WHISTLER PROPAGATION IN THE JOVIAN MAGNETOSPHERE

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Abstract. Computer ray tracing results are presented for lightning generated whistlers propagating in the Jovian Magnetosphere. The waves are launched from a point on the Jovian surface at 66° latitude and propagate approximately along L = 6 out to near the equatorial plane and into the Io plasma torus. The magnetospheric model includes the Io torus centered at the magnetic equator. The torus model is an empirical fit of the density contours presented by Warwick et al. [1979], and the electron density outside of the torus is an adaptation from Sentman and Goertz [1977]. The results clearly indicate that the whistlers propagate through the magnetosphere with very little dispersion until reaching the torus, at which time the dispersion starts to increase very rapidly. We find that the computed dispersions using the assumed electron density model are in excellent agreement with the observed whistler dispersions, thereby confirming the validity of the model.

In addition to the ray path studies, the effect of Landau damping on whistler waves has been investigated as a function of the electron temperature within the torus. For a constant electron temperature of 10^5°K only the lowest frequencies, $\lesssim$1.0 kHz, show appreciable attenuation after passing through the torus. But an increase in the electron temperature of only a factor of three results in a very large attenuation over the entire frequency range observed. This result suggests an upper limit for the electron temperature in the torus of a few times 10^5°K.

Introduction

Data from the plasma wave experiment onboard the Voyager 1 Spacecraft [*Scarf and Gurnett,* 1977] established the presence of whistlers generated by lightning in the Jovian magnetosphere [*Gurnett et al., 1979].* The whistlers observed by Voyager 1 near Jupiter are qualitatively similar to whistlers observed in the earth's magnetosphere, and are characterized by a discrete tone decreasing in frequency with increasing time. The characteristic frequency variation is caused by the dispersive propagation of the lightning impulse through the magnetospheric plasma. For a review of the theory and observations of whistlers in the earth's magnetosphere, see Storey [1953] and Helliwell [1965].

At Jupiter whistlers were only observed over a narrow range of L-shells near the Io plasma torus, from about 5.5 to 6.0 R_J, and within ±10° of the magnetic equator. All of the whistlers observed are believed to have originated from lightning strokes at relatively high latitudes, ~60°, roughly following the magnetic field lines out to the equatorial plane. Two distinctly different classes of whistlers were observed, those with relatively large dispersion of ~500 sec $Hz^{1/2}$ and those with relatively small dispersions of ~50 sec $Hz^{1/2}$. These two classes of whistlers are thought to correspond to whistlers which have, and have not, passed through the high density regions of the Io plasma torus before reaching the spacecraft.

In this paper we present the results of a computer ray tracing analysis of the propagation of whistlers in a model of the Jovian magnetosphere which includes the Io torus. The purpose of this paper is to confirm and extend the simplified initial analysis of whistler propagation in the Jovian magnetosphere given by Gurnett et al. [1979] and to use the whistler measurements as a diagnostic tool for determining characteristics of the magnetospheric plasma. The whistler dispersion is, for example, critically dependent on the plasma density profile along the whistler ray path. We can therefore test a given model of the plasma density distribution by comparing the computed whistler dispersion at a given point with the measured dispersion. In addition, limits on the electron temperature can be obtained from computations of the Landau damping. As will be shown the Landau damping of a whistler is extremely sensitive to the electron temperature, and if the electron temperature of the Io torus is too high then the attenuation becomes unacceptably large for whistlers which have propagated through the torus.

The Model

The Jovian magnetic field was assumed to be a dipole with a magnetic moment of 4.225 gauss R_J^3. A model of the plasma density in the Io torus was obtained by a spline fit interpolation of the density contours published by Warwick et al. [1979]. The torus, in the model, was assumed to be symmetric about the magnetic equator with a maximum density at the center of the torus of about 2500 cm^{-3}. Outside the torus the density profile was an empirical fit to the Pioneer 10 and 11 data of Frank et al. [1976], adapted from the model of Sentman and Goertz [1977]. It was necessary to use the Pioneer data since the flight path of Voyager 1 did not provide any measurements at high latitudes. The combined density model used in the ray tracing computer code is shown in Figure 1. No Jovian ionosphere was included in this model. It is readily demonstrated that the relatively thin ionosphere makes only a minor contribution to the overall dispersion of a whistler.

The computer code used for the whistler ray tracing is based on the Haselgrove [1955] ray tracing equations, and uses the cold plasma index of refraction given by Stix [1962], including the effects of ions. Since the code has been discussed in detail in previous publications [*c.f., Green et al.,* 1977], no description will be included here.

Results

To illustrate some representative ray paths for whistlers in the Jovian magnetosphere a sequence of ray paths was computed starting from a point at the base of the ionosphere, 1.0 R_J, at a latitude of +66°. This initial starting latitude was chosen by trial and error to provide equator crossings at 6 R_J, roughly in the region where whistlers were observed by Voyager 1. Eight frequencies were considered in the frequency range from 0.5 to 7.0 kHz. Each frequency was launched at a different wave

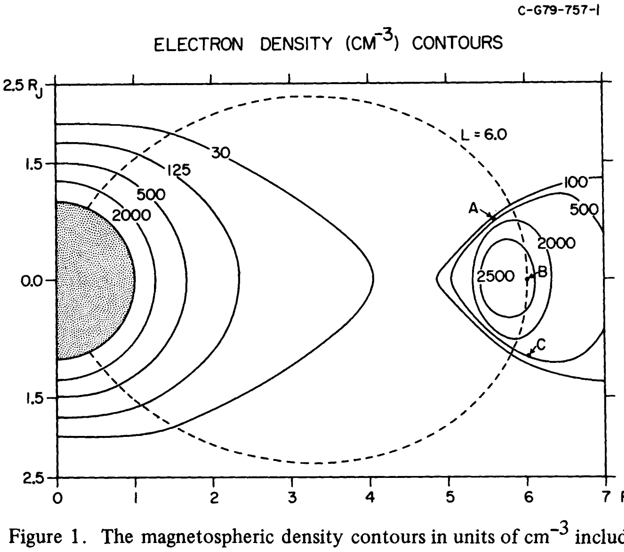

Figure 1. The magnetospheric density contours in units of cm^{-3} including the Io torus. The magnetic field line shown by the dashed line is at L = 6. The locations A, B, and C are points where the dispersions in Figures 3 and 4 were calculated.

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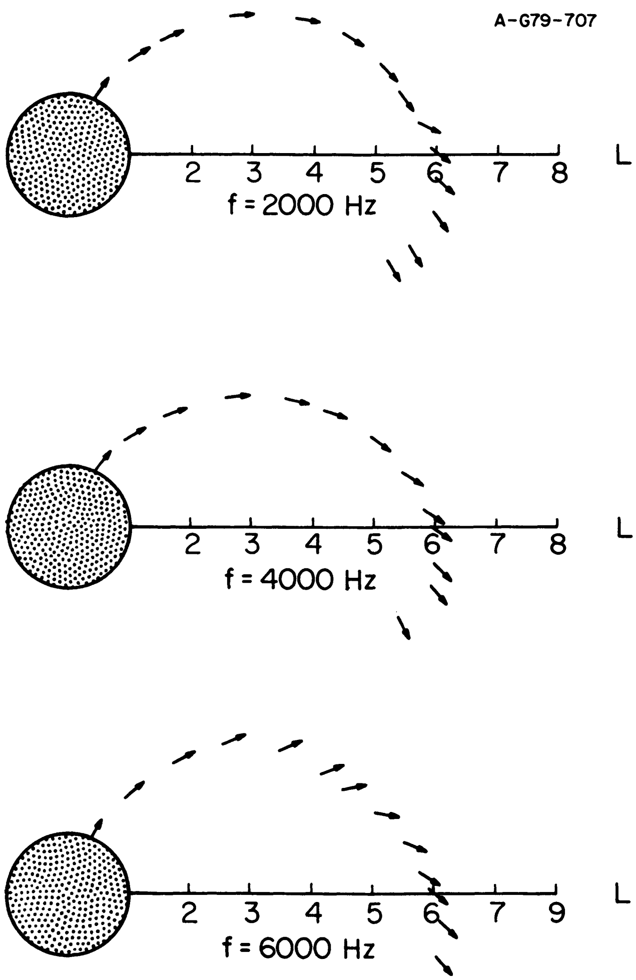

Figure 2. Whistler ray path (tail of vectors) and phase velocity direction (head of vectors) in the Jovian magnetosphere for three representative frequencies: 2 kHz, 4 kHz, and 6 kHz.

normal angle, θ, with respect to the magnetic field, chosen in such a way that the resulting ray paths all cross the magnetic equator at 6 R_J. This procedure is intended to simulate the situation which actually occurs when the signals from a lightning stroke at a fixed point in the atmosphere propagate to a fixed observing point in the magnetosphere. As is well known, a lightning stroke in the atmosphere results in a wide range of wave normal angles at the base of the ionosphere, but only a specific angle at each frequency will lead to a ray path which reaches a specific point in the magnetosphere. According to the results of Rinnert et al. [1979], multiple hop propagation is strongly attenuated in the Jupiter-ionosphere waveguide, so multiple entry points into the ionosphere need not be considered. For the specific starting and ending points used the initial wave normal angles ranged from about +12.6° to -5.5°.

Figure 2 shows the ray paths for three representative frequencies. The tail of each arrow indicates the ray path as determined by the whistler group velocity, while the arrowhead indicates the direction of the wave normal at each point along the ray path. At low altitudes the ray path tends to follow the magnetic field line, very similar to whistler propagation at the earth, even though the plasma parameters in this region are much different than at the earth. As the ray path approaches the higher density region near the plasma torus noticeable refraction effects are evident at all frequencies. For 2 kHz the wave normal tends to refract outward away from the ray path, whereas for 6 kHz the wave normal tends to refract inward toward the ray path. The wave normal behavior at different frequencies is mainly controlled by the plasma density gradient at the point of entry into the torus. In all cases, the direction of refraction is toward the density gradient, as expected from Snell's law. This dependence was verified by launching a 2 kHz ray such that it enters the torus at $L \simeq 6.5$, where the density gradient is directed inward (see Figure 1). The result was that the wave normal is refracted inward toward the ray path, in the direction of the density gradient.

Figure 3 shows the group travel time integrated along the ray path for three different positions within the Io torus. Location A is at a magnetic latitude, λ_m, of +8°, which is close to the northern edge of the torus; location B is at $\lambda_m = 0$ and location C is at $\lambda_m = -9°$, close to the southern edge of the torus. Because the ray paths for each frequency are slightly different the radial distance for locations A and C vary somewhat with frequency. The average radial distance for all eight frequencies for location A was 5.65 R_J, and for location C was 6.08 R_J. These average locations are shown relative to the L = 6 magnetic field line in Figure 1.

The group travel times in Figure 3 show the familiar characteristic of a whistler, which is a decreasing frequency with increasing time. A well known approximation for the dispersion of whistlers is that the travel time, $t - t_o$, is inversely proportional to the square root of the frequency

$$t - t_o = \frac{D}{\sqrt{f}}, \qquad (1)$$

where D is a constant called the dispersion [*Eckersley,* 1935]. This equation is valid for parallel propagation, $\theta \simeq 0$, at frequencies intermediate between the ion and electron gyrofrequency, $f_g^+ < f < f_g^-$. Figure 4 shows a plot of $t - t_o$ versus $1/\sqrt{f}$, which should be a straight line, for the three positions A, B and C. As can be seen, the fit to Eq. 1 is very good, thereby confirming the validity of Eq. 1 for the specific combination of parameters encountered in the Jovian magnetosphere. The best fit dispersion, D, is given for each location in units of sec $Hz^{1/2}$. Note that most of the dispersion occurs within the torus itself, very little having occurred up to point A at the edge of the torus. The small dispersion up to this point is a consequence of the very low plasma density and large magnetic field strength outside of the torus which gives a propagation velocity close to the speed of light over a substantial portion of the ray path. This feature is in sharp contrast to the earth's magnetosphere where the propagation velocity of whistlers is always much less than the speed of light. One unusual consequence of the low dispersion outside of the torus is that t_o in Eq. 1 does not give the time of the lightning stroke, as it would in the case of a terrestrial whistler. This discrepancy is evident in Figure 4, which shows that the intersection of the best fit straight lines does not pass through t = 0. Even though the wave frequency exceeds the proton gyrofrequency near the planet, the effects of ions (assumed to be protons) on the total whistler dispersion are essentially negligible. The

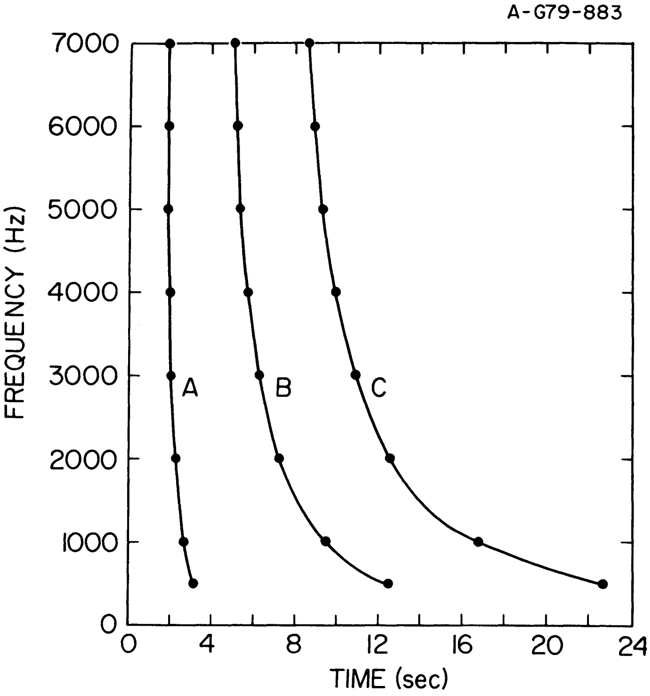

Figure 3. Whistler frequency (Hz) versus arrival time (seconds) for the three locations A, B, and C shown in Figure 1.

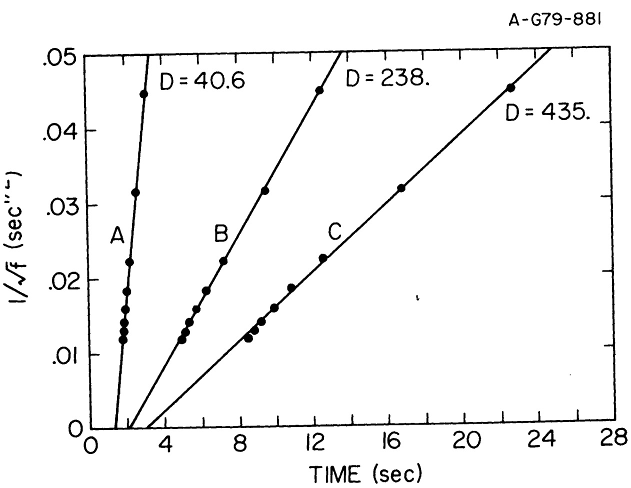

Figure 4. The inverse square root of the whistler frequency versus arrival time for the three torus locations A, B, and C in Figure 1. The best fit whistler dispersion, D, in units of sec Hz$^{1/2}$ are given for each line.

absence of ion effects can be attributed to the large propagation velocity and small contribution to the total dispersion in the region near the planet. At no point does the wave normal angle become sufficiently large to involve ion effects at frequencies below the lower hybrid-resonance frequency.

Having computed representative ray paths and wave normal directions of Jovian whistlers we now investigate the attenuation due to collisionless wave-particle interactions with the magnetospheric plasma. Because of the very high phase velocities outside of the torus, it can be readily shown that the primary wave-particle interactions should occur within the torus where the resonance velocities are low and the largest number of particles can resonate with the wave. Two types of resonant interactions are expected to be important, Landau damping and cyclotron damping. For the relatively large wave normal angles, $\theta \simeq 45^\circ$, which occur in the torus Landau damping is expected to be dominant. Later we discuss the possibility of ducted propagation with $\theta \simeq 0$, for which cyclotron damping (or growth) would be dominant. Starting with the general expression for collisionless damping given by Kennel [1966] and keeping only the m = 0 term (Landau damping) one can obtain the following expression for the damping decrement, Γ, for a Maxwellian plasma

$$\Gamma = -2\frac{V_{ph}}{V_{th}^5} f_g \sqrt{\pi}\, e^{-mV_{ph}^2/2\,kT}\left[\frac{K^2 \sin^2\theta}{4f_g^2}\left(\frac{2kT}{m}\right)^3 + \ldots\right] \qquad (2)$$

where the series in the brackets are the first order terms in a Bessel function expansion, V_{ph} is the phase velocity, V_{th} is the electron thermal velocity, T is the electron temperature, K, is the wave number, k is Boltzmann's constant, and m is the electron mass. The damping decrement was evaluated for each point along the ray path and the total attenuation of the wave obtained from

$$\frac{I}{I_o} = \exp\,(-2\,\sum_i \Gamma_i \Delta_i t) \qquad (3)$$

where I is the wave intensity and Δt is the time interval.

The computed attenuation in decibels for the ray paths discussed earlier are shown in Figure 5 as a function of the wave frequency. These results are for location C, after the whistler has propagated through the torus, thereby suffering the maximum possible attenuation. Three curves are shown for temperatures of 1 x 10^{5}°K, 2 x 10^{5}°K and 3 x 10^{5}°K. As can be seen the attenuation in the frequency range of interest is extremely sensitive to the temperature in the Io torus. For T_3 = 3 x 10^{5}°K appreciable attenuation occurs for all frequencies below 5 kHz. With such large attenuations, up to 100 dB, whistlers could not be detected after passing through the torus. However, for T_1 = 1 x 10^{5}°K the attenuation is drastically reduced and essentially all frequencies down to about 0.5 kHz could propagate through the torus without appreciable attenuation. Since whistlers with frequencies as low as about 2 kHz have been observed after passing through the torus, these results indicate an upper limit to the torus electron temperature of about (2 - 3) x 10^{5}°K. This upper limit to the electron temperature is in very favorable agreement with the results from the Voyager 1 ultraviolet spectrometer which indicate an average torus electron temperature of about 10^{5}°K [*Broadfoot et al.,* 1979].

Discussion

Our analysis has demonstrated the principal characteristic of lightning generated whistlers propagating through the Jovian magnetosphere using a plasma density model adopted from Sentman and Goertz [1977] and Warwick et al. [1979]. Specific comparisons can now be made between the computed and observed whistler dispersion characteristic. Position A which has a computed dispersion of 40.6 sec Hz$^{1/2}$ is intended to correspond to the low dispersion whistlers observed by Voyager 1 near the northern edge of the torus [*Gurnett et al.,* 1979]. These whistlers have an average dispersion of 53.8 ± 18.9 sec Hz$^{1/2}$, which is in very favorable agreement with the computed values. This close agreement supports the validity of the Sentman and Goertz [1977] density model outside of the torus. However, because of the very large whistler propagation velocity and low dispersion outside of the torus the results are rather insensitive to the details of this density distribution. The main point is that the plasma density must be very low outside of the torus to account for the very low dispersions which are observed in this region.

Position C which has a computed dispersion of 435 sec Hz$^{1/2}$ corresponds very closely to the position where the long dispersion whistlers were observed by Voyager 1 near the southern edge of the torus [*Gur-*

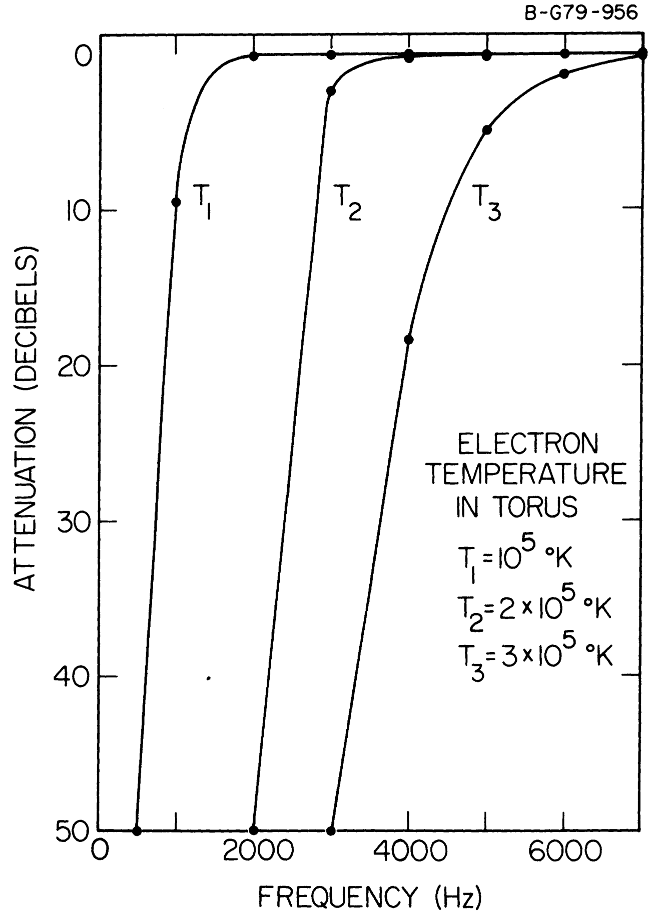

Figure 5. Whistler wave attenuation (decibels) versus frequency for three constant electron temperatures within the torus, T_1 = 10^{5}°K, T_2 = 2 x 10^{-5}°K, and T_3 = 3 x 10^{5}°K. All three curves are for location C within the torus.

nett et al., 1979]. These whistlers are thought to have passed from north to south through the torus on ray paths very similar to those computed in this study. The average dispersion of these long dispersion whistlers is 473 ± 127 sec $Hz^{1/2}$, again in very good agreement with the computed dispersion. This excellent agreement serves to confirm the validity of the Warwick et al. [1979] model for the electron density inside of the torus, since the dispersion at this point is mainly determined by the passage through the torus. As shown by Gurnett et al. [1979], the dispersion after passing through the torus is almost entirely determined by the line integral of the square root of the electron density.

$$D = \frac{1}{2c} \int \frac{f_p}{\sqrt{f_g}} ds \propto \int \sqrt{n}\, ds. \qquad (4)$$

We can conclude from these results that the line integral $\int\sqrt{n}\,ds$ along the L ~ 6 field line through the plasma torus agrees to within about ±25% of the value given by Warwick et al. [1979]. Furthermore, from the Landau damping calculation an upper limit of about (2 - 3) x 10^5°K can be placed on the electron temperature in the torus, which is in excellent agreement with temperature of ~1 x 10^5°K given by Broadfoot, et al. [1979].

The ray path calculations presented in this study have assumed nonducted propagation. Since ducted propagation of whistlers is known to occur in the earth's magnetosphere, with the wave vector guided along the magnetic field by field-aligned density irregularities, the question arises as to whether such ducted propagation occurs in the Jovian magnetosphere. The answer to this question does not significantly affect the dispersion calculations presented, since as pointed out by Helliwell [1965] the group travel time is almost completely independent of the wave normal angle. It does however affect the collisionless attenuation calculations since the Landau damping goes to zero for ducted propagation ($\theta = 0$ in Eq. 2). Cyclotron damping would then be the most important collisionless damping process. It is our opinion however that most, if not all, of the whistlers detected by Voyager 1 were unducted whistlers. Unfortunately, no direct evidence exists to support this view, since wave normal directions are not measured by Voyager 1. The best evidence for the predominance of nonducted propagation comes from the earth's magnetosphere. By comparing whistler rates observed on the ground and in the magnetosphere a strong case can be made that most of the whistlers observed in the earth's magnetosphere are nonducted. This is presumably because trapping in a duct can only occur within a narrow range of initial wave normal directions, which is not satisfied for most whistlers entering the ionosphere. One possible piece of evidence supporting nonducted propagation is the fact that no multiple hop whistlers were detected at Jupiter. For nonducted propagation multiple hops would be strongly attenuated because of the rapid increase in the Landau damping which occurs after the first traversal of the equatorial plane as the wave normal angle approaches the resonance cone [*Sentman and Goertz,* 1977].

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