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Modeling radio emission attenuation lanes observed by the Galileo and Cassini spacecraft

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Abstract

The Cassini gravity-assisted flyby of Jupiter provided an opportunity to investigate radio emission attenuation lanes that were previously observed in the Voyager and Galileo data. The Cassini radio and plasma wave science (RPWS) investigation is the most advanced plasma wave instrument to visit the Jovian system, measuring electric fields over the frequency range from 1 Hz to 16 MHz with high spectral and temporal resolution. The narrow attenuation lanes in the hectometric emission vary in frequency with system III longitude. The lanes have been modeled in the past assuming a high-latitude cyclotron maser instability source region with emission that is efficiently scattered when the ray path is nearly tangent to the Io L-shell (Gurnett et al., 1998). In the current study we carried out ray tracing of radio emission for multiple frequencies and source regions in a magnetosphere that includes an Io L-shell filled with plasma. The half-width of the density distribution perpendicular to the magnetic field line and the central plasma density of the Io L-shell were fitting parameters. We have used the joint Galileo/Cassini observations at numerous frequencies and radial distances extending to 140 R_J to place constraints on model parameters. The results confirm the suggestion that wave refraction can produce the attenuation lanes. We have also been able to restrict the range of possible hectometric source regions and plasma parameters associated with the density model of the Io L-shell.

Keywords: Jovian radio emission; Ray tracing of Jovian HOM; Frequencies; Hectometric source

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 and Ladreiter and Leblanc, 1991). Polarization measurements are consistent with dominantly 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 $L = 6$. Ladreiter et al. (1994) found the source to be in the range $7 < L < 11$; Reiner et al. (1993a, b) and Menietti and Reiner (1996) found source regions at lower L-shells, in the range $3 < L < 7$. Kurth et al. (1997) used radio occultation measurements of Galileo's plasma wave instrument to determine a source location along a $L \gtrsim 7$ magnetic field line.

Gurnett et al. (1998) have identified and explained a well-defined attenuation lane that appears occasionally and is modulated by the rotation of Jupiter (Fig. 1). This attenuation lane occurs in the Jovian hectometric and lower-frequency decametric radiation data from Galileo and Cassini, and is the same feature as the "lanes" reported by Green et al. (1992), Higgins et al. (1995, 1998) and the "drifting gap in the main late source" mentioned by Lecacheux et al. (1980). In the Galileo and Cassini data, and never reported before Gurnett et al. (1998), the center frequency varies systematically with the rotation of Jupiter and has two peaks per rotation. The attenuation band peaks in frequency near 50° central meridian longitude 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 the Io L-shell (Fig. 2). Emission that is nearly tangent to this L-shell may be scattered by density fluctuations or refracted. Thus this attenuation lane has aided in understanding the source location of the HOM emission, and provided a remote means of observing temporal changes in the

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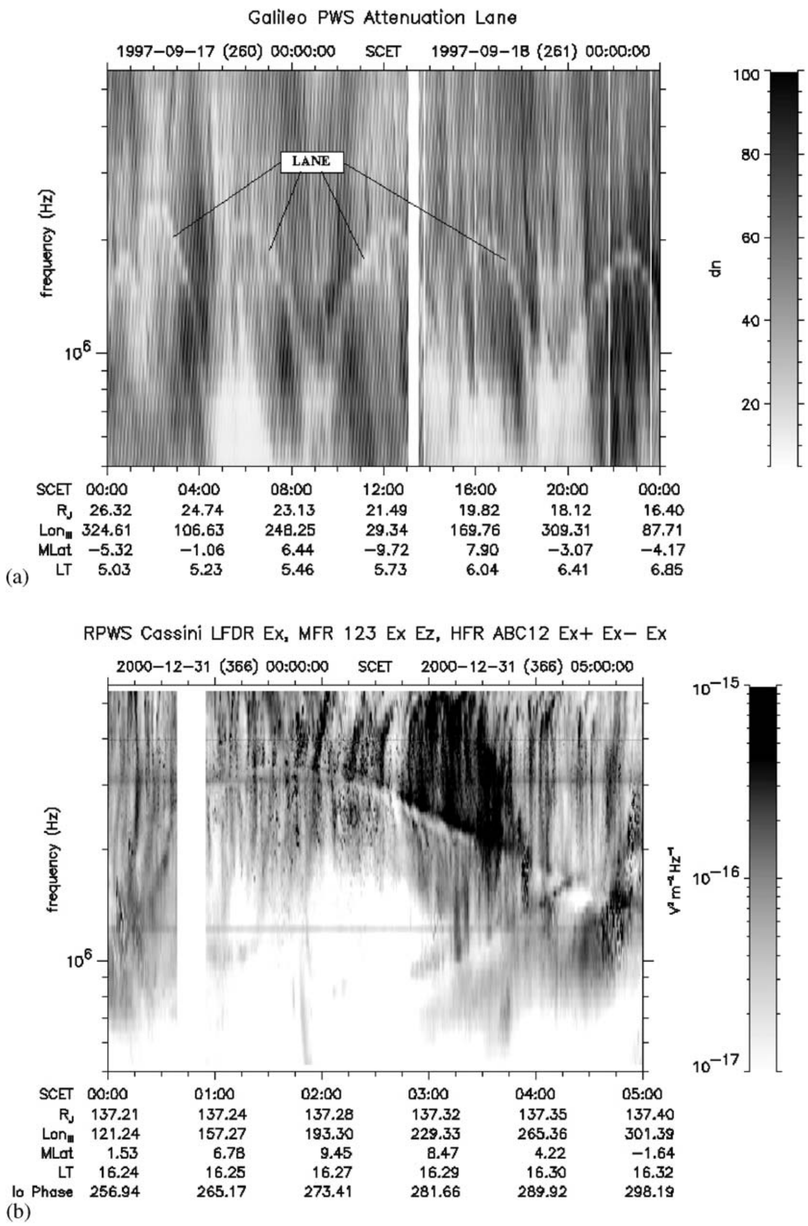

Fig. 1. (a) We show the attenuation lanes observed by Galileo in the hectometric (HOM) emission plotted as a frequency–time spectrogram for day 260 of 1997. Emission intensity is given by the gray-scale to the right of the figure. (b) We show an example of attenuation lanes observed by the radio and plasma wave investigation instrument on board the Cassini spacecraft when it was near closest approach to Jupiter on December 31, 2000. The format is similar to Fig. 1a, and the data extend for a period of 5 h.

magnetosphere near Io. Another result of the observations of Gurnett et al. (1998) is that clear indications of second harmonic radio emission in the HOM and lower DAM frequency range have been identified (Menietti et al., 1998). These emissions provide additional clues to the source location and plasma conditions near the source region.

A survey of existing Galileo plasma wave data (Menietti et al., 2001) indicated that attenuation lanes are present almost all of the time, but are enhanced on occasion. The authors found that the highest-contrast lanes occur on most passes when the Io volcanic activity is also high for that pass. This result is consistent with the hypothesis that increased Io volcanic activity leads to enhanced density in the Io flux tube, and ultimately to a more visible attenuation lane. Most recently the Jupiter flyby of the Cassini spacecraft has provided a large number of observations of HOM emission displaying attenuation lanes. It appears that the occurrence of the attenuation lanes observed by Cassini is similar to that previously observed by Galileo, at least when Cassini was near Jupiter.

Higgins et al. (2001) have performed initial ray tracing studies of HOM emission from sources along a high-latitude

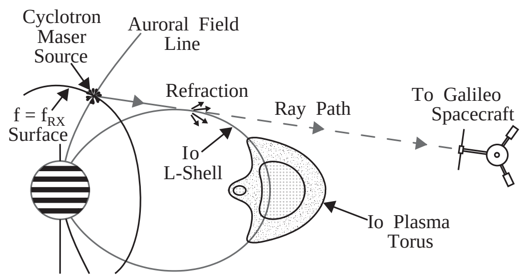

Fig. 2. We show a cartoon of the emission geometry that can account for the attenuation lanes seen in the data.

magnetic field line. They have used a simple model of plasma-filled Io flux tube with a width of 1 Io radius. The flux tube density profile was Gaussian with a central density of 100 cm^{-3}. The results clearly show the effectiveness of refraction to produce an attenuation lane as observed by Galileo. In the present study we extend the initial studies by considering a comprehensive ray tracing study that incorporates many more parameters and more accurately considers the effects of varying the size and central density of the Io L-shell as well as the L-shell of the HOM source region. Using the observations of both Galileo and Cassini, constraints are placed on all of the previously mentioned parameters.

Given the dynamic state of the Jovian magnetosphere, and the uncertainties existing in the radio emission data, the static model presented in this paper is not intended to provide definitive answers to the questions of precise Io flux tube density profile or to the exact source location of HOM. Rather, the study uses a new approach to place more constraints on past models. We acknowledge that variations of the plasma torus density by perhaps a factor of two are possible and that magnetic field model variations exist. Our results are stated as inequalities and the actual parameters might vary due to temporal and spatial effects.

2. Model

The ray tracing code is based on the Haselgrove (1955) equations and has been discussed in the past (cf. Menietti et al., 1987). The code requires as input the initial wave normal angle (ψ_0), frequency, and source location, as well as a model of the magnetic field and plasma density. While the code is three-dimensional, this study was performed in two dimensions, the meridional plane. This approximation is consistent with the finding of Kurth et al. (1997) that the Jovian radio emissions appear to be confined to the meridional plane. The rays at each frequency were launched from a calculated source point of the HOM emission along one of three assumed magnetic field lines, L-shells intercepting the Jovigraphic equator at $r = 10, 20$, and 40 R_J. Even though the magnetic field of Jupiter is not dipolar, we refer to these as L-shells of 10, 20, and 40. We have, however,

Table 1
Calculated L values at the foot of the fieldline

L-shell	10	20	40
$\lambda_{III} = 181.5°$	9.8	28.4	42.4
$\lambda_{III} = 247°$	9.5	17.7	35.4

performed a more quantitative analysis of the lines of magnetic force by calculating the integral invariant, I, where $I = \int_A^{A'} (1 - B/B_m)^{1/2}\, ds$ where ds is the differential path length along the line of force connecting point A with its conjugate point A', and B_m is the magnitude of the magnetic field at points A and A'. We used the approximation of Hilton and Parameter (1971) to estimate L for each of the field lines chosen for our HOM source regions. The results indicate that the calculated values of L depend on the meridian plane as shown in Table 1 for points at the foot of each fieldline.

The emission source locations were near the local RX cutoff frequency, $f_{RX} = f_g/2 + \sqrt{(f_p)^2 + (f_g/2)^2}$, where f_g is the gyrofrequency and f_p is the plasma frequency. As a practical criterion we considered the source to be doppler-shifted 1% above f_{RX}.

For the Jovian magnetosphere we have incorporated the analytical plasma density model of Divine and Garrett (1983), and the O6 with current sheet magnetic field model of Connerney (1993). The O6 magnetic field model is a fit to the Voyager data using a spherical harmonic expansion, and is also a static model. The Divine-Garrett plasma torus model is a 3-D, static, analytical and empirical model with almost azimuthal symmetry, and is based on the Pioneer and Voyager flyby data. This model was used because it lends itself well to ray tracing calculations, and agrees reasonably well (within factors of 2) to the most recently published tabular model (Bagenal, 1994). For the Io torus we have modified the density model of Divine and Garrett (1983) by eliminating the inner plasmasphere. This would be consistent with the work of Warwick and Dulk (1964) and Dulk et al. (1992) who found that the nearly 100% elliptical polarization of Jupiter's decametric emission implies a high-latitude density with an upper limit of about 5 cm^{-3}. In our model magnetosphere we have also added a density-enhanced Io L-shell centered at the location of Io torus "ribbon". Schneider and Trauger (1995) have obtained ground-based images of SII emission from the Io torus. They report that an averaged radial profile shows a maximum intensity at about 5.7 R_J (somewhat inside Io's orbit at 5.91 R_J). The ribbon of SII is colder plasma in emission, but does extend along the Io flux tube for many degrees away from the magnetic equator. We have also done calculations assuming the filled Io L-shell was located at $r = 5.91$ R_J. The results are minimally different.

Analogous to the work of Higgins et al. (2001), we have modeled the density within the Io L-shell as a Gaussian distribution that falls off perpendicular to the field line,

$$n(r,\theta) = n_0\,e^{-(d/w)^2}, \tag{1}$$

where n_0 is the density at the center of the Io L-shell, d is the perpendicular distance from the Io L-shell, and w is (half-width of the distribution) (0.6).

The density within the Io L-shell near the region where HOM emission is nearly tangent (see Fig. 2) is always much larger than the surrounding region of the Jovian magnetosphere.

3. Ray tracing results and observations

Observations from the Galileo plasma wave instrument (PWS) and the Cassini radio and plasma wave investigation (RPWS) have been used in this investigation. Both instruments have been described elsewhere (Gurnett et al., 1992; Gurnett et al., 2003) and will not be described in detail here. The Galileo PWS measures plasma waves and radio emissions over the frequency range from 5.6 Hz to 5.6 MHz. Cassini RPWS has greater sensitivity and frequency resolution and is capable of measurements in the frequency range from 1 Hz to 16 MHz. Using both Galileo and Cassini observations of the attenuation lanes we have attempted to set limits on the parameters n_0 and w. Galileo data is used for $r < 50\ R_J$, while Cassini data provides information for $r > 50\ R_J$. From past studies of the attenuation lanes (Gurnett et al., 1998; Menietti et al., 1998, 1999, 2001; Higgins et al., 1995, 1998, 1999, 2001), we have determined a clear dependence of the attenuation lanes on frequency and system III longitude. From the Galileo data we have chosen a few time intervals where the attenuation lanes are particularly visible and thus allow better measurement of frequency in the center of the attenuation lane. Radio emission data showing distinct attenuation lanes when Cassini was near closest approach to Jupiter were also chosen.

From the data a table was constructed to identify the presence of attenuation lanes at a specific frequency and satellite radial position. The spacecraft jovigraphic latitude was always assumed to be near zero. This is a good approximation for the data used for comparison studies. Any small errors would have an insignificant effect on our results. The frequencies chosen were 1.0, 1.5, 2.0, 2.5, and 3.0 MHz. The radial positions were 15, 20, 25, 30, 35, 40, 43, 48, and 137 R_J. The source of the HOM emission is assumed to lie along the magnetic field line at ~ 1% above the RX cutoff frequency. Source meridian planes at $\lambda_{III} = 181.5°$ and 247° were chosen to provide attenuation lanes at two distinct orientations of the magnetic field. The L-shell of the emission was also a free parameter, and sources were assumed along $L = 10, 20$, and 40. By L-shell we refer to the radial distance at which a magnetic field line (O6 with

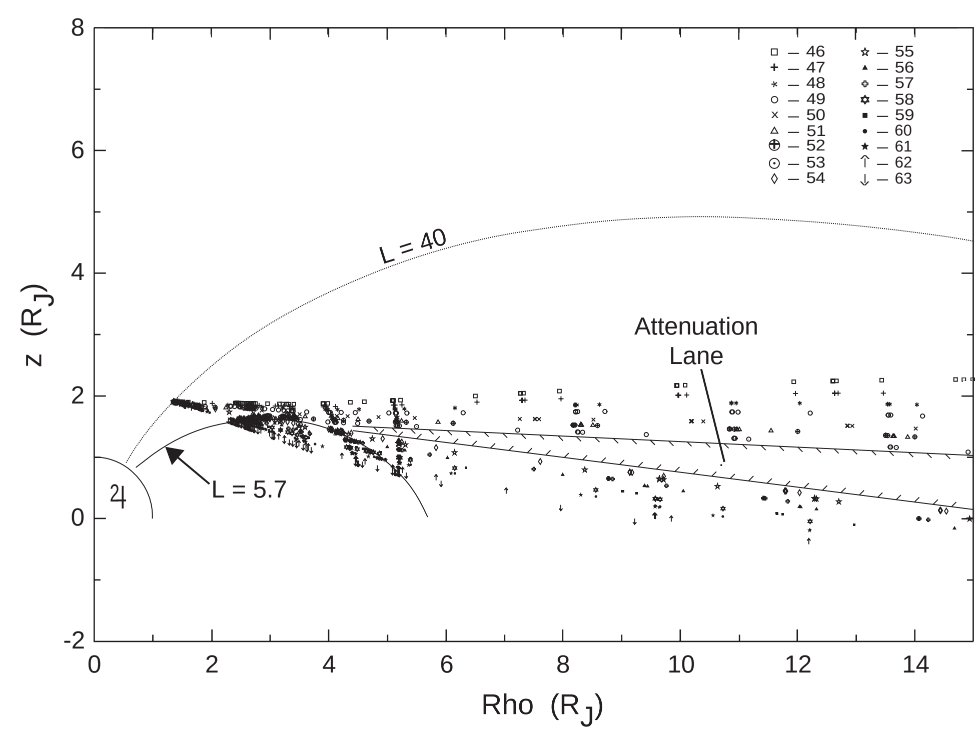

Fig. 3. Ray tracing results for a source of HOM emission near f_{RX} along a magnetic field at $L \sim 40$. The plane of the figure is near $\lambda_{III} = 181.5°$. The field line at $L = 5.7$ has a central density of 10 cm^{-3} and $w = 0.22\ R_{Io}$ (Eq. (1)). The symbols of the ray tracing indicate the initial wave normal angle (ψ) chosen. The refraction due to the Io L-shell produces the attenuation lane observed.

current sheet model) crosses the Jovigraphic equator. The ray tracing results were compared directly to the observational constraints.

The number of different parameters (3 L-shells, 5 widths, w, 6 densities, n_0, 5 frequencies, and 2 source meridian planes) were selected to provide a comprehensive coverage of parameter space while not over-taxing computer resources. Numerous computer runs were made over an extended range of parameters before finally selecting the more limited range chosen. For instance, it was observed that test runs for $L < 10$ or $n_0 = 400\ \mathrm{cm}^{-3}$ were not producing attenuation lanes that agreed with the observations, hence more extensive runs were not considered.

By first choosing a particular source frequency and L-shell location, ray tracing proceeded for a range of assumed parameters of the Io L-shell density model. Plots of the ray tracing results for a given set of Io L-shell density parameters (n_0, d, and w) were then compared to the data constraints. The Io L-shell was assumed to be at $r = 5.7\ R_J$, the nominal position of the torus ribbon as reported by Schneider and Trauger (1995). We thus assume an Io torus that is time-independent. Hundreds of plots were produced for analysis and comparison to the observational constraints. The results were compiled noting which source locations and Io L-shell density parameters agreed best with the observational constraints.

For each chosen frequency and spacecraft radial distance the data were consulted to determine whether or not an attenuation lane existed. The output of a computer run was a plot of ray paths for a range of source parameters. In these plots an attenuation lane was assumed to exist at a particular marked spacecraft radial distance if no or relatively very few rays intersected the jovigraphic equator within several Jovian radii of that position. This determination was made by eye and required study of each of the many hundreds of plots produced. Ideally, a unique set of Io L-shell parameters would have allowed ray paths that produced attenuation lanes in agreement with the data at all frequencies and for both chosen meridian longitudes.

In Fig. 3 we show the results of ray tracing for a range of wave normal angles $46° < \psi < 63°$. The model parameters are given on the plot as $n_0 = 10\ \mathrm{cm}^{-3}$, $w = 0.22\ R_{\mathrm{Io}}$, $f = 2.0$ MHz. The source field line was $L = 40$ in the meridian plane of $\lambda_{\mathrm{III}} = 181.5°$. For clarity we have limited the output to display rays at 1.0 degree intervals. One can see how the emission is refracted near the Io L-shell producing an attenuation lane observed at a distance. For the production runs, ray tracing was conducted for an interval of only 0.1 degree in wave normal angle.

In Figs. 4 and 5 we show samples of ray tracing results demonstrating the influence of modifying the parameters of the Io L-shell density model. Both figures are for HOM source regions lying along $L = 40$ and near the meridian plane $\lambda_{\mathrm{III}} = 247°$, and for emission at $f = 2$ MHz. In Fig. 4 we hold w constant at 0.088 R_{Io} while allowing the central density of the Io L-shell to vary from 10 to 25 cm^{-3}. The width in latitude of the attenuation lane clearly increases as the density increases. Note that the scale on each axis is not the same. The vertical lines were used as diagnostics during the analysis.

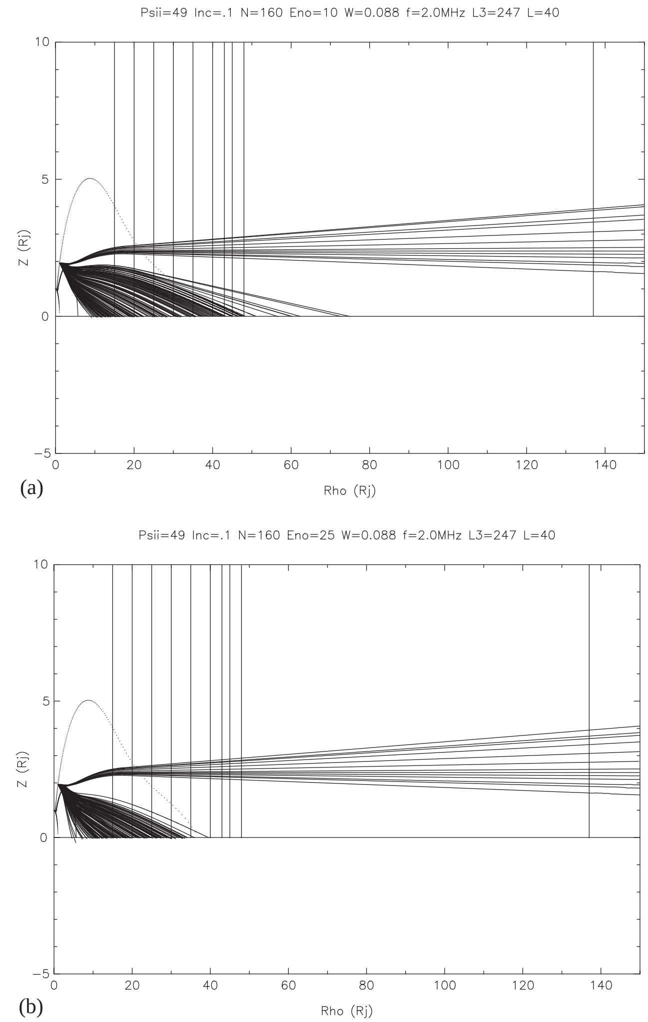

Fig. 4. Ray tracing results showing the effect of changes in the central density of the Io L-shell. These results are for a constant value of $w = 0.088\ R_{\mathrm{Io}}$ with source HOM field line located at $\lambda_{\mathrm{III}} = 247°$ along $L \sim 40$. The density values are 10 cm^{-3} (a) and 25 cm^{-3} (b). Note that the scales along each axis are not the same.

The results indicate that no one set of parameters satisfies ALL the observational constraints at both chosen meridional planes (181.5° and 247°). However, a relatively small range of parameters does. Source positions of HOM lying along both $L = 40$ and 20 can explain the observations of attenuation lanes if a relatively small range of parameters is allowed for the size and shape of the Io L-shell density model. However, source positions along $L = 10$ did not produce attenuation lanes consistent with the observations. In Table 2 we present ranges of parameters for the Io L-shell density model that are consistent with the observations of attenuation lanes. The table includes values for HOM source

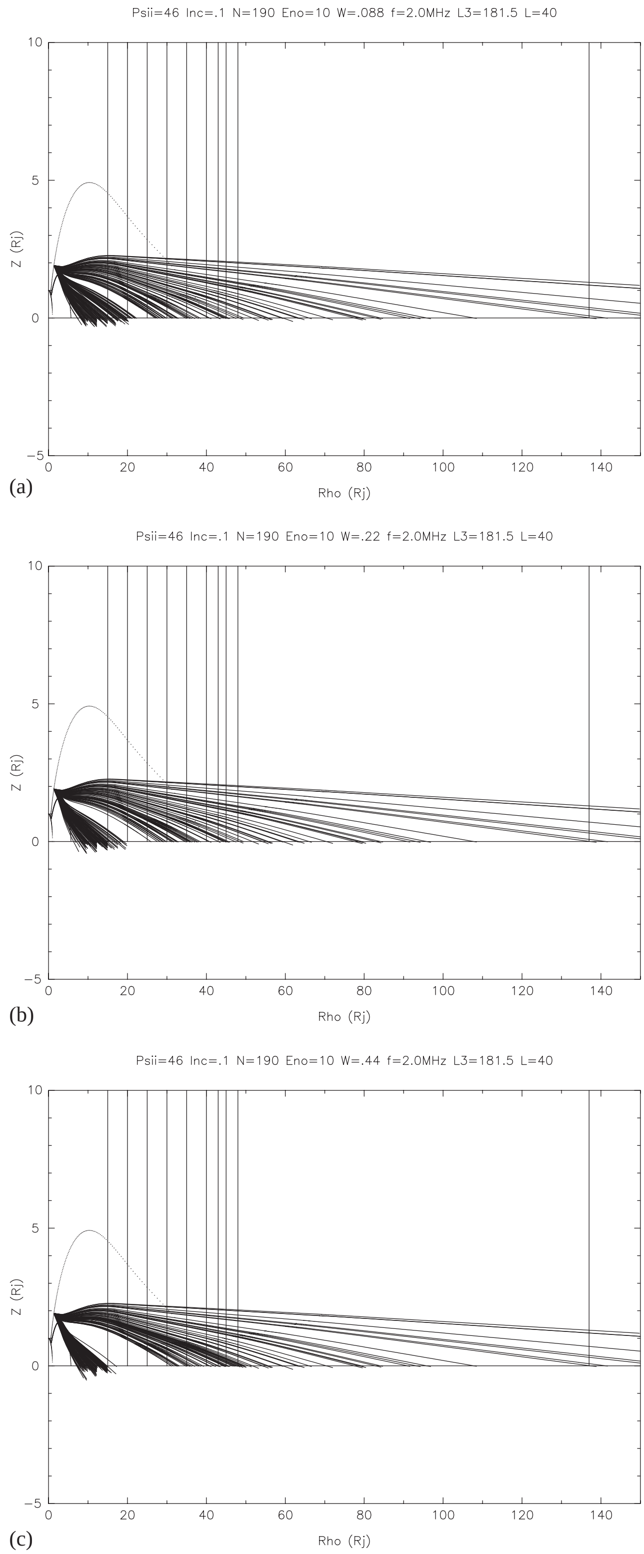

Fig. 5. Ray tracing results showing the effect of changes in the width at half maximum of the Gaussian density distribution for the Io L-shell. In this case there is a constant value of central density of $n_0 = 10$ cm^{-3}, with source HOM field line located at $\lambda_{III} = 181.5°$ along $L \sim 40$. The values of w are 0.088 R_{Io} (a), 0.22 R_{Io} (b) and 0.44 R_{Io} (c). Again note that the scales along each axis are not the same.

Table 2
Acceptable parameters for Io L-shell density model

λ_{III} (deg)	n_0(cm^{-3})	$w(R_{Io})$	L	
247°	5–25	0.088–0.88	40	TAR
247°	5–10	0.088–0.22	40	SAR
181.5°	1–10	0.088–0.88	40	TAR
181.5°	5–10	0.088–0.44	40	SAR
247°	5–10	0.088–0.22	20	TAR
247°	5	0.22	20	SAR
181.5°	1–10	0.22–0.88	20	TAR
181.5°	1–10	0.22–0.88	20	SAR

TAR=total allowable range
SAR= smallest allowable range

locations along both $L = 20$ and 40 for each of the two meridional planes chosen.

4. Summary

Radio wave data showing distinct attenuation lanes from both Galileo ($r < 50\,R_J$) and Cassini ($r > 50\,R_J$) have been used to place constraints on a model of the density of the Io L-shell and source locations of Jovian HOM emission. Ray tracing calculations in the model Jovian magnetosphere have revealed attenuation lanes due to refraction that suggest a relatively small range of values for a density-enhanced Io L-shell. The general theory presented by Gurnett et al. (1998) has been confirmed.

Radio wave ray tracing was performed in two dimensions for two different meridian planes, $\lambda_{III} = 181°$ and 247°. We have traced rays for frequencies of $f = 1, 1.5, 2, 2.5$, and 3 MHz. At each frequency we vary both n_0 and w over a wide range of values. Higher frequency lanes are observed for $\lambda_{III} \sim 180°$ and lower frequency lanes for $\lambda_{III} \sim 247°$. A table of observations has been constructed which identifies the absence or presence of attenuation lanes at each sampled frequency and radial distance, and this was compared to ray tracing results.

Hundreds of plots have been examined and the results indicate that the most likely range of parameters for the Io L-shell magnetic flux tube are:

$$1\,\text{cm}^{-3} < n_0 < 10\,\text{cm}^{-3},$$

$$0.088\,R_{Io} < w < 0.44\,R_{Io}.$$

Such density values are consistent with models of the Io torus and probable filling of the Io L-shell due to active volcanic eruptions on Io. Menietti et al. (2001) have reported a possible correlation of Io volcanic activity and the presence of attenuation lanes observed at Jupiter. The observation of the attenuation lanes may thus be a way to remotely sense the temporal density activity within the Io torus. The results also suggest that the HOM which produces the attenuation lanes has a source location along magnetic field lines in the range $L > 10$. This range is somewhat higher than previously determined from past ray tracing and direction-finding studies, but those studies did not have the additional constraints provided by the attenuation lanes.

As pointed out earlier, this study has not been intended to provide an exact determination of either the Io flux tube density profile or the HOM source location. It is known that the Io torus densities vary both in space and time. Galileo plasma wave observations in the Io torus during a flyby of Io have indicated that the torus density at the time was about a factor of 2 larger since the Voyager 1 flyby of 1979 (Gurnett et al., 1996). In addition, Desch et al. (1994) have argued from Ulysses observations that there are significant azimuthal variations of density in the torus (30–50% density depletions). Our model results can only be described as a static, representative model. We have investigated the effect on our results of varying the Io torus density as well as the magnetic field model. The entire study was initially performed using only a filled Io L-shell and assuming no Io plasma torus. The ray tracing calculations indicated a best match with the radio wave observations of attenuation lanes for a source field line of $L = 20$ with $5\ \mathrm{cm}^{-3} < n_0 < 25\ \mathrm{cm}^{-3}$ and $w < 1.3\ R_{\mathrm{Io}}$. These parameters are surprisingly similar to those listed in Table 2. This gives us confidence that a more dynamic model of the Io torus (perhaps including larger central densities and azimuthal dependence), would not alter our conclusions, and would not substantially change the parameters listed in Table 2. Likewise, modifications due to the introduction of different magnetic field models, such as the VIP4 model (Connerney et al., 1998), have little if any affect on our results, as confirmed by comparing ray tracing runs.

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