Relationship between discontinuities, magnetic holes, magnetic decreases, and nonlinear Alfvén waves: Ulysses observations over the solar poles

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[1] Ulysses magnetic field data are used to study magnetic field microstructure over the solar poles. Magnetic holes (MHs) and magnetic decreases (MDs) are found to be located at the phase-steepened edges of nonlinear Alfvén waves. The phase-steepened edges (directional discontinuities) occur in time-coincidence with MHs, one edge of an MD, or throughout the whole MD. These MH- and MD-related discontinuities have both rotational and compressive properties, perhaps explaining why many directional discontinuities detected in interplanetary space have non-MHD properties. The dispersive, dissipative and compressive features of nonlinear Alfvén waves may be important for the heating of the solar corona. *INDEX TERMS:* 2109 Interplanetary Physics: Discontinuities; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2134 Interplanetary Physics: Interplanetary magnetic fields; 2149 Interplanetary Physics: MHD waves and turbulence

1. Introduction

[2] Magnetic holes (MHs), small scale depressions in the magnetic field magnitude, were first detected in the ecliptic plane [*Turner et al.*, 1977], and have been shown to also exist at heliographic latitudes up to 80° [*Winterhalter et al.*, 2000]. Magnetic decreases (MDs), large scale field depressions bounded by directional discontinuities (DDs) on one or both sides, have been identified at high heliographic latitudes by Ulysses measurements [*Tsurutani and Ho*, 1999; *Tsurutani et al.*, 1999]. It is somewhat controversial as to how MHs and MDs are formed, and what the relationship between the two phenomena might be. Previously published suggestions for their formation are: mirror mode instabilities (only for "linear" holes) [*Winterhalter et al.*, 1994, 2000], Alfvén solitons [*Baumgärtel*, 1999], slow mode shocks [*Farrugia et al.*, 2001], and nonlinear Alfvén wave evolution [*Medvedev et al.*, 1997; *Buti et al.*, 2001].

[3] It is the purpose of this paper to first examine the relationship between MHs, as defined in *Winterhalter et al.* [1994], and MDs as defined in *Tsurutani et al.* [1999]. This intercomparison has not been previously done. For this part of the study, 9 days over the south polar region (days 242–250, 1994), and 9 days over the north polar region (days 208–216, 1995) will be analyzed and intercompared. A second purpose of this paper is to explore the relationship between DDs, MHs, MDs, and Alfvén waves.

2. Method of Analyses

[4] The Ulysses magnetometer and first magnetic field results are described in *Balogh et al.* [1992]. MHs are computer selected by the *Winterhalter et al.* [1994] criterion applied to 1-s magnetic field data. The selection criterion requires that $\left[\Delta\left|\vec{B}\right|/B_0 \geq 0.5\right.$ and the maximum scale size considered is 15 min. MD selection follows the *Tsurutani et al.* [1999] criteria. Directional discontinuities (DDs) are first identified by the *Tsurutani and Smith* [1979] computerized method applied to 1-min average magnetic field data. MDs adjacent to the DDs are identified by hand analyses of 1-s resolution magnetic field data. One requirement of a MD is that $\Delta|B|/B_0 \geq 0.2$. There is no upper limit to the scale size of the MDs.

[5] To determine the properties of the DDs, minimum variance analyses are applied to 1-s resolution magnetic field data. The magnetic field component along the discontinuity normal (B_n) is then determined. Other values such as B_L, the larger field magnitude on either side of the discontinuity and $\Delta|B|$, the change in field magnitude across the discontinuity are measured by hand analyses. We follow the *Smith* [1973] method to determine if the discontinuities are rotational or tangential in nature.

3. Results

[6] The statistical results of the MH/MD intercomparison for the north and south polar intervals is shown in Table 1. For the north polar interval, there were 181 MHs and 104 MDs detected, and for the south polar interval there were 98 MHs and 41 MDs detected. Thus, there were approximately twice the amount of MHs detected as MDs detected for both polar regions. It was also noted (not shown) that MHs sometimes occurred in clusters, perhaps contributing to their higher rate of occurrence. There are approximately twice the amount of MHs and MDs detected over the north pole as over the south pole. At this time it is unclear whether the occurrence rate difference is simply a true north-south asymmetry or a function of time variability over the solar cycle (the north polar pass occurred ~1 year after the south polar pass). Further analyses are needed to give better insight into this issue.

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Table 1. Total number of MHs, MDs, and both for the 9-day intervals near the north and south solar poles. The median time durations for MHs and MDs are indicated in parentheses.

Region	Year	Days	MHs	MDs	Both
North Pole	1995	208–216	181 (59 s)	104 (130 s)	16
South Pole	1994	242–250	98 (69 s)	41 (154 s)	13

[7] Another feature to note in Table 1 is that there are very few cases (~5 to 10%) where both MHs and MDs are identified at the same time (16 and 13 cases in the north and south polar intervals, respectively). Inspection has shown that MHs were often small scale events, whereas MDs were typically (but not exclusively) larger in scale. This can also be noted by the mean durations of MHs and MDs given in the table. MDs are typically double the scale of MHs. It has been found that this feature is caused by the selection criteria. The discontinuity program used for MD identification typically misses features that are smaller than 1 min wide.

[8] The relationship between DDs, MHs, MDs, and Alfvén waves over the polar region is shown in Figure 1. Three consecutive cycles of an Alfvén wave can be noted in the figure. The nonlinear, nonsinusoidal waves can be best detected in the top panel, labelled B_1. The field coordinate system corresponds to the eigenvector directions of the covariance matrix, with B_1, B_2, and B_3 corresponding to the field components along the maximum, intermediate, and minimum eigenvector directions. The three wave cycles are from 0402:00 to 0410:05 UT, 0410:05 to 0424:30 UT, and 0424:30 to 0433:30 UT. A MH was detected at the end of the first wave (~0410:05 UT), a MD at the end of the second wave (~0423:45 to 0424:30 UT), and a MH/MD (both) was detected at the end of the third wave (MH at ~0432:30 UT and MD at ~0432:30 to 0433:30 UT).

[9] Each of the three waves were individually examined using minimum variance analyses and the results are noted at the top. The values λ_1, λ_2, and λ_3 correspond to the maximum, intermediate, and minimum eigenvalues of the covariance matrix, and θ_{nB} corresponds to the angle between the discontinuity normal direction $\hat{n}$ and the ambient magnetic field direction, $\vec{B}_0$. The θ_{nB}

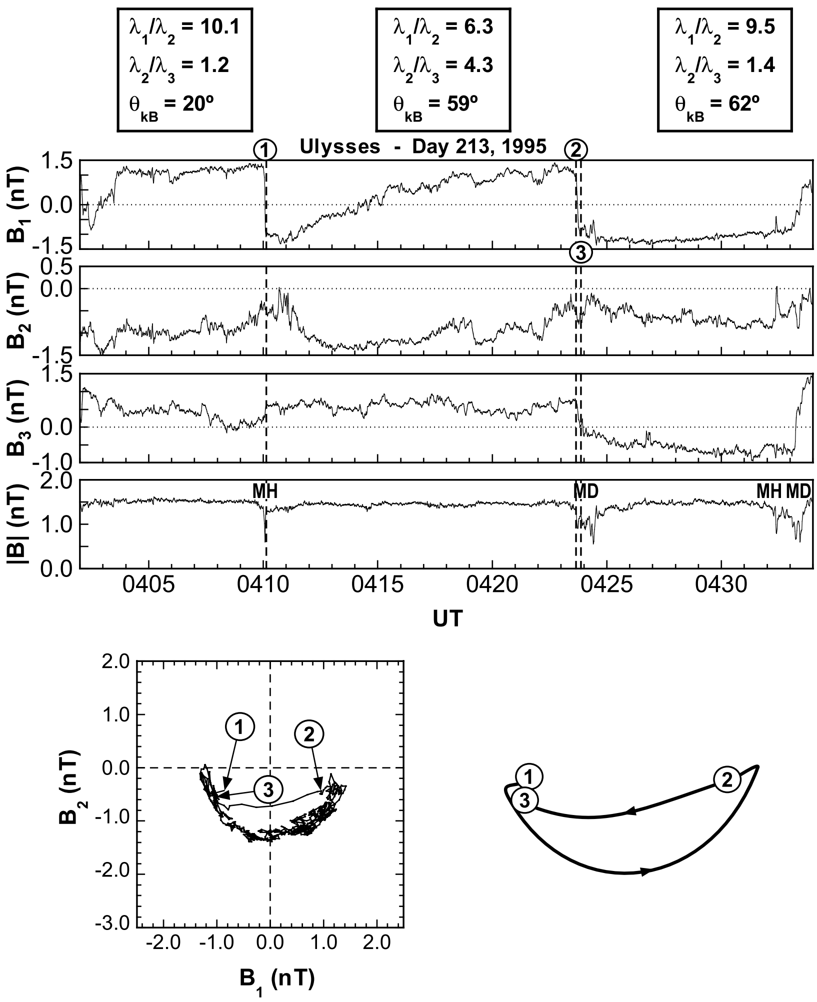

Figure 1. DDs, MHs, and MDs at the edges of three Alfvén waves on day 231, 1995. B_1, B_2, and B_3 are the field components in maximum, intermediate, and minimum variance directions, respectively. The three wave properties are shown in the boxes at the top. The hodogram for the middle wave is shown at the bottom.

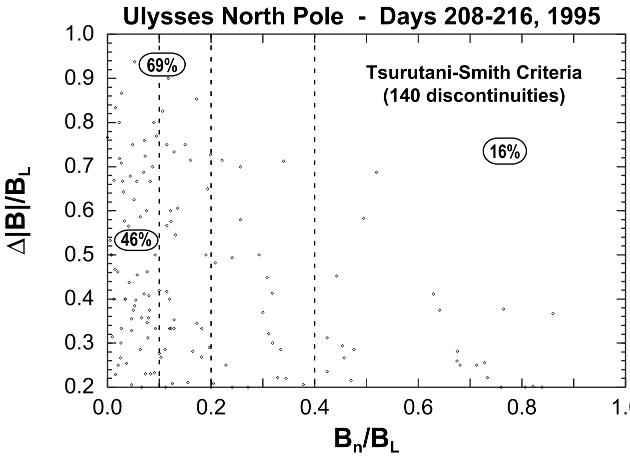

Figure 2. DD properties at the edges of MDs for the north polar pass interval. B_n is the field component along the discontinuity normal, $\Delta|B|$ is the field magnitude change across the discontinuity, and B_L is the larger field magnitude on either side of the discontinuity.

value increases throughout the Alfvén wave sequence from 20° to 59° to 62°.

[10] For the first Alfvén wave, the field dip at ∼0410:05 UT is a "classic" MH. There is a sharp field magnitude decrease from 1.3 to 0.6 nT, then an increase to 1.3 nT. The MH is time coincident with the sharp discontinuity in the magnetic field shown in the B_1 panel. From the B_1 component, it can be noted that the field direction changes substantially, thus it is not a "linear" hole. Also, because the hole is much smaller than 1 min wide, no directional discontinuity is identified by the *Tsurutani and Smith* [1979] discontinuity selection program.

[11] The hodogram from the middle wave is shown in the inset. A hand-drawn "smoothed" curve is shown at the bottom right to guide the reader. The slow rotation portion of the Alfvén wave occurs from points 1 to 2. There is a sharp discontinuity between points 2 and 3. This latter portion is the phase-steepened edge of the Alfvén wave [*Tsurutani et al.*, 1994]. The whole wave has an arc polarization [*Lichtenstein and Sonett*, 1980; *Riley et al.*, 1996; *Vasqez and Hollweg*, 1996; *Medvedev et al.*, 1997; *Del Zanna*, 2001]. The discontinuity at the edge of the Alfvén wave has the following properties: $\lambda_1/\lambda_2 = 93$, $\lambda_2/\lambda_3 = 8.0$, $\Delta|B|/B_L = 0.33$, and $\theta_{nB} = 83°$. Note that the edge of the Alfvén wave at ∼0423:45 UT is the trailing (sunward) edge of the MD for this case. Another discontinuity bounds the other edge of the MD at ∼0424:30 UT. For this DD, $\lambda_1/\lambda_2 = 5.8$, $\lambda_2/\lambda_3 = 4.5$, $\Delta|B|/B_L = 0.5$, and $\theta_{nB} = 88°$.

[12] The third Alfvén wave occurs between ∼0424:30 and ∼0433:30 UT. The MH at ∼0432:30 UT occurs prior to the sharp field rotation (in B_1) from ∼0433:00 to ∼0433:30 UT. In this case the rotation occurs at the antisunward edge of the MD (the MD is from 0432:30 to 0434:30 UT). The properties of this rotation are $\lambda_1/\lambda_2 = 6.8$, $\lambda_2/\lambda_3 = 73$, $\Delta|B|/B_L = 0.47$, and $\theta_{nB} = 87°$.

[13] Figure 2 shows the properties of discontinuities at the edges of MDs for the north polar pass interval. The parameters B_N, B_L, and $\Delta|B|$ were described previously. Two features can be noted in the figure. Many of the discontinuities have small (but nonzero) normal values ($B_n/B_L \leq 0.2$) and large magnitude changes ($\Delta|\vec{B}|/B_L \geq 0.2$, by definition). Past works [*Smith*, 1973; *Neugebauer et al.*, 1984] have identified these as tangential discontinuities. There are other discontinuities detected here with large normal values ($B_n/B_L \geq 0.4$) and large field magnitude changes ($\Delta|B|/B_L \geq 0.2$). Sixteen percent of all discontinuities shown here are of this type. Shocks (fast, intermediate, and slow) may have such jump conditions. For one case, *Farrugia et al.* [2001] have argued for the presence of a slow shock bounding an MD. Clearly more effort is needed in this area.

4. Discussion

[14] The results presented here indicate that MHs and MDs are parts of nonlinear Alfvén waves. Recent simulation results by *Buti et al.* [2001] have shown that nonlinear right-hand polarized waves propagating at large angles to the ambient magnetic field (∼75°) will form complex features at their leading edges. The structures are quite similar to MHs. With longer computational runs, it is found that the MH-like structures broaden to form structures similar to MDs. Thus, one possible interpretation of Figure 1 is that MHs and MDs are time evolutionary parts of nonlinearly steepened Alfvén waves.

4.1. Ideal MHD Discontinuities?

[15] It has been a long standing puzzle why interplanetary discontinuities are not all "ideal" MHD structures (see *Neugebauer et al.* [1984]). Ideal rotational discontinuities (RDs) should have normal components that are constant across the structure with little or no magnetic field magnitude changes. Ideal MHD tangential discontinuities (TDs) are those that have little or no normal components.

[16] Figure 2 shows that 54% of the discontinuities studied have $B_n/B_L > 0.1$ and $\Delta|B|/B_L > 0.2$. Thus, these discontinuities have both large magnetic components along the discontinuity normal and also large field magnitude changes across their structures. These discontinuities have both a rotational and tangential nature. If the majority of directional discontinuities detected in interplanetary space are associated with phase-steepened nonlinear Alfvén waves such as those in Figure 1, this could explain why MHD jump conditions are often not satisfied. Of course, other discontinuities associated with small amplitude waves or with the heliospheric current sheet may well have ideal MHD properties.

5. Final Comments

[17] Particle scattering by the MD portions of the nonlinear Alfvén waves has been previously discussed in *Tsurutani et al.* [1999]. The important point is that wave-particle interactions involve not only pitch angle scattering, but cross-field diffusion as well (due to the interaction with MDs). Classical wave-particle interaction theories that consider only linear waves will not address the latter effects associated with the compressive portion of the waves.

[18] These present Ulysses results imply that Alfvén waves are both dispersive (phase-steepening) and dissipative (compressibility). How rapidly the wave energy dissipates and into what form (plasma waves, plasma heating, etc.) are unknown at this time. Such wave energy dissipation may be important for the heating of the solar corona and acceleration of the solar wind. Near-Sun observations from missions like the Solar Probe should be able to determine what contribution such Alfvén waves may make in this process.

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References

Balogh, A., T. J. Beek, and R. J. Forsyth, et al., The magnetic field investigation on the Ulysses mission: Instrumentation and preliminary scientific results, *Astron. Astro. Suppl. Ser.*, *92*, 221–236, 1992.

Baumgärtel, K., Soliton approach to magnetic holes, *J. Geophys. Res.*, *104*, 28,295–28,308, 1999.

Buti, B., B. T. Tsurutani, M. Neugebauer, and B. E. Goldstein, Generation mechanism for magnetic holes in the solar wind, *Geophys. Res. Lett.*, *28*, 1355–1358, 2001.

Del Zanna, L., Parametric decay of oblique arc-polarized Alfvén waves, *Geophys. Res. Lett.*, *28*, 2585–2588, 2001.

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

Lichtenstein, B. R., and C. P. Sonett, Dynamic magnetic structure of large amplitude Alfvénic variations in the solar wind, *Geophys. Res. Lett.*, *7*, 189–192, 1980.

Medvedev, M. V., V. I. Shevchenko, P. H. Diamond, and V. L. Galinsky, Fluid models for kinetic effects on coherent nonlinear Alfvén waves, II. Numerical solutions, *Plas. Phys.*, *4*, 1257–1285, 1997.

Neugebauer, M., D. R. Clay, and B. E. Goldstein, et al., A re-examination of rotational and tangential discontinuities in the solar wind, *J. Geophys. Res.*, *89*, 5395, 1984.

Riley, P., C. P. Sonett, and B. T. Tsurutani, et al., Properties of arc-polarized Alfvén waves in the ecliptic plane: Ulysses observations, *J. Geophys. Res.*, *101*, 19,987–19,993, 1996.

Smith, E. J., Identification of interplanetary tangential discontinuities, *J. Geophys. Res.*, *78*, 2054, 1973.

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.

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

Tsurutani, B. T., C. M. Ho, and E. J. Smith, et al., The relationship between interplanetary discontinuities and Alfvén waves: Ulysses observations, *Geophys. Res. Lett.*, *21*, 2267–2270, 1994.

Tsurutani, B. T., G. S. Lakhina, and D. Winterhalter, et al., Energetic particle cross-field diffusion: Interaction with magnetic decreases (MDs), *Nonlin. Proc. Geophys.*, *6*, 235–242, 1999.

Turner, J. M., L. F. Burlaga, N. F. Ness, and J. F. Lemaire, Magnetic holes in the solar wind, *J. Geophys. Res.*, *82*, 1921, 1977.

Vasqez, B. J., and J. V. Hollweg, Formation of arc-shaped Alfvén waves and rotational discontinuities from oblique linearly polarized wave trains, *J. Geophys. Res.*, *101*, 13,527–13,540, 1996.

Winterhalter, D., M. Neugebauer, and B. E. Goldstein, et al., Ulysses field and plasma observations of magnetic holes in the solar wind and their relation to mirror-mode structures, *J. Geophys. Res.*, *99*, 23,371–23,381, 1994.

Winterhalter, D., E. J. Smith, and M. Neugebauer, et al., The latitudinal distribution of solar wind magnetic holes, *Geophys. Res. Lett.*, *27*, 1615–1618, 2000.

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