

PITCH-ANGLE DIFFUSION BY WHISTLER MODE WAVES NEAR THE I<sub>o</sub> PLASMA TORUSF. L. Scarf<sup>1</sup>, F. V. Coroniti<sup>1,2</sup>, D. A. Gurnett<sup>3</sup>, and W. S. Kurth<sup>3</sup>

**Abstract.** As Voyager 1 traversed the inner radiation belt of Jupiter, wave-particle interactions involving energetic electrons and whistler mode turbulence were strongly affected by the presence of the I<sub>o</sub> plasma torus. Within the high density torus the resonant electron energy was low and the associated high index of refraction yielded high B-to-E ratios for the wave fields, leading to very strong pitch-angle scattering. We show that significant spatial and temporal variations in plasma conditions produced large fluctuations in local scattering times, and we discuss the problems associated with the evaluation of precipitation lifetimes.

## Introduction

On the basis of radio observations, it was known many years ago that Jupiter has a substantial magnetosphere with a large population of energetic trapped electrons. The first detailed models of the Jovian radiation belts were developed by *Brice, 1972; Thorne and Coroniti, 1972;* and *Kennel, 1972*. These authors assumed that electrons and protons are injected from the magnetosheath or the tail with high magnetic moments, and that they diffuse inward (conserving magnetic moment) to attain very high energies in the inner radiation belt of Jupiter. The models implied that intense whistler mode turbulence would be generated by loss cone instabilities leading to stable trapping limits for energetic electrons, and the early Pioneer 10, 11 observations [see for instance, *Van Allen et al., 1975; Fillius et al., 1976*] were interpreted in terms of the whistler mode pitch-angle scattering. The initial post-Pioneer theoretical analysis of *Coroniti (1975)* was followed by a number of more detailed studies which conclusively established the importance of local loss mechanisms associated with wave-particle interactions at Jupiter. *Barbosa and Coroniti (1976)* carried out the full relativistic calculations for a given model and they compared their predictions with Pioneer 10, 11 data. This analysis was followed by many others [*Baker and Van Allen, 1976; Baker and Goertz, 1976; Scarf and Sanders, 1976; Thomsen et al., 1977a,b; Sentman and Goertz, 1978; Goertz et al., 1979*], and as Voyager 1 approached Jupiter, a primary scientific task involved direct determination of the pitch-angle diffusion effects associated with wave-particle interactions in the inner magnetosphere.

*Scarf et al. (1979)* showed that near and within the I<sub>o</sub> torus the Voyager 1 plasma wave instrument detected a broad-banded turbulence spectrum with upper frequency much less than the local electron cyclotron frequency. They identified the signals as whistler mode waves, and stated that the observed waves appeared to be generally capable of producing the predicted pitch-angle scattering and diffusion. This report contains an initial quantitative analysis of the pitch-angle scattering in the I<sub>o</sub> torus region, based on the Voyager 1 wave observations and on Voyager estimates of the plasma density profile in the inner magnetosphere.

## OBSERVATIONS AND ANALYSIS

The bottom of Figure 1 [taken from the recent Voyager-1 report by *Scarf et al. (1979)*] shows 48-sec peaks (fine lines) and averages (black areas) for each of the 12 upper plasma wave channels, along with profiles of the electron cyclotron frequency ( $f_c^-$ ) and the electron plasma frequency ( $f_p$ ). The top of Figure 1 shows a schematic of the Voyager 1 traversal through the I<sub>o</sub>-associated torus region. The initial penetration of the torus occurred near 0500 spacecraft event time (SCET) as shown by the rapid increase in  $f_p$  ( $= 9 \times 10^3 \sqrt{N_e}$  Hz, where  $N_e$  is the electron density in cm<sup>-3</sup>). At closest approach (1200) Voyager passed through the inner edge of the torus where  $f_p$  dropped to a local minimum of 100 kHz

and then retraversed the torus, passing near the I<sub>o</sub> L-shell at 1500. *Scarf et al. (1979)* noted that the wave electric field levels at frequencies below  $f_c^-$  were generally highest in the high density torus region and decreased appreciably outside the torus (before 0400 and after 2000). On the basis of the observed frequency band ( $f < f_c^-$ ) and the theoretically expected correlation with high density (*Coroniti, 1974; Scarf et al. (1979)*) tentatively identified these strong and persistent low frequency signals as whistler mode waves.

In Figure 1 the significance of the observed E-field wave levels is somewhat obscured by the large changes in the whistler mode index of refraction which occur within the torus region. The index of refraction for parallel propagating whistlers is

$$n^2 = 1 + \frac{f_p^2}{(f + f_c^+)(f_c^- - f)} \quad (1)$$

where  $f_c^+$  is the ion cyclotron frequency for an assumed hydrogen plasma; in the absence of observations on the wave propagation direction, we will assume that the whistlers are propagating along the local magnetic field, even though oblique propagation is likely to occur for  $f < f_{LHR}$ . At the top of Figure 1 we have plotted the local value of  $n(f)$  for a 100-Hz whistler;  $n(f)$  clearly maximizes in the highest density regions of the torus. The cyclotron resonant interaction of energetic electrons with low frequency whistlers is dominated by the  $\underline{V} \times \underline{B}(f)$  Lorentz force due to the

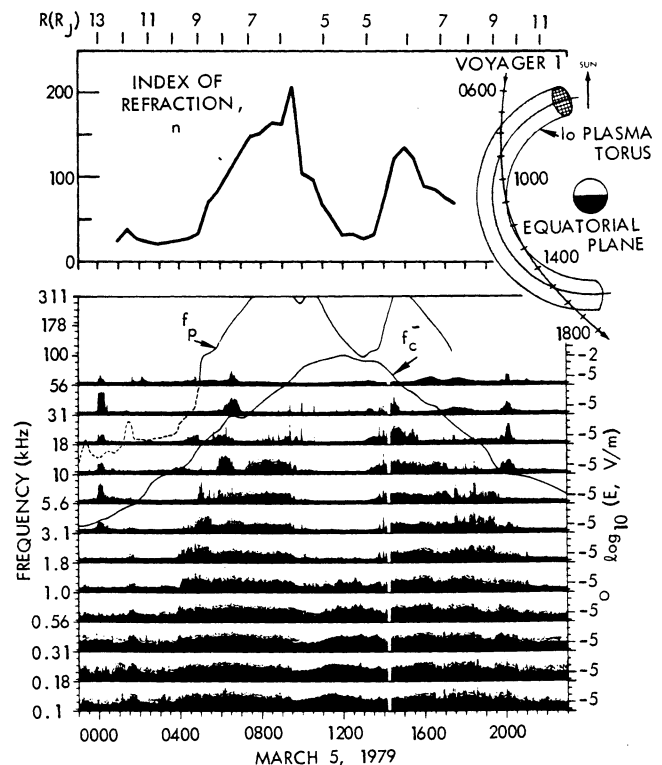


Figure 1. Bottom: Voyager 1 plasma wave observations near closest approach, along with preliminary estimates of the electron plasma frequency (determined by the plasma probe and the radio astronomy instrument) and a preliminary electron cyclotron frequency plot (from the magnetometer).

Top: Calculated index of refraction profile for 100 Hz whistler mode waves propagating parallel to the magnetic field, and a sketch of the I<sub>o</sub> plasma torus with the Voyager 1 trajectory. Whistler mode E-field signals persist from 12 R<sub>J</sub> to closest approach, especially below 1 kHz; however, the whistler magnetic amplitudes are highest within the dense plasma torus.

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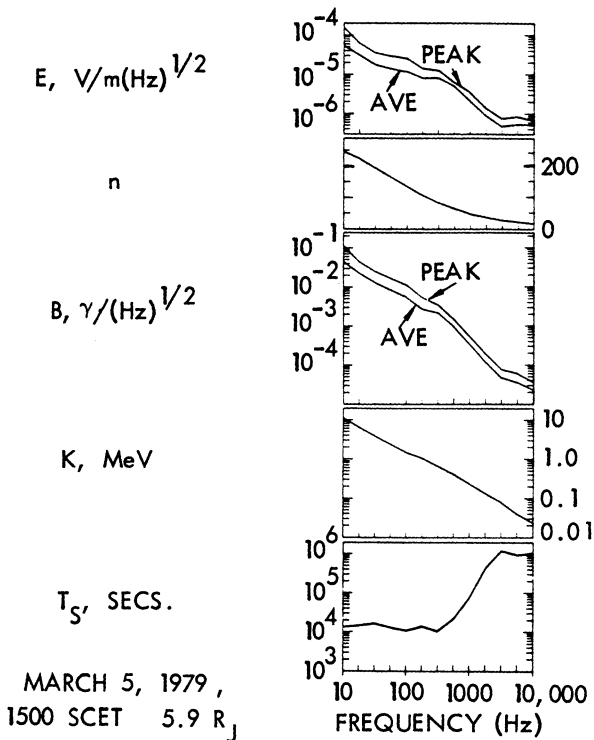


Figure 2. An analysis of the wave-particle interactions for a 96-second interval just after 1500 on March 5. Voyager 1 was near the Io flux tube at  $5.9 R_J$ , and measured a local magnetic field of  $1900 \text{ gamma}$  ( $f_c^- = 53.2 \text{ kHz}$ ) and plasma density of  $1600 \text{ cm}^{-3}$  ( $f_p = 355 \text{ kHz}$ ). The top panel shows the measured electric field ( $E$ ) spectral density; the next panel contains the calculated index of refraction ( $n$ ) for parallel whistlers, and the third panel has the computed magnetic spectral density ( $B$ ) (for the whistler mode). The minimum resonant electron energy ( $K$ ) in MeV as a function of whistler mode frequency is plotted in the fourth panel. The bottom panel shows the calculated local pitch-angle scattering time ( $T_S = D_{aa}^{-1}$ ) based on the average whistler magnetic wave amplitudes. Electrons with  $K > 0.1 \text{ MeV}$  are strongly scattered by the local whistler turbulence.

wave magnetic field  $B(f)$  [Kennel and Petschek, 1966]. Since  $B(f) = n(f) E(f)/c$  for whistlers propagating parallel to  $B_0$ , the resonant wave-particle interaction is clearly stronger near 0800 and 1500, where  $n(f)$  maximizes, than near the  $n(f)$  local minimum at 1200, even though the electric field levels are comparable for these times.

In order to evaluate quantitatively the possible importance of the observed whistler turbulence, we first consider a single 96-sec interval just after 1500 when Voyager was outbound at  $5.9 R_J$ , near the expected position of the Io flux tube. The peak and average electric field amplitudes in  $\text{V/m(Hz)}^{1/2}$  for this 96-sec interval are plotted as a function of frequency in the upper panel of Figure 2. The second panel shows the local parallel whistler index of refraction  $n(f)$ , and the third panel plots the calculated whistler magnetic field amplitude  $B(f)$  in  $\text{gamma/(Hz)}^{1/2}$  using the relation  $B(f) = n(f) E(f)/c$ .

The whistler cyclotron resonant condition for relativistic electrons is  $\gamma(f - k \cdot v/2\pi) = f_c^-$  where  $\gamma = (1 - v^2/c^2)^{-1/2}$ . For  $n(f) \gg 1$  and  $f \ll f_c^-$ , the minimum parallel momentum for resonance is approximately  $-P_{\parallel}/m_e c \approx f_c/nf \approx (f_c/f)^{1/2} B/(4\pi N_e m_e c^2)^{1/2}$ ; hence the minimum resonant kinetic energy  $K = (\gamma - 1) m_e c^2$  scales as  $B/\sqrt{N_e}$  for relativistic ( $\gamma \gg 1$ ) and  $B^2/N_e$  for non-relativistic ( $\gamma - 1 \ll 1$ ) electrons. In the fourth panel in Figure 2 we have plotted the resonant kinetic energy against  $f$ , where  $K$  was calculated from the exact expressions found in Barbosa and Coroniti (1976). For  $10 \text{ Hz} \leq f \leq 1000 \text{ Hz}$ , the resonant energies fall in the range  $0.1 \text{ MeV} \leq K \leq 10 \text{ MeV}$  where extensive electron flux measurements have been obtained by Pioneers 10 and 11, and Voyager 1. At these energies the Pioneer experimenters [Simpson et al., 1974; McIlwain and Fillius, 1975; and Baker and Van Allen, 1976] observed significant electron phase space losses in the inner Jovian magnetosphere.

A rough measure of the strength of the whistler resonant interaction is the local pitch-angle scattering time  $T_S$ , which is defined as the time for an electron to diffuse 1 radian in pitch-angle, assuming that it continuously interacts with the local wave turbulence. The local pitch-angle diffusion coefficient is approximately (Barbosa and Coroniti, 1976)

$$D_{aa} = \frac{1}{4} \frac{[178 B(f)]^2}{\gamma u_{\parallel} n(f)} \left( \frac{f + f_c^+}{f + 2f_c^+} \right) \quad (2)$$

where we assumed  $n(f) \gg 1$  and  $f \ll f_c^-$ , and  $u_{\parallel} = \gamma v_{\parallel}/c$  and  $\gamma$  are to be evaluated through the resonance condition for a given frequency;  $B^2(f)$  is the magnetic field spectral energy density in  $(\text{gamma})^2/\text{Hz}$ . In the bottom panel of Figure 2 we have plotted the local scattering time  $T_S = (D_{aa})^{-1}$  against  $f$  using the calculated magnetic wave amplitudes  $B(f)$ . For energies  $K \geq 0.1 \text{ MeV}$ , the scattering time  $T_S \approx 10^4 \text{ sec}$ , which is long compared to the minimum precipitation lifetime  $T_{\text{min}} \approx 2 L^4 R_J/c \approx 500 \text{ sec}$  at  $L = 6$ , but is comparable to the Jovian corotation period of 10 hours.

The actual electron precipitation lifetime, however, depends on the temporal and spatial variability of the whistler mode amplitudes, and on the fraction of time which the electrons spend interacting with the wave turbulence. For example, bounce motion and rapid radial diffusion or convection can limit the interaction time. In order to explore the spatial and temporal variability of the wave turbulence, in Figure 3 we repeat the full analysis of Figure 2 for 96-sec intervals covering the outbound passage through the Io plasma torus.

During this three-hour period from 1330 to 1630, the wave levels shown in Figure 1 did not appear to vary drastically except at high frequencies ( $f \geq 10 \text{ kHz}$ ); however, the upper panels in Figure 4 illustrate that below  $100 \text{ Hz}$  there were changes in  $E(f)$  covering more than an order of magnitude. Since at low frequencies  $n(f)$  also varied considerably during the torus passage, the magnetic amplitudes computed for parallel whistler propagation showed large variations from hour to hour. In addition, the influence of plasma density changes on the electron resonant energies is clearly demonstrated by the rough factor of 10 increase in  $K$  at all  $f$  near 1330 where  $N_e$  was much lower than at the later times. The combined effects of large changes in  $n(f)$ ,  $B(f)$ , and  $K$  produce the large variations in the local scattering times shown in the bottom panels of Figure 3.

One concern about the simplified scattering time calculations involves the impulsive nature of the measured whistler turbulence. Although the scattering times shown in Figures 2, 3 were computed using 96-sec averages, the large peak-to-average ratios indicate that rapid fluctuations were present. In order to illustrate the degree to which such fluctuations occur, we show in Figure 4 all of the wave amplitudes measured during a 48-sec interval starting at 1430:32 on March 5, 1979. This display of the unaveraged  $E$ -field spectral densities shows that significant changes occurred in the four-second intervals between successive samples at any given frequency, and that some type of time averaging must be performed in order to obtain a precise estimate of the local pitch-angle diffusion time.

Figure 4 also shows that strong turbulence was detected in the 17.8 kHz channel just at the end of this sequence. This brief noise peak is evident in Figure 1, and it can be seen that similar short-duration noise enhancements at higher frequencies were detected elsewhere both below the cyclotron frequency (e.g., the 10-kHz wave peak near 0600) and above the cyclotron frequency (for instance, the 18-kHz noise enhancement at 2000). It is quite possible that the higher frequency waves are not electromagnetic whistler mode waves, but since high frequency whistlers can interact with electrons having low energies it is worth considering how such waves might produce auroral-type precipitation. The peak intensity of the 17.8 kHz wave shown in Figure 4 is  $4.16 \times 10^{-6} \text{ Volts/m(Hz)}^{1/2}$ . Assuming that this represents whistler mode turbulence, we find that the resonant energy is  $20 \text{ keV}$  and that  $D_{aa} \approx 6.5 \times 10^{-5} \text{ sec}^{-1}$ , giving a local scattering time on the order of  $1.5 \times 10^4 \text{ seconds}$ . Thus, if this isolated noise peak does represent whistler mode turbulence, we find that at 1430 the scattering of low energy electrons might be comparable with the pitch-angle scattering of more energetic electrons. However, it is clear from Figures 2, 3 that the most important wave-particle interactions developed near 1530, and that the dominant precipitation involved electrons with energies above a few hundred kilovolts.

Finally, the Io plasma torus apparently has a north-south latitudinal extent of only a few  $R_J$  about the equator [Broadfoot et al., 1979; Warwick et al., 1979; Gurnett et al., 1979], as expected for centrifugal confinement. Hence, strong whistler growth should only occur near the magnetic equator where the index of refraction is high and the largest fraction of the energetic electron distribution can be resonant [Coroniti, 1974; Sentman and Goertz, 1978]. In addition, whistler pitch-angle

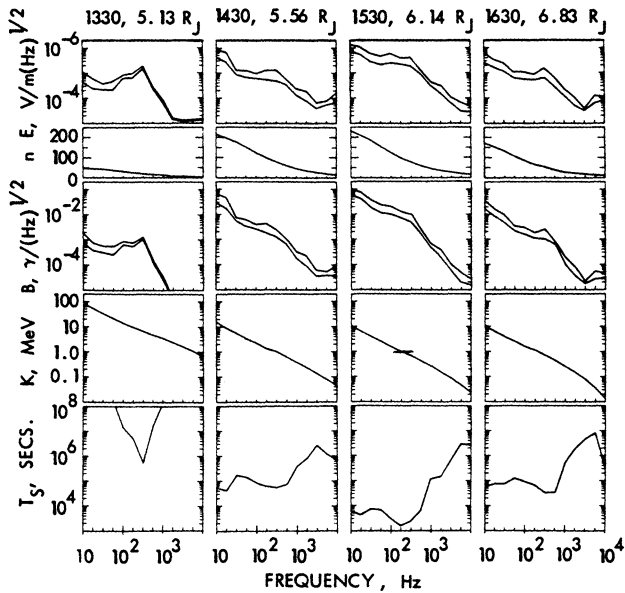


Figure 3. Detailed analyses of the wave-particle interactions for four 96-second intervals as Voyager 1 traveled from the inner edge of the plasma torus (1330) to the outer torus region (1630). The format is the same as Figure 2. The plasma density and magnetic field strength for the four intervals are: (1330)  $N_e = 136 \text{ cm}^{-3}$ ,  $B_0 = 3036$  gammas; (1430)  $N_e = 1645 \text{ cm}^{-3}$ ,  $B_0 = 2300$  gammas; (1530)  $N_e = 1150 \text{ cm}^{-3}$ ,  $B_0 = 1725$  gammas; (1630)  $N_e = 378 \text{ cm}^{-3}$ ,  $B_0 = 1250$  gammas. At the inner edge of the torus the long local scattering times indicate that the electron distribution is quite stable to precipitation losses. Within the torus, electrons with  $K > 0.1$  MeV undergo strong local scattering and have precipitation lifetimes which may be comparable to radial diffusion source times.

scattering should be dominated by near equatorial interactions so that the electron precipitation lifetime  $T_L$  must depend on the bounce-averaged value of  $D_{aa}$  [Lyons et al., 1972]. As a rough estimate for  $T_L$ , if we take  $\pm 1 R_J$  as the latitudinal extent of the torus and  $\pi L R_J / 2$  has the half-length of a flux tube, the bounce-averaged precipitation lifetime is approximately  $T_L \approx (\pi L / 2) D_{aa}^{-1} = (\pi L / 2) T_S$ . For  $L = 6$ , we have  $T_L \approx 10 T_S$  so that the precipitation lifetimes are probably at least an order of magnitude longer than the local scattering times shown in Figures 2 and 3. Of course, a careful evaluation of the precipitation lifetimes should include higher harmonics and Landau resonant interactions arising from oblique whistler propagation [Lyons et al., 1972].

## DISCUSSION

Although the above analysis is clearly incomplete in that Voyager 1 particle data were not included, we can extract several general conclusions about the strength and importance of plasma wave turbulence in the Jovian radiation belts. As anticipated by analogy with the earth's plasmasphere [Lyons and Thorne, 1973] and suggested by the early Jovian density models of Ioannidis and Brice (1971), cyclotron resonant interactions of energetic electrons with whistlers are strongest in the high plasma density regions of the Io torus. The observed electric field wave amplitudes below the electron-cyclotron frequency are enhanced throughout the torus. There the high whistler index of refraction permits a larger fraction of the electron distribution to resonate with the waves, thus leading to rapid whistler mode growth. In addition, whistlers more effectively pitch-angle scatter energetic electrons since at large refractive indices the wave magnetic component is enhanced relative to the wave electric field.

Within the torus, the electric field amplitudes exhibit large temporal and/or spatial fluctuations. The extreme variability at frequencies below 60 Hz opens to question our interpretation that these signals are exclusively whistler mode waves. At this time we cannot exclude the possibility that electrostatic ion cyclotron waves contribute significantly to the observed electric fields. The high variability and uncertain mode identification clearly limit our present ability to make an accurate estimate of whistler pitch-angle scattering time and electron precipitation lifetime. A

future detailed comparison of the plasma wave and energetic electron data and an appropriate averaging of the wave amplitudes should clarify these issues.

The computed estimates of the precipitation lifetimes ( $T_L \approx 10 T_S$ ) yield  $T_L \sim 10^4$  to  $10^6$  sec for  $>1$  MeV electrons and  $T_L \sim 10^6$  to  $10^7$  sec for  $<1$  MeV electrons. Since  $T_L$  greatly exceeds the minimum precipitation lifetime,  $T_{\min} \sim 500$  sec at  $L = 6$ , the energetic electron fluxes should be close to the stably-trapped limit [Coroniti, 1974; Barbosa and Coroniti, 1976], and electron precipitation should be on weak diffusion [Sentman and Goertz, 1978]. The precipitation lifetimes, however, are significantly less than estimates of the radial diffusion time scale  $T_R$  near Io based on analyses of the Pioneer 10 and 11 particle data [Mogro-Compero and Fillius, 1976; Thomsen et al., 1977a,b]. If we use the previous estimates for the radial diffusion coefficient  $D_{LL} = D_0 L^3$  with  $D_0 \approx 2 \times 10^{-9} \text{ sec}^{-1}$  [Thomsen et al., 1977b], the time to diffuse  $1 R_J$  is approximately  $T_R \sim 2 - 20 \times 10^6$  sec, depending on the definition of  $T_R$ . Since the Io torus extends over several L-shells, the time required to diffuse across the torus is probably longer. Since the precipitation lifetime  $T_L < T_R$  for  $>1$  MeV electrons, a significant precipitation reduction in the energetic electron phase space density should be observed in the Voyager 1 data if the above estimate of the radial diffusion coefficient is reasonable. However, the plasma and wave conditions in the torus region may have differed considerably between the time of the Pioneer and Voyager 1 encounters. If the radial diffusion rates near Io were larger than the Pioneer estimate, perhaps due to the enhanced torus densities, the precipitation losses would be less severe. We must await a more complete analysis of the combined Voyager 1 data to examine these problems.

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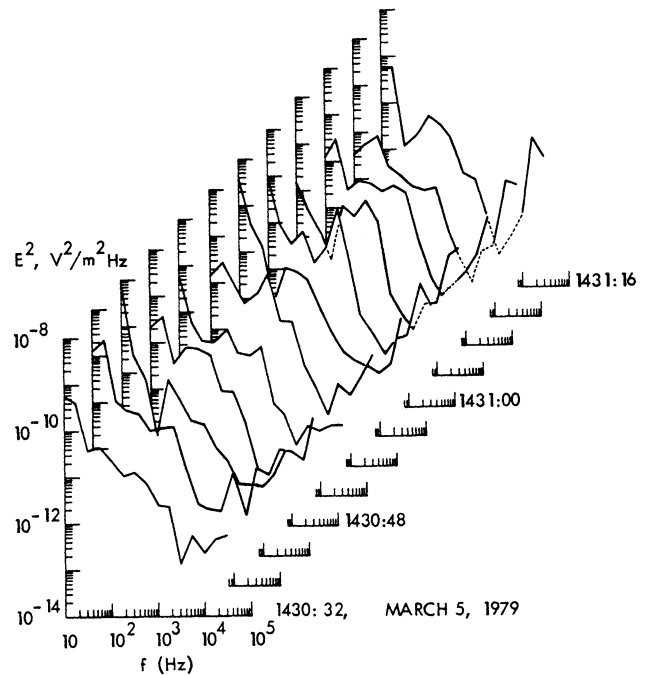


Figure 4. Unaveraged E-field spectral densities measured during a 48-second interval starting at 1430:32. This display shows how rapidly the E-field amplitude changed with time. Although the isolated 18 kHz noise enhancements detected near the end of this interval may not represent whistler mode turbulence, the pitch-angle scattering associated with high frequency whistler waves could affect lower energy electrons, as discussed in the text.

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