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 component of the Alfven waves is well correlated with AE
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 Bs is considerably shorter, about 20-25 min. Southward
 magnetic fields during non-Alfvenic intervals (Vx-Bx
 cross-correlation coefficient of <0.4) are equally
 effective in producing geomagnetic activity. Peak
 correlation coefficients and lags are similar of those
 Alfvenic intervals. From this statistical study, no
 major differences in the magnetospheric response to
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 high-intensity long-duration continuous AE activity
 (HILDCAA) events discussed previously by Tsurutani and
 Gonzalez (1987) are demonstrated to be caused by the
 southward components of the Alfven waves, presumably
 through the process of magnetic reconnection. The lag
 times of AE from Bs were variable from event to event
 (and at different times within the Alfven wave train),
 ranging from 45 min. to as little as 0 min. The cause of
 this variable delay is somewhat surprising and not
 presently well understood.

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Interplanetary Alfvén Waves and Auroral (Substorm) Activity: IMP 8

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Almost 1 year of IMP 8 interplanetary magnetic field and plasma data (days 1-312, 1979) have been examined to determine the interplanetary causes of geomagnetic AE activity. The nature of the interplanetary medium (Alfvénic or non-Alfvénic) and the B_z correlation with AE were examined over 12-hour increments throughout the study. It is found that Alfvénic wave intervals (defined as V_x-B_z cross-correlation coefficients of >0.6) are present over 60% of the time and the southward component of the Alfvén waves is well correlated with AE (average peak correlation coefficient 0.62), with a median lag of 43 min. The most probable delay of AE from B_z is considerably shorter, about 20-25 min. Southward magnetic fields during non-Alfvénic intervals (V_x-B_z cross-correlation coefficients of <0.4) are equally effective in producing geomagnetic activity. Peak correlation coefficients and lags are similar to those of Alfvénic intervals. From this statistical study, no major differences in the magnetospheric response to Alfvénic and non-Alfvénic intervals were obvious. The high-intensity long-duration continuous AE activity (HILDCAA) events discussed previously by Tsurutani and Gonzalez (1987) are demonstrated to be caused by the southward components of the Alfvén waves, presumably through the process of magnetic reconnection. The lag times of AE from B_z were variable from event to event (and at different times within the Alfvén wave train), ranging from 45 min to as little as 0 min. The cause of this variable delay is somewhat surprising and is not presently well understood.

INTRODUCTION

In recent publications [Tsurutani and Gonzalez, 1987; Gonzalez and Tsurutani, 1987] (hereinafter called TG and GT, respectively) it was demonstrated that high-intensity (peak AE > 1000 nT) long-duration ($T > 2$ days) continuous auroral activity (HILDCAA) that sometimes follows magnetic storms is not part of the decay of the magnetic storms but is due to freshly injected solar wind energy. TG (1987) have shown that the solar wind energy injection is associated with Alfvén wave trains propagating outward from the sun typically in the trailing portion of high-speed streams [Coleman, 1966, 1967; Belcher and Davis, 1971]. TG (1987) have also shown that Alfvén waves and the concomitant HILDCAAs can occur independently of magnetic storms. An important question arising from TG was, "How important are Alfvén waves in causing substorms in general?" Are less intense or shorter-duration Alfvén wave trains (or solitary waves) responsible for most of the auroral activity, or do fields associated with tangential discontinuities [Burlaga, 1969; Smith, 1973; Neugebauer et al., 1984] or interplanetary turbulence [Roberts et al., 1987] also play important roles? What is the relative importance of each? If magnetic reconnection is the dominant process of energy transfer from the solar wind to the magnetosphere, does the magnetosphere have distinct responses to different interplanetary sources of southward B_z , e.g., are there discernable differ-

ences when the southward fields are due to fluctuations associated with Alfvén waves or when they are due to tangential discontinuities or pressure (magnetosonic, slow mode) waves?

Another related question left unanswered by TG is, "What is the solar wind energy injection mechanism responsible for the HILDCAAs reported in their paper?" Because the level of geomagnetic activity during HILDCAAs is quite high (by definition), one might expect the process to be reconnection with very short delay times ("directly driven" substorms [Bargatze et al., 1985; Akasofu et al., 1985; Rostoker and Eastman, 1987]). This question could not be definitively answered by TG, in part, due to the large distances of ISEE 3 from the Sun-Earth line during the HILDCAA events. It was noted by TG that ISEE 3 was often near the wings of the halo orbit (GSM $Y \approx \pm 100 R_E$) during the HILDCAA events. Because Alfvén waves with periods less than 10 min in the spacecraft frame have wavelengths less than $\sim 40 R_E$ and because Alfvén waves propagate along the interplanetary magnetic field (IMF) at $V_A \sim 0.1 V_{SW}$ (in the plasma frame) and are not simply convected by the solar wind, the waves measured at ISEE 3 were not necessarily the same ones that impinged upon Earth's magnetosphere and caused the intense geomagnetic activity. The above scenario is one possible explanation for the lack of correlation between the IMF B_z (the figures in this paper indicate $-B_z$, the same as B_z) and AE, found in the previous ISEE 3 data analyses (see detailed discussion by TG).

The purpose of this paper is to address the above ques-

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tions by analyzing interplanetary IMP 8 field and plasma data in addition to geomagnetic activity indices. The IMP 8 spacecraft is much better suited to a study of this type because of the closeness of its orbit to the magnetosphere. This ensures that all but the shortest of Alfvén wavelengths (also wave periods in the spacecraft frame) detected at IMP 8 will also be incident upon the magnetosphere. The following analysis has two parts. First, we statistically examine approximately 1 year of interplanetary data (days 1–312, 1979) to determine the relationship between B_z and geomagnetic activity during both Alfvénic and non-Alfvénic intervals. The specific interplanetary properties that will be determined are the relative ratio of Alfvénic to non-Alfvénic occurrence rates during 1979 (near solar maximum) and the magnetospheric response to both types of interplanetary conditions. In the second part of the study we will reexamine in detail some of the eight 1978–1979 TG HILDCAA events, using IMP-8 interplanetary data. Specific questions addressed are: Is the energy coupling mechanism magnetic reconnection due to the southward component of the Alfvén waves, as many prior results would anticipate [Dungey, 1961; Arnoldy, 1971; Tsurutani and Meng, 1972; Baker et al., 1983; Akasofu et al., 1985; TG, 1987; McPherron, 1987; Kerr, 1987; Tsurutani et al., 1988b; Gonzalez et al., 1989], or are there also important contributions from “viscouslike” interactions, as suggested by Axford [1964], Baliff et al. [1969], Tsurutani and Thorne [1982], Garrett et al. [1974], Maezawa and Murayama [1986], Rostoker and Eastman [1987], and Tsurutani et al. [1989]? Or are resonant absorption of Alfvén waves [Smith et al., 1986] or other mechanisms important [Tsurutani et al., 1988a]?

Detailed analyses of an intense auroral event associated with fluctuating interplanetary fields were carried out in the CDAW 6 workshop (February 1985 JGR special section). The event was similar to HILDCAAs in intensity and by its continuous activity, but the duration of the activity was insufficient (<1 day) to meet the HILDCAA requirements. The results of the CDAW 6 analyses were quite surprising: the correlation coefficients between the interplanetary parameters, e , VB_z , V^2B_z and the geomagnetic indices AU , AL , and AE were quite low (≈ 0.4 – 0.6), and the magnetospheric response time quite short, ~ 20 – 30 min [Tsurutani et al., 1985]. Possible explanations were that substorms were occurring via internal magnetospheric processes (with energy input from a viscouslike interaction or other mechanisms) or that higher-frequency fluctuations are filtered out [Bargatze et al., 1985]. This event has not been explained by existing substorm models. HILDCAA intervals will be examined to determine whether similarly low B_z - AE correlations are found.

The power spectra of interplanetary Alfvénic fluctuations during HILDCAA events are examined to determine whether there are wave periods associated with the (canonical) 60- to 90-min duration of substorms. If the solar wind energy injection mechanism is magnetic reconnection and substorm durations are ~ 60 – 90 min [Akasofu, 1968], one might expect the interplanetary “driver” magnetic fields to have similar north-south switching periods.

METHOD OF ANALYSIS

The IMP 8 magnetic field and plasma data were kindly provided by J. King of the National Space Science Data

Center (NSSDC), Goddard Space Flight Center, Greenbelt, Maryland. Information concerning instrumentation, data acquisition, averaging, and coordinate transformations can be obtained from the NSSDC.

Because we wish to use only uncontaminated solar wind data and to avoid bow shock, magnetosheath, and magnetospheric intervals, we have taken the Slavin and Holzer [1981] model of the bow shock location [see Formisano, 1979] to delete all intervals where IMP 8 was within $1 R_E$ of the calculated bow shock location. The measured V_{SW} values were used in the calculations. The NSSDC had taken a preliminary cut at deleting such potential contamination. Our effort to safeguard against contamination was more stringent and required further deletion of portions of the IMP 8 data set. This effort will reduce part of the potential upstream wave contamination [Tsurutani and Rodriguez, 1981], but certainly not all of it.

To determine the Alfvénicity or non-Alfvénicity of the interplanetary medium, we first form 5-min averages of the magnetic field, similar to the plasma averages. Correlations between V and B are performed on the three separate GSM coordinate components.

An 11-station AE index was made by the University of Alaska group for this and other studies [see Baker et al., 1983; Akasofu et al., 1985]. Magnetometer ground station locations are given in the above works. Correlations between B_z and AE were performed taking the IMP 8 spacecraft position into account. Measured solar wind velocities were used, and the IMF data were normalized for incidence at the nose of the magnetopause (assumed to be $10 R_E$), to calculate AE delay times.

RESULTS

Statistical Studies

Interplanetary magnetic field and AE distributions. To be able to interpret the significance of the coefficients from cross-correlation analyses, it is useful to know the distribution of the various parameters being correlated. It is implicitly assumed that the parameters have “normal” distributions. However, one of the parameters, AE , clearly does not have a “normal distribution” because it is a positive definite quantity.

Figure 1 illustrates the distribution of the 5-min B_z values for all of the interplanetary data of the study (days 1–312, 1979). The field distribution is statistically centered about ~ 0 nT, and it is nearly symmetric about this value. The number of 5-min intervals decreases with increasing deviation from 0, as would be expected in a normal distribution. The peak values of B_z during this yearlong study is ± 20 nT. A normal function of form Ae^{-x^2/σ^2} was determined using the peak in the distribution and the value at $B_z = \pm 2.5$ nT (14×10^2 events). A curve of amplitude $1750e^{-(B_z^2/28 \text{ nT}^2)}$ nT was the result. The amplitude at 2.5-nT increments was calculated and is plotted. It is clear that the bulk of the B_z values can be very nicely represented by a normal distribution function. However, for $|B_z|$ values > 12.5 nT the occurrence rate is higher than one would expect from a normal distribution. This presumably is due to high field strengths associated with solar wind stream-stream interaction regions and driver gas fields [Tsurutani et al., 1988b]. Although this “tail” is

Fig. 1. Distribution of 5-min interplanetary B_z values for days 1-312, 1979. The distribution is normal, centered near 0 nT. Peak B_z values are ± 20 nT. A normal curve fit has been added.

quite small, it is very important. It is the cause of magnetic storms.

Figure 2 shows the distribution of 1-min AE values for the interval of study. As expected, the distribution is quite skewed. Peak occurrence is near the lowest values (~ 40 nT). The occurrence frequency falls off monotonically with in-

Fig. 2. One-minute AE values for days 1-312, 1979. The distribution monotonically decreases with increasing AE.

Fig. 3a

Fig. 3b

Fig. 3. The interplanetary (a) B_x and (b) B_y component distributions for the study interval. The two peaks in the distributions correspond to the Parker spiral and antisprial directions.

creasing AE. The peak AE during the interval of study is ≈ 1500 nT.

For completeness, in Figures 3a and 3b we show the 5-min averages of the interplanetary B_x and B_y components, respectively. Both distributions are centered relatively closely to ~ 0 nT, and both are characterized by bimodal distributions. The two lobes of the distributions are caused by field orientation parallel to and antiparallel to the Parker spiral

TABLE 1. Twelve-Hour Intervals of 1979 IMP 8 Interplanetary Data

Correlation Coefficient at Zero Lag	Number of 12-hour Intervals	Correlation Coefficient $AE-B_z$	Median $AE-B_z$ Lag
V_x-B_x			
0-0.2	12 (13.6)	0.64 (0.18)	50 [42] (18)
0.2-0.4	13 (14.8)	0.72 (0.12)	45 [40] (16)
0.4-0.6	10 (11.4)	0.54 (0.23)	45 [39] (24)
0.6-0.8	27 (30.7)	0.60 (0.18)	50 [47] (21)
0.8-1.0	26 (29.5)	0.64 (0.19)	35 [34] (14)
V_y-B_y			
0-0.2	5 (6.8)	0.68 (0.18)	50 [55] (16)
0.2-0.4	12 (13.6)	0.62 (0.19)	40 [41] (15)
0.4-0.6	15 (17.0)	0.64 (0.21)	45 [42] (21)
0.6-0.8	39 (44.3)	0.61 (0.18)	35 [39] (21)
0.8-1.0	17 (19.3)	0.66 (0.18)	40 [39] (17)
V_z-B_z			
0-0.2	12 (13.6)	0.65 (0.16)	40 [40] (19)
0.2-0.4	12 (13.6)	0.63 (0.21)	45 [47] (17)
0.4-0.6	36 (40.9)	0.59 (0.18)	40 [43] (20)
0.6-0.8	26 (29.5)	0.66 (0.19)	30 [35] (18)
0.8-1.0	2 (2.2)	0.74 (0.10)	55 [53] (7)

Data are divided into 0.2 increments of $V-B$ correlation coefficients. Column 2 is the number of 12-hour intervals, column 3 is the average of the peak coefficient for the $AE-B_z$ ($-B_z \equiv B_s$) cross correlations, and column 4 is the average lag of AE from B_z for the peak correlations. In parentheses are the percentage of the total number of 12-hour intervals (column 2), the standard deviation of the average peak (column 3), and the standard deviation of the lag (column 4). Numbers in brackets in column 4 are averages.

[Thomas and Smith, 1980]. Field direction reversals are associated with crossings of the heliospheric current sheet [Smith *et al.*, 1978]. During this portion of the solar cycle the source of positive sector (outward from the Sun) fields was in the northern hemisphere, and negative sector fields came from the southern hemisphere [Smith *et al.*, 1978]. Positive polarity fields nominally would have negative B_x and positive B_y components in the GSM coordinate system used. Negative polarity fields, located below the current sheet, have positive B_x and negative B_y components of essentially equal magnitude. The equality in the magnitude of the two peaks (of both B_x and B_y distributions) implies equal amounts of time were spent above and below the heliosphere current sheet during the 313-day interval (see Smith *et al.* [1978] for further discussion).

Interplanetary conditions: Alfvénic versus non-Alfvénic interplanetary intervals. To determine statistically the nature of the interplanetary medium and its relationship to geomagnetic activity, we have followed the general format used in the pioneering paper of Belcher and Davis [1971]. Only intervals where at least 66% of the plasma and field data are present are considered. Although all three axes of the IMP 8 velocity and magnetic field data are available, we use the correlation coefficient between V_x and B_x to determine the degree of "Alfvénicity" of the interplanetary medium. The GSM x component of the solar wind velocity is generally orthogonal to the face of the MIT Faraday cup on board IMP 8 and is thus the best determined component of the solar wind velocity (A. Lazarus, personal communication, 1988). For completeness we also show the correlation between V and B for the y and z components. The basic intervals of analyses were chosen to be 12 hours long. Each day was divided into two intervals of analyses, 0000–1200 UT and 1200–2400 UT. This choice was made to ensure that

the data analysis intervals were much longer than the 60- to 90-min time scale of the substorms being analyzed [Akasofu, 1968].

For each 12-hour interval the correlation coefficient between V_x and B_x at zero lag was calculated. These intervals were then binned into increments of 0.2 in correlation coefficient (0–0.2, 0.2–0.4, etc.), as was done in Table 1 of Belcher and Davis [1971]. For each 12-hour interval, cross-correlation analyses between B_s and AE were performed. The peak correlation coefficient at negative lags (the only physically meaningful result) and the lag at this peak were recorded. Thus for each 0.2 correlation coefficient width bin, all the 12-hour interval peak correlation coefficients and lags for those peaks during the year were tabulated. The averages, medians, and standard deviations (of the averages) for the peak correlation coefficients and for the lags were calculated. The results are given in tabular form in Table 1.

The columns of Table 1 from left to right are the correlation coefficient between V_x and B_x at zero lag (V_y-B_y and V_z-B_z correlation coefficients are also shown in the middle and bottom portions of the table, respectively), the number of 12-hour intervals analyzed, the peak correlation coefficient between AE and B_s (the numbers in parentheses are the standard deviations of the distributions), and the median and average (in brackets) lag at peak correlation coefficient (standard deviations of the distributions are in parentheses).

We first focus on the V_x-B_x correlation results (top one third of the table). In the second column it can be noted that there are considerably more events with large correlation coefficients (at zero lag) than small correlation coefficients. Summing up the numbers in the bottom two and top two bins, there are 53 intervals with correlation coefficients between 0.6 and 1.0 and only 25 with correlation coefficients between 0 and 0.4. If we assume that cases with 0.6–1.0

V_x - B_x correlation coefficients are dominated by Alfvén waves and that, conversely, intervals with 0.0–0.4 correlation coefficients are non-Alfvénic intervals, then it can be interpreted that there are more Alfvénic 12-hour intervals than non-Alfvénic intervals with a ratio of approximately 2 to 1.

The results in the third column indicate that the correlation between B_z and AE is in general independent of the type of interplanetary phenomenon leading to the southward B_z . Although the standard deviation in the 12-hour correlation coefficients (in parentheses) can be quite large (as one might expect), the correlation coefficient averages have a relatively narrow range of 0.54–0.72. The statistical results indicate that there is no apparent difference between the AE correlation with B_z during Alfvénic and non-Alfvénic intervals. The average correlation coefficients are 0.60 and 0.64 (0.62 average) for the former and 0.64 and 0.72 (0.68 average) for the latter. Although the correlation is slightly higher during non-Alfvénic intervals, this is not significant in light of the large standard deviations in the distributions of the averages.

The results in the fourth column of Table 1 indicate that the average median lag of AE from B_z has a narrow range of 35–50 min and also a very large standard deviation from the average lag. A standard deviation of 18 min is noted for the 0–0.2 (non-Alfvénic) bin. The standard deviation in the average lag is comparable to that for the Alfvénic intervals. The spacecraft location was taken into account in calculating the AE lags (see discussion in the method of analysis section).

There appears to be no statistically significant difference between the average (or median) lags for Alfvénic and non-Alfvénic intervals. Comparisons between 0.6–1.0 and 0–0.4 cross-correlation bins give 47 and 34 min versus 40 and 42 min, respectively. The average delay is slightly larger for the Alfvénic intervals, but this difference is again less than the standard deviations.

The bottom two thirds of Table 1 illustrate the results binned according to the V_y - B_y and V_z - B_z correlations (at zero lag). The distributions of the correlation coefficients are somewhat different than for the V_x - B_x case. The V_y - B_y correlations also indicate that the number of Alfvénic intervals is larger than non-Alfvénic intervals by 56 to 17. The ratio of Alfvénic intervals is much less when considering the z axes. The ratio is 28 to 24, or approximately unity. However, it should be noted that the z component of the solar wind velocity is the most difficult component to measure using a Faraday cup and is thus subject to the largest errors (A. Lazarus, private communication, 1988). For this reason, we place less faith in these (y and z) results and assume that the x results (best measured) are representative for the period of study.

Figure 4 illustrates Alfvénic interval results in graphical format. Only intervals when V_x - B_x have correlation coefficients of 0.6 and greater (at zero lag) are included. The various panels give (a) the number of events versus the V_x - B_x correlation coefficients, (b) the distribution of AE lags for the peak AE - B_z correlations, and (c) the AE - B_z maximum correlation coefficients. The above information is similar to that given in Table 1 but contains more details.

Figure 4a illustrates the distribution of the V_x - B_x correlation during "Alfvénic" intervals. This histogram has been folded over so that negative correlations between V_x and B_x (due to outward propagating waves along negative polarity

1979 ALFVÉNIC INTERVALS (V_x - B_x C.C. ≥ 0.6)

Fig. 4. Properties of Alfvénic intervals (V_x - B_x correlations > 0.6 at zero lag). The three panels are the number of events (a) for different V_x - B_x correlation coefficients, (b) for different AE - B_z lags, and (c) for B_z - AE maximum correlation coefficients ($B_z = -B_z$).

magnetic fields) are superposed on the positive side. The panel shows that there is a general lack of events with very high correlations (in the interval 0.9–1.0).

Figure 4b illustrates the distribution of lags of AE from B_z . The cross correlation was only run out to lags with physically reasonable values (80 min). A maximum correlation was selected within the 80-min intervals. Thus the distribution of averages should not be artificially skewed. The lag distribution has an asymmetric shape. There are a few events with lags less than 10 min. The peak occurrence is at lags of 20–30 min. There is generally a falling distribution with increasing lag beyond 20–25 min. The average lag, as shown previously in Table 1, 41 min, is considerably larger than the peak in the distribution.

Figure 4c gives the distribution of the maximum correlation between B_z and AE . As previously mentioned, negative correlations, which are unphysical, have not been considered. The distribution is quite broad, ranging from very low values of 0.1–0.2 to very high values of 0.9–1.0. The shape is skewed toward the higher correlation coefficients. The peak occurrence is 0.7–0.8. Because of the skew in the distribution this value is somewhat higher than averages given in Table 1 (0.62).

HILDCAA Case Studies

Test of Alfvénicity and determination of direction of propagation. The earlier results of Belcher and Davis [1971] have indicated that at 1 AU, waves detected in the trailing portions of high-speed streams were generally the purest Alfvén waves detected in the interplanetary medium and were found to be propagating outward from the Sun. The Mariner 5 data used in the Belcher-Davis study was taken in

TABLE 2. Results of Analyses of Several of the *Tsurutani and Gonzalez* [1987] HILDCAA Events

	V_x-B_x	V_y-B_y	V_z-B_z	$AE-B_s$	IMP B_s - ISEE 3 B_s
Day 270, Sept. 27, 1978	+0.86	-0.58	-0.75	+0.63 (~0)	
0000-1800 UT	(pos)				
0600-9000 UT	0.90	-0.46	-0.77	0.53 (~0)	+0.15
Day 271, Sept. 28, 1978	+0.68	-0.31	-0.65	+0.64 (35)	+0.69
0000-1800 UT	(pos)				
1200-1800 UT	0.89	?	-0.80	+0.83 (40-60)	+0.79
Day 117-118, April 27-28, 1979	-0.83	+0.31	+0.50	+0.61 peak (0-25)	+0.83
1800-0600 UT	(neg)				
Day 117	-0.92	+0.43	+0.71	+0.30	
1800-2400 UT					
Day 119, April 29, 1979	-0.63	+0.17	+0.61	0.49 (30)	+0.74
0600-2400	(neg)				
1200-1800	-0.89	+0.33	+0.74	+0.56 (40)	
Day 120, April 30, 1979	-0.60	+0.68	+0.70	+0.63 (45)	+0.58
0000-1800	(neg)				
0600-0900	-0.8	+0.8	+0.8	+0.83 (45)	
Day 144, May 24, 1979	-0.60	+0.48	+0.67	0.59 (~45)	+0.66
0000-2400	(neg)				
0000-0745	-0.90	+0.43	+0.69	0.53 (~30)	
0900-1200	+0.63	-0.32	+0.77	0.70 (~50)	
Day 167, June 16, 1979	-0.80	+0.53	+0.54	0.60 (20)	+0.35
0000-1800	(neg)				
0300-0535	-0.22	0.87	+0.54	0.85 (15)	
1200-1500	-0.90	0.90	+0.81	0.2	

The top row in each entry pertains to the longer 12- to 24-hour intervals, and the bottom entry to the shorter (~3-hour) interval. The columns from left to right are the time interval of study, the correlation between V_x and B_x , V_y and B_y , and V_z and B_z at zero lag, the peak correlation coefficient between B_s and AE (and lag in minutes), and the peak correlation between IMP 8 B_s and ISEE 3 B_s .

1967, during the ascending phase (near the maximum) of the solar cycle. Because five of the eight HILDCAA events of TG are also in the trailing portion of high-speed streams (see their Table 1 and Figure 1) and the other three events were associated with trailing portions of large density enhancements in the solar wind, it is useful to explore the nature of these waves and to determine whether the characteristics are similar to those found by *Belcher and Davis* [1971] in essentially the same phase of the solar cycle, but close to one cycle (12 years) later. (It should be noted that 11 years is actually only one half of the full 22-year solar cycle.)

Due to orbit restrictions, IMP 8 data were available for only four of the HILDCAA events: August 29 through September 4, 1978; April 27 through May 1, 1979; May 23-28, 1979; and June 15-18, 1979. The first two events were associated with high-speed streams, and the last two were related to noncompressive density enhancements (or NCDEs; see *Gosling et al.* [1977]). To determine the "Alfvénicity" of the events, we have analyzed large segments of time, 12-24 hours. There are often substantial data gaps within these intervals, both in number and in length. These are treated by not including them in the correlation analyses. Shorter intervals where there were no data gaps have also been studied. A minimum length of 3 hours was required for the latter studies. This was chosen to correspond to intervals larger than the maximum wavelength of the Alfvén waves detected, 10^{-3} to 10^{-4} Hz (shown later in the power spectral analyses section).

A summary of the results is given in Table 2. Entries 1 and

2 give results for two consecutive days (September 27 and 28, 1978) of TG event 1, entries 3, 4, and 5, three days (April 27-28, 29, and 30, 1979) for TG event 6, entry 6 one day (May 24, 1979) of event 7, and entry 7 one day (June 16, 1979) of event 8 of TG. The results of the analyses of the larger intervals of time are given at the top of each entry and the results from analyses of the shorter intervals (within the same day), at the bottom.

We first look at the results of the analyses of the larger intervals (top row of each entry). It is apparent that all of the V_x-B_x correlations (at zero lag) are greater than or equal to 0.60, consistent with dominance by Alfvén waves. The y and z components are generally less well correlated, perhaps due to the measurement errors discussed previously. The magnetic sector polarity is also indicated in the V_x-B_x column. Comparison of the sign of the V_x-B_x correlation coefficient to the polarity of the IMF can be used to determine the direction of wave propagation. All events are determined to consist of outward (away from the Sun) propagating waves.

Although the correlation between V_x and B_x is >0.60 , the numbers are not unusually high (in comparison to Table 1). The highest value is 0.86 for 0000-1800 UT, day 270, 1978 (entry 1).

The correlation coefficients between V_x and B_x vary considerably between different days of a HILDCAA event. From day 270 (entry 1) to day 271, 1978 (entry 2) the coefficient decreases from 0.86 to 0.68. Likewise for the 3-day sequence of entries 3-5 the correlation coefficient decreases from 0.83 to 0.63 to 0.60. The above cases were

for Alfvén wave trains following high-speed solar wind streams. This decrease may simply be due to the decrease in wave amplitude with time rather than any intrinsic change in the "Alfvénicity" of the wave train. The last two Alfvén wave events, given in entries 6 and 7, follow NCDEs. They have V_x - B_x correlations of 0.60 and 0.80, essentially the same approximate numbers as in the previous examples.

The shorter intervals (bottom rows of each entry) have V_x - B_x correlation coefficients which are considerably higher than the 18- to 24-hour intervals. Typically, the coefficients are close to ≈ 0.90 . An example of the correlation for the three axes is given in Figure 5 (taken from entry 7 of Table 2). The correlation coefficients strongly peak at zero lag and have values of -0.90 , 0.90 , and 0.81 , respectively. The IMP 8 spacecraft is in a positive sector, with the IMF directed outward from the Sun. The waves are propagating away from the Sun.

We have also examined a number of cases where continuous data were available, and we varied the length of the data analyzed. We find that in general, the shorter the interval analyzed, the higher the correlation coefficient. Part of this effect is an artifact from the shorter interval, and part is a real effect associated with a greater focus on fewer substorms. These two causes cannot be separated. Some implications of the result will be discussed later in another section.

Power spectra. The power spectra of AE for the seven intervals are given in Figure 6. The 1σ errors of the spectral estimates are 0.33, 0.27, 0.33, 0.27, 0.27, 0.24, and 0.27 for the seven intervals (top to bottom in the legend). In general, the spectra have a power law shape. The only thing remarkable about the spectra is an occasional upturn in the slope (or bump) near $5-8 \times 10^{-4}$ Hz, or a wave period of 20–30 min. Examples can be found on day 270, 1978; day 271, 1978; day 117, 1979; and day 144, 1979. It is interesting to note that this upturn in slope has approximately the same period as the expansive phase of geomagnetic substorm first discussed by Akasofu [1964]. However, the peaks are equal to or less than 1σ error.

Figure 7 is the corresponding power spectrum of the interplanetary B_z magnetic field component for the same seven events. The spectral slopes again generally agree with power law shapes except for a slight change in slope or bump at 5×10^{-4} to 10^{-3} Hz. The above correspond to durations of 17–35 min. Examples of this feature can be found on day 271, 1978; day 117, 1979; day 144, 1979; and day 167, 1979. However, these power law shifts are generally less than the statistical error.

The ratio of the power spectra of B_z to the power spectra of AE has been examined. There is nothing particularly striking about these results other than a general decrease in ratio with increasing frequency. Therefore this has not been shown. The only event which went against this trend is the day 270, 1978, case.

Relationship between B_z and AE for HILDCAA events. Cross-correlation analyses between B_z and AE were performed for the HILDCAA intervals where IMP 8 data were available. The results for specific intervals of analyses are given in Table 2. For the large intervals of analyses (12–24 hours) it is found that AE is well correlated with B_z . The correlation coefficients have a narrow range of values, from 0.49 to 0.64. Six of seven events fall within an even smaller range of correlation coefficients, 0.59–0.64.

Fig. 5. An example of the relationship between V and B for day 167, 1200–1500 UT. The high correlation at zero lag indicates the field and plasma fluctuations are Alfvénic in nature.

Fig. 6. Power spectra of the interplanetary $-B_z$ for the seven Alfvén wave events in Table 2. Many have slight bumps or upturns in slope at $\sim 5\text{--}8 \times 10^{-4}$ Hz (20- to 30-min period).

Analyses of the shorter time intervals of 3–6 hours generally (but not always) gave higher correlation coefficients. As one example, an analysis of the 6-hour (continuous) interval of September 28 (day 271), 1978 (entry 2), gave a correlation coefficient of 0.83 compared with 0.64 for the larger, 18-hour

Fig. 7. Power spectra of AE for the seven Alfvén wave events in Table 2. Many have slight bumps or upturns in slope at 5×10^{-4} to 10^{-3} Hz (17–35 min). It is interesting to note that this number is approximately the same as substorm expansion phase durations.

Fig. 8. B_z -AE cross-correlation curve for (a) 0000–1800 UT, day 271 and (b) 1200–1800 UT. The curves show the "classic" profiles, with peak coefficients at 35–60 min delay.

interval. However, counterexamples can be found in entries 3, 6, and 7.

These cross-correlation results of the September 28, 1978 (day 271), and the shorter 6-hour interval are illustrated in Figures 8a and 8b respectively. Both cross-correlation curves have smooth, classic profiles. The peak correlation coefficient occurs when AE lags B_z by 30–60 min.

A second example of this classic profile is shown in Figures 9a and 9b for entry 5 of Table 2, corresponding to day 120 or April 30, 1979. In Figure 9a the peak correlation of 0.63 occurs at a delay of ~ 45 min. When the interval of analysis is shortened to 3 hours (Figure 9b), the peak remains at ~ 45 min, is better defined, and becomes much larger, 0.83.

Fig. 9. Same as in Figure 8 for (a) 0000–1800 UT, day 120, and (b) 0600–0900 UT, day 120.

Not all of the HILDCAA intervals analyzed showed the classic smooth profile, however. Figures 10a and 10b illustrate the results of the analyses of entry 7 of Table 2, corresponding to day 167, 1979. The power spectra of B_z was previously shown in Figure 6. The peak correlations of AE with B_z occurred for AE lags of 20 min for the 18-hour interval and only 15 min for the shorter 3-hour interval. The peak correlation coefficient increased from 0.54 to 0.81.

A final example of the short delays of AE from B_z is illustrated in Figure 11. This is the September 27, 1978, event (entry 1) of Table 2. The cross-correlation profile of the 18-hour interval of analysis (Figure 11a) shows a very broad peak centered at zero lag. The correlation coefficient at zero lag (with an uncertainty of 5 min) is 0.63. When a shorter time interval (3 hours) is analyzed (illustrated in Figure 11b), the peak is still at the same relative position, and the correlation coefficient is slightly less, 0.53. The “W” shape

Fig. 10. Same format as Figure 8 for (a) 0000–1800 UT, day 167, and (b) 0300–0535 UT, day 167. In Figure 10b the correlation coefficient is quite striking with a peak (correlation coefficient of 0.83) at short lags (15 min).

of the correlation coefficient as a function of lag is consistent with the presence of a ~ 75 -min quasi-periodic wave in both interplanetary B_z and AE.

SUMMARY AND DISCUSSION

Statistical Study

The analysis of approximately 1 year of near-Earth IMP 8 interplanetary plasma and magnetic field data have indicated that at this portion of the solar cycle (near solar maximum) of the interplanetary medium is dominated by Alfvénic fluctuations (defined by V_x - B_x correlations of >0.60) roughly 60% of the time. The southward B_z component of the Alfvénic

Fig. 11. Same format as Figure 8 for (a) 0000–1800 UT, day 270, and (b) 0600–0900 UT. An interesting feature in Figure 12b is the very short lag time for the correlation coefficient (~ 0 min with an uncertainty of 5 min) and the anticorrelation between $-B_z$ and AE at +45-min and -30 -min lags. This is consistent with ~ 75 -min quasi-periodic interplanetary oscillations directly driving the magnetosphere.

fluctuations is associated with increases in auroral zone (substorm) geomagnetic activity. The correlation between B_z and AE reaches an average peak coefficient at 0.62 with a median lag of 41 min (calculated from Table 1). This is in good agreement with many previous studies correlating the IMF B_z with AE [Arnoldy, 1971; Tsurutani and Meng, 1972; Baker et al., 1983; Akasofu et al., 1985].

The range of the lags of the peak correlation between B_z and AE can be as low as 5 min and as high as the maximum considered in this study, 80 min. The most probable delay is short, 20–25 min. This is considerably less than the median

delay of 41 min, giving an indication of the strong asymmetry in the distribution. These very short delay times are consistent with Bargatze et al. [1985] and Akasofu et al. [1985] findings of “directly driven” magnetospheric responses. In their studies, such cases were found when the geomagnetic activity was high. One possible explanation for the short delays of this study is that the Alfvén wave amplitudes are higher or the wave trains are longer and more continuous during this period near solar maximum.

The southward IMF B_z during non-Alfvénic (defined as V_x-B_x correlation coefficients of <0.4) intervals were also effective in producing geomagnetic activity. The average of the peak correlation coefficients of B_z and AE was 0.68 with a median delay of 45–50 min. These values are quite similar to the results from Alfvénic intervals. There is no apparent difference that we can find from these statistical analyses. We should, however, point out that a statistical study of this type will only point out major, obvious features and differences. Important subtleties may be missed. As one example, in this study we have not attempted to identify the nature of the non-Alfvénic intervals. Some intervals are dominated by tangential discontinuities, others by compressional waves (such as magnetosonic or slow modes), still others by turbulence or bidirectional Alfvén wave propagation [see Roberts et al., 1987]. Shocks have not been removed from the data set. The magnetospheric response to these different phenomena may be significantly different; e.g., ram pressure pulses have been demonstrated to have a substantial effect on AE [Murayama, 1982, 1986; Tsurutani et al., 1985; Gonzalez et al., 1989]. For these reasons, further investigations of the efficiency and nature of magnetospheric coupling for other interplanetary phenomena are warranted and encouraged.

HILDCAA Events

All of the Alfvén wave events for the HILDCAA intervals were found to be propagating outward from the Sun, as previously reported by Belcher and Davis [1971]. However, the waves were not any “purer” (higher V_x-B_x correlation coefficient) than the general 12-hour intervals studied in 1979. We do not have an explanation for this observation.

The cause of the HILDCAA geomagnetic activity is the southward component of the IMF associated with the Alfvén waves, presumed to be due to magnetic reconnection [Dungey, 1961]. In all but one of the seven cases studied, B_z and AE were highly correlated (up to 0.83 correlation coefficient). The shortness of Alfvén wavelengths in comparison to scale sizes of the ISEE 3 halo orbit caused the relatively low ISEE 3 B_z -AE correlation found in the previous TG study. Correlations between IMP 8 B_z and ISEE 3 B_z (shown in Table 2) range from a minimum of 0.35 to a maximum of 0.83.

The lag times for the HILDCAAs from the southward B_z were quite variable, ranging from zero to 45 min. This is somewhat surprising in that all of these intervals were by definition highly active periods (peak AE $> 1,000$ nT). One might expect consistently small delay times, extrapolating from the results of Bargatze et al. [1985]. The B_z -AE cross-correlation results vary from smoothly varying curves with peak correlations at 30–60 min (Figures 8 and 9) to cases where the peak correlation is abrupt and the delay is short, 0–20 min (Figures 10 and 11).

The power spectra of AE and B_z had generally smooth power law shapes with slight variations in slopes. Although many spectra had small bumps or upturns in slopes near $5\text{--}8 \times 10^{-4}$ Hz (20–30 min), these were shown to have magnitudes less than 1σ error and are presumably not real. There was no power in the AE spectra which could correspond to the substorm expansion phase duration or any other substorm feature. There is also no power in the B_z spectra which indicates that the interplanetary Alfvén waves studied did not have any quasi-periodic structures, at least in the studied frequency range. It is possible, however, that such structure may exist for frequencies corresponding to longer durations (3–4 hours). Several researchers believe this is the true substorm duration period. Unfortunately, this was outside the range of the present paper. Some effort should be made to search for possible structures within this frequency region.

The one very unusual event with peak correlation coefficient near zero lag (day 270, 1978, shown in Figure 11) is particularly interesting from this viewpoint. The short, 3-hour interval of analysis results (Figure 11b) has a “W” shape with minimum correlation coefficients at +45 min and –30 min lag. This type of curve would result from a quasi-periodic Alfvén wave train (with period of ~75 min) which is directly driving the magnetosphere auroral electrojet. The power spectrum of B_z shows a peak at approximately this period (Figure 6). One interesting hypothesis that could explain such observations is the existence of a “resonance” between the quasi-periodic Alfvén waves and the magnetosphere. We encourage computer simulation of solar wind magnetosphere interactions to see whether or not such resonances are possible.

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