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Characteristics of Wave-Particle Interactions During Sudden Commencements 2. Spacecraft Observations

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Wave data from the DE 1 spacecraft for 50 sudden commencements were analyzed for amplitude and spectral modifications and correlated with data from ground-based observatories. Changes in wave activity were identified in 14 of the events studied. The changes, which were commonly observed at frequencies below the local electron gyrofrequency, exhibited a complex structure both in frequency and in time and varied considerably among events. The typical event lasted 1-10 min with a maximum narrowband amplitude increase or decrease of 10-30 dB. The onset time of the wave growth was correlated with the arrival of the magnetic disturbance at the spacecraft. Changes were most commonly observed at L shells in the range $3 < L < 6$. Growth was observed on the nightside as well as the dayside, and no clear local time dependence was found. In several cases, growth at frequencies above the local gyrofrequency was noted and identified as auroral kilometric radiation.

1. INTRODUCTION

Distinct changes in magnetospheric wave activity are often observed at ground-based stations during sudden commencements (sc) and sudden impulses (si) in both the ELF-VLF (0.3-30 kHz) [*Morozumi*, 1965; *Hayashi et al.*, 1968] and ULF (0.1-1 Hz) [*Tepley and Wentworth*, 1962; *Oguti and Kokubun*, 1969; *Hirasawa*, 1981; *Olson and Lee*, 1983] bands. The characteristics of such ground-based observations for the ELF-VLF band are described in detail in the accompanying paper [*Gail et al.*, this issue] (referred to as paper 1). In this paper we present in situ observations of magnetospheric wave phenomena during sc obtained with the DE 1 spacecraft. Together, the two studies provide a descriptive model of the phenomenology of wave generation and particle scattering associated with sc. The model is intended to establish an observational basis for understanding how wave-particle interactions in the magnetosphere are affected by dynamic variations in the magnetic field and plasma.

Only limited in situ observations of sc or si wave emissions by spacecraft have been reported [*Kokubun*, 1983; *Korth et al.*, 1985]. *Kokubun* [1983] presented one series of events in which abrupt increases in VLF intensity observed both on board the GEOS 2 geosynchronous spacecraft and at Husafell, Iceland, were associated with sudden increases in the magnetic field strength. *Korth et al.* [1985] examined ELF-VLF waves and energetic electron distributions during six si observed on board GEOS 2. They found that both the electron pitch angle anisotropy and the wave amplitude increased during si when the spacecraft was on the dayside but not the nightside. Using a refinement of the theory of *Kennel and Petschek* [1966] by *Cornilleau-Wehrlin et al.* [1985], Korth et al. showed that the observed increase in wave amplitude was consistent with the measured increase in anisotropy.

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Ground-based and spacecraft observations provide significantly different types of information about wave-particle interactions. Ground-based observations, for which the waves are assumed to have propagated through ducts, are generally limited to waves with small wave normal angles and frequencies below the minimum half-gyrofrequency along the propagation path. Spacecraft are not subject to these limitations and thus provide observations of wave phenomena such as plasmaspheric hiss and auroral kilometric radiation (AKR) which are not normally detected on the ground. During an sc a spacecraft tends to be in motion with respect to the plasma and to be exposed to a distribution of possible wave source regions. In contrast, a ground station may view the output of one or more drifting ducts [*Park*, 1975], each of which represents a continuously identifiable wave source region during the entire sc compression. Unlike ground observations, spacecraft studies are limited by infrequent data availability in the regions of interest at the time of sc and particularly by the lack of high-resolution broadband wave data. As a consequence, the data set analyzed for this paper is more limited in scope than the data set of ground-based observations presented in Paper 1.

2. DESCRIPTION OF DATA SETS

Lists of sc, which provide a consensus identification based on magnetograms from a worldwide network of observatories, were obtained from *NOAA Solar-Geophysical Data*, 1982-1984. A total of 50 sc the 1982-1984 period were identified for which spacecraft data were available. Observations were made with the Dynamics Explorer 1 (DE 1) spacecraft, which was launched in 1981 into a precessing polar orbit with apogee at 4.6 R_E. Wave data were obtained with the University of Iowa sweep frequency receiver (SFR) [*Shawhan et al.*, 1981] using an electric dipole antenna. The SFR measures amplitude of a 128-point spectrum in the band 100 Hz to 400 kHz and an 8-point spectrum in the band 1 Hz to 100 Hz every 32 s. Data in the form of dynamic spectrograms and spectral density plots were used for the analysis. Magnetic field data were obtained with the Goddard Space Flight Center triaxial flux gate magnetometer (MAG-A) [*Farthing et al.*, 1981], which provides 16 vector samples per second with amplitude resolution 1.5 nT. The measurements are presented as the total field, the declination in degrees (measured from the north) of the projection of the field vector on the horizontal plane of the spacecraft, and the inclination in degrees of the field vector from the horizontal plane.

Wave data from ground-based stations were recorded using Stanford University wave receivers at the Antarctic stations Palmer ($L \sim 2.3$), Siple ($L \sim 4.3$), and South Pole ($\Lambda = 73.8°$). The stations (see Paper 1) form a roughly meridional chain collocated within ±1 hour geomagnetic local time.

3. OBSERVATIONS

3.1 Occurrence Statistics

In order to identify wave activity associated with sc, summary plot records in microfiche form for the DE 1 spacecraft were visually scanned for evidence of changes in wave activity in the SFR frequency band associated with the sc. Of 50 sc reported during the 1982-1984 period for which SFR data were available, 14 showed clear evidence of changes in wave activity associated with the sc. The limited frequency, time, and amplitude resolution available in the summary plots means that small or short duration events were probably missed.

A plot of the observations as a function of local time, L shell, and latitude is shown in Figure 1 for $L < 6$. Observations at $L > 6$ accounted for 24 of the 50 sc but for only one event in which wave activity was noted. The concentric circles correspond to L shells with local time marked along the circumference. Circles indicate sc for which a clear change in wave activity was observed on board DE 1 while those for which no change was observed are marked with a cross.

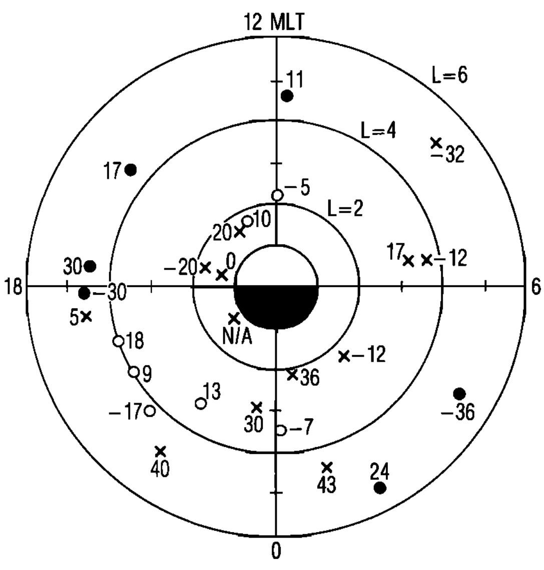

Figure 1. Occurrence of plasma wave emissions during sc as observed by DE 1. Observations are plotted versus L value and local time with geomagnetic latitude given by the plotted value. Events for which a clear change in wave activity was observed on board DE 1 are indicated by circles while those for which no change was observed are indicated with a cross. Events for which wave activity was observed at frequencies above the local electron gyrofrequency are indicated by solid circles.

The sc for which wave activity above the local electron gyrofrequency was observed are indicated by solid circles. The plotted numbers represent the spacecraft geomagnetic latitude at the time of the sc. In the range $3 < L < 6$, changes in wave emissions were detected in 11 of the 18 events studied. Changes were not restricted to any particular local time region. This is significant since both theoretical predictions [*Perona*, 1972] and previous observations [*Korth et al.*, 1985] have suggested that wave growth is preferentially associated with the dayside. Emissions observed inside $L = 6$ occurred at positive and negative magnetic latitudes ranging from 5° to 36°, and no strong latitude dependence was identified.

In order to assess the statistical significance of these observations, a control data set was selected and examined for evidence of similar changes in wave emissions. For each month during the 1982-1984 period, days with the highest, lowest, and median Kp values were identified, and a target time for each day was chosen randomly. Changes in wave activity which occurred within a 3-min or 9-min period beginning 1 min prior to the target time were identified. Of the 84 events for which data were available, 63 had ongoing wave activity which was sufficiently quiescent to allow unambiguous identification of changes (the same criterion was used for candidate sc events). Of these, changes in wave activity were observed in 1 event within the 3-min period and 3 events within the 9-min period. If only the 38 events for which DE 1 was at $L < 6$ are included, the number of events with changes is reduced to 0 for the 3-min period and 2 for the 9-min period. These results indicate that mistaken identifications could account for at most 2-3 of the 14 cases of wave emissions observed during the 50 sc studied.

3.2. Examples

Four examples of wave activity associated with sc are illustrated in Figures 2-5. Each figure shows the dynamic spectrum recorded with the SFR around the time of the sc. The solid curves in the plots indicate the local electron gyrofrequency. The magnetic field measured on board DE 1 corresponding to each sc is shown in Figure 6. In each case, distinct perturbations in the magnetic field and associated changes in wave activity were observed on board DE 1 as well as at Antarctic ground stations. The general characteristics of wave activity observed at ground-based stations during sc were described in detail in paper 1 and will be referred to throughout this section. Ground data used for the first and third examples here were also used as examples in paper 1.

June 12, 1982. Figure 2 shows an sc on June 12, 1982, for which a transient enhancement in the wave amplitude was observed at South Pole, Siple, and Palmer. The enhancement began at 1442:23±:02 UT at South Pole, lasted approximately 6 min, and was followed by wave activity which differed considerably from that prior to the sc. The magnetic perturbation began at South Pole at 1442:42±:02 UT. DE 1 was located at L=4.5, 1735 MLT, 30° geomagnetic latitude (MLAT) at the time of the sc. The magnetic perturbation began at DE 1 at 1443:20±:10 UT, as indicated by the sudden decrease in the declination angle of the magnetic field (Figure 6*a*, although no measurable change in the total field strength was observed. The SFR spectrogram shows an increase in the wave amplitude at frequencies of several kilohertz starting between 1443:16 and 1443:48 UT.

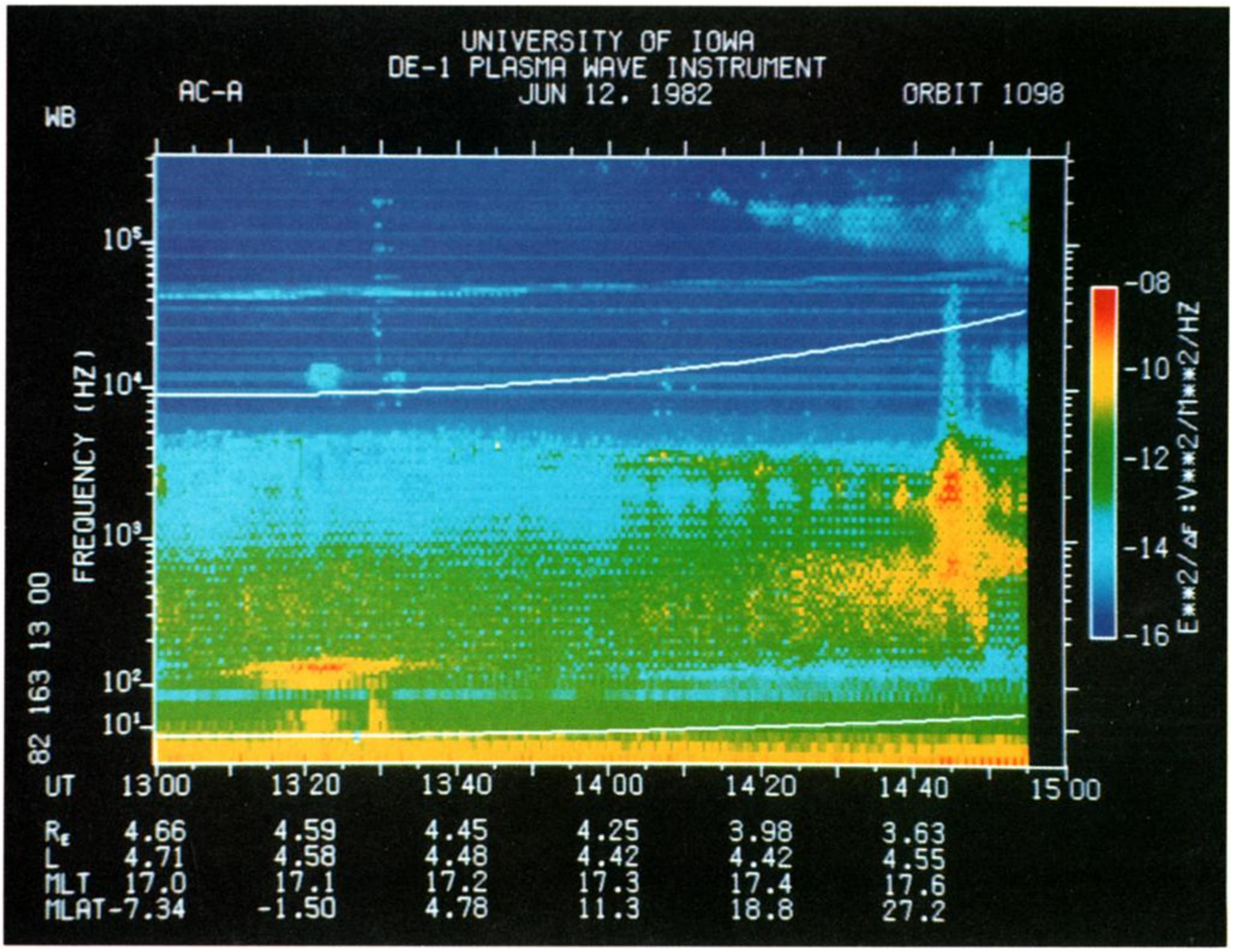

Figure 2. Plasma wave data recorded on board DE 1 during the sc of June 12. 1982.

The amplitude increase appears to have saturated the receiver channel, limiting the validity of both bandwidth and total growth measurements. An enhancement in the emissions above 100 kHz started near 1448 UT, approximately 5 min after the onset of the lower-frequency emissions.

July 13, 1982. Figure 3 shows an sc on July 13, 1982, for which no change in wave activity was observed at South Pole (no data were available from Siple), although a small amplitude enhancement was observed at Palmer beginning at 1617:30±:20 UT. The magnetic perturbation began at South Pole at 1617:20±:10 UT. DE 1 was located at L=4.5, 1525 MLT, 17° MLAT at the time of the sc. The magnetic perturbation began at DE 1 at 1617:38±:05 UT with distinct changes in both the total field strength and the field orientation (Figure 6*b*. The SFR spectrogram shows a sporadic band of emissions in the range 2-6 kHz prior to the sc. At the time of the sc, both the upper and lower frequency limits of the emissions band increased by a factor of approximately 1.5. The wave growth onset occurred between 1617:32 and 1618:04 UT (the resolution limit of the instrument), and the total growth at 3 kHz was approximately 15 dB. There is some evidence of weak emissions near 100 kHz beginning at about 1622 UT.

January 9, 1983. Figure 4 shows an sc on January 9, 1983 for which a transient enhancement in the wave amplitude was observed at South Pole, Siple, and Palmer. The enhancement began at 1543:44±:05 UT at South Pole, lasted approximately 6-8 min, and was followed by wave activity which differed considerably from that prior to the sc. The magnetic perturbation began at South Pole at 1544:28±:02 UT. DE 1 was located at L=5.1, 0355 MLT, −36° MLAT at the time of the sc. The magnetic perturbation began at DE 1 at 1544:28±:10 UT with an abrupt decrease in the declination and a small but clear increase in the total field strength (Figure 6*c*. The SFR spectrogram shows an amplitude increase of about 15 dB in the band 100 Hz to 2 kHz starting between 1544:20 and 1544:52 UT (the resolution limit of the instrument). At approximately 1547 UT, emissions were observed to begin in the band 80-400 kHz.

April 16, 1982. Figure 5 shows an sc on April 16, 1982 for which wave activity lasting over 40 min was triggered at both South Pole and Siple. The enhancement began at 1701:23±:10 UT at South Pole. The magnetic perturbation began at South Pole at 1701:53±:05 UT. DE 1 was located at L=4.3, 2100 MLT, −17° MLAT at the time of the sc. The magnetic perturbation began at DE 1 at 1702:45±:20

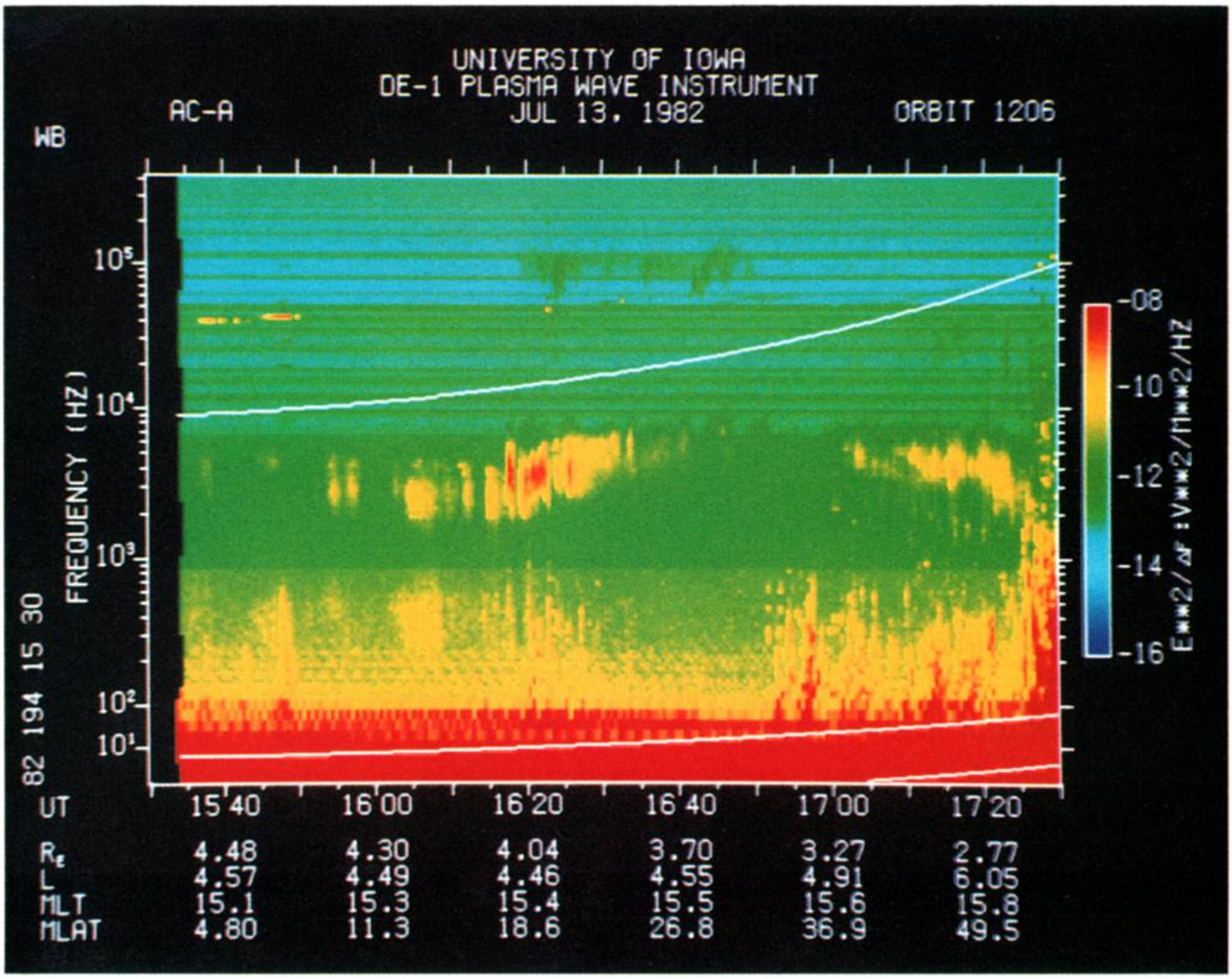

Figure 3. Plasma wave data recorded on board DE-1 during the sc of July 13, 1982.

with an increase in the field strength and a modification of the field direction (Figure 6*d*. The SFR spectrogram shows an amplitude increase beginning in the band 200-500 Hz between 1702:40 and 1703:12 UT (the resolution limit of the instrument) with total growth of 10-15 dB in the band 200 Hz to 2 kHz by 1705 UT.

3.3. *General Observations*

As illustrated by the four examples, the amplitude and spectral response of wave activity during the sc's varied considerably from event to event and exhibited a fairly complex structure both in frequency and in time. The limited sample of 14 events with changes in wave activity prevented a comprehensive characterization of the wave growth, but a number of consistent or otherwise interesting features were identified. Quantitative measurements of these features for wave activity at frequencies less than the local electron gyrofrequency are summarized in Tables 1 and 2.

Each of the 14 events exhibited distinct changes in wave amplitude. Increases in amplitude were observed in 10 of the events and decreases in 4. The duration of the changes, defined loosely as the period over which a deviation in amplitude from the preevent level was observed, was typically 1-10 min, but in several cases was longer than 30 min. The identification of an event duration is somewhat subjective since it is necessary to separate temporal variations in wave activity from possible spatial variations caused by the orbital motion of the spacecraft. The occurrence of an amplitude increase or decrease was not correlated with the sign of the magnetic field change. Magnetic field strength increases were observed at DE 1 in 5 of the 14 events for which data were available, decreases were observed in 3 events, and no change was detected in 6 events. The field strength and wave amplitude changes had the same sign in 4 events and different signs in 3 events. In Table 1, the bandwidth over which growth was observed and the maximum total narrow-band growth are given for emissions which occurred during the first 2 min after the growth onset. The maximum narrow-band growth (or loss) was in the range 10-30 dB for all events except January 29, 1982. The January 29 event exhibited a short (one 32-s sweep period) enhancement of 70 dB at 18 kHz (roughly $\frac{3}{2} f_H$) and 30 dB at frequencies below 1 kHz. The

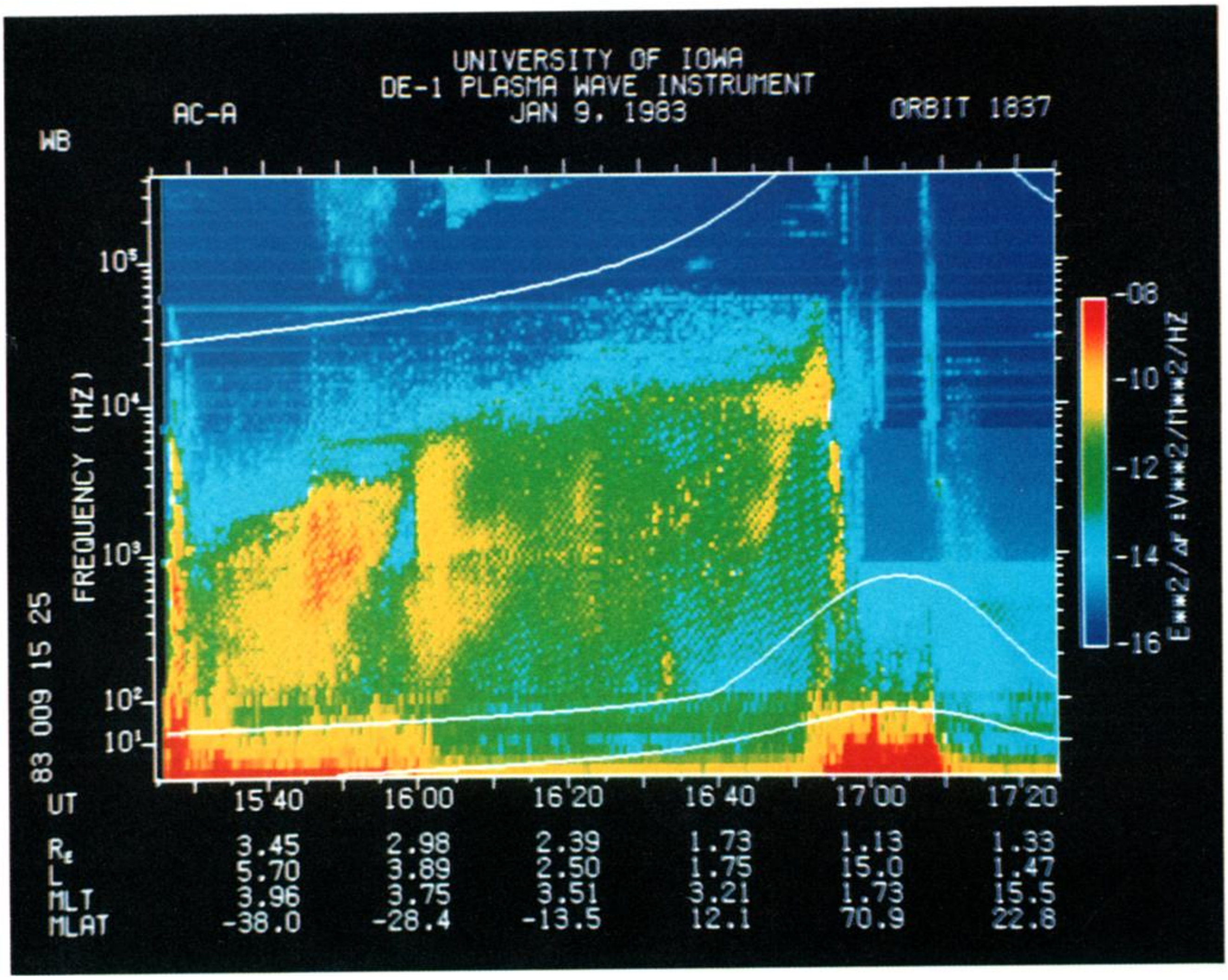

Figure 4. Plasma wave data recorded on board DE 1 during the sc of January 9, 1983.

event was unusual among those studied because of the relatively narrow-band nature of the wave activity above f_H as well as the impulsive spectral characteristics. The frequency and bandwidth of the 18-kHz emissions were similar to the well-documented $\frac{3}{2}f_H$ emissions [*Hubbard and Birmingham*, 1978], although such emissions are most commonly observed at latitudes less than 10° and DE 1 was at 24°.

In each of the events, spectral modifications were associated with the amplitude changes. The wave growth was observed primarily at frequencies below the local electron gyrofrequency. The exceptions included the $\frac{3}{2}f_H$ emissions in the January 29 event, emissions at 25-80 kHz in the October 26, 1982 case, and the 80-400 kHz emissions noted in five of the examples (the location of DE 1 during these events is indicated by solid circles in Figure 1). The growth usually occurred at frequencies associated with previously existing bands of emissions. In three of the four examples (Figures 2, 3, and 5) given in section 3.2 the dominant wave activity in the ELF-VLF band was characterized by a spectrum with well-defined upper cutoff frequency (UCF). In each example the UCF was approximately constant (excluding the step-like increase associated with the sc in Figure 3) for 60 min or more around the time of the SC, whereas the local electron gyrofrequency varied by at least a factor of 2. This information is used in the next section to help determine the location of the wave source region. There was no clear correlation between the wave growth characteristics and spacecraft local time.

The well-defined onset of the magnetic disturbance during sc provided the opportunity for comparison between onset times of the magnetic disturbance and the wave growth. The onset times for the 14 sample events are given in Table 2. In eight of the nine events for which both SFR and MAG-A data were available, the wave growth and magnetic disturbance onsets were simultaneous to within the time resolution of the instruments. The wave growth onset at DE 1 typically occurred at least 30-60 s after the wave growth onset was observed at South Pole. The significance of the relative onset times is discussed in the next section.

4. Discussion

4.1. Wave Modes

Since only electric field data were available for this analysis, a definitive identification of wave modes associated with the observed wave growth was not possible. Based on the

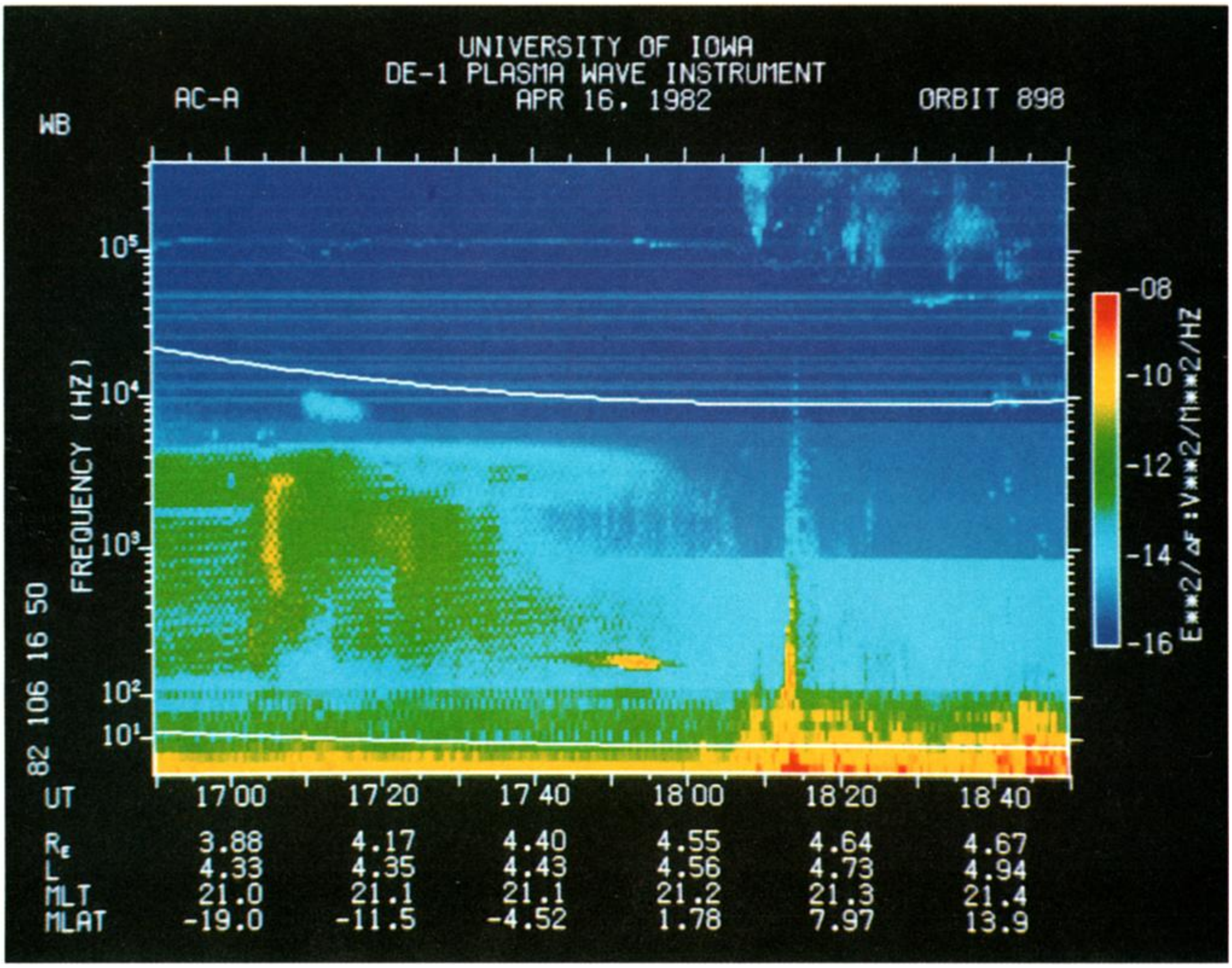

Figure 5. Plasma wave data recorded on board DE 1 during the sc of April 16, 1982.

frequency limitations and the spectral characteristics, we believe that the majority of the observations are consistent with waves propagating in the whistler mode. The observed emissions at frequencies above the local electron gyrofrequency represent exceptions. The $\frac{3}{2}f_H$ emissions are generally attributed to an electrostatic instability [*Hubbard and Birmingham*, 1978]. The 80 to 400-kHz emissions appear to be auroral kilometric radiation (AKR) [e.g., *Gurnett*, 1974].

4.2. Location of Source Regions

Of particular interest for any analysis of the wave growth mechanism is an identification of the wave source region. It might be expected that any spatial dependence in the characteristic features of the wave growth reflects the effects of temporal and spatial variations in the sc disturbance on the wave growth process [e.g., *Perona*, 1972] since the sc disturbance requires several minutes to propagate from the subsolar magnetopause to the magnetotail and the amplitude of the magnetic perturbation is generally larger at local noon than at midnight [*Kuwashima and Fukunishi*, 1985]. The position of the observation alone, however, provides only limited information about the location and extent of source regions, due to the ability of the spacecraft to detect waves originating in distributed regions. Additional information, such as the onset time of the wave growth, the occurrence distribution, and the spectral characteristics, must be used to help identify the source regions.

Onset time. In paper 1 it was suggested that the onset of wave growth at South Pole corresponds to wave generation in the region near local noon. The observed delay between the wave growth onset at South Pole and the arrival of the magnetic disturbance at DE 1 is comparable to the expected propagation delay of the magnetic disturbance from the noon region to the location of DE 1 in each case except for November 7, 1983. It thus appears that wave growth observed by DE 1 was not necessarily associated with the noon source region identified through ground-based observations. Instead, wave growth occurred only after the sc disturbance had propagated to the local time region of the spacecraft. The onset of the tentatively identified AKR emissions occurred with a delay of 2-5 min after the arrival of the magnetic disturbance at DE 1, suggesting that an sc-triggered intermediate process such as energization and precipitation of tail particles into the auroral region may be a prerequisite for the observed AKR generation.

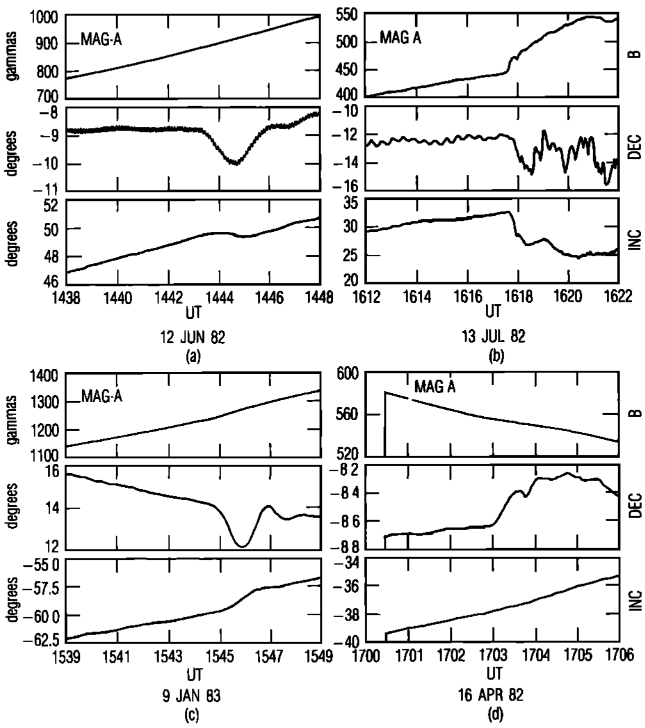

Figure 6. Magnetic field recorded on board DE 1 during the sc of (*a*) June 12, 1982, (*b*) July 13, 1982, (*c*) January 6, 1983, and (*d*) April 16, 1982. The high frequency variation in Figure 6*a* is due to modulation by the spacecraft spin. The labels B, DEC, and INC refer to the magnetic field strength, the declination (from north) of the projection of the field vector on the horizontal plane of the spacecraft, and the inclination of the field vector from the horizontal plane.

Occurrence distribution. The observation of wave growth at nearly all local times suggests that the wave growth process associated with sc is not limited to the dayside region, as had been previously suggested by both observational [*Korth et al.*, 1985] and theoretical [*Perona*, 1972] work. This result is, however, consistent with observations by ground-based receivers of such activity on the nightside as well as the dayside (see paper 1). Taken together with the onset time relations discussed above, the result indicates that triggering of wave growth by the passage of the sc disturbance may be possible at all local times.

Spectral characteristics. The tendency of the UCF to be independent of the local gyrofrequency provides restrictions on the location of the wave source region. If the UCF is a function of the electron gyrofrequency within the source region, then the waves could not have been generated locally. If the UCF is a function of other parameters, such as the electron distribution, local generation requires that the parameters be approximately constant over the spatial region traversed by the spacecraft. The relatively small L shell region traversed by DE 1 during each of the observations suggests the possibility that the UCF is more closely associated with the equatorial gyrofrequency of the field lines passing through the spacecraft than with local parameters. In each of the three examples for which little UCF variation was observed, UCF was approximately equal to the equatorial half-gyrofrequency. The observed UCF can thus be explained by invoking a wave source region located near the equator on field lines passing close to the spacecraft. This result, although not strongly supported, is consistent with the conclusions of paper 1 as well as previous work emphasizing the role of the equatorial region in the generation of whistler mode waves [e.g., *Helliwell*, 1967].

4.3 Comparison With Ground Observations

The spacecraft observations discussed here both support and complement the ground-based results presented in paper 1. The results of both studies indicate that waves can be generated at all local times as a result of the sc. The onset times of the wave growth observed by DE 1 suggest that growth in a given local time region is closely associated with the arrival of the sc disturbance, a feature which is consistent with but could not be directly ascertained from the ground data. The 1 to 10-min event duration corresponds closely to

Table 1. Measured Values for Wave Growth Characteristics Observed During sc at DE 1.

Date	UT	L	MLT	MLAT deg.	f_H kHz	Growth Bandwidth, kHz	Total Growth, dB
Jan. 29, 1982	1744	5.5	0150	24	11	0.1-0.3	30
March 1, 1982	1138	3.5	0005	-7	21	0.2-3	10
April 16, 1982	1702	4.3	2100	-17	16	0.2-2	15
June 9, 1982	0040	4.6	1806	-30	27	saturated	increase
June 12, 1982	1443	4.5	1735	30	25	saturated	25
July 13, 1982	1617	4.5	1525	17	13	2-10	15
Oct. 26, 1982	0029	11.4	0839	-50	15	0.4-2	15
Jan. 9, 1983	1544	5.1	0355	-36	34	0.1-2	15
Feb. 4, 1983	1614	1.7	1340	10	224	0.1-2	-10
March 1, 1983	1154	2.2	1200	-5	108	0.2-3	-20
Oct. 6, 1983	1241	3.4	2150	13	26	0.5-2	-30
Nov. 7, 1983	1140	4.0	2006	9	15	0.1-2	10
Nov. 11, 1983	1110	4.0	1950	18	22	6-8	25
March 6, 1984	0820	4.6	1148	11	11	2-4	-15

Table 2. Measured Values for Wave Growth and Magnetic Perturbation Onset Times at DE 1 and South Pole.

Date	SFR Onset, UT	South Pole ELF-VLF Onset, UT	South Pole Magnometer Onset, UT	MAG-A Onset, UT
Jan. 29, 1982	1745:52-1746:24	1743:47±:02	1744:17±:05	1746:05±:10
March 1, 1982	1140:20-1140:52	1137:25±:02	1137:53±:02	1138:20±:10
April 16, 1982	1702:40-1703:12	1701:23±:10	1701:53±:05	1702:45±:20
June 9, 1982	0039:40-0040:12	0039:35±:15	0039:50±:05	no change
June 12, 1982	1443:16-1443:48	1442:23±:02	1442:42±:02	1443:20±:10
July 13, 1982	1617:32-1618:04	no change	1617:20±:10	1617:38±:05
Oct. 26, 1982	0029:03-0029:35	no change	0029:30±:05	0029:05±:10
Jan. 9, 1983	1544:20-1544:52	1543:44±:05	1544:28±:02	1544:28±:10
Feb. 4, 1983	1614:20-1614:52	1613:50±:02	1614:18±:01	1614:35±:10
March 1, 1983	1153:16-1153:48	1153:40±:10	unclear	no change
Oct. 6, 1983	1243:52-1244:24	1241·00±:30	1241:40±:30	no change
Nov. 7, 1983	1142:00-1142:32	1135:00±:30	1135:40±:30	no change
Nov. 11, 1983	1110:52-1111:24	1110:00±:10	1110:15±:20	no change
March 6, 1984	0819:23-0819:55	unavailable	unavailable	0819:20±:10

the 1 to 8-min transient enhancement commonly observed at ground stations and the 10 to 30 dB growth range is comparable to the ground-based values of 12-29 dB. Wave activity at ground stations was observed in 33 of the 50 sc studied (no ground data were available for 2 sc) and in all but one of the events for which emissions were observed on board DE 1. It is not clear from these limited results how the source regions for waves observed by DE 1 are related to source regions for waves observed on the ground.

5. SUMMARY

Changes in wave amplitude and spectra were observed by DE 1 in 14 out of 50 sc during the 1982-1984 period. The changes were most commonly associated with observations at L shells in the range $3 < L < 6$, having been detected in 61% of sc when DE 1 was in this region but only 25% of sc for $L < 3$ and 4% of sc for $L > 6$. No clear correlation between occurrence probability and local time or magnetic latitude could be identified. The characteristics of the amplitude and spectral modifications were fairly complex and varied considerably among events. Narrow band growth in the range 10-30 dB was typical. In the majority of cases, the waves appear to be electromagnetic whistler mode, although there is some evidence of electrostatic emissions at $\frac{3}{2}f_H$ as well as AKR. Comparison of the growth onset time with the arrival time of the magnetic perturbation suggests that the whistler mode wave emissions are generated in the local time region of the spacecraft, possibly near the equatorial plane. The results are generally consistent with the comprehensive observations from ground-based stations presented in the accompanying paper.

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