

Electrostatic Waves in Jupiter's Magnetosphere

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Abstract : Electrostatic Plasma waves are studied in the Io plasma torus in the magnetosphere of Jupiter using the observed plasma parameters for a three component plasma (e^- , S^+ , O^+). Dispersion relations are calculated for upper hybrid, lower hybrid electron and ion Bernstein modes. Oxygen Bernstein modes show a branched structure due to coupling of sulphur and oxygen modes. Resonant particle energies are calculated. Also the energization of particles by electrostatic Bernstein modes is studied. It is found that electrostatic waves can energize electrons to required energies for electron precipitation. However, ions can be heated to only small energies and therefore other energization mechanism must be operative for ions.

1. Introduction

The brief encounters of the two Pioneer and two Voyager spacecraft with Jupiter have provided a large amount of data about Jupiter's magnetosphere. These include ion and electron temperatures, number densities, charged particle energy spectra and plasma waves (Bagenal and Sullivan¹, Sudder² *et al.*, Scarf *et al.*³, Kurth and Gurnett⁴, Zarka⁵). The most striking feature of the Jovian Plasma wave observations is the close similarity to the plasma-wave phenomena observed in the Earth's magnetosphere. All major types of plasma waves detected in the Jovian magnetosphere have analogs in the Earth's magnetosphere. These include whistler mode chorus and hiss, electrostatic electron cyclotron and upper hybrid emissions, and broadband electrostatic noise. However, Jupiter's magnetosphere is different in many respects. For example, the Earth's magnetosphere extracts essentially all of its energy and plasma from the solar wind. In contrast, Jupiter's magnetosphere is powered by the slowing of Jupiter's spin, and nearly all of the magnetospheric plasma comes from internal sources—the satellite Io and Jovian ionosphere.

Io and its associated neutral clouds inject ionized material into the magnetosphere, producing a plasma torus with a density maximum near the L shell of Io between 4.9 and $7.0 R_J$ (R_J is radius of Jupiter). Io has an atmosphere of SO_2 and SO_2 frost on the surface [Pearl⁶ *et al.*, Smythe⁷ *et al.*].

The following ion species have been observed by spacecraft in the thermal plasma of the Jovian magnetosphere (*e.g.* Geiss⁸ *et al.*) : H^+ , He^{++} and O^{6+} of the solar wind

origin; H^+ , H_2^+ , and H_3^+ , originating from the Jovian ionosphere; and S^{2+} , S^{3+} , S^{4+} , S^{5+} , O^+ , O^{2+} , and O^{3+} , originating from Jupiter's satellite Io. The S and O ion species are especially abundant, particularly in the inner ($L < 10$) and middle ($L < 40$) regions of the magnetosphere. The densest part of the inner magnetosphere is called the Io plasma torus. Io is a very important source of plasma for the Jovian magnetosphere. The composition of the energetic plasma population is also dominated by S and O species. Energetic electrons with energies in excess of 100 keV are also present in the Jovian magnetosphere, and radiation belt particles with energies in the 1-100 MeV range have also been observed (Cravens⁹). The Io torus maps along field lines into Jovian polar regions, and it source of heavy ions (S^+ , O^+ etc.) and electrons which are responsible for producing auroral emissions, [Broadfoot¹⁰ *et.al.*]. Resonant wave-particle interaction leads to a precipitation of particles into the atmosphere which is controlled by plasma waves that are Doppler shifted in the frequency to some integral multiple of the particle cyclotron frequency. While electromagnetic plasma waves cause mainly the pitch angle scattering of high energy particles into the atmospheric loss cone, electrostatic plasma waves should scatter soft energy particles. Electrostatic plasma waves not only cause pitch angle scattering but also energize the particles to higher energies during wave-particle interaction.

In the present work we have studied the electrostatic plasma waves and associated phenomena in the Io plasma torus. In section 2, we describe the dispersion relations for electrostatic plasma waves. In section 3, we calculate the resonant energies of particles. In section 4 the energization of particles during wave-particle interaction is considered. These results are discussed in the light of Jovian aurora. Conclusions are given in section 5. The main aspects of the present work are the calculations performed for Io plasma torus using the observed plasma parameters, resonant energies calculated in a more comprehensive manner, calculation of energization of particles by plasma waves and the discussion of results in the context of Jovian aurora.

2. Dispersion relations

For electrostatic plasma waves, dispersion relation is given by [Clemmow and Dougherty¹¹].

$$(1) \quad \epsilon_0 k^2 = \sum_{\alpha} \left(- \frac{N_{\alpha} e^2}{K T_{\alpha \perp}} \right) \left\{ 1 - i \omega \int_0^{\infty} \exp[-i \omega t - g_{\alpha}(t) dt] \right\}$$

where N_{α} is number density, $T_{\alpha \perp}$ is perpendicular temperature for specie α , e is electron charge, K Boltzmann constant and

$$(2) \quad g_{\alpha}(t) = \frac{K T_{\alpha \parallel} k_{\parallel}^2 t^2}{2 m_{\alpha}} + \frac{K T_{\alpha \perp} k_{\perp}^2 (1 - \cos \Omega_{\alpha} t)}{m_{\alpha} \Omega_{\alpha}^2}$$

Here, $T_{\alpha \parallel}$ is parallel temperature, m_{α} is mass and Ω_{α} is cyclotron frequency. α runs over all species. Using the identity involving modified Bessel functions $I_n(\lambda)$, [Abramowitz and Stegun¹²].

$$(3) \quad \exp(\lambda \cos \Omega t) = \sum_{n=-\infty}^{+\infty} I_n(\lambda) \exp(in\Omega t)$$

$$\text{where } \lambda = \frac{K T_{\perp} k_{\perp}^2}{m \Omega^2}$$

Equation (1) is written as

$$(4) \quad \epsilon_0 k^2 = \sum_{\alpha} \left[-\frac{N_{\alpha} e^2}{K T_{\alpha \perp}} + \frac{\omega N_{\alpha} e^2}{K T_{\alpha \perp}} e^{-\lambda_{\alpha}} \sum_{n=-\infty}^{+\infty} I_n(\lambda_{\alpha}) \right. \\ \left. \left\{ \frac{1}{\omega - n \Omega_{c\alpha}} + \frac{K T_{\alpha \parallel} k_{\parallel}^2}{m_{\alpha}} \frac{1}{(\omega - n \Omega_{c\alpha})^3} \right\} \right]$$

where we have assumed $\frac{K T_{\alpha \parallel} k_{\parallel}^2}{m_{\alpha} \Omega_{c\alpha}^2} \leq 1$. This is equivalent to $k_{\parallel} \rho_{\alpha} \leq 1$ where ρ_{α} is particle gyroradius.

Furthermore, in writing equation (1), a Maxwellian distribution function has been assumed for each particle species. Equation (4) is solved by including three particles species e^{-} , S^{+} , O^{+} and $T_{\alpha \parallel} = T_{\alpha \perp}$ is assumed. Calculations are performed for two cases: Cold torus and warm torus. For cold torus we have used $N_1 = 1.1 \times 10^9/m^3$ and $N_2 = 3.5 \times 10^8/m^3$, electron temperature of 6 eV and ion temperature 9 eV. N_1 and N_2 refer to single ionized sulphur and oxygen respectively. For warm torus we use $N_1 = 1.4 \times 10^8/m^3$ and $N_2 = 4.7 \times 10^7/m^3$, electron temperature of 25 eV and ion temperature 50 eV. Magnetic field strength is taken as 2000 nT, [Belcher¹³].

In the cold plasma limit with the inclusion of two ions the dispersion equation has three roots [Barbosa¹⁴]. These are :

(1) The upper hybrid frequency

$$(5) \quad \omega_{UH}^2 \approx \omega_{pe}^2 + \Omega_{ce}^2$$

(2) The lower hybrid frequency

$$(6) \quad \omega_{LH}^2 = \frac{R}{1+R} \Omega_{ce} \sum_i \frac{Z_i N_i}{N_e} \Omega_{ci}$$

$$\text{where } R = \frac{\omega_{pe}^2}{\Omega_{ce}^2}$$

Here, ω_{pe} is the electron plasma frequency and Z_i is charge for i^{th} ion specie.

(3) The Buchsbaum frequency

$$(7) \quad \omega_B^2 \approx \Omega_{c_1} \Omega_{c_2} \frac{x_2 f_1 + x_1 f_2}{x_1 f_1 + x_2 f_2}$$

where x_1, x_2 are fractional concentration of S^{+} and O^{+} and $f_i = \frac{m_e}{M_i}$ is electron-ion mass ratio for ion species i .

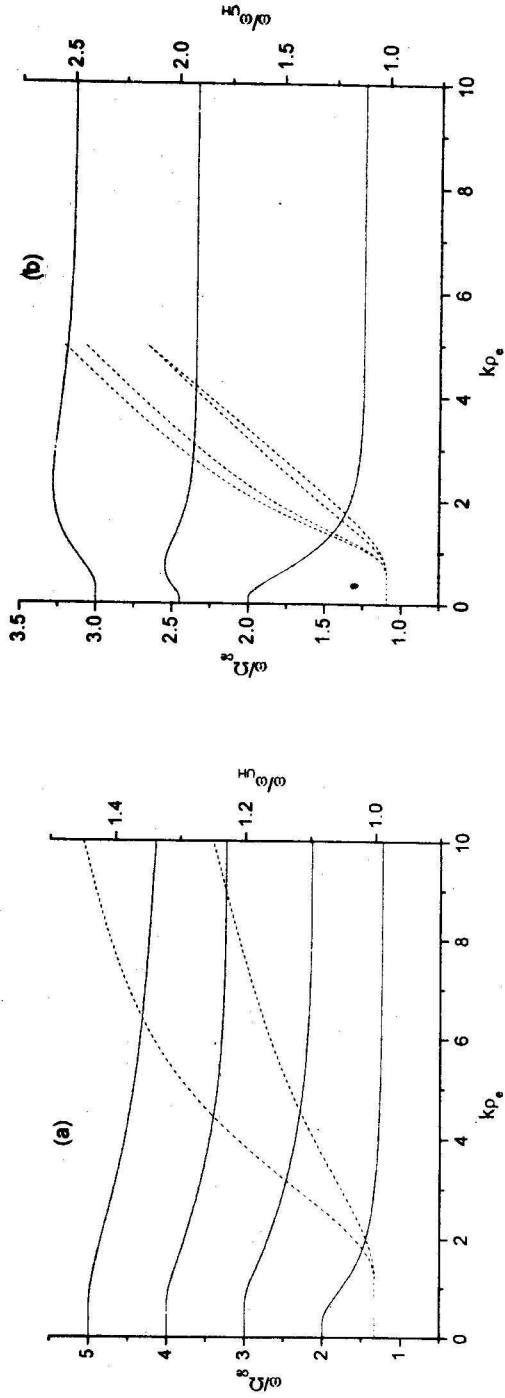


Fig. 1. Dispersion relations for electron Bernstein waves in the Io plasma torus.

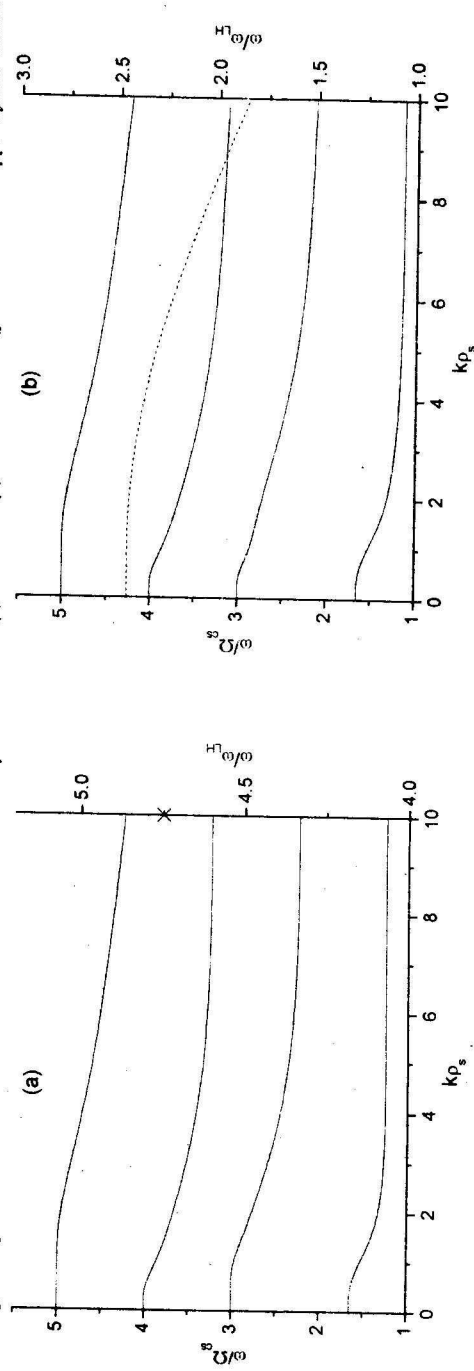


Fig. 2 Dispersion relations for sulphur Bernstein waves in the Io plasma torus. (a) cold torus (b) warm torus. Dashed lines and the cross denote lower hybrid waves.

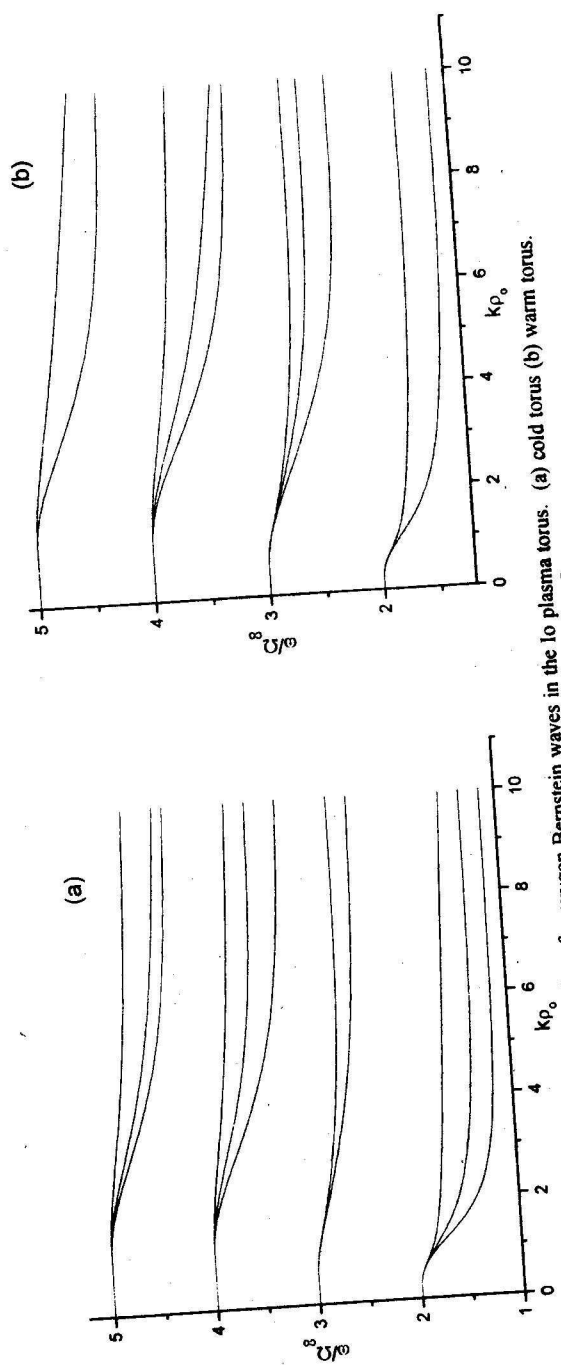
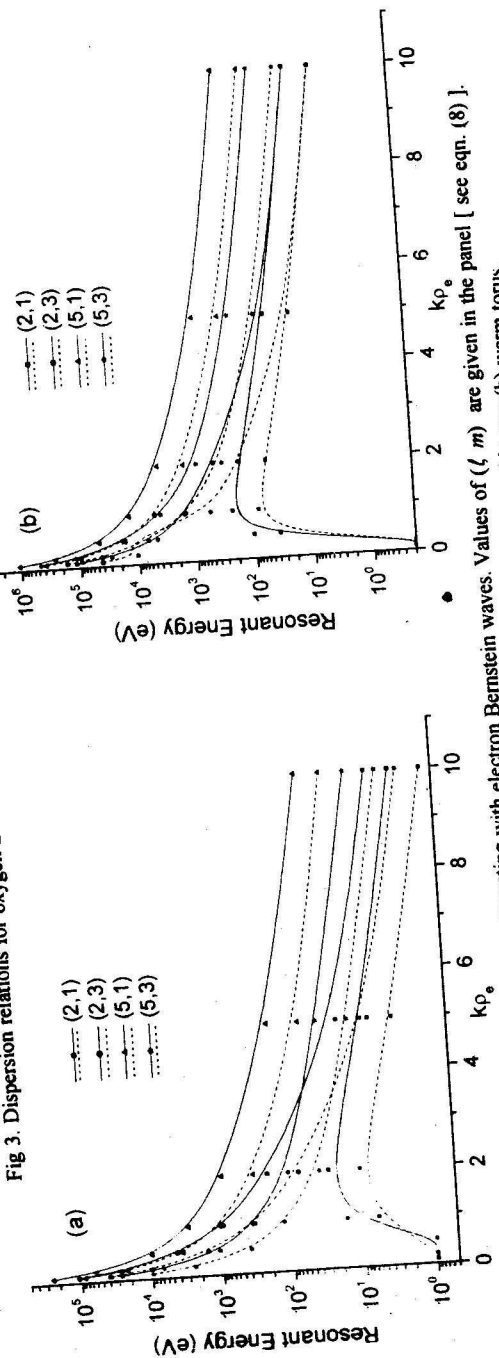


Fig. 3. Dispersion relations for oxygen Bernstein waves in the Io plasma torus. (a) cold torus (b) warm torus.


 Fig. 4 Resonant energies of electron resonating with electron Bernstein waves. Values of (l, m) are given in the panel [see eqn. (8)]. Solid lines are for $\phi = 84^\circ$ and dashed lines are for $\phi = 80^\circ$. (a) cold torus (b) warm torus.

When thermal effects are included equation (4) gives rise to Bernstein modes. In Figure 1, dispersion relation for electron Bernstein modes are shown for both cold and warm torus. In figure 2, sulphur Bernstein modes are shown. Buchsbaum mode can be seen in this figure. For electrons the dispersion relations show a remarkable change from cold to warm torus while sulphur there is not much change. In figure 3, the oxygen Bernstein modes are shown. It may be remarked here that the oxygen Bernstein modes are divided into two or three branches. This effect arises from coupling of sulphur and oxygen ions in the dispersion relation. In figure 1, the dispersion relation for upper hybrid resonance and Figure 2, for lower hybrid resonance are also shown.

3. Resonant Energies

The scattering of trapped particles by plasma waves is dominated by resonant interactions at harmonics of the particle cyclotron frequency. This leads to precipitation of particles into the atmosphere. The resonant condition is given by

$$(8) \quad \omega - k_{\parallel} v_{\parallel} = l\Omega_c$$

where $k_{\parallel}$, $v_{\parallel}$ are components of the wave propagation vector and particle velocity along the ambient magnetic field direction. We note that $\omega/\Omega_c = m + \eta$, where m is an integer.

We have considered three kind of waves : electron Bernstein mode, sulphur Bernstein mode, and oxygen Bernstein mode.

The resonant for electrons, sulphur ions and oxygen ions are shown in Figures 4-8 respectively for both cold and hot plasma torus at two directions of wave propagation vector from ambient magnetic field (ϕ), 80° and 84° . For electrons it is seen that the resonant energies lie between 10eV to 10keV. The specific values depend on the value of $k\rho_e$ and the wave cyclotron harmonic. The values of resonant energies being an order of magnitude higher for hot torus as compared to cold torus. Resonant energies for sulphur and oxygen ions are higher than those for electrons. Further, the sulphur and oxygen cyclotron waves can also interact with oxygen and sulphur ions. These are also shown. The resonant energies for electron cyclotron waves interacting with sulphur and oxygen ions and sulphur and oxygen waves interacting with electrons are several order of magnitude higher where there are no particles are available. These are therefore not shown.

4. Energization of Particles

Electrostatic electron and ion cyclotron waves can heat the particles during resonant wave particle interaction, [Lysak¹⁵ *et.al.*] Energy evolves according to the coupled equations.

$$(9) \quad \frac{dW_{\perp}}{dt} = W_{\perp \text{ turb}} - \frac{3W_{\perp} v_{\parallel}}{R}$$

$$(10) \quad \frac{dv_{\parallel}}{dt} = \frac{3W_{\perp}}{mR} + \frac{e}{m} E_{\parallel}$$

The first term of the first equation represents the heating by electrostatic turbulence and is given by

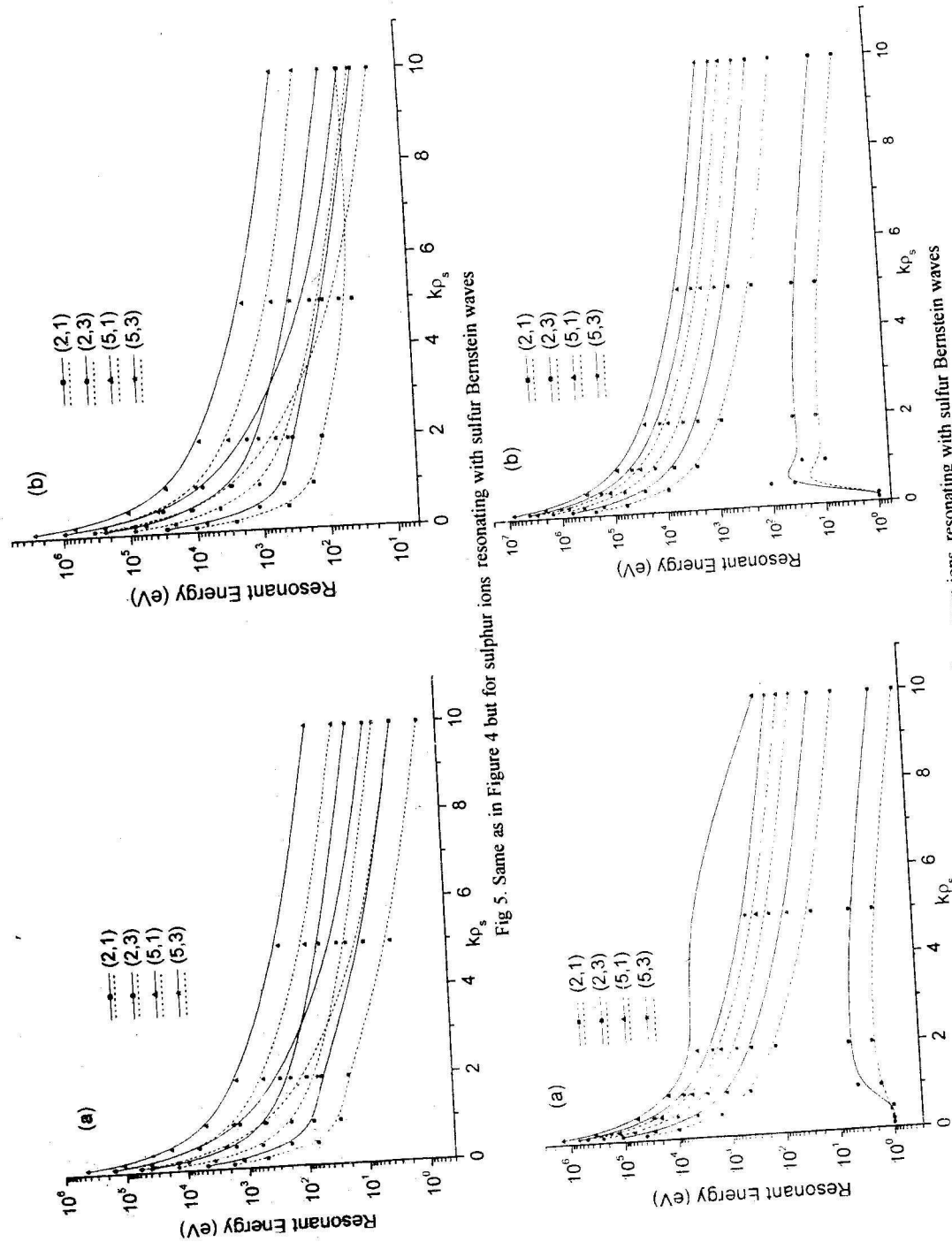


Fig. 5. Same as in Figure 4 but for sulphur ions resonating with sulfur Bernstein waves

Fig. 6 Same as in Figure 4 but for oxygen ions resonating with sulfur Bernstein waves

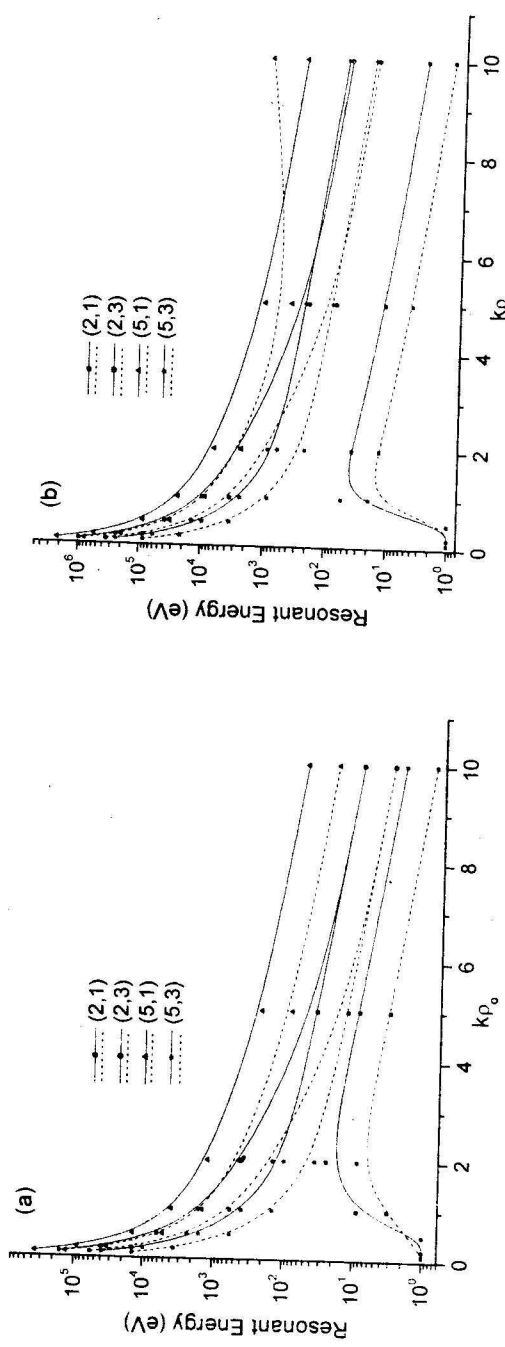


Fig 7. Same as in Figure 4 but for oxygen ions resonating with oxygen Bernstein waves.

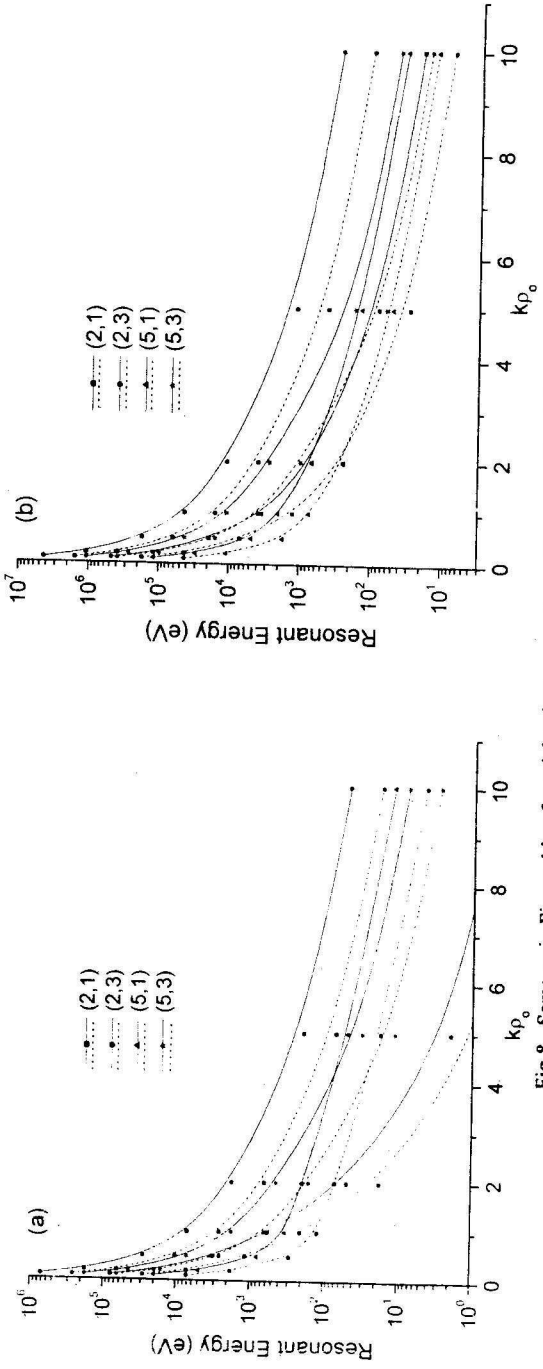


Fig 8. Same as in Figure 4 but for sulphur ions resonating with oxygen Bernstein waves.

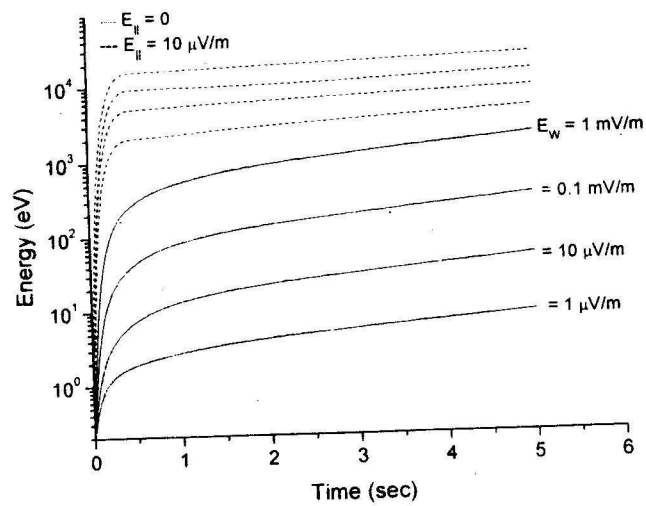


Fig 9. Energy of electrons heated by electron Bernstein waves. Values of parallel electric field ($E_{||}$) and wave electric field (E_w) are as marked.

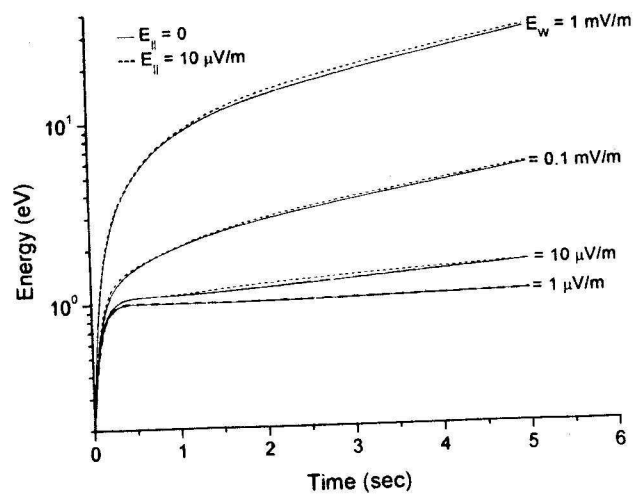


Fig. 10 Same as in Figure 9 but for sulphur ions.

$$(11) \quad W_{\perp \text{ turb}} = e^{\Phi_0} \Omega_c \left[\frac{2m \Omega_c^2}{\pi^2 k_{\perp}^2 W_{\perp}} \right]^{1/4} n$$

for a wave with $\omega = n\Omega_c$.

The second term of the first equation and the first term of the second equation represent the transfer of perpendicular to parallel energy caused by the mirror force. The final term gives the effect of parallel electric fields. The calculation starts at $t = 0$ with $W_{\perp} = 1$ eV and $v_{\parallel} = 0$. The results are shown in Figures 9–11 for electrons, sulphur and oxygen ions. It is found that electrons can be energized up to 20 keV for reasonable values of parallel electric field and wave electric fields, Bhattacharya¹⁶ *et.al.* The ions can be heated to only few tens of eV. Thus, the electrostatic waves can provide a source of energetic electrons for auroral precipitation. However, the electrostatic waves can only provide a source of superthermal ion population which requires other mechanisms for energizing the ions.

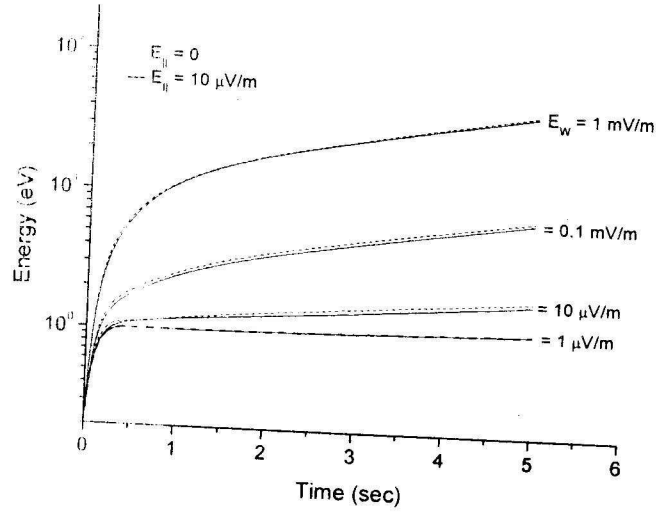


Fig. 11 Same as in Figure 9 but for oxygen ions.

5. Discussion and Calculations

Io plasma torus is a source of particles precipitating in the Jovian auroral ionosphere, [Thorne and Tsurutani¹⁷, Thorne¹⁸, Thorne¹⁹ and Horanyi²⁰ *et.al.*] Electrostatic plasma waves play an important role in the scattering and energizing of these particles. At present it is not completely understood whether the aurora is produced by energetic electrons or energetic ions. In the present work we find that electrostatic plasma waves can energize electrons to sufficiently high energies. However, ions can not be energized to desired energies. Therefore other mechanism of energization are needed for ions. The resonant energies for pitch angle scattering of particles depend on Bernstein harmonic mode and the direction of wave normal. The growth of these waves in the Io plasma torus is governed by energetic tail of the particles which are best described by Kappa distribution function [Summer and Thorne²¹]. Barbosa and Kurth²² have studied

the growth of electron Bernstein waves for first and second harmonic bands using the power law electron distribution function. We are studying the growth of higher harmonic bands for electrons and ions using Kappa distribution function in the Io plasma torus and other outer planets. This will help in identifying the resonant energies of particles which can be pitch angle scattered into the auroral ionosphere. Results will be reported in a future paper.

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