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Plasma Waves in Planetary Magnetospheres

W. S. KURTH AND D. A. GURNETT

Department of Physics and Astronomy, University of Iowa, Iowa City

With the completion of the Voyager 2 encounter with Neptune we have now surveyed the plasma wave spectra of five planetary magnetospheres: Earth, Jupiter, Saturn, Uranus, and Neptune. Here we provide a first general comparison of the various plasma wave modes at each of the planets with the use of a common format for displaying the spectra. The general conclusions are that many of the same types of wave modes are present in each of the magnetospheres, despite great differences in the magnetospheres' sizes, heliocentric distances, energy sources, plasma sources, and magnetic dipole orientations. There are, however, great differences in the relative and absolute intensity of some of the wave modes. Virtually ubiquitous in planetary magnetospheres are electron cyclotron harmonic bands and whistler mode emissions such as hiss and chorus. Ion cyclotron harmonic emissions have been observed where the observed local magnetic field strength was great enough to move these low-frequency waves into the Voyager plasma wave receiver's frequency range. Broadband electrostatic noise has also been observed in the majority of the magnetospheres. In addition to a general survey of the magnetospheric wave modes, an initial assessment of the role of plasma waves in the precipitation of charged particles is presented. Waves seem to have obvious contributions in this aspect for Earth, Jupiter, and Uranus. Weaker wave amplitudes observed at Saturn and Neptune may possibly be due to the specific geometry of the flybys or to quiescent states of the magnetospheres during the encounters.

1. INTRODUCTION

The completion of the Voyager tour of the outer planets means that the initial survey of the plasma wave spectra of five of the known planetary magnetospheres, Earth, Jupiter, Saturn, Uranus, and Neptune, has now been accomplished. The process of comparing the plasma wave observations from these magnetospheres can now begin in earnest. Prior to Voyager it was not clear that similar wave modes would be found in the other plasma regimes of magnetospheres at much greater distances from the Sun and with plasma and energy sources significantly different from those at Earth. In retrospect, such uncertainty seems unwarranted, but we are sure the announcement of terrestriallike plasma waves in all of the magnetospheres of the outer planets would have been met with great excitement and interest in 1977 at the launch of the two Voyager spacecraft. The great benefit of the outer planet observations is that we can now extend models designed to explain the terrestrial plasma waves to different plasma regimes and magnetospheric configurations. By understanding how these changes affect the waves and, conversely, how the differences in the waves affect the magnetospheric plasma, we will better understand the plasma environment of Earth itself. We caution at the outset of this paper, however, that our understanding of the physics of the various magnetospheres, even at Earth, is sufficiently lacking in detail that we can draw only relatively general conclusions at this time. Further, to perform an in-depth comparison, even if the physics were completed, would require a full volume and not a single paper such as this.

Our goal in this paper is to present, for the first time, overviews of the plasma wave spectra from the five planetary magnetospheres (Earth, Jupiter, Saturn, Uranus, and Neptune) in a common form, enabling rather simple comparisons, and to provide a basis for a discussion of the various wave modes present in each case. We will also attempt to summarize the current understanding of the role of plasma waves at each planet in pitch angle scattering and contributions to precipitated fluxes of energetic charged particles.

The basis for our discussions will be Plates 1–5, in which we have selected single-pass overviews of the magnetospheres as viewed by a plasma wave receiver. For Uranus and Neptune our choice was limited to the single Voyager 2 pass at each planet. For Jupiter and Saturn we could choose between the Voyager 1 and 2 passes at each. Because of a minor problem in the Voyager 2 flight data system which adversely affects the upper frequency range of the plasma wave receiver, we have chosen the Voyager 1 encounters. Finally, innumerable Earth-orbiting satellites carrying plasma wave instruments make the choices at Earth quite daunting. Since we will not dwell at length or in detail on the terrestrial observations, we performed no undue selection of terrestrial examples. Instead, we used a satellite with a low-inclination, highly eccentric orbit (ISEE 1) so that we could simulate the general conditions of an outer planet flyby. With the exception of Neptune, these are characterized by near–local noon approaches and predawn departures. Hence we selected an inbound pass originating near local noon and moving inward to a perigee of 2–3 R_E and patched that to data from an outbound pass near dawn. This technique leads to different conditions between the inbound and outbound passes, such as differing magnetic indices and different seasons. Nevertheless, the technique provides a single pass through the terrestrial magnetosphere with which to characterize what we know to be a very complex and dynamic system. We safely speculate that the same complexities exist in the other magnetospheres, but there we are limited to only one or two passes for all of our information. We believe the terrestrial selection technique therefore is fair.

The format of the five plates is similar. In each, the lower panel displays the intensity of waves as a function of frequency (ordinate) and time (abscissa). A false color

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scheme is utilized in which the lowest intensities are represented by blue and the greatest intensities are shown in red. The ISEE data are from a sweep frequency receiver having 128 logarithmically spaced channels. The Voyager observations, while displayed in a similar form, include data from only 16 logarithmically spaced channels. There are differences in the amplitude ranges shown. The Voyager spectrograms emphasize the lower portion of the instrument dynamic range while the ISEE spectrum shows the full instrument dynamic range. Nevertheless, the displays allow the relative importance of various wave modes at a given planet to be assessed, and with some care, comparisons can be made from planet to planet. The general nature of our discussion will not require a great deal of the latter, however.

Superimposed on the frequency-time spectrograms in the plates are profiles of the electron cyclotron frequency $f_{ce} = 28|B|$ where f_{ce} is in units of hertz and B in nanoteslas. In each magnetosphere the cyclotron frequency helps to organize the wave data in a useful manner. In the upper panels of each plate, information on the spacecraft trajectory is given as a function of time. One curve represents the radial distance in planetary radii while the other gives the magnetic latitude as a function of time. L values have been noted across the abscissa at the bottom at distances where the calculation of L provides a reasonable value. For the outer planets these values have been provided by J. E. P. Connerney (personal communication, 1991).

2. EARTH

As explained above, the two passes selected for inclusion in Plate 1 represent an inbound trajectory originating near local noon and an outbound pass ending in the predawn sector. ISEE 1 was chosen for its relatively low inclination, highly eccentric orbit. No great pains were expended to select passes which included a particular mix of wave modes. The result is a "single flyby" set of observations of the terrestrial plasma wave spectrum. The inbound pass begins just outside the bow shock and shows the intense, low-frequency turbulence associated with the terrestrial magnetosheath and the abrupt change in the spectrum at the crossing of the dayside magnetopause. Because the sensitivity of the Voyager plasma wave receiver to the magnetosheath turbulence in the outer planet magnetospheres is not very good [*Moses et al.*, 1990], we do not show this region for the other planets and hence will not discuss the terrestrial magnetosheath further. Moses et al. also provide a very good initial comparison of plasma waves associated with the bow shocks of Earth and the outer planets; hence we will not duplicate that effort herein.

As ISEE approaches Earth, the magnetosphere is characterized by a well-developed set of electron cyclotron harmonic (ECH) bands, sometimes referred to as Bernstein emissions or $(n + 1/2)f_{ce}$ bands. These can be seen from just above the electron cyclotron frequency up to the lower-frequency cutoff of the continuum radiation, which occurs at the local electron plasma frequency, f_{pe}. The $(n + 1/2)f_{ce}$ band containing $f_{\mathrm{uh}} = (f_{ce}^2 + f_{pe}^2)^{1/2}$, sometimes referred to as the UHR (upper hybrid resonance) band, is often intense as seen at the lower edge of the continuum radiation. The ECH emissions normally reach maximum intensity near the plasmapause within a few degrees of the magnetic equator [*Gough et al.*, 1979]. During this pass the magnetic equator is crossed at about 2350 UT on November 12 when ISEE 1 is near 8 R_E. One can see a brief intensification of the UHR band near 10 kHz at this time. Otherwise, the ECH bands are relatively weak throughout this pass. At their peak the terrestrial ECH bands can reach or exceed 1 mV/m in intensity. It was long thought that these electrostatic emissions were responsible for the diffuse aurora at Earth, on the basis of reports [*Kennel et al.*, 1970] of typical intensities of 1–10 mV/m. However, detailed statistical studies [*Belmont et al.*, 1983; *Roeder and Koons*, 1989] have shown that the intensities exceed 1 mV/m only a few percent of the time; hence, only occasionally can these waves put few-keV electrons on strong diffusion. Currently, it is unclear how the diffuse aurora is generated since the ECH bands can make only a relatively small contribution to the pitch angle diffusion required.

Below the f_{ce} contour are intense chorus emissions covering a large portion of the dayside outer magnetosphere. At still lower frequencies a band of whistler mode hiss can be seen in the outer magnetosphere. Inside the plasmasphere, whistler mode hiss can also be seen, covering a much broader range in frequency. This region is defined by the abrupt increase in frequency of the UHR band at about 0150 UT. The hiss is commonly referred to as plasmaspheric hiss.

The whistler mode emissions have been thought to be important in the pitch angle diffusion of energetic electrons since the development of the theory of whistler mode wave-particle interactions [*Kennel and Petschek*, 1966]. In particular, considerable effort has gone into understanding the role of the plasmaspheric hiss as a limit on the trapped radiation population [*Lyons et al.*, 1972; *Lyons and Thorne*, 1973]. More recently, questions have arisen as to the generation of the hiss itself. For example, *Huang et al.* [1983] and *Church and Thorne* [1983] have performed detailed ray-tracing studies to confirm that the trapped radiation in the plasmasphere, particularly near the magnetic equator just inside the plasmapause, can generate the hiss, as previously thought. Both efforts concluded that the plasmasphere can support the observed levels of plasmaspheric hiss; however, neither group can account for the observed levels of hiss by simply amplifying the thermal fluctuations; some embryonic source is required. *Solomon et al.* [1988] propose a solution to the problem. They use differential electron fluxes observed by GEOS 1 during quiet times which are considerably larger than those used in the model of, for example, *Church and Thorne* [1983]. Solomon et al. claim growth rates of >100 dB; hence the observed hiss intensities can be explained as the simple amplification of hiss from background thermal fluctuations. It is not clear that this conclusion holds under disturbed conditions.

The outbound pass shows distinctly different characteristics in the wave spectrum. Here only the $3f_{ce}/2$ band of the ECH emissions is prominent until after about 1300 UT when the $5f_{ce}/2$ band becomes visible. (The magnetometer data are missing for an extended period during this pass, but the lower edge of the $3f_{ce}/2$ band provides a very good guide for the behavior of the cyclotron frequency over most of this interval.) Auroral kilometric radiation is prominent at the highest frequencies later in this outbound pass; the extensions of these emissions down to 70 kHz are, in this case, receiver distortion effects. Continuum radiation can be seen in this pass, but not as easily as in the dayside pass. This

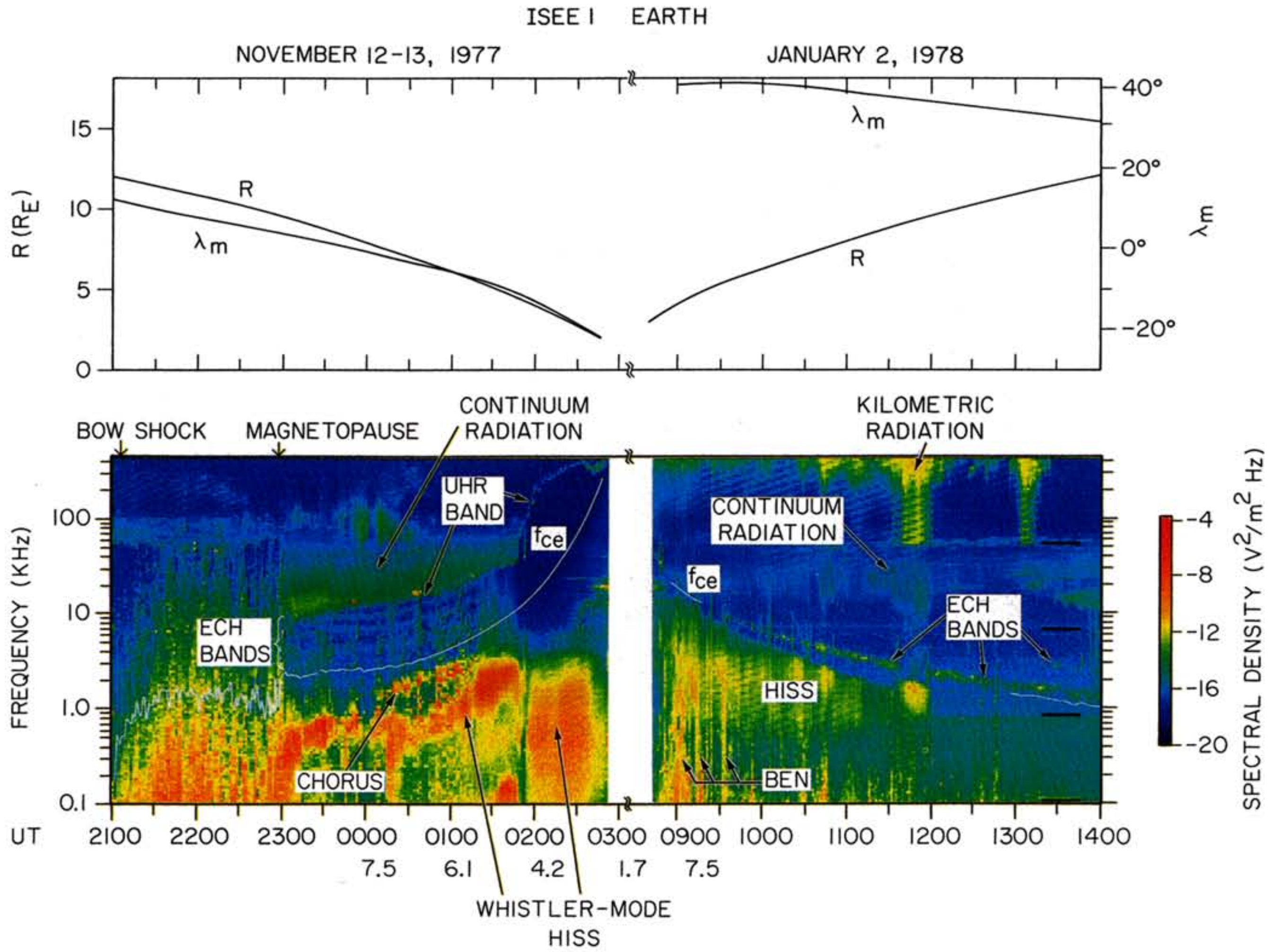

Plate 1. (Bottom) Frequency-time spectrogram made from two ISEE 1 passes at Earth in order to simulate a single "flyby" trajectory. Superimposed on the spectrogram is a line showing the variation of the electron cyclotron frequency f_{ce}. (Top) Variation in radial distance and magnetic latitude as a function of time. The spectrogram is designed to show the nature of the plasma wave spectrum that an interplanetary probe might observe in order to allow comparisons with the outer planet magnetospheric plasma wave observations shown in Plates 2–5. Some of the more prominent features are the electron cyclotron harmonic (ECH) bands, plasmaspheric hiss, whistler mode chorus, and upper hybrid resonance (UHR) band, which shows the variation of the plasma frequency with time, particularly in the inbound portion of the spectrogram. The abrupt increase in frequency of the UHR band defines the plasmapause.

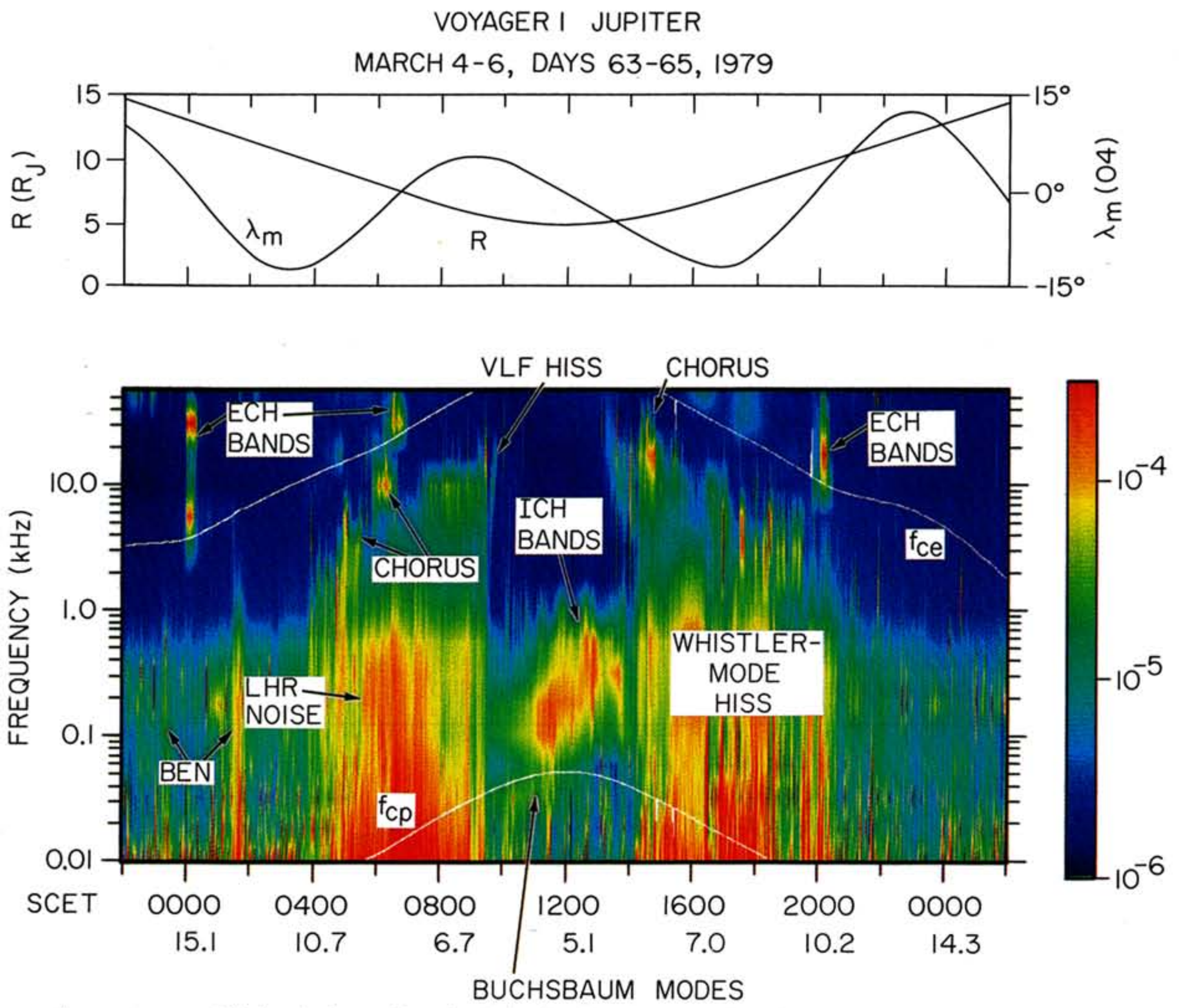

Plate 2. Frequency-time spectrogram and display of trajectory information designed to allow direct comparisons of Jupiter's plasma wave spectrum with similar sets of observations from the other planetary magnetospheres. These data are taken primarily from the region in and near the Io plasma torus, and the abrupt changes in the spectrum at about 0930 and 1415 SCET represent the passage of Voyager 1 from the warm torus into the cold torus and out again. There are numerous plasma wave modes in this pass that could be important in pitch angle scattering electrons or ions. Chorus and hiss are obvious candidates for energetic electron scattering. The lower-frequency portion of the hiss spectrum is believed to be generated as ion cyclotron waves at higher latitudes which then mode convert to the whistler mode. The ECH bands appear briefly owing to their strong confinement to the magnetic equator.

intensity difference is most likely a temporal variation since the dawnside plasmapause is thought to be the primary source location for the continuum radiation at the Earth.

The whistler mode hiss is less intense on the outbound pass, also, and is masked somewhat by broadband bursty emissions which are likely examples of broadband electrostatic noise (BEN). As is often the case, the hiss often occurs beyond the plasmapause; hence it cannot technically be called plasmaspheric hiss. *Thorne et al.* [1973] refer to this as exohiss. The BEN at Earth is usually found at the magnetopause (notice the broadband bursts right at the inbound magnetopause crossing in Plate 1) and along the plasma sheet boundary layer [*Gurnett et al.*, 1976; *Gurnett and Frank*, 1977]. While the mapping of these boundaries to low altitudes is not well understood, there is reason to believe that such field lines map to the auroral oval, perhaps to discrete auroral arcs. Theoretical and observational work over the past several years has indicated that field-aligned ion flows are probably important in the production of BEN. Ion beams found in the boundary layer are thought to be related to ion acceleration in the tail (earthward streaming beams), perhaps via a reconnection process, to magnetically reflected ions (tailward streaming beams), and to cold ionospheric ions of the order of 100 eV representing the ion outflow from the auroral ionosphere [*Schriver and Ashour-Abdalla*, 1990]. *Gary and Omidi* [1987] have shown a correlation between ion beams and BEN and have shown that electron-ion and ion-ion acoustic instabilities along with the lower hybrid drift instability and current-driven ion cyclotron waves could all be at least partly responsible for the waves which can extend upward to the electron plasma frequency. The BEN evidently serves to heat the ionospheric ions as a source of the hot central plasma sheet and to cause isotropic auroral ion precipitation on the nightside [*Dusenbery and Lyons*, 1989].

3. JUPITER

Without a doubt, Jupiter provides the largest and, in many ways, the most complex magnetosphere in the solar system. Its plasma wave spectrum is no less complex. The magnetosphere is driven by the rotational energy of the planet, coupled through an intense magnetic field, which dominates the solar wind energy input. The moon Io with its volcanic activity provides perhaps the most prodigious plasma source in the solar system short of the Sun. Each of these is a factor in generating an intense, broadband, and multifaceted plasma wave spectrum as shown in Plate 2. The first observations of this spectrum were summarized by *Scarf et al.* [1979*b*]. Evidence of the Io torus dominates the inner magnetosphere traversed by Voyager 1 between about 0400 and 2000 spacecraft event time (SCET). Plasma densities near 2000 cm^{-3} extend the local plasma frequency well above the 56-kHz extent of the plasma wave receiver on Voyager and into the planetary radio receiver's range [*Birmingham et al.*, 1981]. The warm, outer portion of the torus is characterized by whistler mode chorus and probably broadband whistler mode hiss. (It should be noted here, though, that Voyager does not measure the magnetic component of the waves and hence these waves could be an electrostatic mode.) The sharp transition to the narrower-bandwidth, lower-frequency noise near closest approach occurs at the boundary between the warm and cold tori. *Gurnett et al.* [1979*a*] reported the existence of VLF hiss at this boundary, analogous to auroral hiss at the Earth, possibly indicative of field-aligned electron beams on the boundary. Inside the cold, inner torus, two distinct emissions have been identified. *Barbosa and Kurth* [1990] have identified electrostatic ion cyclotron harmonic (ICH) emissions just above the proton cyclotron frequency f_{cp} extending up to the lower hybrid resonance frequency. These emissions seem to be confined to small magnetic latitudes and are not displaced in the direction of the centrifugal equator. The emissions below f_{cp} lie closer to the centrifugal equator and have been identified by *Barbosa* [1982] as ion-ion hybrid or Buchsbaum modes associated with the heavier ions in the plasma torus.

Brief encounters with electron cyclotron harmonic (ECH) emissions are found at larger radial distances at frequencies above f_{ce} [*Kurth et al.*, 1980; *Barbosa and Kurth*, 1980]. The occurrences of these waves are brief because of their strong confinement to very small magnetic latitudes, as can be seen by referring to λ_m in the upper panel of Plate 2. *Birmingham et al.* [1981] and *Gurnett et al.* [1981*c*] used the highest frequency band in the series of ECH bands as a measure of the density in the torus. This highest band is known as the upper hybrid resonance band and occurs near the upper hybrid resonance frequency $f_{\text{uh}} = (f_{pe}^2 + f_{ce}^2)^{1/2}$. Knowing the magnetic field strength and hence f_{ce}, one can calculate the plasma frequency using $f_{pe} = 8980\ (n_e^{1/2})$, where f_{pe} is measured in hertz and n_e is the electron density in cm^{-3}. An example of an upper hybrid band can be found in Plate 2 at about 0000 SCET on March 5 near 30 kHz.

Broadband electrostatic noise (BEN) can be seen near the outer edge of the torus, for example near 0140 SCET [*Barbosa et al.*, 1981]. This emission, like its terrestrial counterpart, is thought to be associated with field-aligned ion flows and resulting ion beam instabilities. Barbosa et al. suggest that the BEN could imply local acceleration regions in the middle magnetosphere which are linked to the auroral regions.

Some of the most dominant and perhaps important waves in the inner Jovian magnetosphere are the whistler mode hiss and chorus, particularly in the warm Io plasma torus. The hiss accounts for much of the broadband emission below a few tenths of f_{ce}. Chorus appears in Plate 2 as prominent emissions just below the f_{ce} contour, especially near 0600 and 1500 SCET [*Inan et al.*, 1983; *Coroniti et al.*, 1984]. Whistlers were also discovered in this region [*Gurnett et al.*, 1979*b*], providing some of the evidence of atmospheric lightning at Jupiter. *Barbosa et al.* [1985] have reported noise at about the lower hybrid resonance frequency (LHR noise) in the warm Io torus which is thought to be responsible for a small population of keV electrons. Several studies concentrated on the whistler mode hiss and chorus in order to evaluate the magnitude of pitch angle scattering which might be caused by these waves, by applying the classical Kennel-Petschek [*Kennel and Petschek*, 1966] theory [*Thorne and Tsurutani*, 1979; *Scarf et al.*, 1979*a*; *Coroniti et al.*, 1980]. An example of this application can be seen in Figure 1, from *Coroniti et al.* [1980].

The top panel in Figure 1 represents the electric field spectrum observed by Voyager, including both hiss and chorus. Following the work of *Thorne and Tsurutani* [1979], *Scarf et al.* [1979*a*], and *Coroniti et al.* [1980], and using the magnetic field strength and electron density obtained from

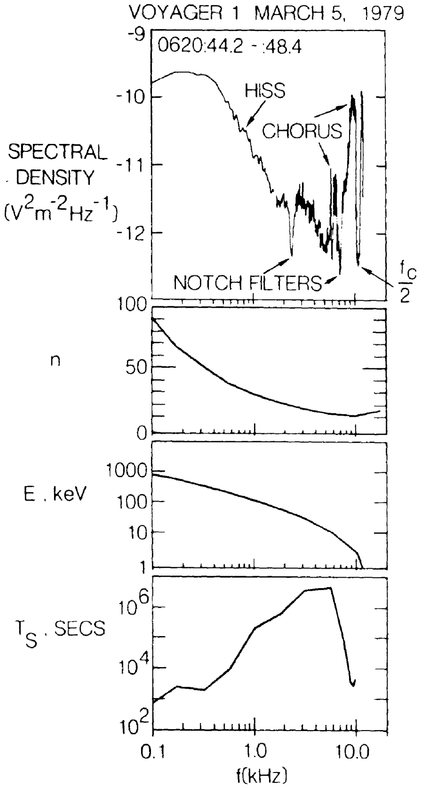

Fig. 1. Illustration of the analysis of pitch angle scattering times for electrons of various energies due to whistler mode waves taken from *Coroniti et al.* [1980]. The spectrum in the top panel is from a time shown in Plate 2 during an intense chorus event near 10 kHz. As described in the text, the electric field spectrum is used to deduce the magnetic field spectrum based on the index of refraction of the local plasma, shown in the second panel. The magnetic field can then be used to calculate the resonant energy of electrons as a function of frequency, shown in the third panel. Finally, the inverse of the pitch angle diffusion coefficient can be used to derive the scattering times in the bottom panel.

the Voyager magnetometer and the planetary radio astronomy investigation, one can calculate the index of refraction $n(f)$ with some assumptions about the composition of the plasma. Then, using the relation $B(f) = n(f)E(f)/c$, where c is the speed of light, one can calculate the wave magnetic field spectrum. The wave magnetic field, then, can be used to calculate the energy of electrons resonant with the waves by

$$E_{\text{res}} = \frac{B^2}{8\pi n_e}\frac{(1-\nu)^3}{\nu} \tag{1}$$

where ν is the wave frequency normalized to f_{ce}. E_{res} is shown in the third panel from the top in Figure 1. Finally, the scattering times T_s can be calculated from the inverse of the pitch angle diffusion coefficient $D_{\alpha\alpha}$.

We are able to conclude, as did *Thorne* [1981, 1983], that the whistler mode hiss can deposit of the order of 3 mW/m^2 into the atmosphere as >100-keV electrons. Integrated over the auroral field lines, this would account for some 10^{13} W in precipitated energy. Thorne estimates, however, that the observed UV auroral intensity requires about 10^{14} W of electron precipitation. While the hiss certainly contributes a significant amount of energy, it is not the primary driver of the Jovian aurora.

Coroniti et al. [1980] carried out similar calculations for the whistler mode chorus. These waves resonate with lower-energy electrons, of a few keV in energy, and can put them on strong diffusion. However, as can be seen in Plate 2, chorus is observed only in localized regions of the torus, and the amplitudes fluctuate significantly over time. *Thorne* [1983] estimates that the chorus can account for only about 10^{12} W of electron precipitation. Again, this is not an insignificant quantity, but even when added to the contribution of the hiss it cannot account for the aurora.

It is important to realize that the early work of *Thorne and Tsurutani* [1979], *Scarf et al.* [1979*a*], and *Coroniti et al.* [1980] assumed the entire plasma wave spectrum below f_{ce} was due to whistler mode waves and that these were attempts to explain the UV aurora. In addition to the fact that the pitch angle diffusion based on the Kennel-Petschek theory does not supply sufficient energy to drive the aurora, it also implies that an unreasonably large radial diffusion coefficient is required to replenish the energetic electrons. The large source of energetic electrons is a result of the very short lifetimes (of the order of hours) which come from the diffusion calculation, which can be seen in the bottom panel of Figure 1. These problems are mitigated, in part, with the identification of numerous other wave modes which have been mentioned here. The very short lifetimes from the whistler mode calculations are associated with a broad region of intense wave activity, generally below a few hundred hertz. It is now apparent that a good portion of this spectrum can be accounted for by electrostatic modes such as the lower hybrid resonance noise reported by *Barbosa et al.* [1985], ion acoustic waves [*Scarf et al.*, 1981], electrostatic ion cyclotron harmonic emissions [*Barbosa and Kurth*, 1990], and Buchsbaum modes [*Barbosa*, 1982]. In addition to explaining some of the difficulties in understanding the application of the Kennel-Petschek theory to the Io torus, these additional modes play significant roles in the energy budget of the torus. For example, *Barbosa et al.* [1985] have shown how the lower hybrid mode can maintain a population of keV electrons in the torus, which in turn can lead to a small but significant anomalous ionization effect.

The other obvious wave mode to look at as a possible precipitation driver for the Jovian aurora is the ECH bands, which for a long time were thought to be responsible for the diffuse aurora at Earth. The intensity of these waves at Jupiter is typically 100 μV/m with occasional bursts to 1 mV/m. *Thorne* [1983] suggests that the larger amplitudes could drive strong diffusion, but *Sittler and Strobel* [1987] state that the electron data are not consistent with strong diffusion. The 10^{12} W estimated by Thorne as the total electron energy precipitated by these waves in the 1- to 10-keV range, in any case, is still not sufficient to account for the aurora.

Even though significant fluxes of precipitating electrons can be accounted for through pitch angle scattering by whistler mode hiss and chorus and by electron cyclotron harmonics, there is still insufficient energy to account for the Jovian UV aurora. Hence, with the *Armstrong et al.* [1981] report of significant decreases in the phase space densities of energetic ions through the warm torus, attention turned to the investigation of energetic ions as a source of the aurora. *Thorne and Moses* [1983] and *Gurnett and Goertz* [1983] both recognized that the whistler modes detected by Voyager near the equatorial region of the torus would couple with the ion cyclotron mode at high latitudes because of the mix of heavier ions in the plasma. For a time it was unclear whether these waves were generated as whistler modes at low latitudes and propagated to higher latitudes, converting into the ion cyclotron modes, or vice versa. *Thorne and Scarf* [1984] showed brief bursts of whistler mode waves with elevated intensities below f_{cp} which they argued were indicative of the amplitudes of the ion cyclotron waves, and hence they argued that the waves were generated in the ion cyclotron mode and propagated toward the equator. Using this model, they suggested that ions with energies of >500 keV would be strongly scattered and subsequently precipitated by the ion cyclotron waves; the whistler mode scattering at lower latitudes would be a subsequent and smaller effect.

The ions precipitated by the ion cyclotron waves can account for about 2×10^{13} W of precipitated energy, still short of the 10^{14}-W auroral requirement [*Thorne*, 1983]. Further, these very energetic ions (>500 keV) would deposit their energy too deep in the atmosphere for the auroral emissions to escape without significant absorption. A possible solution to this dilemma is to extrapolate the precipitated ion spectrum down to 100 keV. These lower-energy ions would make up the remaining energy requirements and would deposit their energy higher in the atmosphere.

Currently, the question of the auroral precipitation driver has not been solved. Some believe that using the extrapolated ion spectrum is an acceptable solution. Others, however, disagree. For example, *Clarke* [1991] believes that the UV emission must be due to electron precipitation, and *Barbosa* [1990] suggests that Einstein X ray observations are consistent with emissions from secondary electrons from an energetic electron precipitation beam, even though the source of the primary electrons, proposed by Barbosa as a parallel electric field, has not been observed.

4. SATURN

The observations of the plasma wave spectrum observed at Saturn by Voyager 1 were first reported by *Gurnett et al.* [1981*a*] and are summarized in Plate 3. The spectrum is well organized by the contour of f_{ce} which separates whistler modes below the contour from electrostatic electron cyclotron harmonic emissions above, especially after closest approach. The electrostatic emissions reported by *Gurnett et al.* [1981*a*], *Scarf et al.* [1982], and *Kurth et al.* [1983] are found primarily in the lowest harmonic band, the so-called $3f_{ce}/2$ band. Some emissions are seen at higher frequencies and likely correspond to upper hybrid resonance emissions, such as near 0500 SCET at about 30 kHz. Virtually all of the ECH emissions are limited to radial distances of $<8\ R_S$. They are most intense near the equatorial plane, which at Saturn is coincident with the magnetic equatorial plane because of the alignment of the magnetic dipole with the rotational axis of the planet. Hence weak magnetic confinement is evident in the ECH band at Saturn. *Kurth et al.* [1983] showed that these waves occur very close to the lower bound of the cyclotron harmonic band and that such behavior can be a result of the speed of the resonant electrons being only a few times the speed of the thermal electrons. The typical intensities of the bands at Saturn are of the order of 30 μV/m, less intense than those at Earth and Jupiter. The low intensities of the ECH bands suggest that they cannot cause strong diffusion of electrons. However, *Kurth et al.* [1983] showed evidence of fluctuations in the intensities of 20- to 30-keV electrons observed by the low-energy charged particle detector while the electrostatic waves were being observed. These observations may indicate that the 20- to 30-keV electrons are on the high-energy tail of the resonant electron spectrum and that there are indeed some wave-particle interactions involved.

Some very interesting and unusual emissions were observed by Voyager 1 prior to closest approach and below the f_{ce} profile. In Plate 3 these emissions are labeled narrowband radio emissions but appear as a diffuse spectrum of radio emissions. That they occur below f_{ce} indicates that the waves are propagating in the ordinary mode, above f_{pe}; this mode can propagate below the cyclotron frequency if it is greater than the plasma frequency. The wideband data show the true character of these emissions, particularly their narrowband nature and the multiplicity of bands [*Gurnett et al.*, 1981*b*]. Gurnett et al. conclude that these narrowband emissions are analogous to the narrowband structures comprising the escaping continuum radiation at Earth.

At even lower frequencies the usual whistler mode hiss and chorus emissions can be found. These occur in a fairly well-defined band inbound in Plate 3 and a less well-defined band outbound. As Voyager 1 approached the equator, the emissions spread downward in frequency to the lowest frequency measured by the plasma wave instrument. The significance of this broadband emission was not generally recognized during the first Voyager encounter, but after the second encounter when a very distinct signature of dust impacting the spacecraft was detected near the ring plane [*Gurnett et al.*, 1983], one must suspect that at least part of the noise spectrum observed centered near 0430 SCET could be due to dust impacts [*Kurth*, 1991].

The whistler mode hiss and chorus found at Saturn are obvious suspects for pitch angle scattering of energetic electrons at Saturn. While these waves are the dominant low-frequency waves below f_{ce}, they are much less intense than at Jupiter. *Scarf et al.* [1984] examined these waves as potential pitch angle scatterers and determined that the amplitudes were simply too small to be important. This conclusion is consistent with the fact that the flux of electrons is 2 orders of magnitude below the stable trapping limit. However, Saturn's magnetosphere was in a very quiescent state during both encounters and was likely immersed in the Jovian tail during the second encounter [*Desch*, 1983]. Hence one cannot take the observed whistler mode emission spectrum as indicative of that which might be responsible for significant pitch angle scattering under more active conditions. Also, since the electromagnetic character of these waves has not been confirmed and since the electron flux is so low, one must leave open the possibility that these waves are not propagating in the whistler mode. Cassini will give us an opportunity to study the role of these waves under a much wider variety of conditions.

5. URANUS

The plasma wave spectrum at Uranus, perhaps more than at any other planet, is dominated by whistler mode emissions

[*Gurnett et al.*, 1986]. The entire closest approach to Uranus is characterized by the band of emissions below about $f_{ce}/2$. The band is very intense, especially on the outbound leg of the encounter, and could be even more intense at the magnetic equator; Voyager 2 only came within about 15° of the magnetic equator on the outbound part of the trajectory. The band of whistler mode emissions shown in Plate 4 is the most intense of any whistler mode emissions detected by either Voyager at any of the outer planets. There is considerable asymmetry in intensity of the band between the inbound and outbound portions of the trajectory, and at least part of this is due to differences in the magnetic latitude, which was much higher on the inbound leg. However, there is evidence of substorm activity at Uranus [*Mauk et al.*, 1987; *Sittler et al.*, 1987], and this could also be a factor in the asymmetry.

Coroniti et al. [1987] have carried out an in-depth study of the very intense whistler mode emissions on the nightside, outbound pass of Uranus and have concluded that the waves are strong enough to put electrons in the range of 3–40 keV on strong diffusion. These authors constructed a model of the plasma distribution at Uranus based on the available plasma and energetic charged particle data as well as information on the density found in the plasma wave data. Using this model and iteratively varying the anisotropies, Coroniti et al. compared maximum wave growth rates as a function of frequency to the observed wave spectrum. The model was then used to compute scattering lifetimes T_s which were compared to the minimum precipitation lifetimes $T_{\min}$ as a function of energy. For electrons with $T_s < T_{\min}$, strong diffusion is inferred. The energy range for which this inequality is met is 3–40 keV; hence strong diffusion is likely. Further, by integrating the calculated scattering rate over the auroral region implied by *Broadfoot et al.* [1986], the total energy precipitated is comparable to that required to drive the UV aurora. Hence Coroniti et al. propose that the strong whistler mode emissions at Uranus can account for the aurora.

The problem with the above conclusion is that the radial diffusion coefficient derived for the energetic electrons [*Cheng et al.*, 1987] is insufficient to replenish the electrons if they are truly being scattered at the strong diffusion limit. *Coroniti et al.* [1987] point out this dilemma but offer no concrete solution. One possible solution suggested is the evidence for substorm activity at Uranus mentioned above, but there is a lack of longitudinal asymmetries in the phase space densities which would be expected for strong injection events associated with the strong whistler mode waves. Coroniti et al. further suggest that some form of energy diffusion could provide a source of electrons by energizing lower-energy electrons before pitch angle scattering them, but significant work on this theory would be required before it could be considered viable.

An interesting phenomenological aspect to the whistler mode band at Uranus is the gap in the occurrence of the emissions at around 1930 SCET, near the time when Voyager 2 was closest to the moon Miranda. Within this gap there are a number of very intense, impulsive waves, perhaps electrostatic in nature. *Kurth et al.* [1986] suggest that the bursty electrostatic waves in this region of the magnetosphere may be related in some way to the generation of very bursty radio emissions near 5 kHz observed primarily on the nightside, outbound pass of the spacecraft. At frequencies below the whistler mode band on the outbound leg there is an intensification of plasma wave emissions. The frequency of this band is close to the lower hybrid resonance frequency; however, no detailed analysis of these waves has been completed.

Other emissions observed during the encounter are largely of the electron cyclotron harmonic variety [*Kurth et al.*, 1987]. The most distinct occurrence of these electrostatic emissions occurs near 1315 SCET when the spacecraft crosses the magnetic equator. In view of the approximately 60° tilt of the dipole at Uranus, this event well illustrates the affinity of these emissions for the magnetic equatorial plane. In fact, there is a slight disagreement between the centroid of this wave event and the offset tilted dipole minimum-B surface, which suggests (or confirms) the relative inaccuracy of this particular field model at the 11- to 12-R_U distance of this event. The 1315 SCET event shows a rather broadband extent of the ECH emissions, suggesting that there are several harmonic bands ranging from the $3f_{ce}/2$ band to the upper hybrid resonance band, in this case probably at $7f_{ce}/2$. Other emissions of the ECH variety can be seen above the cyclotron frequency contour in Plate 4. *Kurth et al.* [1987] discuss these in detail and use them as a key to a profile of the electron plasma frequency over a significant portion of the Voyager 2 trajectory.

The intensity of the ECH waves at Uranus is only of the order of 10 μV/m; hence the waves are well below an intensity required to strongly pitch angle scatter energetic electrons. On the other hand, ECH waves are known to be most intense at the magnetic equator, and the only crossing of the magnetic equator at Uranus was at about 11.5 R_U. In this region of the magnetosphere the flux of electrons is very low, and therefore the flux of resonant electrons is also low. One would expect larger fluxes inward of this particular crossing, and correspondingly larger amplitude ECH waves. Therefore it is entirely possible that electron cyclotron harmonic waves could play an important role in the precipitation of energetic electrons at Uranus, and Voyager 2 would not have seen strong evidence for the intense waves required.

Kurth et al. [1989] discuss the weak, low-frequency waves labeled BEN on the outbound portion of Plate 4. While these waves are also consistent with a whistler mode interpretation, Kurth et al. suggest that they are analogous to the broadband electrostatic noise which characterizes the plasma sheet boundary layer at Earth. The Uranian events occur in regions of the magnetotail containing field-aligned ion flows and are not centered in the plasma sheet, which is suggestive of a boundary layer location.

6. NEPTUNE

The Voyager 2 overview of the plasma wave spectrum at Neptune in Plate 5 is dominated by effects other than plasma wave phenomena [*Gurnett et al.*, 1989]. The two bright features centered near 0300 and 0515 SCET are the result of hundreds of micron-sized dust impacts occurring each second near the two ring (equatorial) plane crossings [*Gurnett et al.*, this issue]. The diffuse emissions seen above a few kilohertz before and after closest approach are actually radio emissions, similar to escaping continuum radiation at Earth [*Kurth et al.*, 1990]. In fact, the most prominent plasma wave phenomena in the spectrum show in Plate 5 are electron

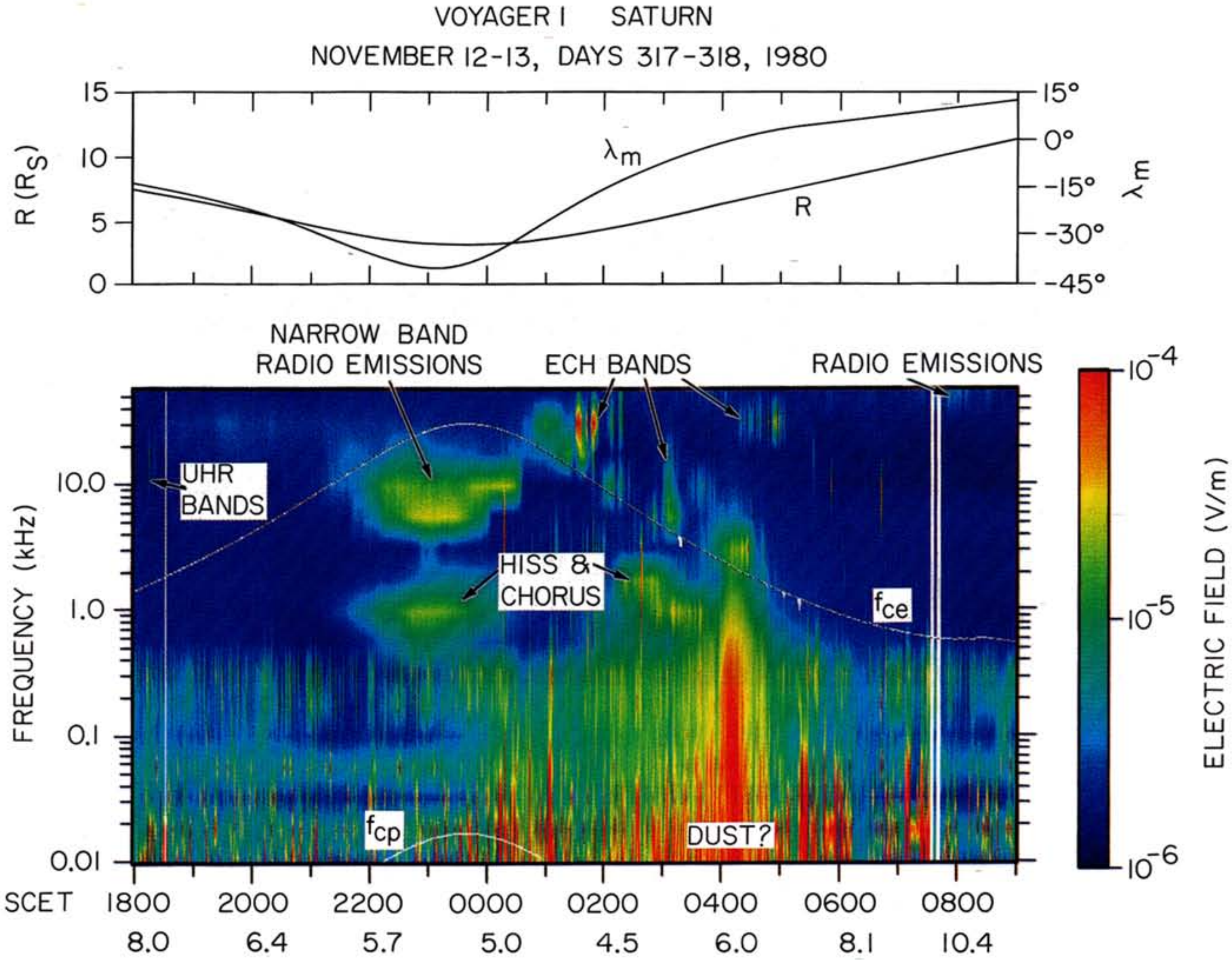

Plate 3. Display similar to Plate 2 but for the Voyager 1 encounter with Saturn. The wave spectrum at Saturn is considerably weaker and more restricted in scope than that at Jupiter. The importance of the magnetic equator for emissions such as electron cyclotron harmonic bands is less than at Jupiter. The broadband burst of noise at the equator near 0415 SCET is possibly due to dust impacting the spacecraft.

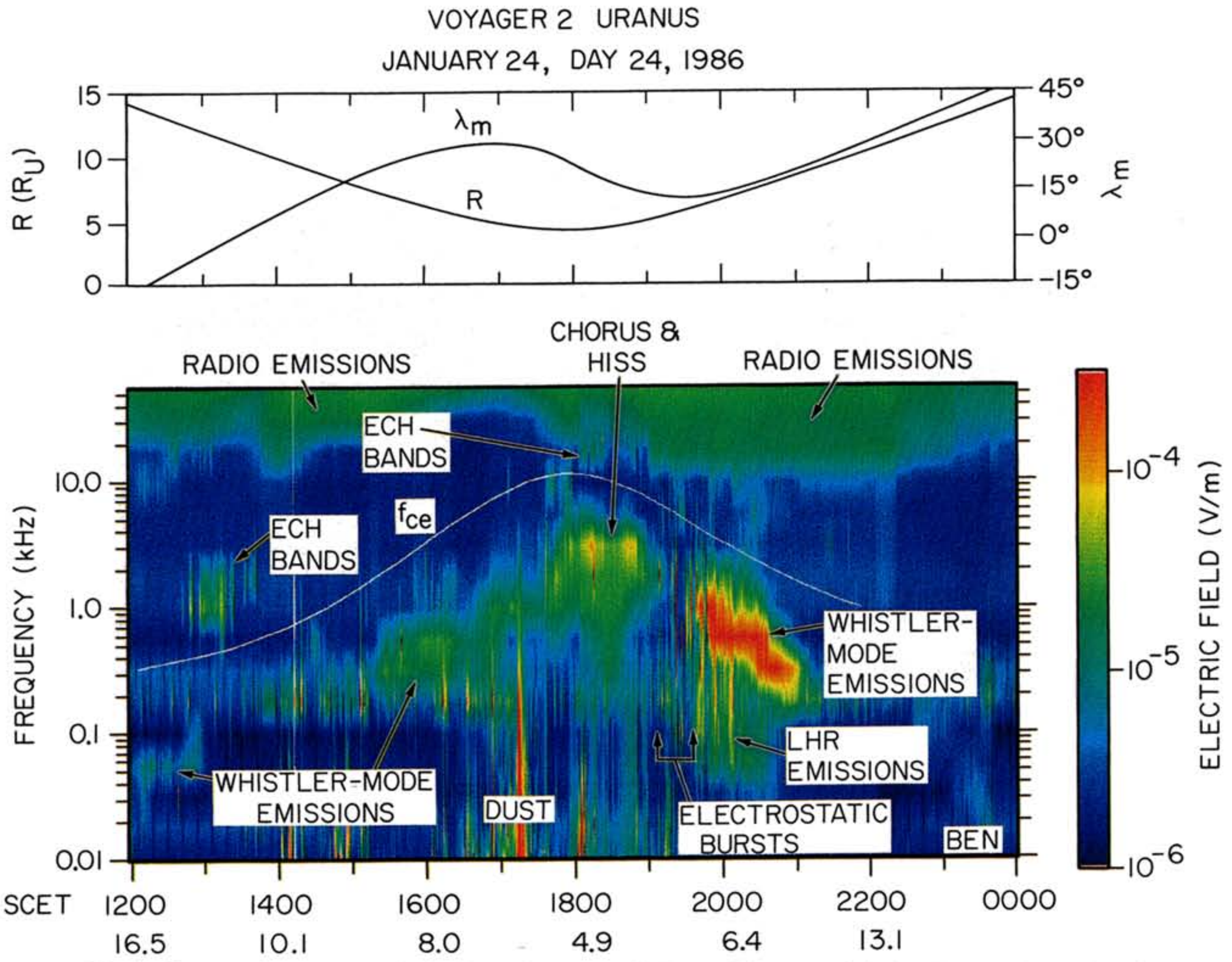

Plate 4. Frequency-time spectrogram for the Voyager 2 encounter with Uranus. This spectrum is dominated by a very intense band of whistler mode emissions in the inner magnetosphere, including some of the most intense emissions of this kind seen by the Voyager spacecraft at any of the outer planets. The ECH bands observed are quite weak, but more intense examples might occur closer to the planet at the magnetic equator, a region not traversed by Voyager 2. At Uranus the whistler mode emissions are clearly intense enough to cause strong pitch angle diffusion; however, radial diffusion coefficients appear to be too small to replenish the 3- to 40-keV electrons which would be deposited into the atmosphere by these waves. There is no obvious resolution to this dilemma at this time.

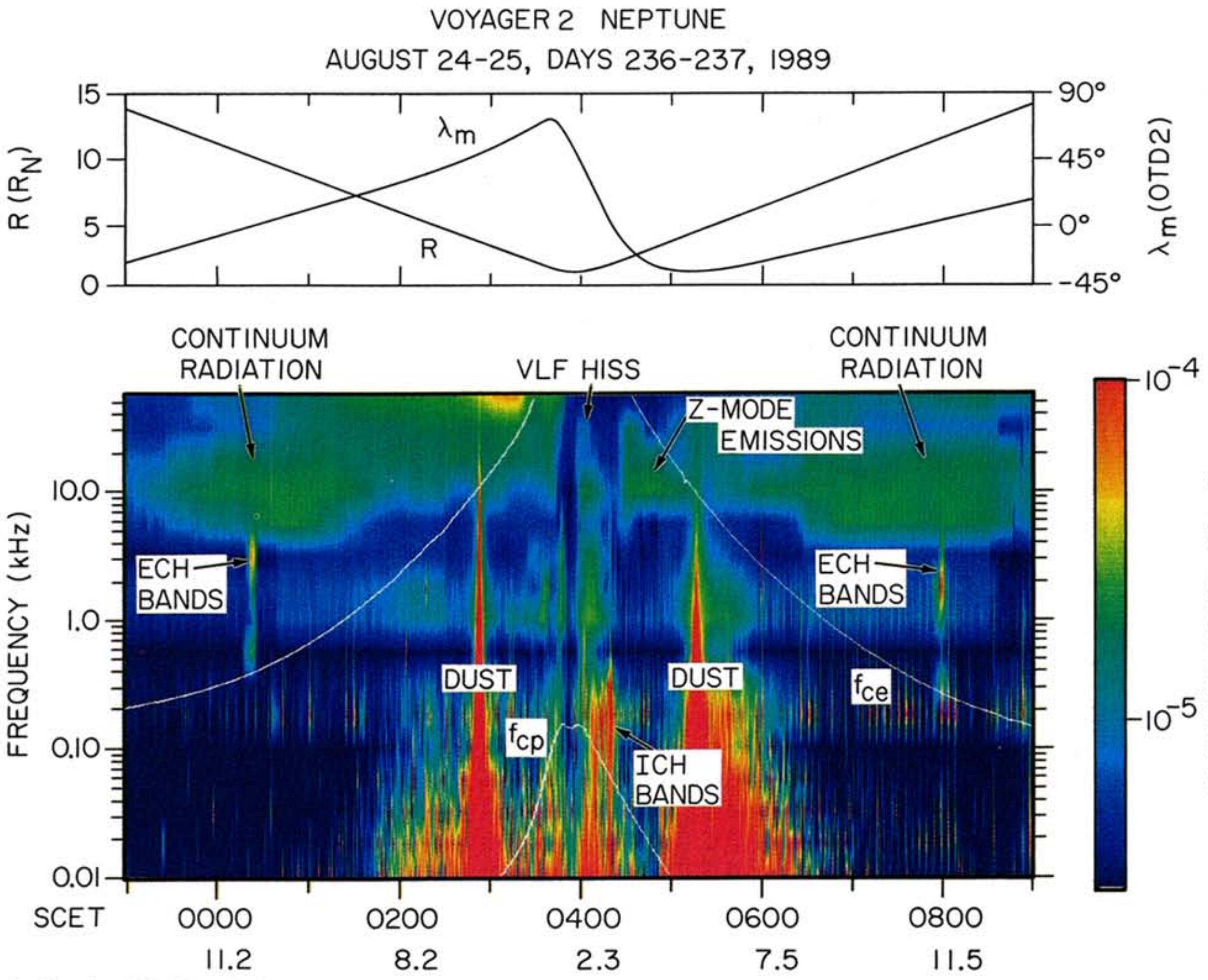

Plate 5. Overview of the Neptune plasma wave spectrum as observed by Voyager 2. The encounter trajectory coupled with a large tilt in the magnetic dipole makes the geometry of this encounter significantly different from the others. For this reason, it is difficult to say whether the relatively weak plasma wave emissions are due to geometric differences or simply to conditions that are not conducive to large wave growth at Neptune. The electron cyclotron harmonic emissions are the most prominent emissions seen here both inbound and outbound near 10 R_N. The intensities of these emissions suggest they do not figure prominently in the diffusion of electrons; however, they are almost certainly responsible for the generation of the low-frequency radio emissions observed in the upper portion of the spectrum. Weak whistler mode emissions are seen between the two encounters with the ring plane and their substantial dust signatures. Included in these whistler modes are lightning-generated whistlers.

cyclotron harmonic emissions near 10 R_N both inbound and outbound, between f_{ce} and the lower-frequency cutoff of the continuum radiation. These, as in all of the other magnetospheres, occur right at the magnetic equator. The large offset of these two features from the dust impact features demonstrates clearly the very large tilt between the magnetic dipole and the rotational axis of the planet [*Ness et al.*, 1989]. Virtually all other plasma wave phenomena observed at Neptune were observed between the two ring plane crossings, very close to the planet. We suggest that the low-altitude, high-latitude pass of the spacecraft at Neptune may have been poorly suited to observing many wave phenomena, such as whistler mode hiss and chorus and even electron cyclotron bands.

While prominently displayed in Plate 5, the electron cyclotron harmonic bands [*Barbosa et al.*, 1990] are not very intense and reach only about 30 μV/m. The planetary radio astronomy investigation has also reported the existence of ECH bands near 150 kHz at the magnetic equator crossing at 0420 SCET when the spacecraft was less than 2 R_N from the planet's center [*Sawyer et al.*, 1990].

The existence of the equatorial ECH bands on the inbound and outbound legs of the encounter trajectory provides a ready explanation for the low-frequency radio emissions shown in Plate 5 and reported by *Gurnett et al.* [1989] and *Kurth et al.* [1990]. The electrostatic emissions were found when Voyager 2 was near the magnetic equator and can be seen near 0030 and 0800 SCET in Plate 5; the radio emissions occur just above the frequency of the upper extent of the ECH band, or near the upper hybrid resonance frequency. These clues, plus evidence of the left-hand, ordinary polarization of the radio waves [*Kurth et al.*, 1990], lead to the conclusion that the radio emissions are the result of mode conversion from the electrostatic upper hybrid resonance band to the ordinary mode electromagnetic emissions. Voyager observed these low-frequency radio emissions on its approach and departure from the planet being beamed into relatively narrow cones close to the magnetic equator. One popular theory for the generation of these waves [see *Jones et al.*, 1987, and references therein] provides for the near-equatorial beaming of ordinary mode emissions from the linear conversion of upper hybrid bands just as is observed at Neptune. Similar evidence exists for this mechanism at Earth (for the nonthermal continuum radiation), at Jupiter, and at Saturn.

Barbosa et al. [1990] provided evidence of another type of emission associated with the magnetic equator at Neptune and argued that this was the ion equivalent of the electron cyclotron harmonic emissions, or ion cyclotron harmonic emissions. These waves appear centered near 0420 just above the proton cyclotron frequency. Another band of emission appears just below the proton cyclotron frequency near closest approach [*Gurnett et al.*, 1989]. Little has been written about these emissions, but their frequency would suggest that they are ion cyclotron waves involving heavy ions. Triton is known to be a source of nitrogen in the Neptune system, but it is not known how these ions are transported into the near vicinity of the planet.

The low intensity of the observed ECH emissions implies that they are unlikely candidates for strong pitch angle scattering. Using the same argument as above for Uranus, though, it is possible that waves of significantly greater intensities occur at intermediate radial distances $10 > R > 2$ R_N. One piece of evidence of this is the persistent observation of 17- to 31-kHz radio emissions seen several hundred Neptune radii from Neptune, implying intense UHR bands at those frequencies. Fluxes of resonant electrons would likely increase at smaller distances, although the ECH emission reported by *Sawyer et al.* [1990] is immersed in a dense, cold plasma and, as is the case in Earth's plasmasphere, may be unsuitable for large wave growth.

Kurth et al. [1990] demonstrated the existence of Z mode emissions just below f_{ce} on the outbound portion of the trajectory between 0430 and 0530 SCET. Some evidence exists suggesting these emissions might also be seen just before closest approach. The Z mode emissions propagate between the upper hybrid resonance frequency (likely to be close to f_{ce} in this region) and the $L = 0$ frequency $f_{L=0}$, where

$$f_{L=0} = -\frac{f_{ce}}{2} + \left(\frac{f_{ce}^2}{4} + f_{pe}^2\right)^{1/2}. \qquad (2)$$

The lower-frequency extent of the Z mode radiation is an upper limit to $f_{L=0}$ and hence may provide some information on the local plasma frequency in this region of the magnetosphere [*Gurnett et al.*, 1990].

Gurnett et al. [1990] provided some of the most important plasma wave observations to date at Neptune. Figure 2 is an example of one of the whistlers whose distinctive frequency-time character leads to the conclusion that there is lightning in the atmosphere of Neptune. Some 16 whistlers were observed, all within a planetocentric distance of about 2 R_N and at magnetic latitudes between −7° and 33°. The dispersion of the whistlers is very large. *Gurnett et al.* [1990] suggest that either the density of the plasma through which the whistlers traveled had to have been very large or there had to have been of the order of 100 bounces of the whistlers to explain the dispersions. Recently, however, *Menietti et al.* [this issue] have completed ray-tracing studies which show that the large dispersions can be explained with as few as one bounce and a modest increase in ionospheric densities from those reported by the radio science investigations [*Tyler et al.*, 1989]. The large dispersions are caused primarily by propagation very close to the resonance cone. With an explanation for the large whistler dispersions, there is little doubt that the source of the signals must be large electrostatic discharges somewhere near the planet; lightning seems to be the only reasonable explanation. It is remarkable that an atmosphere so cold as that of Neptune and so far from the Sun is able to generate weather systems with lightning.

Slow progress in the determination of the local plasma density, weak wave amplitudes, and the lack of a magnetic search coil on Voyager have made headway on the determination of wave modes at Neptune difficult and subject to uncertainty. Whistler mode hiss is thought to be weakly present during the closest approach to the planet. This diffuse emission can be seen at frequencies up to about 30 kHz when the spacecraft is at about 1.15 R_N. This emission's upper frequency cutoff probably provides a reliable lower bound to the electron plasma frequency, above which the whistler mode cannot propagate. The lightning whistlers discussed above are also found within this spectral feature; hence its identification as whistler mode seems secure. The intensity of the whistler mode hiss seems much too small to

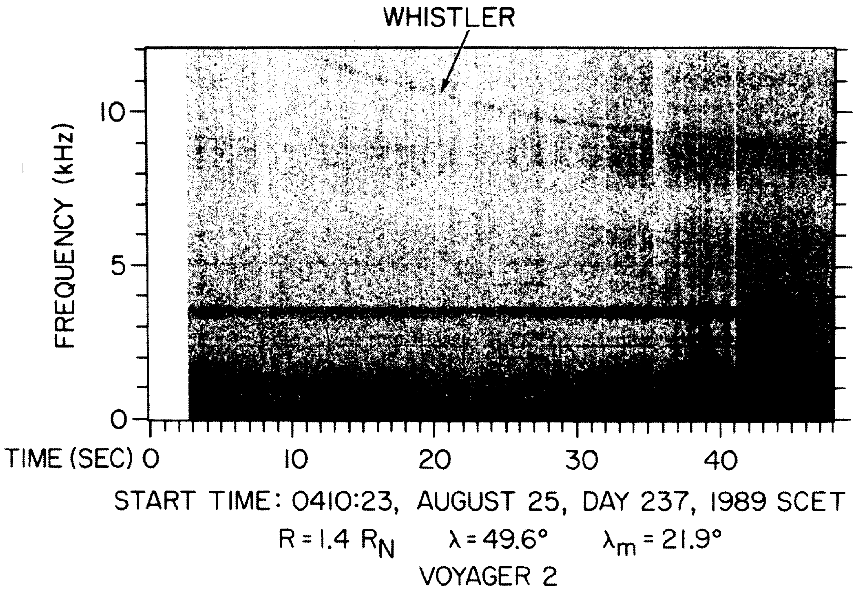

Fig. 2. High-resolution frequency-time spectrogram from the Voyager 2 wideband receiver showing the distinctive form of a lightning whistler generated in Neptune's atmosphere. This is one of the whistlers analyzed in detail by *Gurnett et al.* [1990]. The dispersion of the whistler is very large, because of its propagation through a high-density plasma near the resonance cone. Also seen in this spectrogram is a band near 3 kHz that *Moses and Coroniti* [this issue] suggest may be Z mode emissions at $f_{L=0}$.

be an important source of pitch angle diffusion. Recall that the spacecraft is just above the ionosphere at relatively high magnetic latitudes when this feature is most prominent. At Earth this location would not be conducive to intense whistler mode activity. While the spacecraft did pass through the magnetic equator at 0420 SCET, it was still inside ~2 R_N, and conditions may not be appropriate for strong growth of the hiss here, either. With no evidence to the contrary, we must conclude that there is little or no pitch angle scattering due to whistler mode emissions at Neptune. We emphasize, however, that the trajectory provides a slice through the magnetosphere which is too limited to form the basis for any final conclusions.

One final emission of interest must be noted in this discussion. A band in the range of about 1–3 kHz can be seen near closest approach in Plate 5. High-resolution spectrograms obtained by the waveform receiver (such as that in Figure 2) show that a persistent narrowband emission at about 3 kHz is consistently visible with only about a 0.5-kHz drift in frequency throughout the entire closest approach region. *Moses and Coroniti* [this issue] discuss possible interpretations of this band. They favor an interpretation which labels this band as Z mode emissions at the $L = 0$ frequency. Using this interpretation, they determine a density profile using equation (2). The primary difficulty with this interpretation of the 3-kHz band is that it provides a plasma frequency at 0420 SCET which would seem too low to account for the electron cyclotron harmonic emissions observed at the same time by the planetary radio astronomy investigation at 150 kHz [*Sawyer et al.*, 1990]. An alternate explanation mentioned by Moses and Coroniti but not developed is that there may be some interaction between the spacecraft and the plasma which can explain the band. There may, indeed, be such an interaction, but Moses and Coroniti provide too few details for the merits of such a possibility to be judged.

7. SUMMARY AND CONCLUSIONS

For the first time we have compared the general plasma wave spectra in the magnetospheres of Earth, Jupiter, Saturn, Uranus, and Neptune. Strikingly, there is a close similarity in the modes present in these very different magnetospheres. Each has evidence of whistler mode emissions and electron cyclotron harmonic emissions. While not shown in detail herein, all but Neptune show evidence of whistler mode chorus, and we suspect that the equatorial region of Neptune may contain such emissions, but Voyager did not sample the magnetic equator at intermediate radial distances where chorus might be found. The electron cyclotron harmonic emissions show, to varying degrees, an affinity for the magnetic equatorial plane where growth rates and propagation considerations are optimized. Notably, each of the planets where f_{cp} rose into the plasma wave receiver's frequency range near the magnetic equator shows evidence of an ion mode which is likely to be analogous to the ECH bands. Earth, Jupiter, and Neptune all show distinct evidence of lightning whistlers. Z mode emissions can be found at Earth, Jupiter, and Neptune.

If there are differences in the plasma wave spectra in the planetary magnetospheres, they are most easily seen in the amplitudes of the emissions and in the apparent dominance of certain modes over others. For example, whistler mode emissions are quite intense at Earth, Jupiter, and Uranus, where plausible arguments can be made that these waves (at least at some times and locations) strongly scatter energetic electrons, causing the precipitation of these into the atmosphere. In some cases, most notably Uranus, the estimated electron precipitation is equivalent to that required to account for the observed UV aurora. In the case of Jupiter, even though the whistler mode driven precipitation is only of the order of 10% of that required to account for the aurora, significant energy flow into the atmosphere is attributable to the waves. At least at Jupiter and Earth there are times when ECH bands of the order of 1 mV/m are present to strongly pitch angle scatter energetic electrons. We strongly suspect that the trajectories at the other planets, which avoided the magnetic equator over crucial radial distance ranges, also have ECH bands which are more intense than those observed and hence could be important in electron precipitation. However, such speculation can only wait for orbiter missions to obtain more complete data sets.

The comparison of plasma wave phenomena and especially the assessment of their roles in the energy budget of the magnetospheres are just beginning. As alluded to above, there are many uncertainties and, indeed, dilemmas in understanding the importance of the waves. The whistler mode emissions at Uranus are the obvious example, but the situation at Jupiter is no better understood. Our understanding of pitch angle scattering by whistler mode emissions is continually challenged by apparent mismatches between the observed wave amplitudes and the flux of resonant particles. While the Kennel-Petschek [*Kennel and Petschek*, 1966] theory remains the standard in this discussion, it is clear that we do not fully understand its application in all cases or how to reconcile it with some of the observations in the planetary magnetospheres. In some cases, for example in the Io torus at Jupiter, the difficulties are assuaged by the identification of electrostatic modes, thus easing the Kennel-Petschek requirements for very large replenishment rates of energetic electrons. There are similar gaps in our understanding of the generation and implications of the other wave modes discussed herein. Some advances will be made with detailed modeling based on the data in hand. Other progress will be based on the extended data bases to be provided by Ulysses, Galileo, Cassini, and other orbiters to be flown to Uranus and Neptune.

Finally, it should be acknowledged herein that the exploration of plasma waves in solar system magnetospheres is not yet complete. Observations of waves in Mercury's magnetosphere will likely wait for the Mercury Dual Orbiter mission currently being studied by NASA's Space Physics Division. We as yet do not know of the existence of a magnetosphere at Mars or Pluto. It is fair to assume that these are likely to be considerably smaller than even Mercury's magnetosphere. Hence, given a substantial delay for the completion of a solar system–wide survey and the likelihood of minimal magnetospheres at Mars and Pluto, our current survey results should not be considered vastly incomplete.

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D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 55242.

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