

Electrostatic Wave Excitation in Planetary Magnetospheres: Application to Neptune

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Voyager 2 observations of electrostatic electron and ion cyclotron harmonic waves in Neptune's magnetosphere are addressed. A model of electron Bernstein modes generated by a loss cone distribution of superthermal electrons is scaled to Neptune parameters and a comparison of theory with the observed electron flux shows good agreement. A model of proton Bernstein modes generated by a ring distribution of Tritonogenic nitrogen ions is also investigated and satisfactory agreement with the data are obtained compatible with known properties of the magnetosphere. The success of the model in accounting for electrostatic emissions observed by Voyager over a wide range of sampled parameters recommends its general applicability to planetary magnetospheres.

INTRODUCTION

The Voyager 2 encounter with Neptune produced a remarkable set of measurements of a planetary magnetosphere about which little was known previously. Results obtained thus far have indicated that Neptune's magnetosphere is a complex system having characteristics that are shared with each of the magnetized planets.

The plasma wave instrument (PWS) returned data revealing Neptune as a moderately intense radio emitter and having a plasma wave spectrum that featured a familiar assortment of wave modes seen at other planets [Gurnett *et al.*, 1989; Kurth and Gurnett, 1991]. Some preliminary results concerning electrostatic electron and ion cyclotron harmonic waves (ECH/ICH) were reported by Barbosa *et al.* [1990], who described the observational properties of the emissions and outlined the rudiments of a theoretical scenario for their generation. The present work elaborates on the theory by providing model calculations and a comparison with observations where possible.

The paper draws on the theory of ECH waves [Barbosa and Kurth, 1980] and ICH waves [Barbosa and Kurth, 1990] developed for the planet Jupiter. The ECH model is based on a generalized loss cone pitch angle distribution of superthermal electrons with energies in the range of $T \sim 10\text{--}50 T_{ec}$ above the cool background temperature T_{ec} , which drives an instability of electron Bernstein waves traveling perpendicular to the magnetic field. The threshold flux of electrons able to provide an amplification of ~ 40 dB near the magnetic equator where conditions are optimal for growth is computed and parameterized in terms of the background plasma properties. The general applicability of the model to other

magnetospheres was demonstrated by Kurth *et al.* [1983] and Barbosa and Kurth [1993], who scaled the ECH theory to Saturn and showed the good agreement that the model had with in situ measurements of the superthermal electron population. The present paper extends the procedure to Neptune where once again an excellent correspondence with the data is evident. A summary of results for each of the outer planets is included to show how well the model fares over the large range of parameters that apply to planetary magnetospheres.

In the area of ICH waves this is the first extension of the model to another planet besides Jupiter. The ICH theory is an adaptation of the model for generation of lower hybrid waves by a ring distribution of pickup ions [Barbosa *et al.*, 1985] to include the generation of ion Bernstein modes found in the cold Io torus of Jupiter [Barbosa and Kurth, 1990]. The application of the model to Neptune assumes that a ring distribution of N^+ pickup ions created out of the atomic nitrogen cloud enveloping Triton's orbit diffuse inwards to the inner magnetosphere where they mix with thermal protons from Neptune's ionosphere. The interaction of the two ion populations occurs via the proton Bernstein mode which is driven unstable by the inverted population of N^+ ions which have the characteristics of a ring distribution in velocity space and form a nonthermal bump-on-tail to the total ion distribution function. The favorable circumstances for detection of ICH waves just above the proton cyclotron frequency f_{cp} occurred only for Voyager 1 at Jupiter and Voyager 2 at Neptune where the spacecraft penetrated deep enough in the magnetosphere for f_{cp} to rise above 10 Hz, the lowest-frequency channel of the PWS receiver. The success of the model in accounting for the Voyager observations at Jupiter and Neptune (and we would surmise at other planets in general) is due mostly to the fact that the pickup ion ring distribution of heavy ions is a common feature of outer

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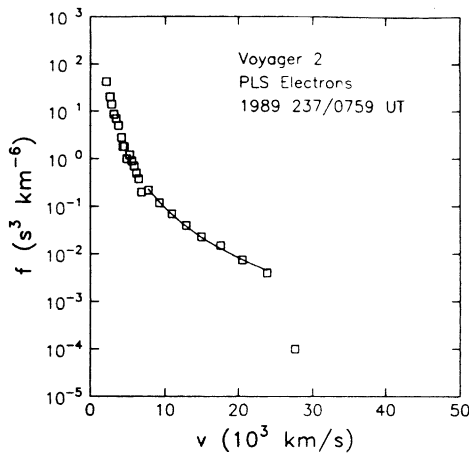


Fig. 1. Plasma science electron measurements for the magnetic equator crossing at $11 R_N$ on the outbound leg. The solid curve is a power law fit to the superthermal component of the distribution.

planet magnetospheres where magnetosphere-satellite interactions dominate the plasma dynamics. This paper thus makes the case for the universality of the theory for both ECH waves and ICH waves.

ECH WAVE ANALYSIS

The plasma wave instrument recorded 2 ECH events when the spacecraft crossed the magnetic equator inbound at $10 R_N$ and outbound at $11 R_N$ [Barbosa *et al.*, 1990]. Just after closest approach there was another magnetic equator crossing and the Planetary Radio Astronomy experiment found evidence for what can be interpreted as an intensified upper hybrid emission [Sawyer *et al.*, 1990] which according to Barbosa and Kurth [1980] falls in the ECH classification scheme of $(n + 1/2)f_{ce}$ emissions also.

For the purpose of comparing with the plasma science (PLS) electron measurements the outbound event at $11 R_N$ is chosen for discussion. Figure 1 shows PLS electron data for the time 0759 U.T. on day 237 precisely when the magnetic equator was crossed. These data illustrate the two component (hot and cold) nature of the electron population that is present throughout most of the Neptunian magnetosphere [Zhang *et al.*, 1991]. A Maxwellian fit to all the cold component in Figure 1 gives $n_{ec} = 0.016 \text{ cm}^{-3}$ and $T_{ec} = 13 \text{ eV}$. Above $v \sim 7 \times 10^3 \text{ km/s}$ there is an apparent change in slope of the distribution function. A power law fit to the superthermal component was made

$$f = 284v^{-3.5} \text{ s}^3 \text{ km}^{-6} \quad (1)$$

with v expressed in units of 10^3 km/s . The power law fit is adopted not for any particular theoretical reason but because it provides a good empirical representation of the data at large superthermal energies. This feature was first pointed out by Barbosa and Kurth [1980], who built their ECH wave generation model on this fact. The power law model holds equally as well for Saturn [Barbosa and Kurth, 1993]. Other studies have employed two-component [Sittler *et al.*, 1983] or three-component [Zhang *et al.*, 1991] Maxwellian fits to the data. An advantage of the Maxwellian form is that one

can conveniently derive a characteristic energy/temperature for the hot component. A disadvantage is that the model drops off too fast, thereby excluding the more energetic (i.e., $E > 10 \text{ keV}$) particles which are detected by the low-energy charged particle (LECP) experiment [Krimigis *et al.*, 1990].

It is interesting to note that the power law can be extended down to the smallest value of v in Figure 1 with no loss of quality to the fit, the correlation coefficient being approximately equal to 1. This aspect may be unique to the Neptunian magnetosphere which is characterized by low densities in comparison to the other outer planets [Belcher *et al.*, 1989]. For the parameters characterizing the cold component, the timescale for Maxwellianization of the distribution is $\sim 2 \times 10^7 \text{ s}$ which in all likelihood exceeds the plasma residence time in the outer magnetosphere. Thus it may simply be the case that the electrons are assembled with a power law distribution (1) at all energies and retain that form in the absence of collisions. In that situation the use of the terms thermal and superthermal may be imprecise but still conveys the general sense of relative energies. Since the theoretical model for ECH wave generation is based on the power law form, it is still applicable to the situation at Neptune although some of the details related to wave propagation and dispersion [e.g., Barbosa, 1985] may be altered as a result of the Lorentzian nature of the thermal distribution function.

Figure 2 shows the superthermal portion of the data replotted in terms of electron flux. Several additional data points from the LECP experiment have been included on the high-energy end. The LECP measurements tend to connect smoothly with PLS electron data at lower energies, thus confirming the slow fall off with energy and power law behavior of the flux $j \propto T^{-3/4}$ predicted by (1).

A comparison of the observations with the Barbosa and Kurth [1980] theory for the generation of Bernstein modes traveling across the magnetic field can be made utilizing the critical flux concept which specifies a threshold flux j_{\perp}^* for 10

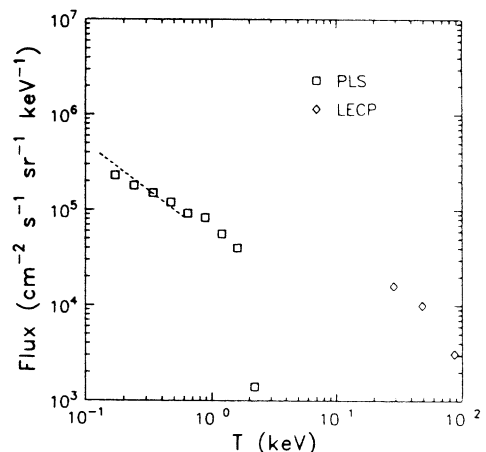


Fig. 2. Superthermal electron flux at 0759 UT on day 237. The dashed curve is the theoretical threshold for electron cyclotron harmonic wave generation plotted over the relevant range of energies $T = 10\text{--}50 T_{ec}$ where the wave-particle interaction is effective. Several high-energy electron fluxes from the low-energy charged particle (LECP) experiment are also plotted which illustrates the slow (power law) fall off of flux with energy.

TABLE 1. Summary of Outer Planet Fluxes

Planet	R	n_{ec}, cm^{-3}	T_{ec}, eV	$Tj_{\perp}^*, \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$	Tj_{\perp} (observed)
Jupiter	7.8	380 ^a	23	2×10^7	1×10^8
Saturn	6	20	10	6×10^6	2×10^7
Uranus	11.5	0.04	10?	9×10^4	...
Neptune	11	0.016	13	5×10^4	4×10^4

R is in planetary radii.

^aBased on $f_{\text{UHR}} = 175 \text{ kHz}$ [Birmingham et al., 1981].

e -foldings of wave amplification. The basic assumptions of that theory are that the flux have a power law dependence in energy $j \propto T^{-N}$ with $N = 1$ and also a loss cone distribution in pitch angles $j \propto \sin^{2M} \theta$ with $M = 1$. Scaled to Neptune the critical flux is given by

$$Tj_{\perp}^* = 1400pR^2\omega/\Omega_{ce} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (2)$$

where T is the kinetic energy in keV, $p = n_{ec}T_{ec}$ is the thermal electron pressure in units of eV/cm^3 , R is the radial distance of the event in units of planetary radii R_N , and ω/Ω_{ce} is the frequency normalized to the electron gyrofrequency. For the electron distribution function shown in Figure 1 we have $n_{ec} = 1.6 \times 10^{-2} \text{ cm}^{-3}$ and $T_{ec} = 13 \text{ eV}$ so that for $\omega/\Omega_{ce} = 1.5$ and $R = 11 R_N$ the above expression becomes

$$Tj_{\perp}^* = 5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (3)$$

which is plotted in Figure 2 as the dashed curve over the limited range of superthermal energies $T \approx 10\text{--}50 T_{ec}$ that are involved in the coupling to low harmonic ECH waves. The comparison with the data demonstrates that the superthermal electron flux is large enough in magnitude to provide sufficient growth of the Bernstein waves. The only untested assumption is that the electrons have a loss cone anisotropy $M \sim 1$, which drives the instability [Barbosa and Kurth, 1980, 1993]. However, on the basis of a large sample of measurements taken at other planets, such a requirement is likely to be satisfied.

Table 1 shows a summary of this procedure for each of the outer planets where simultaneous wave and electron data were available. In the case of Jupiter, Saturn, and Neptune the observed flux is greater than or equals the threshold for wave excitation. The differences may possibly be related to the fact that the model assumes a loss cone anisotropy $M = 1$ and if the anisotropy is less than this value, the required flux would correspondingly be higher, the critical flux being inversely proportional to M . This explanation accords with the situation at Jupiter where the larger density suggests that Coulomb scattering of electrons at low superthermal energies may fill in the loss cone significantly so that only a small anisotropy $M \ll 1$ is possible [Barbosa et al., 1985]. The exceptional case in Table 1 is the planet Uranus where a clear wave event was observed on the inbound leg of Voyager [Kurth and Gurnett, 1991], but no detectable hot electron population was present.

ICH WAVE GENERATION

The other major wave emission discussed in this work is the ion cyclotron harmonic event which the plasma wave

receiver detected at the magnetic equator just after closest approach. Barbosa et al. [1990] gave an outline of a model for the generation of the waves based on a ring instability of pickup N^+ ions diffusing into the inner magnetosphere from the orbit of Triton. We would like to elaborate on the details of the theory and show quantitatively that it can pass muster as a wave excitation mechanism.

The model draws on the theory of Barbosa and Kurth [1990] for the generation of proton Bernstein waves by a ring distribution of unmagnetized heavy ions. For electrostatic waves traveling exactly perpendicular to the magnetic field an instability develops derived from the positive slope $\partial f_{\perp} / \partial v_{\perp} > 0$ of the distribution function. More precisely, if the magnetic field lies along the z axis and the wave is traveling in the x direction, the growth rate is related to $\partial F(v_x = v_R) / \partial v_x > 0$, where F is the reduced distribution function

$$F(v_x) = \iint dv_y dv_z f(\mathbf{v}) \quad (4)$$

evaluated at the resonant velocity $v_R = \omega/k_x$ [Barbosa et al., 1985].

Figure 3 illustrates the bump-on-tail aspect of the ring distribution giving rise to the instability. The ions at lower speeds are protons of Neptunian origin and the bump is

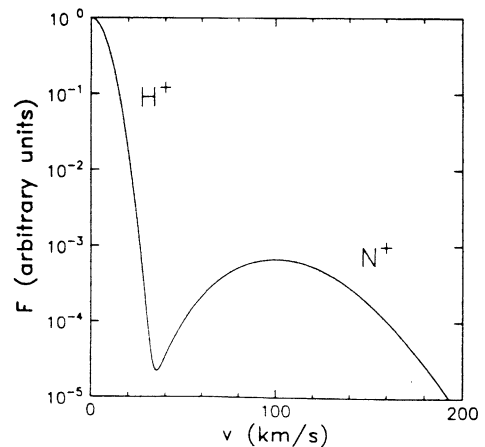


Fig. 3. Sketch of the reduced ion distribution function showing the bump on tail of the N^+ ions diffusing in from Triton's orbit mixing with cool thermal protons from Neptune's ionosphere. The interaction of the two diverse populations leads to a collective wave-particle interaction via the ion Bernstein mode that attempts to thermalize the N^+ ions in the absence of collisions.

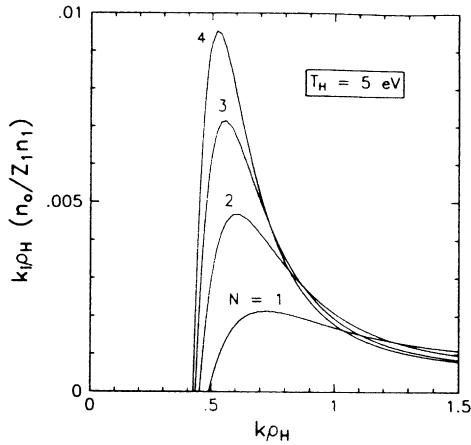


Fig. 4. Convective growth rates for the first harmonic band of the proton Bernstein mode plotted versus the wave number normalized to the proton Larmor radius.

composed of nitrogen ions from Triton. (Triton is believed to be the primary source of low-energy protons in the outer magnetosphere [Cheng, 1989], but at $1.8 R_N$ Neptune is more likely to be the dominant source of cold $T_p < 10$ -eV protons.) At $R_0 = 14 R_N$ the ion gyrovelocity resulting from pickup is $u_0 = 43$ km/s and if the ions diffuse into a distance R , the characteristic speed scales as $u(R) = (R_0/R)^{3/2} u_0 \sim 10^3$ km/s at $R = 1.8 R_N$. The peak in the distribution in principle occurs at $V = u(R)$ and the spreading is due to a variety of effects including wave-particle interactions. Wave growth results from resonant interactions of ions with velocities on the positive slope portion of the distribution $v_R < V$. We note, however, that according to Richardson *et al.* [1991] the characteristic energy of the heavy ion component identified as nitrogen is ~ 1 keV, which implies that if the ions have a ring distribution, the peak speed $V \sim 100$ km/s significantly less than that expected from pickup in the outer magnetosphere and adiabatic compression with transport inward.

This leads naturally to the issue of whether the waves are properly interpreted as electrostatic or electromagnetic modes. Observations of terrestrial ICH waves indicate that they have a significant magnetic component [Gurnett, 1976], which suggests that they are magnetosonic modes [Perraut *et al.*, 1982]. Since the Voyager plasma wave receiver did not have a magnetic sensor and could not determine the magnetic component, it is an open question whether the ICH waves observed at the outer planets are electrostatic or electromagnetic. We are inclined, however, to believe they are electrostatic because of theoretical considerations regarding how they might be generated in the very low β plasma conditions characterizing the cold Io torus of Jupiter and the inner Neptunian magnetosphere. A rather firm estimate of the Alfvén velocity at $1.8 R_N$ yields $V_A \approx 10^4$ km/s which is an order of magnitude greater than the peak velocity V . If ions are to interact with the magnetosonic mode, they must have speeds comparable to the Alfvén velocity which means an energy ≥ 1 MeV. The observed flux of ions at these energies [Krimigis *et al.*, 1990] is too small to produce any significant growth of the magnetosonic mode.

However, because electrostatic waves are characterized by much smaller wave velocities, N^+ ions can resonate with waves that have phase speeds falling in the unstable region of growth; i.e., $\omega/k_x \leq V$. For proton Bernstein modes the phase velocity is of the order of the proton thermal velocity $a_H \sim 100$ km/s for the low ion temperatures characteristic of Neptune's inner magnetosphere.

A quantitative evaluation of the effectiveness of the ring distribution in generating ICH waves can be gotten by computing the convective growth rate. Our previous calculations of the temporal growth rate of ion Bernstein waves may be modified in a straightforward manner to evaluate the imaginary part of the wavenumber $k_i = \epsilon_i / (\partial \epsilon / \partial k)$, where ϵ_i is the imaginary part of the dielectric function related to (4) whose explicit form is given by Barbosa and Kurth [1990] along with expressions for the dielectric function ϵ itself. Figure 4 shows a plot of k_i versus k normalized to the thermal proton Larmor radius ρ_H for several values of ring anisotropy factor N [cf. Barbosa and Kurth, 1990]. The other normalization factor n_1/n_0 represents the density ratio of pickup N^+ ions and background thermal ions.

The application of the theory to Neptune is hindered somewhat due to the large uncertainty regarding the properties of the background plasma. Gurnett *et al.* [1992] have discussed the PWS whistler observations which suggest the strong possibility that a cold dense plasma is present in Neptune's inner magnetosphere which is below the detection threshold of the PLS experiment. Our approach here will be to treat the parameters of the thermal plasma as free but mildly constrained variables and try to determine which values are most compatible with the ICH wave model. Accordingly, we have assumed the thermal plasma to be primarily protons with a density $n_H = 10$ cm $^{-3}$ (the minimum value suggested by Gurnett *et al.* [1992]) and a temperature $T_H = 5$ eV, which is conducive to wave growth. The nitrogen ions are assumed to have a ring distribution with a density $n_N = 1$ cm $^{-3}$ and peak speed $V = 118$ km/s ($T_N = 10^3$ eV) corresponding to the Richardson *et al.* [1991] results for N^+ .

The logarithmic gain of a wave propagating a distance δr transverse to a dipole magnetic field at the equator is then

$$G = k_i \delta r = k_i R \delta x / 3x \quad (5)$$

where $x = \omega / \Omega_{ci}$ is the wave frequency normalized to the ion (proton) cyclotron frequency. With the aid of the numerical results in Figure 4 the gain may be scaled as

$$G = 10 \left(\frac{n_1/n_0}{0.1} \right) \left(\frac{N}{2} \right) \left(\frac{1.8 R_N}{R} \right)^2 \left(\frac{\delta x}{0.2} \right) \quad (6)$$

assuming also that $T_H = 5$ eV and $x = 1.5$ for the first harmonic band.

Sufficient amplification is thus obtainable from the model for a reasonable set of parameters that might apply to the inner magnetosphere at $1.8 R_N$. However, there is not much margin for variation. It is instructive to examine how the result is modified when parameters are varied given the large uncertainty in their values. If the ring anisotropy were as large as 6, and independent theoretical calculations of the evolution of the distribution function give some support to this possibility, then the theory could tolerate a proton density $n_H \sim 30$ cm $^{-3}$. However, if the thermal proton density were as large as $n_H = 100$ cm $^{-3}$, the gain would be

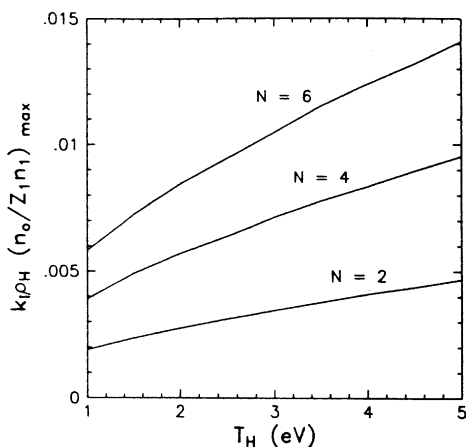


Fig. 5. Maximum convective growth rates for the first harmonic band plotted against the thermal proton temperature T_H .

reduced by a factor of 10 given that $n_1 = n_N = 1 \text{ cm}^{-3}$, and no other compensating changes of that magnitude are feasible.

The proton temperature also has a large uncertainty to it, but there are measurable constraints on it. McNutt [1992] has discussed the limits on proton density and temperature that apply in the situation of their nondetection by the PLS experiment. The hotter the proton temperature is, the smaller the density must be in order to not exceed the detection threshold of the lowest PLS ion channel at 10 eV. Figure 5 shows the maximum of the convective growth rate plotted as a function of T_H for $N = 2, 4,$ and 6 . A decrease in the proton temperature reduces the ion Bernstein wave phase speed relative to the positive slope region of the N^+ ring distribution which is most effective at producing wave growth in the region $\omega/k \sim \sqrt{2}$. If $T_H = 5 \text{ eV}$ is unacceptably large according to the calculations of McNutt [1992], then a smaller value can easily be accommodated. The results shown in Figure 5 indicate that sufficient amplification (10 e -foldings) is obtainable if $N = 6$ even in the case $T_H = 1 \text{ eV}$ and $n_H = 30 \text{ cm}^{-3}$. The smaller temporal growth rate that occurs at smaller T_H is compensated for in the path-integrated growth by smaller wave group velocity $\sim a_H$ so that k_i is approximately constant over this temperature range. Thus the conclusion is that the model successfully accounts for the growth of proton Bernstein waves with the assumption that a cool thermal proton plasma exists having $T_H = 1\text{--}5 \text{ eV}$ and $n_H = 10\text{--}30 \text{ cm}^{-3}$ which reconciles the conflicting requirements of the PLS and PWS experiments over a small window of compatible parameters.

CONCLUSION

A theoretical model for the generation of electrostatic electron and ion cyclotron harmonic waves developed originally for Jupiter has been scaled appropriately for Neptune's magnetosphere. A comparison of the model with electron measurements shows good agreement and the requirements for effective amplification of ion waves would appear to be met also. The result of our analysis of Voyager data at the outer planets leads us to conclude that the model can be successfully applied to planetary magnetospheres in general.

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