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Detailed Observations of the Source of Terrestrial Narrowband Electromagnetic Radiation

by

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ABSTRACT

We present detailed observations of a region near the terrestrial plasmapause where narrowband electromagnetic radiation (previously called escaping nonthermal continuum radiation) is being generated. These observations show a direct correspondence between the narrowband radio emissions and electron cyclotron harmonic waves near the upper hybrid resonance frequency. In addition, electromagnetic radiation propagating in the Z-mode is observed in the source region which provides an extremely accurate determination of the electron plasma frequency and, hence, density profile of the source region. The data strongly suggest the electrostatic waves and not Cerenkov radiation are the source of the banded radio emissions and clearly define the coupling mechanism which must be described by any viable theory.

I. INTRODUCTION

The radio emissions studied in this paper were originally called escaping nonthermal continuum radiation by Gurnett [1975]. A more recent study by Kurth et al. [1981] has presented observations with plasma wave receivers on ISEE 1 and 2 having very high spectral resolution which show the radiation is actually comprised of a series of extremely narrowband emissions with slow variations in both frequency and amplitude with time. Similar narrowband emissions have recently been discovered at both Jupiter [Kaiser and Desch, 1980; Gurnett et al., 1982] and Saturn [Gurnett et al., 1981]. We have, therefore, adopted the nomenclature of Kaiser and Desch and Gurnett et al. in referring to these emissions as "narrowband" radio emissions as opposed to "continuum" radiation.

Even though the narrowband emissions are relatively weak, with power fluxes on the order of 10^{-19} $Wm^{-2}Hz^{-1}$ at a distance of 30 R_E, interest in them has been rekindled since it is an apparently universal radio emission mechanism (at least in planetary magnetospheres if not in other astrophysical settings) and an understanding of the mechanism may lay the foundation to the solution of a number of solar and astrophysical radio phenomena.

There is a growing consensus in the literature that the narrowband electromagnetic emissions are generated from electrostatic waves whose frequency satisfies the relation

$$f \approx (n + 1/2)f_g \approx f_{UHR} \quad (1)$$

where f_g is the electron gyrofrequency and f_{UHR} is the upper hybrid resonance frequency defined by

$$f_{UHR} = \sqrt{f_g^2 + f_p^2} \quad (2)$$

(f_p is the electron plasma frequency). The detailed theory of the conversion mechanism, however, has not been completed. Two basic mechanisms are currently under consideration: a nonlinear, three-wave interaction with low frequency waves (e.g. ion-cyclotron waves) acting as the third wave [Melrose, 1981], and a linear mechanism which converts Z-mode radiation into ordinary-mode electromagnetic radiation near the plasma frequency [Oya, 1971; Jones, 1976; Lembege and Jones, 1982; Okuda et al., 1982]. Barbosa [1982] gives a thorough review of the various theories for the generation of continuum radiation.

In the next section we shall present high resolution frequency-time spectrograms from a region where narrowband radiation is being generated in order to show very accurately the density profile in the source region as well as the relationship between the radio emissions and the relevant characteristic frequencies of the plasma. These observations should provide a solid basis for further theoretical modeling, particularly in the case of the linear conversion mechanism.

II. SOURCE REGION OBSERVATIONS

The event treated in this study was first presented by Kurth et al. [1981] in order to show the direct correspondence between bands of escaping continuum radiation and electrostatic UHR bands near the plasmapause. Figure 1 provides an overview of the event taken as ISEE 1 approached the plasmapause. The data are presented in the form of a frequency-time spectrogram with the intensity of waves plotted as a function of frequency (ordinate) and time (abscissa). Greater intensities are represented by darker areas on the spectrogram. Prior to about 1040:30 UT, the spectrum of narrowband electromagnetic radiation can be seen. The bandwidths of the three bands shown (near 63, 65, and 70 kHz) are about 1-2 kHz such that $\Delta f/f \approx 2\%$. Close examination of the three bands, however, shows that each is composed of numerous bands with $\Delta f \approx 100$ Hz. More examples of these narrow bands can be found in Kurth et al. [1981].

Subsequent to 1040:30 the spectrum is dominated by two sporadic bands near 65 and 70 kHz. Kurth et al. [1981] identified these as $(n + 1/2)f_g$ emissions near f_{UHR} since the frequency spacing between the two is very close to the local electron gyrofrequency and the bands have spectral and temporal characteristics similar to the UHR bands studied by Christiansen et al. [1978] and Kurth et al. [1979b]. The abrupt transition from the electromagnetic bands near 65 and 70 kHz to the two UHR bands at 1040:30 leads to the almost unavoidable conclusion that the two phenonmena are intimately related and that the UHR bands are the likely source of the electromagnetic emissions.

Okuda et al. [1982] reported on the comparison between the electric field strength of the UHR band in the source region and the electric field component of the electromagnetic radiation just beyond the source for two events. For those events, the ratio of the electrostatic to electromagnetic field strength varied between 5×10^2 and 10^3. For comparison, the electric field component of the electromagnetic band near 65 kHz in Figure 1 is ~ 1.3 $\mu V\ m^{-1}$ (integrated over the filter bandwidth of ~ 1.8 kHz). The amplitude of the $(n + 1/2)f_g$ band is ~ 82.5 $\mu V\ m^{-1}$, hence, these values yield a ratio of only 6×10^1, significantly smaller than that reported by Okuda et al. The electric field strength for the electrostatic band, however, was obtained from a spectrum analyzer channel centered at 56.2 kHz with a bandwidth of 5.1 kHz, so it is possible we have underestimated the field strength. Otherwise, the conversion process is evidently operating much more efficiently in this event than in those reported by Okuda et al.

We have attempted to determine the polarization of both the $(n + 1/2)f_g$ bands and the narrowband electromagnetic emissions by examining the variation in electric field amplitude as the dipole antenna rotates with respect to the geomagnetic field. In general, the results are not very reliable, mainly because during this time there are time-varying signals at more than one frequency, hence, the automatic gain controlled (AGC) receiver tracks the most intense signal and it is not always possible to sort out the AGC effects in a reliable manner. There is some evidence near 1040:13 UT that the electromagnetic radiation near 70 kHz is polarized such that the wave electric field is parallel to the geomagnetic field, consistent with ordinary mode radiation. At 1040:49 and 1041:35 UT the electrostatic waves near 65 kHz are apparently polarized nearly perpendicular to the geomagnetic field, consistent with their identification as electron cyclotron harmonic emissions.

A close examination of the post-1041 UT portion of the spectrogram in Figure 1 reveals the presence of another weaker type of emission which varies rapidly in frequency in addition to the UHR band. Figure 2 shows an expanded spectrogram from this time period. It is evident from Figure 2 that there are two different types of emission present after 1041. The two UHR bands are apparent with a frequency spacing of slightly more than 4 kHz. The magnetic field strength taken from the ISEE data pool tape for this time period is 150 nT giving an electron gyrofrequency of about 4.2 kHz. The second type of emission meanders in frequency in apparent disregard of the magnetic field which varies only slightly over this interval. Since we believe the $(n + 1/2)f_g$ bands to be near f_{UHR}, it is most likely this second emission is responding to variations in the electron density, n_e.

We expect to see Cerenkov radiation generated near f_{UHR} at the plasmapause [Taylor and Shawhan, 1974] and, hence, we speculate that the second emission observed in Figure 2 is the so-called Z-mode radiation [Jones, 1976] which propagates between the L=0 cutoff, $f_{L=0}$

[Stix, 1958], and f_{UHR}. To verify this, we can compute the values of the relevant characteristic frequencies of the local plasma, that is, f_{UHR} and $f_{L=0}$. The former has been defined in Equation 2 and the L=0 cutoff occurs at

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

We have stated above that f_{UHR} is in the range of 65 to 70 kHz to satisfy the condition in Equation 1 and the measured gyrofrequency is 4.2 kHz, hence, $f_{UHR} >> f_g$ which implies that f_{UHR} is only slightly greater than f_p. Since f_p apparently varies greatly with time, we shall choose f_p = 65 kHz somewhat arbitrarily to evaluate f_{UHR} and $f_{L=0}$ using Equations 2 and 3. We find that f_{UHR} = 65.1 kHz and $f_{L=0}$ = 62.9 kHz. The difference between these two frequencies is 2.2 kHz, close to one-half the gyrofrequency. (Note that evaluating $f_{UHR} - f_{L=0}$ using Equations 2 and 3 in the limit of $f_p/f_g \to \infty$ gives $f_g/2$ and the exact value varies only slightly as f_p varies from 65 to 70 kHz.)

If our assumption that the weaker, meandering emission is Z-mode radiation propagating between $f_{L=0}$ and f_{UHR} is correct, then, the bandwidth should be 2.2 kHz which is very close to the bandwidth of the emission in Figure 2. What is even more convincing, since the Cerenkov radiation is generated between f_p and f_{UHR} (65 and 65.1 kHz, respectively) there should be an enhancement between these two frequencies observable in the spectrum [Oya, 1971; Jones, 1976]. Indeed, there is a narrow band of enhanced emission along the top of the Z-mode band in Figure 2.

Figure 3 is a schematic representation of a portion of Figure 2 which shows the salient features of the spectrum. The UHR bands are identified as the $(n + 1/2)f_g$ emissions with n = 15 and 16. The Z-mode band shows an overall bandwidth of ~ 2 kHz and an enhancement near the top of the band exaggerated in frequency extent for clarity. The upper and lower cutoffs are labelled f_{UHR} and $f_{L=0}$, respectively, and the lower bound of the enhancement is identified by f_p. It is clear, then, that our assumption of Z-mode radiation is entirely consistent with the observations presented in Figure 2. We can rely with a considerable degree of confidence, then, on the trace of the lower bound of the enhanced band of the Z-mode radiation as a trace of f_p which, in turn, provides a very accurate density profile for the source region since $f_p = 8980\sqrt{n_e}$ where f_p is in Hz and n_e is in cm^{-3}.

One of the first things which can be seen in Figure 2 is a tendency for each $(n + 1/2)f_g$ band to intensify as f_{UHR} approaches it in frequency. This is a classic example of the effect reported by Kurth et al. [1979a] in which the $(n + 1/2)f_g$ harmonic band which contains the most intense band is that which encompasses f_{UHR}.

It has become increasingly apparent that the source region of narrowband electromagnetic radiation is typified by a gradient in density. This is clearly implied by the accepted source regions at the Earth and Jupiter. In both magnetospheres, the magnetopause has been shown to be a source of narrowband emissions [Kurth et al., 1981; Anderson and Kurth, 1982; Gurnett et al., 1979; Gurnett et al., 1982]. Also, the plasmapause at the Earth [Gurnett, 1975; Kurth et al., 1981; Jones, 1981] and the outer edge of the Io plasma torus at Jupiter

[Kaiser and Desch, 1980] are thought to be the primary source regions for narrowband radio emissions at the two planets. All these regions have density gradients as a fundamental physical characteristic. Theoretically speaking, several of the conversion mechanisms require a density gradient so that the electromagnetic radiation can escape to regions of lower f_p. Obviously, it is important, then, to characterize the source region for further theoretical study by specifying the magnitude of the density gradient.

In the general region of the event shown in Figures 1 and 2, the plasma frequency varies from ~ 10 kHz to ~ 100 kHz as the spacecraft traverses the range from 8 to 6 R_E on its inbound trajectory. Hence, n_e varies from about 1.2 to 120 cm^{-3} over this distance. Over a ten-minute period centered near 1046 UT f_p varies from 65 to 80 kHz so that n_e goes from 52 to 79 cm^{-3}. During this time, the radial speed of the spacecraft is about 3.2 km/sec, hence, we can calculate a normalized density gradient $(1/n)\nabla n$ averaged over this ten-minute interval using

$$\left\langle \frac{1}{n}\frac{dn}{dr} \right\rangle = \frac{1}{n_e}\frac{\Delta n_e}{\Delta r} \tag{4}$$

to obtain a value of $\sim 2 \times 10^{-4}$ km^{-1}. Inspection of Figure 2, however, shows much finer-scale variations in n_e. For example, near 1041:50 UT f_p varies from 71.5 kHz to 68 kHz in a time of 1.4 sec corresponding to a distance of 4.5 km. Here, $\Delta n_e \approx 6$ cm^{-3} and $n_e \approx 60$ cm^{-3} so $\Delta n_e/n_e$ is 10% and $(1/n)\nabla n \approx 2 \times 10^{-2}$ km^{-1}, a factor of 100 greater than the average value. If we assume 10 eV is a reasonable temperature for the ions in this region, the gyroradius, ρ_i, for 10 eV protons is ~ 2 km, hence, the scale length for the largest gradients is apparently determined by ρ_i. It is clear from Figure 2, then, that the gradients can vary from 0 to > 10^{-2} km^{-1} in the source region. Obviously, the density profile is quite complex and certainly not monotone in nature.

III. DISCUSSION

We have shown detailed observations of the source region for narrow-band electromagnetic radiation near the terrestrial plasmapause which clearly show the presence of both Z-mode and $(n + 1/2)f_g$ emissions. It is clear from Figure 1 that the electrostatic $(n + 1/2)f_g$ waves are the source of the electromagnetic waves and not the Z-mode radiation since the discrete nature of the radio waves, i.e., emissions predominantly at 65 and 70 kHz, matches the frequency of the n = 15 and 16 harmoninc bands whereas the Z-mode band exists over a continuum of frequencies. The observations also provide a detailed density profile for the source region which can be used as input for theoretical models. The source region is characterized by rapid fluctuations in density on length scales of an ion gyroradius. The magnitude of the gradient $(1/n)\nabla n$ can be as large as 2×10^{-2} km^{-1}.

It is important to consider the implications of the observations presented herein on the various theories. The nonlinear, three-wave mechanism suggested by Melrose [1981] is somewhat adversely affected by this new data. It is clear that the "pump" wave, i.e., the $(n + 1/2)f_g$ band, can be found over a wide range of frequencies with respect to the plasma frequency, since f_p can wander from well below the frequency of the electrostatic band to well above. But inspection of the data in Figure 2 leads to the conclusion that the most intense electrostatic bands are at a frequency very close to or below f_p. If the nonlinear conversion produces an electromagnetic wave in, say, the ordinary mode at a frequency which is at or below f_p, the radio wave cannot escape. Conversion to higher frequencies would help this situation, but the observations in Figure 1 suggest there is very little shift in frequency between the radio emissions and the electrostatic waves. There are regions in Figure 2, however, where the electrostatic waves reside above f_p and these may be perfectly adequate conversion sites for the narrowband emissions.

The observations are probably more critical to the linear coupling mechanisms since they require wave energy residing in one mode which is not freely propagating to couple into the ordinary electromagnetic mode under highly restrictive conditions. Perhaps the most concrete conclusion of this paper is that the ultimate source of wave energy for the generation of narrowband electromagnetic radiation is the electrostatic $(n + 1/2)f_g$ bands near f_{UHR} and not Cerenkov radiation as suggested by Jones [1976]. In fairness to Jones, some of the continuum radiation may actually have the Cerenkov radiation as its source, but since the amplitudes of the $(n + 1/2)f_g$ emissions are much greater, it is not likely Cerenkov radiation is the primary source.

The obvious problem for the linear theory as can be seen in Figure 2 is that the ultimate source of the narrowband electromagnetic radiation exists in a mode other than the Z-mode and often resides at frequencies well below the cold plasma limit to the Z-mode, $f_{L=0}$. Hence, it is necessary to convert the hot plasma electrostatic waves into the Z-mode prior to the Z-mode-to-ordinary-mode process described by Jones. Actually, this variation was initially treated by Oya [1971] who showed that short wavelength electrostatic waves would be transformed into the longer wavelength Z-mode when $f \approx f_{UHR}$. This additional step requires further study, however. Jones [1982] suggests electrostatic UHR waves can become Z-mode waves by propagating in a density gradient and Lembege and Jones [1982] have performed detailed ray tracing of this two-step process. The latter study concludes that if the electrostatic waves do not lie in the first branch of the dispersion relation, only the forward-propagating electrostatic waves (i.e., those propagating towards higher density regions) can couple to the Z-mode and eventually couple to the escaping O-mode.

It is disconcerting, then, to notice in Figure 2 that the most intense $(n + 1/2)f_g$ bands are usually at a frequency below f_{UHR} and f_p as was predicted by Ashour-Abdalla and Kennel [1978]. This implies the electrostatic waves will propagate towards lower densities in the backward mode and, hence, will not have access to the radio window according to Lembege and Jones [1982]. Okuda et al. [1982] and Lembege and Jones have commented that a hot plasma theory is required to adequately describe the short wavelength modes and that a nonlinear treatment is required in the region near f_{UHR}. It would appear that the viability of the linear conversion theory is dependent upon finding a way in which to transform the $(n + 1/2)f_g$ electrostatic waves into the Z-mode and finally into the ordinary mode in an efficient manner.

A possible solution to the dilemma posed for both theories by the existence of the most intense wave below both f_{UHR} and f_p is to argue that the wave intensity is diminished above f_{UHR} by conversion (by either mechanism) to the escaping ordinary mode. That is, the observed spectrum reflects the equilibrium state with part of the wave energy remaining in the electrostatic mode, but with a substantial fraction dissipated via conversion to electromagnetic waves. We do not believe this to be the case, however, since Ashour-Abdalla and Kennel [1978] and Hubbard and Birmingham [1978] both indicate the intensity of $(n + 1/2)f_g$ bands lying above f_{UHR} will have substantially lower intensities than those at or immediately below f_{UHR}.

The obvious conclusion is that the observations presented herein provide information crucial to the understanding of the narrowband emission process, but do not immediately single out any one theory as being most favorable. While considerable work has been done on the linear conversion mechanism, the actual efficiency of the process has yet to be determined. As discussed by Lembege and Jones [1982], there is only a limited range of $k_{\parallel}\rho_e$ which will allow the Z-mode waves to have access to the radio window ($k_{\parallel}$ is the wave number parallel to the magnetic field and ρ_e is the electron gyroradius) and Barbosa [1982] suggests that the actual efficiency of the mechanism would be too low to explain the observations. The nonlinear theory is in a much less advanced state; there are no direct observations to demonstrate a three-wave process is operating and even the identification of the third wave as ion cyclotron waves is speculative. The advantage of the nonlinear mechanism, however, is its greater efficiency, as discussed by Barbosa [1982].

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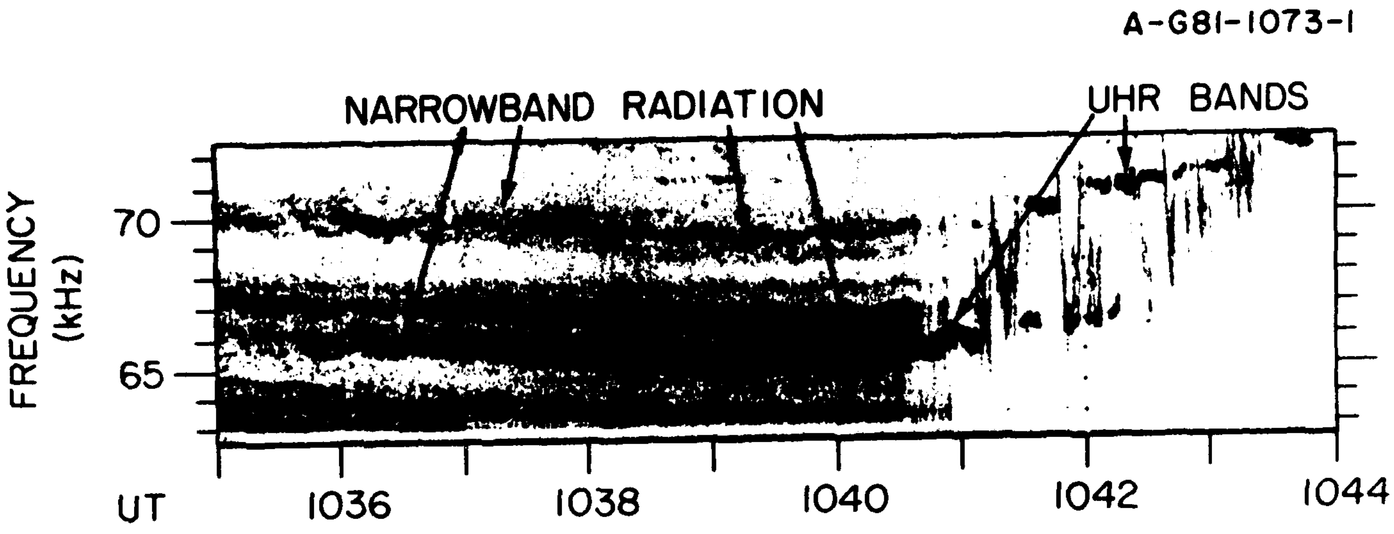
FIGURE CAPTIONS

Figure 1 A frequency-time spectrogram showing a region where electrostatic bands at $(n + 1/2)f_g \approx f_{UHR}$ are being converted into narrowband electromagnetic radiation near the plasmapause.

Figure 2 An expanded spectrogram from the event shown in Figure 1 showing both electrostatic UHR bands and Z-mode radiation in the source region of narrowband electromagnetic emissions.

Figure 3 A stylized sketch of a portion of the spectrogram in Figure 2 showing the salient features of the wave spectrum. Notice that the Z-mode emission spectrum has features which allow a very accurate determination of the density profile in the narrowband radio emission source region.



ISEE 1, DAY 362, DECEMBER 28, 1977
$R = 6.4\ R_E$ MLT = 9.3 HR $\lambda_m = 7.1°$

Figure 1

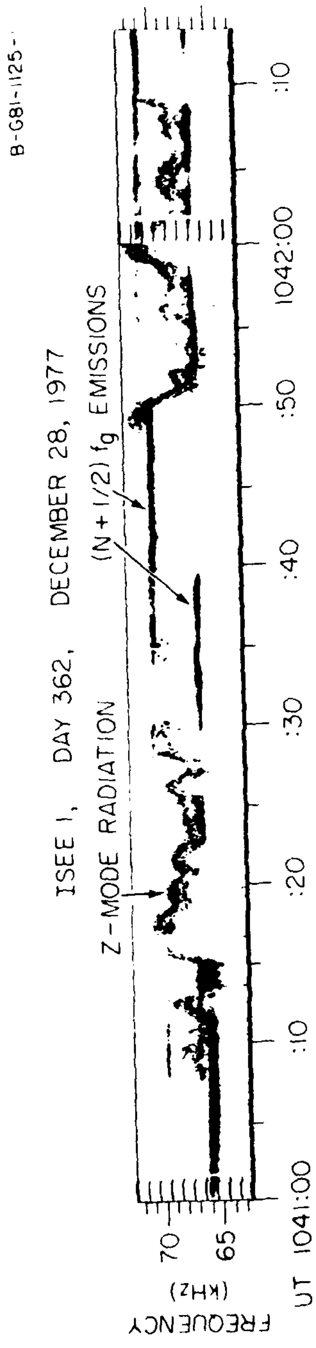
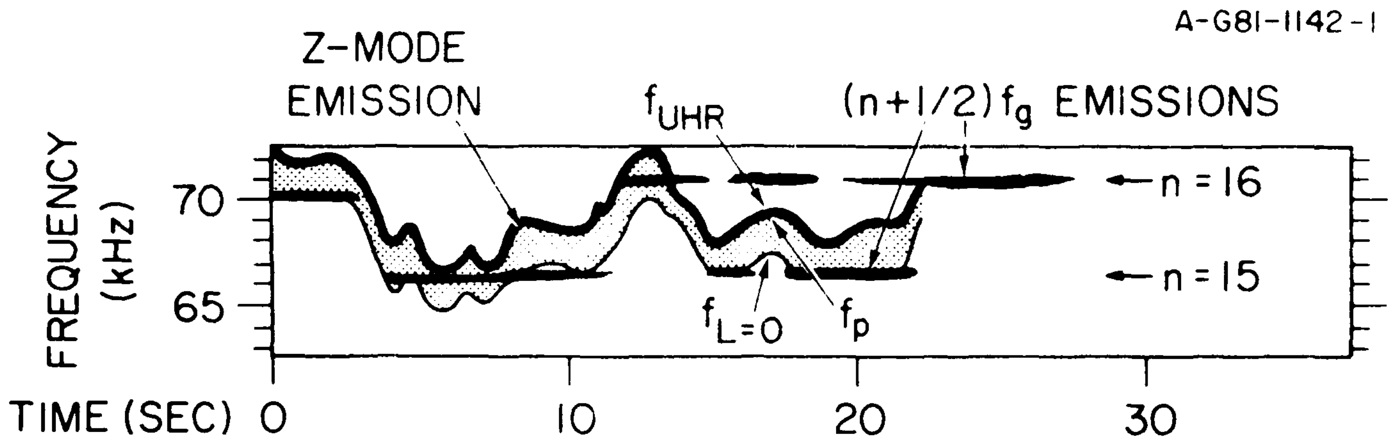

B-G81-1125-
ISEE 1, DAY 362, DECEMBER 28, 1977
Z-MODE RADIATION
(N+1/2) fg EMISSIONS
FREQUENCY (KHz)
70
65
UT 1041:00
:10
:20
:30
:40
:50
1042:00
:10

Figure 2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Z-MODE
EMISSION
f_UHR
(n+1/2) f_g EMISSIONS
← n = 16
← n = 15
f_L=0
f_p
FREQUENCY
(kHz)
70
65
TIME (SEC)
0
10
20
30

Figure 3