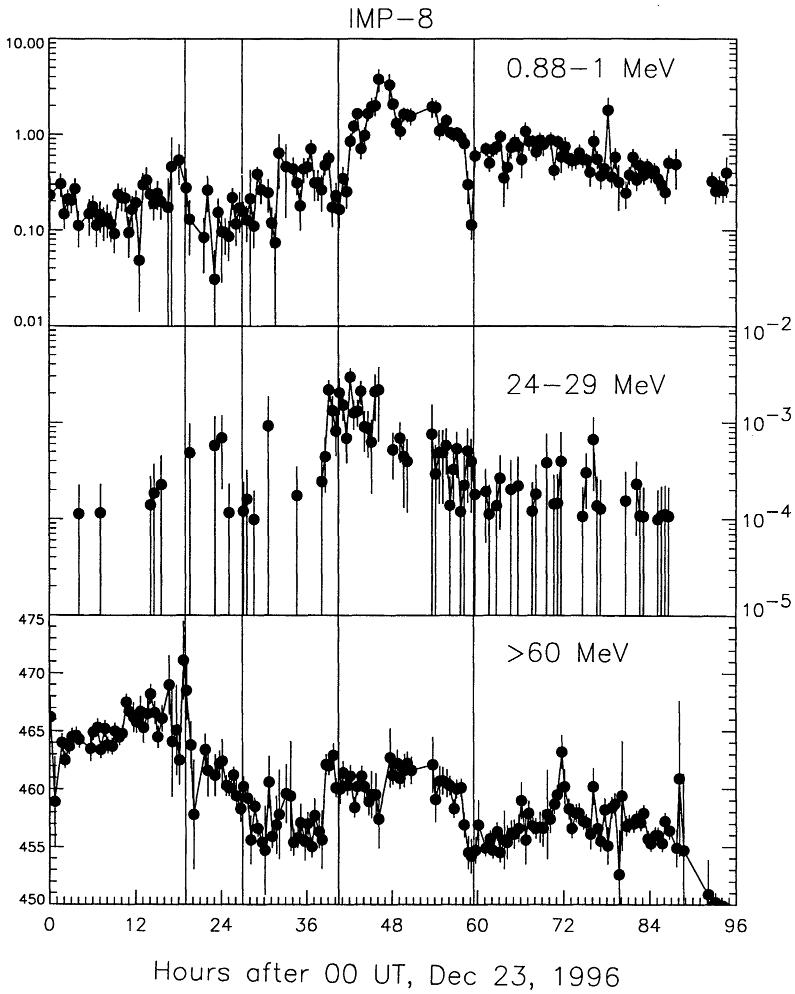

Figure 2. Energy particle fluxes and counting rates in association with the December ejecta from the Goddard medium energy experiment on IMP 8. In the two upper panels (0.88–1 MeV and 24–29 MeV channels), fluxes are given in units of $cm^{-2}s^{-1}ster^{-1}MeV^{-1}$. In the bottom panel (> 60 MeV), units of count rate per second are used.

Throughout the transition, B does not increase monotonically but rather oscillates and shows several nearly discontinuous jumps. Dashed lines in Figure 3 mark the location of two substantial DDs denoted as D1 at 1621 UT and D2 at 1626 UT, with two others at 1619 UT and 1628 UT, respectively. Both D1 and D2 are located ahead of the sharpest gradients, with D2 near the beginning of the steepest decline in N_p. Both appear to be steepened portions of a two-cycle variation of the magnetic field. Beyond this region, there are no comparable magnetic fluctuations. Throughout the region, total pressure is fairly constant, and we therefore conclude that these are not shocks. We limit our interpretation to RDs and TDs in association with waves. We next examine these DDs and their surroundings using (1) minimum variance analyses (section 2.1), (2) velocity and magnetic field correlations (section 2.2), and (3) jump conditions (section 2.3).

2.1. Minimum Variance Analysis

The magnetic field rotates across D1 and D2 by 28° and 36°, respectively. Table 1 shows the results of the minimum variance analysis [e.g., *Sonnerup and Cahill*, 1967; *Lepping and Behannon*, 1980] for D1 using a field resolution of 3 s for two different intervals around the discontinuity, specifically between 1619 UT and 1623 UT and between 1620 UT and 1622 UT. Quantities have been rounded to two significant figures and eigenvalues ζ and eigenvectors $\hat{\mathbf{e}}$ are subscripted with i, j, and k corresponding to the maximum, intermediate, and minimum variances, respectively. The minimum variance direction corresponds to the normal of the discontinuity. In the longer time interval, a nonzero normal magnetic field component $B_{\hat{\mathbf{e}}_k}$ of $\sim$ 4 nT is obtained and there is an acceptable ratio of 3 between the intermediate and minimum eigenvalues. However, the same analysis

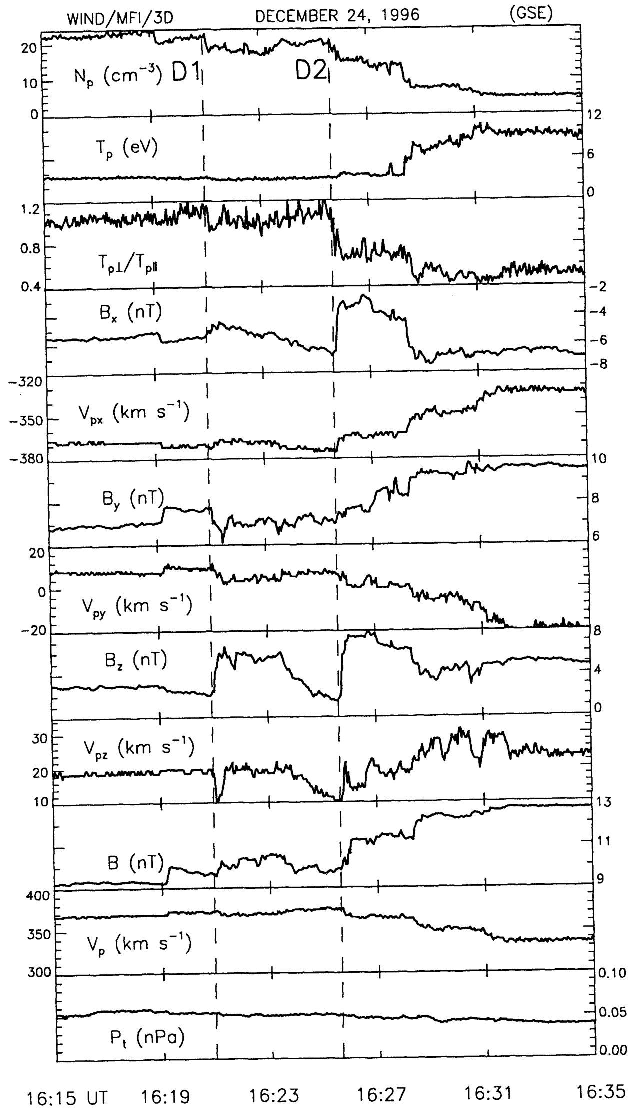

Figure 3. Plasma and magnetic field data in the vicinity of two directional discontinuities marked by vertical lines and denoted as D1 and D2.

on the shorter nested interval gives a conflicting result, with a significantly different normal and an intermediate to minimum variance ratio of 1.25. A ratio below 2 usually indicates that the results are not reliable. Table 2 gives similar results of a minimum variance analysis for D2 between 1624 UT and 1627 UT and between 1624:30 UT and 1626:30 UT. In the longer interval, a nonzero normal magnetic field is again found, but the intermediate to minimum variance ratio is less than 2. In the shorter interval, a ratio near 6 is determined.

A nonzero normal magnetic field component would indicate that the discontinuities are rotational, but the analysis on different time intervals does not give consistent results and could be in error. This error can arise from the close spacing of DDs and the fluctuations between and around them. This makes it difficult to isolate each discontinuity with clearly defined and uniform asymptotic states.

Because the fluctuations and DDs are spatially confined, we next consider a longer interval which includes all the DDs and fluctuations and includes some data beyond where fluctuations are seen. Table 3 gives the minimum variance for 1615–1635 UT. A much smaller normal magnetic field component is now determined. These discontinuities are then in better correspondence with TDs with nearly parallel normals. The apparent success of this minimum variance analysis comes from the inclusion of some downstream and upstream magnetic fields which correspond to the true asymptotic conditions for the discontinuities.

Figure 4 plots the magnetic field and proton velocity in the minimum variance frame (i, j, k) and also includes plots of N_p and T_e. The normal magnetic field is nearly zero at the location of D1 and D2. However, the normal field does systematically fluctuate over the whole time interval. This variation could arise from waves on the TDs.

The approximate parallelism of the normals for D1 and D2 is to be expected if these are distinct discontinuities since they are located near one another and would otherwise intersect if they are locally planar in their transverse dimensions. Another possible interpretation is that the Wind spacecraft crossed the same discontinuity several times because the discontinuity is undulated either by inherent curvature or by wave advection (see section 3.1.4). The difficulty with this idea is that the plasma properties do not reverse across each successive passage of a discontinuity so that one passes from an upstream to downstream state and then back again to the same upstream state. On the whole, each DD gives stronger field and lower density upon crossing. For a single discontinuity, this requires a significant gradient of plasma and field properties along its surface.

2.2. Velocity and Magnetic Field Correlations

Figure 3 shows that the proton velocity in GSE coordinates (V_x, V_y, and V_z) is not well correlated with the magnetic fluctuations in the vicinity of D1 and D2, but there is a strong negative correlation between velocity and magnetic field after the passage of D2 till the end of the transition region. For an Alfvén wave, this correlation is consistent with antisunward propagation since B_x is negative [e.g., *Belcher and Davis*, 1971]. Upstream of D2 the velocity is positively correlated. The sense of correlation should not change across a RD. Across D1, V_y and B_y are positively correlated while V_z and B_z are simultaneously negatively correlated. Again this is not what is expected of a RD. Just after D1, V_z shows an increase to a value nearly equal to that ahead of D1. No corresponding change occurs in

Table 1. Minimum Variance Analysis on D1

Parameter	1619 to 1623 UT	1620 to 1622 UT
Mean B	9.96	9.88
ζ_i	2.79	3.10
$\hat{e}_i$ [a]	(0.18, −0.21, 0.96)	(0.21, −0.22, 0.95)
ζ_j	0.057	0.020
$\hat{e}_j$ [a]	(−0.86, 0.43, 0.26)	(−0.07, 0.97, 0.24)
ζ_k	0.018	0.016
$\hat{e}_k$ [a]	(0.47, 0.88, 0.10)	(0.97, 0.12, −0.19)
ζ_j/ζ_k	3.17	1.25
Mean $B_{\hat{e}_k}$	4.34 ± 0.14	-4.92 ± 0.13

[a] Unit eigenvector in GSE coordinates.

B_z, and so it is possible that no true correlation exists between V_z and B_z. This is consistent with changes in velocity across a TD, which are arbitrary, and with surface waves which can have components of velocity and fields which are out of phase with one another [*Hollweg*, 1982].

If these discontinuities are RDs produced by reconnection, they are inconsistent with the nearly flawless properties of the RD that *Farrugia et al.* [2001] have identified at the earthward edge of the cloud near hour 1 on December 24 in association with a reconnection layer. This RD had nearly the expected Alfvénic correlation between velocity and magnetic field. It was similarly located on the sunward edge of strong plasma and field gradients, but it was not associated with a wave. Velocity and magnetic fields do not correlate as well at D1 and D2, and this inconsistency makes the RD interpretation doubtful.

2.3. Jump Conditions Across Discontinuities

We next discuss jump conditions. Since there are changes in B and N across D1 and D2, the plasma must be anisotropic if these discontinuities are to be identified as RDs. Figure 3 shows that significant proton anisotropy does exist. The DDs also appear to be imbedded in a steepened wave. Simulations of Alfvén waves which steepen to produce imbedded RDs tend to produce constant magnetic intensity waveforms across which the RDs change the field direction but not the plasma anisotropy or other plasma parameters [e.g., *Vasquez and Hollweg*, 1998a, 1998b], in contrast to the present observations. Thus if the discontinuities are RDs, they would more likely result from reconnection than from wave steepening.

Plasma anisotropy imposes stringent conditions on RDs. We expect that the protons contribute most of the ion plasma anisotropy. Alpha particles are present in the cloud but contribute something less than 20% of the pressure of the protons (J. Steinberg, private communication, 1999). The electrons are hotter than the protons, as is generally true in ejecta [e.g., *Osherovich et al.*, 1993; *Richardson et al.*, 1997], and thus they are dynamically more important. We have total electron temperatures but not measurements of their anisotropy. We show below that the amount of electron anisotropy required for a successful identification of RDs can be determined. On the basis of the calculated electron anisotropy, we can at least compare with what plasma conditions are expected on average and draw some inferences about the probability of the discontinuity being a RD.

The typical electron anisotropy in the solar wind is one in which $T_{e\|} > T_{e\perp}$ by no more than 20% [e.g., *Montgomery et al.*, 1968; *Feldman et al.*, 1975; *Phillips et al.*, 1989]. The low-velocity electrons in the core of the distribution have a small mean-free path as compared to 1 AU in this high-density and relatively low temperature region. Exchange between per-

Table 2. Minimum Variance Analysis on D2

Parameter	1624 to 1627 UT	1624:30 to 1626:30 UT
Mean B	10.34	10.57
ζ_i	8.86	9.97
$\hat{e}_i$ [a]	(0.52, 0.073, 0.85)	(0.51, 0.075, 0.86)
ζ_j	0.046	0.052
$\hat{e}_j$ [a]	(−0.84, −0.22, −0.49)	(−0.78, −0.47, −0.42)
ζ_k	0.024	0.0088
$\hat{e}_k$ [a]	(0.15, 0.97, −0.18)	(0.37, 0.88, −0.29)
ζ_j/ζ_k	1.92	5.91
Mean $B_{\hat{e}_k}$	5.60 ± 0.16	3.32 ± 0.09

[a] Unit eigenvector in GSE coordinates.

Table 3. Minimum Variance Analysis on Large Interval

Parameter	1615 to 1635 UT
Mean B	10.84
ζ_i	2.79
$\hat{\mathbf{e}}_i$[a]	(0.37, 0.13, 0.92)
ζ_j	1.74
$\hat{\mathbf{e}}_j$[a]	(−0.61, −0.78, −0.13)
ζ_k	0.16
$\hat{\mathbf{e}}_k$[a]	(0.70, 0.60, −0.37)
ζ_j/ζ_k	10.91
Mean $B_{\hat{\mathbf{e}}_k}$	-0.76 ± 0.40

[a]Unit eigenvector in GSE coordinates.

pendicular and parallel temperatures should be significant and maintain a nearly isotropic core distribution [e.g., *Phillips and Gosling*, 1990; *Hammond et al.*, 1996]. The energetic halo electrons are nearly collisionless and could be anisotropic. However, based on theory [e.g., *Jockers*, 1970] and observations, collisionless electrons do not attain extremely large anisotropies.

Hudson [1970, 1971] used the CGL equations of *Chew et al.* [1956] to show that both RDs and TDs satisfy perpendicular pressure balance

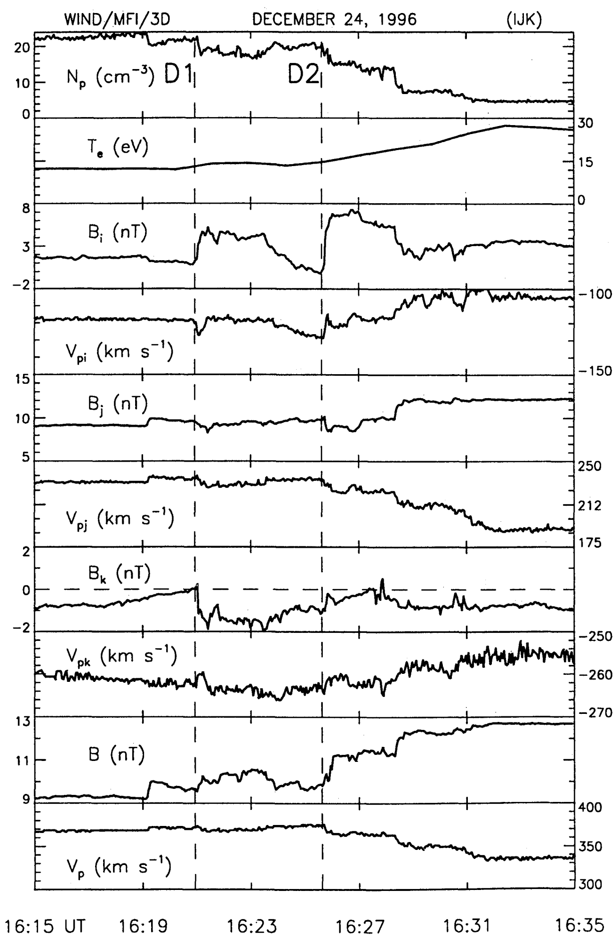

Figure 4. Plot of magnetic fields and plasma in minimum variance frame for the same interval shown in Figure 3.

$$P_{\perp 1} + B_1^2/2\mu_0 = P_{\perp 2} + B_2^2/2\mu_0, \quad (1)$$

where subscripts 1 and 2 refer to the upstream and downstream states, respectively, $P_\perp$ is the sum of ion and electron perpendicular pressures, and cgs units are employed. This condition arises from the conservation of normal momentum and mass flux. RDs satisfy an additional constraint from their conservation of mass flux such that

$$\rho_1(1-\lambda_1) = \rho_2(1-\lambda_2), \quad (2)$$

where $\lambda = (P_{\|} - P_\perp)\mu_0/B^2$, and ρ is the total mass density (which for our purposes can be assumed to be from protons only). This condition arises because the RD must propagate at the Alfvén speed corrected for anisotropy. Note that a decrease in density implies that $\lambda_1 > \lambda_2$. TDs have no mass flux and have unrestricted jumps outside of (1).

Tables 4 and 5 give values for the downstream and upstream conditions at D1 and D2, respectively. At D1, the observed value of $N_1/N_2 = 1.22$, but since the proton λ_{p1} is less than λ_{2p}, the density jump for a RD is 0.98. The expected value is qualitatively and quantitatively inconsistent with the observed value, and we conclude that D1 cannot be a RD in the absence of electron anisotropy.

Consistency with (1) requires that $P_{e\perp 1} - P_{e\perp 2} = 2.17 \times 10^{-2}$ nPa. Assuming $N_e \approx N_p$, this provides a constraint on electron temperatures. We also have the observed values of the total electron temperature upstream T_{1e} and downstream T_{2e} which, by definition, satisfy

$$3T_{1e} = T_{1e\|} + 2T_{1e\perp}, \quad (3)$$

and

$$3T_{2e} = T_{2e\|} + 2T_{2e\perp}. \quad (4)$$

Equations (1)-(4) can be solved for the values of $T_{1e\|}$, $T_{1e\perp}$, $T_{2e\|}$, and $T_{2e\perp}$ which are required to reproduce observed conditions for a RD. As listed in Table 4, we find that a RD requires significant anisotropies on both sides where $T_{e\|}$ exceeds $T_{e\perp}$ by factors of more than 3. This level of anisotropy is well beyond average conditions. *Phillips et al.* [1989] examined cases of extreme anisotropy and usually found these to be associ-

Table 4. Jump Conditions Across D1

Parameter	State 1	State 2
N_p	22 cm^{-3}	18 cm^{-3}
T_p	3.0 eV	3.0 eV
$T_{p\parallel}$	2.76 eV	3.15 eV
$T_{p\perp}$	3.12 eV	2.93 eV
T_e	12.0 eV	14.0 eV
$T_{e\parallel}$[a]	22.74 eV	27.31 eV
$T_{e\perp}$[a]	6.63 eV	7.35 eV
$P_{p\parallel}$	9.72×10^{-3} nPa	9.06×10^{-3} nPa
$P_{p\perp}$	1.10×10^{-2} nPa	8.43×10^{-3} nPa
$B^2/2\mu_0$	3.67×10^{-2} nPa	4.14×10^{-2} nPa
λ_p	-0.0173	0.0077
λ_e[a]	0.7733	0.6942

[a]Required value to reproduce observed rotational discontinuity.

ated with unusually low plasma densities on the trailing edges of high-speed streams, which is not the case here. Thus even under this test, we infer that D1 is unlikely to be a RD.

At D2, $\lambda_{1p} < \lambda_{2p}$, which is not consistent with a RD across which the density decreases. At D2, $N_1/N_2 = 1.33$ while the expected value from proton anisotropy is 0.95. Condition (1) can be satisfied if $P_{e\perp 1} - P_{e\perp 2} = 9.44 \times 10^{-2}$ nPa. Combined with total electron temperatures, the required electron anisotropy can be determined and is listed in Table 5. On the upstream and downstream sides, $T_{e\parallel}$ exceeds $T_{e\perp}$ by factors of 3 and 5, respectively. As in the previous case, we then infer that D2 is also unlikely to be a RD.

3. Discussion

We have argued for the presence of TDs on which waves propagate in a solar ejection. *Janoo et al.* [1998] analyzed DDs within another ejection. Although in the latter case these were identified as RDs, we suggest that some of these could be TDs on which waves propagate. In the work of *Horbury et al.* [2001], many of the DDs were identified as RDs based on minimum variance techniques at a single spacecraft but were determined to be TDs based on three-spacecraft correlative measurements. Horbury et al. reconciled these conflicting results by suggesting that there were surface waves on these TDs.

Although the above observations are few, there is developing evidence for waves on TDs and for their presence in ejecta. Our discussion will focus on the implications of having waves on TDs and their role in ejecta. We will then interpret the origin and evolution of internal structure and waves within the December 1996 ejection.

The solar atmosphere contains a wide range of cross-field structure. Boundaries between flux tubes can be matched by TDs. Waves are present in the corona and have small relative amplitudes as compared to the background magnetic field strength B_0 [e.g., *Hollweg*, 1990; *Roberts*, 2000]. The presence of sharp gradients can give rise to surface waves based on the solutions of linearized magnetohydrodynamic (MHD) equations. In general, waves in nonuniform media can cause heating through resonant absorption. Heating at TDs may also arise through reconnection. Both forms of heating could play a role in the evolution of solar ejecta. We

Table 5. Jump Conditions Across D2

Parameter	State 1	State 2
N_p	20 cm^{-3}	15 cm^{-3}
T_p	3.0 eV	3.0 eV
$T_{p\parallel}$	2.76 eV	3.85 eV
$T_{p\perp}$	3.12 eV	2.58 eV
T_e	13.4 eV	14.7 eV
$T_{e\parallel}$[a]	24.63 eV	31.21 eV
$T_{e\perp}$[a]	7.78 eV	6.44 eV
$P_{p\parallel}$	8.83×10^{-3} nPa	9.23×10^{-3} nPa
$P_{p\perp}$	9.98×10^{-3} nPa	6.18×10^{-3} nPa
$B^2/2\mu_0$	3.67×10^{-2} nPa	4.99×10^{-2} nPa
λ_p	-0.0157	0.0305
λ_e[a]	0.7352	0.5956

[a]Required value to reproduce observed rotational discontinuity.

pose and consider several pertinent questions. How are surface-like waves generated at the Sun? Under what conditions will they "survive" or dissipate near the Sun, or reach the interplanetary medium? What distinctive properties do surface-like waves possess? How do TDs originate inside solar ejecta?

In the interplanetary medium, DDs are commonly observed with widths of the order of the ion gyroradius [e.g., *Burlaga and Ness*, 1969; *Lepping and Behannon*, 1986]. Some of these have been identified as TDs with an average occurrence rate of 0.6 TDs per hour at 1 AU. The occurrence frequency of TDs, as well as RDs, decreases with increasing heliocentric distance. The relative amplitude of waves increases with this distance in a spherically expanding solar wind. How will waves on TDs evolve when they reach large relative amplitudes? Can they interact nonlinearly with the TD and alter its structure so much so that it ceases to satisfy the selection criterion used to identify a TD? If TDs are lost through dynamical processes, would that not imply that there are many more TDs within ejecta near the Sun than when observed in the interplanetary medium?

When TDs encounter the Earth's bow shock, they can generate hot flow anomalies with gross deformation of the magnetopause [*Schwartz et al.*, 2000, and references therein]. Waves on these TDs can provide a normal magnetic field component at the discontinuity. Does the wave then fundamentally alter the TD-bow shock interaction? What are the ramifications for these interactions if waves are common on TDs? What level of geoeffectiveness do discontinuities and the regions they separate in ejecta and clouds potentially possess?

To examine these many questions, we review and expand upon the current understanding of the waves and discontinuities. In section 3.1, we discuss waves in nonuniform media, including their origin, distinct properties, and the role of nonlinearity. The origin and evolution of small-scale structures within ejecta and clouds are considered in section 3.2. In section 3.3, we discuss how discontinuities within ejecta and clouds can elicit specific geoeffects.

3.1. Waves on TDs

We examine the evolution of waves on TDs in section 3.1.1. Then, in section 3.1.2, we consider whether or not the stability of TDs themselves is influenced by these waves.

3.1.1. Wave evolution. Waves are generally affected by nonuniformities and can couple the wave modes of a uniform medium. Media with TDs separated by uniform regions have normal mode solutions in which the intensity of the wave decreases away from the discontinuities [*Roberts*, 1981; *Edwin and Roberts*, 1982; *Hollweg*, 1982; *Mann et al.*, 1992]. As normal modes, field line disturbances at the photosphere can generate surface waves in such media which might reach the corona.

Shear Alfvén modes are resistant to Landau and transit time damping [e.g., *Barnes*, 1966] and are able to escape the lower atmosphere of the Sun [e.g., *Belcher and Davis*, 1971; *Hollweg*, 1981]. We then infer that this mode would always compose one part of the coupled modes which propagate a significant distance into the interplanetary medium.

The fluctuations observed in the December ejecta probably formed at the Sun. Generation in the interplanetary medium is possible if a Kelvin-Helmholtz instability set in at the observed TDs or if they were located near a fast-slow stream interface. We find no evidence of such local generation mechanisms in our observations.

In the interplanetary medium, waves propagating on TDs can be treated locally as planar wave solutions of the MHD equations because the TDs have very small widths and large tranverse spatial scales [*Denskat and Burlaga*, 1977; *Horbury et al.*, 2001]. Along the discontinuity normal, these solutions behave as a sum of exponential functions between TDs and vanish at infinity. If any part of the solution is oscillatory along the normal direction, then the solutions are body waves [e.g., *Roberts*, 1981]. Configurations with Alfvén speed which is lower between TDs than outside can give rise to ducted body waves between two or more TDs, with exponential decay beyond these TDs corresponding to an evanescent wave.

In the December ejection, the Alfvén speed increases monotonically across the TDs. If there are no background gradients between the TDs, then this situation would give rise to true surface wave solutions.

Observationally, we find that the fluctuations are confined to the vicinity of the TDs and their amplitude beyond the TDs does decay with distance. However, we cannot fully reconstruct the waveform and determine whether its amplitude between the TDs and along the normals is only a sum of exponentials or has oscillations. Thus we cannot distinguish between true surface waves and ducted body waves in this case. We shall then refer to these fluctuations generally as surface-like waves.

Wave nonlinearity generally plays an important role in the interplanetary medium. Thus we should not rely solely on linear wave solutions to describe observed fluctuations. We will show below how wave nonlinearity makes it more likely that fluctuations are body rather than true surface waves in the interplanetary medium.

At finite amplitudes, surface waves can become solitary waves [e.g., *Hollweg and Roberts*, 1984; *Ofman and Davila*, 1997]. Moreover, nonlinearity could transform fluctuations from independently propagating modes to one in which a steady cascade of fluctuation energy occurs. Alfvénic fluctuations in the interplanetary medium appear to be governed by turbulent cascades [e.g., *Bavassano et al.*, 1982; *Horbury et al.*, 1996]. In a turbulent cascade, local properties vary from site to site with a great deal of phase disorder. However, there is a restoration of organization and symmetry over many ensembles, permitting a statistical description of the fluctuations. Alfvénic fluctuations can exist over large regions so that the large amount of data makes the statistical description meaningfully applicable.

Waves of the kind seen in the December ejecta are located in isolated areas; consequently, a single spacecraft can neither fully reconstruct the waves locally, nor can it easily acquire a set of statistical data for the waves. This situation will make surface-like waves difficult to understand observationally. The surface-like waves also exist in a region of phase order due to a TD which in effect contributes to the intermittency (the decreased spatial occupancy) of the turbulent medium at small scales where dissipation is expected. From the viewpoint of turbulence, intermittency further complicates the statistical description of these waves.

It is conceivable that these surface-like waves resemble the average Alfvénic fluctuations seen in high-speed streams. In the work of *Hollweg* [1982], a stream was modeled as having a set of uniform flux tubes bounded by TDs. The properties that surface wave solutions possess in such a stream differ from uniform Alfvén modes. Hollweg noted that for Alfvénic fluctuations the observed minimum variance direction [e.g., *Belcher and Davis*, 1971; *Burlaga and Turner*, 1976; *Denskat and Burlaga*, 1977; *Horbury et al.*, 2001], and polarization [e.g., *Matthaeus and Goldstein*, 1982; *Roberts et al.*, 1987a, 1987b; *Goldstein et al.*, 1995a, 1995b] are more consistent with surface waves than with pure Alfvén waves. The correspondence is promising but incomplete. In particular, observed fluctuations do not satisfy equipartition of kinetic and magnetic energies over large sampling times [e.g., *Matthaeus and Goldstein*, 1982; *Marsch and Tu*, 1990; *Goldstein et al.*, 1995b], whereas surface wave solutions can only deviate locally from equipartition between TDs but not when their energies are integrated over all space.

The actual nature of the fluctuations would be affected by all sources of nonuniformity to some degree. The confinement of all gradients to TDs is an oversimplification because the solar wind has a number of sources of nonuniformity. There are observed variations of plasma and field between TDs [e.g., *Burlaga*, 1969]. Some large-scale variations can be associated with structure at the Sun [e.g., *Thieme et al.*, 1988]. Velocity shears and compressions at the largest scales could provide an important source of energy for turbulent cascades [e.g., *Coleman*, 1968; *Ghosh et al.*, 1998; *Goldstein et al.*, 1999; *Smith et al.*, 2001]. Alfvén waves nonlinearly interact to produce cross-field gradients in the background [*Parenti et al.*, 1997; *Vasquez and Hollweg*, 1999] which are of the order of their wavelengths and can significantly alter their wave vector directions and induce resonant absorption [*Vasquez and Hollweg*, 2001]. The induced background is a form of the zero-frequency mode discussed in MHD turbulence [e.g., *Shebalin et al.*, 1983; *Bondeson*, 1985; *Montgomery and Matthaeus*, 1995; *Ng and Bhattacharjee*, 1996; *Bhattacharjee et al.*, 1998, 1999]. As a result of all these smooth gradients, body waves rather than true surface waves are more likely to propagate in the solar wind.

3.1.2. Fate of TDs in the solar wind. A property common to all DDs, whether TDs or RDs, in the solar wind is their decreasing occurrence frequency with increasing heliocentric distance [*Behannon*, 1978; *Tsurutani and Smith*, 1979; *Neubauer and Barnstorf*, 1981; *Mariana et al.*, 1983; *Lepping and Behannon*, 1986; *Tsurutani and Ho*, 1999]. Apart from observational selection effects, this decrease can only be explained by the statistical loss of the surface area of DDs through dynamics which either widens the DDs beyond recognition or alters their structure [see *Vasquez and Hollweg*, 2001, Appendix B]. Vasquez and Hollweg advanced an explanation of the loss of RDs based on simulations which show how resonant absorption and cascades can remove wave-imbedded RDs.

A TD current layer can continually widen when resistivity is present and become so enlarged that its width exceeds a discontinuity criterion. Anamolous resistivity may arise from instabilities generating waves, such as drift waves [e.g., *Kadomtsev*, 1965; *Goldston and Rutherford*, 1995], which can demagnetize ions and/or electrons. Resistivity can also allow the layer to undergo tearing mode instability [e.g., *Furth et al.*, 1963; *Rutherford*, 1973; *Priest and Forbes*, 2000] which alters the topology of the layer so that it is no longer a TD.

Velocity shear at a TD current layer can make the TD Kelvin-Helmholtz (KH) unstable, breaking it up [e.g., *Sen*, 1964; *Neugebauer et al.*, 1986]. *De Keyser and Roth* [1997, 1998] showed that velocity shear can give rise to normal electric fields which can act as a barrier to ions or electrons populating the TD layer. For sufficiently large velocity shear, TDs can lose equilibrium due to this barrier.

Waves on TDs could contribute to the loss of TDs in the solar wind in several ways. First, the tearing mode can be energized by Alfvénic surface waves and force reconnection [e.g., *Hahm and Kulsrud*, 1985; *Matthaeus and Lamkin*, 1985; *Uberoi*, 1994; *Uberoi et al.*, 1996; *Uberoi and Zweibel*, 1999; *Vekstein*, 2000]. Second, wave resonances can make current layers more susceptible to velocity shear instabilities [*Hollweg et al.*, 1990; *Yang and Hollweg*, 1991]. Third, wave nonlinearity can lead to significant advection of the TD and could cause the TD current layer to disrupt into wave disturbances. The imposition of a wave magnetic field component along a TD normal allows wave disturbances to propagate away from the TD. This process corresponds to the Riemann problem in which a time-constant magnetic field component is imposed on an initial TD [e.g., *Lin and Lee*, 1995; *Scholer and Cremer*, 2000]. Since the wave magnetic field varies back and forth, the disrupted layer would be periodically reconstituted in the absence of dissipation. However, if dissipation exists, then irreversible alteration of the TD layer would occur.

Waves on TDs could further enhance anomalous dissipation and indirectly destabilize TDs. A turbulent cascade among these waves would produce waves at small scales where particle interactions occur. Resonant absorption of waves in the current layer could also lead to dissipation by producing small perpendicular scales, driving a cascade [*Vasquez and Holweg*, 2001], or generating highly oblique ion cyclotron modes near the ion gyrofrequency [*Markovskii*, 2001].

3.2. Structure Within Solar Ejecta

Imbedded structures could arise at several places between the formation of a magnetic flux rope and its arrival at Earth. Flux ropes rising in the solar convection zone are buffeted continuously by turbulent flows which can generate structure on small spatial scales. These flux ropes emerge mostly at the boundaries of supergranular convection cells. The eruptive process itself can introduce structure, through reconnection. Simulations of 3-D reconnection in the Earth's tail [*Birn and Hesse*, 1990, and references therein] reveal that a multiplicity of topologies can indeed arise. This could be equally true of ejecta [e.g., *Gosling et al.*, 1995]. In the interplanetary medium, there exist large-scale velocity shears which could distort ejecta and introduce structure. Ulysses observed differences between mid-latitude and low-latitude CMEs which may arise in this way [*Neugebauer*, 1999, and references therein].

The observations presented above indicate that very sharp boundaries forming TDs and RDs can occur within magnetic clouds and ejecta. The presence of discontinuities places constraints on the solar ejecta and their interaction with their surroundings. Pressure balance is locally required across TDs bounding flux tubes. Reconnection can lead to RDs and to the internal rearrangement of fields or connections with fields outside the cloud. With this in mind, structure can be used as a probe to test the relationship of magnetic clouds to surrounding ejecta and to discern whether magnetic clouds are a part of the overall ejecta (presumably the interplanetary manifestation of a CME) or a type of ejecta. Structure can also indicate how magnetic clouds and ejecta change with distance from the Sun and how they might have arisen.

The December 1996 ejecta featured strong nonuniformities. Typically these have sharp boundaries and can be bounded by TDs. Regions with much higher than normal density and also having nearly uniform or decreasing temperatures and bulk speeds have been identified in the solar wind and are called noncompressive density enhancements (NCDEs) [e.g., *Gosling et al.*, 1977]. *Gosling et al.* [1977] suggested a possible relation with solar ejecta. In the December 1996 ejecta, we find similar NCDEs inside the ejecta or separating ejecta material from the interplanetary medium.

Low T_p is an acknowledged reliable signature of ejecta material [e.g., *Richardson et al.*, 1997] (see also review by *Gosling* [1990, and references therein]). Looking back at Figure 1 (T_p panel), we see four regions of low T_p starting from 14 hours and ending at 60 hours. These four regions are separated by structure with high T_p near or above average interplanetary conditions. The first region starts at a hindrance of cosmic ray particles (Figure 2) and ends at a reconnection layer near 26 hours [*Farrugia et al.*, 2000, 2001]. The second region starts at 27 hours and ends at 40.5 hours, where we identified TDs. The third region starts at 43 hours and stops at 49 hours near a DD whose nature has not been analyzed. The fourth region begins at 51 hours and ends at 60 hours, where a magnetic hole is located.

The nature and origin of interruptions to ejecta material observed by interplanetary probes are worth investigating. In the work of *Larson et al.* [1997] on the October 18-20, 1995, ejecta, a large number of sporadic disconnections of magnetic field lines from the Sun were inferred. Larson et al. postulated a mixture of field topologies (two ends, one end or none connected to the Sun) to explain these observations, where disconnections arose through reconnection between bundles of adjacent ejecta field lines. Another possibility is reconnection of ejecta with the interplanetary field lines, which appears to be the case in the December 1996 ejecta. In this scenario, reconnection leads to part of the ejecta being peeled off, which then at Wind appears separate from the rest. A model where ejecta field lines are pinched off by reconnection and appear as separate regions was elaborated by *Cargill et al.* [1996].

Another open question which should be addressed is whether or not the NCDEs are filaments, whose eruption can be related to ejecta and clouds [e.g., *Wilson and Hildner*, 1986; *Forbes*, 2000]. Studying the February 10, 1997, magnetic cloud, *Gopalswamy et al.* [1998] were able to isolate a density enhancement behind the cloud and identify it with the erupting filament.

Even more elaborate structure was observed in the October 1995 cloud [e.g., *Larson et al.*, 1997; *Lepping et al.*, 1997; *Janoo et al.*, 1998]. Many DDs were located inside the cloud and were identified as RDs. Some of these could very well be TDs, perhaps with surface waves distorting minimum variances, which could divide the cloud into distinct regions or represent rapid gradients of a single structure. Across the discontinuities, the primary change was in the orientation of the magnetic field. Viewing the cloud locally as a flux rope [e.g., *Burlaga*, 1988; *Lepping et al.*, 1990; *Farrugia et al.*, 1993; *Osherovich et al.*, 1995], the rotation of the field across these TDs could be due to a change in the pitch of field to the axial field. Then the magnetic field twists on magnetic flux surfaces at different pitch angles away from the central axis. The discontinuities approximately represent current sheets where the spatial variation of pitch angle is very rapid, as also noted by *Janoo et al.* [1998].

Magnetic clouds are generally configurations which radially expand as they move away from the Sun [e.g., *Klein and Burlaga*, 1982; *Moushovias and Poland*, 1978; *Farrugia et al.*, 1991, 1993; *Garren and Chen*, 1994]. Modeling this expansion leads to cooling much greater than observed and so implies that significant coronal heating occurs within ejecta and clouds [e.g., *Kumar and Rust*, 1996]. One source of heating may come from magnetic stresses which produce small-scale current layers which become unstable and release heat [e.g., *Parker*, 1994]. Large-scale current sheets may also evolve when CMEs erupt. *Lin and Forbes* [2000] found that reconnection in these sheets can sustain the outward motion of the CME. If current sheets do form in the corona, then the TDs observed near 1 AU may be their remnants. Another source is wave heating at resonant layers within coronal loops [e.g., *Ofman et al.*, 1996, 1998]. Surface-like waves may be a related signature of such wave heating.

3.3. Geoeffects of Discontinuities in Ejecta

When ejecta and clouds interact with the Earth's magnetosphere, disturbed conditions result, such as geomagnetic storms [e.g., *Zhang and Burlaga*, 1988; *Gosling et al.*, 1991] (see also review by *Farrugia et al.* [1997]). This general trend can be further refined by the behavior of parameters, such as field orientation which can influence reconnection at the magnetopause, and dynamic pressure which influences the shape and scale of the magnetosphere, throughout the passage of the ejecta and cloud. Directional discontinuities organize field direction and can be associated with plasma and field strength variations which alter dynamic pressure. These changes impinge upon various regions of geospace in a short time span. As such, they can elicit rapid responses from other parts of geospace and influence geomagnetic activity.

Sometimes these substructures can lead to strong effects at Earth, as can be seen from the work of *Jordanova et al.* [2001]. They observed a DD in the sheath of the May 14-17, 1997, ejecta. At this DD, the field turned strongly south and the "ϵ" parameter, a commonly used measure of the Poynting flux into the magnetosphere [*Perreault and Akasofu*, 1978], underwent a large increase. It is this southward turning which initiates the major disturbances and, in particular, triggers the main phase of the storm. In general, rapid southward turnings of the interplanetary magnetic field at the DDs often elicit a magnetospheric transition from quiet to disturbed conditions.

The detailed nature of the interaction of discontinuities and the bow shock has received considerable attention. This interaction depends on the nature of the discontinuity. RD interactions lead to density enhancements and magnetic intensity depressions in the magnetosheath which can penetrate the magnetosphere depending on field orientation [e.g, *Yan and Lee*, 1996; *Hubert and Harvey*, 2000].

TD interactions with the bow shock can cause hot flow anomalies [e.g., *Schwartz et al.*, 1985, 1988, 2000; *Paschmann et al.*, 1988; *Burgess*, 1989; *Thomas et al.*, 1991]. These can in turn deform the magnetopause and affect the ionosphere [*Sibeck et al.*, 1998, 1999]. The flow is due to an electric field component ($= -\mathbf{V}_{sw} \times \mathbf{B}$ where $\mathbf{V}_{sw}$ is the solar wind velocity) on at least one side of the TD which draws reflected ions away from the bow shock and along the TD current layer.

Another aspect of this interaction with Earth which has not been so far discussed is the influence of waves on TDs. These waves could provide a magnetic field component along the TD normal which penetrates the bow shock and alters the structure of the interaction region. With a wave magnetic field along the TD normal, reflected ions from the shock could be led to or deflected from the current layer depending on whether the total magnetic field points toward or away from the layer.

4. Summary and Conclusions

From plasma and field data, we have concluded that a set of DDs in the December 1996 ejecta and magnetic cloud are TDs. Their surrounding fluctuations are either true surface waves or ducted body waves which are evanescent outside the region of the TDs. We believe that this is the first identification of TDs and accompanying waves within an ejection or cloud.

The identification was made by a process of elimination using a succession of tests. Agreement with minimum variance analysis is achieved for long time intervals spanning both discontinuities. Velocity and magnetic field variations have uncorrelated changes across the DDs which are not consistent with RDs but are possible for TDs and surface-like waves. Proton anisotropy changes across the DDs as do density and field strength. The density jump across a RD is constrained by plasma anisotropy. The observed proton anisotropy cannot even account for the direction of density change, let alone for its magnitude. Electron total temperatures have been measured, but not the electron anisotropy. We determined the level of electron anisotropy required for a successful identification of a RD and found it to be far in excess of average expected plasma conditions. RDs are then unlikely.

The TDs are themselves part of a larger structure of enhanced density within the cloud. They are located in an area which tends to exclude energetic particles and to separate cool, cloud-like plasma from warm, interplanetary-like plasma. The TDs form a boundary between these plasmas. Waves on the TDs would then propagate along these boundaries. The waves and

TDs probably originate from the Sun. Thus these waves could be a signal showing how the structured solar atmosphere alters well-known uniform wave mode properties, as was anticipated by theory.

Waves of low frequency and/or large amplitude can advect TDs and could break up current layers into wave disturbances. This breakup could contribute to the loss of TDs with increasing heliocentric distance. Waves could also supply energy to the growth of a resistive tearing instability and force reconnection. The magnetic topology at the current layer would change greatly, and the TD would effectively be lost based on observational selection criteria.

The discontinuities that we have discussed contribute to the structure of ejecta and clouds. The difference between RDs and TDs is significant in terms of evolutionary processes and relationships of various structures. The presence of waves can make identification difficult. Where confined to a region of space, minimum variance may still be useful if the time interval can extend beyond the limits of the waves. Velocity and magnetic field correlations which vary in unexpected ways may also betray the presence of waves. For cases where plasma and field jumps occur, RDs can be strongly constrained by plasma anisotropy.

Hot flow anomalies can result when TDs interact with the Earth's bow shock. In that case, we infer that one aspect of interest for the December 1996 ejecta is that they should produce hot flow anomalies at the bow shock. The presence of waves on TDs is likely to complicate these interactions and is a subject worth pursuing in future work.

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References

Barnes, A., Collisionless damping of hydromagnetic waves, *Phys. Fluids*, *9*, 1483, 1966.

Bavassano, B., M. Dobrowolny, F. Mariani, and N. F. Ness, Radial evolution of power spectra of interplanetary Alfvénic turbulence, *J. Geophys. Res.*, *87*, 3617, 1982.

Behannon, K. W., Heliocentric distance dependence of the interplanetary magnetic field, *Rev. Geophys.*, *16*, 125, 1978.

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

Bhattacharjee, A., C. S. Ng, and S. R. Spangler, Weakly compressible magnetohydrodynamic turbulence in the solar wind and the interstellar medium, *Astrophys. J.*, *494*, 409, 1998.

Bhattacharjee, A., C. S. Ng, S. Ghosh, and M. L. Goldstein, A comparative study of four-field and fully compressible magnetohydrodynamic turbulence in the solar wind, *J. Geophys. Res.*, *104*, 24,835, 1999.

Birn, J., and M. Hesse, The magnetic topology of the plasmoid flux rope in a MHD-simulation of magnetotail reconnection, in *Physics of Magnetic Flux Ropes*, edited by C. T. Russell, E. R. Priest, and L. C. Lee, *Geophys. Monogr. Ser.*, vol. 58, p. 655, AGU, Washington, D. C., 1990.

Bondeson, A., Cascade properties of shear Alfvén turbulence, *Phys. Fluids*, *28*, 2406, 1985.

Burgess, D., On the effect of a tangential discontinuity on ions specularly reflected at an oblique shock, *J. Geophys. Res.*, *94*, 472, 1989.

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

Burlaga, L. F., Magnetic clouds: Constant alpha force-free configurations, *J. Geophys. Res.*, *93*, 7217, 1988.

Burlaga, L. F., and N. F. Ness, Tangential discontinuities in the solar wind, *Sol. Phys.*, *9*, 467, 1969.

Burlaga, L. F., and J. B. Turner, Mircoscale "Alfvén waves" in the solar wind at 1 AU, *J. Geophys. Res.*, *81*, 73, 1976.

Burlaga, L.F., E. Sittler, F. Mariani, and R. Schwenn, Magnetic loop behind an interplanetary shock: Voyager, Helios and IMP 8 observations, *J. Geophys. Res.*, *86*, 6673, 1981.

Burlaga, L.F., R. P. Lepping, and J. A. Jones, Global configuration of a magnetic cloud, in *Physics of Magnetic Flux Ropes*, edited by C.T. Russell, E.R. Priest, and L.C. Lee, *Geophys. Monogr. Ser.*, vol. 58, p. 373, AGU, Washington, D. C., 1990.

Cargill, P. J., J. Chen, D. S. Spicer, and S. T. Zalesak, Magnetohydrodynamic simulations of the motion of magnetic flux tubes through a magnetized plasma, *J. Geophys. Res.*, *101*, 4855, 1996.

Chew, G. F., M. L. Goldberger, and F. E. Low, The Boltzmann equation and the one-fluid hydromagnetic equations in the absence of particle collisions, *Proc. R. Soc. London, Ser. A*, *236*, 112, 1956.

Coleman, P. J., Turbulence, viscosity, and dissipation in the solar-wind plasma, *Astrophys. J.*, *153*, 371, 1968.

De Keyser, J., and M. Roth, Equilibrium conditions for the tangential discontinuity magnetopause, *J. Geophys. Res.*, *102*, 9513, 1997. (Correction, *J. Geophys. Res.*, *102*, 19,943, 1997.)

De Keyser, J., and M. Roth, Equilibrium conditions and magnetic field rotation at the tangential discontinuity magnetopause, *J. Geophys. Res.*, *103*, 6653, 1998.

De Keyser, J., M. Roth, and A. Söding, Flow shear across solar wind discontinuities: Wind observations, *Geophys. Res. Lett.*, *25*, 2649, 1998.

Denskat, K. U., and L. F. Burlaga, Multispacecraft observations of microscale fluctuations in the solar wind, *J. Geophys. Res.*, *82*, 2693, 1977.

Edwin, P. M., and B. Roberts, Wave propagation in a magnetically structured atmosphere, III, The slab in a magnetic environment, *Sol. Phys.*, *76*, 239, 1982.

Fainberg, J., V. A. Osherovich, R. G. Stone, R. J. MacDowall, and A. Balogh, Ulysses observations of electron and proton components in a magnetic cloud and related wave activity, in *Solar Wind Eight*, edited by D. Winterhalter et al., *AIP Conf. Proc.*, *382*, 554, 1996.

Farrugia, C. J., L. F. Burlaga, V. A. Osherovich, and R. P. Lepping, A comparative study of dynamically expanding force-free constant-alpha magnetic configurations with applications to magnetic clouds, in *Solar Wind Seven*, edited by R. Schwenn and E. Marsch, p. 611, Tarrytown, N. Y., 1991.

Farrugia, C. J., L. F. Burlaga, V. A. Osherovich, I. G. Richardson, M. P. Freeman, R. P. Lepping, and A. J. Lazarus, A study of an expanding interplanetary magnetic cloud and its interaction with the Earth's magnetosphere: The interplanetary aspect, *J. Geophys. Res., 98,* 7621, 1993.

Farrugia, C. J., L. F. Burlaga, and R. P. Lepping, Magnetic clouds and the quiet-storm effect at Earth, in *Magnetic Storms*, edited by B. T. Tsurutani, et al., *Geophys. Monogr. Ser.*, vol. 98, p. 91, AGU, Washington, D. C., 1997.

Farrugia, C. J., et al., Multi-instrument study of the December 1996 magnetic cloud and associated interplanetary disturbances, in *The Solar Wind-Magnetosphere System 3*, edited by H. K. Biernat, S. J. Bauer, and C. J. Farrugia, p. 99, Aust. Acad. of Sci., Vienna, Austria, 2000.

Farrugia, C. J., et al., A reconnection layer associated with a magnetic cloud, *Adv. Space Res.*, in press, 2001.

Feldman, W. C., J. R. Asbridge, S. J. Bame, M. D. Montgomery, and S. P. Gary, Solar wind electrons, *J. Geophys. Res.*, *80*, 4181, 1975.

Forbes, T. G., A review on the genesis of coronal mass ejections, *J. Geophys. Res.*, *105*, 23,153, 2000.

Furth, H. P., J. Killeen, and M. N. Rosenbluth, Finite-resistivity instabilities of a sheet pinch, *Phys. Fluids*, *6*, 459, 1963.

Garren, D. A., and J. Chen, Lorentz self-forces on curved current loops, *Phys. Plasmas*, *1*, 3425, 1994.

Ghosh, S., W. H. Matthaeus, D. A. Roberts, and M. L. Goldstein, The evolution of slab fluctuations in the presence of pressure-balanced magnetic structures and velocity shears, *J. Geophys. Res.*, *103*, 23,691, 1998.

Goldstein, B. E., M. Neugebauer, and E. J. Smith, Alfvén waves, alpha particles, and pickup ions in the solar wind, *Geophys. Res. Lett.*, *22*, 3389, 1995a.

Goldstein, B. E., E. J. Smith, A. Balogh, T. S. Horbury, M. L. Goldstein, and D. A. Roberts, Properties of magnetohydrodynamic turbulence in the solar wind as observed by Ulysses at high heliographic latitudes, *Geophys. Res. Lett.*, *22*, 3393, 1995b.

Goldstein, M. L., D. A. Roberts, A. E. Deane, S. Ghosh, and H. K. Wong, Numerical simulation of Alfvénic turbulence in the solar wind, *J. Geophys. Res.*, *104*, 14,437, 1999.

Goldston, R. J., and P. H. Rutherford, *Introduction to Plasma Physics*, Inst. of Phys. Publ., Philadelphia, Pa., 1995.

Gopalswamy, N., et al., On the relationship between coronal mass ejections and magnetic clouds, *Geophys. Res. Lett.*, *25*, 2485, 1998.

Gosling, J. T., Coronal mass ejections and magnetic flux ropes in interplanetary space, in *Physics of Magnetic Flux Ropes*, edited by C. T. Russell, E.R. Priest, and L.C. Lee, *Geophys. Mongr. Ser.*, vol. 58, p. 344, AGU, Washington, D. C., 1990.

Gosling, J. T., E. Hildner, J. R. Asbridge, S. J. Bame, and W. C. Feldman, Noncompressive density enhancements in the solar wind, *J. Geophys. Res.*, *82*, 5005, 1977.

Gosling, J. T., D. J. McComas, J. L. Phillips, and S. J. Bame, Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, *96*, 7831, 1991.

Gosling, J. T., J. Birn, and M. Hesse, Three-dimensional magnetic reconnection and the magnetic topology of coronal mass events, *Geophys. Res. Lett.*, *22*, 869, 1995.

Hahm, T. S., and R. M. Kulsrud, Forced magnetic reconnection, *Phys. Fluids*, *28*, 2412, 1985.

Hammond, C. M., J. L. Phillips, G. K. Crawford, and A. Balogh, The relationship between electron density and temperature in coronal mass ejections, in *Solar Wind Eight*, edited by D. Winterhalter et al., *AIP Conf. Proc.*, *382*, 558, 1996.

Hollweg, J. V., The energy balance of the solar wind, in *The Sun as a Star*, edited by S. Jordan, *NASA Spec. Publ.*, *SP-450*, 355, 1981.

Hollweg, J. V., Surface waves on solar wind tangential discontinuities, *J. Geophys. Res.*, *87*, 8065, 1982.

Hollweg, J. V., MHD waves on solar magnetic flux tubes: Tutorial review, in *Physics of Magnetic Flux Ropes*, edited by C. T. Russell, E. R. Priest, and L. C. Lee, *Geophys. Mongr. Ser.*, vol. 58, p. 23, AGU, Washington, D. C., 1990.

Hollweg, J. V., and B. Roberts, Surface solitary waves and solitons, *J. Geophys. Res.*, *89*, 1984.

Hollweg, J. V., G. Yang, V. M. Cadez, and B. Gakovic, Surface waves in an incompressible fluid: Resonant instability due to velocity shear, *Astrophys. J.*, *349*, 335, 1990.

Horbury, T. S., A. Balogh, R. J. Forsyth, and E. J. Smith, Magnetic field signatures of unevolved turbulence in solar pole flows, *J. Geophys. Res.*, *101*, 405, 1996.

Horbury, T., D. Burgess, M. J. Fränz, and C. J. Owen, Three spacecraft observations of solar wind discontinuities, *Geophys. Res. Lett.*, *28*, 677, 2001.

Hubert, D., and C. C. Harvey, Interplanetary rotational discontinuities: From the solar wind to the magnetosphere through the magnetosheath, *Geophys. Res. Lett.*, *27*, 3149, 2000.

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

Hudson, P. D., Rotational discontinuities in an anisotropic plasma, *Planet. Space Sci.*, *19*, 1693, 1971.

Janoo, L., et al., Field and flow perturbations in the October 18-19, 1995 magnetic cloud, *J. Geophys. Res.*, *103*, 17,249, 1998.

Jockers, K., Solar wind models based on exospheric theory, *Astron. Astrophys.*, *6*, 219, 1970.

Jordanova, V. K., C. J. Farrugia, R. M. Thorne, G. V. Khazanov, G. D. Reeves, and M. F. Thomsen, Modeling ring current proton precipitation by EMIC waves during the May 14-16, 1997, storm, *J. Geophys. Res.*, *106*, 7, 2001.

Kadomtsev, B. B., *Plasma Turbulence*, Academic, San Diego, Calif., 1965.

Klein, L. W., and L. F. Burlaga, Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *87*, 613, 1982.

Kumar, A., and D. M. Rust, Interplanetary magnetic clouds, helicity conservation, and current-core flux-ropes, *J. Geophys. Res.*, *101*, 15,667, 1996.

Larson, D. E., et al., Tracing the topology of the October 18-20, 1995, magnetic cloud with $\sim$0.1 - 10^2 keV electrons, *Geophys. Res. Lett.*, *24*, 1911, 1997.

Lepping, R. P., and K. W. Behannon, Magnetic field directional discontinuities, 1, Minimum variance errors, *J. Geophys. Res.*, *85*, 4695, 1980.

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

Lepping, R. P., J. Jones, and L. F. Burlaga, Magnetic field structure of interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *95*, 11,957, 1990.

Lepping, R. P., et al., The Wind magnetic field investigation, *Space Sci. Rev.*, *71*, 207, 1995.

Lepping, R. P., et al., The Wind magnetic cloud and events of October 18-20, 1995: Interplanetary properties and as triggers for geomagnetic activity, *J. Geophys. Res.*, *102*, 14,049, 1997.

Lin, J., and T. G. Forbes, The effects of reconnection on the coronal mass ejection process, *J. Geophys. Res.*, *105*, 2375, 2000.

Lin, R. P., et al., A three-dimensional plasma and energetic particle investigation for the Wind spacecraft, *Space Sci. Rev.*, *71*, 125, 1995.

Lin, Y., and L. C. Lee, Simulation of the Riemann problem associated with magnetotail reconnection, *J. Geophys. Res.*, *100*, 19,227, 1995.

Lopez, R. E., Solar cycle invariance in solar wind proton temperature relationships, *J. Geophys. Res.*, *92*, 11,189, 1987.

Mann, G., E. Marsch, and B. Roberts, Surface and body waves in solar wind flow tubes, in *Solar Wind Seven*, edited by E. Marsch and R. Schwenn, p. 495, Pergamon, Tarrytown, N. Y., 1992.

Mariani, F., B. Bavassano, and U. Villante, A statistical study of MHD discontinuities in the inner solar system: Helios 1 and 2, *Sol. Phys.*, *83*, 349, 1983.

Markovskii, S. A., Generation of ion cyclotron waves in coronal holes by MHD waves, *Astrophys. J.*, *557*, 337, 2001.

Marsch, E., and C.-Y. Tu, On the radial evolution of MHD turbulence in the inner heliosphere, *J. Geophys. Res.*, *95*, 8211, 1990.

Marubashi, K., Structure of the interplanetary magnetic clouds and their solar origins, *Adv. Space Res.*, *6*, 335, 1986.

Matthaeus, W. H., and M. L. Goldstein, Measurement of the rugged invariants of magnetohydrodynamic turbulence in the solar wind, *J. Geophys. Res.*, *87*, 6011, 1982.

Matthaeus, W. H., and S. L. Lamkin, Rapid reconnection caused by finite amplitude fluctuations, *Phys. Fluids*, *28*, 303, 1985.

McGuire, R. E., T. T. von Rosenvinge, and F. B. McDonald, The composition of solar energetic particles, *Astrophys. J.*, *301*, 938, 1986.

Montgomery, D., and W. H. Matthaeus, Anisotropic modal energy transfer in interstellar turbulence, *Astrophys. J.*, *447*, 706, 1995.

Montgomery, M. D., S. J. Bame, and A. J. Hundhausen, Solar wind electrons: Vela 4 measurements, *J. Geophys. Res.*, *73*, 4999, 1968.

Moushovias, T. C., and A. I. Poland, Expansion and broadening of coronal loop transients: A theoretical explanation, *Astrophys. J.*, *220*, 675, 1978.

Mulligan, T., C. T. Russell, and J. G. Luhmann, Solar cycle evolution of the structure of magnetic clouds in the inner heliosphere, *Geophys. Res. Lett.*, *25*, 2959, 1998.

Neubauer, F. M., and H. Barnstorf, Recent observational and theoretical results on discontinuities in the solar wind, in *Solar Wind Four*, edited by H. Rosenbauer, *Rep. MPAE-W-100-81-31*, p. 168, Max-Planck-Inst. für Aeron., Katlenburg-Lindau, Germany, 1981.

Neugebauer, M., The three-dimensional solar wind at solar activity minimum, *Rev. Geophys.*, *37*, 107, 1999.

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, 1984.

Neugebauer, M., C. J. Alexander, R. Schwenn, and A. K. Richter, Tangential discontinuities in the solar wind: Correlated field and velocity changes and the Kelvin-Helmholtz instability, *J. Geophys. Res.*, *91*, 13,694, 1986.

Ng, C. S., and A. Bhattacharjee, Interaction of Shear-Alfvén wave packets: Implication for weak magnetohydrodynamic turbulence in astrophysical plasmas, *Astrophys. J.*, *465*, 845, 1996.

Ofman, L., and J. M. Davila, Solar wind acceleration by solitary waves in coronal holes, *Astrophys. J.*, *476*, 357, 1997.

Ofman, L., J. M. Davila, and J. Shimizu, Signatures of global mode Alfvén resonance heating in coronal loops, *Astrophys. J. Lett.*, *459*, L39, 1996.

Ofman, L., J. A. Klimchuk, and J. M. Davila, A self-consistent model for the resonant heating of coronal loops: The effects of coupling with the chromosphere, *Astrophys. J.*, *493*, 474, 1998.

Ogilvie, K. W., et al., SWE, a comprehensive plasma instrument for the Wind spacecraft, *Space Sci. Rev.*, *71*, 55, 1995.

Osherovich, V. A., C. J. Farrugia, and L. F. Burlaga, Dynamics of aging magnetic clouds, *Adv. Space Res.*, *13*, 57, 1993.

Osherovich, V. A., C. J. Farrugia, and L. F. Burlaga, Nonlinear evolution of magnetic flux-ropes, 2, Finite beta plasma, *J. Geophys. Res.*, *100*, 12,307, 1995.

Parenti, S., M. Velli, G. Poletto, S. T. Suess, and D. J. McComas, Magnetic flux tubes at 3 AU?, *Sol. Phys.*, *174*, 329, 1997.

Parker, E. N., *Spontaneous Current Sheets in Magnetic Fields*, Oxford Univ. Press, New York, 1994.

Paschmann, G., G. Haerendel, N. Sckopke, E. Möbius, H. Lühr, and C. W. Carlson, Three-dimensional plasma structures with anomalous flow directions near the Earth's bow shock, *J. Geophys. Res.*, *93*, 11,279, 1988.

Perreault, P., and S.-I. Akasofu, A study of geomagnetic storms, *Geophys. J. R. Astron. Soc.*, *54*, 547, 1978.

Phillips, J. L., and J. T. Gosling, Radial evolution of solar wind thermal electron distributions due to expansion and collisions, *J. Geophys. Res.*, *95*, 4217, 1990.

Phillips, J. L., J. T. Gosling, D. J. McComas, S. J. Bame, S. P. Gary, and E. J. Smith, Anisotropic thermal electron distributions in the solar wind, *J. Geophys. Res.*, *94*, 6563, 1989.

Priest, E. R., and T. G. Forbes, *Magnetic Reconnection: MHD Theory and Applications*, Cambridge Univ. Press, New York, 2000.

Richardson, I. G., Using energetic particles to probe the magnetic topology of ejecta, in *Coronal Mass Ejections*, edited by N. U. Crooker, J. A. Joselyn, and J. Feynman, *Geophys. Monogr. Ser.*, vol. 99, p. 189, AGU, Washington, D. C., 1997.

Richardson, I. G., C. J. Farrugia, and H. V. Cane, A statistical study of the behavior of the electron temperature in ejecta, *J. Geophys. Res.*, *102*, 4691, 1997.

Roberts, B., Wave propagation in a magnetically structured atmosphere, 2, Waves in a magnetic slab, *Sol. Phys.*, *69*, 39, 1981.

Roberts, B., Waves and oscillations in the corona, *Sol. Phys.*, *193*, 139, 2000.

Roberts, D. A., L. W. Klein, M. L. Goldstein, and W. H. Matthaeus, The nature and evolution of magnetohydrodynamic fluctuations in the solar wind: Voyager observations, *J. Geophys. Res.*, *92*, 11,021, 1987a.

Roberts, D. A., M. L. Goldstein, L. W. Klein, and W. H. Matthaeus, Origin and evolution of fluctuations in the solar wind: Helios observations and Helios-Voyager comparisons, *J. Geophys. Res.*, *92*, 12,023, 1987b.

Rutherford, P. H., Nonlinear growth of the tearing mode, *Phys. Fluids*, *16*, 1903, 1973.

Scholer, M., and M. Cremer, Kinetic structure of the magnetotail reconnection layer and of slow mode shocks, in *The Solar Wind-Magnetosphere System 3*, edited by H. K. Biernat, S. J. Bauer, and C. J. Farrugia, p. 285, Aust. Acad. of Sci., Vienna, Austria, 2000.

Schwartz, S. J., et al., An active current sheet in the solar wind, *Nature*, *318*, 269, 1985.

Schwartz, S. J., R. L. Kessel, C. C. Brown, L. J. C. Woolliscroft, M. W. Dunlop, C. J. Farrugia, and D. S. Hall, Active current sheets near the Earth's bow shock, *J. Geophys. Res.*, *93*, 11,295, 1988.

Schwartz, S. J., G. Paschmann, N. Sckopke, T. M. Bauer, M. Dunlop, A. N. Fazakerley, and M. F. Thomsen, Conditions for the formation of hot flow anomalies at Earth's bow shock, *J. Geophys. Res.*, *105*, 12,639, 2000.

Sen, A. K., Effect of compressibility on Kelvin-Helmholtz instability in a plasma, *Phys. Fluids*, *7*, 1293, 1964.

Shebalin, J. V., W. H. Matthaeus, and D. Montgomery, Anisotropy in MHD turbulence due to a mean magnetic field, *J. Plasma Phys.*, *29*, 525, 1983.

Sibeck, D. G., N. L. Borodkova, G. N. Zastenker, S. A. Romanov, and J. A. Sauvaud, Gross deformation of the dayside magnetopause, *Geophys. Res. Lett.*, *25*, 453, 1998.

Sibeck, D. G., et al., Comprehensive study of the magnetospheric response to a hot flow anomaly, *J. Geophys. Res.*, *104*, 4577, 1999.

Smith, C. W., W. H. Matthaeus, G. P. Zank, N. F. Ness, S. Oughton, and J. D. Richardson, Heating of the low-latitude solar wind by dissipation of turbulent magnetic fluctuations, *J. Geophys. Res.*, *106*, 8253, 2001.

Sonnerup, B., and L. Cahill Jr., Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.*, *72*, 171, 1967.

Thieme, K. M., E. Marsch, and R. Schwenn, Relationships between structures in the solar wind and their source regions in the corona, Proceedings of the Sixth International Solar Wind Conference, vol. 1, *NCAR Tech. Note 306+Proc.*, p. 317, Natl. Cent. for Atmos. Res., Boulder, Colo., 1988.

Thomas, V. A., D. Winske, M. F. Thomsen, and T. G. Onsager, Hybrid simulation of the formation of a hot flow anomaly, *J. Geophys. Res.*, *96*, 11,625, 1991.

Tsurutani, B. T., and C. M. Ho, Review of discontinuities and Alfvén waves in interplanetary space: Ulysses results, *Rev. Geophys.*, 37, 517, 1999.

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, 1979.

Uberoi, C., Resonant absorption of Alfvén waves near a neutral point, *J. Plasma Phys.*, *52*, 215, 1994.

Uberoi, C., and E. G. Zweibel, Alfvén resonances and forced reconnection, *J. Plasma Phys.*, *62*, 345, 1999.

Uberoi, C., L. J. Lanzerotti, and A. Wolfe, Surface waves and magnetic reconnection at a magnetopause, *J. Geophys. Res.*, *101*, 24,979, 1996.

Vasquez, B. J., and J. V. Hollweg, Formation of spherically polarized Alfvén waves and imbedded rotational discontinuities from a small number of entirely oblique waves, *J. Geophys. Res.*, *103*, 335, 1998a.

Vasquez, B. J., and J. V. Hollweg, Formation of imbedded rotational discontinuities with nearly field aligned normals, *J. Geophys. Res.*, *103*, 349, 1998b.

Vasquez, B. J., and J. V. Hollweg, Formation of pressure-balanced structures and fast waves from nonlinear Alfvén waves, *J. Geophys. Res.*, *104*, 4681, 1999.

Vasquez, B. J., and J. V. Hollweg, Evolution and dissipation of imbedded rotational discontinuities and Alfvén waves in nonuniform plasma and the resultant proton heating, *J. Geophys. Res.*, *106*, 5661, 2001.

Vekstein, G., On the correspondence between forced magnetic reconnection and Alfvén resonances, *Phys. Plasmas*, *7*, 3808, 2000.

Wilson, R. M., and E. Hildner, On the association of magnetic clouds with disappearing filaments, *J. Geophys. Res.*, *91*, 5867, 1986.

Yan, M., and L. C. Lee, Interaction of interplanetary shocks and rotational discontinuities with the Earth's bow shock, *J. Geophys. Res.*, *101*, 4835, 1996.

Yang, G., and J. V. Hollweg, The effects of velocity shear on the resonance absorption of MHD surface waves: Cold plasma, *J. Geophys. Res.*, *96*, 13,807, 1991.

Zhang, G., and L. F. Burlaga, Magnetic clouds, geomagnetic disturbances, and cosmic ray decreases, *J. Geophys. Res.*, *93*, 2511, 1988.

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