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CONTINUUM RADIATION IN PLANETARY MAGNETOSPHERES

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ABSTRACT

With the completion of the Voyager tour of the outer planets, radio and plasma wave instruments have executed the first survey of the wave spectra of Earth, Jupiter, Saturn, Uranus, and Neptune. One of the most notable conclusions of this survey is that there is a great deal of qualitative similarity in both the plasma wave and radio wave spectra from one magnetosphere to the next. In particular, in spite of detailed differences, most of the radio emissions at each of the planets have been tentatively classified into two primary categories. First, the most intense emissions are generally associated with the cyclotron maser instability. Second, a class of weaker emissions can be found at each of the magnetospheres which appears to be the result of conversion from intense electrostatic emissions at the upper hybrid resonance frequency into (primarily) ordinary mode radio emission. It is this second category, often referred to as nonthermal continuum radiation, which we will discuss in this review.

We review the characteristics of the continuum spectrum at each of the planets, discuss the source region and direct observations of the generation of the emissions where available, and briefly describe the theories for the generation of the emissions. Over the past few years evidence has increased that the linear mode conversion of electrostatic waves into the ordinary mode can account for at least some of the continuum radiation observed. There is no definitive evidence which precludes the possibility that a nonlinear mechanism may also be important.

INTRODUCTION

With the Voyager tour of the outer planets now complete we can say with certainty that the occurrence of nonthermal continuum radiation in planetary magnetospheres is ubiquitous. The magnetospheres of Earth, Jupiter, Saturn, Uranus, and Neptune all show evidence of this type of radio emission. In this review we will concentrate on the observations of the emissions at the various planets and compare the spectra and temporal characteristics of the continuum radiation. We will briefly mention some of the various theoretical treatments of the generation of continuum radiation, although this is not meant to be a theoretical review. We will take a close look at one theoretically predicted characteristic of continuum radiation, however. The linear mode conversion theory has held a prominent place in the literature as mechanism for generating continuum radiation. This theory predicts a specific beaming angle with respect to the magnetic field depending on local plasma conditions. We will comment on the consistency of observations with this prediction at the various planets.

We point out that Jones [1985, 1988] provided very thorough reviews of the subject of nonthermal continuum radiation at the two previous workshops on Planetary Radio Emissions held in Graz. This review is designed to avoid duplication of much of the material in the two previous reviews. We hope that the combination of Jones' reviews and this one will form a complete set of information on the subject.

What is Continuum Radiation?

This review is concerned with generally low frequency, low amplitude planetary radio emissions which are thought to be generated by mode conversion from electrostatic waves near the upper hybrid resonance frequency on a density gradient in planetary magnetospheres. There is evidence that linear conversion through the so-called 'radio window' is responsible for at least some of the observed emissions in this class. There is also reason to believe that nonlinear conversion of the electrostatic wave energy into electromagnetic waves is feasible. The resulting waves, if generated above the surrounding solar wind plasma frequency, will propagate freely out of the magnetosphere and make up at least part of the low-frequency portion of the planet's radio spectrum. These escaping emissions are generally smoothly varying in amplitude, but highly structured in frequency, often being composed of a number of narrowband lines. If generated at frequencies below the surrounding solar wind plasma frequency, the waves will be confined to the density cavity formed by the planet's magnetosphere. Multiple reflections and the superposition of emissions at different frequencies form a spectrum which, in addition to showing slow variations in amplitude with time, also show a diffuse, broadband or 'continuum' spectrum. This component is commonly referred to as the trapped continuum radiation.

The subject of this review has suffered from a lack of a suitably descriptive and acceptable name. Gurnett [1975] called the terrestrial manifestation of the emission nonthermal continuum radiation and this remains the most widely used term. Jones [1980] introduced the term myriametric radiation meaning a wavelength of ten thousand meters or, alternately, myriads of wavelengths. The second meaning offered a solution to the paradox that was demonstrated by later studies of the 'continuum' radiation [e.g. Kurth et al., 1981]. They showed that the emission is generated as narrowband emissions making the term continuum radiation misleading. It is the superposition of bands at many different frequencies and the Fermi-Compton scattering process which smooths the spectrum of the trapped component. Gurnett et al. [1981, 1983] utilized the term narrowband electromagnetic emissions when referring to the narrowband emission lines observed in the escaping component at Saturn and Jupiter. Barbosa [1982] in a review of the subject, utilized the term 'low-level VLF and LF radio emissions' but this nomenclature never caught on in the literature. If any consistent nomenclature has evolved for these emissions it is the use of the term myriametric for the narrowbanded escaping component and continuum radiation for the trapped component; continuum radiation arguably remains the term of choice for the entire emission spectrum.

It is this author's view that this emission should eventually be known by its generation mechanism. The community has begun to identify a number of planetary radio emissions as cyclotron maser emissions because of their being generated by that instability. It would be most acceptable to identify continuum radiation by its generation mechanism so that differences in its appearance due to propagation and other influences could be avoided. In view of a lack of thorough understanding of the emission mechanism for continuum radiation, this approach does not currently yield a consistent label.

EARTH

Most of what we know and understand about continuum radiation is derived from terrestrial observations. These have aided our progress considerably in understanding similar emissions in the outer planet magnetospheres. Of course, it is also clear that our observations of continuum radiation from the other planets has been useful in understanding the terrestrial emissions. The first definitive studies of terrestrial continuum radiation were given by Gurnett and Shaw [1973], and Gurnett [1975]. These papers described the spectrum of the emission, recognized the trapped and escaping component, suggested a source region near the dawnside plasmapause, and even suggested that the electromagnetic waves were, in some way, associated with the intense electrostatic waves near the upper hybrid resonance frequency. Other significant observations of continuum radiation at the Earth included those of Kurth et al. [1981] who described the escaping component of the emission, in detail, and who provided definitive evidence that the radiation was generated in narrow bands from regions where intense upper hybrid resonance emissions occurred. Jones [1980] showed a similar event as observed by GEOS 1 and also concluded that the continuum radiation had its source in the intense upper hybrid band.

Figure 1 shows the two components of terrestrial continuum radiation for three different examples. The lower frequency component is trapped and exhibits a larger amplitude, presumably because of the buildup of wave energy in the magnetospheric cavity. The higher frequency component can show considerable spectral structure, as in the upper panel of Figure 1, although this is not always the case. This component is typically of lower amplitude than the trapped component because the waves are free to propagate directly away from the source and into the solar wind. Since the wave frequency is greater than the solar wind plasma frequency, there is no reflection at the magnetopause. Figure 2 [D. A. Gurnett, personal communication, 1991] shows a series of narrowband emissions emanating from the upper hybrid band at the terrestrial plasmapause. This example demonstrates how the spectrum of escaping continuum radiation can often appear as a series of narrowband emissions.

In a long series of papers (c.f. Jones [1988] and references therein) Jones built upon ideas originating with Budden [1961] and which were applied to terrestrial radio emissions by Oya [1971]. Jones explained the continuum radiation with a linear wave conversion mechanism (LWCM) which essentially relied on the fact that electrostatic waves with the appropriate wave normal angle at the plasma frequency in the presence of a density gradient would convert into ordinary mode radio waves. Others criticized this theory as being inefficient [Melrose, 1981; Barbosa, 1982, Rönnmark, 1983]. These issues will be discussed further in the theory section. However, Jones' theory had the advantage that it made some very specific predictions about beaming angles and polarization which could be measured experimentally. Jones et al. [1987] showed a very clear example of a pair of emissions at the magnetic equator observed by Dynamics Explorer 1 which matched the beaming predictions of the LWCM very closely, even though polarization measurements could not be made because of the very weak nature of the event. Gurnett et al. [1988] then provided several examples of continuum radiation near the magnetic equator wherein the polarization was found to be consistent with the LWCM theory. A statistical study has subsequently been performed by Morgan and Gurnett [1991] which seems to discount, in part, the beaming prediction since the null expected near the magnetic equator is usually not observed. These recent observations suggest that Jones' theory does explain at least some of the available continuum observations. It is not clear from the observations, however, that the linear theory explains the entire continuum spectrum.

JUPITER

It is not surprising that Jupiter exhibits the most spectacular continuum radiation spectrum of all the known planetary magnetospheres. The entire radio emission spectrum of the planet is extraordinary in terms of both amplitude and spectral extent. The same is true for the continuum radiation.

Jovian continuum radiation was first reported by Scarf et al. [1979] and was described in detail by Gurnett et al. [1980]. The most obvious of the two components at Jupiter is the trapped emission, largely due to the very deep density cavity carved by the magnetosphere; the minimum reported density is $\sim 10^{-5}$ cm^{-3} [Moses et al., 1987] compared to a solar wind density of about 0.4 cm^{-3}. The trapped continuum spectrum is characterized by a power law of the form $f^{-\alpha}$ where α is typically about 3-6 [c.f. Gurnett et al., 1980]. Hence, over 4 orders of magnitude in density or two in frequency, the spectrum grows by 60 dB over the escaping spectrum before it cuts off at the local plasma frequency. Clearly, the trapped continuum radiation dominates the low-frequency wave spectrum in all but the innermost regions of the Jovian magnetosphere and the plasma sheet. Figure 3 [from Kurth, 1986] shows a typical wideband spectrogram of Jovian continuum radiation in the lower panel below about 6 kHz. This particular example shows that narrowband intensifications can be superimposed upon a more diffuse or continuous trapped spectrum. The lower frequency cutoff of the radiation, near 1.5 kHz in Figure 3, is commonly interpreted as the local plasma frequency. This identification relies on the assumption that the cutoff is local to the observing point. If this assumption does not hold, then the cutoff is an upper limit to the plasma frequency at the observing point.

Recent work by Kennel et al. [1987], Moses et al. [1987], and Barbosa et al. [1990b] provide evidence for electrostatic waves propagating in the Z-mode at the L=0 cutoff [Stix, 1962] just on the northern and southern edges of the plasma sheet in the near tail. The observations also show upper hybrid bands just at the lower frequency extent of the emission in the deep lobes of the tail [Barbosa and Kurth, 1990]. These observations suggest that the same conversion mechanism(s) for generating electromagnetic waves from electrostatic emissions exist in the tail at Jupiter and can account for the existence of the waves even at such very low frequencies as a few tens of Hertz.

As spectacular as the trapped continuum radiation is at Jupiter, the escaping component is perhaps even more so. Gurnett et al. [1983] showed that this portion of the continuum spectrum, as at Earth and Saturn, was characterized by numerous narrowband emissions. They also showed that the narrow bands appeared at different frequencies from one time to the next, although it was never clear whether an individual band drifted in frequency or a band at one frequency faded out as a new one at a different frequency grew in intensity. The upper portion of the Jovian continuum spectrum in the lower panel of Figure 3 shows a set of at least three of these narrowband tones at frequencies (> 8 kHz) which allow the waves to escape the magnetosphere. The spectrogram in Figure 3 has a time scale of 48 seconds. For comparison, a typical terrestrial escaping continuum radiation spectrum is provided in the top panel of Figure 3 with an identical time scale.

New methods of processing the wideband data from Jupiter have recently cleared up the question of how the frequency of the narrowband emissions vary. As shown in Figure 4, the bands clearly drift in frequency with time. In this example the entire 'family' of bands exhibit similar variations in frequency with time. Perhaps more important, however, is the observation that the characteristic time scale for the spectral drifts in these bands is a few hours. In fact, there are examples in which the drift from maximum to minimum frequency or vice versa can take about 5 hours, strongly suggesting a geometrical explanation for the change in frequency. This can be understood by realizing that the rotation period of Jupiter is about 10 hours and during this period the spacecraft executes a complete pass in longitude and samples the full range of magnetic latitudes offered by the tilted dipole at whatever geographic latitude the spacecraft happens to be during the rotation. Jones [1980] suggested that a continuum radiation source at the magnetic equator which was extended in radial distance at the Earth might produce an emission band whose frequency varies smoothly as viewed from a spacecraft moving in latitude. While this effect was not found at the Earth [Kurth et al., 1981], the variation of frequency with time exhibited by the Jovian escaping continuum radiation is certainly consistent with such a prediction.

With such a fertile field in which to apply the LWCM, Jones [1986, 1987] set out to show that the model could explain the Jovian kilometric radio emissions. The model depends critically on the density and magnetic field structure of the magnetosphere and both of these at Jupiter are quite complex. For some sample emissions, Jones demonstrated that sources situated at particular locations just north or south of the magnetic equator could explain many details of emissions beamed into small magnetic latitudes. He applied his theory to both the narrowband and broadband kilometric radiation [Kaiser and Desch, 1980] and not specifically to the narrowband emissions shown in Figure 4. Nevertheless, the example reproduced here (in Figure 5) shows that the beaming depends in detail on the plasma and field models; one need only change one of these in small detail or move the source to a slightly different latitude to get a totally different beaming angle. Figure 5 is an example of Jones' modeling of the Jovian kilometric sources. With such a crucial dependence on a poorly known and likely time variable density model, it is not likely that the narrowband emissions can be used with much usefulness to remotely sound the source region as Jones [1986] and Jones and Leblanc [1987] have suggested. While we do not argue that the technique appears to work, the scheme requires the detailed knowledge of the density model as mentioned above and only applies if the model used is accurate. Alternatively said, one could always assume emission at a given latitude and determine something about the density structure of the magnetosphere at the source region, but which approach would provide useful and reliable information?

Since Jones [1986, 1987] has suggested that both the broadband and narrowband kilometric radiation at Jupiter can be explained by the LWCM theory, one must include these emissions in a discussion of continuum radiation at Jupiter. In addition to demonstrating beaming properties consistent with the LWMC theory, the narrowband and broadband kilometric radiation exhibit primarily the ordinary-mode polarization which would be consistent with the mode conversion theory. This result suffered from some initial confusion in the literature, but the current understanding of these polarizations is summarized in Figure 20 and Table 2 of Kaiser [1989]. That the narrowband kilometric radiation was likely related to escaping continuum radiation was suggested by Kurth [1986].

SATURN

Saturn displays both trapped and escaping continuum radiation components. The escaping continuum radiation was reported by Gurnett et al. [1981] as a series of narrowband electromagnetic emissions. Figure 6 is from Gurnett et al. [1981] and shows examples of the Saturnian escaping electromagnetic bands. The first panel shows a number of bands extending up to near the 12-kHz limit of the Voyager 1 wideband receiver. The additional panels show the persistence of the most intense band near 5-6 kHz. These bands were very clear and distinct features of the low frequency radio emission spectrum of the planet. Gurnett et al. showed that some of the bands, particularly one near 5 - 6 kHz, could be seen by both Voyager spacecraft from a wide range of observation points. This suggests the bands are first, freely-propagating radio emissions, and second, generated at rather stable sources in the magnetosphere. Gurnett et al. noticed that there were several line spacings which seemed to stand out in the narrowband emission spectra. Given that the bands have their origin in electrostatic bands near the upper hybrid frequency which are most intense between harmonics of the electron cyclotron frequency, Gurnett et al. identified the band spacings with the equatorial magnetic field near some of Saturn's major moons. Jones [1983] applied the LWCM theory to some of the narrowband emissions at Saturn and determined that a particular density ledge observed by the plasma instrument on Voyager 1 might be the source for this particular band.

The trapped component of the Saturnian continuum radiation was very difficult to observe and was only discovered as a result of a study looking for Jovian continuum radiation propagating down the Jovian magnetotail during times when both Voyager 2 and Saturn were near or actually in the Jovian tail [Kurth et al., 1982]. This study showed that continuum radiation was observable by Voyager 1 when there was no alignment with the Jovian tail, hence, there must be a source in Saturn's magnetosphere.

Figure 7 shows a wideband spectrogram of the trapped Saturnian continuum radiation in the lower panel and a spectrum averaged over 4 seconds in the upper panel. The 4-second average spectrum in Figure 7 exhibits a lower frequency cutoff near 500 Hz (corresponding to a plasma density of about 3×10^{-3} cm^{-3}). The emission was barely detectable by the Voyager plasma wave instrumentation, primarily because of the short antennas used. Kurth et al. suggested that because the density cavity in Saturn's magnetosphere was not very deep compared to the surrounding solar wind density, the trapped continuum spectrum could not be very intense. At Jupiter, the Q of the very deep density cavity allows for a more efficient confinement of waves.

URANUS

The detection of continuum radiation at Uranus was even more challenging than at Saturn. The trapped component was no more intense than at Saturn, but because of our Saturn experience, we expected a weak component and focussed our detection techniques to find such emissions. The result was a clear signature of trapped continuum radiation [Kurth et al., 1990b] in a region of the magnetosphere where upper hybrid waves had been previously reported [Gurnett et al., 1986; Kurth et al., 1987]. Figure 8 shows some of the continuum observations presented by Kurth et al. [1990b]. The conclusion was that the upper hybrid bands were the source of the continuum radiation.

The same study which identified the trapped continuum radiation [Kurth et al., 1990b] also provided evidence of an escaping component at higher frequencies. The understanding of the escaping component, however, is confused by another low-frequency radio component at Uranus known as the sporadic narrowband radio emission reported by Gurnett et al. [1986] and Kurth et al. [1986]. Figure 9 [from Kurth et al., 1986] shows the frequency-time character of the narrowband bursty emissions at Uranus. This emission shows very rapid amplitude variations; some bursts have durations of only seconds. The spectral structure of the bursty emissions is very similar to that of escaping continuum radiation. It has numerous narrowband components and sometimes shows a diffuse background. It is not clear whether the bursty emissions are generated by conversion (either linear or nonlinear) from upper hybrid bands or some other mechanism. As shown in Figure 10, the bursty emissions (shown by times along the trajectory in radial distance and magnetic latitude indicated by thick lines) are beamed to low magnetic latitudes, a fact which would seem to be consistent with the LWCM theory and suggest the emissions are generated in the same way as continuum radiation. It is not clear whether the diffuse background emission is the true escaping component and distinct from the narrowband bursty emissions, or that the two are related by a common source mechanism and they both make up the escaping component. Kurth et al. [1986] suggested that a continuum radiation conversion mechanism (be it linear or nonlinear) might be able to produce bursty emissions if the beam were very narrow and the source region were rotating rapidly as would be expected in Uranus' highly-tilted magnetosphere. If the latter is the case, one cannot explain the lack of the low frequency bursty component at Neptune which has a similar obliquely rotating magnetic field.

NEPTUNE

The primary radio emission observations made by the plasma wave investigation at Neptune were of escaping continuum radiation [Gurnett et al., 1989; Kurth et al. 1990a]. The Neptune encounter provided a very good set of observations for the study of these emissions. The large tilt of the magnetic field with respect to the rotational axis of Neptune provided ample opportunity to observe relatively narrowband beaming into a region close to the magnetic equator. The passage of Voyager 2 into very small radial distances from the planet allowed the spacecraft to traverse both the right-hand and the left-hand cutoffs at the frequency of the escaping continuum radiation component to demonstrate, by means of no decrease in wave amplitude as the right-hand cutoff was crossed, that the radio emissions were primarily left-hand polarized in the plasma convention (ordinary mode); this is consistent with the continuum radiation identification. Further, observations of electrostatic upper hybrid bands at the magnetic equator [Gurnett et al., 1989; Barbosa et al., 1990a] just at the lower frequency bound of the radio wave spectrum provide a very likely source for the radio emissions. Hence, we have identified the spectrum, polarization, beaming characteristics, and source for the Neptunian escaping continuum radiation and they are all consistent with our understanding of the generation of continuum radiation at the Earth and other planets.

Figure 11 summarizes many of the Voyager plasma wave investigation's observations of escaping continuum radiation at Neptune. The diffuse radio emission seen before and after closest approach above about 5 kHz is the radio emission itself. The brief, intense bursts of emissions at about 0030 and 0800 SCET are electrostatic electron cyclotron harmonic emissions at the magnetic equator. The highest frequency band of these electrostatic emissions is the upper hybrid resonance (UHR) band which is the likely source for the lowest frequency electromagnetic emissions observed at Neptune. It is suspected that upper hybrid emissions extend along the magnetic equator toward smaller radial distances where the plasma frequency is larger. Hence, the upper hybrid bands closer to Neptune would provide the sources for the higher frequency emissions seen in Figure 11. One can also notice that the waves appear to cross the cyclotron frequency f_{ce} at about 0300 and 0500 SCET with no diminution in amplitude, providing evidence that they are propagating in the ordinary mode. Figure 12 shows wideband spectra of the escaping Neptunian continuum radiation; the local minimum in the spectrum near 7.2 kHz is likely due to a notch filter in the receiver at that frequency designed to limit interference at the third harmonic of the 2.4-kHz power supply. As is the case at the other planets, the spectrum exhibits a diffuse background and suggestions of narrowband emissions.

Figure 13, taken from Kurth et al. [1990a], shows the tendency for the low-frequency Neptunian radio emissions to be beamed into low magnetic latitudes. While there are local minima in the received intensities in the day 240, 0648 and 2254 SCET examples which might be suggestive of detailed evidence of the LWCM's beaming pattern, the feature is asymmetric with respect to magnetic equator and not always present. We take these observations to be consistent with the LWCM theory, but not proof of its applicability to the Neptune emissions.

THEORIES FOR THE GENERATION OF CONTINUUM RADIATION

Observational evidence has shown for some time that intense electrostatic emissions at the upper hybrid resonance frequency were the source of the continuum radiation [Jones, 1980; Kurth et al., 1981]. The challenge, therefore, is to understand how the energy in the electrostatic waves is converted into electromagnetic waves which can escape the source region. While this is not meant to be a review of theory, it is appropriate to briefly outline the two approaches which have been taken to understand the generation of the continuum radiation. Both approaches are based on the conversion of electrostatic upper hybrid bands to electromagnetic waves. One, that promoted most vigorously by Jones [c.f. Jones, 1988 and references therein], is a linear conversion mechanism which relies on some fraction of the electrostatic waves which propagate in a density gradient to reach the so-called 'radio window' at the local plasma frequency with an appropriate wave normal angle such that they can couple into electromagnetic waves with a polarization which is predominantly left-hand. There are variations on Jones' theory, such as that by Okuda et al. [1982]. The other approach is based on the contention that the number of electrostatic waves which actually have access to the 'radio window' is a set of measure zero and, therefore, some more efficient mechanism must be found. While this approach does not deny that the linear conversion is operable, it contends that a nonlinear mechanism can more easily provide the necessary conversion efficiency. Nonlinear theories have been suggested by Melrose [1981], Rönnmark [1983], Christiansen et al. [1984], and Murtaza and Shukla [1984]. Some of these suggest the coalescence of the upper hybrid waves with some low frequency turbulence to form a third, electromagnetic wave. Others suggest the decay of the electrostatic wave into the electromagnetic wave and a low-frequency wave.

The linear theory has attracted the greater share of the attention in the literature due to the diligent efforts of D. Jones and the fact that very specific tests of polarization and beaming angles were suggested. As mentioned above, these predictions have been borne out in specific events studied using the Dynamics Explorer plasma wave receiver at Earth. There is clear acceptance in the literature that the linear mechanism can explain at least these specific events and may, in fact, contribute to some portion of the continuum radiation spectrum observed. The remaining question is whether the linear mechanism, alone, can account for the entire continuum spectrum at any or all of the planetary magnetospheres. Progress on this question has been slow, partially because specific predictions from the nonlinear theory have not been available for verification through experiments or observation.

The primary criticism of the linear theory has been by Melrose [1981], Barbosa [1982], and Rönnmark [1989] generally on the grounds that the linear theory has insufficient efficiency to generate the observed radio wave spectrum from the available upper hybrid wave amplitudes. Independently, Melrose, Barbosa, and Rönnmark [1983] suggested that the coalescence of upper hybrid waves with some lower frequency wave, such as high harmonic ion Bernstein waves above the lower hybrid resonance frequency would be more efficient. More recently, Rönnmark [1991] has suggested that the decay of electrostatic upper hybrid waves would work as well and does not require large amplitude low frequency waves which are required in the coalescence model but which are not observed in all cases. Barbosa [1982] argues that the requirement of the LWCM theory on the electrostatic wave vector is so stringent that only a set of measure zero waves would actually satisfy the condition for conversion, hence, the efficiency would be insufficient. Rönnmark [1989] calculates the efficiency of the LWCM to be a factor of 10^{-3} too small. On the other hand, Rönnmark [1991] calculates the efficiency of the nonlinear decay process to be approximately that required to account for the observed radio wave amplitudes. Rönnmark [1989] further suggests that the general beaming associated with the LWCM theory is likely to hold for other mechanisms which produce radiation near the local plasma frequency. He also argues that the focussing of electrostatic wave vectors into the favored orientation for linear conversion is inconsistent with propagation studies [c.f. Engel and Kennel, 1984] which show a preference for azimuthal, not radial propagation.

An Examination of the Beaming Hypothesis

Several references have been made above to the beaming hypothesis of the linear mode conversion theory of Jones. The LWCM theory predicts that the electromagnetic waves will be beamed at an angle to the magnetic field $\psi = \tan^{-1}(f_{ce}/f_{pe})^{1/2}$ where f_{ce} and f_{pe} are the electron cyclotron and plasma frequencies, respectively, at the conversion site. Given that the most intense upper hybrid waves occur within a few degrees of the magnetic equator in a simple dipole field with density gradients perpendicular to the field, this prediction suggests that the electromagnetic waves will be emitted into beams which are roughly symmetric about the magnetic equator.

We reviewed the recent verifications of this hypothesis using Dynamics Explorer 1 data from the Earth [Jones et al., 1987; Gurnett et al., 1988]. The detailed direction-finding and polarization capabilities are not generally available for measurements at the outer planets with Voyager. To be sure, the planetary radio astronomy investigation can provide some information on polarization [Warwick et al., 1977] but the spectral coverage of the continuum radiation is limited to only a few channels and often to its 1-kHz channel, only. Direction-finding, as it is done with Voyager, is primarily by observing onsets and cutoffs of emissions and folding these observations in with the geometry of the magnetosphere in order to assess likely source regions. Typically, the use of those times when a source region would either come into or disappear from view around the planet are the most useful aspects of this technique. In almost all cases, some model for the emission mechanism must be assumed in order to begin to limit feasible source regions.

Most information on beaming provided by Voyager comes as a result of a statistical study of emission intensities as functions of geometry. For example, the escaping continuum radiation at Neptune was observed almost exclusively at small magnetic latitudes, hence, we conclude that the emissions are beamed from the equatorially-located upper hybrid bands into a restricted range of angles nearly perpendicular to the equatorial magnetic field. This information is suggestive, but because of its statistical nature, it is difficult to make definitive measurements such as those from Dynamics Explorer. One can conclude that the near-equatorial beaming of the Neptunian emissions is consistent with Jones' beaming hypothesis, but in detail, it is difficult to differentiate between that model and one which simply favors emission nearly perpendicular to the magnetic field which is a common radio emission beaming geometry. The cyclotron maser mechanism generates beams which are close to perpendicular to the magnetic field at the source, for example.

We summarize the beaming observations based on this mixture of definitive and subjective observations. Perhaps the best examples of beaming which are consistent with Jones' prediction are those specific events studied by Jones et al. [1987] and Gurnett et al. [1988]. The smoothly varying narrowband emissions at Jupiter shown in Figure 4 are also very suggestive of an observation which matches Jones' predictions, especially since the time scale for the frequency variations are similar to those for variations in the spacecraft magnetic latitude. The low magnetic latitude escaping continuum radiation at Uranus and Neptune is at least consistent with the beaming prediction of Jones, although the observations are equally consistent with other models, since accurate beaming angle measurements have not been reported to date. On the other end of the scale, Kurth et al. [1981] reported no consistent observation of the predicted variations in terrestrial escaping continuum radiation frequency with magnetic latitude and concluded that the beaming at Earth is not consistent with Jones' theory. This statement does not conflict with the discovery of some specific events which are consistent with the theory, but suggests that much of the terrestrial emission may not be beamed as the theory predicts. This conclusion seems to be supported by Morgan and Gurnett [1991]. The narrowband emissions at Saturn have been analyzed by Jones [1983] and he finds that at least one band can be attributed to a density feature at the magnetic equator. It is not clear that this is a unique solution, however; the lack of a tilted dipole at Saturn makes the determination of beaming at Saturn with two simple flybys of Voyager-class spacecraft almost impossible. Little or no information exists on beaming of the escaping diffuse emissions from Uranus [Kurth et al., 1990b], however, Kurth et al. [1986] demonstrate that the sporadic narrowband emissions are beamed primarily into low magnetic latitudes. Should one wish to classify these bursty emissions as escaping continuum radiation, they would appear to fit generally within the beaming prediction.

SUMMARY AND CONCLUSIONS

The Voyager observations have allowed the determination that continuum radiation is an entirely ubiquitous radio emission phenomenon from planetary magnetospheres and that there is evidence to conclude that conversion of electrostatic upper hybrid waves into electromagnetic waves is responsible for the emission although this aspect has not been proven for every planet. There is definitive evidence that the beaming and polarization predictions of the linear wave conversion mechanism hold true in some specific cases and other, less definitive evidence that the beaming prediction holds in a more general way at various planets. Still, there is no evidence to suggest that one or more nonlinear mechanisms could not also be responsible for some of the continuum emissions observed in the solar system.

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FIGURE CAPTIONS

Fig. 1: Examples of trapped and escaping continuum radiation spectra obtained at the Earth demonstrating the relatively greater intensity of the trapped component and the tendency for narrowband emissions to occur in the escaping component.

Fig. 2: An excellent example of the generation of narrowband electromagnetic emissions from a series of upper hybrid bands at the terrestrial plasmapause. Since these waves are at frequencies well above the solar wind plasma frequency, they can escape from the magnetospheric cavity and form part of the escaping continuum radiation spectrum.

Fig. 3: Examples of narrowband structures in Jovian and terrestrial continuum radiation [from Kurth, 1986]. Bottom panel: The Jovian continuum radiation in this example consists of the lower frequency trapped component with both diffuse and narrowband elements. The higher frequency escaping component consists of a series of narrowband emissions. Top panel: The terrestrial example of escaping continuum radiation is strikingly similar to the Jovian example when displayed on a similar time scale.

Fig. 4: A spectacular family of drifting narrowband electromagnetic emissions from Jupiter. The time scale of the frequency variations is similar to that for the variations of geometrical parameters such as magnetic latitude and suggests beaming may be responsible for the frequency drifting.

Fig. 5: A model for Jovian narrowband and broadband kilometric radiation beaming proposed by Jones [1987, 1988]. Notice how details of the density model and the latitude of the source play a major role in determining the direction of the various beams.

Fig. 6: Examples of escaping narrowband electromagnetic bands observed by Voyager 1 near Saturn [from Gurnett et al., 1981].

Fig. 7: The trapped component of Saturnian kilometric radiation [from Kurth et al., 1982].

Fig. 8: Observations of the continuum radiation detected at Uranus [from Kurth et al., 1990]. Notice that there is both a low-frequency trapped component as well as a higher frequency component which could be the escaping component of Uranian continuum radiation.

Fig. 9: The sporadic narrowband radio emissions from Uranus [from Kurth et al., 1986]. It is not clear whether these emissions are the Uranian equivalent of escaping continuum radiation or not. The narrowband quality of the emissions is certainly suggestive, but the very bursty nature is not a typical characteristic of continuum radiation at other planets.

Fig. 10: The trajectory of Voyager 2 in magnetic latitude as it departed from Uranus showing times when the sporadic narrowband emissions were detected [from Kurth et al., 1986]. This construction demonstrates that the bursty emissions are beamed towards low magnetic latitudes.

Fig. 11: Low frequency radio and plasma wave observations at Neptune showing the escaping continuum radiation above about 5 kHz at larger radial distances and the electrostatic emissions (near 0030 and 0800 SCET) which are likely the source of the electromagnetic waves.

Fig. 12: The spectrum of the low frequency radio emissions observed at Neptune [from Kurth et al., 1990]. Like continuum radiation at the other planets, this emission shows both a diffuse background and narrowband emissions.

Fig. 13: A series of low frequency radio emissions from Kurth et al. [1990] showing their preference for low magnetic latitudes. While two of these sets of emissions suggest a local minimum in intensity near the magnetic equator as would be expected under the beaming prediction of the linear wave conversion mechanism, the evidence for the specific beaming predicted by the LWCM theory is not strong.

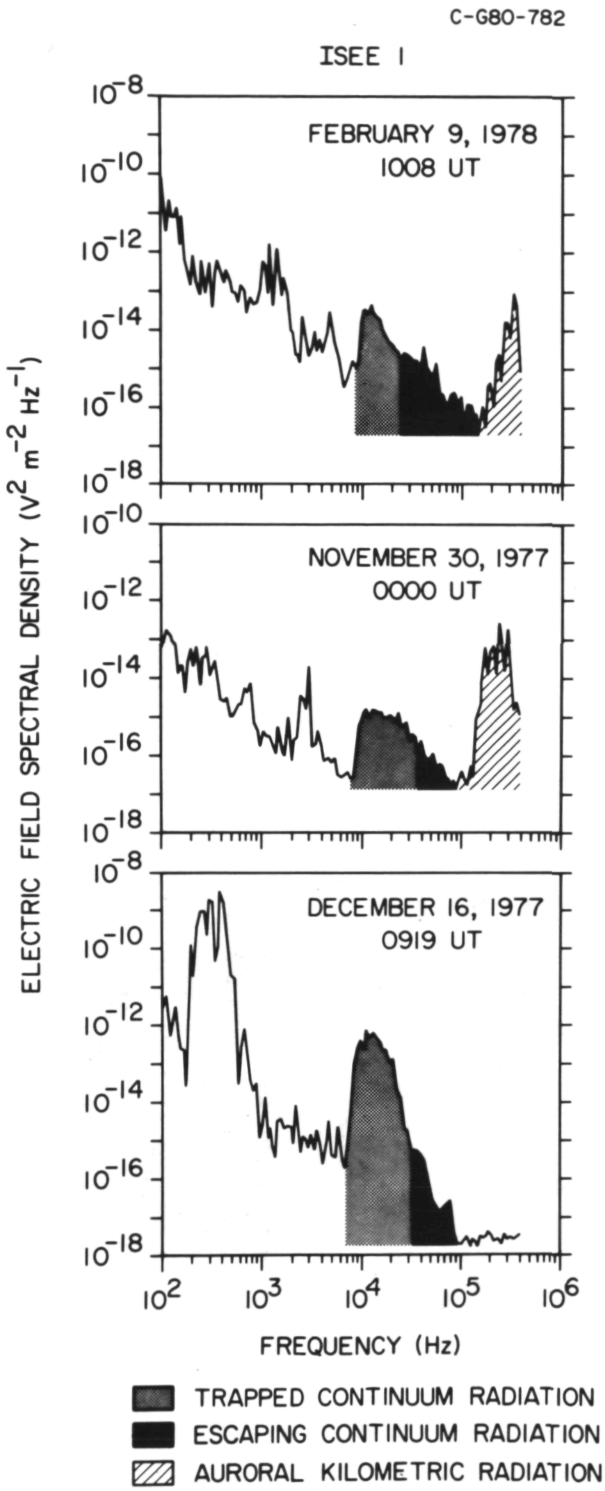
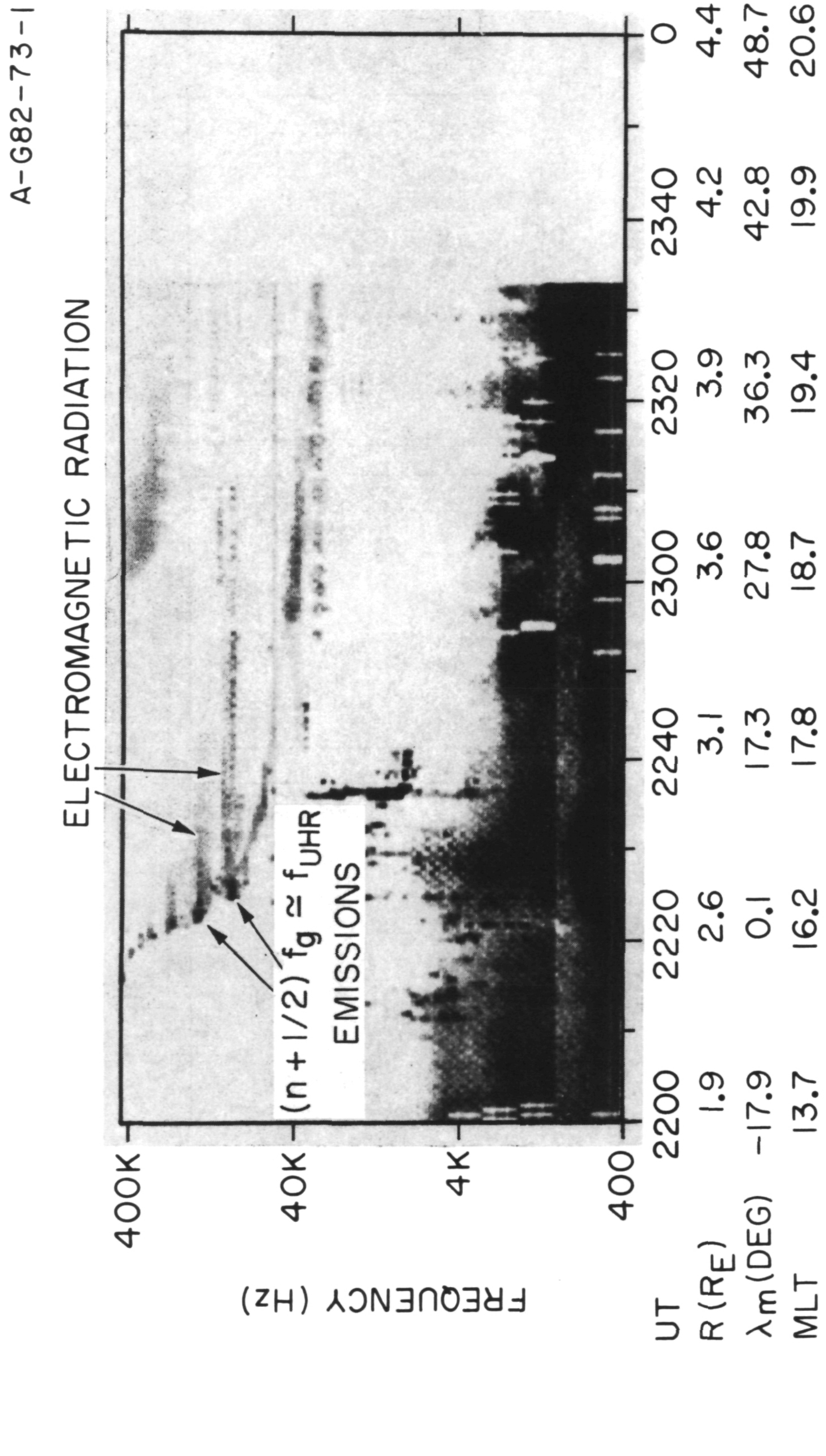

C-G80-782
ISEE I
FEBRUARY 9, 1978
1008 UT
NOVEMBER 30, 1977
0000 UT
DECEMBER 16, 1977
0919 UT
ELECTRIC FIELD SPECTRAL DENSITY ($V^2 m^{-2} Hz^{-1}$)
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^2
10^3
10^4
10^5
10^6
FREQUENCY (Hz)
TRAPPED CONTINUUM RADIATION
ESCAPING CONTINUUM RADIATION
AURORAL KILOMETRIC RADIATION

Figure 1



A-G82-73-1
ELECTROMAGNETIC RADIATION
(n + 1/2) $f_g \simeq f_{UHR}$
EMISSIONS
FREQUENCY (Hz)
400K
40K
4K
400
UT 2200 2220 2240 2300 2320 2340 0
$R (R_E)$ 1.9 2.6 3.1 3.6 3.9 4.2 4.4
λm(DEG) -17.9 0.1 17.3 27.8 36.3 42.8 48.7
MLT 13.7 16.2 17.8 18.7 19.4 19.9 20.6
ELECTRIC FIELD, DE-1, OCTOBER 28, DAY 303, 1981

Figure 2

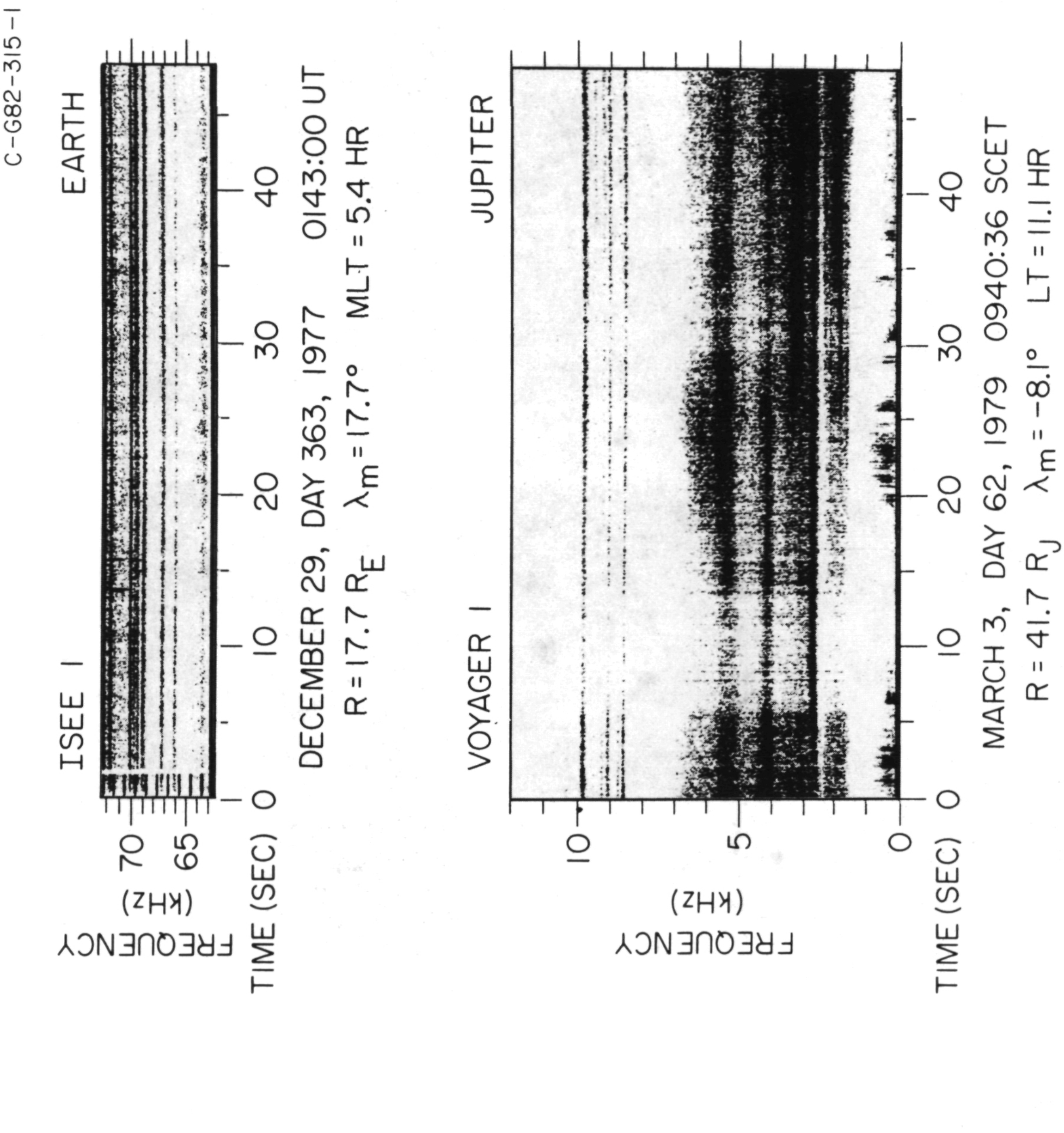

C-G82-315-1
ISEE I
EARTH
FREQUENCY (kHz)
70
65
TIME (SEC)
0
10
20
30
40
DECEMBER 29, DAY 363, 1977 0143:00 UT
R = 17.7 R_E λ_m = 17.7° MLT = 5.4 HR
VOYAGER I
JUPITER
FREQUENCY (kHz)
10
5
0
TIME (SEC)
0
10
20
30
40
MARCH 3, DAY 62, 1979 0940:36 SCET
R = 41.7 R_J λ_m = -8.1° LT = 11.1 HR

Figure 3

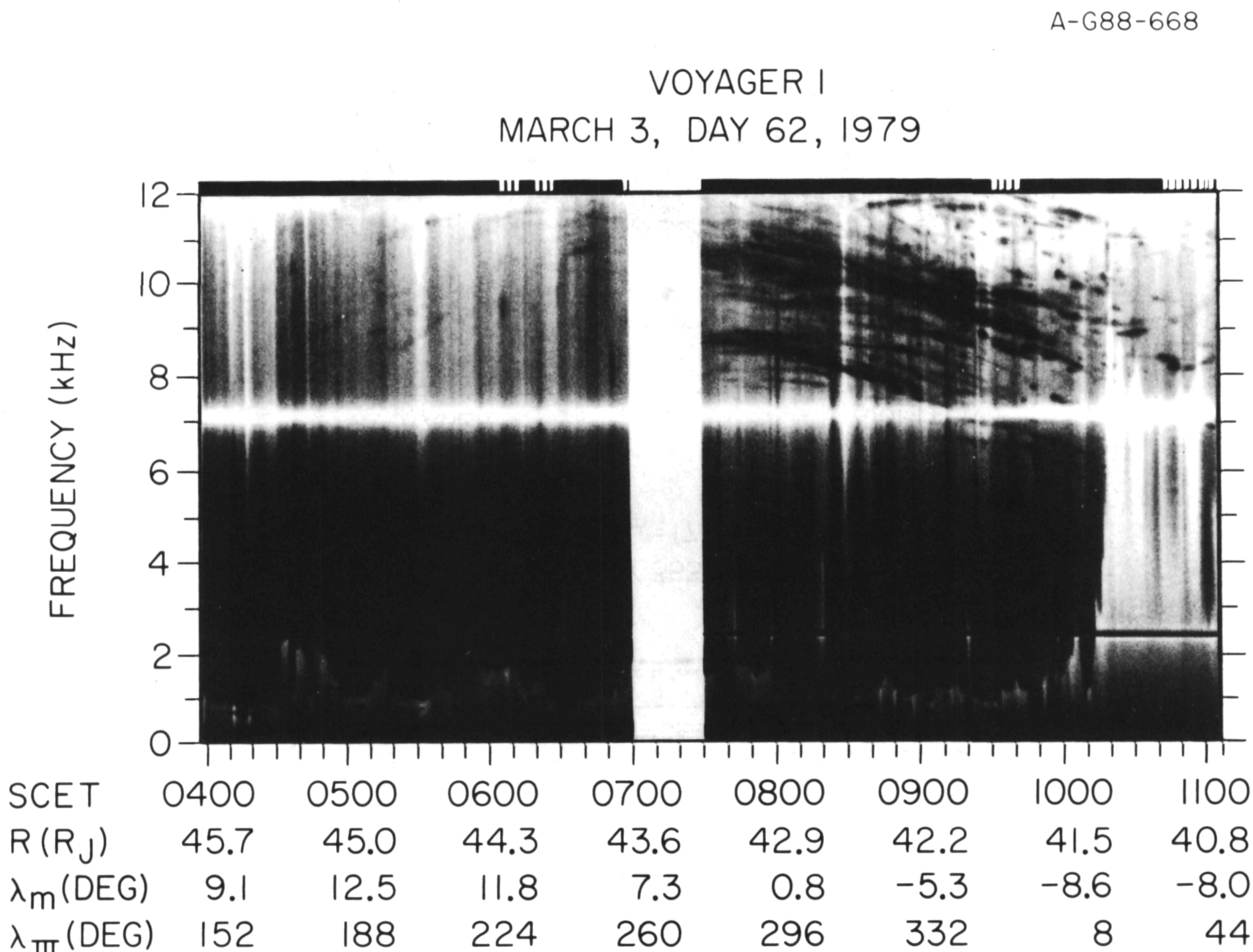
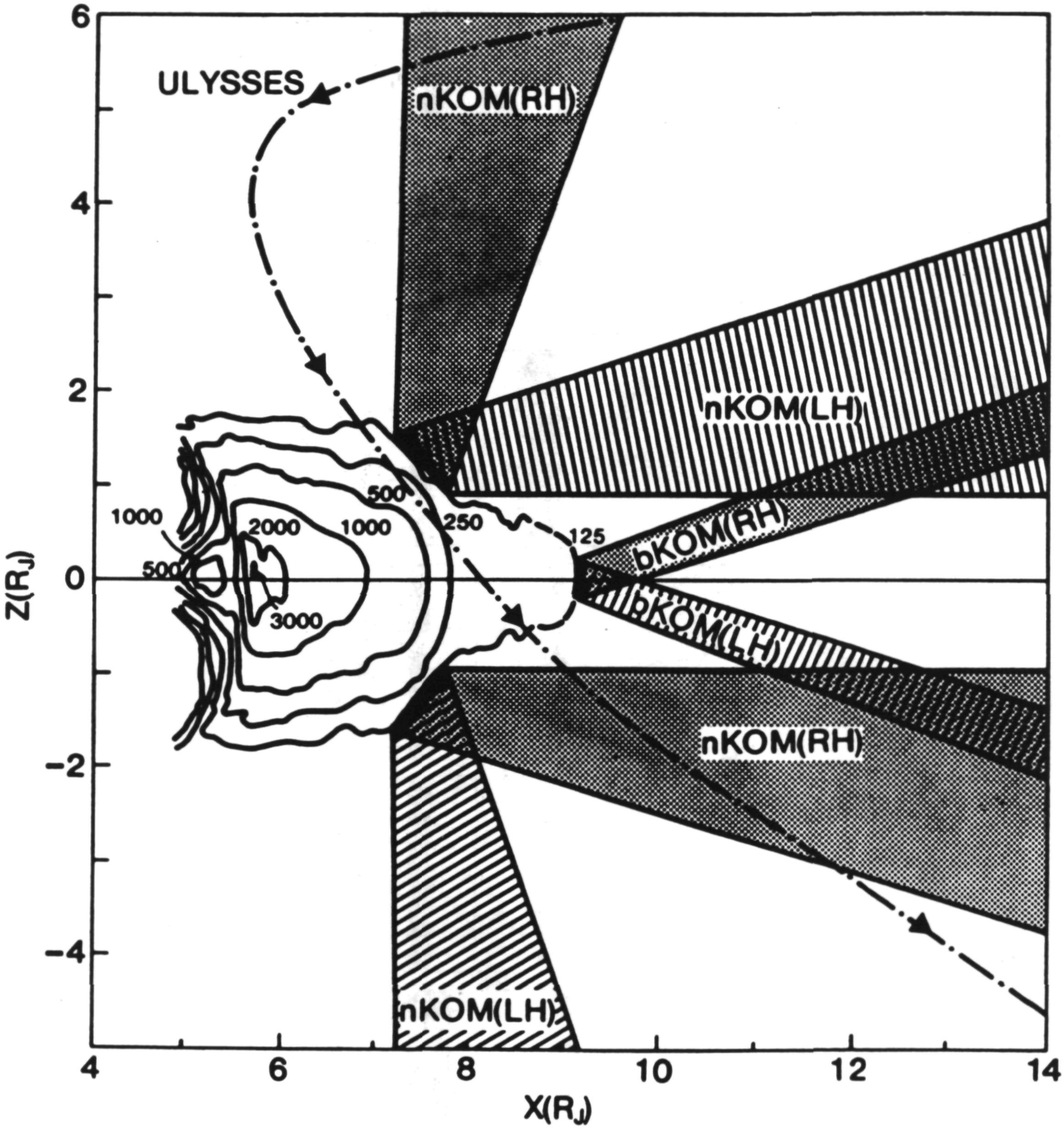

A-G88-668
VOYAGER I
MARCH 3, DAY 62, 1979
FREQUENCY (kHz)
12
10
8
6
4
2
0
SCET 0400 0500 0600 0700 0800 0900 1000 1100
R (R_J) 45.7 45.0 44.3 43.6 42.9 42.2 41.5 40.8
λm (DEG) 9.1 12.5 11.8 7.3 0.8 -5.3 -8.6 -8.0
λIII (DEG) 152 188 224 260 296 332 8 44

Figure 4



ULYSSES
nKOM(RH)
nKOM(LH)
bKOM(RH)
bKOM(LH)
nKOM(RH)
nKOM(LH)
1000
500
2000
1000
3000
500
250
125
Z(R_J)
X(R_J)
6
4
2
0
-2
-4
4
6
8
10
12
14

Figure 5

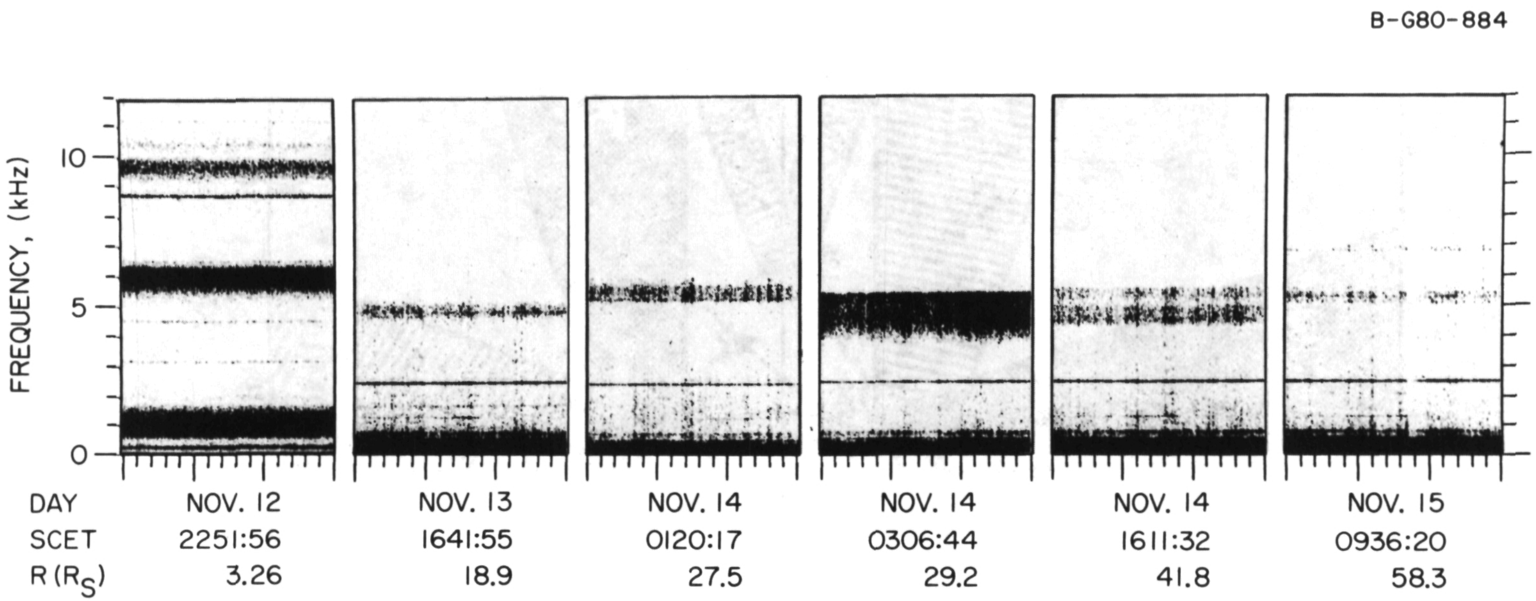

B-G80-884
FREQUENCY, (kHz)
10
5
0
DAY
SCET
R (R$_S$)
NOV. 12
2251:56
3.26
NOV. 13
1641:55
18.9
NOV. 14
0120:17
27.5
NOV. 14
0306:44
29.2
NOV. 14
1611:32
41.8
NOV. 15
0936:20
58.3

Figure 6

B-G82-306-1

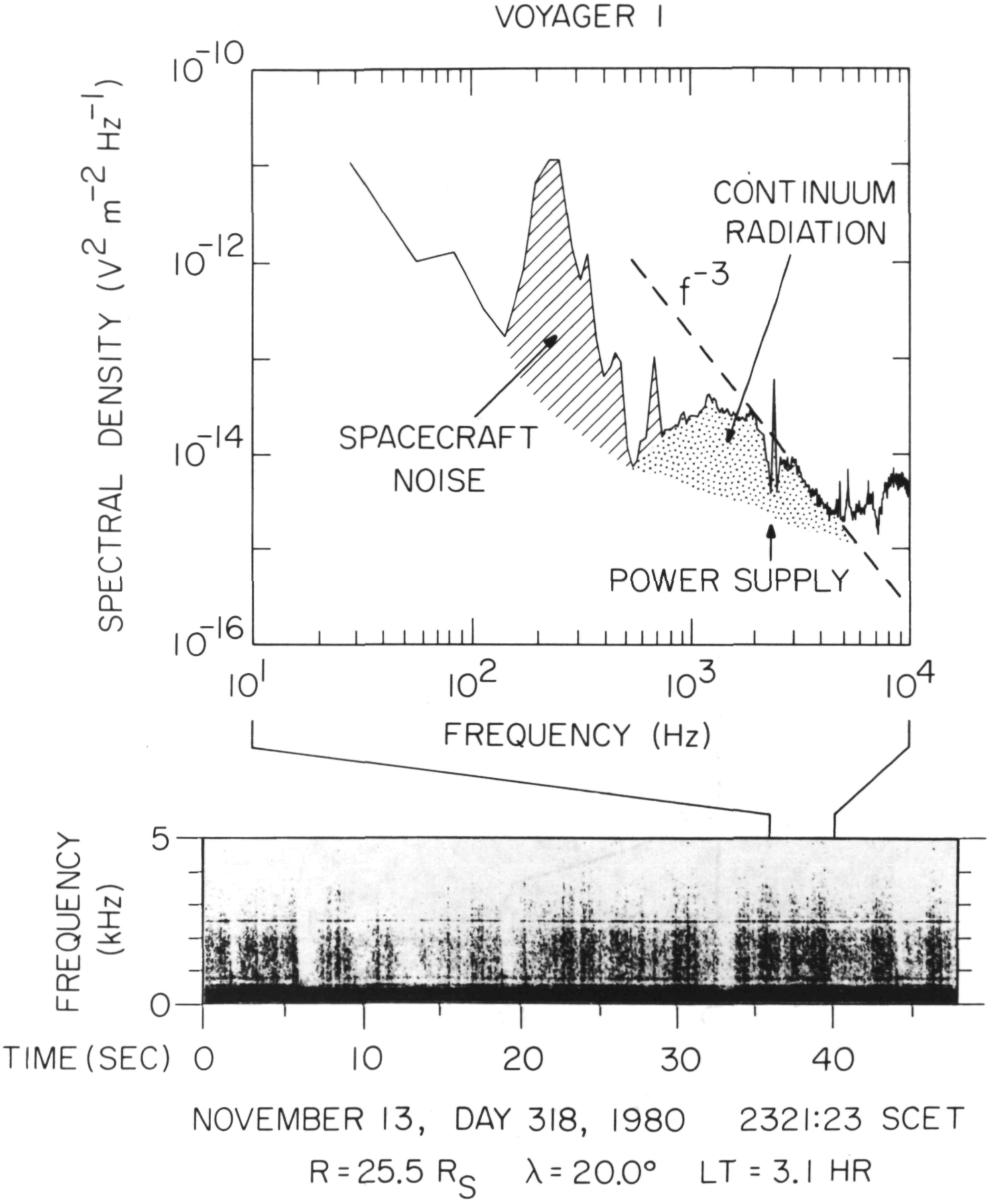


Figure 7

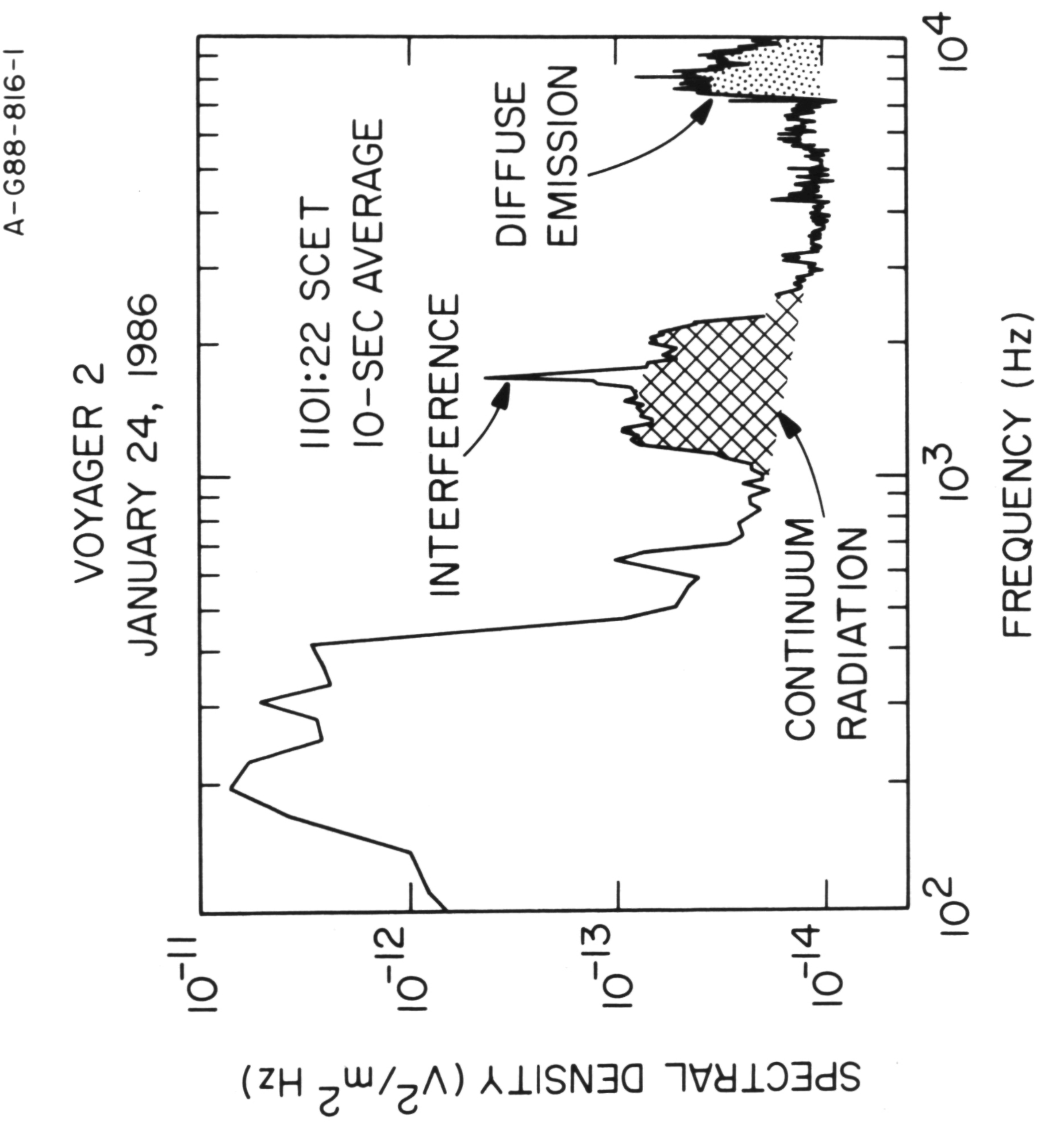

A-G88-816-1
VOYAGER 2
JANUARY 24, 1986
1101:22 SCET
10-SEC AVERAGE
INTERFERENCE
DIFFUSE
EMISSION
CONTINUUM
RADIATION
SPECTRAL DENSITY (V^2/m^2 Hz)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^2
10^3
10^4
FREQUENCY (Hz)

Figure 8

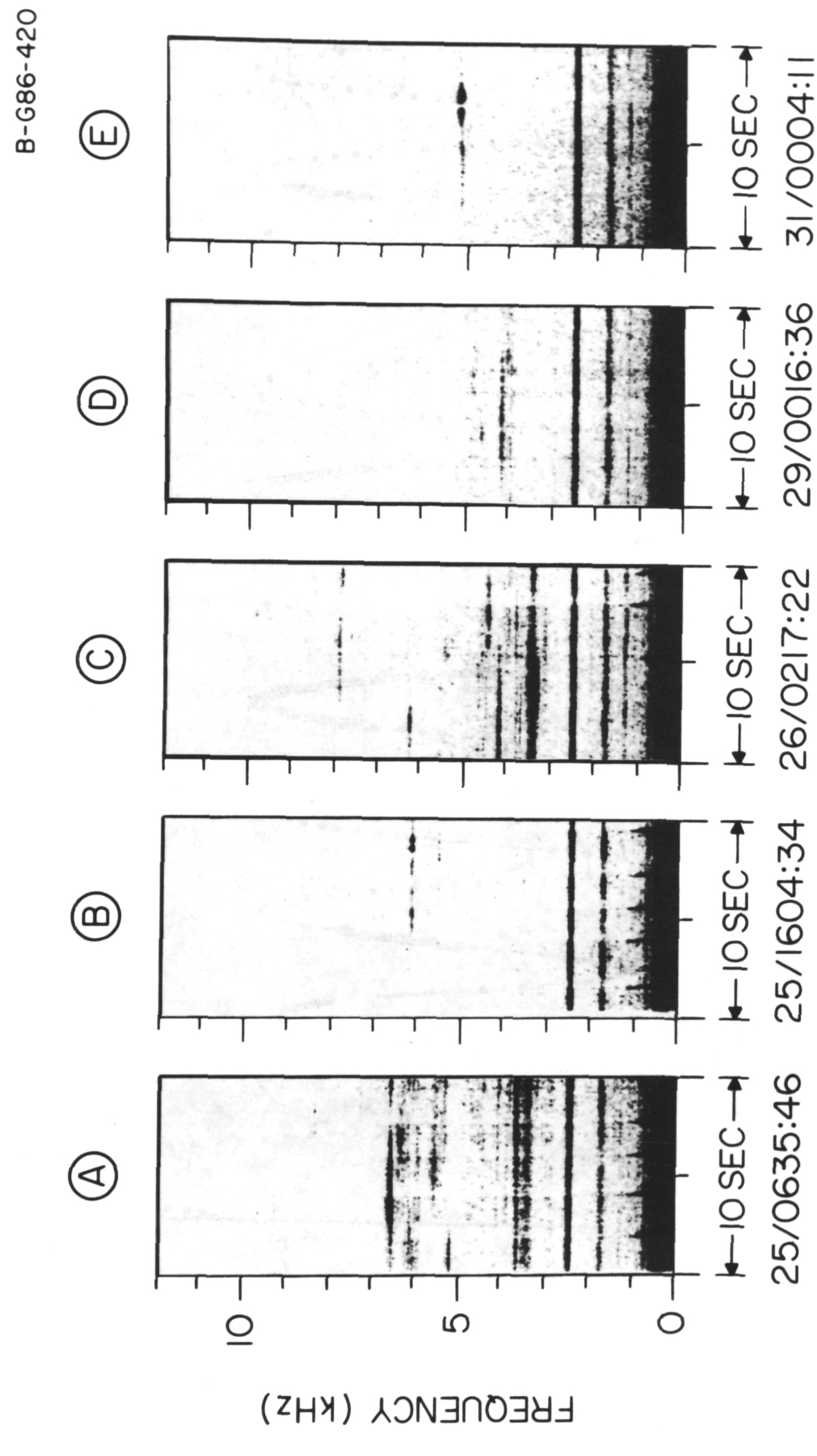

B-G86-420
A
B
C
D
E
10 SEC
10 SEC
10 SEC
10 SEC
10 SEC
25/0635:46
25/1604:34
26/0217:22
29/0016:36
31/0004:11
VOYAGER 2 JANUARY 1986
FREQUENCY (kHz)
0
5
10

Figure 9

A-G86-274

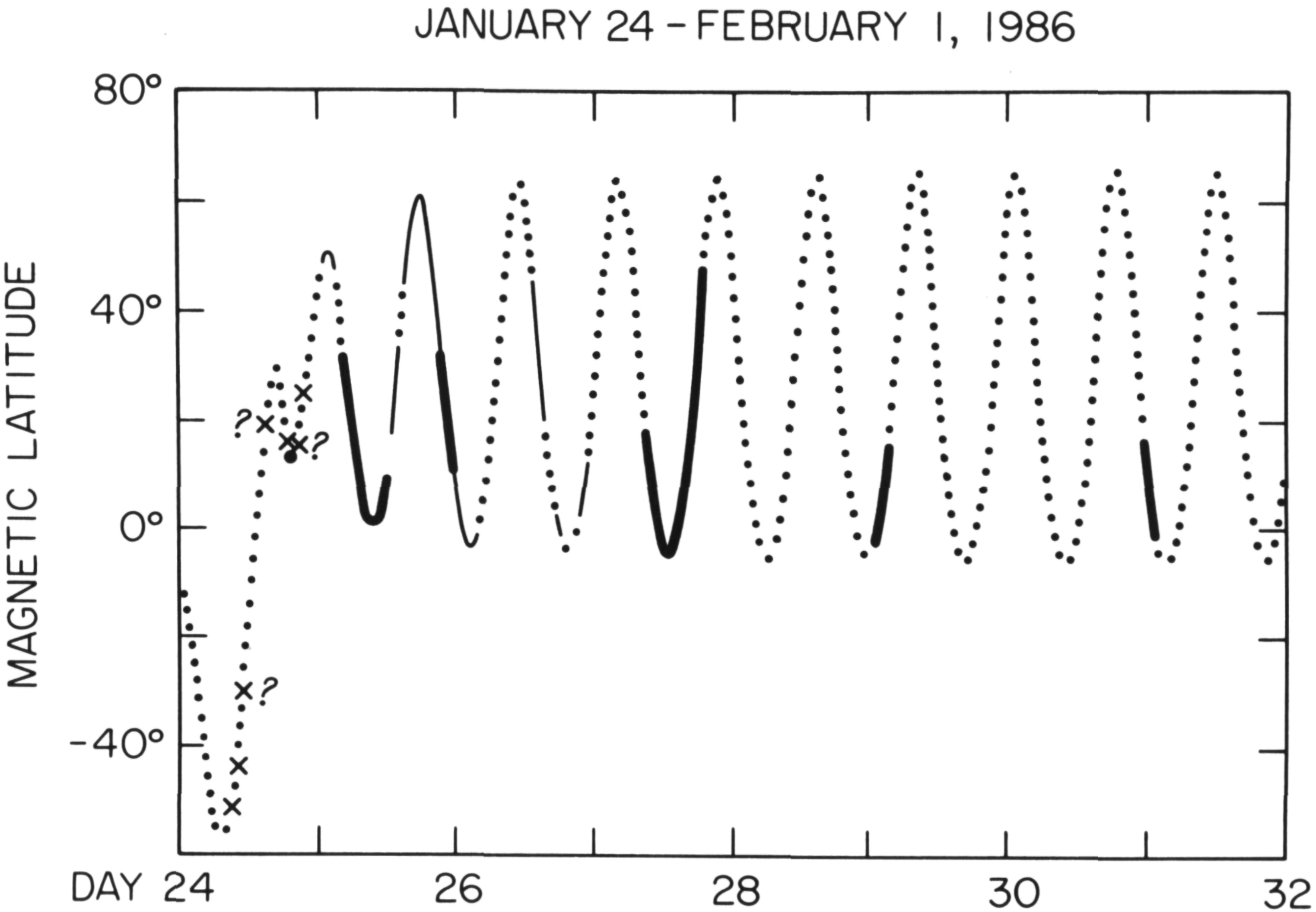


Figure 10

B-G91-637

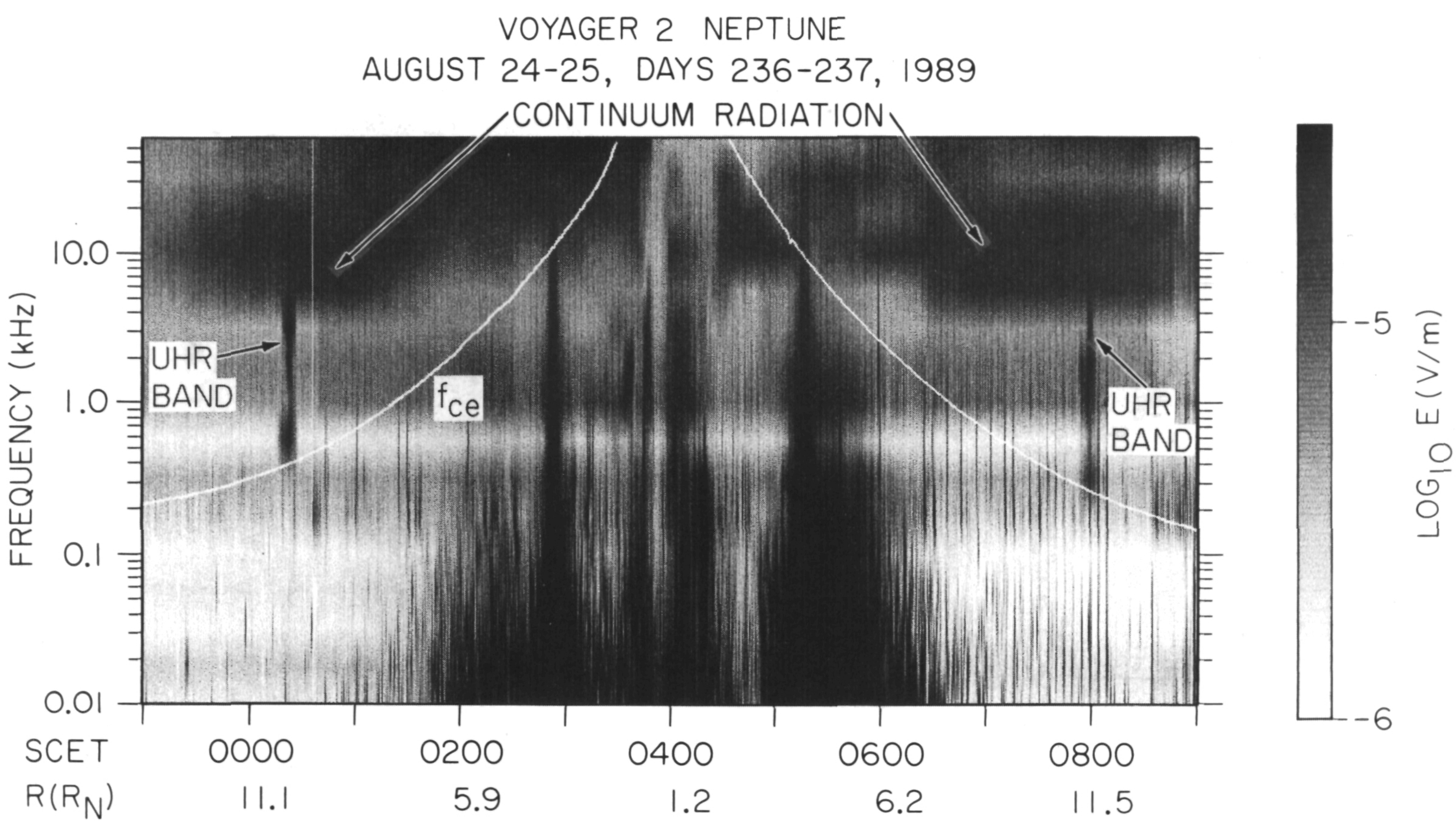


Figure 11

B-G90-98

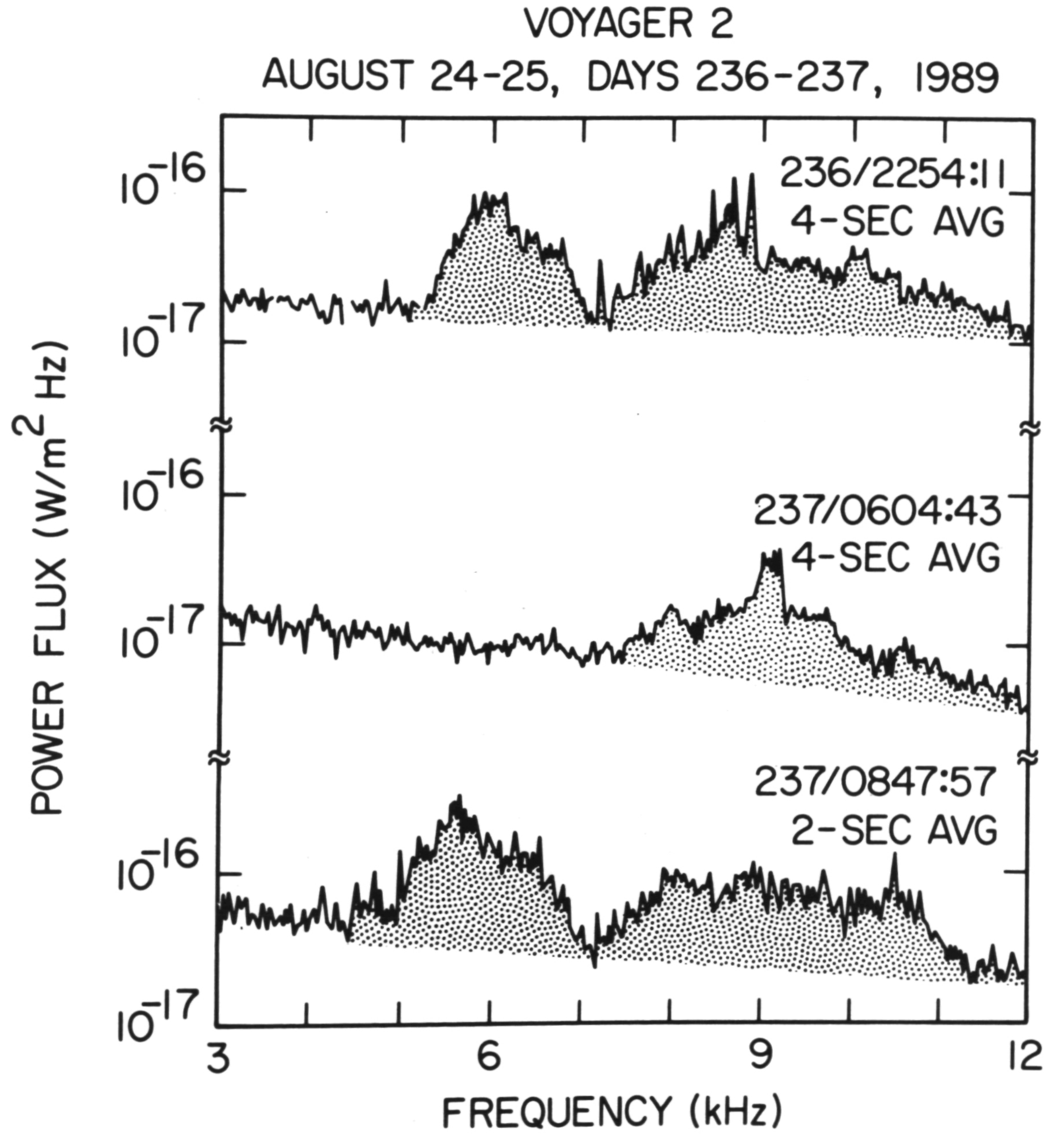


Figure 12

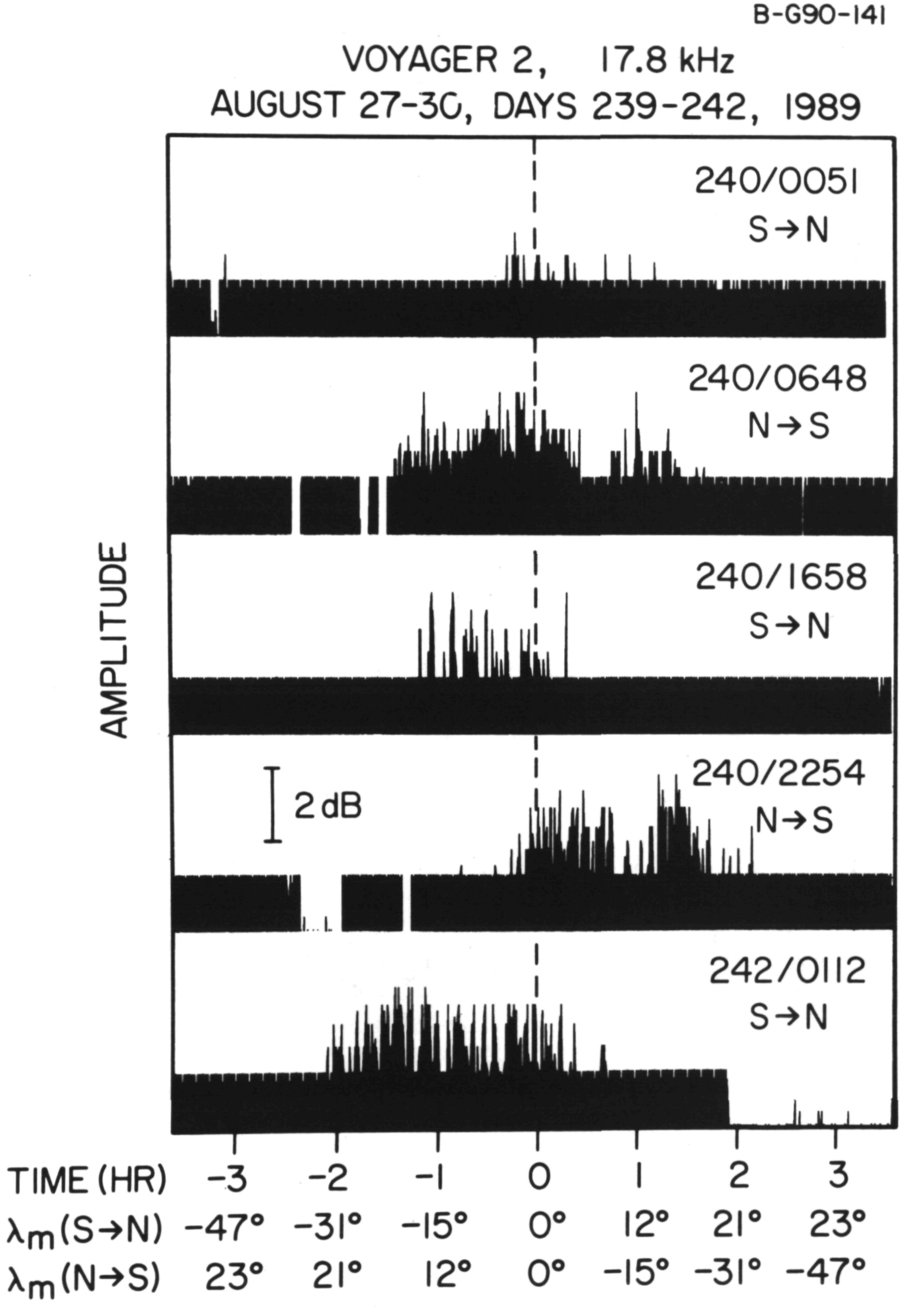

B-G90-141
VOYAGER 2, 17.8 kHz
AUGUST 27-30, DAYS 239-242, 1989
240/0051
S→N
240/0648
N→S
240/1658
S→N
240/2254
N→S
2 dB
242/0112
S→N
AMPLITUDE
TIME (HR) -3 -2 -1 0 1 2 3
λm(S→N) -47° -31° -15° 0° 12° 21° 23°
λm(N→S) 23° 21° 12° 0° -15° -31° -47°

Figure 13