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CRITERIA OF INTERPLANETARY PARAMETERS CAUSING INTENSE MAGNETIC STORMS (Dst < -100nT)

AUTORES/AUTHORSHIP

W.D. Gonzalez-A.
Bruce T. Tsurutani

RESUMO - NOTAS / ABSTRACT - NOTES

Ten intense storms ($Dst < -100nT$) occurred during the 500 days of August 16, 1978 to December 18, 1979. From our analysis of ISEE-3 field and plasma data, it is found that the interplanetary cause of these storms are long-duration (> 3 hours), large and negative ($< -10nT$) IMF B_z events, associated with interplanetary duskward-electric fields $> 5mV/m$. Because we find a one-to-one relationship between these interplanetary events and intense storms, we suggest that these criteria can, in the future, be used as predictors of intense storms by an interplanetary monitor such as ISEE-3. These B_z events are found to occur in association with large amplitudes of the IMF magnitude (13-30nT) within two days after the onset of either high-speed solar wind streams or of solar wind density enhancement events, giving important clues to their interplanetary origin. Some obvious possibilities will be discussed. The close proximity of the B_z events and magnetic storms to the onset of high speed streams or density enhancement events is in sharp contrast to interplanetary Alfven waves and HILDCAA events previously reported by the authors (Tsurutani and Gonzalez, 1986) and thus the two interplanetary features and corresponding geomagnetic responses can be thought of as being complementary in nature. An examination of opposite polarity (northward) B_z events with the same criteria ($\tau > 3$ hrs, $B_z > 10nT$) show that their occurrence is similar both in number as well as in their relationship to interplanetary disturbances, and that they lead to low levels of geomagnetic activity.

OBSERVAÇÕES / REMARKS

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AUTOR(ES):
W.D. Gonzalez-A.
Bruce T. Tsurutani*

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*Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

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CRITERIA OF INTERPLANETARY PARAMETERS CAUSING INTENSE MAGNETIC STORMS ($D_{st} < -100$ nT)

by

Walter D. Gonzalez*

and

Bruce T. Tsurutani

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109

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*also at the Instituto de Pesquisas Espaciais, Sao Jose dos Campos, Brazil

CRITERIA OF INTERPLANETARY PARAMETERS CAUSING INTENSE MAGNETIC STORMS ($D_{st} < -100$ nT)

ABSTRACT

Ten intense magnetic storms ($D_{st} < -100$ nT) occurred during the 500 days of August 16, 1978 to December 28, 1979. From our analysis of ISEE-3 field and plasma data, it is found that the interplanetary cause of these storms are long-duration (> 3 hours), large and negative (< -10 nT) IMF B_Z events, associated with interplanetary duskward-electric fields > 5 mV/m. Because we find a one-to-one relationship between these interplanetary events and intense storms, we suggest that these criteria can, in the future, be used as predictors of intense storms by an interplanetary monitor such as ISEE-3. These B_Z events are found to occur in association with large amplitudes of the IMF magnitude (13-30 nT) within two days after the onset of either high-speed solar wind streams or of solar wind density enhancement events, giving important clues to their interplanetary origin. Some obvious possibilities will be discussed. The close proximity of the B_Z events and magnetic storms to the onset of high speed streams or density enhancement events is in sharp contrast to interplanetary Alfven waves and HILDCAA events previously reported by the authors (Tsurutani and Gonzalez, 1986) and thus the two interplanetary features and corresponding geomagnetic responses can be thought of as being complementary in nature.

An examination of opposite polarity (northward) B_Z events with the same criteria ($\iota > 3$ hrs, $B_Z > 10$ nT) show that their occurrence is similar both in number as well as in their relationship to interplanetary disturbances, and that they lead to low levels of geomagnetic activity.

Although 90% of the events were associated with high-speed streams and interplanetary shocks, the amplitude of the storms had little dependence on the strength of the shocks.

1. INTRODUCTION

The origin of geomagnetic storms in the interplanetary medium has been investigated for over two decades (e.g., Akasofu and Chapman, 1963; review by Akasofu, 1981). The suggestion that the southward component of the IMF ($-B_Z$ in solar magnetospheric coordinates) as the dominant parameter responsible for the development of the storm's main phase has proven to be successful toward a quantitative understanding of the origin of such development (e.g., Rostoker and Falthammar, 1967; Russell et al., 1974; Burton et al., 1975; Perrault and Akasofu, 1978; Feldstein et al., 1984). However, we are still far from the final stages of this quantitative understanding toward the goal of predicting the occurrence of a geomagnetic storm from the knowledge of interplanetary parameters. Furthermore, the solar and interplanetary origins of southward IMFs are presently almost totally unknown.

The purpose of this paper is to study the solar wind origins of geomagnetic storms by using the unique (practically continuous) observations provided by the ISEE-3 satellite while it was at its halo orbit around the sunward libration point (about 240 earth radii in front of the earth). During the selected time interval for our study (August 16, 1978 to December 28, 1979) the satellite provided a full set of magnetic field (Frandsen et al., 1978) and plasma (Bame et al., 1978) data. The D_{st} plots used for the identification of magnetic storms were kindly prepared by the Geophysical Institute of the University of Alaska. In this report we present the results obtained for a class of intense magnetic storms, defined by the storm-index D_{st} being less than -100 nT. The restriction to this class of storms provided us a limited set of events suitable for a detailed study. With the criteria used to select intense storms, only ten events were found during the 500 days of our data set, with peak D_{st} values ranging between -110 nT and -220 nT.

To complete our study, we have also included a complementary analysis of northward IMF B_Z events. We use the same interplanetary criteria that was discovered for the causes of magnetic storms (except northward rather than southward fields), and determine the northward IMF events' rate of occurrence, solar wind stream dependence and geomagnetic effects.

In addition, a study of the role of interplanetary shocks on the development of the main phase of geomagnetic storms is briefly discussed.

2. INTENSE STORM EVENTS AND INTERPLANETARY CONDITIONS.

Because the search for relationships between geomagnetic storms and interplanetary shocks has been a matter of primary interest for many years (e.g., Akasofu and Chapman, 1963; Akasofu, 1981; Smith et al; 1986), we start this section with a study of the relatioship between the amplitude of a geomagnetic storm (peak D_{st} value) and the strength of the interplanetary shock preceeding it. Information on the interplanetary shocks that occurred during the time interval of our study, as identified and discussed by Tsurutani and Lin (1985), Smith et al. (1986) and Bavassano-Cattaneo et al. (1986), have been used in order to compare their strengths with the intensities of magnetic storms. Smith et al. (1986) have presented a detailed study about a definite relationship between the occurrence of storm sudden commencements and the presence of interplanetary shocks.

Figure 1 shows the normalized occurrence of shocks, for selected intervals of their strengths, as a function of peak D_{st} values of the magnetic storms that occurred within an expected time lag (0-3 days) after their arrival to the Earth's magnetopause. The shocks were grouped in three classes: weak, medium and strong, according to their corresponding high speed stream's velocity increase: $V <$ 100 km s^{-1}, $V =$ 100-250 km s^{-1} and $V >$ 250 km s^{-1}, respectively. It is noted in this figure that there is no indication for any clear relationship between shock-strength and amplitude of the magnetic storms. Both weak and strong shocks seem to have similar possibilities of being related to magnetic storms of a given amplitude. There is some indication from this limited data set that the most intense magnetic storms (with peak D_{st} values > 150 nT) are related to medium-strength shocks.

Figure 2 schematically shows features related to the ten intense storms that occurred during the time interval of our study. For each of them, the peak value, the date and the approximate UT (number between parentheses) of the D_{st} events are indicated at the end of each case. All these events involved the presence of long duration, large and negative values of the IMF B_z component (see discussion below) within one to three hours prior to the D_{st} event (after the solar wind transit time of about one hour between the satellite position and the magnetopause has been subtracted). The corresponding peak B_z values are indicated in this figure. All these B_z events occurred during time intervals with large IMF $|B|$ values. The corresponding peak $|B|$ values are also given in this figure.

The presence of interplanetary shocks were identified for nine of the events, within a time interval of 0-2 days prior to the events. Figure 2 also shows the approximate times of their observations at ISEE-3 together with their corresponding magnetosonic Mach numbers. Finally, for the one event where a shock was not present, a type of a non-compressive density enhancement (NCDE) event (Gosling et al., 1977) was identified, and is indicated in this figure.

Figure 3 illustrates one of the nine D_{st} events that occurred in association with an interplanetary shock (April 4, 1979). The magnetic storm had a particularly high intensity (peak D_{st} 200 nT). However, the associated interplanetary shock was weak (Mach number 1.0, V < 100 km s^{-1}). The amplitude of the D_{st} event is argued to be related to the large amplitude, long duration, negative B_Z event following the shock. The stronger shock at the beginning at April 5, 1979 (Mach number 3.0, V 250 km s^{-1}) did not cause a major storm (D_{st} -50 nT) because B_Z was largely northward during that event. The two interplanetary shocks can be easily identified by the abrupt magnetic field and velocity increases (plus density and temperature increases) indicating the occurrence of fast forward shocks (Tsurutani and Lin, 1985; Smith et al., 1986).

Figure 4 shows the D_{st} event of September 18, 1979 that did not involve the presence of a shock. The intense storm followed a large amplitude, long duration, negative B_Z event, as in the prior case. However the event is preceded only by a large density enhancement event. This is similar to non-compressive density enhancements, as described by Gosling et al. (1977).

3. NORTHWARD IMF B_Z EVENTS.

Because the intense magnetic storms discussed above were associated to long-duration (> 3 hours), large-amplitude IMF B_Z (< -10 nT) events with related electric field amplitudes > 5 mV/m, a natural question arises with respect to the occurrence frequency, association to interplanetary features and related geomagnetic activity levels of similar IMF B_Z events with the opposite (northward) polarity. We have made such a study and present the results below.

From a statistical study of the same IMF and plasma data set used in the previous section, it is found that eleven opposite IMF B_Z polarity events occurred during the same time interval. These events are listed and described in Table 1.

Column one gives the dates and the approximate Universal Times for the onset of the IMF B_Z events. Among these eleven northward B_Z events, three followed or preceded negative B_Z events (discussed in the previous section) and are thus indicated by an asterisk. The second and third columns of this table give the peak B_Z values (in nT) and the duration (in hours) of the events, respectively. The fourth column gives the peak |B| values during these events. The fifth column gives information on the relationship of the events to interplanetary shocks (nine cases) or to NCDE events (two cases). The approximate lag times (in hours) of the events with respect to the shocks and also the shock strengths (indicated by their magnetosonic Mach numbers) are given in this column. For the cases with zero lag-time (indicated), the B_Z event followed the interplanetary shock within the same hour. The NCDE events associated with two of the cases preceded the positive B_Z events by a few hours to less than one day. The last two columns of Table 1 give information on the geomagnetic activity during the events, as measured by the AE and D_{st} indices. A transit time of about one hour between satellite and magnetopause was assumed in the table. The AE activity was considered to be "zero" when AE < 100 nT. In the D_{st} column, the letter "R" stands for a recovery phase of a magnetic storm, the letter "Q" for a defined quiet-world day and the "plus" symbol for the existence of positive values of D_{st} associated with solar wind ram pressure increases.

Figure 5 is one example (November 11, 1979) among the nine positive B_Z events that occurred in association with an interplanetary shock. As shown in Table 1, this event lasted approximately six hours with peak B_Z values around +20 nT. The event followed an interplanetary shock by about 12.5 hours. The shock's onset was about 0130 UT of the same day and had a Mach number of 2.5. During this event, the AE and D_{st} values were very low (around zero), apart from a positive D_{st} increment due to solar wind ram pressure increases.

This event also has one of the longest (about two days) and continuous northward B_Z duration. Notice that when B_Z is still positive, but < 10 nT (0600-1400 UT November 12), the AE activity is non-negligible (up to a 300-nT level). However, there are very large B_Y values (up to 18 nT) after 0300 UT which may be related to reconnection via a magnetic configuration described by Cowley (1979). The AE increase occurs approximately one hour after the arrival of the strong B_Y fields to the magnetosphere.

Figure 4 is an example (September 18-19, 1979) of a positive B_Z event that occurred in association with an NCDE event. This case is an example of a combined negative/positive B_Z event, from which the negative part was associated with an intense magnetic storm. The relationship of this event to that of the NCDE event is not obvious and is presently under study. The positive B_Z event lasted for about three hours. During this time, the AE values were close to zero and the D_{st} values showed a recovery from the magnetic storm associated with the preceding negative B_z event. This period corresponded to a World Quiet Day, as indicated by the letter "Q" in Table 1.

4. DISCUSSION

Although Figure 2 shows only the peak values of the B_Z events that arrived to the magnetopause approximately one to three hours prior to the occurrence of the peak values of the ten intense storms, a common feature found for all those storms was the presence of long duration (> 3 hours), large and negative values (<-10 nT) of the IMF B_Z component, with the associated interplanetary duskward electric field having values > 5 mV/m. Additionally, it was found that there were no other interplanetary events meeting these criteria during the interval of study, giving a one-to-one correspondence between intense magnetic storms and interplanetary B_Z events of this type. Furthermore, the B_Z events which had characteristics near the threshold values seem to correspond to magnetic storms with peak D_{st} values close to -100 nT, thus suggesting that this relationship may also extend to moderate storms.

A detailed study of this interesting correspondence, as well as of its relationship to interplanetary quantities that involve B_Z (e.g., Perrault and Akasofu, 1978; Akasofu, 1981; Murayama, 1982; Baker et al., 1983; Tsurutani et al., 1985; Gonzalez, 1986), falls outside the scope of the present work. Nevertheless, we can advance that the B_Z flux (duskward electric field) values when integrated across their corresponding durations (> 3 hours), show a fairly clear positive linear relationship with the peak D_{st} values (correlation coefficient of about 0.75). When the duration factor is suppressed, the correlation decreases quite substantially. Notice that such a relatively high correlation coefficient of 0.75 was found even without taking into account loss processes during the development of these intense storms. Therefore, at least for intense storms, it is argued that not only the amplitude but also the duration of the negative B_Z events have definite contributions for the development of the storms. Previous studies on the B_Z relationship to storms gave much attention mostly to the amplitude of B_Z (Burton et al., 1975; Murayama, 1982), although suggestions about the importance of the B_Z event-duration were advanced by Russell et al. (1974) with respect to moderate storms, and by other authors with respect to substorms and geomagnetic activity predictions (e.g., Arnoldy, 1971; Joselyn et al., 1981).

As shown in Figure 2 and Table 1, the occurrence frequency and association to interplanetary features of both southward and northward B_Z events are very similar. Thus, during the 500 days of our study, ten (eleven) southward (northward) B_Z events occurred within two days after the onset of either a high-speed stream (nine cases for both types of B_Z events) or of a density enhancement (one case for a southward B_Z event and two cases for northward B_Z events). Both types of B_Z events also occurred during time intervals with large values of the total interplanetary magnetic field intenisty (13-30 nT for southward B_Z events and 14-40 nT for northward B_Z events).

The similarities between both types of B_Z events represent important clues for studies of their interplanetary origins. Interplanetary processes closely responsible for both types of B_Z events are under present investigation. Some interplanetary structures that seem to be related are the following: 1) B_Z structures existing upstream of high-speed streams which get amplified by shock compression, 2) turbulent fields that are produced in stream-stream "interaction regions" between high-velocity streams overtaking a lower velocity streams (Dessler and Fejer, 1963; Smith and Wolfe, 1978), 3) Kinky heliospheric current sheets (Tsurutani et al., 1984) that occur in highly compressed regions between solar flare-associated shocks and the cold driver gases, 4) magnetic clouds (Klein and Burlaga, 1982), that are either magnetic tongues associated with solar disturbances or are detached "bubbles".

The level of geomagnetic activity during the positive B_Z events was generally quiet (Table 1), even though such events followed large-scale "active" solar wind features such as high-speed streams and NCDE events. It should be noted, however, that a non-negligible level of AE activity (100-200 nT) and a regime of recovery phase from a magnetic storm were present in some cases. The storm activity was related to the large amplitude-southward B_Z fields that sometimes follow the onset of high-speed streams or of NCDE events, as in the negative B_Z events of Section 2. On the other hand, the low-level AE activity could be associated with convection enhancement caused by the solar wind velocity increases via a viscous-type of interaction, and/or to the large-amplitude values of the IMF B_Y component, via a B_Y dominant reconnection event. In either possibility, the enhanced convection is expected to be only of minor amplitude (e.g., Gonzalez and Mozer, 1974, Mozer, 1984) when compared to the much larger ones produced by southward B_Z events.

The intensity of the small AE activity related to the positive B_Z events correlated very poorly with the shock strength (correlation coefficient only around 0.15). This complements the results previously mentioned regarding the lack of any correlation between the intensity of magnetic storms and the strength of the shocks that preceded them.

Recently, Akasofu and Tsurutani (1984) reported unusual auroral features related to an event that looks very similar to a positive B_Z event. Thus, the events reported in this section can be studied in the context of magnetospheric features that are mostly not yet understood.

5. CONCLUSIONS.

It was shown that the interplanetary cause for the two intense magentic storms (D_{st} < -100 nT) that occurred from August 16, 1978 to December 28, 1979, were long duration (> 3 hours), large and negative (< -100 nT) IMF B_Z events, associated with interplanetary duskward - electric fields > 5 mV/m. Because we find a one-to-one relationship between these interplanetary events and intense storms, we suggest that these criteria can, in the future, be used as a predictor of intense storms by an interplanetary monitor such as ISEE-3. However, a study on the relationship of these criteria to other quantities argued to be associated to magnetospheric activity, such as in Akasofu (1981), remains to be done.

These B_Z events are found to occur in association with large amplitudes of the IMF magnitude within two days after the onset of either a high-speed stream or of a density enhancement event. An examination of similar opposite polarity (northward) B_Z events showed that their occurrence is similar both in number as well as in their relationship to interplanetary disturbances. This may suggest to us that both types of B_Z events may be due to random fluctuations of the interplanetary magnetic field in and out of the ecliptic plane. This could put severe limitations on the possibility of predicting such events by solar observations. On the other hand, the fact that these B_Z events occur within 0-2 days after the onset of a high-speed stream or of a density enhancement event, and that they also occurred during time intervals with large values of the total IMF intensity, give important clues to their interplanetary origin. Certainly the predictability of the occurrence of such features are in our reach within the near-future.

Finally, although nine of the ten storms involved the presence of high-speed streams, it was shown that the shock strength and the intensity of the storm are not correlated at all, leaving the importance of interplanetary shocks restricted mainly to the study of sudden storm commencements (Smith et al., 1986). In addition, it was also found that the intensity of the small AE activity related to the positive B_Z events correlated very poorly with the shock strength (correlation coefficient of only 0.15).

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FIGURE CAPTIONS

Figure 1: Normalized occurrence of interplanetary shocks, during August 16, 1978 - December 28, 1979, with selected strength intervals (strong, medium, and weak) as functions of the intensity of the related magnetic storms (given by peak D_{st}).

Figure 2: Schematic representation of the ten events. For each of them, the approximate times (Universal Time) and magnitudes related to peak D_{st}, peak B_z, peak $|B|$ and to the interplanetary shocks are shown. The shock magnitude (strength) is given by the Mach number. The event with an asterisk had discontinuous data.

Figure 3: Example of the interplanetary magnetic field and some of the plasma data measured by ISEE-3. Corresponding values of AE and D_{st} are also plotted. Interplanetary shocks of small and large magnitudes are indicated with s and S, respectively. (The Mach numbers for s and S are about 1 and 3, respectively).

Figure 4: Event with no interplanetary shock present. The density panel shows an enhancement of a NCDE type, possibly related to the B_Z and D_{st} events.

Figure 5: Interplanetary magnetic field and plasma data measured by ISEE-3 for the event of November 11, 1979. Corresponding values of AE and D_{st} are also plotted.

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TABLE 1. Summary of parameters related to the eleven positive B_z events. See text for details.

Date (UT)	Peak B_z (nT)	Duration (hours)	Peak $\|B\|$ (nT)	Shock-Relationship		AE (nT)	D_{st}
				Lag (hours)	Mach Number		
December 17-18, 1978 (22:00)	15	3	26	NCDE	—	0	0
February 21, 1979* (11:00)	20	4	22	9	2.2	0	R
April 3* (10:30)	12	3	14	37	1.0	0	R
April 5 (01:00)	20	4	33	0	2.9	150	R
April 5 (10:00)	30	4	40	9	2.9	200	0
May 29-30 (21:30)	15	3	23	3.5	2.2	150	0^+
August 20 (06:00)	18	6	30	0	1.7	150	0^+
September 18-19* (17:00)	12	3	15	NCDE	—	0	R(Q)
October 6 (16:30)	18	3	20	6.5	2.1	0	R
October 7 (05:00)	16	4	20	19	2.1	200	R
November 11 (14:00)	20	6	23	12.5	2.5	0	0^+

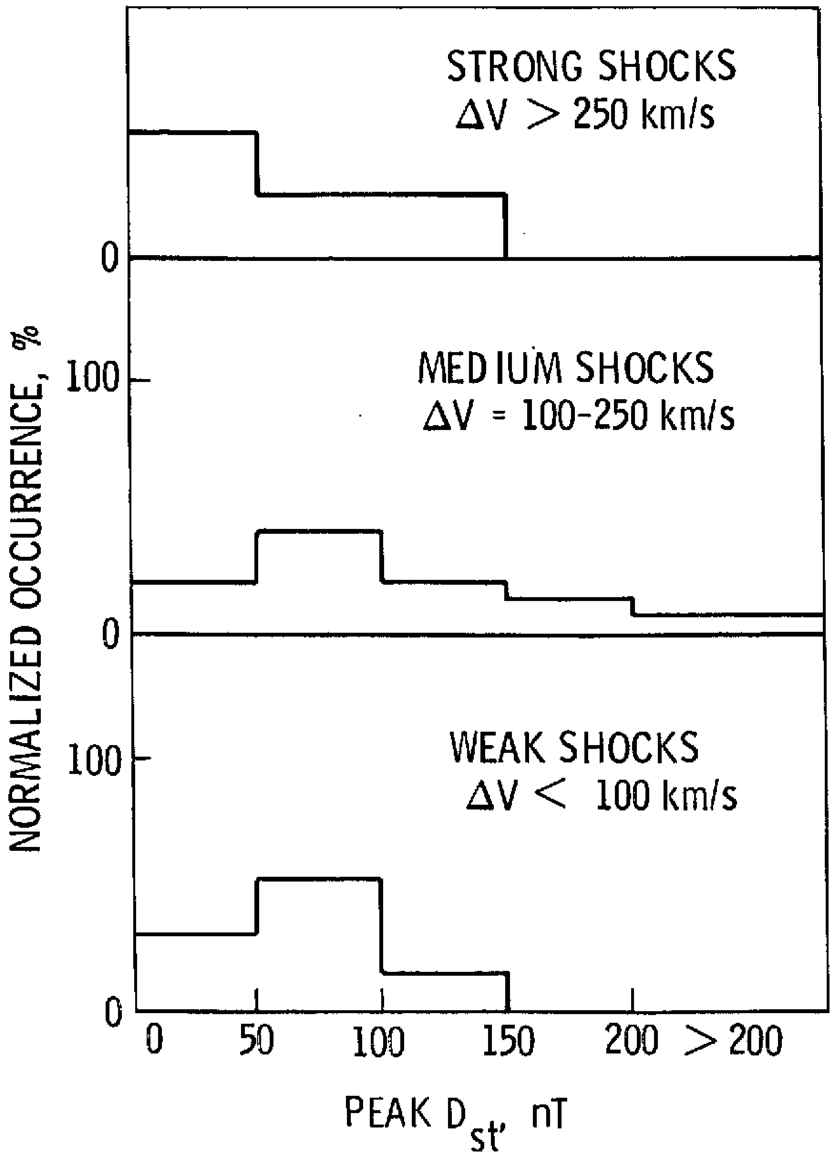

STRONG SHOCKS
ΔV > 250 km/s
0
MEDIUM SHOCKS
ΔV = 100-250 km/s
100
0
WEAK SHOCKS
ΔV < 100 km/s
100
0
NORMALIZED OCCURRENCE, %
0
50
100
150
200
> 200
PEAK D_st, nT

Figure 1

LARGE D_{st} EVENTS (< -100 nT)

(AUG. 16, 1978 — DEC. 28, 1979)

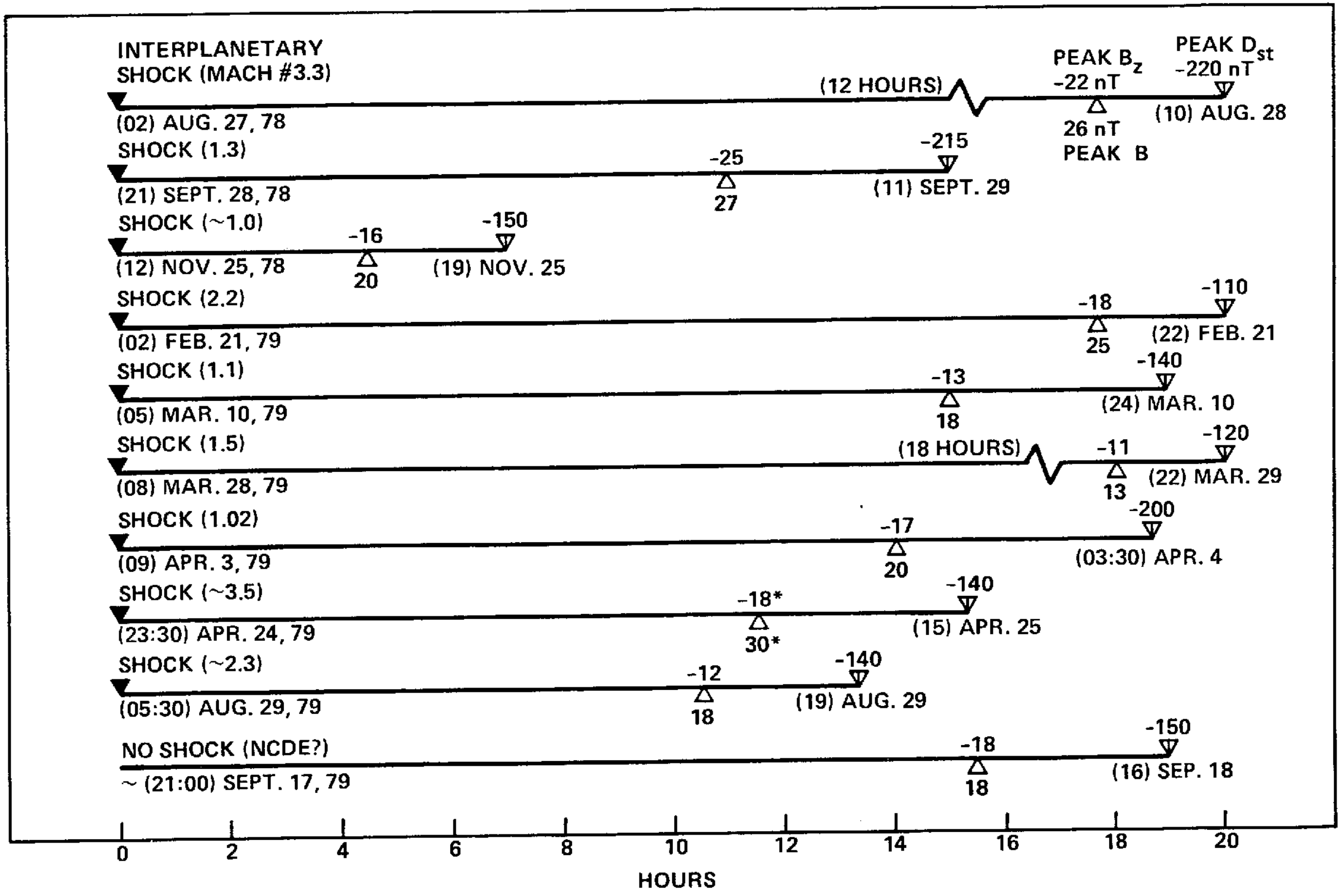
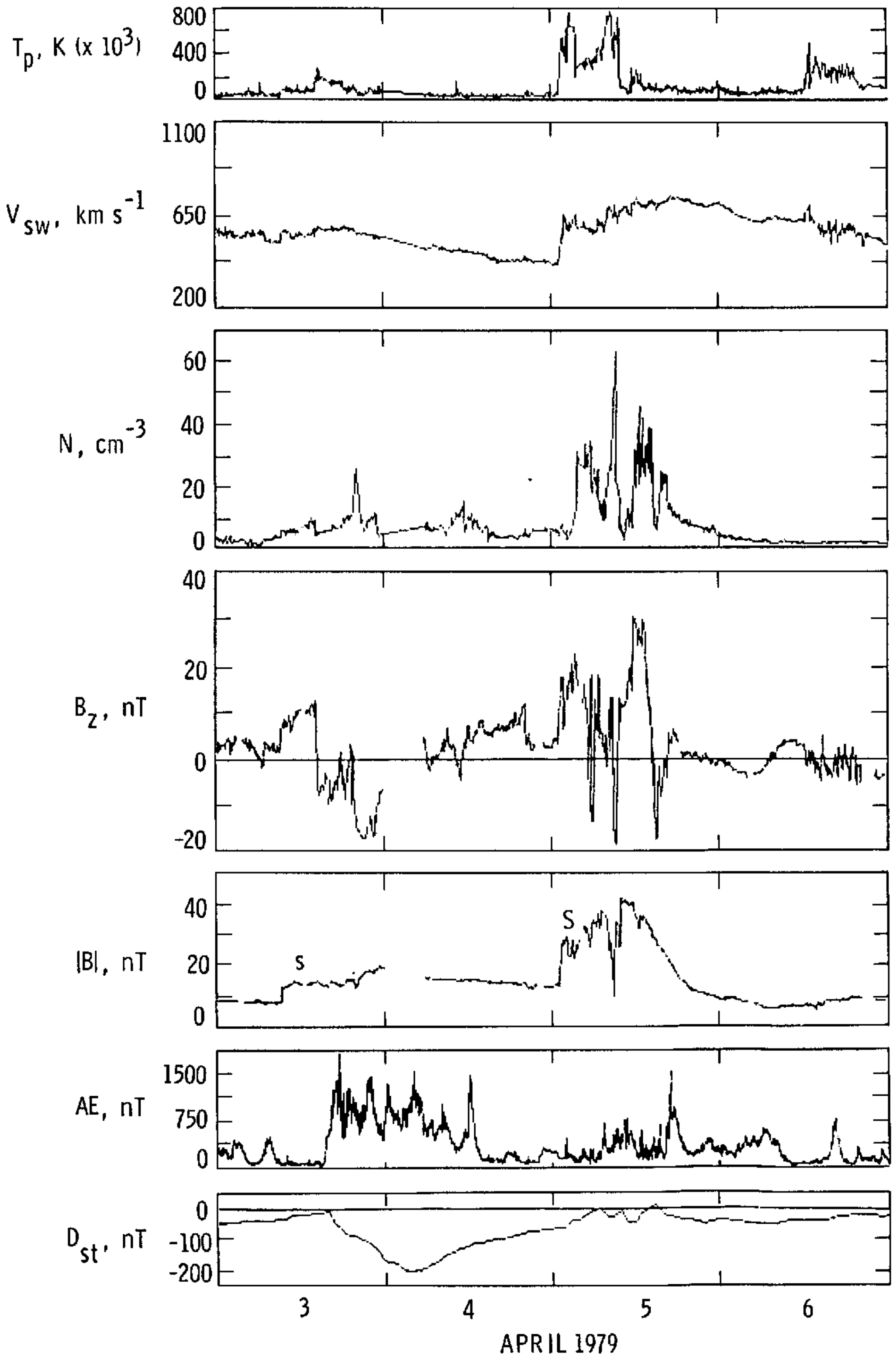


Figure 2



T_p, K (x 10^3)
800
400
0
V_sw, km s^-1
1100
650
200
N, cm^-3
60
40
20
0
B_z, nT
40
20
0
-20
|B|, nT
S
s
40
20
0
AE, nT
1500
750
0
D_st, nT
0
-100
-200
3
4
5
6
APRIL 1979

Figure 3

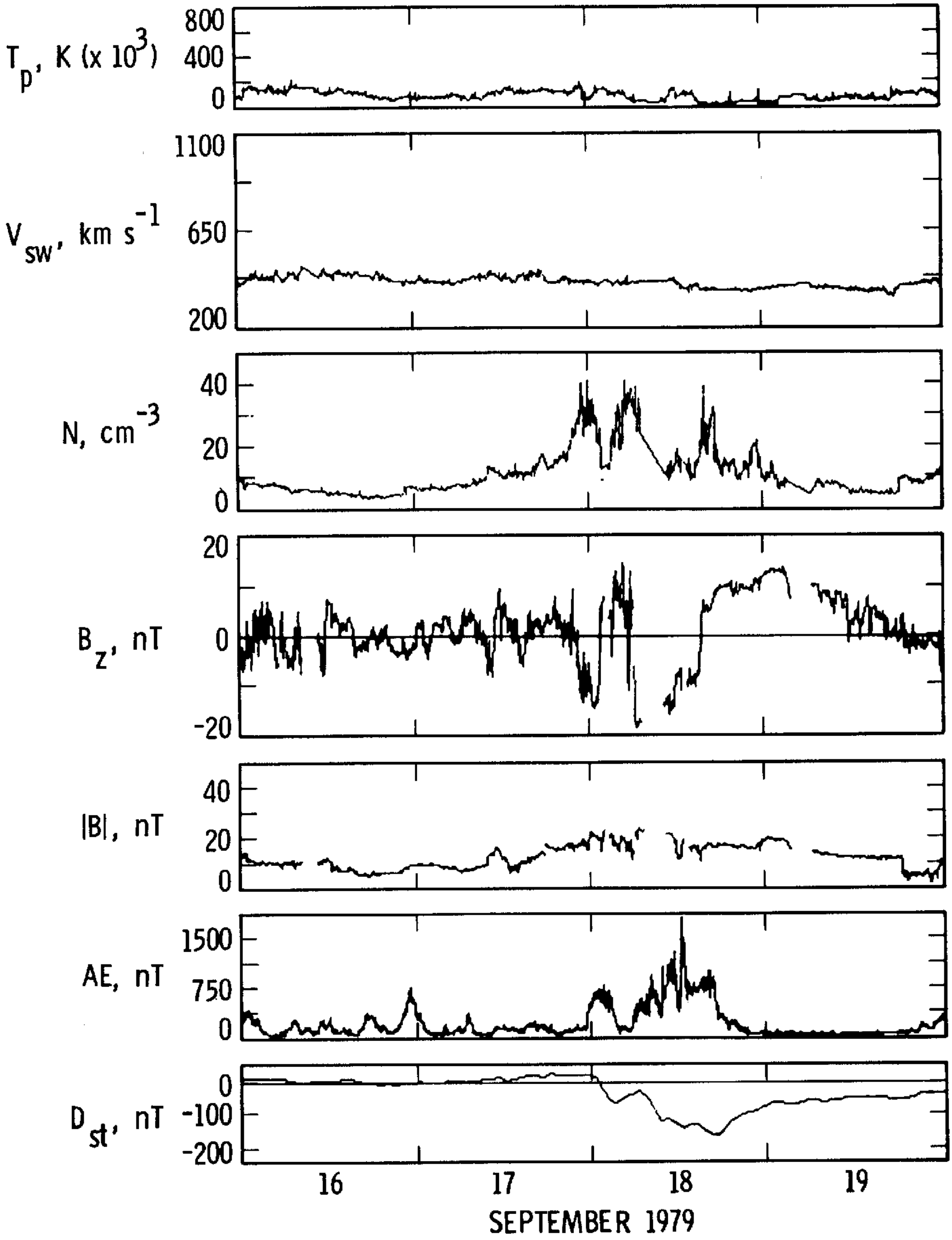
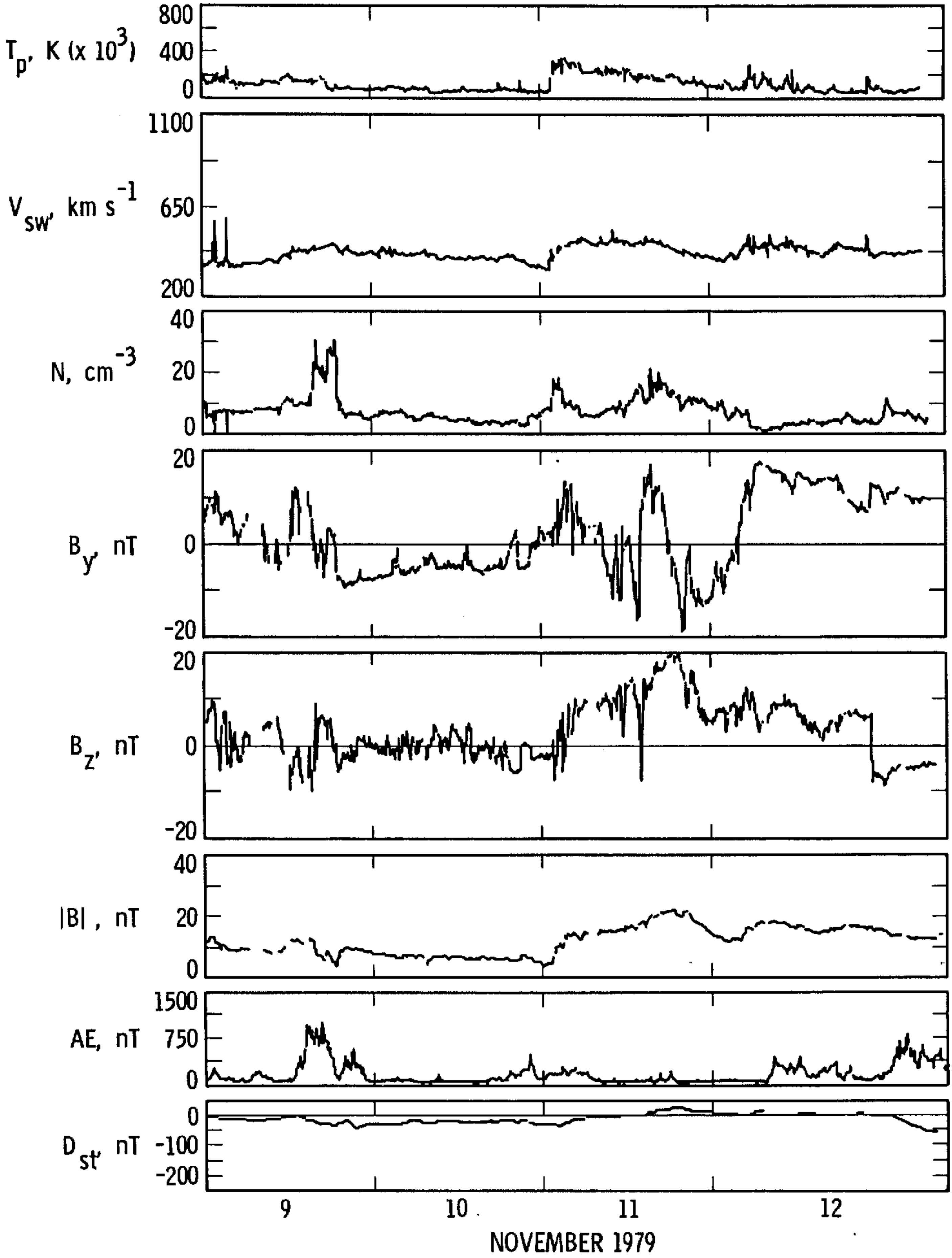

T_p, K (x 10^3)
800
400
0
V_sw, km s^-1
1100
650
200
N, cm^-3
40
20
0
B_z, nT
20
0
-20
|B|, nT
40
20
0
AE, nT
1500
750
0
D_st, nT
0
-100
-200
16
17
18
19
SEPTEMBER 1979

Figure 4



T_p, K (x 10^3)
800
400
0
V_{sw}, km s^{-1}
1100
650
200
N, cm^{-3}
40
20
0
B_y, nT
20
0
-20
B_z, nT
20
0
-20
|B| , nT
40
20
0
AE, nT
1500
750
0
D_{st}, nT
0
-100
-200
9
10
11
12
NOVEMBER 1979

Figure 5