Coordinated Measurements of Slot Region Electron Precipitation by Plasmaspheric Wave Bands

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It has been hypothesized by Lyons et al. that electrons in the slot region are precipitated by cyclotron resonance interactions with the plasmaspheric whistler mode wave bands. The energy spectra and the variations with $L$ shell of the energy bands of the precipitating electrons have been found by Imhof et al. (1974) to be consistent with cyclotron resonance by waves in the few hundred Hz to few kHz range. Now, for the first time, simultaneous measurements have been made of the precipitating electron spectra, the wave frequency distributions, and the plasma density profiles. The electron measurements were performed from the P78-1 low-altitude satellite, whereas the wave and plasma density observations were made with the plasma wave experiment on the ISEE 1 spacecraft. Broad bands are often observed in the electron energy spectra with a well-defined low-energy cutoff that decreases in energy with increasing $L$ value in a manner consistent with that calculated for first-order cyclotron resonance with waves at the high-frequency cutoff of the band. On the basis of the electron spectra from P78-1 and the plasma densities obtained from the upper hybrid resonance frequencies measured on ISEE 1, the hiss cutoff frequencies are calculated for an assumed first-order cyclotron resonance interaction and compared with the wave spectral density profiles measured on ISEE. Overall, the plasma wave and the electron measurements are consistent with each other, supporting the earlier hypothesis for the precipitation mechanisms.

INTRODUCTION

Theoretical explanations have been offered for the formation of the slot region between the inner and outer radiation belts where the fluxes of trapped energetic electrons are often very low during quiet times [Lyons et al., 1972]. Lyons et al. [1972] proposed that the reason for the low trapped fluxes is that the electrons are lost to the atmosphere through resonant interactions with the band of whistler mode waves observed inside the plasmasphere. The pitch angle distributions predicted by these authors throughout the slot region and the outer plasmasphere near the equatorial plane were later found to be consistent with Explorer 45 observations [Lyons and Williams, 1975]. Considering pitch angle diffusion at all multiples of the cyclotron-harmonic resonance plus the Landau resonance, Lyons et al. [1972] were able to account for the location of the high-latitude edge of the inner belt as a function of electron energy and for the removal of electrons to levels near zero throughout the slot region. The calculated loss rates were in good agreement with observations of the decay of the trapped population. From a balance between these pitch angle scattering losses and inward radial diffusion from an average outer zone source of electrons, Lyons and Thorne [1973] were able to explain the quiet time structure of energetic electrons in the earth's radiation belts.

Broadband whistler mode waves in the ELF/VLF frequency range are known to be persistent within the plasmasphere [Gurnett and O'Brien, 1964; Taylor and Gurnett, 1968; Russell et al., 1969; Dunkell and Hellwell, 1969; Thorne et al., 1973]. Hiss bands are detected even at very low $L$ shells (<2) within the inner radiation belt [Tsurutani et al., 1975]. Since plasmaspheric hiss appears to play an important role in the removal of trapped electrons, studies have been devoted to its origin and to the characteristics of wave propagation [Thorne et al., 1979]. Attempts have been made to achieve a self-consistent solution of the wave generation and particle diffusion [Etcheto et al., 1973], but a complete theoretical explanation is still to be achieved.

We are now at a position where the next important step is to measure the waves and the precipitating electrons simultaneously. In some past investigations extending to low latitudes [Oliven and Gurnett, 1968; Vampola et al., 1971], searches have been made for correlations between wave emissions and precipitated electron fluxes but it has not generally been possible to find one-to-one correspondence. For cause and effect studies the coordinated measurements should cover the same narrowly localized regions of space. This requirement for close spatial coordination is complicated by the fact that electron loss rates in the slot region are often quite low and the precipitating electrons can generally be observed only in the drift loss cone and not in the bounce loss cone; i.e., the electron precipitation is observed only as a result of the accumulation of loss processes occurring over a broad longitude range. Furthermore, the waves at $L \approx 2$–3 are probably present over a wide longitude region. Therefore, for study of the wave-particle interactions it is important to restrict the possible longitudes of interaction to the
close vicinity of the wave measurements. Such a narrow longitude range of interaction can be achieved if the electron measurements are performed just east of the eastern edge of the South Atlantic Anomaly, where the fluxes of quasi-trapped electrons begin to build up. Ideally, the wave measurements should be carried out in this same region of space and at nearly identical times.

From a 2-year data base involving two satellites we have been able to find suitable coordinations in the slot region within narrow time and space restrictions. One of the satellites was the P78-1 low-altitude (600 km) polar orbiting spacecraft containing a high-resolution electron spectrometer. The other satellite was ISEE 1, which is in a highly eccentric earth orbit with an apogee geocentric radial distance of about 22.5 Rs. The data of interest here at $L = 2-3$ were all taken near perigee, which was at a height of about 2500 km above the surface of the earth. Since the orbital period of the ISEE 1 satellite, ~2.4 days, was much longer than the 96-min period of the P78-1 spacecraft, the times of occurrence of perigee for ISEE were the pacing items in establishing the optimum times of coordination. The coordinations are summarized schematically in Figure 1, where the longitudes of observation for the two spacecraft at the $L$ shells of interest are plotted. On each date the longitude points from the closest coordinations are connected by a straight line. From the listed time differences one sees that the coordinations were mostly within a couple of hours of each other, with the longest time difference being 3.5 hours. On some occasions the ISEE coverage did not extend fully to the slot region where peaks were observed in the P78-1 electron data, and in such cases the longitude of the closest $L$ value for ISEE is represented. The lack of a precise correspondence in $L$ in some cases is acceptable, since the hiss cutoffs observed in the spectral density plots typically do not change rapidly with $L$. The 17 cases selected for study on the basis of the coordination criteria were all at relatively quiet times from the standpoint of geomagnetic activity. The Dst index was never at a higher negative value than $-21 \gamma$, and the $Kp$ index was never above 3°.

Descriptions of the satellites and instrumentation are provided elsewhere [Imhof et al., 1981b; Gurnett et al., 1978, 1979], so only a very brief summary is given here. The P78-1 satellite was launched into a 96.7° inclination, nearly circular orbit at ~600 km on February 24, 1979. The energetic electron data presented here were acquired with a spectrometer containing a 1000-µm-thick silicon detector having an area of 4.5 cm² and surrounded by a plastic scintillator-photomultiplier anticoincidence shield to reduce background counts from penetrating particles. Continuous multichannel spectra were obtained with a 256-channel pulse height analyzer covering the energy range 68–1120 keV. The inherent energy resolution of the spectrometer is 20 keV full width at half maximum (FWHM). The spectrometer was designed with a collimation angle of ±15° FWHM and a relatively large geometric factor of 0.69 cm² sr. The collimator axis is placed at 90° to the satellite spin axis, which is oriented perpendicular to the orbit plane. The satellite spins with a period of ~5.5 s. For all of the data presented here the
counting rate versus pitch angle profiles revealed that the electrons were locally trapped. They were, however, precipitating from the radiation belts by virtue of being observed at positions where the mirror points have a minimum altitude below ~100 km at some longitude in the drift path, i.e., the electrons were only quasi-trapped.

The plasma wave instruments on the ISEE 1 and 2 spacecraft were designed to provide measurements of the electric and magnetic fields of plasma waves over the frequency ranges from about 5 Hz to 2 MHz and 5 Hz to 10 kHz, respectively. The electric field wave data used in this paper were acquired with the narrow-band sweep frequency receiver on ISEE 1. This receiver provides an essentially constant fractional frequency resolution of about 0.065 over the frequency range, from 100 Hz to 400 kHz, and a dynamic range of 100 dB. Electron density contours can be obtained from the emissions at the upper hybrid resonance frequency [Gurnett et al., 1979].

**DATA FROM COORDINATIONS BETWEEN THE TWO SATELLITES**

During the coordinated cases in 1979 and 1980, bands were often observed in the energy spectra of the quasi-trapped electrons. Selected spectra from a satellite pass on April 20, 1980, are shown in Figure 2. Raw counts in each channel are presented. Each of the spectra was accumulated at angles of 65°-115° to the magnetic field line during one spin of the satellite. These slot region bands are clearly much wider than the narrowest peaks observed in the inner radiation belt with the same instrument [Imhof et al., 1981a, b]. However,

**Fig. 2.** Energy spectra, in the form of raw counts, of the quasi-trapped electrons measured at selected times during a pass of the P78-1 spacecraft through the slot region.

**Fig. 3.** For three passes of the P78-1 satellite through the slot region the central energies of the electron bands are plotted as a function of L shell. The vertical bars indicate the full width at half maximum values.
as in the inner belt, the central energies of the bands decrease with increasing $L$ value.

For three of the coordinated passes the $L$ dependences of the bands are shown in Figure 3. Electron spectra were often measured in both the northern and southern hemispheres, and, generally, both sets of data are consistent with each other, indicating that the situation is reasonably steady over at least a few tens of minutes time interval. Out of the 17 coordinations studied, in seven cases similar bands were observed in both the northern and southern hemispheres, in three cases the spectra were free of bands in both hemispheres, and in five cases no data were acquired in one of the hemispheres, leaving only two passes where bands were observed in one hemisphere and were not present in the

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observations at the conjugate region. Only in the latter two cases should one consider the possibility that a time burst could account for the low-energy cutoff of a band of electrons, but in those instances the peaks were not very pronounced above the smooth continuum. Clearly, in the majority of cases the shapes of the bands are determined by a reasonably steady phenomenon. Since the bands are rather broad the central energies are not well defined, and therefore vertical bars have been included to show the full width at half maximum values. The lower edge of each band is perhaps the best defined parameter associated with the precipitation mechanism(s), since the trapped spectrum is normally falling with increasing energy and therefore the upper half-maximum point may indicate little selectivity in the precipitation. On each of the coordinated passes the L shell intervals over which electron bands were observed are illustrated schematically in Figure 4.

For some of the coordinated sets of data the electric field spectral densities measured during 36-s intervals at selected positions in the slot region are provided in Figures 5–12. The plasma frequency cutoffs, as defined by visual inspection, at \( \sim 2.2 \text{ kHz}, \sim 1.25 \text{ kHz}, \sim 1 \text{ kHz}, \sim 2 \text{ kHz}, \) and \( \sim 0.75 \text{ kHz} \) can be seen on July 1, 1979, August 6, 1979, March 3, 1980, April 20, 1980 and June 2, 1980, respectively. On the three other dates shown, September 22, 1979, October 16, 1979, and March 15, 1980, the cutoffs in the hiss band are not as sharp and pronounced. It should be noted that the upper hiss cutoff associated with the lower energy cutoff of the electron peaks is often at a considerably higher frequency (0.7–4 kHz) than the frequency of maximum wave intensity, which is typically in the 250–700 Hz range. In the right-hand section of each plot an electron energy spectrum is shown. When possible, the wave and electron data are at nearly the same L value, but in some cases the wave measurements did not extend down to the region where electron peaks were observed, and then the wave data are shown at the lowest L value.

The cold plasma densities can be obtained from the observed upper hybrid resonant (UHR) frequencies, sometimes on both the inbound and outbound passes of the ISEE spacecraft. The measured densities have been corrected to equatorial values on the basis of a diffusive equilibrium model [Park, 1972, 1980] for which the correction factors ranged from 1.35 to 1.70. The plasma densities obtained by this approach are plotted in the middle section of each of Figures 5–12. In some cases significant differences exist between the inbound and outbound data, and these may reflect local time variations in the plasma densities. The
equatorial plasma densities at the $L$ shell of interest have been taken from the UHR data near that point, if available, or from an extrapolation of the values measured on higher $L$ shells assuming an $L^{-4}$ dependence. If no UHR data are available, as on February 1, 1980, then an $L^{-4}$ plasma density profile normalized to 3000 cm$^{-3}$ at $L = 2$ has been assumed.

Based on the equatorial plasma density and the lower cutoff edge (half-way position) below the peak in the electron spectrum, the corresponding wave frequencies have been calculated for an assumed first-order cyclotron resonance with waves traveling parallel to the magnetic field lines. The waves may be unducted and traveling with a large wave normal angle; such a condition would result in less than a factor of 2 increase in the resonant frequency for a wave normal angle of 60°. The Landau resonance has been neglected, since it occurs only over a small range of pitch angles near 90°. Higher order harmonic cyclotron scattering may also occur, but Lyons et al. [1972] found that inclusion of the higher harmonics does not change significantly the diffusion rate at the edge of the loss cone. The wave frequency for first-order cyclotron resonance is indicated by an arrow labeled LE (lower edge) in the left-hand section of each figure for comparison with the wave intensities measured from the ISEE spacecraft. The resonant frequencies corresponding to the peak energies $P$ are also shown. A hatched band is provided in each figure to illustrate the full range of wave frequencies that could be responsible for first-order cyclotron resonance precipitation of the electrons observed above threshold. On some of the coordinated passes such as July 1, 1979, August 6, 1979, March 3, 1980, and June 2, 1980, the wave frequency derived from the lower edge of the electron band is in quite good agreement with the frequency of the hiss cutoff. However, on April 20, 1980, the two frequencies differ by a factor of 3.4. Although in this case the times and longitudes were close, the reasonably large frequency difference may reflect rapid temporal or spatial changes. If any of the wave-particle interactions take place at off-equatorial positions, then, of course, the resonant energies would be increased for a given wave frequen-
cy. On other satellite passes such as March 15, 1980, the wave intensities are low as are the fluxes of precipitating electrons.

In Figure 13 the frequencies of the hiss cutoffs as inferred from the electron measurements are plotted against the cutoff frequencies observed directly. Although considerable scatter exists in the data, overall the plasma wave and electron measurements are generally close to the straight
The frequencies of the hiss cutoffs as inferred from the electron measurements plotted against the cutoff frequencies observed directly. A straight line designating a one-to-one correspondence is also shown. The seven points plotted in the figure represent those cases where both an L-dependent electron band and a well-defined hiss cutoff within the frequency range of interest were observed. This comparison provides further support for the hypothesis that electrons in the slot region are removed by pitch angle diffusion resulting from resonant interactions with the existing plasmaspheric hiss frequency distributions.

Under the assumption that the electron precipitation results from cyclotron resonance with the plasmaspheric hiss band, then the precipitating fluxes should relate quantitatively to the wave intensities and the fluxes of electrons trapped at high altitudes on the same field lines. With the present data quantitative comparisons are limited by the lack of simultaneous electron measurements near the equator and by the variations with longitude of the quasi-trapped electron fluxes. In addition, the rapid variation with frequency in the wave intensity near the hiss cutoff can introduce errors associated with our lack of knowledge of the cold plasma density in the near equatorial region. Nonetheless, we have attempted to perform such comparisons, and the results are presented in Figure 14. Here, the electron fluxes at the center of the band are plotted as a function of the spectral density (volts$^2$/meter$^2$/hertz) measured at a frequency below the hiss cutoff where the wave intensity is not strongly dependent upon frequency. If no band is present, then the flux is plotted at the highest value in the spectrum, typically just above the threshold energy. If the hiss cutoff is not evident, then the intensity is taken from a flat region within the range of frequencies corresponding to the energies of the electrons observed. The selection of frequencies to be used is somewhat arbitrary, but we have attempted to employ a consistent criterion.

In the cross-correlation plot of Figure 14 the data display considerable scatter, which is not significantly different if only the seven cases with well-defined electron bands and hiss cutoffs are considered. Some of the scatter may reflect variations in the fluxes of electrons trapped at higher altitudes. However, the precipitating electron fluxes tend to be lower when the electric field spectral densities are weaker. Specifically, in four out of the five cases when the spectral density is below $10^{-12}$ V$^2$/m$^2$/Hz, the electron fluxes are less than those existing in 10 out of the 12 cases when the spectral density is above $10^{-12}$ V$^2$/m$^2$/Hz. This degree of correlation is consistent with the hypothesis that much of the electron precipitation in the slot region is caused by cyclotron resonance interactions with plasmaspheric hiss, but indeed other mechanisms involving waves of natural or even man-generated origin [Vampola, 1977] may also be important.

In all 17 cases presented here, the precipitating electrons were measured only in the drift loss cone and not in the bounce loss cone; i.e., strong pitch angle diffusion was not observed. To be sure, all of the data were acquired during geomagnetically quiet times, and we therefore cannot speculate here on the occurrence in the slot region of strong diffusion in association with major storms.

From the coordinations in the slot region the findings can be summarized as follows:

1. Plasmaspheric hiss with upper frequency cutoffs of $\approx0.7$ kHz to $\approx4$ kHz was observed nearly simultaneously with measurements of the precipitating electrons.
2. Bands appeared in the energy spectra of precipitating electrons. Both the central energies and the upper and lower half-maximum values decreased with increasing L shell.
3. Cold plasma densities were obtained from the upper hybrid resonance frequencies measured on both the inbound and outbound passes of the ISEE spacecraft.
4. The three parameters (wave frequency, electron energy, and electric field spectral density) were plotted in Figure 14. The electron fluxes at the center of the band are plotted as a function of the spectral density measured at a frequency below the hiss cutoff where the wave intensity is not strongly dependent upon frequency. If no band is present, then the flux is plotted at the highest value in the spectrum, typically just above the threshold energy. If the hiss cutoff is not evident, then the intensity is taken from a flat region within the range of frequencies corresponding to the energies of the electrons observed.
gy, and plasma density) were found to be mutually consistent with the precipitation being caused by cyclotron resonance interactions with the plasmaspheric hiss taking place near the equator.

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