Electrostatic Noise Bands Associated With the Electron Gyrofrequency and Plasma Frequency in the Outer Magnetosphere

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Naturally occurring noise bands near the electron plasma frequency are frequently detected by the University of Iowa plasma wave experiment on the Imp 6 satellite in the region from just inside the plasmapause to radial distances of about 10 R_E in the outer magnetosphere. The electric field strength of these noise bands is usually small with typical broad band electric field strengths of about 2 μV m^{-1}. A magnetic field has been detected only in a few unusually intense cases, and in these cases the magnetic field energy density is several orders of magnitude smaller than the electric field energy density. The bands are observed at all magnetic latitudes covered by the Imp 6 orbit ($|\lambda_m| \lesssim 45°$) and appear to be a permanent feature of the outer magnetosphere. They are found at all local times and occur least frequently in the quadrant from 18 to 24 hours. The bands appear to consist of two distinct spectral types which we have called diffuse and narrow band. In both types the center frequency of the noise band is bounded by consecutive harmonics of the electron gyrofrequency, and these noise bands occur most often between harmonics that are near the local electron plasma frequency. They appear to merge continuously into two other types of plasma wave emissions that are found in dissimilar regions of the magnetosphere (upper hybrid resonance noise, also called region 3 noise, inside the plasmasphere and $(n + \frac{1}{2})f_g$ harmonics in the outer magnetosphere). It is suggested that this smooth merging is caused by changes in the plasma wave dispersion relation that occur as the spacecraft moves from the cold plasma within the plasmasphere into the warm non-Maxwellian plasma found in the outer magnetosphere.

INTRODUCTION

Several types of plasma wave noise bands have been observed by rocket- and satellite-borne radio noise experiments at frequencies near the electron plasma frequency and the electron gyrofrequency. A noise band that extends between the local plasma frequency and the local upper hybrid resonance frequency has been observed in the ionosphere and the plasmasphere by *Walsh et al.* [1964], *Bauer and Stone* [1968], *Gregory* [1969], *Muldrew* [1970], and *Hartz* [1970]. More recently, *Mosier et al.* [1973] reported observations of a similar noise band (called upper hybrid resonance noise, or region 3 noise) inside the plasmasphere at frequencies between the local plasma and upper hybrid resonance frequencies. Incoherent Cerenkov radiation from thermal electrons may generate upper hybrid resonance noise, and the propagation of the wave energy appears to be adequately described by cold plasma theory [*Mosier et al.*, 1973; *Taylor and Shawhan*, 1974].

Intense narrow band electrostatic emissions (called $(n + \frac{1}{2})f_g$ harmonics) have been detected in the outer magnetosphere by Ogo 5 with wave frequencies between harmonics of the local electron gyrofrequency [*Kennel et al.*, 1970; *Fredricks and Scarf*, 1973; *Scarf et al.*, 1973]. The generation of the $(n + \frac{1}{2})f_g$ harmonics cannot be understood in terms of cold plasma theory. Instead an electrostatic instability driven by a non-Maxwellian electron velocity distribution is believed to generate these waves [*Fredricks*, 1971; *Young et al.*, 1973].

Weak electromagnetic continuum radiation has been observed in the outer magnetosphere at frequencies above the local electron plasma frequency [*Gurnett and Shaw*, 1973; *Gurnett*, 1975]. This radiation was originally called $f > f_p$ noise; however, it has recently been called nonthermal continuum radiation because of the broad frequency spectrum and the essentially constant amplitude over large regions of space and long periods of time.

The continuum radiation has two components. One component is at frequencies greater than the solar wind plasma frequency and can escape from the magnetosphere into the solar wind. The second component is at frequencies less than the solar wind plasma frequency and is trapped in the outer magnetosphere by the reflective boundaries formed by the magnetopause and the plasmapause [*Gurnett*, 1975]. In some cases this radiation has a sharp lower cutoff at the local electron plasma frequency that provides an accurate determination of the electron number density [*Gurnett and Frank*, 1974].

The University of Iowa plasma wave experiment on board the Imp 6 satellite has detected electrostatic noise bands in the outer magnetosphere that occur between harmonics of the local electron gyrofrequency, most often between harmonics that are near the local plasma frequency. These emissions are found throughout a large region in the magnetosphere, occurring from well inside the plasmapause to radial distances as great as 10 R_E. Such bands are detectable on about two thirds of all the Imp 6 magnetospheric passes and are essentially a permanent feature of the magnetosphere. These bands typically have small electric field amplitudes, with broad band field strengths usually about 2 μV m^{-1}, and they probably have not been previously observed because of the low amplitudes at which they occur.

The characteristics of these electrostatic noise bands change as the spacecraft moves from inside the plasmasphere to larger radial distances in the outer magnetosphere. Well inside the plasmasphere the noise bands have characteristics similar to upper hybrid resonance noise, while at larger radial distances in the outer magnetosphere the noise bands often develop characteristics similar to the $(n + \frac{1}{2})f_g$ harmonics. Thus these observations suggest that there is a connection between these two different types of naturally occurring noises which are found in dissimilar regions of the magnetosphere.

This paper briefly describes the University of Iowa Imp 6 plasma wave experiment, presents an observational study of the diffuse and narrow band electrostatic noise observed by the University of Iowa experiment, and examines the connection between these noise bands and the other types of noises found in the plasmasphere and the outer magnetosphere.

DESCRIPTION OF THE EXPERIMENT

The Imp 6 spacecraft was launched on March 13, 1971, from the Eastern Test Range at Cape Kennedy, Florida. The highly elliptical orbit had an initial perigee and apogee at geocentric radial distances of 6610 km and 212,630 km, respectively. The orbit inclination was 28.7°, and the period was slightly greater than 100 hours. The spacecraft was spin-stabilized, rotating with a period of about 11 s about the z axis, which was oriented normal to the ecliptic plane.

The University of Iowa plasma wave experiment consists of a complement of electric dipole and magnetic loop antennas, two identical frequency spectrum analyzers, and two broad band AGC (automatic gain control) receivers. Seven different antennas are used by the experiment to detect both electrostatic and electromagnetic plasma wave phenomena. These include three orthogonal 'long' electric dipole antennas, one 'short' electric dipole antenna, and three orthogonal loop antennas. Two of the long electric antennas, E_x and E_y, are perpendicular to the spin axis and have tip-to-tip lengths of 54.0 m and 93.2 m, respectively. The third long antenna, E_z, is parallel to the spin axis and has a tip-to-tip length of 6.55 m. The short electric dipole antenna is mounted on the magnetometer boom. This antenna consists of two wire cage spherical elements whose centers are separated by 0.38 m. Each magnetic loop antenna consists of a one-turn loop with an area of slightly less than 1 m^2. The loop antenna assembly is mounted on a boom that extends approximately 4 m from the body of the spacecraft.

Several combinations of these antennas may be connected to either of two identical spectrum analyzers. Each of these spectrum analyzers consists of 16 filter channels with bandwidths of about 15% of the center frequency. There are four filter channels for each decade in frequency, covering the frequency range from 20 Hz to 200 kHz.

Each filter channel has two detectors, a peak detector and an average detector. The peak detector measures the largest signal strength seen during each sample interval of 5.11 s, has a time constant equal to 0.1 s, and is reset to zero at the start of each new sample interval. The average detector has a time constant equal to the 5.11-s sample interval and continuously measures the time average signal strength over one sample interval. Each filter channel has a dynamic range of 100 dB with a sensitivity of about 10 μV for a sine wave signal at the center frequency of the filter channel. The output of each detector is a dc voltage that is approximately proportional to the logarithm of the signal amplitude seen at the input of the spectrum analyzer.

Operated in conjunction with the long electric antennas, electric field strengths as low as 0.2 $\mu V\ m^{-1}$ can be measured. The sensitivity of the magnetic loop antennas is a function of frequency and varies from about 2.0 mγ at 36 Hz to about 10.0 $\mu\gamma$ at 16.5 kHz.

In addition to the digital data available from the two spectrum analyzers, two broad band AGC receivers make it possible to produce detailed frequency-time spectrograms of narrow band and transient wave phenomena. The wide band receivers have eight different configurations that are obtained by different combinations of switching between the two spectrum analyzers and three different ranges of frequency coverage. The data researched for this paper were usually recorded in a mode that cycles between the electric and magnetic antennas and the frequency ranges 650 Hz to 10 kHz, 11 kHz to 19 kHz, and 21 kHz to 29 kHz.

ELECTROSTATIC NOISE BANDS OBSERVED BY IMP 6

Identifying characteristics. A portion of the spectrum analyzer data from a typical Imp 6 magnetospheric pass is shown in Figure 1. The data shown were recorded as the spacecraft moved outward from about 2.0-R_E to about 10.0-R_E geocentric radial distance. The data presented are the raw voltage outputs of the two spectrum analyzers (proportional to the logarithm of the signal amplitude), one of which is connected to the E_y electric dipole antenna and the other of which is connected to the M_y magnetic loop antenna. The dynamic range of each frequency channel (100 dB) is represented by the distance from the base line of one channel to the base line of the next channel. Each vertical bar represents the time average electric (or magnetic) field strength measured over a time interval of 81.8 s, and the dots immediately above each bar represent the peak field strength seen over the same time interval.

The large signal strengths seen in the lowest-frequency channels of the electric field data are caused by interference that is produced when the loop antenna boom assembly shadows the spacecraft solar array panels. As the spacecraft spins, the shadow of the loop antennas produces voltage transients on the solar array panels and the associated connecting wiring. The result is interference that is picked up by the plasma wave experiment, particularly at low frequencies. The magnitude of this interference, which we call solar array interference, is dependent upon the properties of the plasma surrounding the spacecraft. Specifically, when the spacecraft crosses the plasmapause, the amplitude of the interference increases greatly. This effect is seen at about 0300 UT in the electric field data shown in Figure 1.

A second indication of the plasmapause location is shown in the magnetic antenna filter channel data of Figure 1. A strong hiss band is observed from about 0130 to 0300 UT, covering the frequency range from about 200 Hz to 3 kHz with an abrupt termination at approximately 0300 UT. This hiss, called plasmaspheric hiss, is confined to the interior of the plasmasphere and terminates close to the location of the plasmapause [*Russell et al.*, 1969; *Russell and Holzer*, 1970; *Thorne et al.*, 1973]. Plasmaspheric hiss is observed on most Imp 6 passes through the plasmasphere, and the termination of the hiss and the increase in amplitude of the solar array interference provide a definite indication that the plasmapause has been crossed.

The inset in Figure 1 shows an electrostatic noise band of the type that is frequently found on Imp 6 passes through the magnetosphere. The noise band first becomes evident in the electric dipole antenna data at about 0220 UT in the 178-kHz filter channel. No corresponding signals are observed in the magnetic loop antenna data. The center frequency of the noise band decreases systematically as the radial distance of the spacecraft increases with an abrupt decrease from 100 to 16.5 kHz near the plasmapause crossing at about 0300 UT. This abrupt decrease in frequency suggests that the frequency of the noise band may be related to the electron number density, which also decreases abruptly at the plasmapause boundary.

The most likely resonance frequencies that could be associated with this noise band occur at the electron plasma frequency f_p and the upper hybrid resonance frequency f_{UHR}:

$$f_{UHR} = (f_p^2 + f_g^2)^{1/2} \qquad (1)$$

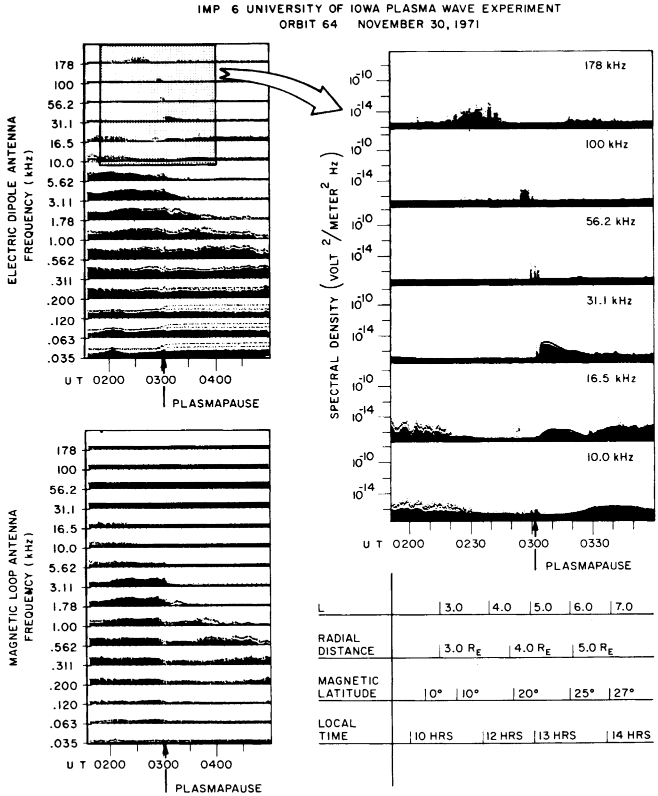

Fig. 1. Spectrum analyzer data from a typical outbound Imp 6 magnetospheric pass from near a 2.0-R_E to 10.0-R_E geocentric radial distance. The inset shows an electrostatic noise band of the type found on about two thirds of all Imp 6 passes through this region of the magnetosphere. The noise band decreases in frequency with increasing radial distance, with an abrupt decrease in frequency near the plasmapause boundary. The plasmapause is identified by the sudden increase in the magnitude of the solar array interference in the low-frequency electric antenna channels and by the sudden termination of the plasmaspheric hiss in the low-frequency magnetic antenna channels. The frequency of the bands both inside and just outside the plasmapause boundary is near the local plasma frequency typically observed in these respective regions.

$$f_p = (1/2\pi)(e^2 n/m\epsilon_0)^{1/2} \quad (2)$$

$$f_g = (1/2\pi)(eB/m) \quad (3)$$

where n is the electron number density and B is the static magnetic field. Both the plasma frequency and the upper hybrid resonance frequency change abruptly at the plasmapause boundary similar to the change in frequency of the electrostatic noise band shown in Figure 1.

In addition, the center frequency of this noise band is comparable to the electron plasma frequency expected in this region of the magnetosphere. Center frequencies of 100 kHz and 16.5 kHz, for example, would correspond to electron number densities of 120 cm^{-3} and 3.3 cm^{-3}, respectively. The noise band occurs at these frequencies near the inside and outside edges of the plasmapause, and these electron number densities are typical of those measured inside and outside the plasmapause [*Carpenter et al.*, 1969; *Harris et al.*, 1970].

Electrostatic noise bands of this type are observed on about two thirds of all Imp 6 magnetospheric passes and have characteristics similar to those in the example shown in Figure 1. The bands are most easily identified during quiet geomagnetic periods ($Kp \leq 2$). The characteristic variation in frequency with radial distance (as shown in Figure 1) can easily be recognized on magnetospheric passes when Kp has low values. During more disturbed geomagnetic periods these bands either do not exist or are hidden by other types of noises with greater amplitudes than those of the electrostatic noise bands.

Region of occurrence. Since the frequency of these noise bands increases as the spacecraft moves to lower radial distances in the plasmasphere, it is probable that such bands occur at frequencies greater than 178 kHz (the upper spectrum analyzer filter channel) at lower altitudes in the plasmasphere. At higher altitudes, beyond the plasmapause, these noise bands are observed to decrease in bandwidth and intensity until, beyond about 10 R_E, they are no longer observed even though Imp 6 samples radial distances to about 30 R_E. Thus these bands are observed in the interior of the magnetosphere and probably extend to lower altitudes in the plasmasphere, where upper hybrid resonance noise has been observed.

A survey was made of the location of all such electrostatic noise bands that were observed during the first year of operation of the Imp 6 plasma wave experiment. These noise bands

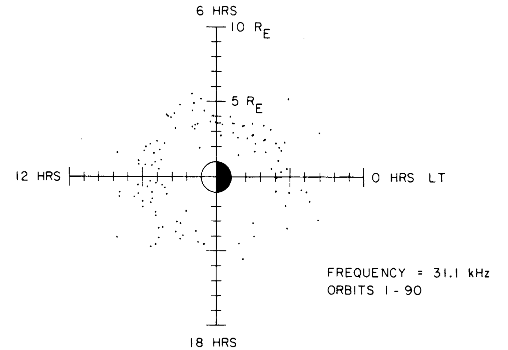

Fig. 2. The location of the largest signal strength seen in the 31.1-kHz filter channel for all electrostatic noise bands of the type shown in Figure 1. The data surveyed were the result of a full year of operation of the University of Iowa Imp 6 plasma wave experiment, and thus all local times were nearly evenly sampled. The bands are found at all local times, occurring least frequently from 18 to 24 hours. At 31.1-kHz they occur at radial distances near 4–5 R_E and tend to occur at somewhat larger radial distances near local evening than near local morning. This location corresponds roughly with typical locations of the plasmapause boundary, as would be expected if the bands occur at frequencies near the local plasma frequency.

were observed at all magnetic latitudes sampled by the Imp 6 orbit ($|\lambda_m| \lesssim 45°$).

Figure 2 shows the locations at which electrostatic noise bands of the type shown in Figure 1 were observed in the 31.1-kHz spectrum analyzer filter channel as a function of local time and radial distance. The data plotted are the points at which the greatest intensity was measured at 31.1 kHz for all bands observed during the first year of operation of the experiment. Since the major axis of the orbit moves through one rotation in local time per year, Figure 2 represents a nearly equal sampling of all local times. The peak response in the 31.1-kHz channel occurs at radial distances of 4–5 R_E and shows a tendency to occur at larger radial distances near local evening than near local morning. The noise bands occur at all local times, least often in the quadrant from 18 to 24 hours.

The location at which the 31.1-kHz electrostatic noise bands occur, particularly the tendency for the bands to occur at larger radial distances near local evening, suggests the general location of the plasmapause boundary [*Chappell et al.*, 1971]. This local time variation further supports the association of these noise bands with the local plasma frequency, since 31.1 kHz is typical of the plasma frequency near the plasmapause boundary.

Spectral characteristics. Electrostatic noise bands of the type shown in Figure 1 appear to occur as two distinct spectral types in the wide band spectrograms. The first type appears in the spectrograms as one or more narrow, well-defined lines with bandwidths of a few hundred hertz. We have called this spectral type narrow band electrostatic noise because of its appearance in the wide band spectrograms. The second type, which we call diffuse electrostatic noise, consists of one or more bands, generally a few kilohertz in width, often with a sharp upper-frequency cutoff. The diffuse electrostatic noise frequently has nulls that occur at twice the spacecraft spin rate,

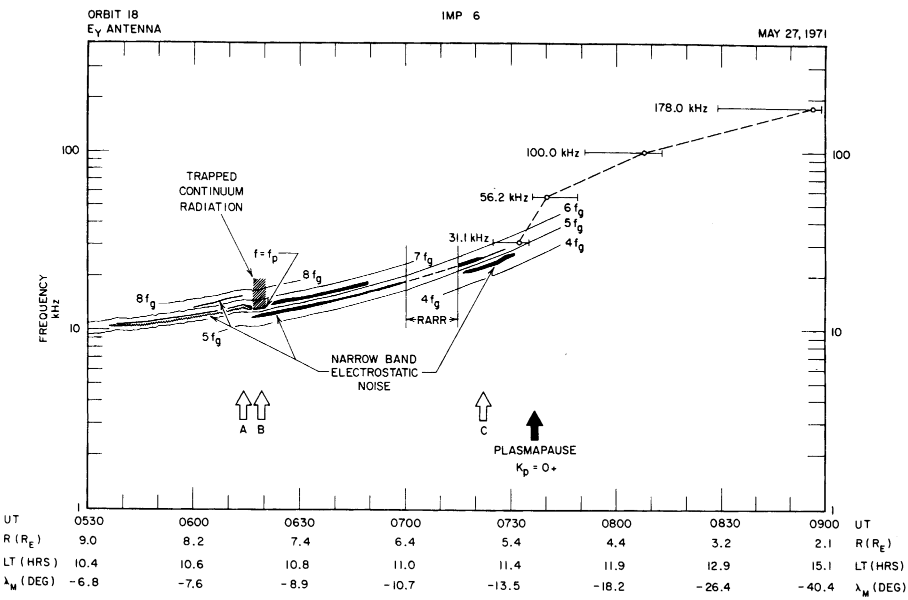

Fig. 3. An inbound Imp 6 magnetospheric pass, orbit 18, from about a 9-R_E to a 2-R_E geocentric radial distance illustrating an example of narrow band electrostatic noise. The narrow band electrostatic noise is resolved into four distinct bands in the wide band receiver data that occur at frequencies between consecutive harmonics of the electron gyrofrequency as determined by measurements from the NASA/GSFC magnetometer experiment. The bands tend to occur between higher harmonic numbers as the spacecraft moves to larger radial distances beyond the plasmapause boundary. This behavior, the abrupt change in frequency in crossing the plasmapause, and the identification of the plasma frequency at 0620 UT all suggest that the local plasma frequency has a strong influence on the frequency at which the narrow band electrostatic noise occurs.

and the narrow band electrostatic noise does not have spin-modulated intensity.

An example of narrow band electrostatic noise is shown in Figures 3 and 4. The data shown in Figure 3 illustrate the frequencies at which the narrow band electrostatic noise is observed by the wide band receiver and the upper four spectrum analyzer filter channels. The open circles represent the time at which the largest signal strength was seen in each spectrum analyzer filter channel, and the horizontal bars represent the time interval during which any signal was present in that channel. The data shown were recorded from the E_y dipole antenna during an inbound magnetospheric pass, orbit 18, from about 9 R_E to 2 R_E near local noon.

The narrow band electrostatic noise is evident in the 178-kHz filter channel at about 2 R_E. The frequency of the noise band sweeps down fairly uniformly with increasing radial distance until the plasmapause boundary is reached near 5 R_E. The center frequency decreases abruptly at the plasmapause boundary, and the noise band is observable in the wide band receiver data just outside the plasmapause.

Spectrograms of wide band receiver data corresponding to points labeled A, B, and C in Figure 3 are shown in Figure 4. These high-resolution spectrograms resolve the noise band into four distinct narrow bands which do not cross harmonics of the electron gyrofrequency as the spacecraft moves to larger radial distances beyond the plasmapause. (Values for harmonics of the electron gyrofrequency labeled f_g, $2f_g$, etc., in Figures 3 and 4 were calculated from simultaneous measurements of the geomagnetic field strength by the NASA/GSFC magnetometer experiment on Imp 6). The lowest frequency band is found in the frequency interval bounded by the fourth and fifth harmonics of the electron gyrofrequency, and it extends to radial distances slightly beyond the plasmapause. A second band is found between the fifth and sixth harmonics of the electron gyrofrequency, and it extends to a radial distance of about 8 R_E. This noise band decreases in frequency at a rate slightly less than the rate of decrease of the harmonics of the electron gyrofrequency, as can be seen in Figure 3. A third band is found between the sixth and seventh harmonics of the electron gyrofrequency from about 7 to 9 R_E. A fourth band is found between the seventh and eighth harmonics near 8 R_E.

At about 0620 UT, labeled B in Figures 3 and 4, the noise bands are observed coincidentally with some trapped continuum radiation that is visible in the wide band spectrograms for several minutes. Nulls occurring at twice the spacecraft spin rate are visible in the wide band spectrogram of the trapped continuum radiation shown in Figure 4. These nulls indicate that the sharp lower cutoff frequency of the trapped radiation is equal to the local plasma frequency [*Gurnett and Shaw*, 1973]. Thus for the time period near 0620 UT the plasma frequency can be positively identified from this lower-frequency cutoff.

The narrow band electrostatic noise at 0620 UT occurs between the consecutive harmonics of the electron gyrofrequency that are immediately above and immediately below the plasma frequency. Thus the plasma frequency appears to strongly influence the frequency at which the bands occur at larger radial distances in the magnetosphere as well as near the plasmapause boundary.

The wide band receiver data in the spectrograms of Figure 4 also show that the amplitude of the narrow band electrostatic noise is not modulated by the spacecraft spin, as is the trapped continuum radiation. The nulls near the lower cutoff frequency of the trapped radiation are a result of the definite orientation of the wave electric field vector parallel to the geomagnetic field. Since such nulls are not observed for the narrow band electrostatic noise, it is concluded that the wave electric field vector of the narrow band electrostatic noise is not strongly oriented either parallel to or perpendicular to the geomagnetic field.

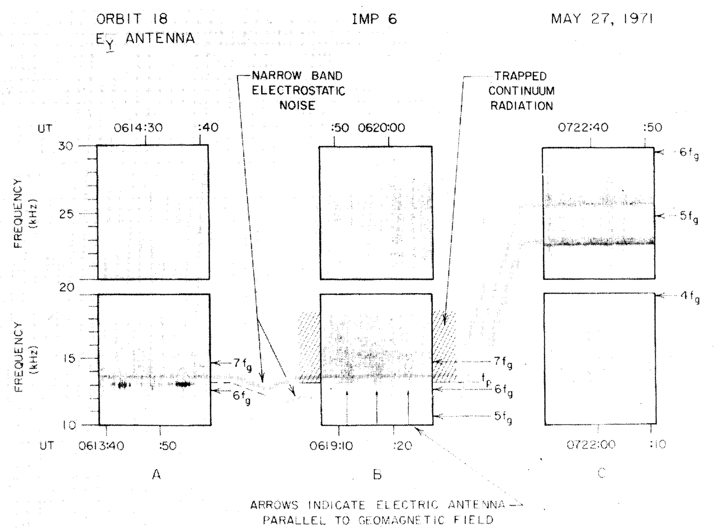

Fig. 4. Wide band spectrograms of the narrow band electrostatic noise at points labeled A, B, and C in Figure 3. The narrow band electrostatic noise consists of several well-defined lines which do not have nulls in intensity as the spacecraft rotates, as does the trapped $f > f_p$ electromagnetic noise observed at 0620 UT in spectrogram B. The absence of nulls suggests that the direction of the wave electric field vector of the narrow band electrostatic noise is not strongly oriented either parallel to or perpendicular to the geomagnetic field.

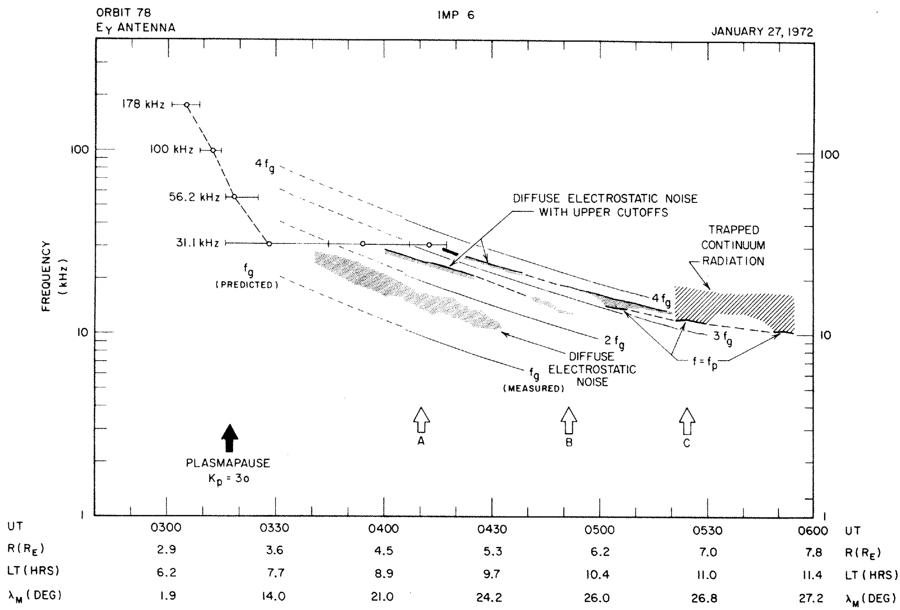

Fig. 5. An outbound Imp 6 magnetospheric pass, orbit 78, from about a 3-R_E to an 8-R_E geocentric radial distance illustrating an example of diffuse electrostatic noise. The diffuse electrostatic noise is resolved into three distinct bands in the wide band receiver data. These noise bands are bounded by consecutive harmonics of the electron gyrofrequency determined by measurements from the NASA/GSFC magnetometer experiment as indicated. The noise bands tend to occur between harmonics that are near the local plasma frequency as identified from the lower cutoff frequency of the trapped $f > f_p$ electromagnetic noise.

Another Imp 6 magnetospheric pass, orbit 78, illustrating the second spectral type, which we call diffuse electrostatic noise, is shown in Figures 5 and 6. The wide band receiver data show that the diffuse electrostatic noise consists of three distinct bands. The center frequencies of these noise bands are bounded by consecutive harmonics of the electron gyrofrequency at radial distances beyond the plasmapause, as were the center frequencies of the narrow band electrostatic noise.

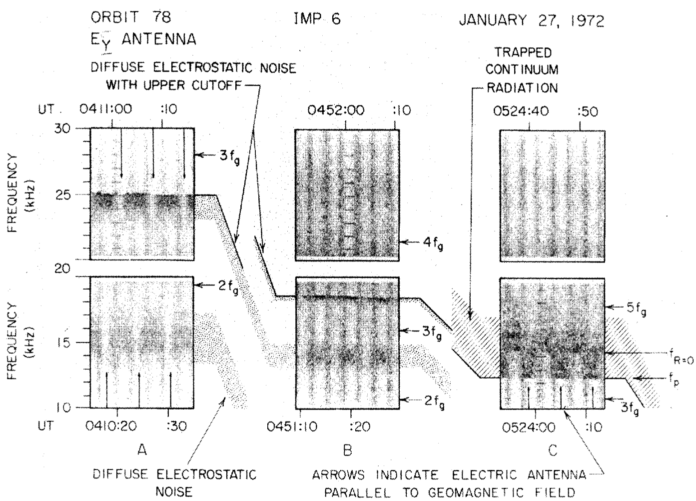

Fig. 6. Wide band spectrograms of the diffuse electrostatic noise at points labeled A, B, and C in Figure 5. The diffuse electrostatic noise consists of faint noise several kilohertz in width, sometimes with a sharp upper cutoff frequency. The diffuse noise bands frequently have nulls that occur at twice the spacecraft spin rate. The position of these nulls indicates that the electric field vector of the noise bands is oriented perpendicular to the geomagnetic field. A lower cutoff frequency which appears to be at the local plasma frequency develops for a short time near 0505 UT.

The band between the second and third harmonics and the band between the third and fourth harmonics are observed to have a sharp upper-frequency cutoff, while the band between the first and second harmonics has no distinct upper cutoff.

Wide band spectrograms of the noise bands at points labeled A, B, and C in Figure 5 are shown in Figure 6. As is shown in spectrogram A, the bands are observed to have nulls that occur at twice the spin rate of the spacecraft. The position of these nulls indicates that the wave electric field vector of the diffuse electrostatic noise is oriented perpendicular to the geomagnetic field direction. All values of the geomagnetic field used in this paper were measured by the NASA/GSFC magnetometer experiment on board Imp 6, with the exception of those specifically labeled predicted, for example, the values from 0300 to 0405 UT in Figure 5, which were computed from the Jensen-Cain expansion for the geomagnetic field.

The plasma frequency can be identified at large radial distances by the sharp lower-frequency cutoff of the trapped continuum radiation as shown in spectrogram C of Figure 6. The diffuse electrostatic noise on orbit 78, similar to the narrow band electrostatic noise observed on orbit 18, is seen to occur between harmonics of the electron gyrofrequency which are near the local electron plasma frequency.

Near 0505 UT, as is shown in Figure 5, the noise band between $3f_g$ and $4f_g$ develops a sharp lower-frequency cutoff. It is seen that nulls at twice the spacecraft spin rate occur at both the upper-frequency and the lower-frequency cutoff, which indicates that the wave electric field vector is parallel to the geomagnetic field at the lower-frequency cutoff and perpendicular to the geomagnetic field at the upper-frequency cutoff. Because of the orientation of the wave electric field and the frequency at which the lower cutoff occurs in relation to the lower-frequency cutoff of the trapped continuum radiation (see Figure 5) it is reasonable to believe that the lower cutoff frequency of this diffuse noise band is equal to the local plasma frequency. A few other cases of diffuse electrostatic noise have a sharp lower-frequency cutoff similar to that of the example shown in Figures 5 and 6; however, this sharp lower cutoff is not usually observed.

Narrow band electrostatic noise and diffuse electrostatic noise are not often observed on the same magnetospheric pass; however, in a few cases they are observed simultaneously. The narrow band electrostatic noise tends to extend to larger radial distances in the outer magnetosphere. Both types of noise can exist continuously for distances of several earth radii beyond the plasmapause boundary.

Wave electric field strength and associated wave magnetic field strength. Figure 7 shows the distribution of electric field spectral densities that were measured for all noise bands of the type shown in Figure 1 during the first year of operation of the University of Iowa experiment. These data represent the largest signal strength for the bands in the 31.1-kHz spectrum analyzer filter channel.

Values for the electric field spectral densities were calculated by assuming the wave electric field to be equal to the voltage measured at the antenna divided by one-half the tip-to-tip length of the antenna. In addition, the noise bands were assumed to have a bandwidth larger than the effective spectrum analyzer filter bandwidth to calculate values for spectral density. This assumption is valid for most cases of diffuse electrostatic noise; however, it is not valid for the narrow band electrostatic noise because it typically has a bandwidth of about one-tenth that of the spectrum analyzer filter channels. The error introduced by this assumption could cause the actual spectral densities of the narrow band electrostatic noise to be a factor of about 10 larger than those shown in Figure 7. Since this is not a large error in terms of the ranges of the data (10^8 in spectral density), no attempt was made to correct values of spectral density for the narrow band electrostatic noise.

Either narrow band electrostatic noise or diffuse electrostatic noise was observed on about two thirds of the total number of magnetospheric passes during the first year of operation of the Imp 6 experiment. The noise bands occur most often with a peak wave electric field spectral density near 10^{-15} V^2 m^{-2} Hz^{-1}, corresponding to a broad band field amplitude of about 2 μV m^{-1}. It is uncertain whether the low occurrence of bands shown near a spectral density of 10^{-16} V^2 m^{-2} Hz^{-1} results from less relative occurrence or masking due to variations in the background levels of other types of waves received by the antenna, for example, the nonthermal continuum radiation.

In most cases of these types of noise bands no wave magnetic field was observed; however, there was an observable wave magnetic field component in the digital spectrum analyzer data for eight out of the approximately 110 noise bands investigated. These eight cases are examined in Figure 8.

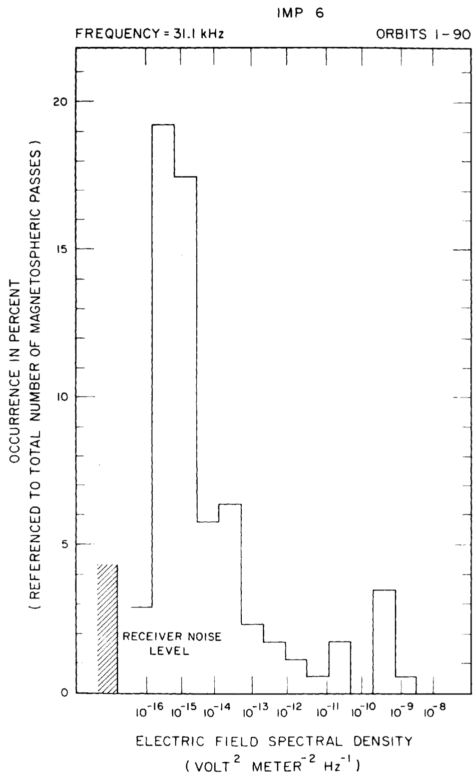

Fig. 7. The frequency of occurrence of the peak electric field spectral density of the noise bands at 31.1 kHz. The occurrence in percent is based on the total number of magnetospheric passes in the first year of operation of the University of Iowa Imp 6 plasma wave experiment. These noise bands occurred on about two thirds of all magnetospheric passes with a peak electric field spectral density most often near 10^{-15} V^2 m^{-2} Hz^{-1}. This is equivalent to a broad band field strength of about 2 μV m^{-1}.

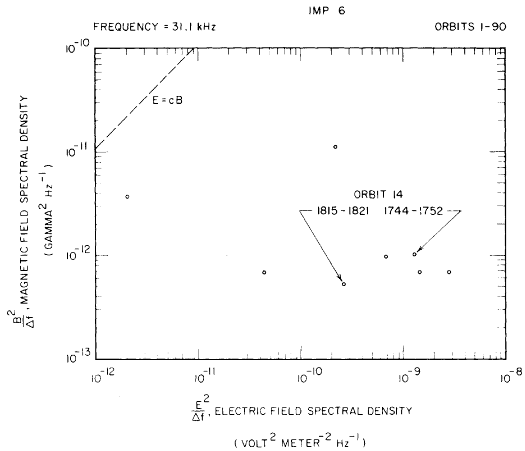

Fig. 8. The peak electric field spectral density as a function of the peak magnetic field spectral density for the eight out of 110 cases in which noise bands were observed with a wave magnetic field component. The value of the wave magnetic field energy density is about 4 orders of magnitude less than the value of the electric field energy density, and these eight cases correspond to observations for which the bands have unusually intense electric field strengths. Five other cases exist with wave electric field spectral densities between 10^{-11} V^2 m^{-2} Hz^{-1} and 10^{-8} V^2 m^{-2} Hz^{-1} for which no wave magnetic field was detected.

For each occurrence the peak electric field energy density of the bands is plotted as a function of the peak magnetic field energy density. The peak signal strength plotted represents the largest signal observed in the 31.1-kHz filter channel during the time interval over which the noise band was observed in that filter channel.

As can be seen in Figure 8, the peak electric field energy density of the noise bands is typically about 4 orders of magnitude greater than the peak magnetic field energy density, and these eight cases are associated with unusually intense values of wave electric field strength. Seven of these eight cases had values of electric field spectral density in excess of 10^{-11} V^2 m^{-2} Hz^{-1}. There were five other cases of noise bands with peak electric field spectral densities between 10^{-11} V^2 m^{-2} Hz^{-1} and 10^{-8} V^2 m^{-2} Hz^{-1} for which no associated wave magnetic field was observed.

It is not possible to determine experimentally if the weaker noise bands (electric field spectral densities below 10^{-12} V^2 m^{-2} Hz^{-1}) have wave magnetic fields with energy densities 4 orders of magnitude less than their electric field energy densities. If these bands do have a proportionally weak wave magnetic field, they could not be detected with the magnetic antenna on Imp 6.

The relationship between the wave magnetic field strength and the wave electric field strength has been investigated in detail for one specific pass, the inbound portion of orbit 14. On this pass, noise bands were observed with a particularly intense wave electric field and a detectable wave magnetic field. Figure 9 shows the raw voltage outputs from the upper six spectrum analyzer channels on this pass. At least two distinct noise bands can be distinguished sweeping upward in frequency as the spacecraft approaches the plasmapause at about 1820 UT. These noise bands are particularly intense in the 31.1-kHz electric field channel, and a weak but clear response is evident at corresponding times in the 31.1-kHz magnetic field channel.

Figure 10 shows a plot of the corresponding electric and magnetic field spectral densities measured by the peak detector of the 31.1-kHz filter channel as the spacecraft passed through the region containing these noise bands. The 5.11-s samples of magnetic field spectral density in Figure 10 were calculated by subtracting the noise level spectral density of the magnetic receiver in order to reduce the error caused by the preamplifier noise at small signal levels. The peak wave magnetic field intensity of these bands is not simply proportional to the peak electric field intensity, although there is a clear tendency for the magnetic field strength to increase as the electric field strength increases. For a given value of magnetic field the electric field varies by about 3 orders of magnitude.

In summary, the following observations have been made concerning the wave magnetic field that is occasionally observed in association with these noise bands. First, the wave magnetic field is only observed for unusually intense cases of electric field strength, and it is not always observed for all such cases. Second, the energy density of the wave magnetic field is 1–4 orders of magnitude lower than the wave electric field energy density. Finally, although there is a tendency for the wave magnetic field strength to increase as the electric field strength increases, there appears to be no well-defined relationship between the wave electric field strength and the wave magnetic field strength as would exist for electromagnetic waves well above the plasma frequency [e.g., see *Gurnett and Shaw,* 1973; *Gurnett,* 1974].

We have chosen to refer to these bands as electrostatic noise

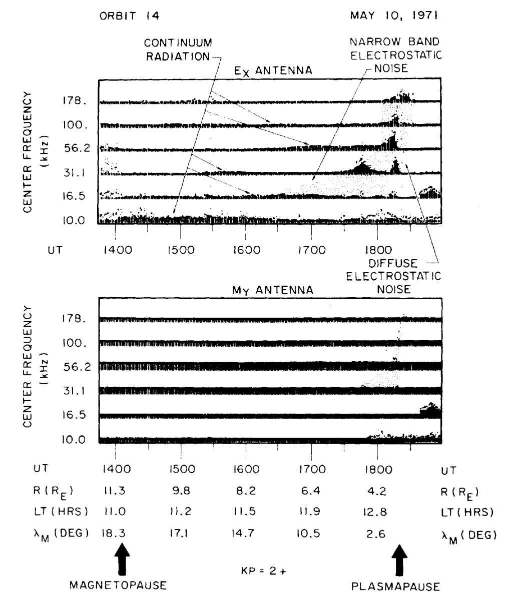

Fig. 9. The raw voltage outputs of the highest six spectrum analyzer filter channels for an inbound magnetospheric pass that contains unusually intense noise bands at 31.1 kHz near the plasmapause boundary at 3 R_E. These noise bands were observed to have wave magnetic fields coincidently with the large amplitude electric fields. Examination of the wide band receiver data shows that these bands consist of both spectral types of noise bands, narrow band electrostatic noise and diffuse electrostatic noise. The noise bands develop a wave magnetic field just above the upper-frequency limit of the wide band receiver (29 kHz), and thus it is not possible to resolve the spectral characteristics of the magnetic field component of the noise bands.

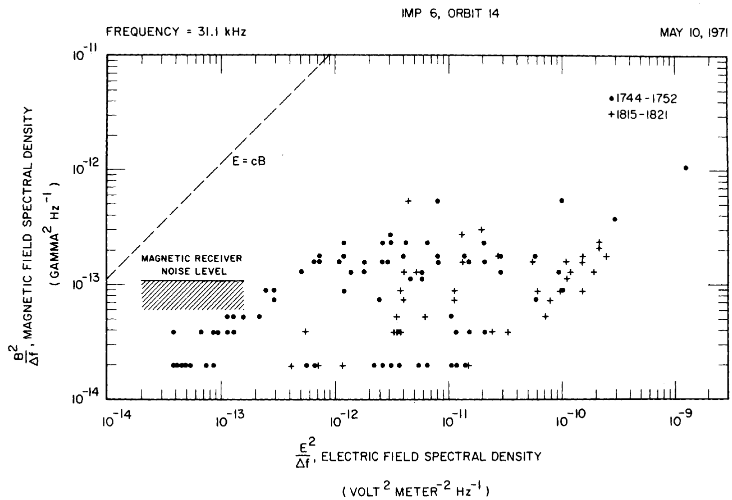

Fig. 10. A plot of the wave magnetic field spectral density as a function of the wave electric field spectral density for the noise bands on the inbound pass of orbit 14. The data plotted are the outputs of the peak detector of the 31.1-kHz filter channel which is sampled once each 5.11 s. The magnetic receiver noise level spectral density has been subtracted from all magnetic field strengths plotted in this figure to reduce errors caused by noise at small signal levels. The magnetic field energy density of the bands is 1–4 orders of magnitude less than the electric field energy density. The wave magnetic field of the noise bands tends to increase as the electric field increases; however, for a particular value of magnetic field spectral density the electric field spectral density varies by about 3 orders of magnitude.

bands because the dominant wave energy is contained in the wave electric field and because a wave magnetic field is infrequently and inconsistently observed. In addition, theories of electrostatic instabilities predict electrostatic noise at frequencies between harmonics of the electron gyrofrequency [*Fredricks*, 1971; *Young et al.*, 1973], and these noise bands occur with characteristics similar to those electrostatic instabilities.

The observed wave magnetic field could be a result of coupling between these electrostatic modes and other electromagnetic modes of propagation, or it could be caused by electromagnetic resonances that have characteristics that are similar to those of the electrostatic resonances but have an associated magnetic field. *Cheng* [1975] has calculated dispersion characteristics and growth rates for electromagnetic instabilities propagating perpendicular to the static magnetic field; however, no instability analysis has been done for modes propagating along the field at the time of writing of this paper.

RELATIONSHIP TO UHR NOISE AND $(n + \frac{1}{2})f_g$ HARMONICS

Near the plasmapause the diffuse electrostatic noise frequently has characteristics that are similar to the upper hybrid resonance noise observed at lower altitudes in the ionosphere and plasmasphere. Figure 11 shows an example of diffuse electrostatic noise observed near the plasmapause that has characteristics similar to those of the upper hybrid resonance noise. The diffuse electrostatic noise develops a sharp lower cutoff similar to that of the example previously discussed in Figure 5. This noise band has a sharp upper-frequency cutoff, and it develops a sharp lower-frequency cutoff at 1617 UT near 5.0 R_E. At 1625 UT and 1628 UT near 4.7 R_E the lower-frequency cutoff has become well defined, and intensity modulations at twice the spacecraft spin rate are observed. At 1648 UT the lower frequency cutoff is no longer observed.

The position of the maxima in the spin modulation of the noise band indicates that the wave electric field vector is aligned parallel to the geomagnetic field at the lower cutoff frequency. Waves that occur at or near the local plasma frequency would be expected to have an electric field which is aligned parallel to the geomagnetic field. Because of the alignment of the wave electric field vector and the similarity of this example to the one discussed in Figure 5 it is reasonable to conclude that the lower cutoff frequency is equal to the local plasma frequency.

The local plasma frequency (defined by the sharp lower cutoff of the noise band), the electron gyrofrequency (measured by the NASA/GSFC magnetometer experiment on Imp 6), and the upper hybrid resonance frequency (calculated from equation (1)) have been indicated next to the wide band spectrograms shown in Figure 11. The calculated upper hybrid resonance frequency occurs near to, but not at, the sharp upper cutoff frequency of the diffuse electrostatic noise. It was this close correspondence observed for several examples of the diffuse electrostatic noise which initially led to the incorrect conclusion that the diffuse electrostatic noise was upper hybrid resonance noise observed beyond the plasmapause with the upper cutoff frequency equal to the local upper hybrid resonance frequency [*Shaw and Gurnett*, 1972].

As the examples discussed in this paper have shown, these noise bands are constrained to frequencies bounded by consecutive harmonics of the electron gyrofrequency at radial distances outside the plasmasphere. In addition, the positive identification of the local plasma frequency from the sharp lower-frequency cutoff of the trapped continuum radiation conclusively shows that these bands cannot have an upper cutoff frequency equal to the local upper hybrid resonance frequency [*Gurnett and Shaw*, 1973].

The diffuse electrostatic noise does appear to be related to the upper hybrid resonance noise observed at lower altitudes

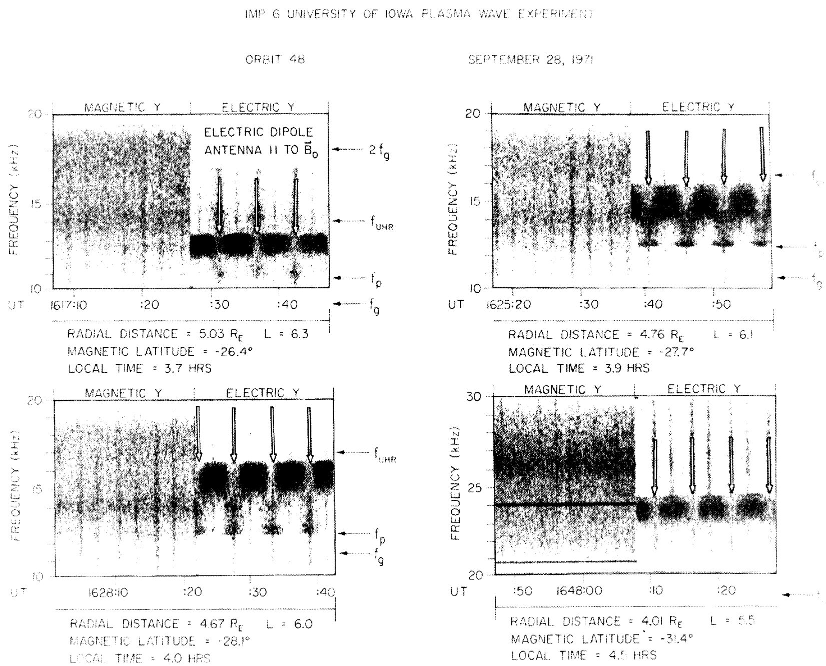

Fig. 11. An example of diffuse electrostatic noise with a sharp upper cutoff frequency and a sharp lower cutoff frequency that exists for about 20 min. The electric field vector is oriented perpendicular to the geomagnetic field at the upper cutoff frequency and parallel to the geomagnetic field at the lower cutoff frequency. This type of noise has characteristics similar to those of the upper hybrid resonance noise observed at lower altitudes in the plasmasphere and ionosphere, but the frequency at which the noise occurs is strongly controlled by harmonics of the electron gyrofrequency when it is observed at radial distances outside the plasmasphere.

in the following sense, however. *Mosier et al.* [1973] report an example of upper hybrid resonance noise observed well inside the plasmasphere with the Imp 6 GSFC radio astronomy experiment on an inbound magnetospheric pass on orbit 15 at

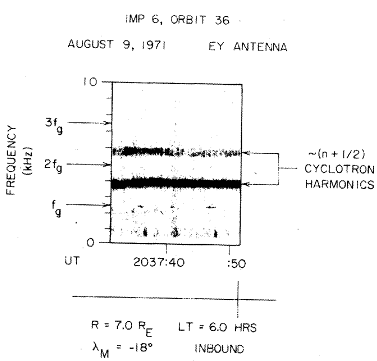

Fig. 12. An example of $(n + \frac{1}{2})f_g$ harmonics that have been previously observed by Ogo 5 in the outer magnetosphere. These harmonics occur at somewhat larger radial distances in the magnetosphere and have different spectral characteristics from those of the electrostatic noise bands observed by the University of Iowa experiment. They also have broad band electric field strengths about 3 orders of magnitude larger than those typical of the diffuse and narrow band electrostatic noise. In many cases, however, the electrostatic noise bands have been observed to merge continuously into regions which contain $(n + \frac{1}{2})f_g$ harmonics.

frequencies of several hundred kilohertz (well above the upper frequency channels of the University of Iowa experiment). Figure 1 of *Mosier et al.* [1973] shows that this noise continues downward in frequency to frequencies as low as 30 kHz as the spacecraft moves from the interior of the plasmasphere toward the plasmapause boundary. Examination of the University of Iowa plasma wave experiment data from orbit 15 confirms that the upper hybrid resonance noise observed by Mosier et al. develops into the electrostatic noise bands observed by the University of Iowa experiment outside the plasmapause. However, outside the plasmapause these noise bands are strongly controlled by the harmonics of the electron gyrofrequency and are no longer related to the local upper hybrid resonance frequency.

At larger radial distances in the magnetosphere, intense narrow band harmonics that are similar to the $(n + \frac{1}{2})f_g$ cyclotron harmonics observed by *Kennel et al.* [1970] are found in the Imp 6 data. An example of this type of harmonics observed on orbit 36 near 7 R_E is shown in Figure 12. These harmonic emissions have spectral characteristics more similar to those reported by *Kennel et al.* [1970] and *Fredricks and Scarf* [1973] than do the diffuse electrostatic noise bands and the narrow band electrostatic noise. These harmonic emissions tend to disappear and reappear in the spectrograms with time scales of the order of a few minutes, while the electrostatic noise bands reported in this paper exist continuously in the wide band spectrograms for periods of tens of minutes to hours. In addition, the $(n + \frac{1}{2})f_g$ harmonics typically have broad band electric field strengths (1–10 mV m^{-1}) about 3 orders of magnitude greater than those typical of the diffuse and narrow band electrostatic noise [*Kennel et al.*, 1970].

In many cases, regions containing diffuse electrostatic noise and narrow band electrostatic noise have been observed to merge smoothly into regions containing this type of harmonic emission, which is probably the $(n + \frac{1}{2})f_g$ harmonics previously observed in the outer magnetosphere. This merging appears to be a process that occurs over several earth radii as the spacecraft moves outward from the plasmapause, during which time the spectral characteristics of the electrostatic noise bands change to those more typical of the $(n + \frac{1}{2})f_g$ harmonics. Thus the electrostatic noise bands appear to be related to the $(n + \frac{1}{2})f_g$ harmonics as well as the upper hybrid resonance noise.

This merging process may occur because of changes in the plasma characteristics in the different regions of the magnetosphere containing these different types of emissions. Electron number densities inside the plasmasphere are large ($\sim$1000 cm^{-3}), and temperatures are low ($\sim$1 eV). Moving out through the plasmapause and into the plasma sheet, we find an energetic particle population with low densities and high temperatures ($n_e \sim 1$ cm^{-3} and $T_e \sim 1$ keV). Near the plasmapause there must occur a transition between these regions in which some combination of cold plasmaspheric electrons and warm plasma sheet electrons may exist.

At large radial distances in the outer magnetosphere the generation of the $(n + \frac{1}{2})f_g$ harmonics may be explained by electrostatic instabilities that are generated by the warm plasma sheet electrons in combination with a low background density of cold electrons, as is suggested by *Young et al.* [1973]. Toward the plasmasphere the cold electron population density increases, while the warm electron population density decreases until inside the plasmasphere the warm plasma sheet population has disappeared and the electrostatic instabilities are no longer generated. Instead noise can be generated by incoherent Cerenkov radiation from low-energy electrons. The propagation of this noise would be characteristic of the cold plasma dispersion relation, and it would be observed as upper hybrid resonance noise.

The electrostatic noise bands observed by the University of Iowa Imp 6 plasma wave experiment usually occur during the transition between these two different regions of the magnetosphere (near the plasmapause). The continuous merging of the electrostatic noise bands with upper hybrid resonance noise and $(n + \frac{1}{2})f_g$ harmonics appears to represent a smooth transition between these three types of noise as the spacecraft moves from the plasmasphere to the plasma sheet. This continuous merging is probably caused by changes in the plasma characteristics that modify the generation and propagation of these types of naturally occurring magnetospheric emissions.

DISCUSSION

Fredricks [1971] has proposed a theory refined by *Young et al.* [1973] to explain the generation of the $(n + \frac{1}{2})f_g$ harmonics observed in the outer magnetosphere. These electrostatic instabilities are generated by a non-Maxwellian electron velocity distribution consisting of a cold species coexisting with a warm species that has a peak at some nonzero velocity in the distribution of the velocity component perpendicular to the geomagnetic field.

Taylor and Shawhan [1974] have performed detailed calculations of the electric and magnetic field spectral densities generated by Cerenkov radiation from low-energy electrons at frequencies between the local plasma frequency and the upper hybrid resonance frequency. These calculations indicate that sufficiently large electric fields are generated and thus that incoherent Cerenkov radiation from thermal electrons may explain the generation of upper hybrid resonance noise.

Observations of electrostatic noise bands by the Imp 6 University of Iowa plasma wave experiment reported in this paper suggest that these types of noises are related. This relationship is apparently caused by changes in the propagation and generation of the noise, which is observed as the spacecraft moves through different regions of the magnetosphere that contain dissimilar plasma constituents.

The dispersion relation for electrostatic modes in an infinite homogeneous plasma with a constant magnetic field is the *Harris* [1959] dispersion relation. Assuming the ions to be infinitely massive and evaluating this dispersion relation for a cold electron velocity distribution f_c,

$$f_c = \delta(v_\parallel)\delta(v_\perp)/2\pi v_\perp \quad (4)$$

(where $v_\parallel$ and $v_\perp$ are the velocities parallel and perpendicular to the static magnetic field), we have

$$\tan^2 \alpha = (f_p^2 - f^2)(f^2 - f_g^2)/f^2(f^2 - f_{UHR}^2) \quad (5)$$

where α is the angle of the wave vector measured with respect to the static magnetic field direction. Equation (5) is the same as the expression for the resonance cone angle predicted by cold plasma theory [*Stix*, 1962]. A wave with frequency f has an index of refraction equal to infinity ($|\mathbf{B}| \equiv 0$) when its wave vector is at the resonance cone angle given by real solutions of (5).

Wave energy generated by Cerenkov radiation from thermal electrons occurs at wave vector angles near the resonance cone angle for wave frequencies less than f_{UHR} and greater than the maximum of f_p or f_g. Thermal effects and collisions effectively prevent the index of refraction from reaching infinity, and the waves generated are electromagnetic ($|\mathbf{B}| \neq 0$). Cerenkov emission is thus an example of the generation of electromagnetic radiation near an electrostatic limit described by the Harris dispersion relation.

Young et al. [1973] have used this electrostatic dispersion relation to explain the generation of $(n + \frac{1}{2})f_g$ harmonics observed by Ogo 5 [*Kennel et al.*, 1970; *Fredricks and Scarf*, 1973]. There are also similarities between the types of emissions discussed by Young et al. and the narrow band electrostatic noise and diffuse electrostatic noise observed by the University of Iowa experiment.

Young et al. discuss two types of instabilities, 'flutelike' modes for which $k_\parallel \equiv 0$ and modes which have a finite $k_\parallel$. The flutelike modes require a sharp positive slope in the distribution of $v_\perp$ and a high warm plasma density for waves at frequencies near $3/2f_g$. For frequencies somewhat above $3/2f_g$ the required threshold density and the sharpness of the positive slope in $v_\perp$ decrease. In addition, decreasing the ratio of the number density of the cold species to that of warm species, i.e., N_c/N_w, requires a larger threshold density to generate the instability.

Diffuse electrostatic noise has characteristics similar to those expected from the flutelike electrostatic modes. The diffuse electrostatic noise is found near the outside edge of the plasmapause boundary, where N_c/N_w would be expected to be the largest. At larger radial distances in the magnetosphere the diffuse electrostatic noise is seldom found. Diffuse electrostatic noise is most often observed during quiet geomagnetic periods, when N_c/N_w might be larger at greater distances beyond the plasmapause, and thus the threshold density required for the instability to occur would be lower. Finally, diffuse electrostatic noise is seldom found at frequencies near or below $3/2f_g$. Most often the frequency is significantly higher than $3/2f_g$ (see Figure 5, for example). Under these conditions the flutelike modes might exist and explain the generation of the diffuse electrostatic noise.

The narrow band electrostatic noise observed by the University of Iowa experiment is generally observed at higher harmonic numbers than the diffuse electrostatic noise. Young et al. predict the existence of high-frequency doublets and triplets for which $k_{\parallel} \neq 0$, separated by approximately the electron gyrofrequency. These modes are predicted to exist at frequencies only slightly above multiples of the electron gyrofrequency; however, bands are often observed well above the exact multiples (see the band between $4f_g$ and $5f_g$ in Figure 3, for example).

The analysis performed by Young et al. adequately explains many of the qualitative features of the bands observed by the University of Iowa experiment. To describe the generation of these noise bands in a more quantitative manner would require a detailed knowledge of the electron velocity distribution and a numerical evaluation of the electrostatic dispersion relation.

The Harris dispersion relation does not explain the associated wave magnetic field that has been infrequently observed by the University of Iowa experiment. It is possible that the instabilities causing this noise are electromagnetic in nature with characteristics similar to the electrostatic limit. This is similar by analogy to the Cerenkov radiation believed responsible for the generation of upper hybrid resonance noise. Such an electromagnetic instability, similar to the instabilities investigated by *Cheng* [1975], might be related to the generation of other types of naturally occurring electromagnetic noise near the plasma frequency, such as type 3 radio noise bursts, terrestrial kilometric radiation [*Gurnett*, 1974], and nonthermal continuum radiation [*Gurnett*, 1975].

Some evidence that the nonthermal continuum radiation may be related to these electrostatic noise bands is found in the University of Iowa experiment data. Figure 9 shows an example of continuum radiation observed between the plasmapause and magnetopause at frequencies from 10 to 100 kHz. The continuum radiation in the 56.2-kHz spectrum analyzer filter channel is observed with an amplitude that is larger than the amplitudes typically observed at other orbital locations. Several other examples of continuum radiation with enhanced amplitudes observed in association with intense occurrences of the electrostatic noise bands are discussed by *Gurnett* [1975]. Both the nonthermal continuum radiation and the electrostatic noise bands have the largest amplitudes in the local morning and early afternoon sectors of the magnetosphere. These observations suggest that the nonthermal continuum radiation may be generated by electromagnetic radiation propagating away from regions containing these electrostatic noise bands.

A second possibility that may explain the generation of the wave magnetic field observed with intense occurrences of the electrostatic noise bands is that electromagnetic modes are coupled to the electric field, which is generated by a purely electrostatic instability. Some evidence to indicate this possibility is found in the data collected by the University of Iowa experiment. Some examples are found that are more intense than those with an associated wave magnetic that have no wave magnetic field. In addition, there appears to be no clear functional relationship between the intensity of the wave electric field and that of the wave magnetic field (see Figure 10).

The continuous transition between the upper hybrid resonance noise observed at lower altitudes in the plasmasphere, the electrostatic noise bands observed near the plasmapause, and the $(n + \frac{1}{2})f_g$ harmonics observed at larger radial distances in the outer magnetosphere strongly suggests that these three types of noise are related to the Harris electrostatic dispersion relation or to a corresponding electromagnetic dispersion relation that reduces to the electrostatic relation in the proper limit.

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REFERENCES

Bauer, S. J., and R. G. Stone, Satellite observations of radio noise in the magnetosphere, *Nature, 218*, 1145, 1968.

Carpenter, D. L., C. G. Park, H. A. Taylor, Jr., and H. C. Brinton, Multiexperiment detection of the plasmapause from Eogo satellites and Antarctic ground stations, *J. Geophys. Res., 74*, 1837, 1969.

Chappell, C. R., K. K. Harris, and G. W. Sharp, The day side of the plasmasphere, *J. Geophys. Res., 76*, 7632, 1971.

Cheng, C. Z., Ordinary electromagnetic mode instability, *J. Plasma Phys.*, in press, 1975.

Fredricks, R. W., Plasma instability at $(n + 1/2)f_c$ and its relationship to some satellite observations, *J. Geophys. Res., 76*, 5344, 1971.

Fredricks, R. W., and F. L. Scarf, Recent studies of magnetospheric electric field emissions above the electron gyrofrequency, *J. Geophys. Res., 78*, 310, 1973.

Gregory, P. C., Radio emission from auroral electrons, *Nature, 221*, 350, 1969.

Gurnett, D. A., The earth as a radio source: Terrestrial kilometric radiation, *J. Geophys. Res., 79*, 4227, 1974.

Gurnett, D. A., The earth as a radio source: The nonthermal continuum, *J. Geophys. Res., 80*, 2751, 1975.

Gurnett, D. A., and L. A. Frank, Thermal and suprathermal plasma densities in the outer magnetosphere, *J. Geophys. Res., 79*, 2355, 1974.

Gurnett, D. A., and R. R. Shaw, Electromagnetic radiation trapped in the magnetosphere above the plasma frequency, *J. Geophys. Res., 78*, 8136, 1973.

Harris, E. G., Unstable plasma oscillations in a magnetic field, *Phys. Rev. Lett., 2*, 34, 1959.

Harris, K. K., G. W. Sharp, and C. R. Chappell, Observations of the plasmapause from Ogo 5, *J. Geophys. Res., 75*, 219, 1970.

Hartz, T. R., Low frequency noise emissions and their significance for energetic particle processes in the polar ionosphere, in *The Polar Ionosphere and Magnetospheric Processes*, p. 151, Gordon and Breach, New York, 1970.

Kennel, C. F., F. L. Scarf, R. W. Fredricks, J. H. McGehee, and F. V. Coroniti, VLF electric field observations in the magnetosphere, *J. Geophys. Res., 75*, 6136, 1970.

Mosier, S. R., M. L. Kaiser, and L. W. Brown, Observations of noise bands associated with the upper hybrid resonance by the Imp 6 radio astronomy experiment, *J. Geophys. Res., 78*, 1673, 1973.

Muldrew, D. B., Preliminary results of Isis 1 concerning electron density variations, ionospheric resonances, and Cerenkov radiation, *Space Res., 10*, 786, 1970.

Russell, C. T., and R. E. Holzer, AC magnetic fields, in *Particles and Fields in the Magnetosphere*, D. Reidel, Dordrecht, Netherlands, 1970.

Russell, C. T., R. E. Holzer, and E. J. Smith, Ogo 3 observations of ELF noise in the magnetosphere, 1, Spatial extent and frequency of occurrence, *J. Geophys. Res., 74*, 755, 1969.

Scarf, F. L., R. W. Fredricks, C. F. Kennel, and F. V. Coroniti, Satellite studies of magnetospheric substorms on August 15, 1968, *J. Geophys. Res.*, *78*, 3119, 1973.

Shaw, R. R., and D. A. Gurnett, Magnetospheric electron density measurements from upper hybrid resonance noise observed by Imp 6, *Res. Rep. 72-37*, Univ. of Iowa, Iowa City, 1972.

Stix, T. H., *The Theory of Plasma Waves*, p. 14, McGraw-Hill, New York, 1962.

Taylor, W. W. L., and S. D. Shawhan, A test of incoherent Cerenkov radiation for VLF hiss and other magnetospheric emissions, *J. Geophys. Res.*, *79*, 105, 1974.

Thorne, R. M., E. J. Smith, R. K. Burton, and R. E. Holzer, Plasmaspheric hiss, *J. Geophys. Res.*, *78*, 1581, 1973.

Walsh, D., F. T. Haddock, and H. F. Schulte, Cosmic radio intensities at 1.225 and 2.0 Mc measured up to an altitude of 1700 km, *Space Res.*, *4*, 935, 1964.

Young, T. S. T., J. D. Callen, and J. E. McCune, High-frequency electrostatic waves in the magnetosphere, *J. Geophys. Res.*, *78*, 1082, 1973.

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