Rapid evolution of magnetic decreases (MDs) and discontinuities in the solar wind: ACE and Cluster

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[1] An experiment was conducted to identify and measure the same magnetic decreases (MDs) and interplanetary discontinuities at two different points in space separated by ~0.01 AU along the radial distance from the sun. The ACE and Cluster satellite data were used in this study. Solar wind speeds measured at Cluster were used to calculate the approximate (earlier) times of arrival at ACE. The field component changes at both spacecraft were intercompared to ensure that the same discontinuities were detected. Out of 7 MDs/discontinuities selected, 6 were identified at ACE. The MDs/discontinuities were identified within 7 s to 35 s of the convection times. The MD thicknesses at Cluster were substantially smaller than at ACE. The ratio of thicknesses varied from 0.21 to 0.045. One possible interpretation of this observation is that the Alfvén wave front (rotational discontinuity) is steepening by a factor of greater than 15 per wavelength propagated. This may have important consequences for the generation of high frequency turbulence in interplanetary space. It is noted that the 6 discontinuities transited the ~0.01 AU distance from ACE to Cluster with essentially the solar wind convection speed. A possible mechanism contributing to this feature is discussed. **Citation:** Tsurutani, B. T., F. L. Guarnieri, G. S. Lakhina, and T. Hada (2005), Rapid evolution of magnetic decreases (MDs) and discontinuities in the solar wind: ACE and Cluster, *Geophys. Res. Lett.*, *32*, L10103, doi:10.1029/2004GL022151.

1. Introduction

[2] It has been shown that nonlinear, $\Delta\vec{B}/B_0 \sim 1$ to 2, Alfvén waves propagating in interplanetary space steepen in phase (see general discussion of cometary wave phase steepening by *Tsurutani et al.* [1997]), leading to discontinuities at the wave fronts [*Tsurutani et al.*, 1994]. Other phenomenon detected in interplanetary space are magnetic decreases, or MDs [*Tsurutani and Ho*, 1999]; these structures are also called magnetic holes [*Turner et al.*, 1977], as well as by other names. These are regions of decreased field intensities filled with hot plasma. MDs are pressure balance structures [*Winterhalter et al.*, 1994]. Protons within MDs are noted to be preferentially heated perpendicular to the ambient magnetic field [*Fränz et al.*, 2000; *Neugebauer et al.*, 2001]. *Tsurutani et al.* [2002a] have demonstrated that MDs are located at the phase-steepened edges of Alfvén waves and *Tsurutani et al.* [2002b] have suggested that MDs are created by a diamagnetic effect from the perpendicularly heated ions. *Dasgupta et al.* [2003] showed [see also *Lee and Parks*, 1983; *Li and Temerin*, 1993] that the Ponderomotive Force is a possible mechanism for the ion heating. Additional possible mechanisms are wave-wave interactions [*Vasquez and Hollweg*, 1999], evolution of nonlinear Alfvén waves [*Medvedev et al.*, 1997; *Buti et al.*, 2001] and beam microinstabilities [*Neugebauer et al.*, 2001].

[3] It is the purpose of this paper to examine the rate of evolution of MDs. The approach will use spacecraft measurements at two different points along the solar wind radial flow path: ACE orbiting the L1 libration point ~0.01 AU upstream of the Earth, and the Cluster spacecraft in Earth-orbit.

2. Method of Analyses

[4] Seven cases of MDs/discontinuities were selected from the catalog of Cluster discontinuities compiled by *Knetter et al.* [2004]. Mr. Knetter took particular care to avoid foreshock and other contamination problems to obtain clean interplanetary discontinuities. All seven of the selected events had long period Alfvén waves preceding the discontinuities and MDs with the discontinuities.

[5] We use the Cluster measured solar wind velocities at the time of the MDs/discontinuities (only one Cluster satellite measurement was used), and the distance between ACE and Cluster to estimate the solar wind propagation times. The ACE magnetometer data was analyzed at the appropriate times to attempt to identify the same MDs/discontinuities as those detected at Cluster. A search within ±10 min of the calculated convection time was made. The magnetic field components, their changes throughout the discontinuity and the field both before and after the event were used in the identification. We were able to identify 6 out of 7 of the Cluster MDs/discontinuities in the ACE data set.

3. Results

[6] Figure 1 shows a discontinuity (the long duration Alfvén wave preceding to the discontinuity is not shown) in the Cluster high resolution magnetic field data on day 50, 2001. Note that Figure 1 contains only 47.3 s of high resolution magnetometer data. The discontinuity was detected at all four Cluster spacecraft. The coordinate

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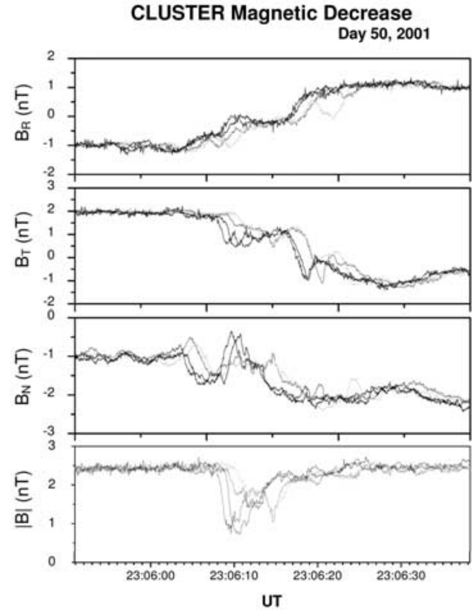

Figure 1. A Cluster discontinuity detected in the four Cluster spacecraft. The event occurred on day 50, 2001. A magnetic decrease (MD) is noted to occur simultaneously with the discontinuity. See color version of this figure in the HTML.

system is RTN, where $\hat{R}$ points away from the sun, $\hat{T} = \hat{\Omega} \times \hat{R}/|\hat{\Omega} \times \hat{R}|$, where $\hat{\Omega}$ is the north rotation pole, and $\hat{N}$ completes the right-hand system. The discontinuity begins at ~2306:03 UT and ends at approximately ~2306:27 UT (because of the asymptotic nature of the beginning and end of the discontinuity, these times are only approximate values). The discontinuity duration is ~24 s. Across the discontinuity, B_R changes from ~−1.0 nT to +1.1 nT, B_T from ~2.0 nT to ~−1.0 nT and B_N from ~−1.0 nT to −2.2 nT. There are some waves superposed on top of the discontinuity. Other than this, the discontinuity has the same form at all four spacecraft (at this time the maximum separation was ~500 km).

[7] There is a magnetic field magnitude decrease (MD) coincident with the discontinuity (bottom panel), but its rate of change with time is different from the field rotation of the discontinuity. Whereas the field components within the discontinuity change slowly with time and are more or less symmetric, the field magnitude changes are more asymmetric. The field magnitude decreases abruptly (particularly in two of the spacecraft) and recovers more gradually. The MD begins abruptly, slightly after the discontinuity begins (~2306:07–08 UT) and ends gradually with the discontinuity termination. The field magnitude rate of change is small from 2306:16 to 2306:27 UT. The field magnitude is ~2.5 nT before and after the MD/discontinuity with a minimum value of ~ 1.0 nT at the peak decrease.

[8] It has been noted both here and in previous studies (T. Knetter, personal communication, 2003) that discontinuities and MDs typically begin and end at about the same time. Because the MDs are defined only by their field magnitudes, they are easier to identify. Here we will use the $1/e$ value of the pre-event field magnitude to minimum value and the 1/e value of the post-event field magnitude to the minimum value to define the MD onsets and ends, respectively. The difference between the onset and termination times give the MD durations (since the solar wind speeds were relatively constant, the durations can be easily converted to thicknesses). For the MD in Figure 1, the onset time is 2306:11 UT and the end time is 2306:17 UT. Thus the duration is ~6s.

[9] Figure 2 shows what we have identified as the same discontinuity/MD at ACE. As previously mentioned, Cluster solar wind velocity measurements were used to estimate the time of passage of the discontinuity/MD at ACE, assuming only solar wind convection. Secondly the change in the magnetic field components were compared with those at Cluster. If both the approximate time of occurrence and the field components matched, then we believed that we had identified the same discontinuity at an earlier time.

[10] The ACE B_R component varies from ~−0.5 nT to 2.0 nT. The B_T component varies from ~2.5 nT to ~−0.8 nT, and B_N varies from ~−1.2 nT to ~−2.3 nT across the MD. This compares quite well to the discontinuity variations at Cluster, giving confidence that the same discontinuity had been identified. The field magnitude varies from ~2.8 nT before the discontinuity to ~3.1 nT after the event. This is somewhat different from the ~2.5 nT values before and after the MD noted at Cluster.

[11] The discontinuity at ACE is smoothest in the B_T component. It begins at ~2155:33 UT and ends at ~2156:16 UT. The full discontinuity thickness is thus ~43 s. The MD $1/e$ beginning and end are ~2155:43 UT and 2156:16 UT, or a duration of ~33 s. Note that the $1/e$ MD duration at Cluster is a factor of ~0.18 (6 s/33 s) that of ACE while the discontinuity thickness ratio is a factor of ~0.56 (24 s/43 s).

[12] In Figure 2, it can be noted that the minimum magnetic field magnitude within the MD is ~2.2 nT. At

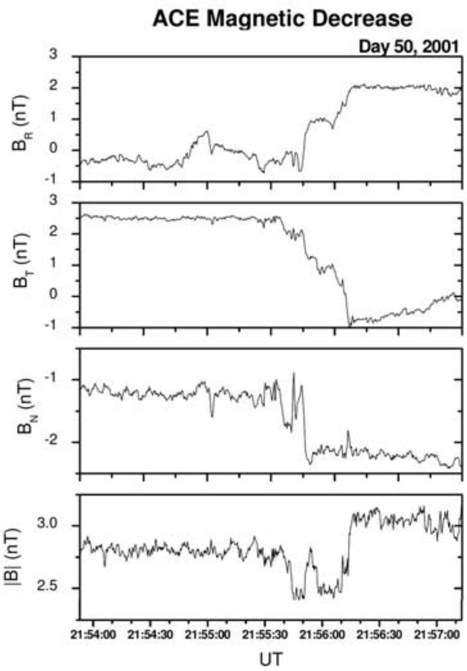

Figure 2. The same discontinuity/MD at ACE, as found at Cluster in Figure 1.

Table 1. MD Predicted Times and Detection Times at ACE

Year 2001		ACE Location (GSE, R_E)			Cluster Location (GSE, R_E)							
DOY	Date	X	Y	Z	X	Y	Z	Measured Cluster MD (UT)	Measured Vx (km/s)	Calculated Delay Time (ACE - Cluster)	Predicted ACE MD (UT)	Measured ACE MD (UT)
34 (33)	02/03 (02)	240.04	−18.22	24.50	14.23	9.66	6.61	00:27:30	−366.2	63:34	23:23:56	N/A
43	02/12	237.69	−28.87	22.59	17.09	6.91	5.16	15:58:43	−413.2	56:30	15:02:13	15:02:05
50	02/19	236.25	−34.90	19.12	18.92	4.03	3.21	23:06:14	−286.5	70:44	21:55:30	21:55:57
51 (a)	02/20	235.97	−35.43	18.50	17.36	0.94	−3.39	11:18:27	−305.6	73:11	10:05:16	10:05:51
51 (b)	02/20	235.97	−35.43	18.50	17.29	0.89	−3.47	11:28:12	−305.3	75:21	10:13:51	10:14:09
77 (76)	03/18 (17)	226.15	−35.76	−1.65	18.24	−4.00	4.48	00:29:14	−317.7	70:27	23:18:47	23:18:17
77	03/18	226.15	−35.76	−1.65	16.23	−6.84	−3.34	15:02:02	−320.6	69:33	13:52:29	13:52:22

Cluster, the minimum was much lower, ~1.0 nT. The amount of field magnitude decrease from the ambient was ~0.6 nT at ACE and ~1.5 nT at Cluster. Thus the MD decrease at Cluster is deeper and narrower than that at ACE.

[13] The seven discontinuities/MDs at Cluster are listed in Table 1. From left-to-right the columns are: the day of year, the date (the figures contain only the DOY), the ACE location in GSE coordinates, the Cluster location in GSE coordinates, the time of the MD at Cluster, the measured x-component of the solar wind velocity, the calculated transit time from ACE to Cluster, the MD arrival time at ACE assuming solar wind convection alone, and the measured MD detection time at ACE. In the next-to-last event, the Cluster day 77 event was detected on day 76 at ACE, thus the notation on the DOY and date.

[14] There are several notable features in Table 1. All seven events occurred in slow speed solar wind streams with the maximum speed of the events only 413 km/s. An important result can be found in a comparison between the last two columns. The MD arrival times assuming convection alone and the measured arrival times (at ACE) are extremely close to each other. For the day 50 event illustrated in Figures 1 and 2, the time difference is only 27 s out of a total transit time of 71 min 11 s. For the other five events where MDs were identified at ACE, the difference between the convection times and actual times varied from a minimum of 7 s (day 77) to a maximum of 35 s (day 51, event a).

[15] Table 2 summarizes the properties of the 6 events detected at both ACE and Cluster. From left-to-right the columns are: the event day, the maximum magnetic field magnitude decrease (from the ambient value) at Cluster, the maximum magnetic field magnitude decrease at ACE, and the MD duration at Cluster and at ACE. The decrease in magnetic field magnitude at Cluster is often, but not always, greater than that at ACE. A particularly large decrease occurred on day 77 (76). The decrease duration relationship between Cluster and ACE is far more clear. In all six cases, the MD durations at Cluster were smaller than at ACE. The ratio of MD durations at Cluster to those at ACE varied from 0.21 to 0.045.

4. Conclusions and Speculation

[16] We have been able to identify the same discontinuities/MDs at ACE that were detected at Cluster in six out of seven times. The difference between the "predicted" (using Cluster solar wind speeds) and measured times were only 7 to 35 s in total durations of 56 to 75 min. Thus it seems clear that MDs are almost purely convected solar wind structures. This would be expected if they were diamagnetic cavities formed by local perpendicular heating of the solar wind plasma.

[17] In all six cases, the duration of the MDs were considerably smaller at Cluster than at ACE. One possible interpretation of this result is that the Alfvén wave phase-steepened fronts are becoming sharper with time (and with solar wind convection). To get an approximate value for this rate, we make the following (arbitrary) assumptions: 1) the Alfvén wavelength is half the distance between the two spacecraft or ~0.005 AU. This will give a temporal scale of ~30 min in either spacecraft frame. 2) The Alfvén phase speed is typically 50 km/s. This relatively low value is used since these events occur in somewhat high density plasmas (slow solar wind). 3) The transit time from ACE to Cluster is ~70 min. 4) The steepening factor is ~5 times (a conservative value). Putting these values together implies that Alfvén wave phase fronts have steepened a factor of ~5 while the wave has traveled only ~0.28 λ in the plasma frame. Thus the wave phase front steepens by a factor of ~15 during propagation of one wavelength.

[18] One might question why the discontinuities and MDs stay together during their propagation from ACE to Cluster? Oblique wave propagation is perhaps one factor. However there is another feature, the nonlinear interaction between the discontinuity/Alfvén wave and the MD. A simple calculation will serve to illustrate this point. If the plasma β (the ratio of the plasma pressure to the magnetic pressure) outside the MD is ~2 and the magnetic field inside the MD is half that of the outside value, then the β value inside the MD is 11. Assuming equal temperatures inside and outside the MD, the Alfvén wave phase speed would thus be ~0.3 the value outside the MD, or ~15 km/s, a very low value. For larger magnetic field decreases, the wave phase speed will be even lower. The minimum magnetic field within the MD is the most important value. The very low wave phase speed at this point will not allow the wave/discontinuity to propagate easily through the MD.

Table 2. MD Properties at Cluster and at ACE

	Magnetic Field Decrease (nT)		Decrease Duration (s)	
DOY, 2001	Cluster	ACE	Cluster	ACE
43	~2.8	~2.8	~8	~35
50	~1.5	~0.6	~6	~33
51 (a)	~1.7	~1.5	~2.6	~13
51 (b)	~2.6	~2.0	~3.3	~48
77 (76)	~4.6	~0.9	~0.8	~16
77	~1.2	~2.6	~8.3	~46

[19] Of course the above wave-MD interaction is only a first order effect. New (perpendicularly) heated plasma will be continuously created at the phase steepened edge of the Alfven wave, and the wave will be propagating through this new plasma. Numerical simulations are needed to better understand this complex nonlinear and dynamic interaction.

[20] Finally it should be noted that wherever MDs are a prominent feature in a plasma, care should be taken in interpretation of the magnetic field power spectrum. These nonpropagating features should not be interpreted as waves nor as wave power.

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