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A Test of Two Theories for the Low-Frequency Cutoffs of Nonthermal Continuum Radiation

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Two theories have been proposed that differently identify the frequencies of the low-frequency cutoffs of nonthermal continuum radiation. The first of these theories states that the two low-frequency cutoffs occur at the local plasma frequency and $R = 0$ cutoff frequency, with the continuum radiation propagating in the ordinary mode between the cutoffs and a mixture of ordinary and extraordinary mode above the upper cutoff. The second theory suggests that the two low-frequency cutoffs occur at the local $L = 0$ cutoff frequency and plasma frequency, with the continuum radiation being generated by Cerenkov emission in the Z mode between the local plasma frequency and upper hybrid resonance frequency. Mode coupling at the local plasma frequency was suggested to generate continuum radiation in the ordinary mode which freely propagates to remote regions of the magnetosphere. In this paper, several examples of continuum radiation observed in the outer magnetosphere by Imp 6 and ISEE 1 are analyzed in detail, and it is shown that these cutoff frequencies occur at the local plasma frequency and $R = 0$ cutoff frequency. In addition, no substantive evidence is found in the outer magnetosphere for a component of continuum radiation propagating in the Z mode.

INTRODUCTION

Numerous observations of weak electromagnetic radiation emitted from the Earth's magnetosphere and from the Jovian magnetosphere have been made by several satellites, among them IMP 6, IMP 8, Hawkeye 1, ISEE 1 and 2, and Voyager 1 [*Brown*, 1973; *Gurnett and Shaw*, 1973; *Gurnett*, 1975; *Scarf et al.*, 1979]. This radio emission, called the nonthermal continuum, consists of waves propagating in each of two high frequency modes possible in a magnetized plasma, which are commonly called the ordinary mode (O mode) and the extraordinary mode (X mode) [*Allis*, 1963].

Continuum radiation is observed in the earth's magnetosphere at frequencies greater than the local plasma frequency. Because both the O mode and the X mode do not have access to regions where the wave frequency is less than the local plasma frequency, these waves are trapped within the earth's magnetosphere at frequencies less than the solar wind plasma frequency, possibly escaping the magnetosphere through the geomagnetic tail [*Gurnett*, 1975; *Melrose*, 1980].

Direction-finding measurements have shown that continuum radiation from the earth is emitted from a broad region several earth radii thick outside the plasmapause on the dawnside of the magnetosphere. This region begins near local noon and extends through the local morning regions of the outer magnetosphere [*Gurnett*, 1975]. *Frankel* [1973] has suggested that these waves could be generated by gyrosynchrotron radiation emitted by electrons in the 200-keV to 1-MeV energy range. *Gurnett and Frank* [1976], however, have observed the occurrence of a continuum radiation 'storm' simultaneously with the injection of low-energy electrons, ~1-30 keV, into the outer radiation zone, concluding that continuum radiation may be generated by some plasma instability involving electrons in this lower-energy range. It has been suggested, for example, that continuum radiation may be generated by conversion of intense electrostatic waves into electromagnetic radiation [*Gurnett*, 1975; *Gurnett and Frank*, 1976; *Kurth et al.*, 1979; *Gurnett et al.*, 1979; *Melrose*, 1980].

Continuum radiation in the earth's magnetosphere is frequently observed to have two distinct lower-frequency cutoffs that are sharp and well defined in high-resolution frequency-time spectrograms obtained with the wide band receivers of the type flown on Imp 6, ISEE 1 and 2, and Voyager 1 and 2. *Gurnett and Shaw* [1973] previously identified the frequencies at which these two cutoffs occur using data from the Imp 6 plasma wave instrument. The lowest cutoff was determined to be at the local plasma frequency f_p, and the upper cutoff at the local $R = 0$ cutoff frequency $f_{R=0}$, where

$$f_{R=0} = \frac{f_g}{2} + \sqrt{f_p^2 + (f_g/2)^2} \tag{1}$$

and f_g is the local electron gyrofrequency [see *Stix*, 1962]. The plasma frequency and the $R = 0$ cutoff frequency are bounding frequencies below which no wave energy can exist in the O mode and the X mode, respectively. The observation of the two lower-frequency cutoffs is thereby readily explained by the propagation characteristics of O mode and X mode waves.

Recently, *Jones* [1976*a*, *b*] proposed an alternative explanation for these lower-frequency cutoffs. Jones suggested that energy is generated by Cerenkov emission from low-energy electrons at frequencies between the local upper hybrid resonance frequency f_{UHR},

$$f_{UHR} = \sqrt{f_p^2 + f_g^2} \tag{2}$$

and the greater of the plasma frequency or the electron gyrofrequency.

Similar radiation characterized by enhanced wave amplitudes in this frequency range has been observed by numerous investigators at lower altitudes in the ionosphere and plasmasphere [*Walsh et al.*, 1964; *Bauer and Stone*, 1968; *Gregory*, 1969; *Muldrew*, 1970; *Hartz*, 1970; *Mosier et al.*, 1973]. These waves, called upper hybrid resonance noise, propagate in a third plasma wave mode at high frequencies in a cold, magnetized plasma. Waves in this mode, called the Z mode, do not have access to regions where the wave frequency is greater than the local upper hybrid resonance frequency or less than the local $L = 0$ cutoff frequency $f_{L=0}$,

$$f_{L=0} = \frac{-f_g}{2} + \sqrt{f_p^2 + (f_g/2)^2} \tag{3}$$

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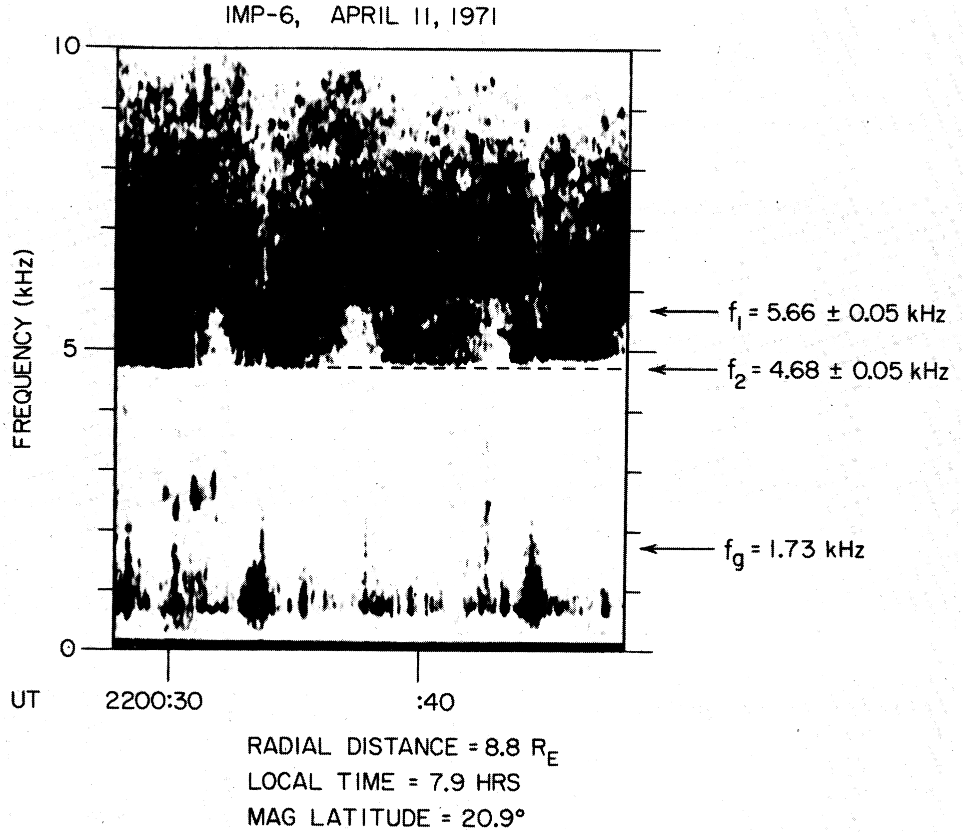

Fig. 1. An example of continuum radiation containing two lower-frequency cutoffs and spacecraft spin modulation. The lower-frequency cutoffs, f_1 and f_2, were measured at about 2200:30 UT as indicated by the dashed line. For this example, 1.62 kHz $\leq f_g \leq$ 1.96 kHz, if $f_1 = f_{R=0}$ and $f_2 = f_p$; 1.92 kHz $\leq f_g \leq$ 2.41 kHz, if $f_1 = f_p$ and $f_2 = f_{L=0}$; f_g = 1.73 kHz (NASA/GSFC magnetometer). The identification $f_1 = f_p$ and $f_2 = f_{L=0}$ is inconsistent with the Imp 6 magnetometer measurements; however, the identification $f_1 = f_{R=0}$ and $f_2 = f_p$ is in agreement with the magnetometer measurements.

As a consequence, these waves are trapped in a limited region of space in the earth's magnetosphere defined by bounding surfaces where the $L = 0$ cutoff frequency and upper hybrid resonance frequency equal the wave frequency.

In contrast to upper hybrid resonance noise, continuum radiation is observed to extend over a much larger frequency range, consisting of waves at frequencies well above the local upper hybrid resonance frequency. *Jones* [1976*a*, *b*] suggests that coupling between *Z* mode waves and waves in the *O* mode at frequencies near the local plasma frequency generates the nonthermal continuum, which subsequently propagates to remote regions in the magnetosphere at frequencies well above the local upper hybrid resonance frequency.

On the basis of this mechanism, Jones has suggested that the identification of the lower-frequency cutoffs of continuum radiation by *Gurnett and Shaw* [1973] was incorrect. Jones suggests that the lower cutoff actually occurs at the local $L = 0$ cutoff frequency instead of f_p and that the upper cutoff occurs at f_p rather than at the $R = 0$ cutoff frequency.

Data are presented in this paper to demonstrate that these cutoffs are not at $f_{L=0}$ and f_p as suggested by Jones, hereafter called the $f_{L=0}/f_p$ theory and that, furthermore, the original identification by Gurnett and Shaw, hereafter called the $f_p/f_{R=0}$ theory, is correct. Cutoff frequencies of the nonthermal continuum have been used to measure accurately the local plasma density in the low-density regions of the earth's magnetosphere [*Gurnett and Frank*, 1974] and Jupiter's magnetosphere [*Scarf et al.*, 1979; *Gurnett et al.*, 1979]; hence the proper identification of these frequencies is important for confirming the accuracy of such measurements.

EXPERIMENTAL COMPARISONS OF THE $f_p/f_{R=0}$ THEORY AND THE $f_{L=0}/f_p$ THEORY

Figure 1 is a frequency-time spectrogram of nonthermal continuum radiation observed by the plasma wave experiment on Imp 6 well beyond the plasmapause (~9 R_E) near local morning. This spectrogram shows the wave electric field detected by one of the long electric dipole antennas on Imp 6. Imp 6 is spinning with a period of about 11 seconds, and the spin axis of the spacecraft is oriented normal to the ecliptic plane. The spectrogram in Figure 1 shows that the continuum radiation has two distinct low-frequency cutoffs, labeled f_1 and f_2 in this figure. Waves at frequencies between f_1 and f_2 are observed to be highly spin modulated, while the waves at frequencies above f_1 have little, if any, spin modulation.

If the spacecraft spin axis is oriented perpendicular to the geomagnetic field, a single dipole antenna can be used to differentiate between wave electric fields aligned parallel and perpendicular to the magnetic field direction. This differentiation can be made because the antenna has a gain factor that is a maximum when the electric field vector is aligned parallel to the antenna elements and a minimum when the electric field vector is aligned perpendicular to the antenna elements. Accordingly, waves with electric fields parallel to the geomagnetic field will be spin modulated with nulls in the modulation occurring when the antenna is perpendicular to the magnetic field direction. Similarly, waves with electric fields perpendicular to the magnetic field will have nulls in the spin modulation that occur when the antenna is parallel to the magnetic field direction.

For the data shown in Figure 1 the angle between the spin axis of Imp 6 and the geomagnetic field direction is 87°. The components of the geomagnetic field were measured by the NASA/GSFC magnetometer experiment on Imp 6 and were provided by N. Ness and D. Fairfield of the Goddard Space Flight Center. Since the spacecraft spin axis is essentially perpendicular to the magnetic field direction, the orientation of the wave electric field vector can be determined for the data shown in Figure 1. The wave electric field between the two cutoff frequencies is oriented parallel to the geomagnetic field in each of these examples and also in all other cases that have been previously analyzed.

The cutoff frequencies shown in Figure 1 have been measured with an accuracy of ±50 Hz, which is twice the bandwidth resolvable in the spectral analysis of these data. To test the $f_p/f_{R=0}$ theory, it is assumed that $f_1 = f_{R=0}$ and that $f_2 = f_p$. By using (1), the electron gyrofrequency can be calculated from these two measurements by

$$f_g = f_1\left(1 - \frac{f_2^2}{f_1^2}\right) \tag{4}$$

To test the $f_{L=0}/f_p$ theory, it is assumed that $f_1 = f_p$ and that $f_2 = f_{L=0}$, and the electron gyrofrequency is calculated from (3) to be

$$f_g = f_2\left(\frac{f_1^2}{f_2^2} - 1\right) \tag{5}$$

These two equations, (4) and (5), yield different values for the electron gyrofrequency, which can be compared to the electron gyrofrequency derived from the value of the local magnetic field B_0 measured by the Imp 6 magnetometer ($f_g = 28B_0$ where B_0 is in gammas). A comparison of the predictions of (4) and (5) with the measured gyrofrequency provides a definitive test for the validity of these two respective identifications of the cutoff frequencies.

The difference Δf between values of f_g obtained from (4) and (5) is often small, 10 to 20% of the measured gyrofrequency for most cutoff frequencies observed in the magnetosphere; therefore high frequency resolution measurements are essential to determine unambiguously these cutoff frequencies. The value of Δf can be calculated by subtracting (4) from (5) and is given by (6)

$$\Delta f = \frac{(f_1 - f_2)^2(f_1 + f_2)}{f_1 f_2} \tag{6}$$

Using (4) and (5) to calculate the value of f_g at about 2200:30 UT from the data shown in Figure 1, we have, including the measurement uncertainty,

1.62 kHz $\leq f_g \leq$ 1.96 kHz	$f_p/f_{R=0}$ theory
1.92 kHz $\leq f_g \leq$ 2.41 kHz	$f_{L=0}/f_p$ theory
f_g = 1.73 kHz	NASA/GSFC magnetometer

It is apparent that the value of f_g calculated from the $f_{L=0}/f_p$ theory does not agree with the value of f_g measured by the Imp 6 magnetometer, even considering a conservative estimate of ±50 Hz for the accuracy of the frequency measurement obtained by use of the high-resolution Imp 6 wide band data. Furthermore, the value of f_g calculated from the $f_p/f_{R=0}$ theory is in agreement with the value of f_g measured by the Imp 6 magnetometer.

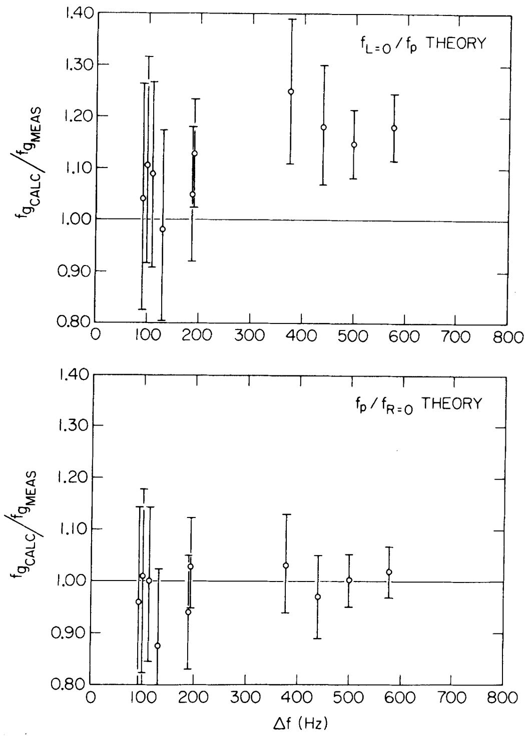

Fig. 2. An analysis of 10 examples of continuum radiation observed by Imp 6 and ISEE 1. Within the experimental accuracies of measurement the electron gyrofrequency calculated from the $f_p/f_{R=0}$ theory, $f_{g\mathrm{CALC}}$, agrees with the simultaneous magnetometer measurements, $f_{g\mathrm{MEAS}}$. The electron gyrofrequency calculated from the $f_{L=0}/f_p$ theory is not in agreement with $f_{g\mathrm{MEAS}}$ except for small values of Δf, the difference between the two calculated gyrofrequencies. For small values of Δf it is expected that it would be difficult to distinguish between the two theories because of the experimental uncertainties in the measurement.

In order to demonstrate that this agreement is representative of more than one isolated example, a total of 10 examples of continuum radiation exhibiting sharp low-frequency cutoffs with spin modulation were selected for analysis. These examples were selected from wide band data collected from the Imp 6 spacecraft and the ISEE 1 spacecraft. The result of this analysis is shown in Figure 2.

Figure 2 contains two graphs that compare the measured electron gyrofrequency with the electron gyrofrequency calculated from the $f_{L=0}/f_p$ theory and the $f_p/f_{R=0}$ theory. It is evident that the values of the electron gyrofrequency calculated from the $f_{L=0}/f_p$ theory are not in general agreement with the magnetometer measurements made simultaneously with the plasma wave measurements. (Measurements of the geomagnetic field on ISEE 1 were made by the UCLA magnetometer and were provided by C. T. Russell through the ISEE data pool tape.) In particular, the only data for which any agreement is achieved are at low values of Δf, for which differentiation between the two theories would be expected to be difficult owing to the experimental uncertainties in the measurement. In contrast with this result, the values of the electron gyrofrequency calculated from the $f_p/f_{R=0}$ theory agree with the magnetometer measurements for all 10 ex-

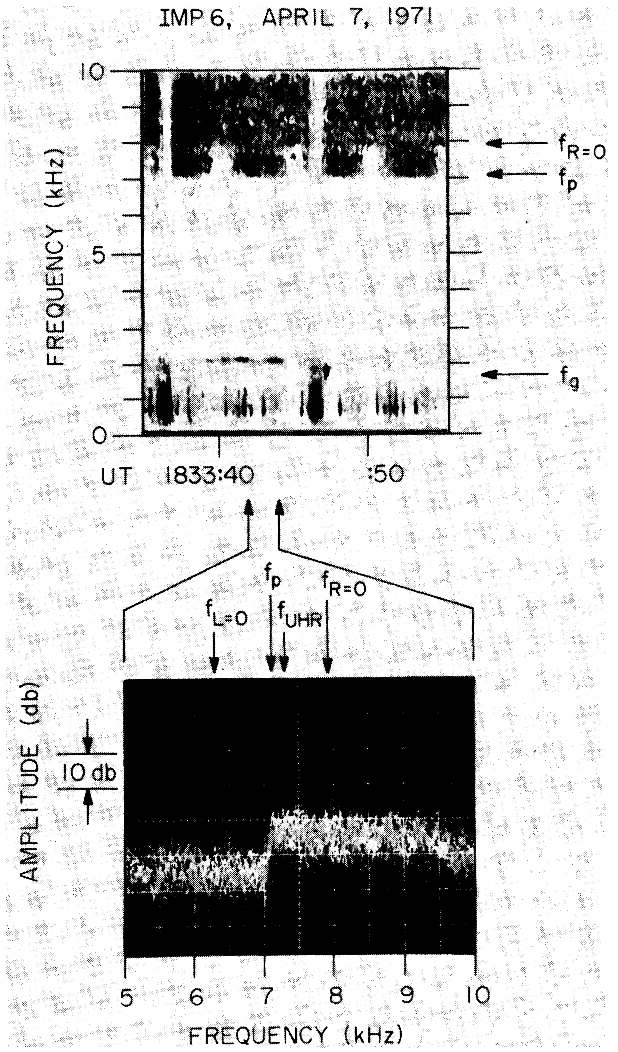

Fig. 3. The lower panel shows the amplitude of an example of continuum radiation as a function of frequency. These data were collected over the time interval shown on the frequency-time spectrogram in the upper panel. The abrupt lower-frequency cutoff is apparent at 7.1 kHz; however, no enhanced wave amplitudes are observed between f_p and f_{UHR}, strongly suggesting that no substantive wave components are generated by Cerenkov radiation in this frequency interval.

amples selected. The results of the analysis shown in Figure 2 demonstrate that these cutoffs are at the local plasma frequency and $R = 0$ cutoff frequency as originally proposed by *Gurnett and Shaw* [1973] and not at the $L = 0$ cutoff frequency and plasma frequency as suggested by *Jones* [1976*a*, *b*].

In addition to the conclusive evidence already provided, several other observations also indicate that the theory proposed by Jones is not applicable to continuum radiation in the outer magnetosphere. Figures 3 and 4 show the amplitudes of two examples of continuum radiation plotted as a function of frequency. These plots contain a superposition of spectrum analyzer sweeps (0.05 s/sweep) obtained over the 2-s interval defined by the arrows pointing to the spectrogram in the top panel of Figures 3 and 4. Neither example shows any evidence of an increase in the wave amplitudes between f_p and f_{UHR}, where waves generated locally by Cerenkov radiation would be expected to be found. Enhancements greater than 20 dB between f_p and f_{UHR} are characteristic of Z mode waves produced by Cerenkov emission in the plasmasphere and ionosphere (see *Hartz* [1970, Figure 1] and *Mosier et al.* [1973, Figure 4] for examples).

The absence of an enhancement in amplitude between f_p and f_{UHR} strongly suggests that continuum radiation observed in the outer magnetosphere does not contain any substantive component locally generated in the Z mode. Instead, it is apparent that these waves are predominantly O mode and X mode waves that appear to have propagated to the spacecraft from more distant sources. Occasionally, cases are observed that contain more complicated frequency structures, which may be related to the generation of these waves. These structures usually resemble harmonic bands or discrete emissions, however, and appear to be considerably different from structures expected for waves generated by Cerenkov emission in the Z mode (see *Gurnett and Shaw* [1973] for representative examples).

In addition to the arguments already presented, an exami-

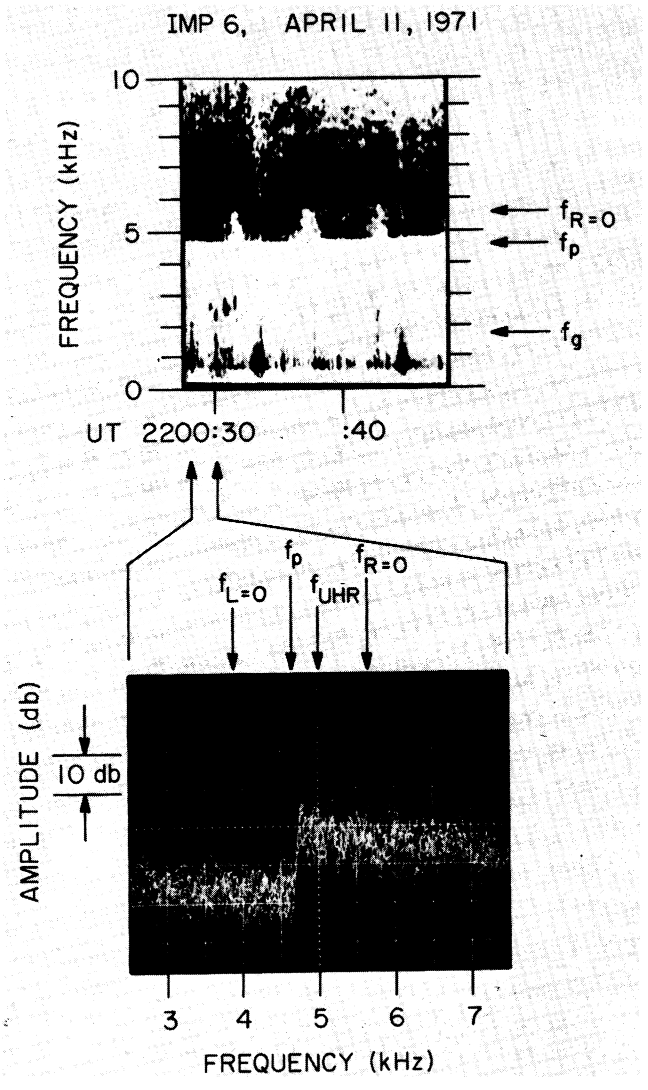

Fig. 4. The amplitude of the continuum radiation shown in Figure 2 as a function of frequency. Again, no enhanced amplitudes are observed for waves between f_p and f_{UHR}, as is typical of upper hybrid resonance noise observed at lower amplitudes within the plasmasphere and ionosphere.

nation of the polarization of the wave electric field of the nonthermal continuum near these cutoff frequencies provides strong evidence that these waves are predominantly O mode and X mode waves. It can be shown [see *Stix* [1962] that the wave electric field vector for the X mode is perpendicular to the magnetic field and circularly polarized, rotating around the magnetic field in the right-hand sense at the $R = 0$ cutoff frequency. The wave electric field vector for the O mode is linearly polarized in the direction parallel to the magnetic field direction at the plasma frequency.

For waves in the Z mode generated by Cerenkov emission, the wave electric field would be expected to be most intense in the direction of the resonance cone, which varies from an angle of 90° with respect to the magnetic field at f_{UHR} to 0° at the greater of f_p or f_g. At the $L = 0$ cutoff frequency the electric field is perpendicular to the magnetic field and circularly polarized rotating around the magnetic field in the left-hand sense. At f_{UHR} the wave electric field is linearly polarized perpendicular to the geomagnetic field.

The polarization of the continuum radiation near the two lower cutoffs is readily explained by the characteristics of the ordinary and extraordinary modes. Of the X mode, the O mode, and the Z mode, only the O mode is oriented parallel to the geomagnetic field direction at any bounding frequency. The X mode is strongly polarized perpendicular to the geomagnetic field at $f_{R=0}$. Consequently, if O mode radiation is present between the two cutoffs and a mixture of O mode and X mode radiation is present above the upper-frequency cutoff, the observed polarization can be explained in a straightforward manner by the characteristics of O mode and X mode radiation. If the lower cutoff occurred at the $f_{L=0}$ cutoff frequency, however, the observed polarization would be completely inconsistent with the characteristics of Z mode radiation at the $L = 0$ cutoff frequency. In summary, the observed polarization is contrary to that predicted by the $f_{L=0}/f_p$ theory [*Jones*, 1976*a*, *b*] and completely consistent with that predicted by the $f_p/f_{R=0}$ theory [*Gurnett and Shaw*, 1973].

DISCUSSION

We have shown, in some detail, that the characteristics of nonthermal continuum radiation observed in the outer magnetosphere are consistent with the expected characteristics of ordinary and extraordinary mode waves described by cold plasma theory. The alternate theory, proposed by *Jones* [1976*a*, *b*], does not maintain consistency between theory and observation in several ways. First, this theory is not consistent with simultaneous measurements of the local magnetic field made by the Imp 6 and ISEE 1 magnetometers. Second, there is no definite indication of a substantive component of continuum radiation observed in the Z mode in the outer magnetosphere. If, as according to Jones, the continuum is produced in this region by Cerenkov radiation in the Z mode, subsequently coupling into O mode radiation at the local plasma frequency, significant wave electric fields would be expected to be observed in the Z mode. Finally, the observed polarization of the wave electric field at the cutoff frequencies is inconsistent with that predicted using Jones' interpretation.

We wish to emphasize that while we disagree completely with Jones' identification of these cutoff frequencies, which are commonly observed in the outer magnetosphere, we do not necessarily disagree with his hypothesis that mode coupling between the O mode and the Z mode may occur in some regions of the magnetosphere. In other regions, for example within the plasmasphere, energy generated by Cerenkov radiation in the Z mode coupling into O mode radiation might generate freely propagating radio emissions at higher frequencies. In the outer magnetosphere, however, there is little evidence to indicate that substantial wave energy is generated by Cerenkov radiation at frequencies below about 30 kHz or that this mechanism contributes significantly to the generation of continuum radiation. Most of the local generation of waves near f_p and f_g in the outer magnetosphere appears to require generation mechanisms characteristic of other types of plasma instabilities, such as those proposed to explain $(n + 1/2)f_g$ harmonics [*Fredricks*, 1971; *Young et al.*, 1973; *Ashour-Abdalla and Kennel*, 1978; *Hubbard and Birmingham*, 1978; *Rönnmark et al.*, 1978].

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