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EXOS-B/SIPLE STATION VLF WAVE-PARTICLE INTERACTION EXPERIMENTS: 1. GENERAL DESCRIPTION AND WAVE-PARTICLE CORRELATIONS

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Abstract. In situ measurements of both energetic particles and VLF waves have been carried out in a joint program involving the Japanese satellite EXOS-B and the Siple Station VLF transmitter. A general description of the experiment is given as well as some results concerning wave-particle correlations. Detailed analysis of the observed wave characteristics is given in a companion paper. Correlations of electron flux and pitch angle anisotropy in the energy range from 85 eV to 6.9 keV with waves in a range from 300 Hz to 9 kHz are examined. These electrons sometimes have a pitch angle distribution with a peak flux at 90° pitch angle (so-called pancake distribution). On five passes out of a total of 50 during the summer campaign in 1979, the energy of the electrons that showed a high pitch angle anisotropy shifted upward as the satellite moved into the plasmasphere, crossing the plasmapause in the equatorial region. In two cases out of five, strong Siple signals were observed in the geomagnetic equatorial region just outside the plasmapause, in association with such a pancake pitch angle distribution of electrons. The Siple signals are most likely amplified by the cyclotron instability due to the high pitch angle anisotropy (HPAA), although the flux of resonant electrons was relatively small. For three other cases of HPAA, the satellite location was so far away from the Siple meridian that the signal level, even if amplified, was too weak to be detected by the satellite. Emissions associated with Siple signals were detected on five (two equatorial and three high latitude) passes, which were all confined on 6 days after a large magnetic storm. On the days when the Siple triggered emissions were observed, the pitch angle anisotropy was low, but the electron flux at resonant energies in the equatorial region was four or five times larger than that on other non-triggering days in all energy channels from 85 eV to 6.9 keV.

1. Introduction

VLF emissions triggered by manmade VLF signals transmitted from the ground have been observed for more than 15 years [Helliwell et al., 1964] but their generation mechanisms are still in question, even though there is a fairly general agreement among researchers that they are caused by nonlinear waveparticle interactions in the magnetosphere (see Matsumoto [1979] for review). In order to study these interactions under controlled conditions a high-power VLF transmitter connected to a 21 km dipole antenna was installed by Stanford University at Siple Station, Antaractica [Helliwell and Katsufrakis, 1974]. Ground observations of the output of the injected VLF waves and of the associated triggered emissions have been made at a magnetically conjugate station, Roberval, Quebec, Canada; these data have revealed many interesting new facts concerning nonlinear mechanisms of wave growth and triggering in the magnetosphere (e.g., Helliwell [1979] for review). However, the ground observations give only indirect information concerning the wave amplitude or the energetic electron distribution function in the emission generation region.

In the present paper we report the first simultaneous measurements of Siple transmitter signal amplitude and energetic electron flux near the Siple-Roberval meridian during wave injection experiments. These measurements have been carried out by using the Japanese satellite EXOS-B (Jikiken) in the interval July 1979-January 1980. A preliminary short report of this experiment has been given elsewhere [Kimura et al., 1981a,b], and selected data have been published in a form of data book [Kimura et al., 1981c]. Similar experiments using the Explorer 45, IMP 6 and ISEE 1 satellites have been performed in the past and have yielded interesting results [Inan et al., 1977; Bell et al., 1981]. In particular, the results showed the details of the frequency spectra of triggered emissions, which had never previously been revealed by ground observations. However, these experiments gave information concerning the energetic particle distributions for energies only above 25 keV.

The EXOS-B/Siple Station joint experiments were carried out in two different periods, one in summer (July, August, and September 1979) and the other in winter (December 1979-January 1980). The telemetry signal from EXOS-B was tracked at the NASA station in Rosman, North Carolina, in the summer campaign. The telemetry signals received at Rosman were sent to Stanford University in real-time by means of a telephone line. Workers at Stanford University then communicated with Siple Station by using a real time ATS 3 satellite link. This communication system thus enabled us to perform a closed loop active experiment, i.e., EXOS-B → Rosman → Stanford → Siple → EXOS-B. Therefore, we could change, for example, transmitter power and frequency format on a real-time basis while monitoring the wave and particle activities. In the winter campaign, the telemetry data acquisition was made at the NASA stations in Quito and Santiago.

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Studies of wave-particle correlations, based on in situ satellite observations, are important in understanding the generation mechanisms of various plasma waves, and the dynamics of energetic particles in the magnetosphere. In the past, several satellite studies have been made on the relationship between natural VLF emissions and energetic particles (see for example, Thorne et al. [1973,1977], Tsurutani and Smith [1977], Anderson and Maeda [1977], Baker et al. [1981] and relevant references cited in their papers). These studies have provided important information on wave particle interactions taking place in the magnetosphere. However, no satellite study on the relationship between energetic particles and coherent VLF signals using in situ measurements for both particles and waves has yet been made.

The present paper mainly describes the correlations between energetic electrons in the energy range from 85 eV to 6.9 keV and VLF signals transmitted from Siple Station. Detailed wave characteristics are discussed in a companion paper by Bell et al. [this issue] (hereinafter called paper 2). Results reported here are limited to those obtained in the summer period. The correlations between natural VLF emissions and particles and data observed in the succeeding winter (austral summer) period are still under study.

In section 2, a brief description is given of the VLF receiver and particle detector onboard the EXOS-B satellite. Section 3 gives a general description of the experimental results. The particle pitch angle anisotropy and its correlation with Siple signal amplitude is described in section 4. The relationship between Siple triggered emissions and the energetic electron distribution is discussed in section 5. Section 6 is devoted to discussion and conclusions.

2. Instrumentation

The EXOS-B (Jikiken) satellite was launched on September 16, 1978, from Kagoshima Space Center. The orbit is eccentric with an apogee $\sim$30,000 km, perigee $\sim$250 km and an inclination $\sim 31^{\circ}$. A wideband VLF receiver (0.3-9 kHz), and electron flux detector (4 eV-6.9 keV) were onboard the satellite along with other diagnostic instruments [Matsumoto et al., 1981; Kubo et al., 1981]. For Siple signal reception, a 103 m tip to tip dipole antenna was used. The receiver had a dynamic range of 50 dB at each of two gain settings, separated by 20 dB. The receiver saturation level was 3.5 μV/m at 5 kHz for the high-gain case and 35 μV/m for the low-gain case.

The collimator window for the electron flux detector was directed perpendicular to the satellite spin axis, with a width of 4° in the polar direction and of 13° in the azimuthal direction. In order to deduce the pitch angle distribution from the measured particle flux, it is required to determine the absolute direction of the satellite spin axis. The spin axis direction was to be determined by data from the magnetometer (MGF) and sun sensor (SAS) onboard the satellite. Unfortunately, however, the operation of the magnetometer became degraded after December, 1978. Therefore in our analysis it was necessary to use sun sensor data, in conjunction with certain symmetry properties of particle flux, in order to determine the pitch angle distribution in a self-consistent manner. In this method, the direction of the satellite spin axis was first determined that could give rise to the observed pitch angle distribution. Then the condition was applied that the pitch angle distribution must be symmetric about 90°. The further condition that the spin axis must be directed in nearly the same direction for at least several days, allowed a unique determination of the spin axis direction, because the satellite precession angle was sufficiently small. A similar technique was used by Baker et al. [1981] for the spin axis determination for a geostationary satellite. Therefore, in case that the flux does not show any clear periodic fluctuation synchronized with the satellite spin motion the pitch angle distributin can not be determined.

The pitch angle distribution thus determined does not always cover the whole pitch angle range from 0° to 180°, but rather a limited range, say from 40° to 140°, although it always covers a range around 90°. The lowest and highest measurable pitch angles depend on the spin axis direction of the spacecraft in reference to the geomagnetic field direction.

3. General Description of the Experimental Results

Siple Station is located at 84°W and 76°S geographic (5°W geomagnetic; $L \sim 4.2$). Since the Siple signals are expected to propagate primarily in the vicinity of the Siple meridian, the experiments were performed only for satellite passes which lay within $\pm 60^{\circ}$ of the Siple longitude, on L shells in the range $2 < L < 5$, and at latitudes near the geomagnetic equator, for the period from July 15 to August 12. Beginning on August 14, high geomagnetic latitude passes as well as the equatorial passes were selected. This change was made because the equatorial passes were all located in the afternoon sector, whereas on the ground, the rate of occurrence of Siple triggered emissions peaks in the early morning hours [Carpenter and Miller, 1976].

Summaries of the tracked orbits in the summer experiments are illustrated in Figure 1 where the satellite local time (SAT-LT), geomagnetic longitude (GM-LONG) and latitudes (GMLAT), and L values are plotted. The passes on which Siple signals were observed are marked by open circles in the longitude column and those on which VLF emissions were observed are marked by solid triangles in the local time column. Siple signals were detected on about 50% of the passes, and VLF emissions triggered by Siple signals were observed on August 14, 15, 17, 18, and 19, these passes being marked by an asterisk in Figure 1 in the latitude column.

Out of 50 passes in the summer campaign, whistlers were detected on 29 passes, which corresponds to about 58% in occurrence probability. On the other hand, out of 25 passes on which Siple signals were detected, whistlers were detected on 18 passes. The occurrence probability is thus 72% which is higher than the 58% of general whistler detection. This tendendy may imply that the detection of Siple signals is dependent on the conditions of whistler mode propagation through

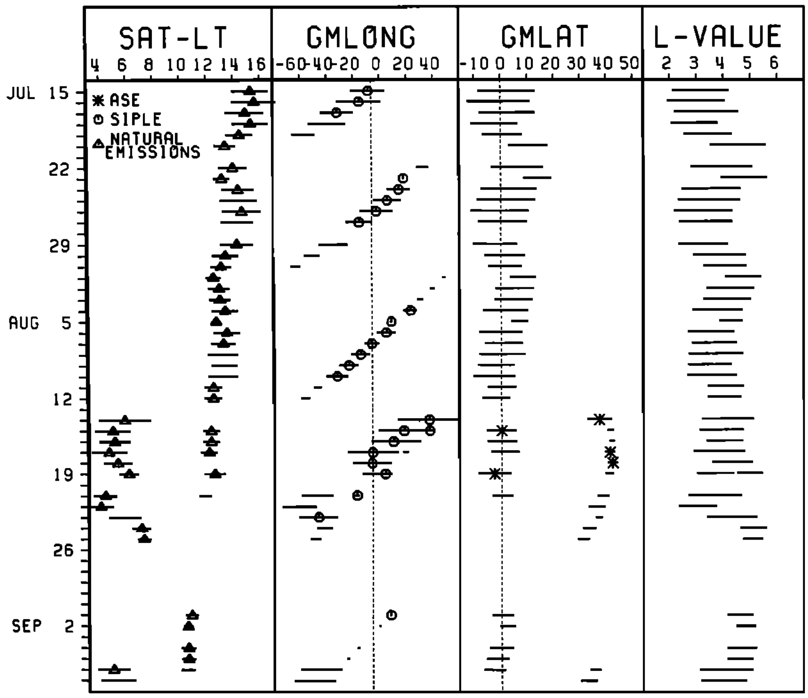

Fig. 1. Summary of the orbits during the EXOS-B/Siple Station joint experiments made in the period from July 15 to September 7,1979.

the ionosphere and magnetosphere to the satellite.

For the passes on which Siple signals were observed continuously, the duration of the signal detection was examined for the equatorial passes in the summer period. There were 8 cases in which the duration was less than 5 minutes, 1 case in which the duration was between 5 and 10 minutes, 5 cases between 10 and 15 minutes, and 4 cases between 15 and 30 minutes. In the statistics, each detection isolated by meaningful time intervals (longer than several tens of seconds) on.one pass was counted as a separate case.

As to the geomagnetic activity in relation to the observed passes, Figure 2 indicates the Kp indices during the experimental period. It is very interesting that four passes out of the five passes on which Siple triggered emissions were detected are concentrated in a geomagnetically very quiet period, just after a large magnetic storm on August 13.

Electron pitch angle distributions during the Siple triggering events were generally not highly anisotropic with rather high flux density for a wide energy range, whereas intense Siple signals not associated with triggered emissions were observed when the electron pitch angle distribution was highly anisotropic.

4. Amplification of Siple Signals Associated with Pancake Pitch Angle Distribution.

Siple signals were detected by EXOS-B mostly when the satellite was located within $\pm 25^{\circ}$ in geomagnetic longitude from the Siple geomagnetic meridian plane. The average intensity of the Siple signals was approximately 1 μV/m in this region. Assuming that the plasma frequency and cyclotron frequency were 65 kHz and 22 kHz, respectively, at $L \sim 3.4$, the refractive index at 5 kHz for longitudinal propagation becomes 6. Then the wave magnetic field corresponding to the above electric field is approximately 0.02 pT. The plasma frequency utilized is based on a diffusive equilibrium model, that accounts for the observed propagation time of the signal from Siple station to the satellite.

Data from two days, August 6 and 7, on which the satellite passes were quite close to the Siple meridian, are shown in Figures 3 and 4. These figures give simultaneous presentation of electron fluxes and corresponding wave dynamic spectra on a compressed time scale. In each figure, the VLF dynamic spectrum is shown in the upper panel in an f-t format with a frequency scale from 0 to 10 kHz. The electron flux in 8 energy channels is illustrated as a function of time below. On the left of each row, average energies of each channel are given, while on the right the maximum flux (top of the scale) in elec/(sr cm^2 s eV) is given. The scale for the electron flux is linear. On the horizontal axes are given UT, L value, geomagnetic latitude, local time, and local cyclotron frequency.

In Figure 3, it is evident that ELF noise below 1 kHz and a chorus band with a center frequency around the equatorial cyclotron frequency are coexisting. The latter is commonly seen outside the plasmapause [Dunckel and Helliwell, 1969]. A half cyclotron frequency gap is also seen in this chorus [Tsurutani and Smith, 1974; Anderson and Maeda, 1977]. In the August 7 event, as shown in Figure 4, strong ELF hiss for frequencies less than 1 kHz is also present. Figure 5 shows expanded spectrograms for the times indicated by arrows on the time axis of the wave spectrum panels in Figures 3 and 4.

These figures reveal an interesting feature of the energetic electron flux. In almost all energy channels, the electron flux is strongly modu-

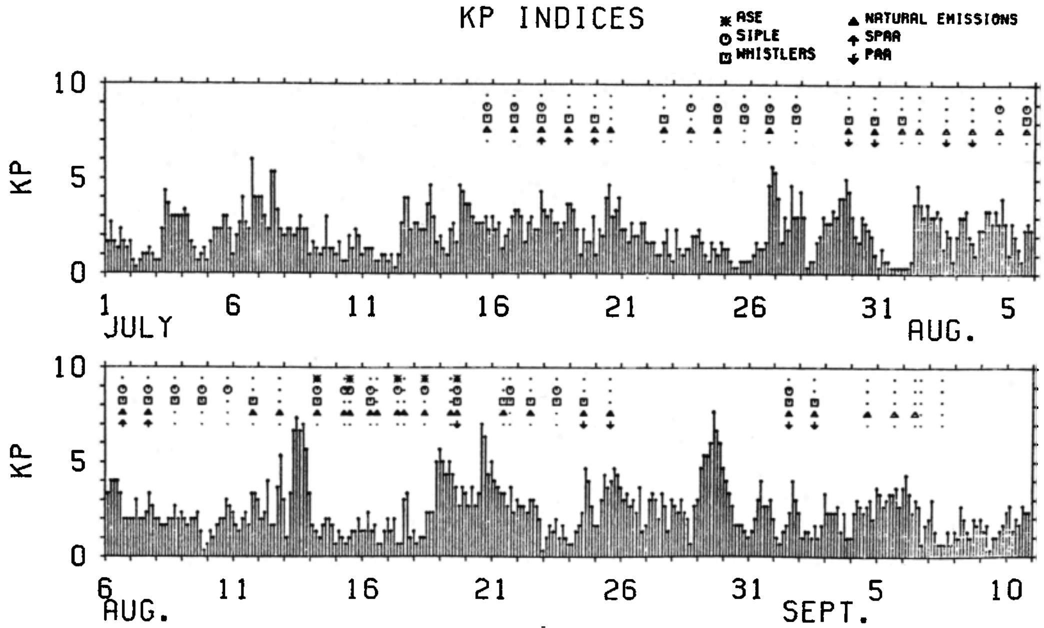

Fig. 2. Geomagnetic activity represented by Kp indices and summary results during the experiments. Detection of the Siple signal (open circles), whistlers (squares), natural VLF emissions (triangles), high pitch angle anisotropy or HPAA (upward-pointing arrows), and medium pitch angle anisotropy or HPAA (downward-pointing arrows) at the satellite are marked for each pass.

lated with a period of about 50 s, which is half of the spin period of the satellite. This means that the electron pitch angle distribution is highly anisotropic with respect to the geomagnetic field. Detailed analysis of the pitch angle distribution taking into account the satellite attitude with respect to the geomagnetic field shows that the peaks in each flux variation correspond to the flux in the direction of 90° pitch angle. Such a pitch angle distribution is usually called a 'pancake type' [Lyons et al., 1972; Lyons and Williams, 1975a,b]. In Figure 6a the observed pitch angle distributions for the August 6 case are shown for several different energies. In Figure 6b are shown the corresponding pitch angle distributions smoothed by a curve fitting technique. The fitting was made by assuming a form, $f(\alpha) = a_1 \sin^{m_1}\alpha + a_2 \sin^{m_2}\alpha$, where α is the pitch angle and a_1, a_2, m_1, and m_2 are the constants obtained by the fitting. Some sample val-

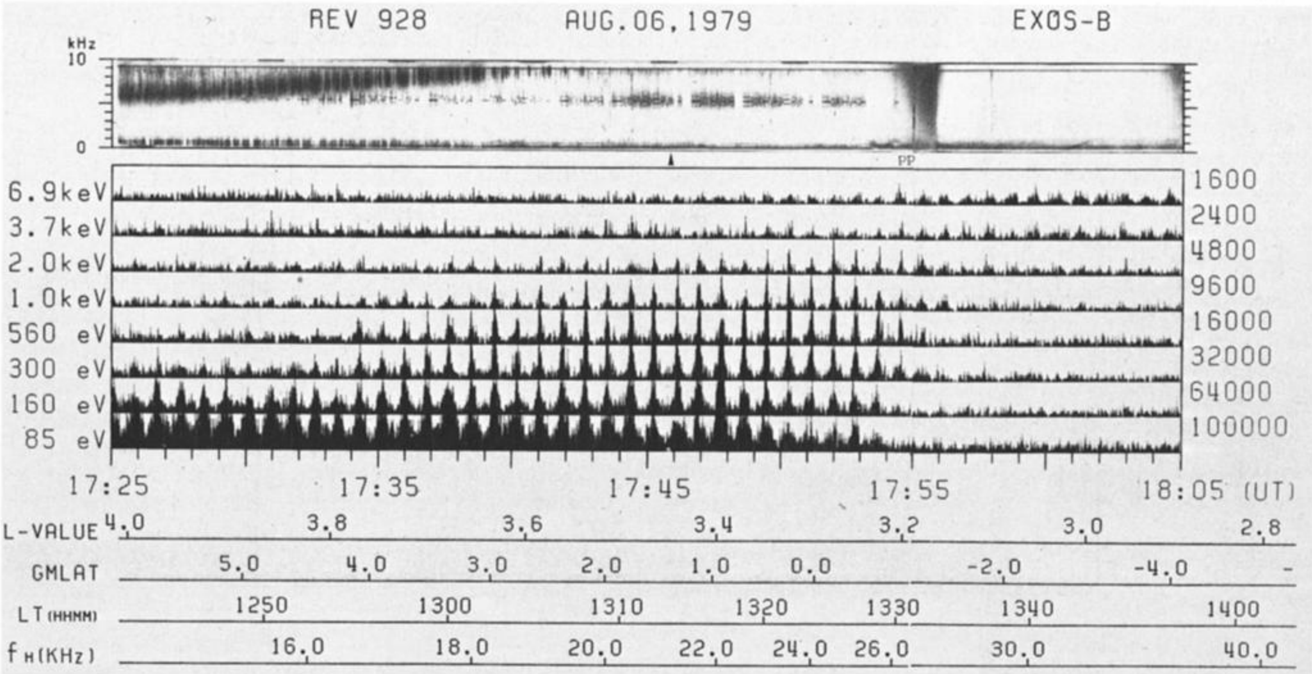

Fig. 3. Electron fluxes and corresponding VLF wave spectra on August 6. High pitch angle anisotropy (HPAA) is seen. Strong Siple signals are observed from 1732 to 1753 UT.

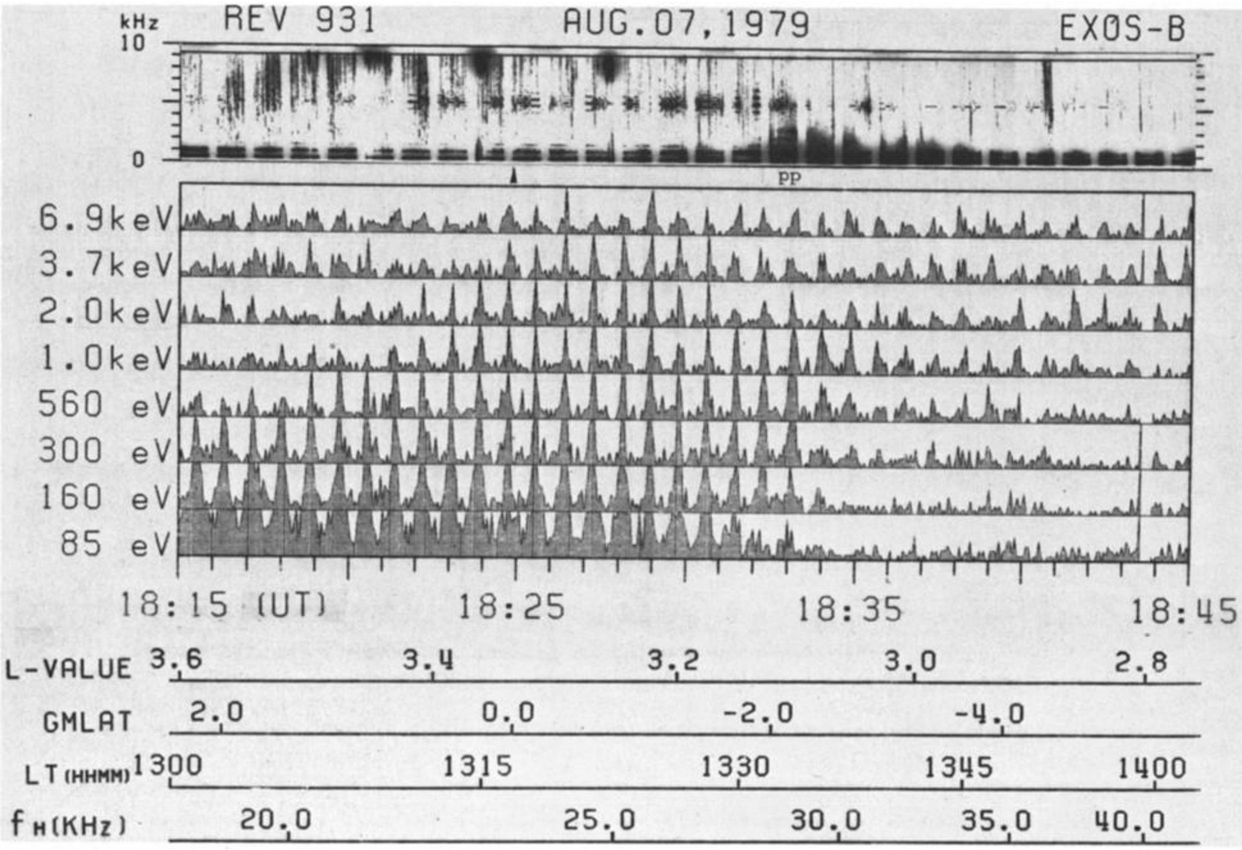

Fig. 4. Electron fluxes and corresponding VLF wave spectra on August 7. High pitch angle anisotropy (HPAA) is seen. Strong Siple signals are observed from 1821 to 1852 UT.

ues of these constants at two different time slots for the August 6 event are tabulated in Table 1. Sharper peaks show higher pitch angle anisotropy. As seen in these figures, the energy at which the anisotropy is maximum, shifts upward from the lowest (85 eV) to the highest (6.9 keV) energy channel as the satellite moves into the plasmasphere. The location of the plasmapause is marked by 'pp' in the upper panel of Figures 3 and 4 and was identified by a measurement of the antenna impedance at 22.3 kHz [Kimura and Hashimoto, 1981]. This impedance usually changes sharply during plasmapause crossings due to the change in the cold plasma density. The phenome-

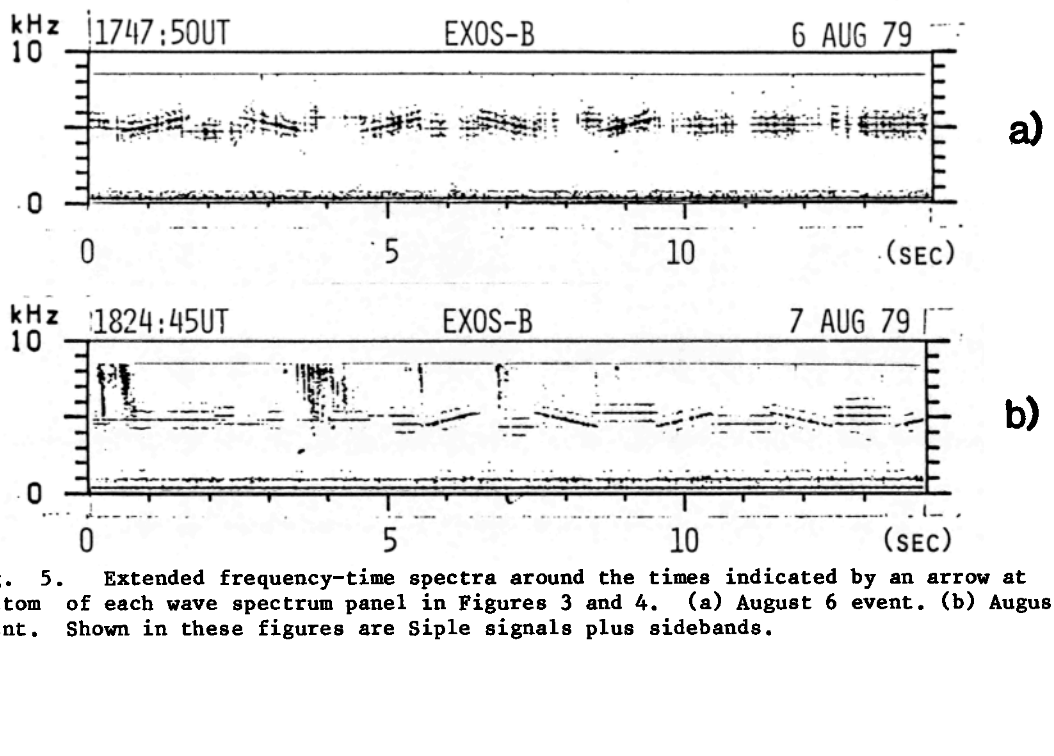

Fig. 5. Extended frequency-time spectra around the times indicated by an arrow at the bottom of each wave spectrum panel in Figures 3 and 4. (a) August 6 event. (b) August 7 event. Shown in these figures are Siple signals plus sidebands.

Table 2. Location of the Satellite Orbits on Which the Siple ASEs Were Detected

Date	Time UT	Satellite Local Time	Geomagnetic Latitude	Geomagnetic Longitude	Altitude km	L	f_H kHz	f_{Heq} kHz	Siple TX On, UT
Aug. 14,	0749	0415	41.6°	19.3°	5393	3.29	198.2	22.0	0745
1979	0759	0548	40.4°	41.3°	9355	4.03	83.7	12.5	0835
Aug. 15,	1357	1142	5.1°	35.4°	22053	4.57	9.3	9.0	1355
1979	1405	1150	3.9°	35.2°	21155	4.42	10.2	10.2	1451
Aug. 17,	0930	0436	42.9°	-5.7°	6348	3.83	164.9	19.7	0920
1979	0936	0512	43.1°	3.6°	7764	4.23	118.8	11.2	0945
Aug. 18,	1000	0411	42.0°	-21.1°	5562	3.48	201.4	20.9	1000
1979	1005	0445	42.9°	-12.8	6764	3.94	150.1	14.4	1025
Aug. 19,	1625	1144	3.4°	-1.2°	20330	4.27	11.3	11.3	1625
1979	1705	1242	-4.5°	3.2°	14324	3.32	23.9	24.1	1721
Siple*			-64.8°	-5.0°		4.1			

*Transmitted frequency: $f_c + 0.5 \sim f_c - 0.5$ kHz ($f_c = 5.05$ kHz)
Transmitted power: 130 $\sim$ 150 kW

Two cases (August 15 and 19) were observed in the vicinity of the geomagnetic equatorial plane, and three cases (August 14, 17, and 18) were observed at high geomagnetic latitudes around 40°N. The frequency of the Siple transmissions was 5.05 kHz for these events. This value was around half the local or equatorial cyclotron frequency (f_{Heq}) in the equatorial cases, and was nearly equal to or less than half the equatorial cyclotron frequency on the corresponding geomagnetic field lines in the high latitude cases.

Figure 8 gives simultaneous representation of

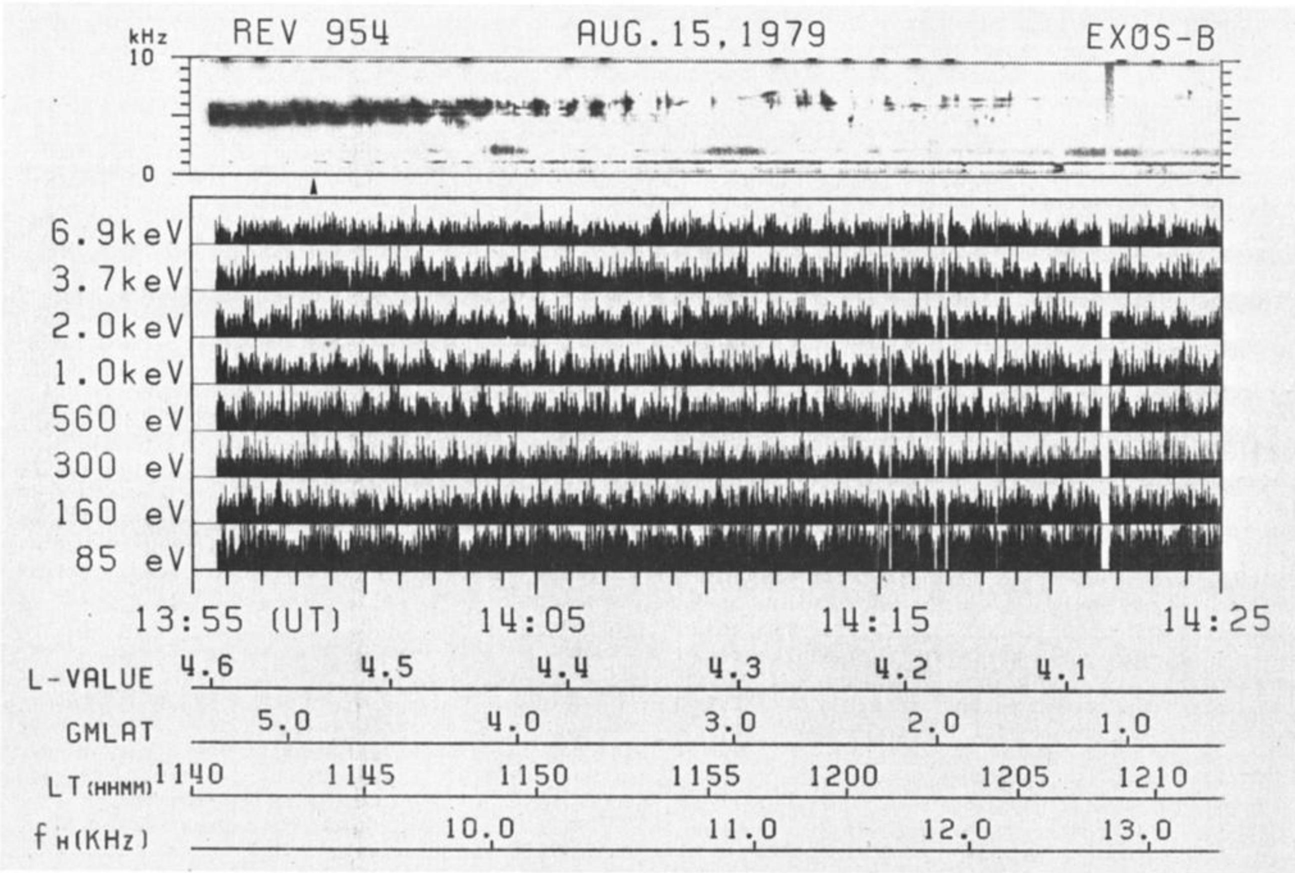

Fig. 8. Electron fluxes and corresponding VLF wave spectra on August 15. Triggered emissions are observed from 1355 to 1408 UT in the equatorial region. Characteristic features are high fluxes without high pitch angle anisotropy.

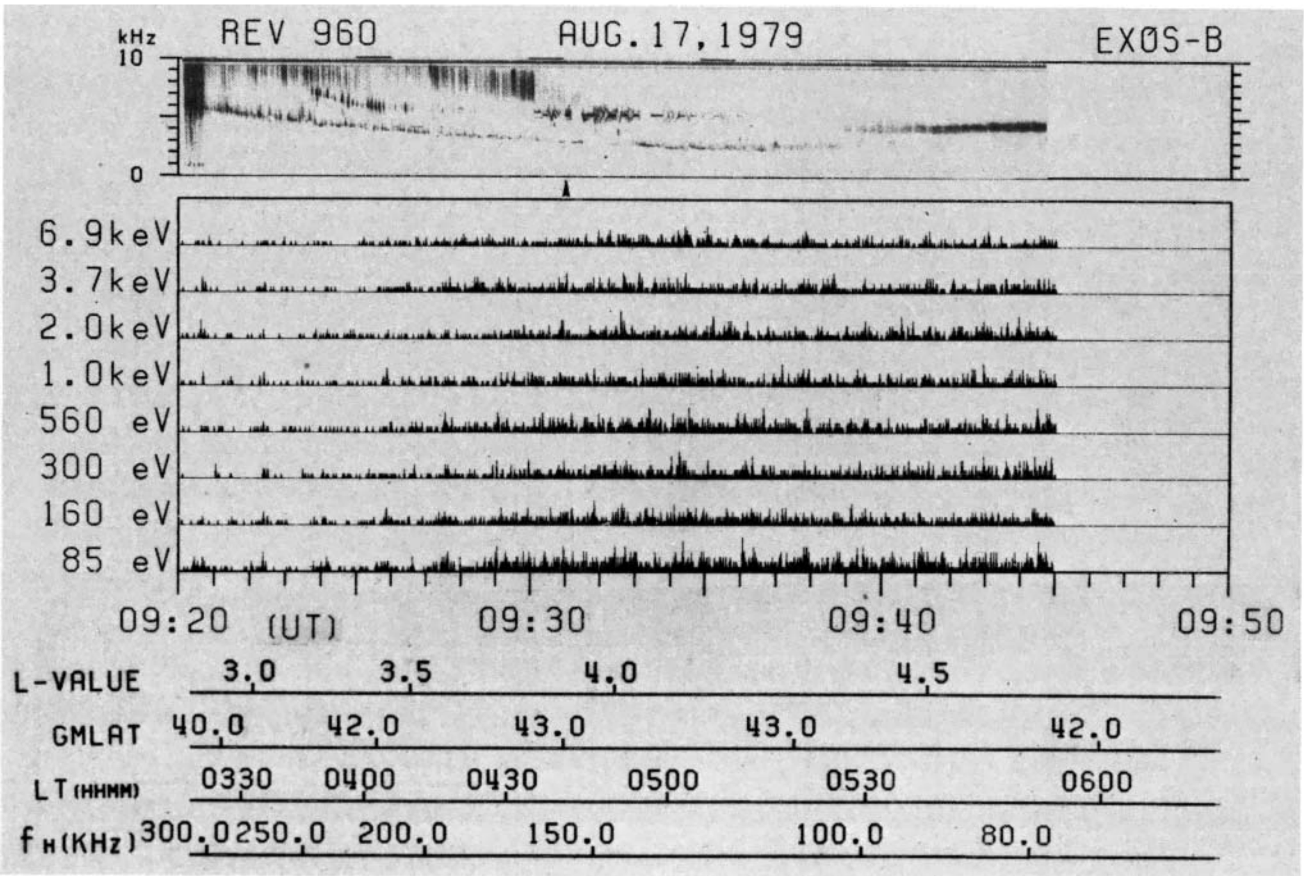

Fig. 9. Electron fluxes and corresponding VLF wave spectra on August 17. Triggered emissions are observed from 0930 to 0937 UT on the high latitude orbit. The enhancement of electron fluxes in all energy channels is seen only when the triggered emissions were observed.

the electron flux and corresponding wave dynamic spectra on a compressed time scale for August 15. For a part of the time portion, a detailed VLF spectrum is also shown in Figure 10a. In this case, triggering took place not by direct signals (a and b in the figure), but by echoing ones (a' and b'). In this event, the satellite traversed the equatorial region, and only low pitch angle anisotropy was observed but high fluxes were seen for all energy channels.

Figure 9 shows data observed on the high latitude orbit of August 17, on which triggered emissions were observed, a sample extended spectrum of which is shown in Figure 10b. It is evident that ASEs were triggered by direct signals. The geomagnetic latitude of the satellite location was around 40°N. In this case, the electron flux was much smaller than the equatorial case shown in Figure 8. However, a gradual enhancement of electron fluxes in all energy channels was seen during the time when the triggered emissions were observed from 0930 to 0937 UT. This enhancement continued until the end of the observation period.

On this day, the satellite observation began at 0920 UT, when Siple transmissions were at a frequency of 3.96 kHz. Up to 0930 UT only a weak signal was detected by the EXOS-B receiver. At 0930 UT the transmission frequency was shifted up to 5.05 kHz and almost immediately were observed strong Siple signals accompanied by triggered emissions.

The relationship between the Siple signals and the background emission spectra is interesting. As illustrated in Figure 11, at 0920 UT the natural noise consisted of only weak wideband hiss, whose lower cutoff frequency was near the local LHR frequency and whose upper cutoff was around half of the equatorial cyclotron frequency. When the Siple signals entered this weak hiss band at 0923 UT, the Siple signal was slightly intensified. At this time there was also a strong hiss band that appeared in the middle of the weak hiss band, and the center frequencies of these hiss bands were gradually decreasing as the spacecraft moved outwards. At 0930 UT, when the Siple frequency was increased, the new frequency fell into this strong hiss band. In addition to the flux increase mentioned above, such a situation might have improved the ability of the Siple signals to trigger ASEs.

At the Siple conjugate ground station, Roberval, Siple triggered emissions were observed at 0850, 0905, and 0920 UT by 1 min synoptic observation, and so unfortunately no simultaneous ground and satellite observations are available around 0930 UT. Triggered emissions were not seen in the 0935 UT recording at Roberval.

On a similar high latitude passes observed on August 14 and 18, Siple-triggered emissions were also observed, while the electron fluxes were about the same magnitude as those observed on August 17, when Siple signals were observed to trigger VLF emissions.

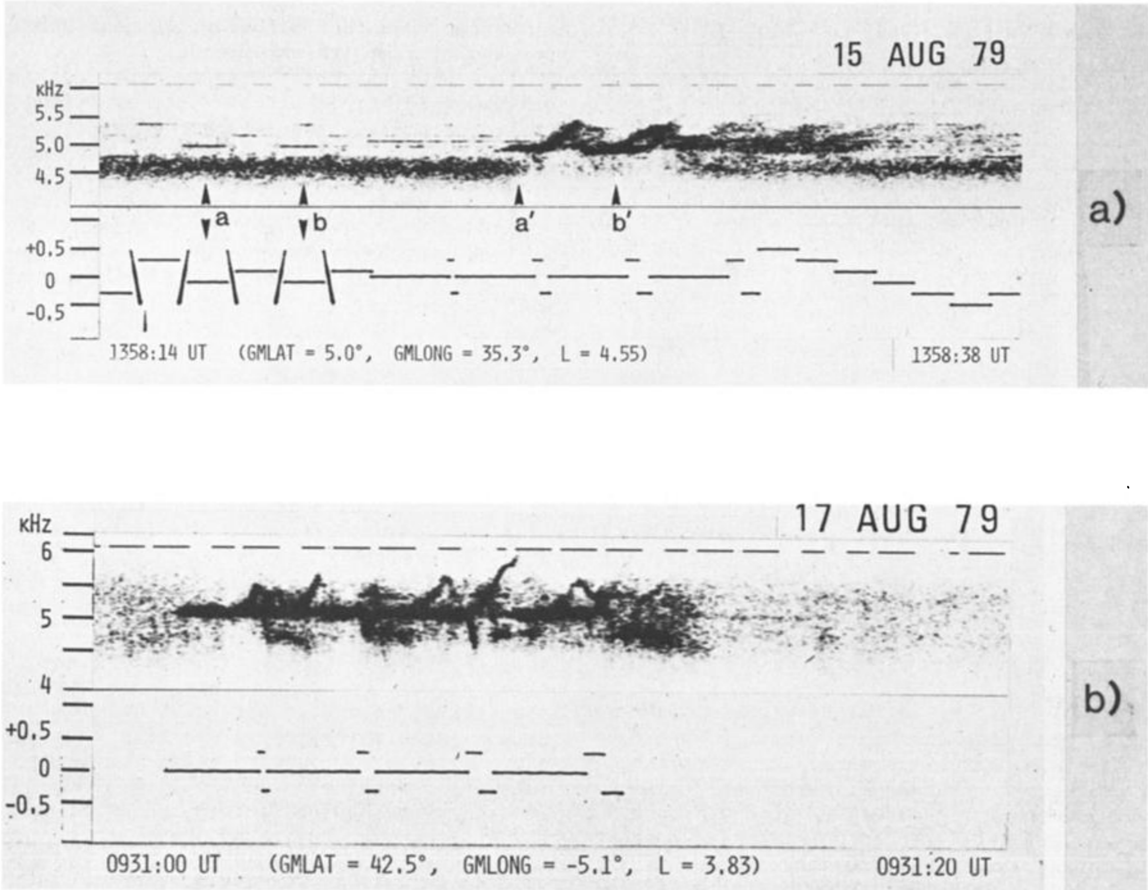

Fig. 10. Extended frequency-time spectra around the times indicated by an arrow at the bottom of each wave spectrum panel in Figures 8 and 9. (a) August 15 event (the signals indicated by arrows a and b corresponding to the direct signals and those of a' and b' being emissions triggered by the echoes of a and b). (b) August 17 event (emissions being triggered by the direct signals).

If the pitch angle distribution at the equatorial plane is not isotropic but peaked at 90° in pitch angle, the observed flux at a geomagnetic latitude of 40° will be much less than the flux at the equator for the same L value, taking into account the invariance of the magnetic moment. The high latitude events on August 14, 17, and 18 may actually be such cases.

From this point of view, for the August 14, 17, and 18 events, the electron fluxes at the magnetic equator on the same field lines may have been comparable with or higher than those observed on August 15 in the equatorial region. Therefore, one of the necessary conditions for ASE generation may well be a high flux of electrons in the energy range between 0.5 and 10 keV around $3 < L < 5$. This finding appears to complement the work of Anderson and Maeda [1977] in which it was found that naturally produced VLF emissions outside the plasmasphere were associated with enhanced intensities of low-energy electrons in the 1 to 10 keV range.

On August 19, the characteristics of the energetic electrons were rather different from those in the August 15 event, although in both events observations were made near the magnetic equatorial plane. On this day, emissions triggered by Siple signals were observed for about a 10-s period at 1705 UT, when the satellite was located at $L \sim 3.3$, and a geomagnetic latitude and longitude of 5°S and 3.2°E, respectively. At this time, the energetic electron flux was as low as one-half or one-third of that in the August 15 event for keV energy channels.

According to the detailed wave analyses discussed in paper 2, there was a whistler mode duct near $L \sim 3.3$ which appeared to have been involved in the generation of the ASEs that were observed on EXOS-B as well as at Roberval and Palmer stations. It was also found that EXOS-B did not pass through the duct although it did pass through the same L shell. If the duct was located near the Siple-Roberval meridian plane, the satellite would have been about 8° east of the duct. Such a difference in longitude may explain the somewhat lower electron fluxes observed at the satellite location.

At 1625 UT on the same day, a phenomenon showing entrainment interaction between Siple signals and whistler-triggered emissions was observed by EXOS-B (see paper 2). Around this time, energetic electron fluxes were $1.5 \sim 2$ times larger than those at 1705 UT, and some anisotropy in the pitch angle distributions was observed, which would result in a positive growth rate based on the Kennel-Petschek [1966] theory.

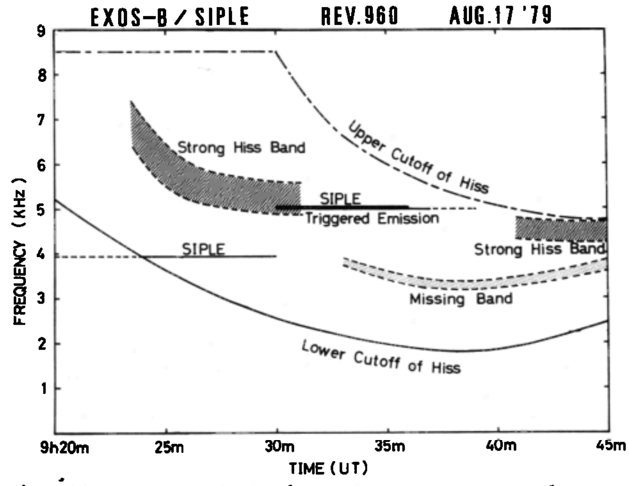

Fig. 11. A sketched view of VLF spectrum observed on August 17. The missing band refers to a portion of the spectrum, in which the noise level is very low.

6. Discussions and Conclusions

It was found that strong Siple signals observed within $\pm 10^{\circ}$ from the Siple meridian by the EXOS-B (Jikiken) satellite were well correlated with a pancake pitch angle distribution (called HPAA) of electrons with energies from 0.3 to 6.9 keV. When the HPAA structure in these energy channels disappears, the intensity of the Siple signal suddenly decreases. Such correlations were observed on two days, August 6 and 7, during equatorial passes outside the plasmapause.

As described in section 4, the calculated linear growth rate of waves at Siple transmitter frequencies was positive during the time that the Siple signals were intensified. The peak growth rates calculated were 5×10^{-6} on August 6 and 3.5×10^{-5} on August 7, which are values normalized by the angular electron cyclotron frequency. The corresponding e-fold times are 1.38 and 0.2 s for August 6 and 7, respectively.

It is noted that the HPAA is not a sufficient condition for detection of strong Siple signals. Even if an HPAA exists, the Siple signals could not be detected, if the signal intensity prior to the amplification is too low. Therefore, it is also necessary that the location of the spacecraft be within $\pm 10^{\circ}$ of the Siple meridian.

When the Siple signals triggered ASEs on the equatorial crossing pass of August 15, and on the high latitude pass of August 14, 17, and 18, large electron fluxes were found in all energy channels from 85 eV to 6.9 keV in the equatorial interaction region, although the pitch angle distribution above the lowest measurable pitch angle ($\sim 40^{\circ}$) was not highly anisotropic. However, when particle fluxes did not show any clear periodic fluctuation due to the satellite spin motion, the pitch angle distribution and thus the anisotropy factor could not be determined. Actually, on the above triggering events, it is evident that the particle fluxes were not constant with spin phase. Therefore it is possible that there existed a low but sufficient pitch angle anisotropy needed for triggering assisted by the high fluxes of resonant electrons.

We can draw the following two conclusions from our summer campaign experiment:

1. When high pitch angle anisotropy (HPAA) was observed, Siple signals were amplified but no triggered emissions were observed.
2. When a high flux of energetic electrons with a low pitch angle anisotropy was detected, triggered emissions were observed.

A possible interpretation of these facts is as follows. On days when the HPAA was observed, the flux of energetic electrons at resonant velocity was low because the flux of the energetic particles with $v_{\parallel} \simeq 0$ ($\alpha \simeq 90^{\circ}$) were dominant. However, a sufficient growth rate for Siple signal amplification was achieved assisted by the high pitch angle anisotropy, because the whistler mode growth rate is determined by the product of the particle flux at resonant velocity and the pitch angle anisotropy. On the other hand, triggering of emissions, which is believed to be caused by a nonlinear modification of the distribution function in velocity space [see, e.g. Matsumoto, 1979], could not be reached because the resultant nonlinear growth rate for triggering would be small owing to the low flux in the vicinity of the resonant velocity, even if the modification takes place. On the contrary, on triggering days the flux of energetic particles was high with low pitch angle anisotropy. The high flux at resonant velocity produces a large nonlinear growth rate after nonlinear modification of the gradient of the distribution function in velocity space, which produces triggered emissions. Therefore, the necessary conditions for triggered emissions are the existence of (1) a sufficiently high particle flux in the range of resonant energy with some anisotropy and (2) a sufficiently strong triggering signal intensity that could nonlinearly modify the distribution function.

These two conditions, however, cannot be necessary and sufficient for triggering because we have one example on September 1 when no triggered emissions were associated with a rather strong Siple signals even though the electron flux was sufficiently high with some anisotropy (PAA). There must be other controlling factors. These points, however, must be investigated in more detail in future work.

The triggered ASEs were observed with a high probability in a geomagnetically quiet period just after a large magnetic storm, as shown in Figure 2. This finding is in keeping with the work of Carpenter and Miller [1976], concerning ground observations of Siple transmitter signals at the geomagnetically conjugate point, Roberval. Their study revealed that Siple signals were observed with a high probability on quiet days after magnetic storms and that the Siple signals observed on the ground at Roberval were in most cases amplified as a result of wave-particle interactions. For the other 4 passes during the period from August 14 to 19, Siple signals were observed only on the high latitude pass of August 15 and the pitch angle distribution for these passes was very similar to those of Siple triggering events. The reason why triggering did not occur may be due to the fact that Siple signals were too weak at those locations, so that they could not modify the distribution functions to result in nonlinear effect needed for triggering. The occurrence of triggering also depends on wave

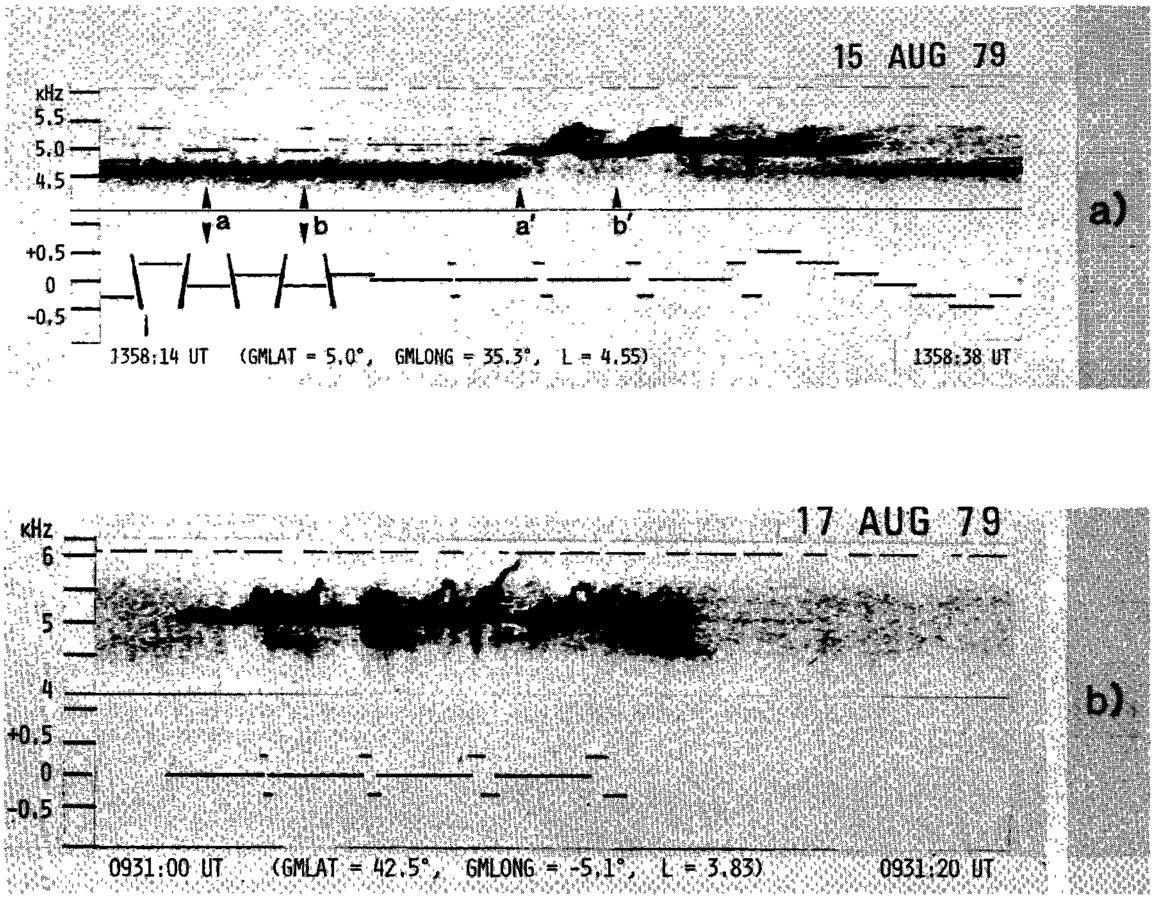

Fig. 10. Extended frequency-time spectra around the times indicated by an arrow at the bottom of each wave spectrum panel in Figures 8 and 9. (a) August 15 event (the signals indicated by arrows a and b corresponding to the direct signals and those of a' and b' being emissions triggered by the echoes of a and b). (b) August 17 event (emissions being triggered by the direct signals).

If the pitch angle distribution at the equatorial plane is not isotropic but peaked at 90° in pitch angle, the observed flux at a geomagnetic latitude of 40° will be much less than the flux at the equator for the same L value, taking into account the invariance of the magnetic moment. The high latitude events on August 14, 17, and 18 may actually be such cases.

From this point of view, for the August 14, 17, and 18 events, the electron fluxes at the magnetic equator on the same field lines may have been comparable with or higher than those observed on August 15 in the equatorial region. Therefore, one of the necessary conditions for ASE generation may well be a high flux of electrons in the energy range between 0.5 and 10 keV around $3 < L < 5$. This finding appears to complement the work of Anderson and Maeda [1977] in which it was found that naturally produced VLF emissions outside the plasmasphere were associated with enhanced intensities of low-energy electrons in the 1 to 10 keV range.

On August 19, the characteristics of the energetic electrons were rather different from those in the August 15 event, although in both events observations were made near the magnetic equatorial plane. On this day, emissions triggered by Siple signals were observed for about a 10-s period at 1705 UT, when the satellite was located at $L \sim 3.3$, and a geomagnetic latitude and longitude of 5°S and 3.2°E, respectively. At this time, the energetic electron flux was as low as one-half or one-third of that in the August 15 event for keV energy channels.

According to the detailed wave analyses discussed in paper 2, there was a whistler mode duct near $L \sim 3.3$ which appeared to have been involved in the generation of the ASEs that were observed on EXOS-B as well as at Roberval and Palmer stations. It was also found that EXOS-B did not pass through the duct although it did pass through the same L shell. If the duct was located near the Siple-Roberval meridian plane, the satellite would have been about 8° east of the duct. Such a difference in longitude may explain the somewhat lower electron fluxes observed at the satellite location.

At 1625 UT on the same day, a phenomenon showing entrainment interaction between Siple signals and whistler-triggered emissions was observed by EXOS-B (see paper 2). Around this time, energetic electron fluxes were $1.5 \sim 2$ times larger than those at 1705 UT, and some anisotropy in the pitch angle distributions was observed, which would result in a positive growth rate based on the Kennel-Petschek [1966] theory.

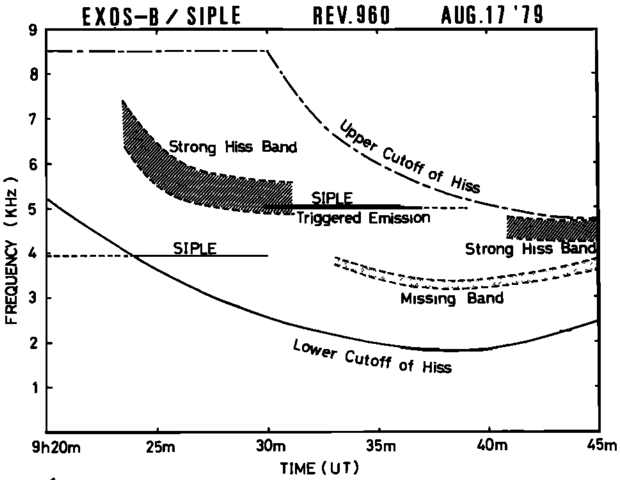

Fig. 11. A sketched view of VLF spectrum observed on August 17. The missing band refers to a portion of the spectrum, in which the noise level is very low.

6. Discussions and Conclusions

It was found that strong Siple signals observed within $\pm 10^{\circ}$ from the Siple meridian by the EXOS-B (Jikiken) satellite were well correlated with a pancake pitch angle distribution (called HPAA) of electrons with energies from 0.3 to 6.9 keV. When the HPAA structure in these energy channels disappears, the intensity of the Siple signal suddenly decreases. Such correlations were observed on two days, August 6 and 7, during equatorial passes outside the plasmapause.

As described in section 4, the calculated linear growth rate of waves at Siple transmitter frequencies was positive during the time that the Siple signals were intensified. The peak growth rates calculated were 5×10^{-6} on August 6 and 3.5×10^{-5} on August 7, which are values normalized by the angular electron cyclotron frequency. The corresponding e-fold times are 1.38 and 0.2 s for August 6 and 7, respectively.

It is noted that the HPAA is not a sufficient condition for detection of strong Siple signals. Even if an HPAA exists, the Siple signals could not be detected, if the signal intensity prior to the amplification is too low. Therefore, it is also necessary that the location of the spacecraft be within $\pm 10^{\circ}$ of the Siple meridian.

When the Siple signals triggered ASEs on the equatorial crossing pass of August 15, and on the high latitude pass of August 14, 17, and 18, large electron fluxes were found in all energy channels from 85 eV to 6.9 keV in the equatorial interaction region, although the pitch angle distribution above the lowest measurable pitch angle ($\sim 40^{\circ}$) was not highly anisotropic. However, when particle fluxes did not show any clear periodic fluctuation due to the satellite spin motion, the pitch angle distribution and thus the anisotropy factor could not be determined. Actually, on the above triggering events, it is evident that the particle fluxes were not constant with spin phase. Therefore it is possible that there existed a low but sufficient pitch angle anisotropy needed for triggering assisted by the high fluxes of resonant electrons.

We can draw the following two conclusions from our summer campaign experiment:

1. When high pitch angle anisotropy (HPAA) was observed, Siple signals were amplified but no triggered emissions were observed.
2. When a high flux of energetic electrons with a low pitch angle anisotropy was detected, triggered emissions were observed.

A possible interpretation of these facts is as follows. On days when the HPAA was observed, the flux of energetic electrons at resonant velocity was low because the flux of the energetic particles with $v_{\parallel} \simeq 0$ ($\alpha \simeq 90^{\circ}$) were dominant. However, a sufficient growth rate for Siple signal amplification was achieved assisted by the high pitch angle anisotropy, because the whistler mode growth rate is determined by the product of the particle flux at resonant velocity and the pitch angle anisotropy. On the other hand, triggering of emissions, which is believed to be caused by a nonlinear modification of the distribution function in velocity space [see, e.g. Matsumoto, 1979], could not be reached because the resultant nonlinear growth rate for triggering would be small owing to the low flux in the vicinity of the resonant velocity, even if the modification takes place. On the contrary, on triggering days the flux of energetic particles was high with low pitch angle anisotropy. The high flux at resonant velocity produces a large nonlinear growth rate after nonlinear modification of the gradient of the distribution function in velocity space, which produces triggered emissions. Therefore, the necessary conditions for triggered emissions are the existence of (1) a sufficiently high particle flux in the range of resonant energy with some anisotropy and (2) a sufficiently strong triggering signal intensity that could nonlinearly modify the distribution function.

These two conditions, however, cannot be necessary and sufficient for triggering because we have one example on September 1 when no triggered emissions were associated with a rather strong Siple signals even though the electron flux was sufficiently high with some anisotropy (PAA). There must be other controlling factors. These points, however, must be investigated in more detail in future work.

The triggered ASEs were observed with a high probability in a geomagnetically quiet period just after a large magnetic storm, as shown in Figure 2. This finding is in keeping with the work of Carpenter and Miller [1976], concerning ground observations of Siple transmitter signals at the geomagnetically conjugate point, Roberval. Their study revealed that Siple signals were observed with a high probability on quiet days after magnetic storms and that the Siple signals observed on the ground at Roberval were in most cases amplified as a result of wave-particle interactions. For the other 4 passes during the period from August 14 to 19, Siple signals were observed only on the high latitude pass of August 15 and the pitch angle distribution for these passes was very similar to those of Siple triggering events. The reason why triggering did not occur may be due to the fact that Siple signals were too weak at those locations, so that they could not modify the distribution functions to result in nonlinear effect needed for triggering. The occurrence of triggering also depends on wave activity at other frequencies and on the frequency of the Siple signal.

According to Lyons et al. [1972], the pancake pitch angle distributions are the evidence of a past history of scattering by ELF plasmaspheric hiss. We have inspected the wave spectra carefully and found out that ELF hiss in the frequencies less than 1 kHz was observed by EXOS-B mostly when the pancake distributions were detected. On the other hand, on triggering days, the intense fluxes of electrons with low anisotropy were observed. These fluxes might be newly injected electrons, because the events were concentrated in the period after the strong magnetic storm. These results appear to be in favor of the model developed by Lyons et al. [1972].

As mentioned previously, EXOS-B/Siple Station wave injection experiments were also carried out in the period December 1979-January 1980, and the full results of these experiments will be reported in a separate paper. It is, however, appropriate to mention here that in the winter (December 1979-January 1980) period there were no observations of triggered emissions stimulated by the Siple signals. This circumstance was consistent with the fact that the observing locations of the satellite during the winter period were in the southern hemisphere (8°-20°S), well before the direct signal reached the equatorial interaction region where emission generation is thought to take place. Other factors which may also have influenced the outcome of the winter experiments, such as ionospheric absorption and satellite local time, are presently under study.

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