The Relationship Between Interplanetary Discontinuities and Alfvén Waves: Ulysses Observations

by

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ABSTRACT

The rate of occurrence of interplanetary discontinuities (ROID) is examined using Ulysses magnetic field and plasma data from 1 to 5 AU radial distance. from the Sun and at high heliospheric latitudes. It is found that there are two regions in interplanetary space where the ROID is high: in stream-stream interaction regions and in Alfvén wave trains. This latter feature is particularly obvious at high heliographic latitudes when Ulysses enters a high speed stream associated with a polar coronal hole. These streams arc characterized by the presence of continuous, large-amplitude ($\Delta\vec{B} / |B|$ -1-- 2) Alfvén waves and an extraordinarily high ROID value (- 150 discontinuities/day). In a number of intervals examined, it is found that (rotational) discontinuities arc an integral part of the Alfvén wave: they represent - 90° phase rotation of the wave out of the full 360° rotation of the wave. These large amplitude nonlinear Alfvén waves thus appear to be phase steepened.

The nonlinear Al fvén waves arc spherical] y polarized, i.e., the tip of the perturbat ion vector resides on the surface of a sphere (a consequence of constant |B|). Analyzing the slowly rotating part of the wave (- 270" phase rotation), there is a slight arc in the B_1 - B_2 hodogram, suggesting an almost linear polarization. The rotation associated with the steepened edge of the wave (the discontinuity) completes the 360" phase rotation and thus is an i nt egral part of the Alfvén wave. The best description of these waves and discontinuities is a "spherical arc polarization".

INTRODUCTION

The rate of occurrence of interplanetary discontinuities (ROID) is highly variable (Burlaga, 197 1). Variations in the number of discontinuities per day can increase or decrease by factors of 10 or more from one day to the next. At present, this variability is not wc]] understood.

Both the temporal and radial distance variations of discontinuity occurrence rates were previously studied using a two-spacecraft (Pioneers 10 and 11) technique (Tsurutani and Smith, 1979, hereafter referred to as '1'S). The two (radially-aligned) spacecraft measurements were used to remove the temporal variations. It was found that there was an apparent decrease in the ROID with radial distance from the sun, a decrease that was interpreted as a simple thickening of the discontinuities with decreasing ambient magnetic field strength. Because TS (1979) used identification criteria that depended on the thickness of discontinuities for all distances between 1 and 5 AU, at larger distances where the field was weaker, some of the thicker discontinuities fell outside o! detection. An empirical relationship to normalize the rate of occurrence to 1 AU was derived, e⁻(r-1)/4, where r is in units of AU from the sun.

The purpose of this note is to examine the ROID as a function of solar wind stream structures, as Ulysses first travels from 1 to 5 AU and then as the spacecraft travels to high heliospheric latitudes. A second objective of the note is to examine and discuss the detailed relationship between discontinuities and Alfvén waves, particularly (hose occurring in the trailing portions of high-speed streams.

Discontinuity Selection Criteria

Discontinuities are identified by sharp changes in the direction and/or magnitude of the interplanetary magnetic field. The criteria for a "sharp" change and how much of a change, is, of course, arbitrary. TS (1979) have used $|\Delta\vec{B}|/|B| \geq 0.5$ and $|\Delta\vec{B}| \geq 2\delta$ where the value δ is the field variance on either side of the discontinuity. $\Delta\vec{B}$ is the change in one minute average vectors separated by 3 minutes. Lepping and Behannon (1986, hereafter referred to as LB) have used a criteria that the field change direction by at least 30° within one minute. The expression for the angular change is $\theta = \cos^{-1} \vec{B}_1 \cdot \vec{B}_2 / |B_1||B_2| \geq 30°$ where $\vec{B}_1$ and $\vec{B}_2$ are the upstream and downstream magnetic field vectors, respectively. There are slight differences in the above two discontinuity selection criteria, and there are thus some differences in the rates of occurrence. The "TS criteria is less stringent and therefore it gives a greater rate of occurrence. Values deduced from both criteria will be shown. Both will be normalized to 1 AU by the $e^{-(r-1)/4}$ factor.

RESULTS

Figure 1 illustrates scatter plots of the normalized number of discontinuities per day (vertical scale) versus the daily average of the magnetic field magnitude (left panel) and of the solar wind velocity (right-panel). The triangles are the ROID values using the TS criteria and the circles the ROID values using the LB criteria. The scatter plots represent data analyzed from July 1-30, 1992 when Ulysses was at 5.2 AU at - 15.00 heliographic latitude. There is no obvious ROID dependence on either solar wind velocity or magnetic field magnitude for either selection criteria. Simi lar scatter plots have been constructed for discontinuity ies at 1 AU and 3 AU, with essentially the same results.

Figure 2 illustrates the day-to-day ROID variation for this month-long interval, in July of 1992. The top two panels are the hourly averages of the solar wind velocity and the density. Below are the 3 components and magnitude of the interplanetary magnetic field in Solar Heliospheric (SH) coordinates. In this system, X is directed radially outward from the sun, Y is $\hat{\Omega} \times \hat{X} / |\hat{\Omega} \times \hat{X}|$, where $\hat{\Omega}$ is the solar rotation axis, and $\hat{Z}$ completes the right-hand system). The bottom two panels are the number of discontinuities per day using the TS and the LB criteria. Data gaps were take into account in determining these normalized values.

There are several noteworthy features found in the Figure. First, high ROID values occur at sti-cam-stream interaction regions. Examples can be noted in July 3-6 and 20, and to a lesser extent in July 15. However, the highest ROID values for this interval occur from Jul y 24-3 1, in the trailing portion of a high speed stream. This region is characterized by large directional changes in the field with time scales of 10 min. to days. These fluctuations have been examined and are found to be Alfvén waves (discussed later). The ROID value reaches -150 discontinuities/day (normalized) and remains at this constant value as the amplitude of the Al fvén waves decreases.

From 16-19 July, the ROID value is exceptionably low, essentially zero/day. This interval contains a magnetic cloud (Klein and Burlaga, 1982), a region where there are few Alfvén waves or discontinuities (Zwickl et al. , 1983; Tsurutani et al., 1988, Neugebauer and Alexander, 1991; Tsurutani and Gonzalez, 1 993). This region has been identified by its magnetic field properties.

Figure 3 has the same format as Figure 2, but at - 3'1° latitude in September of 1993. Here Ulysses is above the heliospheric current sheet (Smith et al., 1993), and is in a continuous high speed stream associated with a polar coronal hole (Phillips et al., 1994). The velocity of -- 800 km/s is relatively constant. The region is characterized by continuous, large amplitude, $\Delta\vec{B} / |B|$ -1 — 2, transverse waves. Comparison of $\Delta\vec{B}$ to $\Delta\vec{V}$ indicates that these are Alfvén waves propagating radiall y outward from the sun (not shown to conserve space). The normalized discontinuity occurrence rate is almost continuously high, -100-200 for the 'I'S criteria and ~ 75-150 for the LB criteria. These values are 2-3 times the ROID value typically detected in the ecliptic plane.

'1'able I shows the ROII) values at three different heliocentric distances and latitudes. It is clear that there is a latitude dependence which presumably is due (o the fraction of the time [hat Ulysses spends within coronal hole high speed streams.

Figure 4 shows onc minute averages of the interplanetary magnetic field data in S11 coordinates for January 17, 1992. Ulysses is at a radial distance of 5.2 AU and a latitude of 1°. The discontinuities detected using the "1'S criteria arc indicated by vertical lines.

To examine the relationship between Alfvén waves and discontinuities, wc examine the interval 0519 to 0614 UT, day 17, 1992. By examining the cross-correlation between V_x and B_x and V_y and BY, we find that this and neighboring intervals consist of Alfvén waves propagating away from the sun (- 0.6 correlation coefficient at zero lag).

Wc have divided the above interval into two parts: from 0519 to 0610 UT, where the field changes slowly due to the wave and from 0610 to 0614 UT where there is a discontinuity (identified by both the TS and the LB methods). The entire interval is also examined. The field in SH coordinates is shown in Figure 4, with the vertical lines giving the TS discontinuity times.

The B_1 - B_2 hodograms for the interval 0519-0614 and the two sub-intervals arc shown in Figure 5, B_1 corresponds to the field component in the direction of maximum variance, B_2 the field in the direction of intermediate variance and B_3 the minimum variance direction (Sonnerup and Cahill, 1967; Smith and Tsurutani, 1976). The hodogram for the slow rotation is shown on the bottom left, and the discontinuity on the bottom right and the whole interval on the top, As can be noted from Figure 4, the field magnitude is almost totally constant throughout the interval. The slowly rotating part of the Alfvén wave is therefore a spherical wave (the Perturbation vector rotates on the surface of a sphere, a consequence Of a constant B magnitude). The hodogram indicates that this portion of the wave has an arc-like profile. It consists of a phase rotation of - 270°. The perturbation vector rotates across tbc arc and the partially back. The discontinuity (found to be rotational) also has an arc-like polarization. The - 90° phase rotation of the discontinuity completes the 360" phase rotation. The (total) perturbation vector sequence dots not complete a symmetric ellipse, but is more like the tip of a windshield wiper. It rotates across and back. This can be seen in the hodogram of the whole interval.

We have examined the relationship between discontinuities and Alfvén waves for other intervals. We find that discontinuities occur at the edges of Alfvén waves between - 35% and - 65% of the time, depending 011 the level of interplanetary activity, At this time a couple dozen events have been examined in detail using principal axis techniques. We find the above Alfvén wave/discontinuity arc polarizations arc typical.

CONCLUSIONS AND DISCUSSION

We have shown the ROID value is highest where there arc Alfvén waves present. This is most obvious at high heliographic latitudes where high speed streams emanate from coronal holes. These streams arc dominated by Alfvén waves. We verify that there is, in general, a lack of correlation between ROID values and V_{SW} and |B|. This is because there arc interplanetary intervals with high V_{sw} and |B|, which are devoid of both Alfvén waves and discontinuities (magnetic clouds) and also intervals of moderate V_{SW} and low |B| where discontinuities are abundant (trailing portions of high speed streams). There arc, of course, also intervals where the ROID, V_{sw} and |B| values arc all high, e.g., stream-stream interaction regions and the beginning part of high speed streams. Taking all four regions together, one can now understand why a correlation between the ROIDs, V_{sw} and |B| dots not exist.

We have examined a number of cases of the detailed relationship between Alfvén waves and discontinuities. In this study wc have limited our examination to Alfvén wave train intervals only. In Figure 5, wc have shown one such example. in this particular case, wc find that the (discontinuity is actually part of the Alfvén wave, comprising approximately - 90" or less of the phase rotation of the total wave (3600). l'bus, this large amplitude, $\Delta\vec{B}/|B|$ -1-2 nonli near Alfvén wave appears to be phase- steepened, with the rotational discontinuity y being the steepened edge (at this time wc do not know whether the discontinuities occur at the leading or trailing edges). From our initial examination of the data, wc cannot tell if this is a stable configuration or not. Computer simulation results and theoretical arguments arc somewhat mixed on the topic as well. This will remain as a topic of future research.

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I'able 1, The ROID for Three Different Heliocentric Distances and Latitudes

FIGURE CAPTIONS

Fig. 1 The lack of correlation between the rate of occurrence of discontinuities and field magnitude (l It, left panel) and solar wind velocity (right panel). Scatter plots have been produced for one month of data at 1, 3 and 5 AU. We only show the 5 AU data. The other results arc similar.

Fig. 2 The relationship between the IMF stream structures and the rate of occurrence of discontinuities at 5.2 AU. Discontinuities occur most frequently where larger amplitude transverse fluctuations (Alfvén waves) are present (see B_Z panel). These waves are present primarily in two regions: stream-stream interaction regions (possibly a mixture of freshly created waves/turbulence and fossil waves) and in the [railing portions of high speed streams (fossil waves),

Fig. 3 Same as for the above Figure, but at high (- 37°) heliographic latitudes (4.4 AU). Note that large amplitude $\Delta\vec{B}/|B| \sim 1-2$ waves arc almost continuously present. The (normalized) rate of discontinuity occurrence is approximate] y 2-4 times higher than in the ecliptic plane.

Fig. 4 One (1) minute average magnetic field data at 5.2 AU (10 latitude). Discontinuities selected by the T-S criteria are indicated by vertical lines. The discontinuities arc found on the edges of Alfvén waves.

Fig. 5 The B_1-B_2 hodogram for the Alfvén wave (without the trailing discontinuity) at 0519-0610 UT January 17, 1992 (5.2 AU, left-bottom panel) and for the trailing discontinuity (right-bottom panel). The wave portion consists of a -270° phase rot at ion, linear] y-polari zed (on a spherical surface). The discontinuity portion has also a - '90° phase rotation but with the opposite sense as the prior (Alfvén) interval. Thus the Alfvén wave plus discontinuity comprise a 360° wave (top panel). The RD is the steepened part of the nonlinear Alfvén wave.

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Correlation Between Discontinuity and IMF and Solar Wind

Data Interval: July 1 - 30, 1992

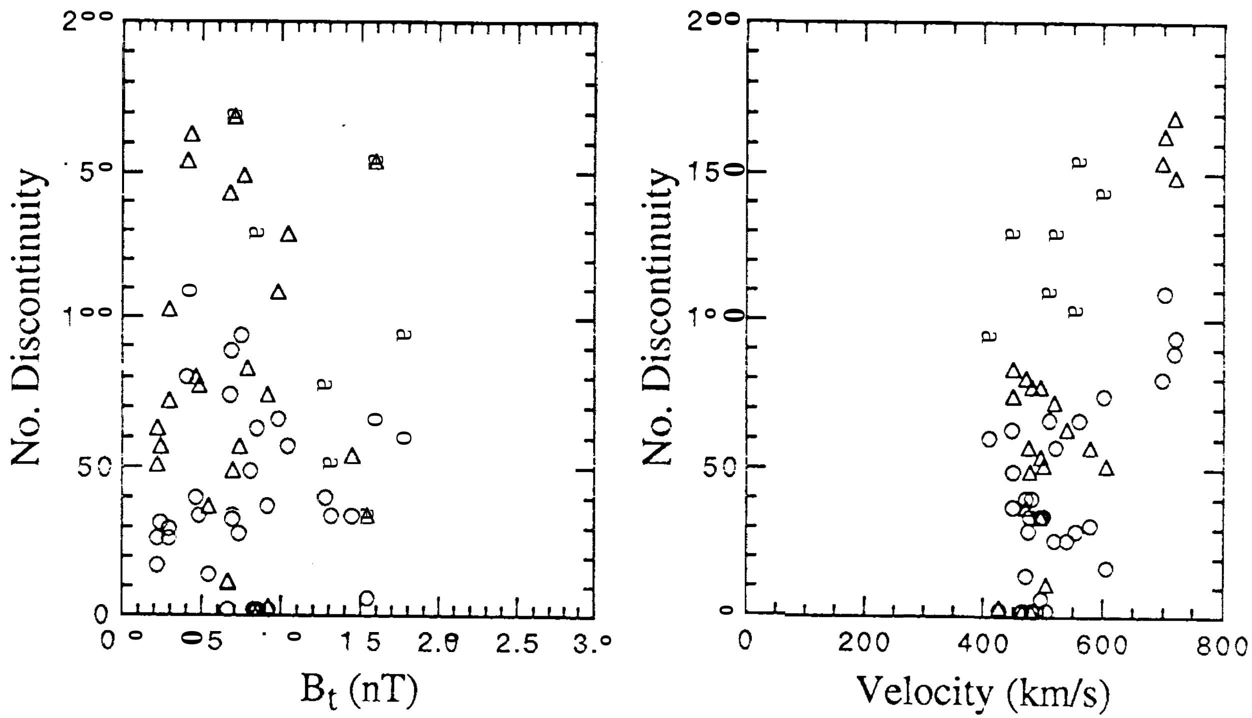


Fig. 1

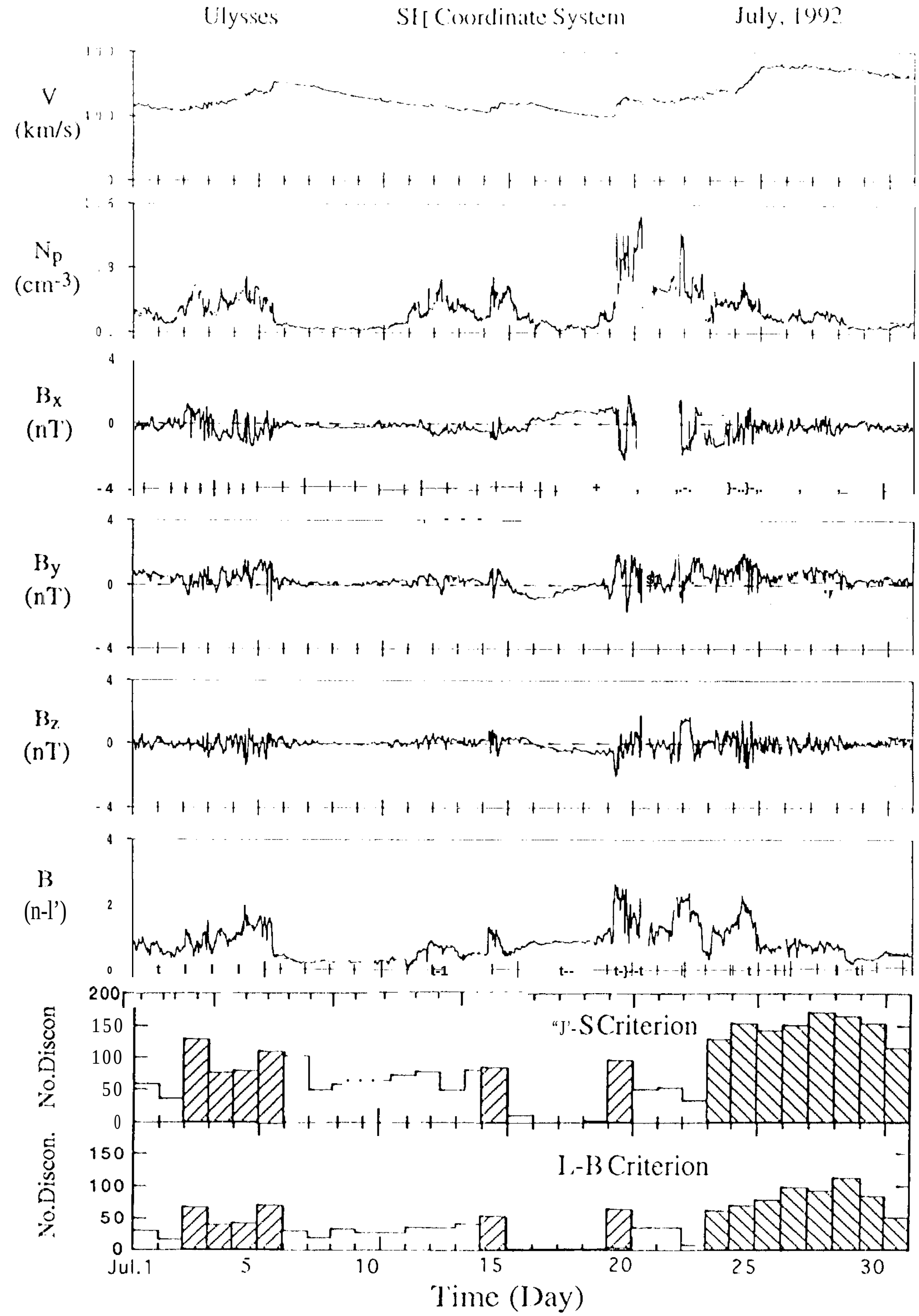

Ulysses
SH Coordinate System
July, 1992
V
(km/s)
Np
(cm-3)
Bx
(nT)
By
(nT)
Bz
(nT)
B
(nT)
No.Discon
"T"-S Criterion
No.Discon.
L-B Criterion
200
150
100
50
0
Jul.1
5
10
15
20
25
30
Time (Day)

Fig. 2

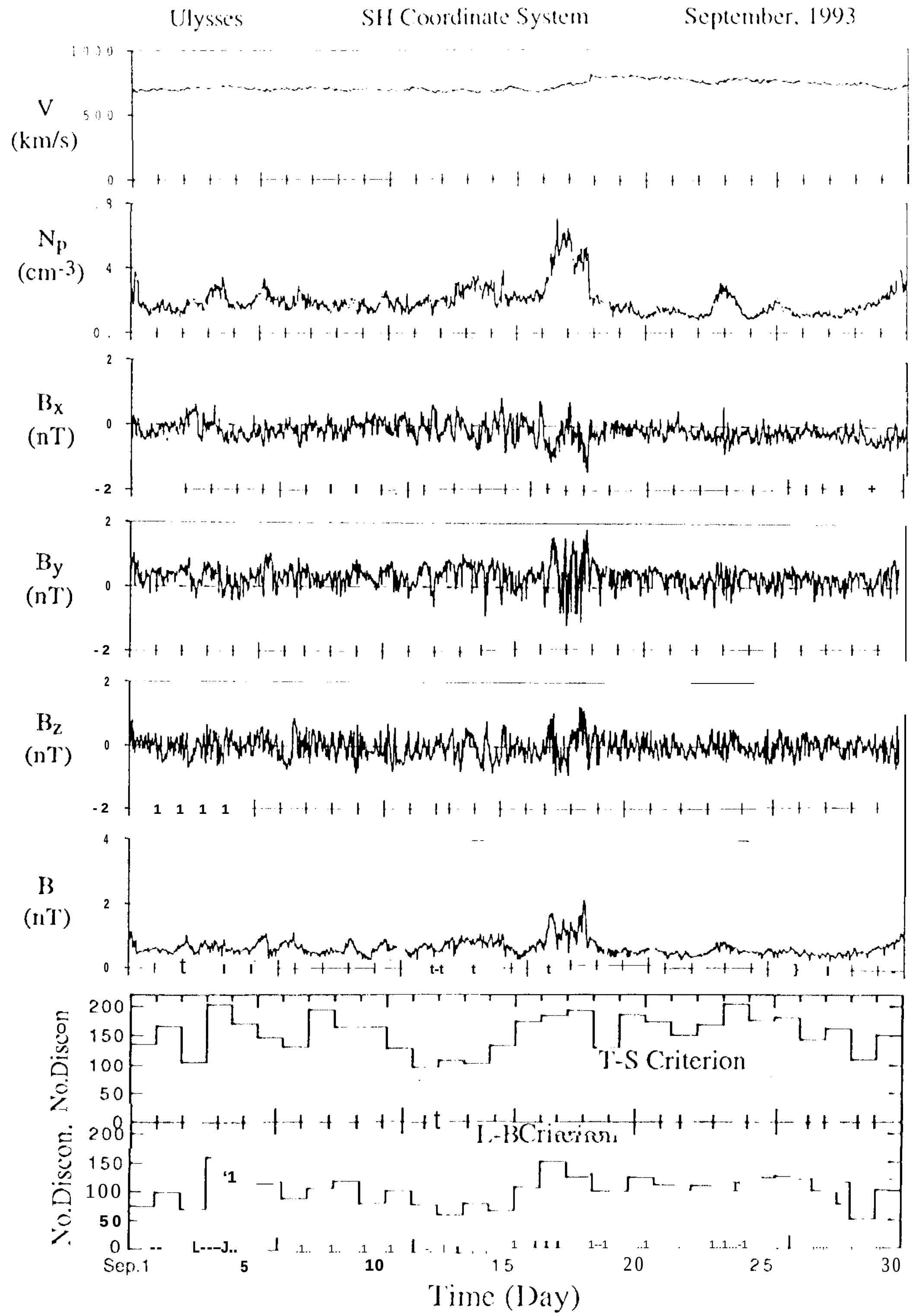
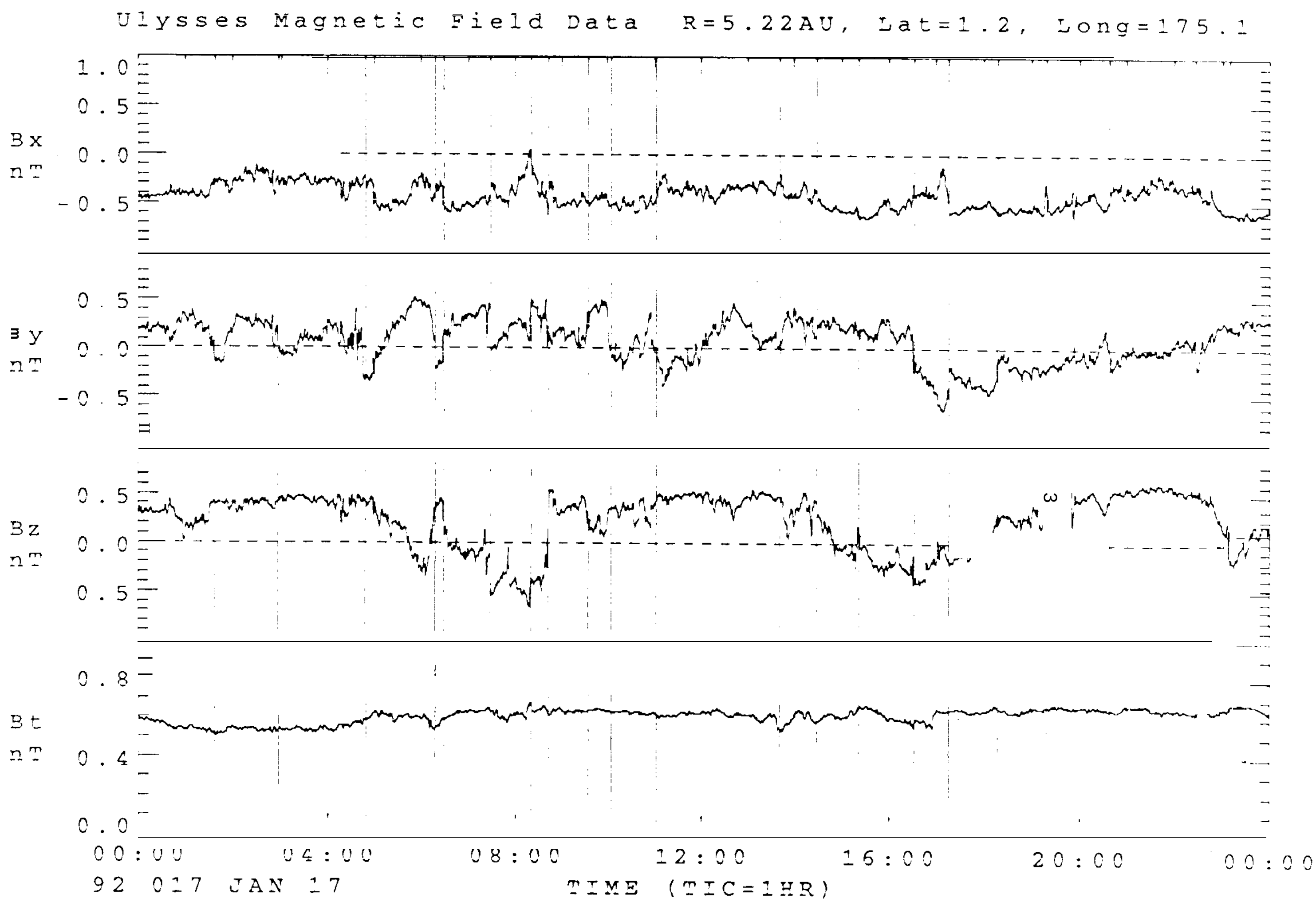

Ulysses
SH Coordinate System
September, 1993
V (km/s)
Np (cm-3)
Bx (nT)
By (nT)
Bz (nT)
B (nT)
No.Discon.
T-S Criterion
L-BCriterion
Sep.1
5
10
15
20
25
30
Time (Day)

Fig. 3


Ulysses Magnetic Field Data R=5.22AU, Lat=1.2, Long=175.1
Bx
nT
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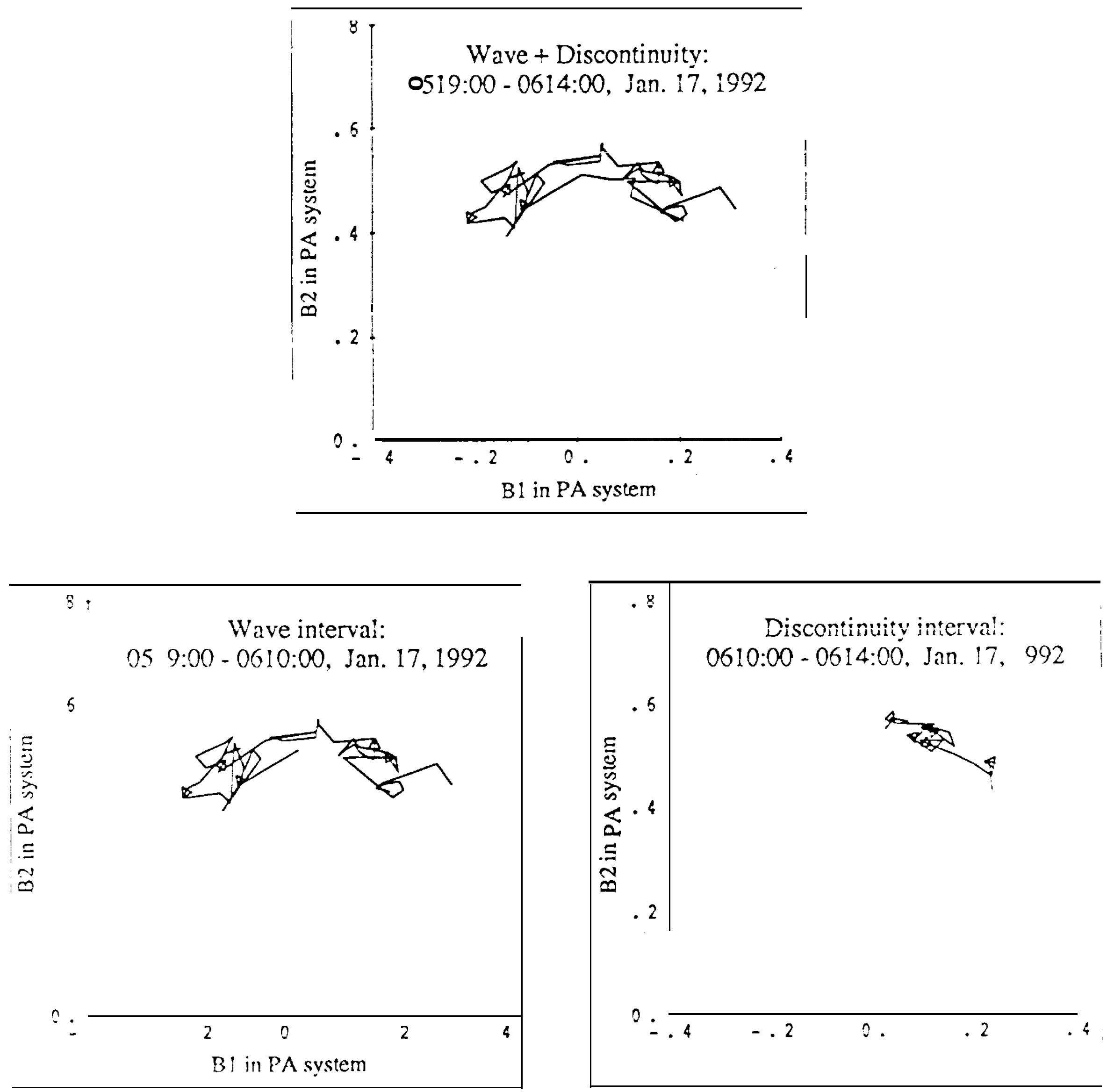
0.5
0.0
-0.5
By
nT
0.5
0.0
-0.5
Bz
nT
0.5
0.0
0.5
3
Bt
nT
0.8
0.4
0.0
00:00
04:00
08:00
12:00
16:00
20:00
00:00
92 017 JAN 17
TIME (TIC=1HR)

Fig. 4



Wave + Discontinuity:
0519:00 - 0614:00, Jan. 17, 1992
B2 in PA system
B1 in PA system
Wave interval:
05 9:00 - 0610:00, Jan. 17, 1992
B2 in PA system
B1 in PA system
Discontinuity interval:
0610:00 - 0614:00, Jan. 17, 992
B2 in PA system

Fig. 5