

# An unusual rotationally modulated attenuation band in the Jovian hectometric radio emission spectrum

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**Abstract.** A well-defined attenuation band modulated by the rotation of Jupiter has been found in the spectrum of Jovian hectometric radiation using data from the Galileo plasma wave instrument. The center frequency of this band usually occurs in the frequency range from about 1 to 3 MHz and the bandwidth is about 10 to 20 percent. The center frequency varies systematically with the rotation of Jupiter and has two peaks per rotation, the first at a system III longitude of about  $50^\circ$ , and the second at about  $185^\circ$ . It is now 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. The peak at  $50^\circ$  system III longitude is attributed to radiation from a southern hemisphere source and the peak at  $185^\circ$  is from a northern hemisphere source. The attenuation is thought to be caused by coherent scattering or shallow-angle reflection from field-aligned density irregularities near the Io L-shell. The narrow bandwidth indicates that the density irregularities are confined to a very narrow range of L values ( $\Delta L = 0.2$  to  $0.4$ ) near the Io L-shell.

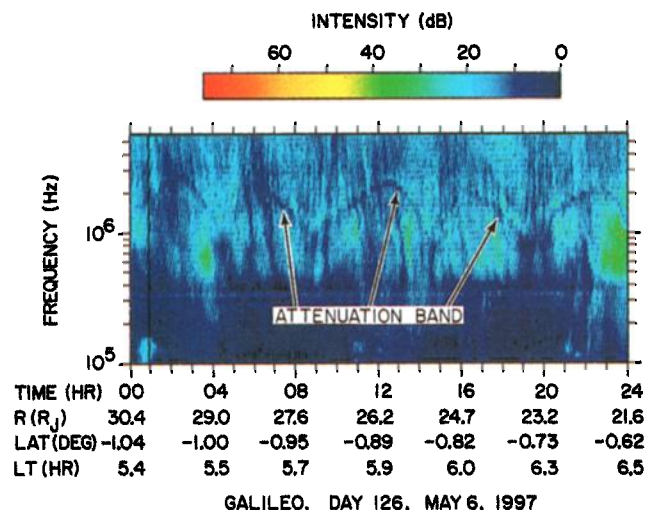
## 1. Introduction

In this paper we discuss a rotationally modulated attenuation band that was recently discovered in the Jovian hectometric radio emission spectrum using data from the Galileo spacecraft, which is in orbit around Jupiter [Johnson *et al.*, 1992]. The attenuation band usually occurs in the frequency range from about 1 to 3 MHz and is possibly related to narrowband features called "drifting gaps" or "lanes" observed in the Voyager 1 and 2 radio emission data by Lecacheux *et al.* [1980] and Higgins *et al.* [1995]. The attenuation band observed by Galileo typically occurs at frequencies above the frequencies of the "lanes" or "gaps" observed by Voyager. The absence of comparable observations in the Voyager data is probably due to the strongly degraded sensitivity of the Voyager radio astronomy instrument at frequencies above about 1.3 MHz [Lecacheux *et al.*, 1980]. The bandwidth of the attenuation band observed by Galileo is usually about 10 to 20 percent, and the attenuation can be as large as 30 dB. The most striking feature of the Galileo observations is that the center frequency of the attenuation band varies systematically with the rotation of Jupiter, with two parabolically shaped peaks per rotation. The

purpose of this paper is to describe the main features of the attenuation band, and to present an explanation of its origin.

## 2. Observations

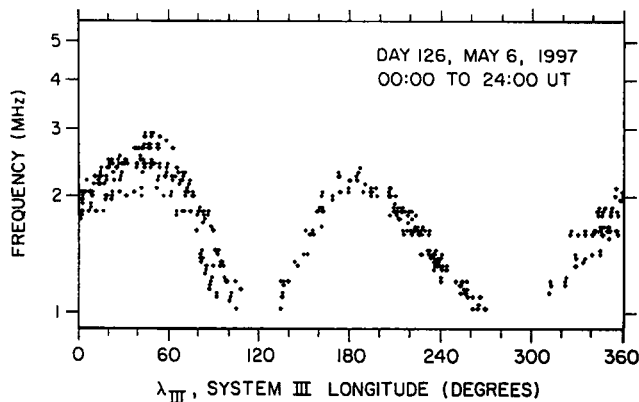
The observations presented here are from the Galileo plasma wave instrument, which provides measurements of plasma waves and radio emissions over a frequency range from 5.6 Hz to 5.6 MHz [Gurnett *et al.*, 1992]. A frequency-time spectrogram illustrating the attenuation band is shown in Figure 1. The spectrogram shows the electric field intensities for a 24-hour interval on May 6, 1997, as the spacecraft was approaching Jupiter near the equatorial plane on the dawn side of the magnetosphere. The radial distance during this interval varied from 30.4 to 21.6 Jovian radii ( $R_J$ ). The frequency scale covers a range from 0.1 to 5.6 MHz. The electric field intensities are color coded, with red being the most intense and blue being the least intense. An intensity scale is given at the top of the spectrogram. As can be seen, an intense broadband radio emission is evident for the entire duration of the spectrogram from about 0.5 MHz to more than 5 MHz. This type of radio emission was first discovered during the Voyager 1 flyby of Jupiter [Warwick *et al.*, 1979; Lecacheux *et al.*, 1980; Alexander *et al.*, 1981; Carr *et al.*, 1983] and is called hectometric radiation, since the wavelengths are in the hectometer (hundred meter) range. Polarization and direction-finding measurements by the Ulysses spacecraft provide strong evidence that the Jovian hec-



**Figure 1.** A frequency-time spectrogram showing the attenuation band observed in the Jovian hectometric radio emission spectrum.

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**Figure 2.** The center frequency of the attenuation band in Figure 1 plotted as a function of the system III longitude of the spacecraft.

tometric radiation is generated at high altitudes along the auroral field lines by the cyclotron maser mechanism [Ladreitner and Leblanc, 1991; Reiner et al., 1993a, 1993b; Ladreitner et al., 1994; Kurth et al., 1997].

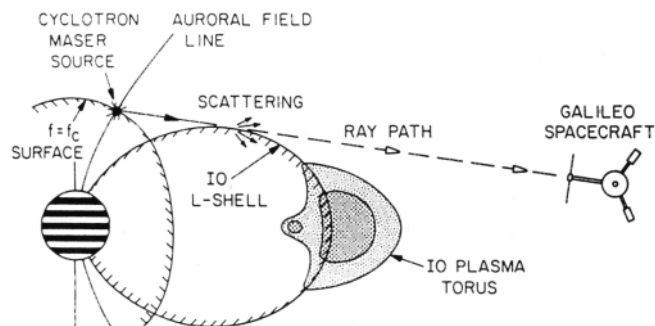
As can be seen in Figure 1, the center frequency of the attenuation band has well-defined parabolically shaped peaks that repeat approximately every five hours. It is easily verified that two peaks occur per Jovian rotation. Evidence for this rotational control is given in Figure 2, which shows the center frequency for the band in Figure 1 plotted as a function of the spacecraft system III (1957.0) longitude,  $\lambda_{III}$ . For a discussion of the system III longitude system, see Dessler [1983]. As can be seen, the center frequency has two clearly defined peaks, the first at  $\lambda_{III} \approx 50^\circ$ , and the second at  $\lambda_{III} \approx 185^\circ$ . The two peaks correspond roughly to times when the magnetic dipole axis of Jupiter is tilted away from and toward the spacecraft, respectively.

The characteristics of the attenuation band vary considerably, both on short and long time scales. The attenuation band almost always occurs within a frequency range from about 1 to 3 MHz. The bandwidth at the 10 dB points, measured between the two edges of the band, is typically about 10 to 20 percent, and in a few cases can be as large as 30 percent. When the bandwidth is large (i.e., greater than 30 percent), it is often difficult to distinguish the attenuation band from other structures that are present in the Jovian hectometric spectrum. The attenuation at the center frequency varies considerably, from about 3 dB, which is the limit below which the band cannot be detected, to more than 30 dB. Occasionally there are narrowband enhancements at the upper or lower edge of the attenuation band. Enhancements of this type can be seen from about 08:00 to 09:00 UT and from about 19:00 to 20:00 UT in Figure 1. Very rarely there is evidence of an attenuation band at the second harmonic of the main band. A second harmonic feature of this type can be seen from about 17:00 to 19:00 UT in Figure 1. Usually the attenuation band is most clearly identifiable at intermediate radial distances, from about 15 to 50  $R_J$ . The difficulty in identifying the attenuation band at large radial distances, beyond about 50  $R_J$ , is believed to be mainly due to the lower intensities at larger distances, which makes the band more difficult to identify

because of the lower signal-to-noise ratio. The disappearance of the band at small radial distances, inside about 15  $R_J$ , appears to be more fundamental. As the spacecraft approaches Jupiter, the frequency usually decreases, eventually causing the band to disappear as the frequency approaches the lower limit of the hectometric emission band (i.e., below about 1 MHz). Evidence of this radial distance dependence can be seen in Figure 1. The peak frequency starts at about 2.7 MHz at 30  $R_J$ , and decreases to about 1.8 MHz at 22  $R_J$ . This trend continues into the next day, and within a few hours the band has disappeared. The occurrence also varies considerably from orbit to orbit. Over the roughly two-year period for which we have data the band can be detected about 25 percent of the time. When the attenuation band is present it can usually be identified over a period ranging from days to weeks. The reason for the long-term variability is not known. A preliminary study has been carried out to search for control at the 42.46 h period of Io's orbit. However, no obvious Io control could be identified.

### 3. Interpretation

The very regular periodic variation, with two peaks per rotation, strongly suggests that the Jovian magnetic field plays a crucial role in controlling the frequency of the attenuation band. Since the hectometric radiation is believed to be generated by the cyclotron maser mechanism, it is not surprising that some degree of magnetic control is involved. For the low-density conditions that exist in the high-latitude region of the Jovian magnetosphere, where the hectometric radiation is believed to be generated, cyclotron maser radiation is expected to be emitted into a cone-shaped beam around the magnetic field at or near the local electron cyclotron frequency,  $f_c = 2.80B$  MHz, where the magnetic field  $B$  is in gauss. For a discussion of the theory of cyclotron maser radiation, see Goldstein and Goertz [1983]. Initially, we thought that a null in the radiation pattern could produce the attenuation band as the Jovian rotation sweeps the null over the spacecraft. However, since the radiation pattern is controlled by the electron distribution function, we concluded that the required distribution functions were much too sensitive to the details of the auroral acceleration process to produce such a repeatable pattern. So we decided to look for an



**Figure 3.** A model that attributes the attenuation to scattering or shallow-angle reflections in the region where the ray path is tangent to the Io L-shell.

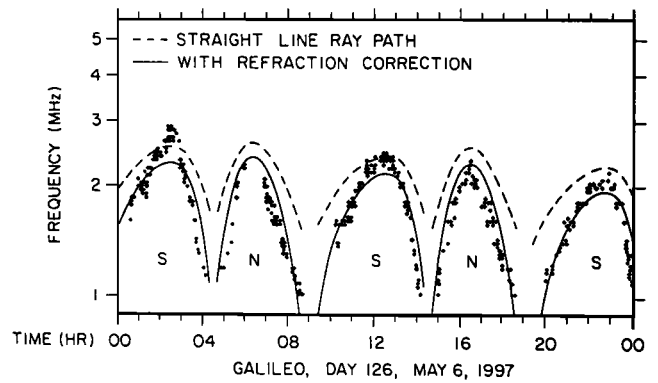
explanation that depends on a more invariant quantity, such as the magnetic field geometry.

It is known that Io is responsible for a highly structured and complex plasma torus with large density gradients, field-aligned currents, and other complex processes (see *Bagenal, 1994*). If one considers the propagation of radiation from a high-latitude cyclotron maser source, it is evident that the ray path must pass through or near the Io L-shell. It occurred to us that density gradients associated with the Io L-shell could then preferentially scatter the hectometric radiation in the region where the ray path is nearly tangent to the magnetic field. Possible scattering mechanisms could include, for example, coherent scattering from short-wavelength density fluctuations or shallow-angle reflections from field-aligned density structures.

As a simple model we assumed that the scattering occurs in the region where the ray path is tangent to the magnetic field at the Io L-shell. The relevant geometry for this model is shown in Figure 3. Since hectometric radiation is believed to be generated along the auroral field lines at or very near the electron cyclotron frequency, the source was assumed to be located at the intersection of a high-latitude auroral field line and the  $f = f_c$  surface, where  $f$  is the observing frequency. Since for  $f = 1$  to 3 MHz, the wave frequency at these high latitudes is well above the electron plasma frequency ( $f_p = 8980\sqrt{n_e}$  Hz, where  $n_e$  is in  $\text{cm}^{-3}$ ), to a first approximation the ray path is a straight line. The source was assumed to lie in the magnetic meridian plane. This assumption is consistent with the occultation measurements of *Kurth et al. [1997]*, which show that the radiation appears to be propagating outward near the magnetic meridian plane.

To test the above model, straight line ray paths were computed from the spacecraft to a source located in the magnetic meridian plane along an auroral field at a large ( $L = 55$ ), but otherwise arbitrary, L-value. As can be seen from the geometry, the ray path is relatively insensitive to the exact choice of the source L-value. The  $O_6$  model [*Connerney, 1993*] was used for the magnetic field computations. The elevation of the ray path (relative to the equatorial plane) was adjusted until the ray path was tangent to the Io L-shell (i.e.,  $L = 5.9$ ). Once the tangent ray path was found the electron cyclotron frequency at the source was computed. According to the model strong attenuation would be expected at this frequency. Lower frequencies, which originate farther from Jupiter, do not pass through the Io L-shell, and therefore would not be expected to suffer any scattering. Higher frequencies, which originate closer to Jupiter, pass through the Io L-shell, but would be expected to suffer only minimal scattering, since the path length through the scattering region is much smaller and the magnetic field tangency condition is not satisfied.

The results of the above ray path calculation are shown in Figure 4. The black dots are the center frequencies of the attenuation band measured from Figure 1. The dashed lines give the emission frequency at the source from the tangent ray path computation. The curves marked "N" are for a northern hemisphere source, and the curves marked "S" are for a southern hemisphere source. As can be seen the computed emission frequencies follow the basic trend in the measured frequencies quite well. The parabolic frequency modulation is caused by the north-south motion of the tan-



**Figure 4.** A comparison of the computed emission frequencies along the tangent ray path with the measured frequencies of the attenuation band in Figure 1.

gent ray path as Jupiter rotates. The emission frequency increases as the intersection of the ray path with the auroral field line moves toward Jupiter (i.e., to higher cyclotron frequencies), and vice versa. For a northern hemisphere source the peak frequency occurs when Jupiter's north magnetic pole is tilted toward the spacecraft (i.e.,  $\lambda_{III} = 185^\circ$ ), and for a southern hemisphere source the peak frequency occurs when the north magnetic pole is tilted away from the spacecraft (i.e.,  $\lambda_{III} = 50^\circ$ ). Note that the peak frequencies decrease as the spacecraft approaches Jupiter, in agreement with the observations. This variation occurs because the elevation angle of the tangent ray path increases as the spacecraft approaches the Io L-shell, thereby decreasing the cyclotron frequency at the source.

Although the computed emission frequency curves have the correct qualitative dependence, the exact shape does not accurately follow the trend in the data, particularly at the lowest frequencies. This discrepancy is believed to be due to refraction by the Io plasma torus. Near the outer edges of the torus, the torus essentially acts as a prism. Even though the wave frequency is well above the plasma frequency, over the long path length from the torus to the auroral field line, small deviations in the ray path angle can cause significant shifts in the emission frequency. For  $f \gg f_p$ , it is easy to show [*Stix, 1962*] that the index of refraction,  $n = \sqrt{1 - (f_p/f)^2}$ , is given to a good approximation by  $n = 1 - (1/2)f_p^2/f^2$ , where the second term represents a small correction from the free space value (i.e.,  $n = 1$ ). Note that since the index of refraction is less than one, the ray is bent away from the torus, therefore reducing the emission frequency. For small deviation angles it is easy to see from simple geometric optics considerations that the frequency shift is proportional to  $1/f^2$ . Therefore, to correct for refraction we have shifted all of the frequencies downward by an amount  $\Delta f = k/f^2$ , where  $k$  is a constant. The constant  $k$  has been adjusted to give a good fit to the data at low frequencies. The results are shown by the solid lines in Figure 4. As can be seen the refraction correction substantially improves the overall fit. The best fit  $k$ -value is  $k = 1.7 \text{ MHz}^3$ . This  $k$ -value corresponds to deviation angles of  $\Delta\theta = 1.0^\circ$  at  $f = 3.0 \text{ MHz}$ , and  $\Delta\theta = 9.0^\circ$  at  $f = 1.0 \text{ MHz}$ . Comparisons with exact ray tracing calculations by *Wang [1994]* for similar ray paths using the plasma

density model of *Divine and Garrett* [1983] show that these angular deviations are quite reasonable.

#### 4. Discussion

A strong case has been made that the attenuation band observed in the Jovian hectometric radiation by Galileo is caused by scattering in the region where the ray path is nearly tangent to the magnetic field at the Io L-shell. From the bandwidth (10 to 20%) of the attenuation band and the ray path geometry, one can show that the range of L-shells involved in the scattering process is approximately  $\Delta L \simeq 0.2$  to 0.4. Two scattering mechanisms have been considered: coherent scattering and shallow-angle reflection. Coherent scattering involves density irregularities with spatial scales comparable to the wavelength of the electromagnetic wave. Density irregularities of this type could be produced, for example, by short-wavelength instabilities driven by field-aligned electron beams or currents. Evidence for such field-aligned electron beams at  $L \simeq 5.6$ , just inside the Io L-shell, have been provided by the VLF hiss observations of *Morgan et al.* [1994]. Multiple reflections of Alfvén waves excited by Io, such as proposed by *Gurnett and Goertz* [1981], could also account for current-driven instabilities along the Io L-shell. Shallow-angle reflection is basically a geometric optics mechanism whereby large reflection coefficients can occur if the ray path is nearly tangent to the surface of the density irregularity. Plasma observations [*Bagenal*, 1994] show that large density gradients exist near the inner edge of the Io torus. If these density structures are aligned along the magnetic field, as often occurs in a magnetized plasma, then strong reflections would be expected when an electromagnetic wave is incident at a small angle to the magnetic field. Such reflections could occur even when the spatial scales are much larger than the wavelength, although the range of allowed incidence angles (relative to the magnetic field) becomes quite small when the plasma frequency is well below the wave frequency. For  $n_e = 100 \text{ cm}^{-3}$ , which, according to the model of *Wang et al.* [1995], is a reasonable estimate for the electron density near the outer edge of the torus, it is easy to show that the maximum allowed incidence angles (relative to the magnetic field) for total internal reflection are approximately  $\alpha = f_p/f \simeq 0.09$  to 0.03 radians (i.e.,  $5.0^\circ$  to  $1.7^\circ$ ) for  $f = 1$  and 3 MHz. These small incidence angles provide a simple explanation for why the scattering is localized near the tangency point. Unfortunately, very little is known about the spatial spectrum of density fluctuations at high latitudes along the Io L-shell, so it is difficult to provide a quantitative evaluation of the attenuation that would arise from such a scattering mechanism.

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