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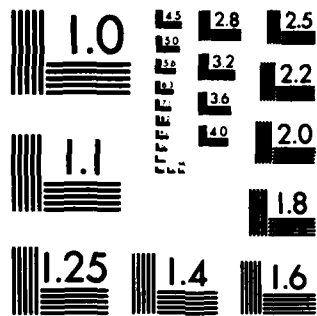
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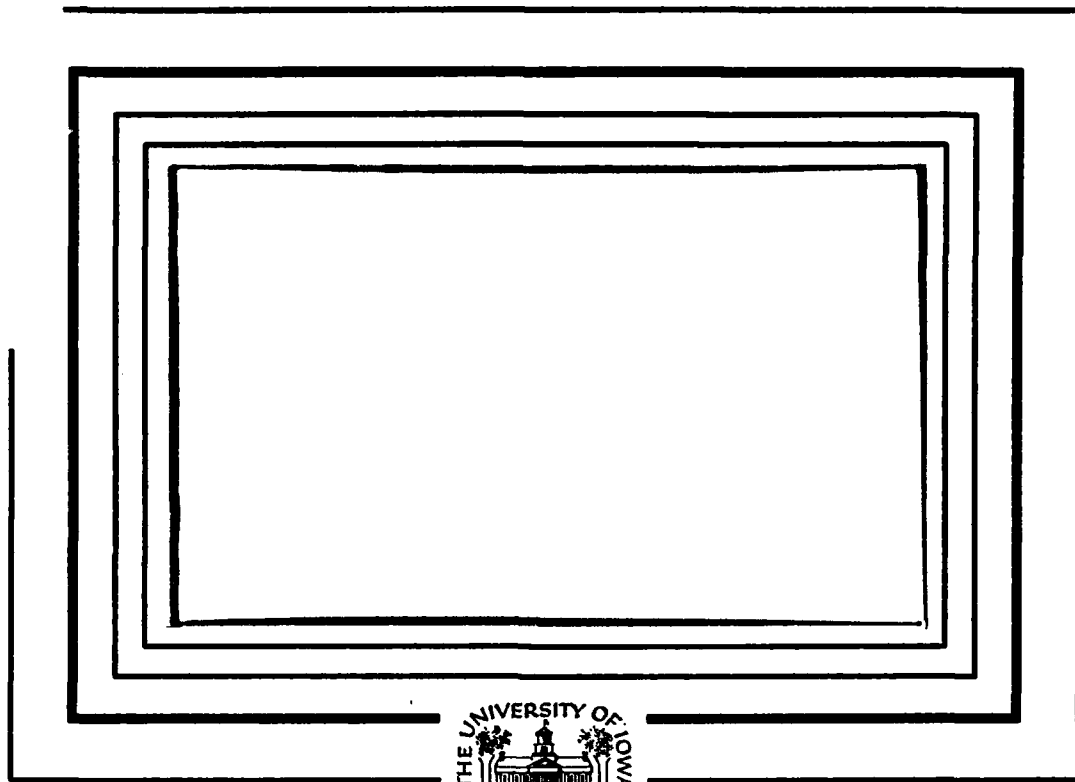
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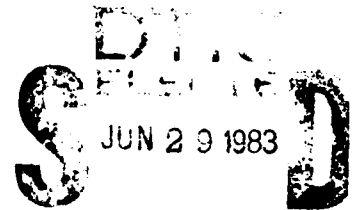
Ion Cyclotron Waves in the Io Plasma Torus:
Polarization Reversal of Whistler Mode Noise

by

D. A. Gurnett and C. K. Goertz

January 1983
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ABSTRACT

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Because of the presence of multiple ion species in the Io plasma torus whistler mode noise can be converted to ion cyclotron waves via a polarization reversal process at the local crossover frequency. Using whistler mode intensity measurements in the Jovian magnetosphere from Voyager 1 we estimate the pitch-angle diffusion rates that would occur if the noise is converted to ion cyclotron waves. Typical pitch-angle diffusion coefficients range from $D_{\alpha\alpha} \approx 10^{-6} \text{ sec}^{-1}$ for protons resonating near the equator to $D_{\alpha\alpha} \approx 10^{-4} \text{ sec}^{-1}$ for 10 keV O^{+} ions resonating at high latitudes. Although complete bounce averaged diffusion coefficients have not yet been computed, preliminary estimates indicate that the energetic ion precipitation caused by these waves may be able to account for the EUV auroral emissions at the foot of the torus field lines.

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I. INTRODUCTION

The Voyager 1 flyby of Jupiter demonstrated that intense EUV auroral emissions are present at high latitudes in the Jovian atmosphere [Broadfoot et al., 1979]. It is now generally accepted that the charged particle precipitation responsible for the aurora is caused by wave-particle interactions in the Io plasma torus. Nearly a decade ago it was predicted that right-hand polarized whistler mode noise would be generated by energetic electrons in the Jovian magnetosphere and that pitch-angle scattering by these waves would be the dominant loss process for these particles. These expectations were given strong support by the Pioneer 10 and 11 energetic particle measurements which showed electron pitch-angle distributions consistent with a whistler mode scattering process [Van Allen et al., 1975; Fillius et al., 1976], and were confirmed by the Voyager 1 plasma wave observations of intense whistler mode noise in the inner regions of the magnetosphere [Scarf et al., 1979a]. Because the whistler mode noise reached peak intensity in the Io plasma torus, it was immediately suggested [Thorne and Tsurutani, 1979; Scarf et al., 1979b] that pitch-angle scattering by the whistler mode noise could account for the aurora observed at the foot of the torus L-shells. Integrated over the entire auroral zone (from L=5 to L=9) the energy input worked out to be a few times 10^{13} watts. However, later estimates by Sandel et al. [1979] showed that an electron energy input of about 1.7×10^{14} watts was required to produce the aurora.

Thus, although whistler mode scattering of electrons produces a very substantial energy input into the atmosphere, it is not quite adequate to explain the aurora.

The whistler mode scattering mechanism for producing the Jovian aurora was further criticized by Goertz [1980], who pointed out, among other things, that there is no way of resupplying an electron energy loss of 10^{14} watts in the torus. Instead, Goertz suggested that the aurora was produced by pitch-angle scattering of protons. It is well established that energetic protons and ions with energies of several hundred keV are strongly depleted in the vicinity of the Io torus [Thomsen et al., 1977a; Krimigis et al., 1979]. The favored wave mode for scattering protons and ions is the ion cyclotron mode. The generation of ion cyclotron waves in the vicinity of the torus has been considered by Thorne and Moses [1983]. The principal difficulty with the ion cyclotron scattering mechanism is that up to the present time no observations have been reported of ion cyclotron waves in the Io torus. In this paper we examine the possibility that the heavy ion precipitation is due to ion cyclotron waves produced by polarization reversal of whistler mode noise generated in the torus.

II. POLARIZATION REVERSAL IN THE IO PLASMA TORUS

As shown by Stix [1962], when two or more positive ion species are present in a plasma the index of refraction for the left-hand and right-hand polarized modes cross for propagation parallel to the magnetic field. The frequency where the modes cross is called the crossover frequency f_x , and is given by the equation $D = 0$ in the notation of Stix. The crossover frequency was first discussed in detail by Smith and Brice [1964]. They showed that one crossover frequency occurs between each adjacent pair of ion cyclotron frequencies. For waves propagating at an angle to the magnetic field the two modes split apart as shown in Figure 1, and the polarization reverses as the wave frequency crosses the crossover frequency. The left-hand polarized branch (L) then connects smoothly and continuously to the right-hand polarized branch (R). The right-hand polarized mode is called the whistler mode and the left-hand polarized mode is called the ion cyclotron mode. Because of the polarization reversal, the ion cyclotron mode and whistler mode are actually on the same branch of the dispersion relation. Therefore, a whistler mode wave propagating through an inhomogeneous plasma is converted directly to an ion cyclotron wave at the crossover frequency. Ion cyclotron whistlers provided the first example of this polarization reversal phenomena [Gurnett et al., 1965].

Because several ion species are present in the Io torus polarization reversal effects should occur at frequencies near and below the proton cyclotron frequency. As discussed by Bridge et al. [1979] O^+ and S^{2+} are believed to be the dominant species in the torus, which is the primary region of interest. Since both O^+ and S^{2+} have the same mass to charge ratio ($m/q = 16$) it doesn't matter which ion is used in the model, because both ions have the same cyclotron frequency. A model for the proton and heavy ion concentration and the resulting variation of the crossover frequency with distance s along a magnetic field line is shown in Figure 2 for a field line passing through the torus at $L = 6$. The proton and heavy ion concentrations are from a diffusive equilibrium model given by Tokar et al. [1982]. As can be seen the crossover frequency varies from just below the proton cyclotron frequency, f_{CH+} , near the equatorial plane to just above the heavy ion cyclotron frequency, f_{CO^+} , in the outer regions of the torus. As indicated in the bottom panel, right-hand polarized whistler mode waves (R) propagating away from the equator are converted to ion cyclotron waves (L) as soon as the crossover frequency passes below the wave frequency. Because whistler mode waves propagating away from the equator do not encounter the crossover frequency until they reach the outer edge of the torus, ion cyclotron waves generated by this mechanism can only be observed outside of the torus. The low frequency limit of the band of ion cyclotron noise generated by this process is the local crossover frequency. The upper frequency limit is determined by the crossover frequency at the equator, f_{xe} .

For positively charged particles the resonance energy for parallel propagation is given by

$$W = \frac{1}{2}mc^2 \frac{1}{n} \left(\frac{f c l}{f} \pm 1 \right)^2, \quad (1)$$

where mc^2 is the rest mass energy and n is the index of refraction. The minus sign gives the energy for resonance with left-hand polarized ion cyclotron waves, and the plus sign gives the energy for the "anomalous" resonance with right-hand polarized whistler mode waves. The top panel of Figure 3 shows the index of refraction at a representative frequency of 20 Hz for the torus model described in Figure 2, and the bottom panel shows the corresponding resonance energy for protons and O^+ ions.

As can be seen from the bottom panel of Figure 3, the resonance energies all have a discontinuity at the polarization reversal. This discontinuity arises because of the sign change in Equation 1 as the polarization reverses. Except for the discontinuity at the crossover, the proton resonance energy tends to increase with increasing distance from the equator, varying from about 45 keV near the equator to about 10 MeV at $s = 3 R_J$. For proton energies less than about 10 MeV the primary region for resonant wave particle interactions is within about $3 R_J$ of the magnetic equator. The variation of the O^+ resonance energy along the magnetic field line is more complicated and is characterized by an abrupt null at the points ($s = \pm 5 R_J$) where the wave frequency crosses the O^+ cyclotron frequency. As can be seen from Equation 1, the parallel resonance energy goes to zero whenever the wave frequency crosses

the cyclotron frequency. It is not certain that the wave remains in the ion cyclotron mode as it crosses f_{C0^+} , because the crossover is again encountered just above f_{C0^+} . However, the O^+ concentration is very low in this region so it is unlikely that the polarization will reverse back to the whistler mode. Similar cyclotron resonance effects also occur for other heavier ion species even farther from the equator.

III. PITCH-ANGLE SCATTERING RATES

We now investigate the pitch-angle scattering produced by the low frequency right-hand polarized and left-hand polarized waves. A representative electric field spectrum of the whistler mode noise detected in the Io torus by Voyager 1 is shown in Figure 4. This spectrum is one of several given by Scarf et al. [1979b] and was selected from near the L = 6 field line so that it can be compared with the torus models in Figures 2 and 3. The noise in Figure 4 is believed to be entirely due to whistler mode emissions because, except for a small range of frequencies just below the proton cyclotron frequency, the whistler mode is the only mode that can propagate in this frequency range. There is no evidence of an enhancement near f_{CH^+} that would suggest that the ion cyclotron mode is present near the equator at this frequency. From the local ion concentration the crossover frequency is estimated to be about $f_x = 28$ Hz. As can be seen from Figure 2, all waves below 28 Hz, down to about 8 Hz, should be converted to ion cyclotron waves as the waves propagate away from the equator.

The relevant quantity for evaluating pitch-angle scattering is the diffusion coefficient D_{xx} , where x is the cosine of the equatorial pitch angle, $x = \cos \alpha_0$. Using the results of Schulz and Lanzerotti [1974], the average diffusion coefficient for parallel propagation can be shown to be

$$\begin{aligned}
 D_{xx} &= \left\langle \frac{1}{2} \left(\frac{y}{x}\right)^2 \cos^2 \alpha \left(\frac{f \sin^2 \alpha \pm f_{ci}}{f \pm f_{ci}}\right)^2 \left(\frac{n n_{Re}}{c^2}\right) \left(\frac{E_{1e}^2(f)}{\Delta f}\right) \left(\frac{\omega_{ci}}{B}\right)^2 \right\rangle \\
 &= \left(\frac{y}{x}\right)^2 \langle D(s) \cos^2 \alpha \rangle
 \end{aligned}
 \tag{2}$$

where $y = \sin \alpha_0$, α is the local pitch-angle, f_{ci} the local ion gyro-frequency, n is the local index of refraction, n_{Re} is the index of refraction of the R wave at the equator and $E_{1e}^2(f)/\Delta f$ is the equatorial electric field spectral density evaluated at the resonance frequency

$$f = \pm f_{ci} / (1 - v n \cos \alpha / c) \tag{3}$$

where v is the particle's speed. The angular bracket indicates bounce averaging. In the derivation of Equation 2 we have used the relation $E_{\perp} = B_{\perp} c/n$ between the electric (E_{\perp}) and magnetic (B_{\perp}) field amplitudes of the wave and assumed that for parallel propagation the wave energy is conserved, i.e., $(B_{\perp}^2/n)A = \text{constant}$ where A is the cross sectional area of a flux tube. Note that Equation 2 predicts a value $D(s)$ which is a factor $\eta = 1 + v \cos \alpha / v_g$ ($v_g = \text{group velocity at resonance}$) larger than the equations used by Scarf et al. [1979b] and Thorne [1983]. This difference is due to a different definition of the effective bandwidth for resonance. Schulz and Lanzerotti use $\Delta f = 1/t$ where t is the interaction time, whereas Scarf and Thorne essentially use $\Delta f = 1/\eta t$.

The L waves we predict to exist outside the torus have $f < f_{cH^+}$ and we see that protons can only resonate if their parallel speed exceeds c/n_L . The resonance energy for protons interacting with L waves ranges from a minimum value at $f = f_{xe}$ to a maximum at $f = f_x$. The resonance energy for heavy ions ranges from zero ($f = f_{ci}$) to large values. The R waves occur in two frequency bands, $f < f_x$ and $f > f_{xe}$. Since the index of refraction for R waves depends on frequency, an ion of a given energy can in general interact with three different frequencies via the anomalous resonance (see Figure 21 of Schulz and Lanzerotti [1974]). At the equator ($s = 0$) a 1 MeV proton resonantly interacts with R waves at 2 Hz, 6 kHz and 60 kHz. Interactions with high frequency R waves are negligible because of the low wave intensity at high frequencies. The intensity at 2 Hz is not measured. However, it is likely that the spectrum in Figure 4 extends well below 10 Hz. The low frequency portion of the spectrum can be represented by $E_{1e}^2/\Delta f = 10^{-7}/f \text{ V}^2 \text{ m}^{-2} \text{ Hz}^{-1}$ with f in Hz. Using $n_R(2 \text{ Hz}) \approx 400$ we obtain $D(s = 0) = 4 \times 10^{-4} \text{ s}^{-1}$ for a 1 MeV proton. At $s = 1 R_J$ the same 1 MeV proton is in resonance with a 50 Hz R wave for which $n_R = 150$. The corresponding diffusion coefficient is $D(s = 1 R_J) = 6 \times 10^{-6} \text{ s}^{-1}$. If no polarization reversal had occurred, a 1 MeV proton would resonate only with very high frequency R waves beyond $s = 1.5 R_J$ and the diffusion coefficient $D(s > 1.5 R_J)$ would be negligibly small. However, at $s = 2 R_J$ a 1 MeV proton is in resonance with a 10 Hz L wave via the normal cyclotron resonance. The diffusion coefficient is $D(s = 2 R_J) = 10^{-5} \text{ s}^{-1}$, many orders of magnitude larger than if the

polarization reversal had not occurred. The effect of the polarization reversal is to provide a significant increase in the pitch-angle scattering of protons outside the torus. Beyond $s = 2.5 R_J$, a 1 MeV proton would be in resonance with L waves of frequencies exceeding 28 Hz. No L waves exist above this frequency, so beyond $s = 2.5 R_J$ a 1 MeV proton can only be in anomalous resonance with very high frequency R waves ($f > 10$ kHz) which have low intensities and cause negligible diffusion.

For energetic heavy ions (such as O^+) which are known to constitute a significant fraction of the energetic ion population, the polarization reversal has similar but even more dramatic consequences. As we have indicated, O^+ ions with low energies can resonate with the L waves in regions where $f = f_{cO^+}$. Outside the torus O^+ ions with energies less than a few MeV have $vn/c \ll 1$ and we can write a good approximation

$$D_{O^+}(s > 2 R_J) = \frac{\cos^2 \alpha}{v^2} \left(\frac{n_{Re}(f_{ci})}{n_L(f_{ci})} \right) \frac{E_{le}^2(f_{ci})}{\Delta f} \left(\frac{\omega_{ci}}{B} \right)^2 \quad (4)$$

Even though the numerical factor $(\omega_{ci}/B)^2$ is 256 times smaller than that for protons the diffusion coefficient can be large because D is inversely proportional to v^2 rather than c^2 . For example, at $s = 5 R_J$, D is $10^{-6} s^{-1}$ for a 1 MeV O^+ ion and $10^{-4} s^{-1}$ for a 10 keV O^+ ion. For a 1 MeV O^+ ion the diffusion coefficient D varies from $2 \times 10^{-5} s^{-1}$ at the equator, where it depends in a complicated way on pitch angle, to $\lesssim 10^{-7} s^{-1}$ at $s = 2 R_J$, increasing to $10^{-6} s^{-1}$ between $s = 2 R_J$ and

$s = 3 R_J$. Between $s = 3 R_J$ and $s = 5.5 R_J$, D is nearly constant at $10^{-6} s^{-1}$. Beyond $s = 5.5 R_J$, D decreases rapidly to very low values. The value between $s = 3 R_J$ and $s = 5.5 R_J$ is inversely proportional to energy whereas the value of D near the equator (i.e., inside the torus) is quite insensitive to energy.

The bounce averaged diffusion coefficient is given by

$$D_{xx} = \left(\frac{y}{x}\right)^2 \frac{\int D(s) \cos^2 \alpha dt}{\int dt} = \left(\frac{y}{x}\right)^2 \frac{4}{T_b v} \int_0^s D(s') \cos \alpha(s') ds' \quad (5)$$

where T_b is the particle's bounce period. To evaluate this integral precisely requires numerical integration. However, a fair estimate can be obtained by noting that $\cos^2 \alpha = 1 - y^2 B/B_e$ and $B = B_e [1 + (3/4 L R_J)^2 s^2]$. For protons we find $D_{xx} \sim 10^{-5} s^{-1}$, nearly independent of y and energy. For O^+ ions we find $D_{xx} \approx (10^{-6}/W)s^{-1}$ for $W < 1$ MeV, with W in units of MeV. Had we included the factor η the value of the proton diffusion coefficient would be reduced by a factor of about 8. For O^+ ions the factor η is near 1, which does not significantly change the value of D_{xx} .

The resonance interaction of electrons with the low frequency whistlers has been discussed by Scarf et al. [1979b]. They estimate the bounce averaged pitch-angle diffusion coefficient for 1 MeV electrons at $6.14 R_J$ as $D_{xx} \approx 2 \times 10^{-5} s^{-1}$. Since the lifetime of particles is inversely proportional to D_{xx} we expect 1 MeV electrons to be lost more rapidly than 1 MeV protons and O^+ ions. However, the strong depletion

of the inward diffusing protons and heavy ions at the orbit of I_0 requires $D_{LL} \tau \sim 2.6 \times 10^{-2}$ [Thomsen et al., 1977a,b and Thorne, 1983] where D_{LL} is the radial diffusion coefficient. For electrons Thomsen et al. [1977a,b] estimate $D_{LL} \tau \sim 0.4$. If D_{LL} is the same for electrons and ions (as is thought to be the case) observations show that electrons are lost less rapidly than protons and ions, contrary to our expectations. We have no simple explanation for this discrepancy. One possibility would be that the waves are not whistlers. In that case no gyroresonant pitch-angle scattering of electrons and ions would occur. That, of course, leaves us with the problem of explaining the strong ion losses. Another possibility is that the radial diffusion coefficient may not be the same for electrons and ions. It has been proposed by several authors (see for example, Siscoe and Summers [1981]) that in the torus there is an enhanced radial transport because of density gradient driven instabilities. It is possible that the wavelength of the most unstable waves ($\sim 0.1 R_J$) is smaller than the gyroradius of the energetic ions. One would then expect the energetic ions to average over the fluctuations, which would reduce the transport. Electrons are magnetized and would be carried along by the random movements of the magnetic field lines.

The importance of the pitch-angle scattering for the EUV observations depends on whether the diffusion is in the strong or weak limit. If the diffusion is weak ($D_{xx} T_b \ll y_c^2 \approx 1/L^3(4 - 3/L)^{1/2}$, where y_c is the sine of the equatorial loss cone), the pitch-angle distribution is anisotropic and only very few particles are in the loss cone. If the diffusion is strong the distribution is isotropic and the loss-cone is

filled. Strong precipitation, of course, requires a large number of particles in the loss cone. The numbers calculated above would indicate that 1 MeV protons are between weak and strong diffusion. The fact that Van Allen [1976] observes a non-isotropic proton pitch-angle distribution at ~ 1 MeV also indicates that the proton scattering has not yet reached the strong diffusion limit. The same is true for 1 MeV O^+ ions. However, O^+ ions below about 100 keV should be in strong diffusion because their bounce period is long ($> 10^3$ seconds) and their diffusion coefficient is large ($> 10^{-5} \text{ s}^{-1}$). We predict that these heavy ions contribute most importantly to the particle precipitation and to the production of auroral EUV emission.

IV. DISCUSSION

We have explored the possibility that whistler mode noise generated by energetic electrons in the Io plasma torus can be converted to ion cyclotron waves by a polarization reversal process. It has been shown that ion cyclotron waves produced by the polarization reversal at the crossover frequency interact with energetic protons and heavy ions over a broad range of energies, from less than 10 keV to above 10 MeV. This energy range corresponds to the range where energetic ion fluxes are strongly depleted in the Io torus. Both the "anomalous" resonance with right-hand polarized waves and the normal cyclotron resonance with left-hand polarized waves are important. The anomalous resonance provides the dominant interaction inside the torus, and the normal cyclotron resonance is the dominant interaction outside the torus. Estimates of the pitch-angle diffusion coefficients show that these waves cause significant pitch-angle scattering for both protons and heavy ions. For protons the region of strong pitch-angle scattering is confined to within a few R_J of the equator. For O^+ ions the region of strong pitch-angle scattering extends farther from the equator, almost down to the foot of the field line. Below about 100 keV the O^+ diffusion coefficients exceed the strong diffusion limit. Although detailed bounce average diffusion calculations have not yet been performed, our estimates indicate that the low frequency whistler mode noise and associated

ion cyclotron waves can cause significant losses of energetic ions from the Io torus, thereby possibly accounting for the aurora at the foot of the torus field lines. We also note that the depletion of inward diffusing electrons should be stronger than that of protons and 1 MeV heavy ions. This result is in disagreement with the observations which show that electrons are lost less rapidly. This disagreement suggests that the radial diffusion coefficient for energetic ions may be different from the radial diffusion for electrons. It could also indicate that the electric field noise observed in the torus has been erroneously identified as whistler mode waves. Because the Voyager 1 plasma wave instrument did not measure magnetic fields or polarization it cannot be conclusively proven that the intense low frequency electric field noise is propagating in the whistler mode, as has been widely assumed. If the noise is not propagating in the whistler mode then the entire issue of pitch-angle scattering by whistler mode waves would have to be re-examined.

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FIGURE CAPTIONS

- Figure 1 The index of refraction of the right- and left-hand polarized modes for a plasma with two species of positively charged ions.
- Figure 2 A model for the ion distribution along the $L = 6$ magnetic field line and the resulting variation of the crossover frequency with distance along the field line.
- Figure 3 The index of refraction and resonance energies for the torus model in Figure 2. The "anomalous" resonance refers to the interaction between ions and right-hand polarized whistler mode waves.
- Figure 4 A representative Voyager 1 electric field spectrum of whistler mode waves near the equator in the Io torus. Waves in the cross-hatched region are converted to ion cyclotron waves as they propagate away from the equator.

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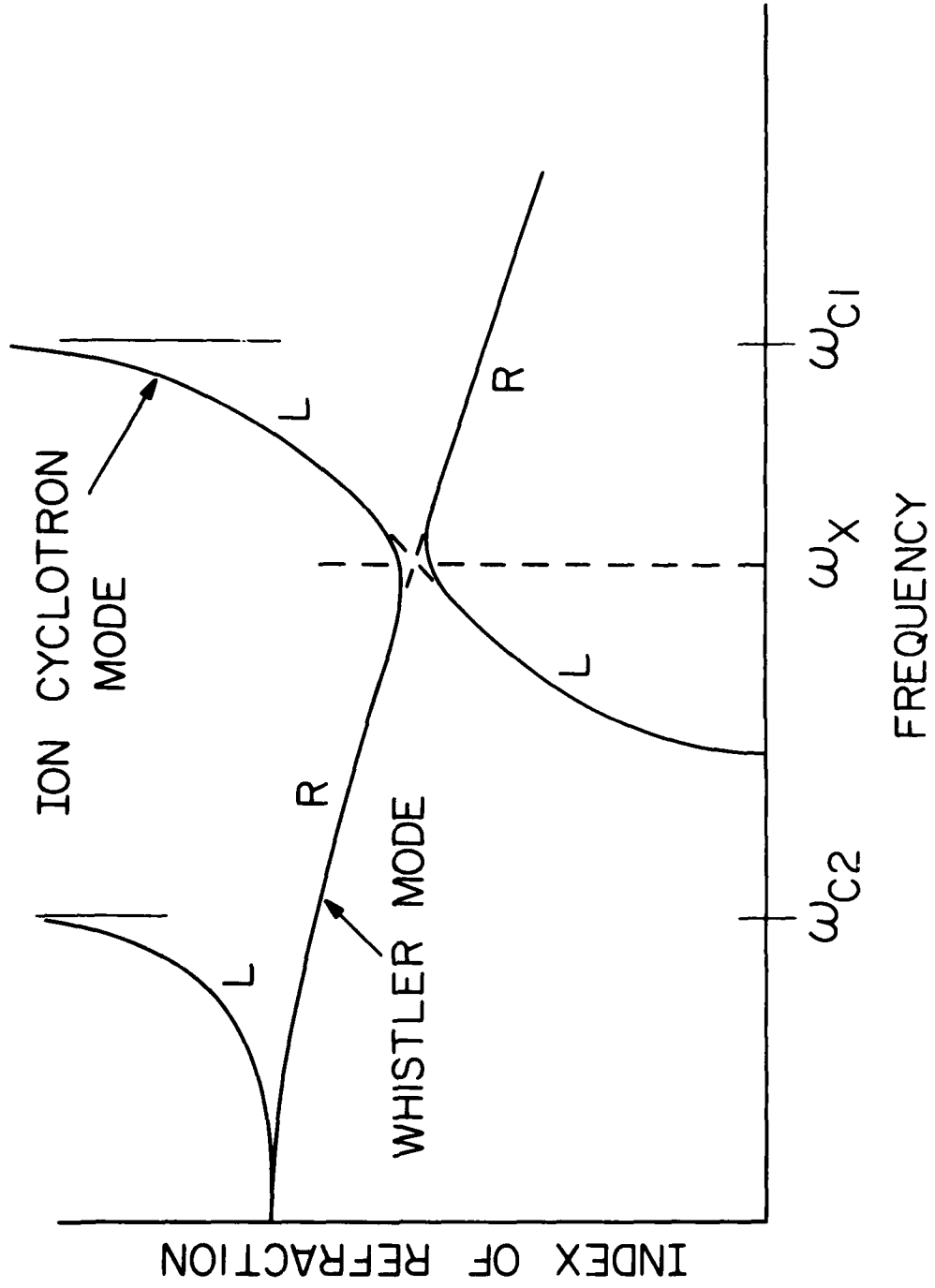


Figure 1

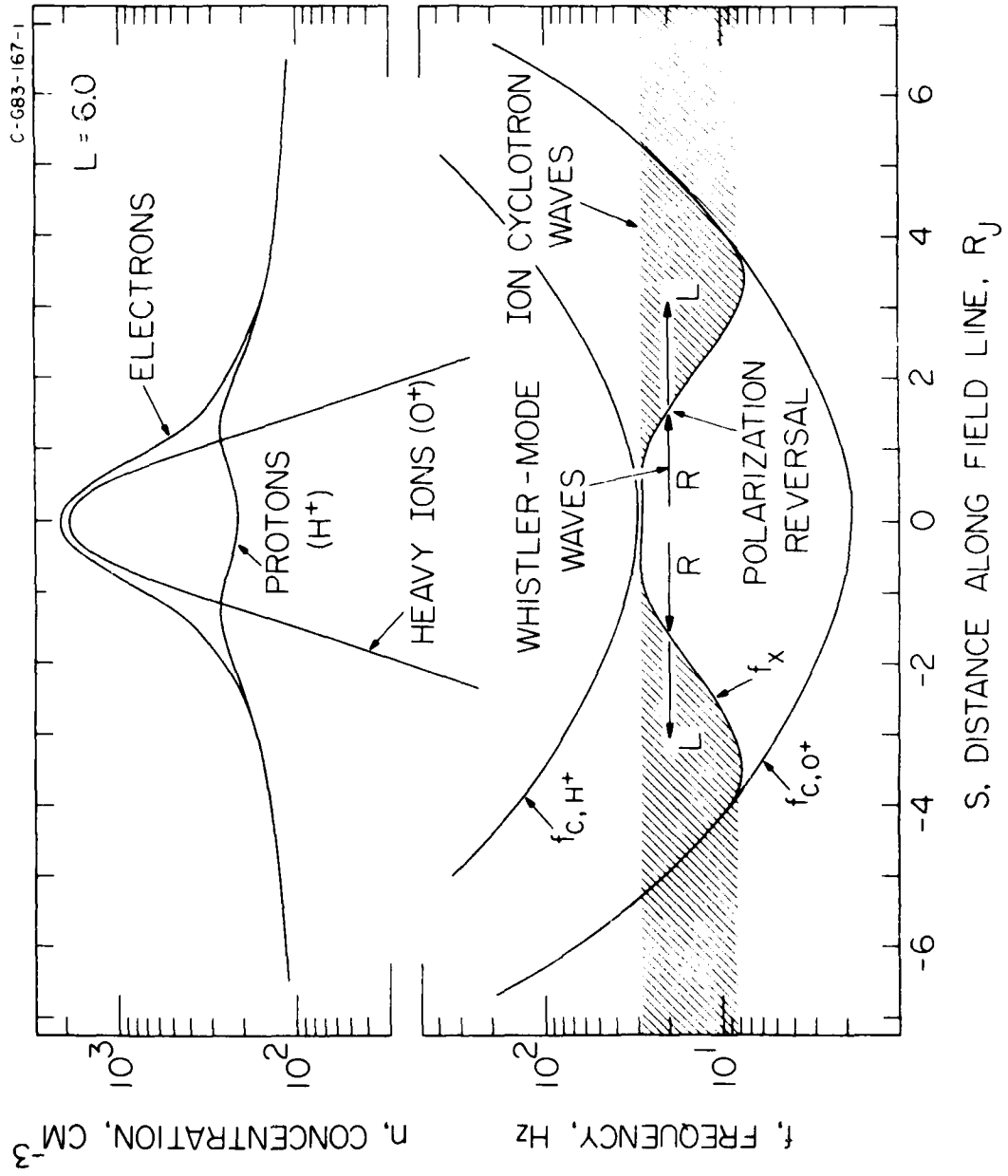


Figure 2

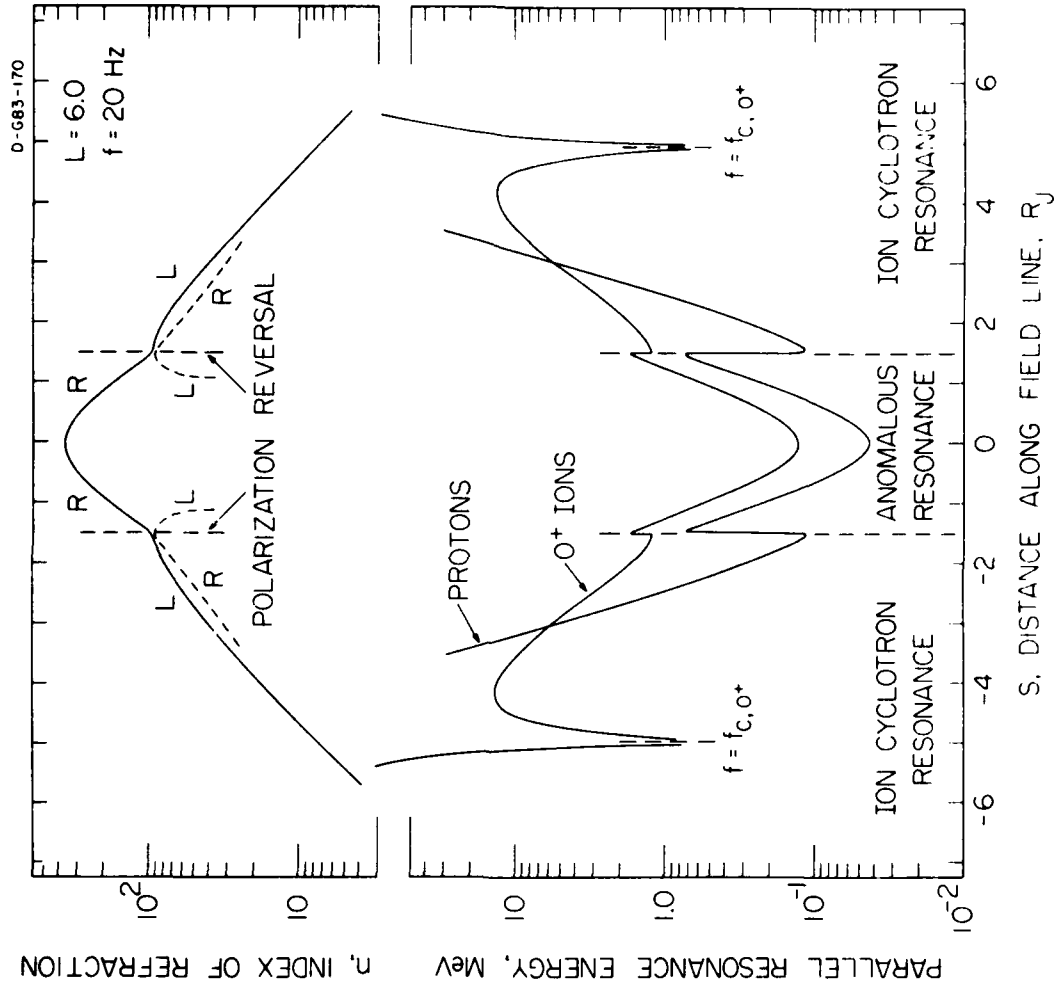


Figure 5

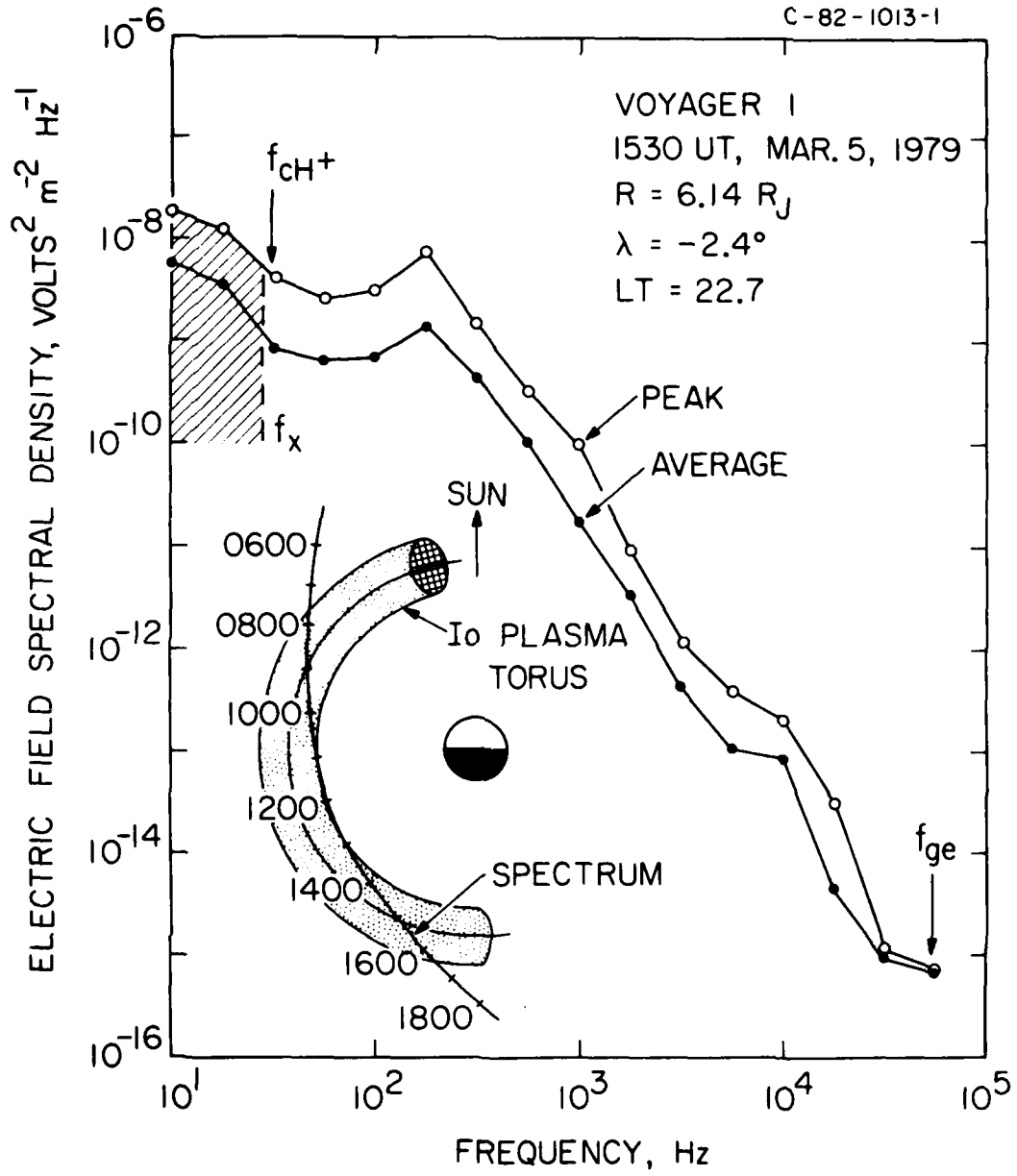


Figure 4

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