Narrow Spectral Peaks in Electrons Precipitating From the Slot Region

W. L. Imhof, J. B. Reagan, and E. E. Gaines
Space Sciences Laboratory, Lockheed Palo Alto Research Laboratory

R. R. Anderson
Department of Physics and Astronomy, University of Iowa

Narrow L-dependent peaks commonly occur in the energy spectra of electrons precipitating from the inner radiation belt at \( L = 1.5-1.85 \), and the cause of the peaks has been attributed to cyclotron resonance interactions with waves generated by VLF transmitters. In the slot region, L-dependent peaks have also been reported at \( L \approx 2-3.5 \), but these have been predominately wider and consistent with their origin being cyclotron resonance interactions involving naturally occurring hiss. Here we investigate the frequent occurrence of narrow peaks in electrons precipitating at \( L \approx 2 \). From coordinated wave and plasma density measurements it is found that if the narrow peaks are formed by first-order cyclotron resonant interactions occurring close to the magnetic equator between narrow band waves and the trapped electron population, then the equatorial plasma density gradients are unusually steep. This finding is consistent with the evidence previously obtained by other techniques for structured plasma density profiles in that L shell region of space.

INTRODUCTION

From low-altitude satellites, narrow peaks are often found in the energy spectra of electrons precipitating from the inner radiation belt into the drift loss cone. It has been suggested that the narrow peaks may result from cyclotron resonance interactions with nearly monochromatic waves generated by ground-based VLF transmitters [Imhof et al., 1974; Vampola and Kuck, 1978; Koons et al., 1981]. More recently, the variations of the peak energies with L value observed in coordination with measurements of both the narrow band waves and the cold plasma density profiles have provided strong evidence that the peaks observed at \( L = 1.5-1.85 \) result from cyclotron resonance interactions near the magnetic equator with waves produced by ground-based VLF transmitters [Imhof et al., 1981].

In the slot region of the radiation belts, Imhof et al. [1974] reported the appearance of L-dependent peaks in the energy spectra of precipitating electrons, but these peaks were generally much broader and less pronounced than those found in the inner belt. As part of an investigation which provided evidence that ground-based VLF transmitters precipitate substantial quantities of energetic electrons in the slot region, Vampola [1977] reported the observation of L-dependent precipitation spikes in the region \( 2 \leq L \leq 3.5 \). The widths of the peaks were not addressed in detail. Coordinated plasma wave and electron measurements were recently found by Imhof et al. [1982] to support the hypothesis that broad bands in the electron energy spectra were caused by cyclotron resonance interactions with the plasmaspheric hiss taking place near the equator.

Here with the same instrumentation as that used by Imhof et al. [1981, 1982] and with similar coordination techniques, we investigate the narrow peaks occasionally observed in the energy spectra of electrons precipitating from the radiation belts near \( L = 2 \). It is important to understand the origin of these very narrow peaks at L shells higher than those on which narrow peaks are commonly observed.

COORDINATED WAVE AND ELECTRON DATA

In order to permit comparisons of the observed narrow electron peaks with the wave and plasma density environments, we shall make use of coordinated measurements performed with an electron spectrometer on the P78-1 satellite and with the plasma wave instrument on the ISEE 1 spacecraft. This same technique has been used previously for studies of the narrow peaks observed in the inner belt [Imhof et al., 1981] and the broad bands occurring in the slot region [Imhof et al., 1982]. The electron data were acquired with a high-resolution electron spectrometer on the P78-1 satellite, which was launched into a 96.7° inclination nearly circular orbit at \( \sim 600 \)-km altitude on February 24, 1979. The spectrometer contains 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 \( 69-1120 \) keV. The inherent energy resolution of the spectrometer is \( \sim 20 \) keV full width at half maximum (FWHM). The spectrometer was designed with a collimation angle of \( \pm 15° \) 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 \( \sim 5.5 \) s. For all of the electron data presented here the counting rate versus pitch angle profiles revealed that the particles were locally trapped. They were, however, precipitating from the radiation belt by virtue of being observed at positions where the mirror points have a minimum height below \( \sim 100 \)-km altitude 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 0.07 over the frequency range from 100 Hz to 400 kHz and a dynamic range of 100 dB. In the frequency range of interest here the discrete receiver channels are as follows with a filter bandwidth of $\pm 224$ Hz: 10.0, 10.6, 11.2, 11.8, 12.9, 13.5, 14.7, 16.0, 16.6, 17.9, 18.5, 20.0, 21.1, 22.5, 23.8, 25.2, 27.4, and 28.8 kHz. Electron density contours can be obtained from the emissions at the upper hybrid resonance (UHR) frequency [Gurnett et al., 1978, 1979]. The electron density values derived from the University of Iowa Plasma Wave Experiment have been found to be in good agreement with those obtained from multiple whistler paths [Carpenter et al., 1981].

A 2-year data base involving the two satellites has been searched for suitable coordinations in which narrow peaks were observed at $L$ values near and above 2. It was also required that upper hybrid resonance frequencies were observed from the ISEE 1 satellite and that the spacecraft passed through an $L$ value near 2 within about 2 hours or less of the time at which the electron peaks were observed from the P78-1 satellite. The further restriction was made that the electron observations were performed east of the wave and plasma density measurements and within 120° in longitude. The coordinations are summarized schematically in the lower portion of Figure 1, where the longitudes of observation for the two spacecraft at the $L$ shells of interest are plotted. Since narrow peaks in this $L$ shell region seldom occur, the total data base available for the study is relatively small. In each of these cases, P78-1 data were acquired at two longitude crossings, one in the northern and one in the southern hemisphere. The $L$-dependent peaks in both hemi-
found that the diffusion rate at the edge of the loss cone was
VLF emissions by Alpha system transmissions has been
but generally only a single peak was observed at one time.
Off-equatorial interactions have not been considered here. Off-equatorial interactions
inferred plasma densities for each of the two frequencies,
Koons et al. [1981] have shown that over the L shell range of
frequencies traveling at 0 ø (ducted) or at an unducted angle
the magnetic equator with waves of two representative
Inferred plasma densities that would be
required to account for the observed narrow peaks at L \geq 2
they result from first-order cyclotron resonance near
the magnetic equator. Plasma densities corresponding to
the electron peaks observed in the coordinated cases are plotted
in the lower portions of Figures 2a and 2b. It is assumed that
the peaks result from first-order cyclotron resonance near
the magnetic equator with waves of two representative
frequencies traveling at 0º (ducted) or at an unducted angle
of 60º to the magnetic field line. Ray-tracing calculations by
Koons et al. [1981] have shown that over the L shell range of
interest here the wave normal angle lies between 62º and 64º,
almost independent of the plasma density profile. Accordingly,
ducted waves may lead to resonance interactions and well-defined narrow peaks at energies and/or L shells
higher than those produced by ducted waves.

The frequency of 22.3 kHz was selected on the basis of a previous investigation [Imhof et al., 1981] in which it was
found that 23-kHz waves, such as those generated at 22.3
kHz by the transmitter at Northwest Cape, Australia, were
responsible for the prominent peaks observed in the L = 1.5-1.85 region. The second frequency of 13 kHz has been
selected as a test case on the basis of the known presence of
transmitters at such frequencies operating in the Soviet
Union at high power levels. The Soviet Alpha transmitters
cycle through frequencies of 11.91, 12.65, and 14.88 kHz
[e.g., Inan and Hellliwell, 1982]. The Alpha transmitters run
at much higher power levels (~400 kW) than those of the U.S. Omega navigation system (~10 kW). The triggering of
VLF emissions by Alpha system transmissions has been observed by Inan and Hellliwell [1982], indicating that these transmissions may contribute to the electron precipitation.
Inferred plasma densities for each of the two frequencies,
22.3 kHz and 13 kHz, are shown for waves traveling at 0º
and at 60º to the magnetic field line.

Second- or higher-order harmonic resonances may contribute
to the electron precipitation, but Lyons et al. [1972] found that the diffusion rate at the edge of the loss cone was
not affected much by the higher-order harmonic cyclotron
scattering. Accordingly, second-order harmonic resonances
have not been considered here. Off-equatorial interactions
could lead to higher-energy resonances, but special mecha-
nisms would be required to produce narrow peaks.

Also plotted in Figures 2a and 2b are plasma densities corresponding to the upper hybrid resonance frequency,
\( f_{\text{UHR}} \), measured on ISEE 1. Examples of the observed upper hybrid resonance frequencies in the narrow band sweep frequency receiver data are shown in Figure 3. The densities derived directly from \( f_{\text{UHR}} \) using the relation
\( f_{\text{UHR}} = f_p^2 + f_g^2 \), where \( f_p \) is the electron plasma frequency and \( f_g \) is the electron gyrofrequency, are off-equatorial and have been corrected to equatorial concentrations for a diffusive equilib-
rium model. For this purpose, model calculations (\( T_e = 1600^\circ K \); 90% O^+, 8% H^+, and 2% He^+ at 1000 km) have
been taken from Park [1972, 1980]. The correction factors
used in the normalizations to equatorial concentrations ranged from 1.1 to 2.0 in all of the cases considered here. KP
information is also shown in Figure 2, both the current 3-
hour value and the sum for the preceding 24 hours.

For each group of coordinated measurements provided in
Figures 2a and 2b, several sets of plasma densities are shown, those obtained from the measured electron resonant
energies assuming near-equatorial cyclotron resonance at
each of two frequencies and for waves traveling at 0º and at
60º to the magnetic field line as well as those derived from
the measured upper hybrid resonance frequencies. "Best
fit" curves are drawn through each of these sets of plasma
densities. The plots suggest that the two frequencies and the
two wave normal angles probably cannot all play a signifi-
cant role in each case, and one is motivated to select the
optimum curve in each L shell interval. However, it is
known that changes by a factor of 2 to 3 in electron
concentration at a fixed L value may occur within a few
degrees longitude [Carpenter and Park, 1973], and it is
therefore conceivable that each of the curves could apply in
a different longitude interval. However, typically when only
one peak is observed at a given L value, it seems unlikely
that the same resonant energy would result from a coincident
cancellation of the changes in plasma density with longitude
and the variation in resonant energy for the two frequencies
and the two wave normal angles assumed.

In none of the cases considered here do the plasma
densities derived from the upper hybrid resonant frequencies
overlap in L value those obtained from the observed electron
peaks. On three coordinations the ISEE measurements
extend down to the L values of the electron peaks, but in this
region the \( f_{\text{UHR}} \) values are above the 400-kHz upper limit of
the receiver, and therefore only lower limits to the plasma
densities can be derived. On June 26, 1981, and August 20,
1982, this lower limit is below all or virtually all of the plasma
densities derived from the electron observations, and there-
fore the UHR measurements do not provide firm guidance in
selecting a plasma density curve. However, on August 29,
1980, the four lowest curves near \( L = 2 \) are below this limit
and can therefore be excluded as applicable points.

On some dates such as June 26, 1981, August 20, 1981, and
perhaps August 29, 1980, one can fit the data in Figures 2a
and 2b to a single monotonic plasma density versus L profile,
with a proper selection of frequency and wave angle in each
L shell interval. However, any of the fits require that the
plasma density gradients be quite steep near \( L = 2 \). On the
other two dates, pronounced variations with L or longitude
in the plasma density profiles are required, and neither of
these profiles can be fitted to a monotonic curve. On
For each of two coordinations are plotted the near-equatorial plasma densities corresponding to the upper hybrid resonance frequencies, $f_{\text{UHR}}$, measured on ISEE and corrected to equatorial concentrations on the basis of a diffusive equilibrium model. Also shown are the plasma densities calculated on the basis of the electron peak energies for the principal harmonic resonances assuming two different frequencies and two different wave angles with respect to the magnetic field lines. In the top sections the central energies of the electron peaks are plotted.

Fig. 2a.

For each of three coordinations are plotted the near-equatorial plasma densities corresponding to the upper hybrid resonance frequencies, $f_{\text{UHR}}$, measured on ISEE and corrected to equatorial concentrations on the basis of a diffusive equilibrium model. Also shown are the plasma densities calculated on the basis of the electron peak energies for the principal harmonic resonances assuming two different frequencies and two different wave angles with respect to the magnetic field lines. In the top sections the central energies of the electron peaks are plotted.

Fig. 2b.
October 14, 1981, the upper hybrid resonant measurements in themselves indicate a structured plasma density profile near \( L = 3 \). The September 1, 1981, data require that the plasma density undergo major changes between \( L = 2.3 \) and 3.0 or that the density profiles be quite different at the longitudes applicable to the upper hybrid resonance measurements compared with those at which the electron spectrum observations were performed. Evidence for structured plasma density profiles has been obtained in previous experimental measurements. Edgar [1977] found that steep density gradients exist at \( L = 2 \). More recently, Inan et al. [1982] found that the plasma density profiles may display a rapid dropoff around \( L = 1.8 \).

**NARROW PEAKS AT \( L \approx 2 \) OBSERVED JUST EAST OF ANOMALY**

On rare occasions, extremely narrow peaks at \( L \approx 2 \) were observed at positions slightly east of the South Atlantic Anomaly where electrons in the drift loss cone can just begin to build up. An unusual set of electron measurements at \(-59^\circ\)E longitude on November 1, 1979, is shown in Figure 4. At lower \( L \) values, negligible fluxes of quasi-trapped electrons were observed. Although electron peaks are commonly found at positions just east of the anomaly, these observations are especially noteworthy in view of the extremely narrow widths of the peaks.

The electron peak energies obtained from the spectra in Figure 4 are plotted as a function of \( L \) in the upper portion of the left-hand section of Figure 5. In the lower portion of the plot the inferred plasma density versus \( L \) shell profiles are shown for waves of frequency 13 or 22.3 kHz traveling at 0° or 60° to the magnetic field lines along with model densities of 3000 \((L/2)^{-4}\) cm\(^{-3}\) and 1500 \((L/2)^{-4}\). An \( L^{-4} \) plasma density profile is consistent with those used previously for this type of study [Imhof et al., 1981] and also represents a best fit to the OGO 5 measurements of Chappell et al. [1970]. Unfortunately, coincident measurements from ISEE 1 of the plasma density profiles are not available, since that spacecraft was near apogee, but the absolute densities obtained from upper hybrid resonance measurements presented for other cases earlier in this paper and by Imhof et al. [1981] are typically within a factor of 2 of the first of these models.

Additional rare examples of peaks being observed at longitudes just east of the anomaly are provided in the other two sections of Figure 5. Here are plotted the cold plasma density profiles that would be required to account for the observed \( L \) shell variations in the peak energies. For the three examples in Figure 5 the observed electron peaks are consistent with their formation by first-order cyclotron resonance with either of the assumed wave frequencies only if the cold plasma density versus \( L \) shell profiles are extremely steep and the densities are unusually low at the higher \( L \) shell end of the range considered. The inferred steep falloffs in the plasma densities with increasing \( L \) value may be associated with the general geomagnetic disturbance conditions in effect at those times.

**SUMMARY AND DISCUSSION**

Perhaps the first and most fundamental question to consider is whether the narrow peaks observed on rare occasions...
near and above \( L = 2 \) are part of the same family of peaks that commonly occur on lower \( L \) shells in the inner belt. If both sets of peaks originate from the same wave-particle interaction mechanism with waves generated by ground-based VLF transmitters, then it is necessary in some cases that the cold plasma densities be exceptionally low and in all of the cases that the density decrease very rapidly with increasing \( L \) value. These are not unexpected possibilities, since unusual variations and structure in the plasma densities are known to occur. It is perhaps more difficult to
conceive of another source mechanism for very narrow peaks that does not involve nearly monochromatic waves of transmitter origin. We therefore interpret the present data as providing further evidence in addition to that already existing for the occasional occurrences of very steep gradients in the near-equatorial cold plasma at \( L \) values near 2.

The plasma densities need not be as low if the wave frequencies correspond to those generated by the Soviet Alpha navigation transmitters, but in several observed cases the densities must still be unusually small even at frequencies as low as ~13 kHz. Since there are no known powerful transmitters in regular operation at frequencies below ~10 kHz, the need for exceptionally low plasma densities cannot be avoided simply by invoking a lower wave frequency.

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**References**


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