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Effectiveness of near-grazing incidence reflection in creating the rotationally modulated lanes in the Jovian hectometric radio emission spectrum

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Abstract. The Galileo plasma wave instrument has identified a narrow (in frequency) attenuation band in the hectometric emission that varies in frequency with system III longitude. It is possible to model this emission band assuming a high-latitude cyclotron source region with emission that is efficiently attenuated when the ray path is nearly tangent to an L shell that is close to the Io flux tube [*Gurnett et al.*, 1998]. The data suggest that the mechanism for attenuating the emission is very efficient, with the ratio of attenuated to unattenuated emission $I/I_0 < 0.02$, and not a strong function of frequency. In this paper we demonstrate that incoherent scattering alone cannot explain the attenuation lane, which does not preclude coherent scattering by uncertain processes. We find rather that the source of attenuation is consistent with near-grazing incidence reflection of emission from an L shell that is near the Io flux tube (a caustic surface).

1. Introduction

Jovian hectometric (HOM) radio emissions are generally described as emissions in the frequency range of ~200 kHz to ~3 MHz [cf. *Carr et al.*, 1983; *Ladreiter and Leblanc*, 1991]. Polarization measurements are consistent with a predominantly X-mode emission. The source mechanism is most likely the cyclotron maser instability, and the source region has been thought to be at L shells higher than L = 6.

Gurnett et al. [1998] have identified and explained a well-defined attenuation lane that appears occasionally and is modulated by the rotation of Jupiter (Figure 1). This attenuation lane occurs in the Jovian hectometric and lower-frequency decametric radiation data from Galileo and is apparently the same feature as the "lanes" reported by *Green et al.* [1992] and *Higgins et al.* [1995, 1998] and the "drifting gap in the main late source" mentioned by *Lecacheux et al.* [1980]. As reported by *Gurnett et al.* [1998], the Galileo data indicate that the center frequency of the lane varies systematically with the rotation of Jupiter and has two peaks per rotation. The attenuation band peaks in frequency near 50° central meridian longitude (CML) due to sources of HOM in the southern hemisphere, and it peaks near 185° due to sources in the northern hemisphere. It is believed that the attenuation occurs as the ray path from a high-latitude cyclotron maser source passes approximately parallel to the magnetic field near the northern or southern edges of an L shell containing the Io flux tube (IFT). Emission that is nearly tangent to this L shell may be coherently scattered by density fluctuations or reflected at near-grazing incidence (see Figure 2). Thus this attenuation lane has aided in understanding the source location of the HOM emission. *Higgins et al.* [1999] show a lower-frequency extension of the rotationally modulated lanes and point out a possible caustic surface evidenced by enhanced emission sometimes seen adjacent to the lanes. The low-frequency component of the lanes is qualitatively fit by the model of *Gurnett et al.* [1998]. Another exciting additional result of the observations of *Gurnett et al.* [1998] is that clear indications of second harmonic radio emission in the HOM and decametric frequency range have been identified (*Menietti et al.*, 1998). These emissions provide additional clues to the source location, propagation paths, and plasma conditions near the source region.

In this paper we use the observations to investigate the efficiency of near-grazing incidence reflection as the source of the emission attenuation. We do not explore the question of coherent scattering because of the lack of information such as the presence or nature of periodic

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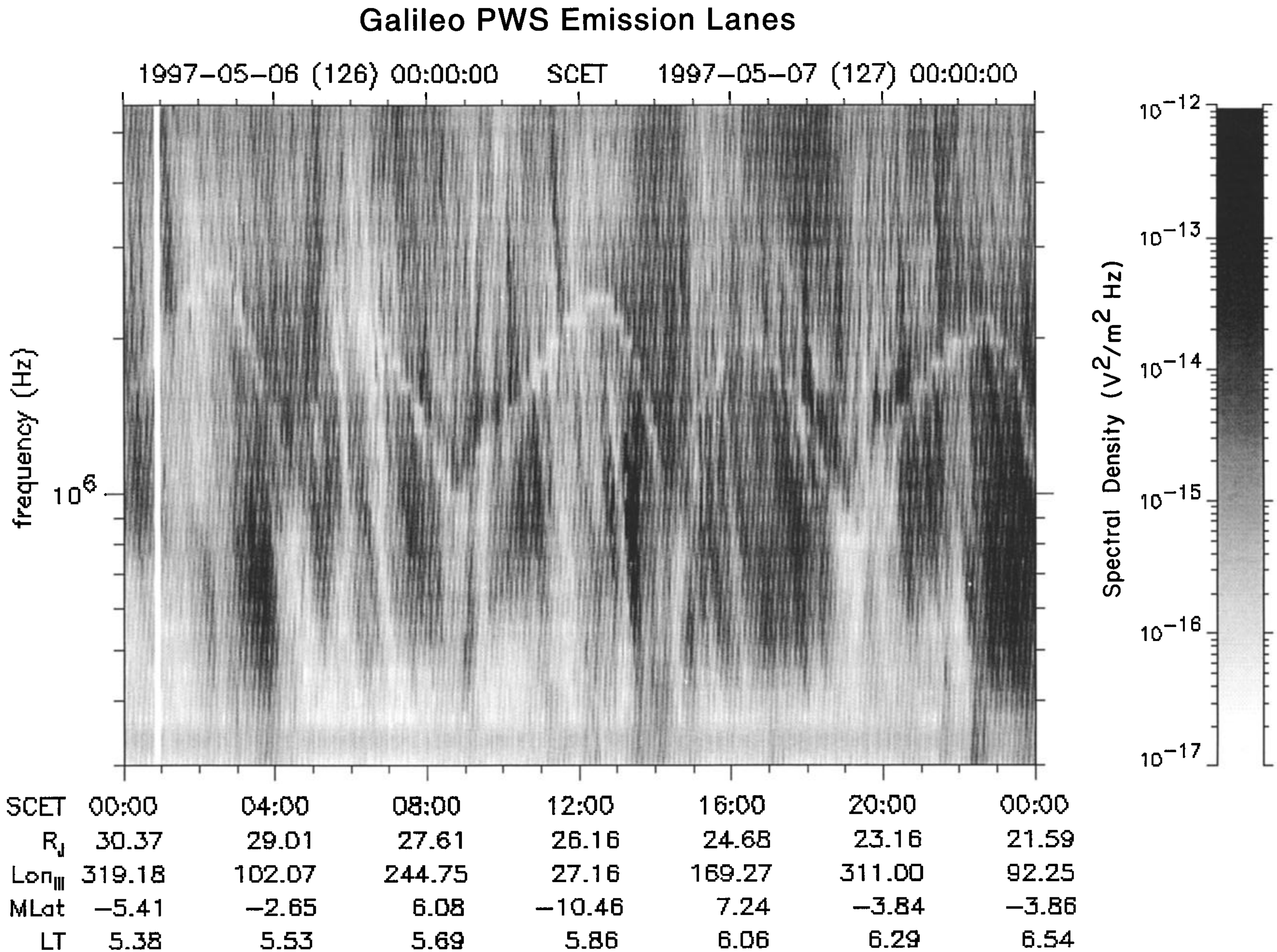

Figure 1. Attenuation lanes in the hectometric (HOM) emission observed for day 126 of 1997.

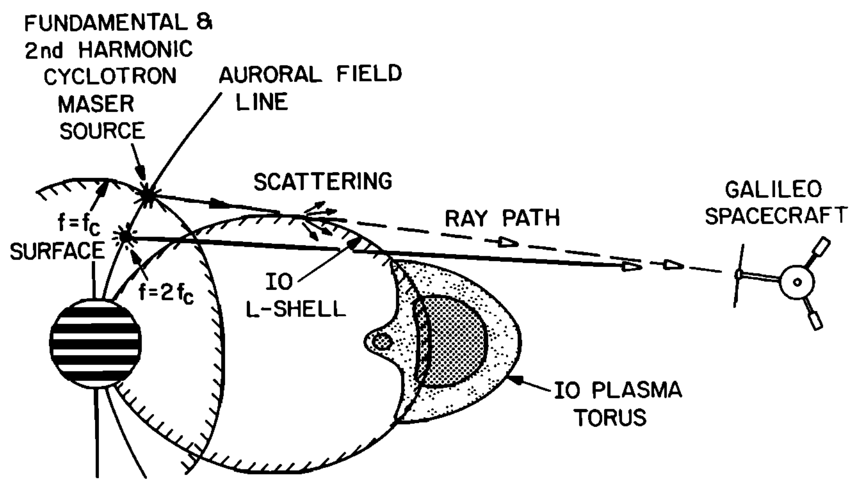

Figure 2. Cartoon of the emission geometry that can account for the attenuation lanes seen in the data. Both fundamental and harmonic HOM emission are depicted.

density fluctuations necessary to model the process. The results indicate that near-grazing incidence reflection can produce the attenuation lanes and imply that similar attenuation signatures may be observed in other planetary magnetospheres.

2. Analysis

In Figure 3 we have stacked three independent plots of the power spectral density as a function of frequency. The curves are for three different times from Figure 1: 0259, 0700, and 1229 UT. It is seen that the depth of the attenuation lane is large relative to the emission adjacent to the lane, indicating the efficiency of the attenuation mechanism. We obtain for the three times $I/I_0 = 8.7 \times 10^{-3}$, $I/I_0 = 5.7 \times 10^{-3}$, and $I/I_0 = 1.3 \times 10^{-2}$, respectively, where I is the spectral density at the center of the lane and I_0 is the average spectral density at the lane edge. The data points chosen for the lane edge (first point of the steepest slope of the spectral density curve) are shown as circles.

Scattering of the emission can take place from the plasma as well as from any neutral gas particles along the Io flux tube. Incoherent scattering from density fluctuations, however, is not efficient enough to produce the observed attenuation. As described by *Krall and Trivelpiece* [1973] for the plasma limit of $k \lambda_d \ll 1$, the differential scattering cross section is

$$d\sigma/d\Omega = r_0^2 N_e (1 + \cos^2 \theta)/4$$

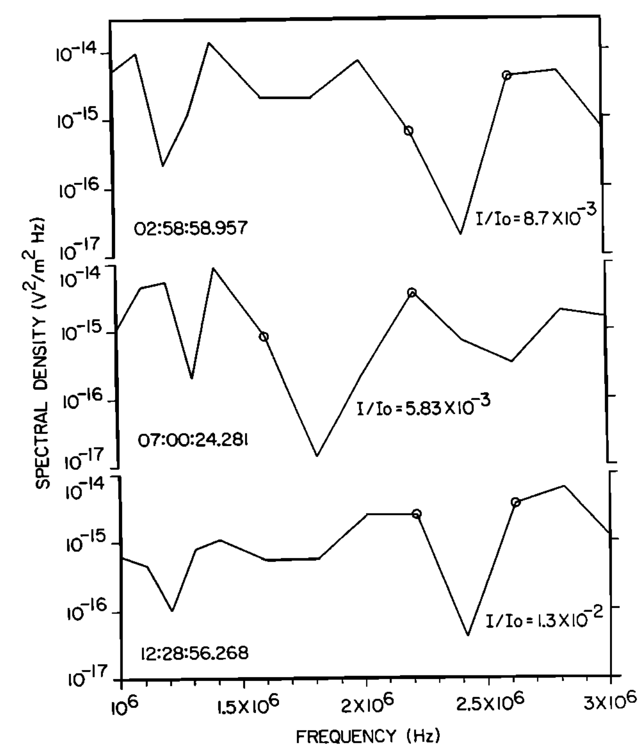

Figure 3. Plots of power spectral density versus frequency (including the attenuation lane) for three times from Figure 1: 0259, 0700, and 1229 UT. In all three cases the ratio of I/I_0 (see text) is ≤ 0.02. The circles indicate the data points adjacent to the attenuation lane.

where λ_d is the Debye length, r_0 is the classical electron radius, N_e is the number density of scattering electrons per cm^{-3}, and θ is the angle between the incident and scattered waves. Within a factor of 2 this is the same as the expression for Thomson scattering. For calculation purposes we express this as an optical depth defined in terms of an opacity [cf. *Aller*, 1963, pp. 151, 169] as

$$\tau \sim \kappa \rho H$$
$$\kappa \rho = 0.667 \times 10^{-24} N_e \quad \text{(Thomson scattering)}$$
$$I = I_0 \exp(-\tau)$$

where ρ is mass density and κ is the opacity (cm^2/gm); $\kappa \rho$ is thus defined as the scattering coefficient per cm^3. H is the distance over which scattering occurs. From Figure 1 we make a reasonable estimate of $H \sim 1\ R_J$. With $\tau \sim 3$, we expect $I/I_0 \lesssim 0.050$ which is consistent with the data of Figure 2. For a reasonable estimate of $N_e \lesssim 5.0$ [cf. *Bagenal*, 1994] and $\rho = 2.67 \times 10^{-21}$ gm/cm^3 (50% sulfur, 50% oxygen), we find that $\kappa \sim 0.125$ cm^2/gm. However, this would require that $H \sim 9 \times 10^{21}$ cm $= 1.26 \times 10^{12} R_J$! Conversely, if we assume $\kappa \rho H \sim 3$, we find even for an overestimate of $\rho \sim 5.3 \times 10^{-21}$ gm/cm^{-3} (assuming 100% sulfur ions), $H = 1\ R_J$, then $\kappa \sim 7.8 \times 10^{10}$ cm^2/gm! Thus incoherent scattering alone cannot explain the attenuation lane. This does not preclude coherent scattering processes, however, which we do not consider here because of a lack of in situ information necessary to model such mechanisms.

In a simple model, we consider a reflection of radio emission from a plasma interface (a caustic surface), where the surface is the L shell containing the Io flux tube (IFT). We assume a steep gradient in plasma density near this L shell. From *Corson and Lorraine* [1962, chapter 11] we can write the expressions for the reflec-

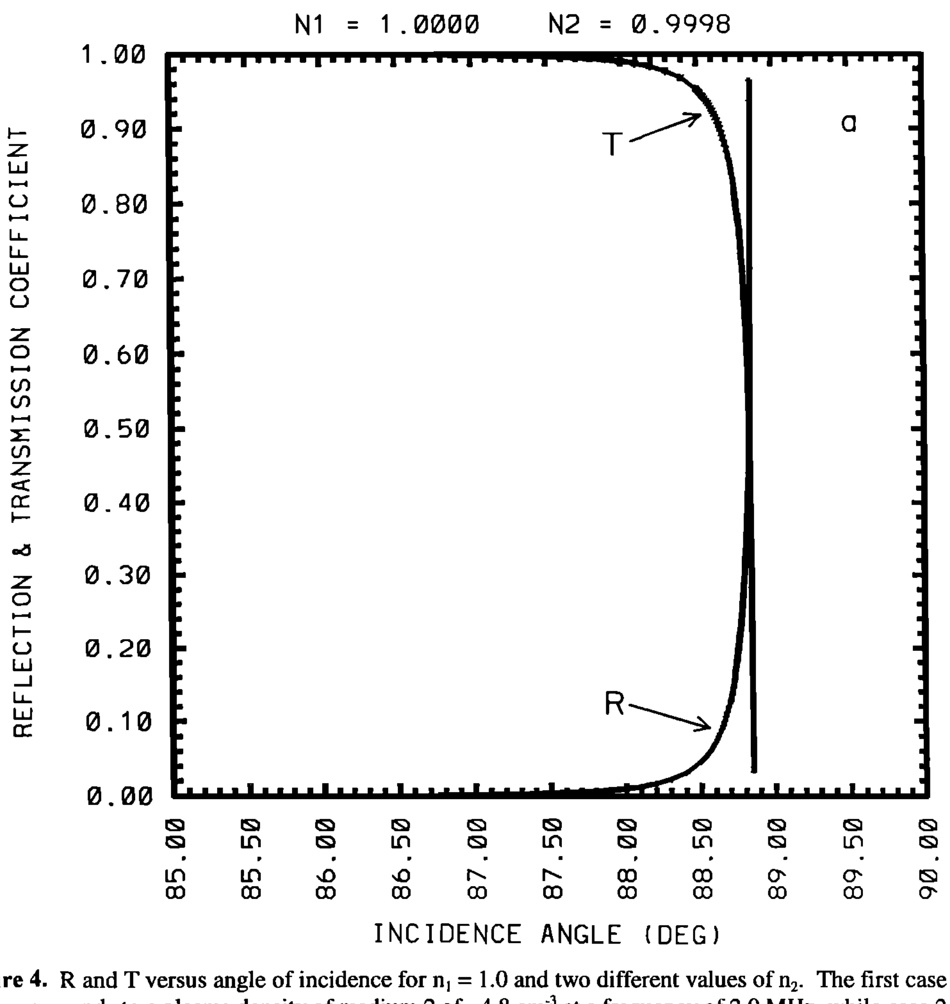

Figure 4. R and T versus angle of incidence for $n_1 = 1.0$ and two different values of n_2. The first case (Figure 4a) corresponds to a plasma density of medium 2 of ~4.8 cm^{-3} at a frequency of 2.0 MHz, while case 2 (Figure 4b) is for a density of medium 2 of ~5.8 cm^{-3} at a frequency of 1.0 MHz.

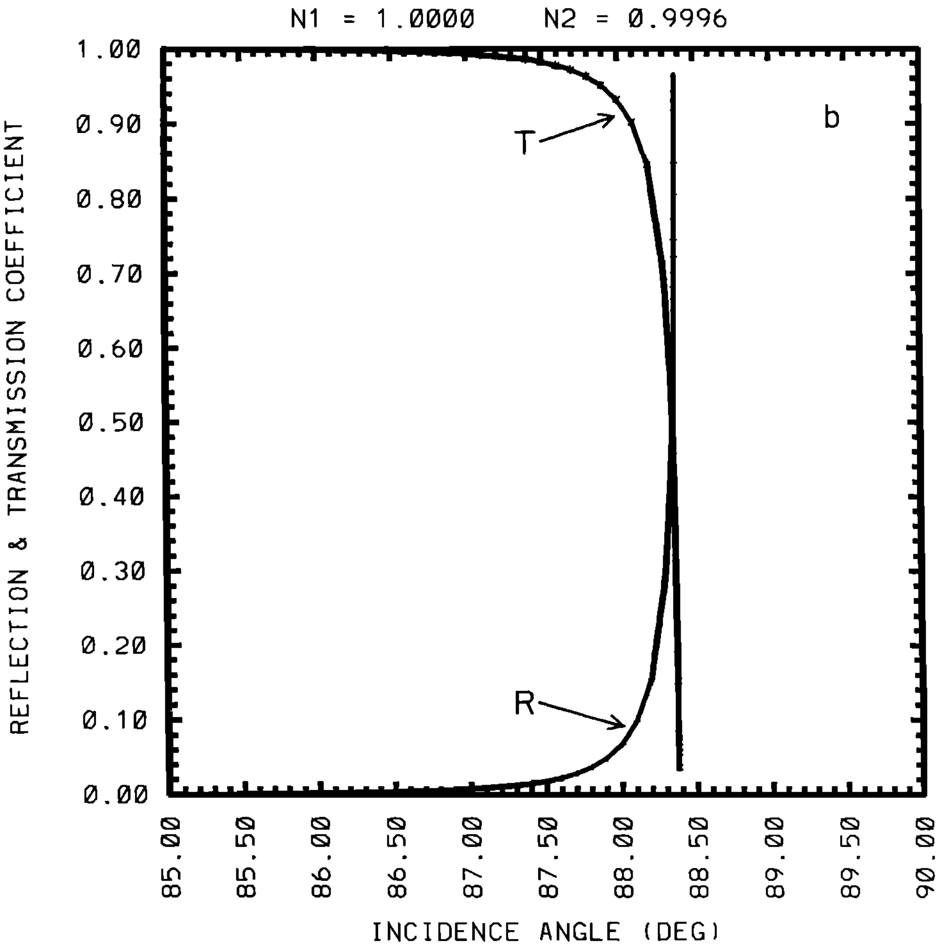

Figure 4. (continued)

tion and transmission coefficients for a plane wave incident upon a surface with a distinct index of refraction. The angle of incidence is θ_i and angle of transmission is θ_t:

$$R = \left[\frac{\frac{n_1}{n_2}\cos\theta_i - \cos\theta_t}{\frac{n_1}{n_2}\cos\theta_i + \cos\theta_t}\right]^2,$$

$$T = \frac{4\left(\frac{n_1}{n_2}\right)\cos\theta_i\cos\theta_t}{\left[\frac{n_1}{n_2}\cos\theta_i + \cos\theta_t\right]^2}$$

Here n_1 and n_2 are the indices of refraction for medium 1 (region from the source region to the L shell containing the IFT) and medium 2 (inside the L shell containing the IFT, i.e., the caustic surface), respectively. These expressions are for a wave with an electric field in the plane of incidence, but the results are nearly the same for a wave with an electric field either in or perpendicular to the plane of incidence. We calculate the magnitude of the index of refraction using cold plasma theory, with the Jovian magnetospheric plasma model of *Divine and Garrett* [1983] and the O6 magnetic field model [*Connerney*, 1993]. We assume the emission is in the frequency range between 1.0 and 2.0 MHz and the wave normal angle is near zero. A typical point of tangency of the radio emission with the caustic surface is assumed near r = 4.6 R_J, θ = 55.2° (Jovicentric coordinates). For the region away from the source region but not near the caustic surface (medium 1), the index of refraction, n_1, is approxi-

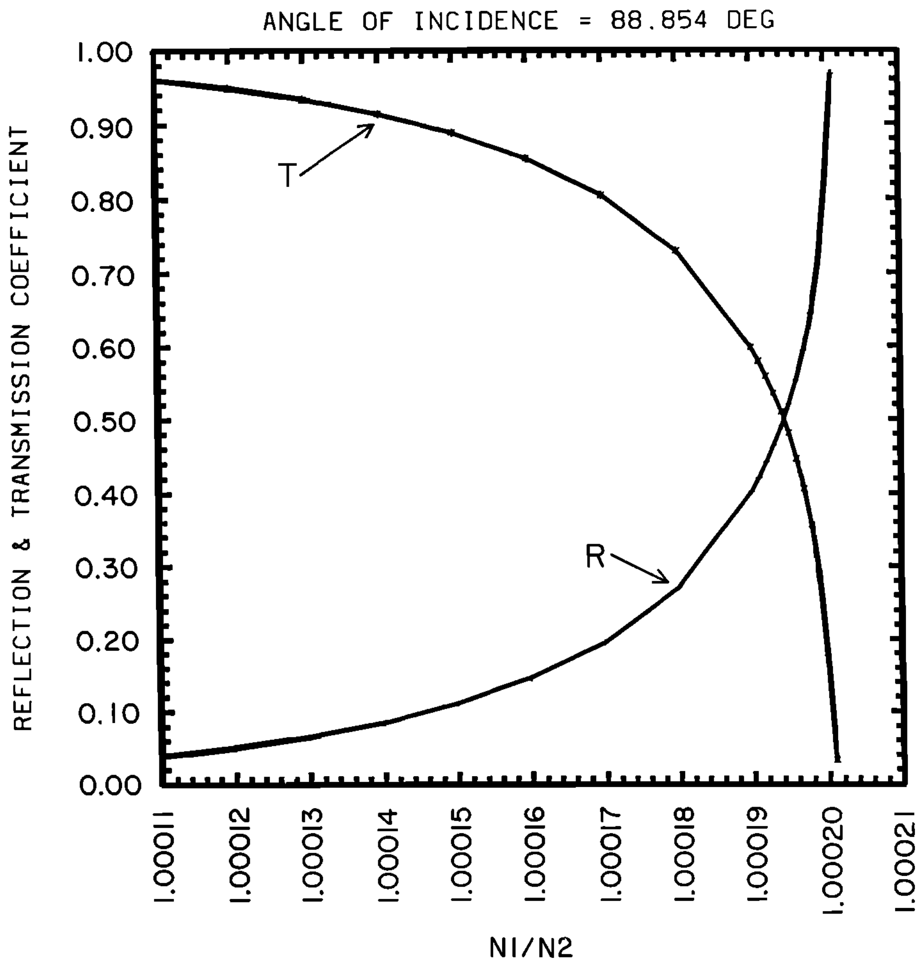

Figure 5. R and T versus a range of the ratio n_1/n_2. We have chosen an angle of incidence $\theta_1 = 88.85°$. R becomes quite large for a ratio $n_1/n_2 \sim 1.0002$.

mately equal to 1.0. To determine the density along the L shell near the point of tangency, we consult a model of the Io torus [*Bagenal*, 1994] (see also the website at http://dosxx.colorado.edu/torus/dens_o4_b94_txt.dat). From this model it is clear that large changes in density of over 2 orders of magnitude occur perpendicular to the magnetic field at the edge of the Io torus (i.e., near the L shell containing the IFT) within distances less than 0.1 R_J. Values of density near the point of tangency varied over a distance of ~0.1 R_J perpendicular to L from ~10^{-3} cm^{-3} outside the torus (medium 1) to ~1 cm^{-3} along the L shell of the boundary of the Io torus (medium 2). We do not know the density within an Io flux tube that has been recently filled by active volcanic activity, but values within the range 3.0-6.0 cm^{-3} for the caustic surface are only slightly larger than those of the model.

In Figure 4 we plot R and T for $n_1 = 1.0$ and two different values of n_2. The first case corresponds to a plasma density of medium 2 of ~4.8 cm^{-3}, at a frequency of 2.0 MHz, while case 2 is for a density of medium 2 of ~5.8 cm^{-3} at a frequency of 1.0 MHz. It is clear that near-grazing incidence, within about 1° of tangency with the magnetic field, can produce very high degrees of reflection consistent with the data. In Figure 5 we plot R and T versus a range of the ratio n_1/n_2. We have chosen an angle of incidence $\theta_1 = 88.85°$. R becomes quite large for a ratio $n_1/n_2 \sim 1.0002$. For right-hand extraordinary mode emission with $n_1 = 1.0$, angle of incidence (wave normal angle) ~89° (~1°), and frequency in the range of 1-2 MHz, this would correspond to a plasma density on the high-density side of the caustic surface of about 4-5 cm^{-3}. This is determined from the cold plasma index of refraction with a gyrofrequency obtained from the O6 magnetic field model near the point of tangency. Such densities may be associated with periods of higher Io volcanic activity.

3. Summary and Conclusions

Attenuation lanes observed in the Galileo radio emission data can be explained by the model proposed by *Gurnett et al.* [1998] assuming the emission is reflected at near-grazing incidence at the plasma boundary near the L shell containing the Io flux tube. This boundary forms a caustic surface that reflects the HOM emission in the range of frequencies 1-2 MHz. The large change in reflection coefficient occurs for emission within about 2° of tangency with the magnetic field. This small angle is consistent with the observed narrow width of the attenuation lanes, which have a bandwidth of 10-20%. For frequencies in the range of 1-2 MHz this small bandwidth corresponds to a source region of only about 0.1 R_J along the magnetic field line (L ~50) for gyroresonant emission. For the simple model of reflection at a caustic surface, the values of density necessary to produce strong reflection and low transmission near the interface are perhaps 2-5 times larger than model values. The density along the L shell need be ≤6 cm^{-3}. Current models of the Io torus [cf. *Bagenal*, 1994; *Wang et al.*, 1998] show similar but somewhat smaller densities near the point of tangency used in the above calculations (namely, ~1.0 cm^{-3}). We suspect that the intermittent observation of the attenuation lane is related to the periodic increase in density of the IFT due to increased volcanic activity on Io.

Our model is quite simple and assumes a sharp density gradient perpendicular to the magnetic field at the caustic surface. This assumption is not unreasonable assuming large periodic outflows of plasma along the IFT. We would expect that plasma flowing along the IFT would produce a sharp density gradient perpendicular to the magnetic field line within an ion gyroradius or so. At the point of tangency of the radio emission and magnetic field that we calculated, i.e., r ~ 4.6 R_J and θ ~ 55.2°, we expect the ion gyroradius to be r_H ~ 600-700 m. We expect the caustic surface to have a thickness of about the diameter of Io, which is about 1700 km. For emission near 1-2 MHz, the wavelength is approximately equal to $r_H/2$, and strong reflection of the radio emission near such a sharp density gradient will occur. If the plasma of the IFT is considered to be semiconducting, then the reflection coefficients are increased and still consistent with the assumption of near-grazing reflection of the radio emission.

Another possible source of attenuation would result from reflection of right-hand extraordinary (RX) mode emission or ordinary (O) mode emission at the RX cutoff frequency f_{RX} or the plasma frequency f_p, respectively. For frequencies near 1 MHz and electron gyrofrequencies near 160 kHz, these correspond to number densities along the L shell containing the IFT of several tens of thousands of particles per cm^{-3}. Such densities are found near Io [*Gurnett et al.*, 1996] but not at higher latitudes along the L shell, and we conclude that such attenuation is also unlikely. Because of a lack of necessary information, such as evidence of plasma modulation in the Io torus, coherent scattering of the radio emission by density fluctuations has not been modeled in this study.

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References

Aller, L. H., *Astrophysics: The Atmospheres of the Sun and Stars*, p. 2150, Ronald Press, New York, 1963.

Bagenal, F., Empirical model of the Io plasma torus: Voyager measurements, *J. Geophys. Res.*, *99*, 11,043, 1994.

Carr, T. D., M. D. Desch, and J. K. Alexander, Phenomenology of magnetospheric radio emissions, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 226-284, Cambridge Univ. Press, New York, 1983.

Connerney, J. E. P., Magnetic fields of the outer planets, *J. Geophys. Res.*, *98*, 18,659, 1993.

Corson, D. R., and P. Lorrain, *Introduction to Electromagnetic Fields and Waves*, pp. 357-408, W. H. Freeman, New York, 1962.

Divine, N., and H. B. Garrett, Charged particle distributions in Jupiter's magnetosphere, *J. Geophys. Res.*, *88*, 6889, 1983.

Green, J. L., J. R. Thieman, C. Higgins, S. F. Fung, R. M. Candey, and L. Aist-Sagara, Lane features in Jovian hectometric radio emissions, in *Planetary Radio Emissions III*, edited by H. O. Rucker, S. J. Bauer, and M. L. Kaiser, pp. 91-103, Austrian Acad. of Sci., Vienna, 1992.

Gurnett, D. A., W. S. Kurth, A. Roux, S. Bolton, and C. F. Kennel, Galileo plasma wave observations in the Io plasma torus and near Io, *Science*, *274*, 391, 1996.

Gurnett, D. A., W. S. Kurth, J. D. Menietti, and A. M. Persoon, An unusual rotationally modulated attenuation band in the Jovian hectometric radio emission spectrum, *Geophys. Res. Lett.*, *25*, 1841, 1998.

Higgins, C. A., J. L. Green, J. R. Thieman, S. F. Fung, and R. M. Candey, Structure within Jovian hectometric radiation, *J. Geophys. Res.*, *100*, 19,487, 1995.

Higgins, C. A., J. R. Thieman, S. F. Fung, J. L. Green, and R. M. Candey, Latitudinal structure within Jovian hectometric radiation, *J. Geophys. Res.*, *103*, 26,679, 1998.

Higgins, C. A., J. R. Thieman, S. F. Fung, J. L. Green, and R. M. Candey, Jovian dual-sinusoidal HOM lanes features observed by Galileo, *Geophys. Res. Lett.*, *26*, 389, 1999.

Krall, N. A., and A. W. Trivelpiece, *Principles of Plasma Physics*, pp. 575-588, McGraw-Hill, New York, 1973.

Ladreiter, H. P., and Y. Leblanc, The Jovian hectometric radiation: An overview after the Voyager mission. *Ann. Geophys.*, *9*, 784, 1991.

Lecacheux, A., B. Boller-Pedersen, A. C. Riddle, J. B. Pearce, A. Boischot, and J. W. Warwick, Some special characteristics of the hectometric Jovian emission, *J. Geophys. Res.*, *85*, 6877, 1980.

Menietti, J. D., D. A. Gurnett, W. S. Kurth, and J. B. Groene, Second harmonic radio emission at Jupiter, *Geophys. Res. Lett.*, *25*, 4425, 1998.

Wang, K., R. M. Thorne, R. B. Horne, and W. S. Kurth, Cold torus whistlers: An indirect probe of the inner Jovian plasmasphere, *J. Geophys. Res.*, *103*, 14,987, 1998.

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