ION DIFFUSION IN THE IO PLASMA TORUS

by

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MASTER'S THESIS

This is to certify that the Master's thesis of

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ABSTRACT

The pitch-angle scattering of protons due to resonance with left-hand polarized ion cyclotron waves and anomalous resonance with right-hand polarized whistler mode waves was studied as a means for producing the EUV auroral emissions at the foot of the Io torus field lines. A polarization reversal process can convert whistler mode noise to ion cyclotron waves at the local crossover frequency due to the presence of multiple ion species in the Io plasma torus. Local crossover frequencies were computed along a dipole field line at $L = 5.85$ to determine the latitudes at which whistler mode waves would be converted to ion cyclotron waves. Resonance frequencies for right-hand and left-hand polarized waves were determined along the field line using the computed values of resonance energies for parallel propagation. Three anomalous resonance frequencies were identified in the range .7 Hz to 80 kHz from the magnetic equator to approximately $s = 1.5\ R_J$. Using electric field measurements from Voyager 1, believed to be due to whistler mode noise, bounce averaged diffusion coefficients were computed for both types of resonance for the case of a 1 MeV proton with an equatorial pitch angle of 30°. The total coefficient was $0.7 \times 10^{-6}\ \mathrm{sec}^{-1}$, within the range for weak to strong diffusion, indicating that proton precipitation into the atmosphere due to resonance with both types of waves may account for

the EUV emissions. The diffusion coefficient for protons resonating with whistler mode waves was approximately ten times greater than the coefficient for protons resonating with ion cyclotron waves.

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INTRODUCTION

During the Voyager 1 flyby of Jupiter, auroral activity in the form of EUV (extreme ultraviolet) emissions was detected [Broadfoot et al., 1979]. The activity was located on Jupiter's nightside in both hemispheres over a latitude range of 65 to 75 degrees. Broadfoot et al. noted that this range of latitude corresponded to the foot of the magnetic field lines which pass through the plasma torus surrounding the orbit of Io. Magnetospheric physics defines an L value as the value of the radius at which a magnetic field line crosses the equator of a planet in units of the planet's radius. Here $L = R(\text{equator})/R_J$ where R_J = radius of Jupiter. An L shell is a surface of constant L value. In this parlance, the auroral zone was found to be at the foot of L shells from $L = 5$ to $L = 9$, which is the region of the Io torus.

Work over the past decade has lead to the conclusion that the charged-particle precipitation into the atmosphere resulting in the aurora is due to wave-particle interactions in the Io plasma torus. However, the nature of the wave-particle interaction has not been clear. In the first detailed models of the Jovian radiation belts, it was predicted that energetic electrons would generate right-hand polarized whistler mode noise and that pitch-angle scattering of the electrons by these waves would precipitate electrons into the atmosphere. This prediction was supported by the Pioneer 10 and 11 experiments which measured electron pitch-angle distributions in agreement with scattering by whistler mode waves [Van Allen, 1976; Fillius et al., 1976]. After Scarf et al. [1979] confirmed that the Voyager 1 plasma wave instrument detected whistler mode waves and that the noise was most intense in the Io torus, it was suggested that the aurora at the foot of torus field lines was caused by pitch-angle scattering of electrons by the whistler mode noise in the torus [Scarf et al., 1979; Thorne and Tsurutani, 1979]. However, because the electron energy input into the auroral zone due to whistler mode scattering was computed to be a few times 10^{13} Watts, the process was discounted as an explanation for the aurora when Sandel et al. [1979] demonstrated that an electron energy input of 1.7×10^{14} Watts was necessary for the aurora.

In addition, Goertz [1980] noted that while it was known that protons and ions with energies of several hundred keV are lost in the torus [Thomsen et al., 1977], significant electron losses in the torus had not been observed. He also noted that there was no known continuous power supply of 10^{14} Watts in the torus. His alternative explanation was that the aurora was due to pitch-angle scattering of protons in the torus, which was known to be an area of increased plasma density. He observed that the rate of loss of protons was adequate to power the aurora. However, the wave mode primarily responsible for pitch-angle scattering of protons--the ion cyclotron mode--has never been observed in the Io torus.

The purpose of this work was to study the hypothesis that the aurora results from pitch-angle scattering of protons in resonance with two types of wave modes: 1) left-hand polarized ion cyclotron waves generated by polarization reversal of whistler mode noise produced in the torus, and 2) right-hand polarized whistler mode waves. The resonance of protons with ion cyclotron waves is referred to as cyclotron resonance and the resonance of protons with whistler mode waves is referred to as anomalous resonance [Schultz and Lanzerotti, 1974]. A proton of given total energy and equatorial pitch angle is pictured as resonating with either type of wave, depending on the latitude, as it orbits Jupiter. The diffusion coefficient, the pertinent quantity for assessing pitch-angle scattering, was calculated for protons with several total energies ranging from 10 keV to 10 MeV and a variety of equatorial pitch angles.

The calculation of a diffusion coefficient required several steps. First, the crossover frequency--the frequency below which a wave is right-hand polarized and above which a wave is left-hand polarized--was calculated along a dipole field line at $L = 5.85$ in steps of 1° latitude. Then the frequencies of both left-hand and right-hand polarized waves with which a proton of given total energy and equatorial pitch angle would resonate along the field line were computed using an expression for resonance energy and the Doppler shift condition. These resonance frequencies were compared to the crossover frequencies to determine if a computed resonance frequency with a specific polarity at a given latitude could exist at that latitude. The resonance frequencies whose polarities agreed with the crossover data were then used, along the electric field intensity measurements from Voyager I, to compute a diffusion coefficient.

All calculations required the concentrations of the particle species present in the Jovian magnetosphere at L = 5.85: protons (H^+), electrons, O^{2+}, S^{2+}, S^+, and SO_2^+. These concentrations were taken from a diffusive equilibrium model by Tokar et al. [1982] and are shown in Figure 1.

Several assumptions were used in this study. The magnetosphere was modeled as a perfect dipole field. The waves were pictured as propagating parallel to the field line and energy conservation was assumed (damping was not taken into account). The latter two assumptions will be discussed in the following chapters.

II. POLARIZATION REVERSAL OF WHISTLER MODE NOISE

Stix [1962] demonstrated that if the energy flow of a wave in a plasma containing two or more positive ion species is along the magnetic field line, there is a frequency at which the indices of refraction for the left-hand and right-hand polarized modes are equal. Using the notation of Stix, this frequency, called the crossover frequency f_x, is given by D = 0 where

$$D = \sum_s \frac{f_{ps}^2 \, f_{cs}}{f(f^2 - f_{cs}^2)} \tag{1}$$

where f_{ps}^2 is the plasma frequency squared for the s^{th} species and f_{cs} is the cyclotron frequency for the s^{th} species.

One crossover frequency occurs between each adjacent pair of ion cyclotron frequencies [Smith and Brice, 1964]. If the angle between the wave normal vector $\vec{k}$ and the magnetic field line is greater than a critical value θ_c then the indices of refraction for the two modes cross. As Figure 2 shows for the case of a plasma for two species of positively charged ions, the left-hand and right-hand modes split at f_x. The left-hand polarized branch (L), the ion cyclotron mode, connects to the right-hand polarized branch (R), the whistler mode. A whistler mode wave of a certain frequency propagating away from the equator is converted to an ion cyclotron wave at the latitude where the wave's frequency just exceeds the crossover frequency. The first example of such a polarization reversal was given by ion cyclotron whistlers [Gurnett et al., 1965].

Because there are five species of positive particles in the Io torus at L = 5.85, there are four crossover frequencies at each latitude, or alternatively, at each distance from the equator along the field line. Figure 3 is a plot of the crossover frequencies from the equator to s = 5 R_J and shows that there is one crossover frequency between each adjacent pair of ion cyclotron frequencies. Each of the four crossover frequencies is just below the upper cyclotron frequency for small s values and just above the lower cyclotron frequency for large s values. Polarization reversal should affect waves with frequencies just above a crossover frequency. Thus, at each latitude there are four frequency ranges corresponding to ion cyclotron waves. The lower limit for each range is the crossover frequency at that latitude and the upper limit is the crossover frequency at the equator.

III. RESONANCE WITH ION CYCLOTRON WAVES AND WHISTLER MODE WAVES

Ion cyclotron resonance occurs when a positively-charged particle, spiraling about a magnetic field line in a left-handed sense, observes that its angular frequency is equal to the frequency of an ion cyclotron wave whose electric field vector is also rotating in a left-handed sense. The particle and wave are travelling in opposite directions ($v_\parallel$ is opposite to v_p, the phase velocity) and so in the particle's frame of reference, the wave has a higher frequency than in the laboratory frame of reference. This is expressed by the Doppler shift condition

$$\omega - k_\parallel v_\parallel = \omega_c \tag{2}$$

where ω is the frequency of the wave in the laboratory frame of reference, ω_c is the angular frequency of the particle, $v_\parallel$ is the component of the particle's velocity parallel to the magnetic field line, and $k_\parallel$ is the component of the wave normal vector $\vec{k}$ parallel to the field line ($k_\parallel = k$ since parallel propagation is assumed).

Anomalous resonance occurs when a positively charged particle, again spiraling about a magnetic field line in a left-handed sense, moves in the same direction as a whistler-mode wave, but with a greater speed than the phase velocity of the wave ($v_\parallel > v_p$). Although in the laboratory frame the electric field vector of the wave rotates in a right-handed sense, the particle sees it rotate in a left-handed sense with a frequency equal to its angular frequency. In the particle's frame of reference, the wave has a lower frequency than in the laboratory frame of reference. This is expressed by the Doppler shift condition

$$\omega - k_{\parallel} v_{\parallel} = -\omega_c \quad . \tag{3}$$

The effect of particle resonance with a wave can be seen by examining the expression for conservation of the first adiabatic invariant applicable to charged particle motion in a magnetic field:

$$\mu = \frac{\sin^2\alpha}{B} = \text{constant} \tag{4}$$

where μ is the magnetic moment, α is the local pitch angle (the angle between the magnetic field and the particle's velocity) and B is the local magnetic field. At the mirror point, the point along the field line at which the particle turns around in its motion, $\alpha = 90°$ and $B = B_m$, the magnetic field value at the mirror point. Then

$$\mu = \frac{1}{B_m} \tag{5}$$

and (4) can be written as

$$\frac{\sin^2 \alpha}{B} = \frac{1}{B_m} \tag{6}$$

or

$$\sin^2 \alpha = \frac{B}{B_m} \tag{7}$$

Equation (7) shows that there is some value of the pitch-angle α_c at which B_m equals the maximum value of the magnetic field. For pitch angles less than α_c, no mirror point exists and the particle no longer bounces back and forth along the field line, but precipitates into the atmosphere.

When the particle is in resonance with a wave, the wave's electric field amplitude increases and the particle's velocity component perpendicular to the magnetic field ($v_\perp$) decreases. Because the total energy of the particle is conserved, the velocity component parallel to the magnetic field ($v_\parallel$) increases. Since $v_\parallel = v \cos \alpha$ where v is the constant velocity of the particle, the pitch angle α is and the particle is pitch-angle scattered into the loss cone.

To determine the resonance frequencies at a specific latitude, one begins with the Doppler shift resonance condition:

$$\omega - k_{\parallel} v_{\parallel} = \pm\omega_c \tag{8}$$

where the (+) sign refers to resonance with left-hand polarized waves and the (-) sign refers to resonance with right-hand polarized waves. Solving for $v_{\parallel}$, one finds that

$$v_{\parallel} = \frac{\omega \mp \omega_c}{k_{\parallel}} \quad . \tag{9}$$

The parallel resonance energy $W_{\parallel}$ is then

$$W_{\parallel} = \frac{1}{2}m\ v_{\parallel}^2 = \frac{1}{2}m\ \left(\frac{\omega \mp \omega_c}{k_{\parallel}}\right)^2 \quad . \tag{10}$$

Using $k_{\parallel} = n\omega/c$ and $2\pi f = \omega$, Equation 10 becomes, after some rearrangement,

$$W_{\parallel} = \frac{\frac{1}{2}m\ c^2}{n^2}\ \left(\frac{f_{CH^+}}{f} \mp 1\right)^2 \tag{11}$$

where the (-) sign refers to resonance with left-handed waves and the (+) sign refers to resonance with right-handed waves.

An alternative expression for $W_{\parallel}$ can be found using $W_{\parallel} = \frac{1}{2}m\ v_{\parallel}^2$ and the conservation of the first adiabatic invariant, Equation 4.

$$W_{\parallel} = \frac{1}{2}m\ v_{\parallel}^2 = \frac{1}{2}m(v\ \cos\ \alpha)^2 = W_T(1 - \sin^2\alpha) \tag{12}$$

where W_T is the total energy of the particle. From Equation A,

$$\frac{\sin^2\alpha}{B} = \frac{\sin^2\alpha_o}{B_o} \tag{13}$$

where α_o is the equatorial pitch angle and B_o is the value of the static magnetic field at the equator at L = 5.85. From this equation it is clear that

$$\sin^2\alpha = \frac{B}{B_o}\sin^2\alpha_o \tag{14}$$

and then Equation 12 becomes

$$W_{\parallel} = W_T(1 - \frac{B}{B_o}\sin^2\alpha_o) \quad . \tag{15}$$

The resonance frequencies are those frequencies for which the value of $W_{\parallel}$ given by Equation 15 is equal to the value of $W_{\parallel}$ given by Equation 11.

Graphical illustrations of left-hand and right-hand resonance frequencies are obtained by rearranging Equation 11:

$$n_L^2 = \frac{\frac{1}{2}m\ c^2}{W_\parallel} \left(\frac{f_{CH^+}}{f} - 1\right)^2 \tag{16}$$

for the left-hand case and

$$n_R^2 = \frac{\frac{1}{2}m\ c^2}{W_\parallel} \left(\frac{f_{CH^+}}{f} + 1\right)^2 \tag{17}$$

for the right-hand case. Figure 4 includes graphs of ${n_L}^2$ and the right side of Equation D for the case of a 1 MeV proton with equatorial pitch angle of 30° resonanting at 21 degrees latitude. The intersection of the two graphs marks the left-hand resonance frequency between the cyclotron frequencies for protons and O^{2+} ions.

Figure 5 includes graphs of n_R and the right side of Equation 17 ? for the same case as in Figure 4. The three intersections of the two graphs mark the right-hand resonance frequencies.

IV. CONCLUSIONS

For the case of 1 MeV protons with an equatorial pitch angle of 30° the bounce-averaged diffusion coefficient for parallel propagation was calculated to be 1.7×10^{-6} sec^{-1}. The contribution of anomalous resonance to the coefficient was ten times greater than the contribution of ion cyclotron resonance to the coefficient. From Thomsen and Thorne, it is known that $D_{LL}\ \tau \simeq 2.6 \times 10^{-2}$ where τ, the lifetime of the particle, is inversely proportional to D_{xx} and D_{LL} is the radial diffusion coefficient. Using this relationship and the calculated value for D_{xx}, the value of D_{LL} is estimated to be consistent with earlier estimates of D_{LL}. Pitch-angle scattering of protons by ion cyclotron waves and whistler mode waves does, in part, account for the EUV auroral emissions at the foot of the Io torus field lines.

REFERENCES

Broadfoot, A. L., et al., Extreme ultraviolet observations from Voyager 1 encounter with Jupiter, Science, 204, 979, 1979.

Fillius, W., C. McIlwain, A. Mogro-Compero, and G. Steinberg, Evidence that pitch angle scattering is an important loss mechanism in the inner radiation belt of Jupiter, Geophys. Res. Lett., 3, 33, 1976.

Goertz, C. K., Proton aurora on Jupiter's nightside, Geophys. Res. Lett., 7, 365, 1980.

Gurnett, D. A., and C. K. Goertz, Ion cyclotron waves in the Io plasma torus: Polarization reversal of whistler mode noise, Geophys. Res. Lett., 10, 587, 1983.

Gurnett, D. A., S. D. Shawhan, N. M. Brice, and R. L. Smtih, Ion cyclotron whistlers, J. Geophys. Res., 70, 1665, 1965.

Sandel, B. R., et al., Extreme ultraviolet observations from Voyager 2 encounter with Jupiter, Science, 206, 962, 1979.

Scarf, F. L., F. V. Coroniti, D. A. Gurnett, and W. S. Kurth, Pitch-angle diffusion by whistler mode waves near the Io plasma torus, Geophys. Res. Lett., 6, 653, 1979b.

Scarf, F. L., D. A. Gurnett and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, Science, 204, 991, 1979a.

Schulz, M., and L. J. Lanzerotti, Particle Diffusion in Radiation Belts, Springer, Heidelberg, 78, 1974.

Smith, R. L., and N. Brice, Propagation in multicomponent plasmas, J. Geophys. Res., 69, 5029, 1964.

Stix, T. H., The Theory of Plasma Waves, McGraw-Hill, N.Y., 10, 1962.

Thomsen, M. F., C. K. Goertz, and J. A. Van Allen, On determining magnetospheric diffusion coefficients from the observed effects of Jupiter's satellite Io, J. Geophys. Res., 82, 5541, 1977b.

Thorne, R. M., and B. T. Tsurutani, Diffuse Jovian aurora influenced by plasma injection from Io, Geophys. Res. Lett., 6, 649, 1979.

Tokar, R. L., D. A. Gurnett, F. Bagenal, and R. R. Shaw, Light ion concentrations in Jupiter's inner magnetosphere, J. Geophys. Res., 87, 2241, 1982.

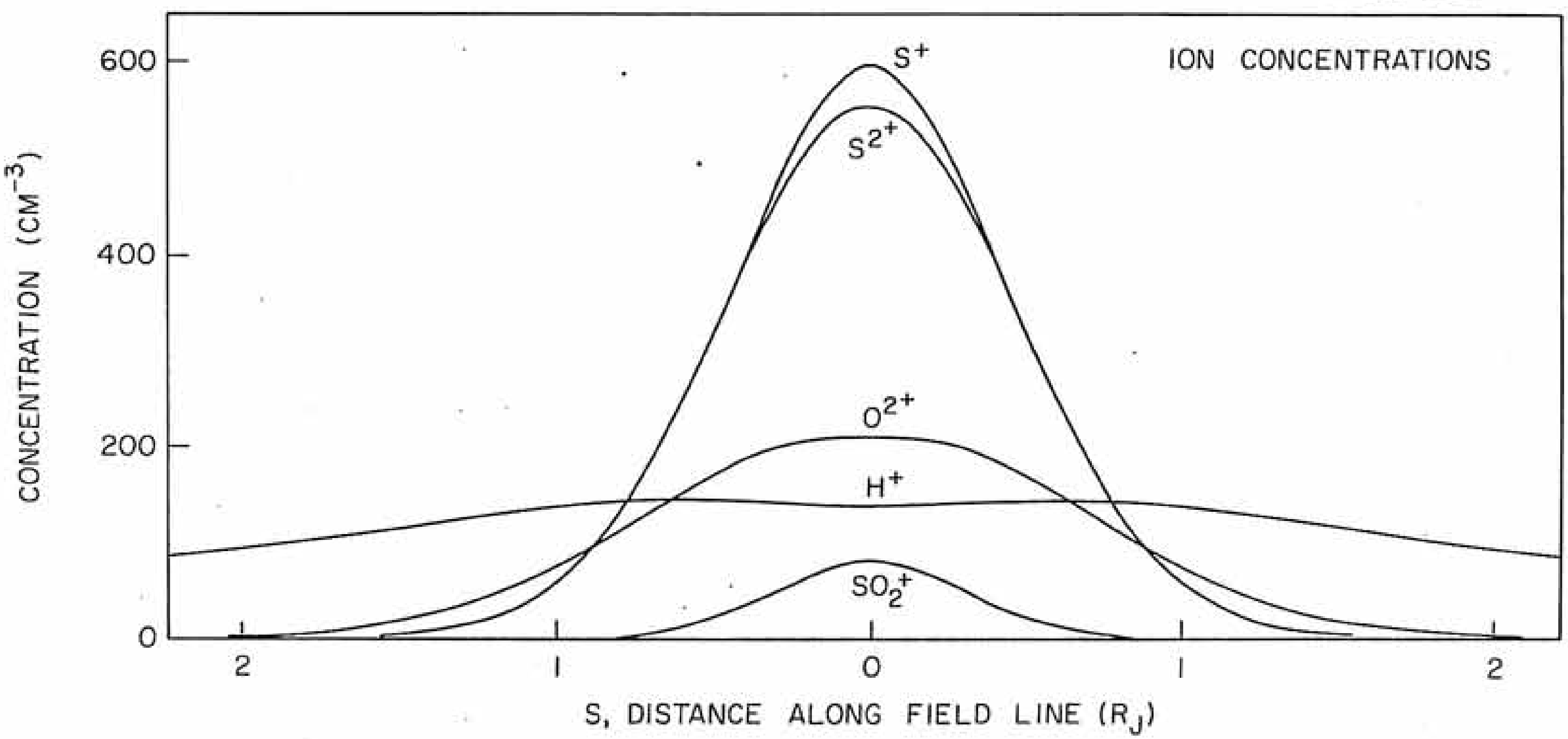
Van Allen, J. A., High-energy particles in the Jovian magnetosphere, Jupiter, ed. by T. Gehrels, U. of Arizona Press, Tucson, Arizona, 928, 1976.

APPENDIX

FIGURES

Figure 1 Concentrations of the 5 ion species in the Io plasma torus at $L = 5.85$.

A-G83-984



ION CONCENTRATIONS
S^+
S^{2+}
O^{2+}
H^+
SO_2^+
CONCENTRATION (CM^{-3})
600
400
200
0
2
1
0
1
2
S, DISTANCE ALONG FIELD LINE (R_J)

Figure 2 Cyclotron and crossover frequencies at L = 5.85 and resonance frequencies used in the calculation of the diffusion coefficient for a 1 MeV proton with an equatorial pitch angle of 30°.

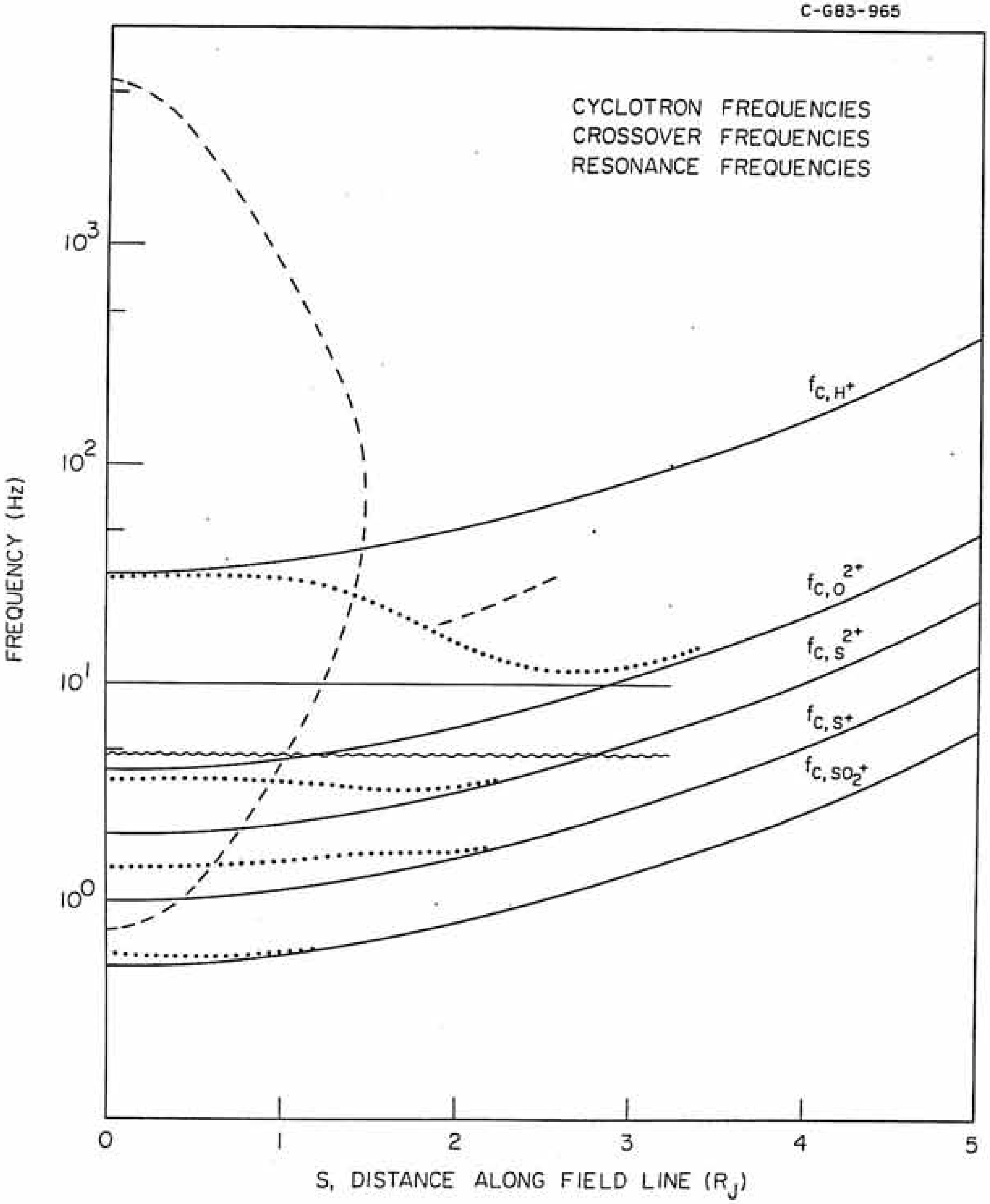
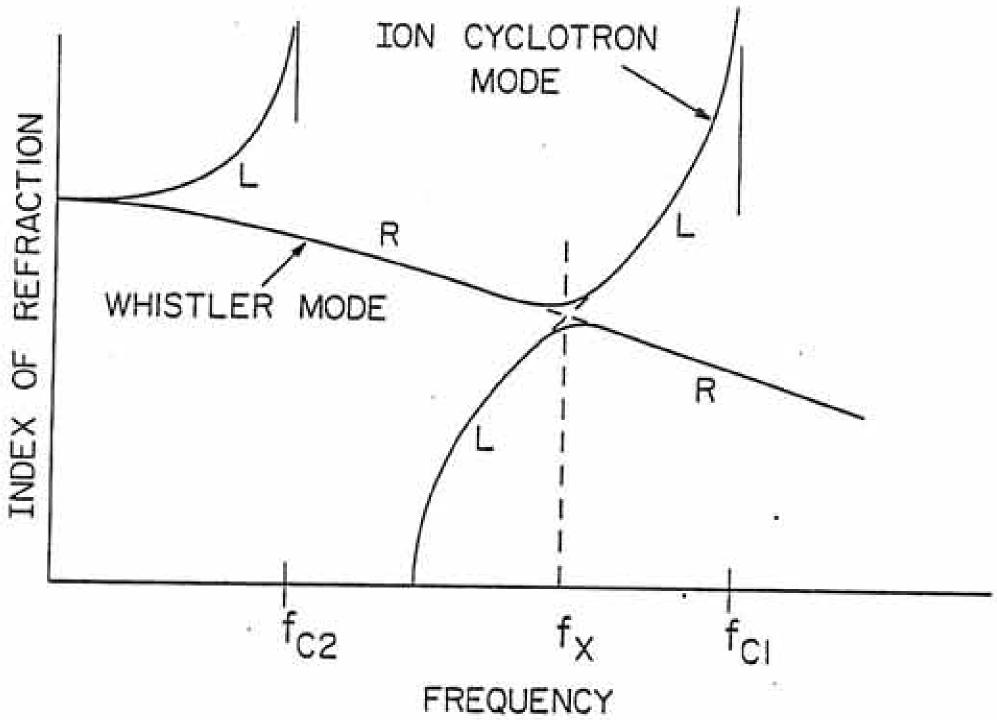

C-G83-965
CYCLOTRON FREQUENCIES
CROSSOVER FREQUENCIES
RESONANCE FREQUENCIES
FREQUENCY (Hz)
10^3
10^2
10^1
10^0
f_{c,H^+}
$f_{c,O^{2+}}$
$f_{c,S^{2+}}$
f_{c,S^+}
f_{c,SO_2^+}
0
1
2
3
4
5
S, DISTANCE ALONG FIELD LINE (R_J)

Figure 3 An illustration of the indices of refraction for the whistler mode and the ion cyclotron mode for a plasma containing two positive species.

A-G83-1031



CROSSOVER FREQUENCY

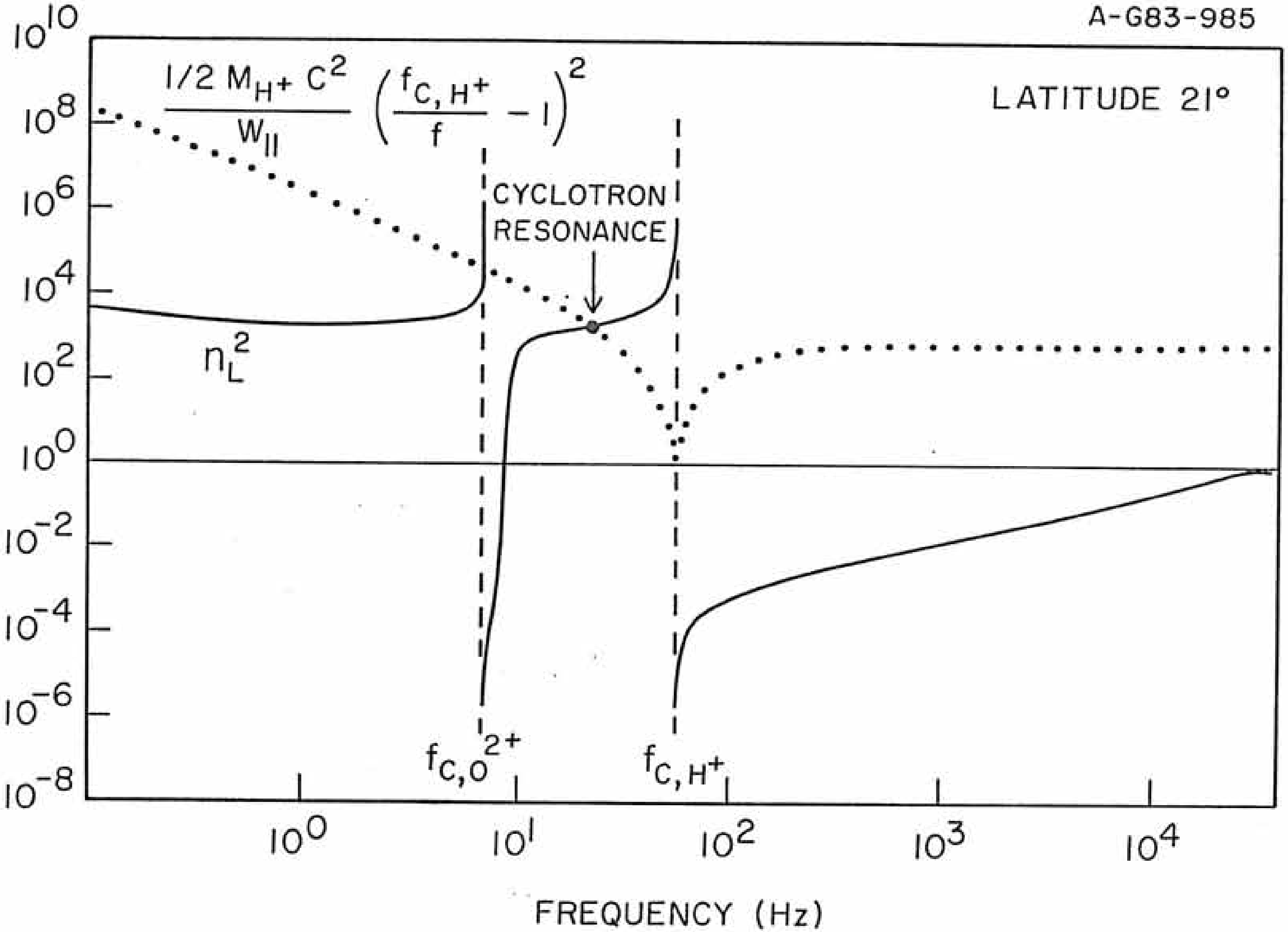
$$D = \sum_s \frac{f_{ps}^{\ 2}\ f_{cs}}{f(f^2 - f_{cs}^{\ 2})} = 0$$

RESONANCE CONDITION

$$W_{\parallel} = \frac{1}{2} m_{H^+} c^2 \frac{1}{(n(f))^2} \left(\frac{f_{CH^+}}{f} \pm 1\right)^2$$

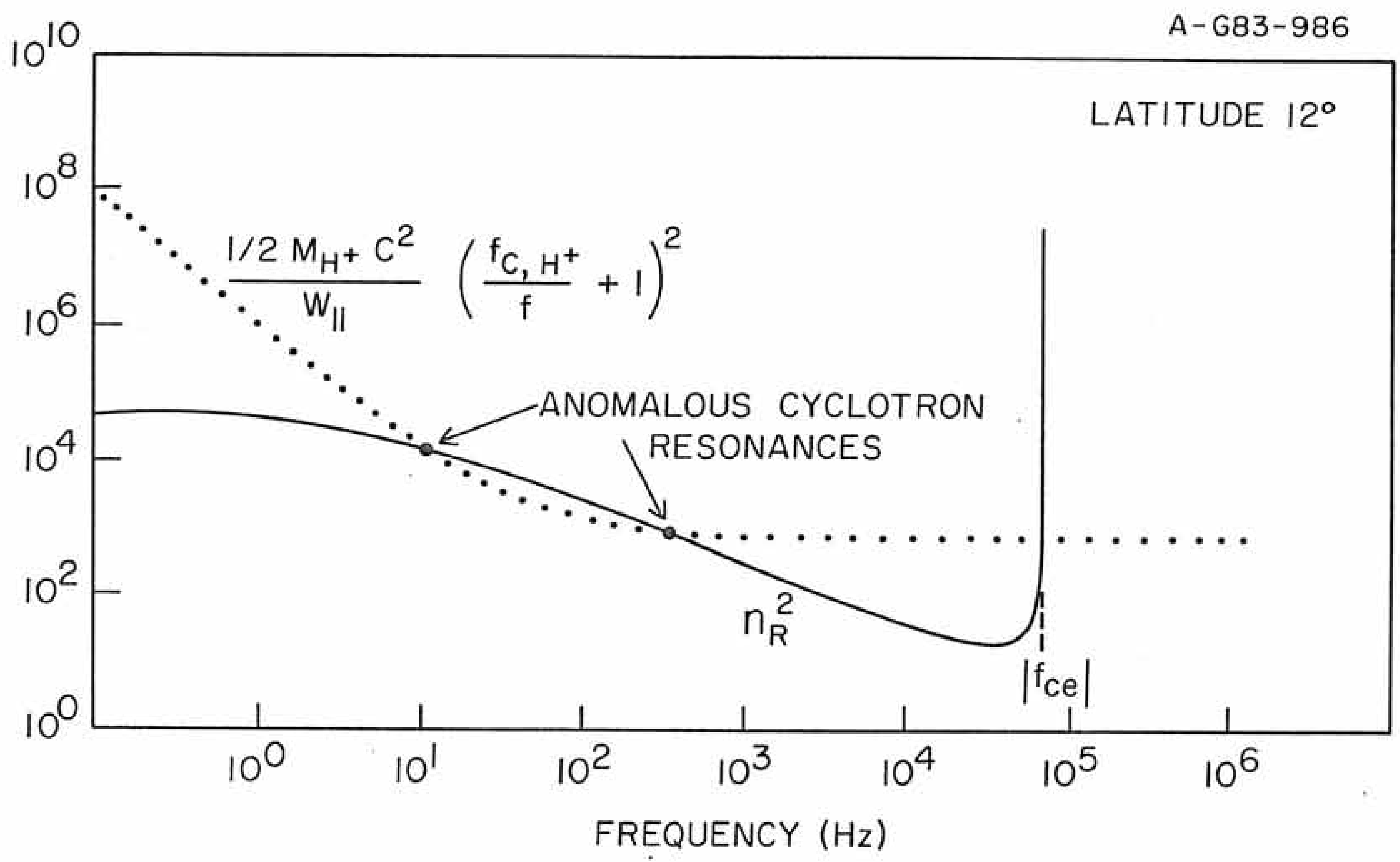
Figure 4 An illustration of the left-handed resonance frequency for a 1 MeV proton with an equatorial pitch angle of 30°.

A-G83-985



10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$\frac{1/2\, M_{H^+} C^2}{W_{\parallel}} \left(\frac{f_{C,H^+}}{f} - 1\right)^2$
LATITUDE 21°
CYCLOTRON RESONANCE
n_L^2
$f_{C,O^{2+}}$
f_{C,H^+}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
FREQUENCY (Hz)

Figure 5 An illustration of the right-handed resonance frequencies for a 1 MeV proton with an equatorial pitch angle of 30°.


A-G83-986
LATITUDE 12°
$\frac{1/2\, M_{H^+} C^2}{W_{\parallel}} \left(\frac{f_{c,H^+}}{f} + 1 \right)^2$
ANOMALOUS CYCLOTRON RESONANCES
n_R^2
$|f_{ce}|$
10^{10}
10^8
10^6
10^4
10^2
10^0
10^0 10^1 10^2 10^3 10^4 10^5 10^6
FREQUENCY (Hz)