Ion cyclotron waves observed at Galileo's Io encounter: Implications for neutral cloud distribution and plasma composition


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Abstract. We present observations of ion cyclotron waves measured by the magnetic field experiment onboard the Galileo spacecraft during its encounter with Jupiter's satellite Io on December 7, 1995. The waves exhibit highly coherent oscillations, with a period between 2 and 3 seconds. They are left-handed, nearly circularly polarized, and their plane of polarization is nearly perpendicular to the background field. Their power spectra reveal peaks close to the gyrofrequencies of $\mathrm{SO}_2^-$ and, sometimes, $\mathrm{SO}_4^-$. The waves are interpreted as m = 0 modes generated by a gyroresonance of pickup ions, whose source is neutral particles originating from Io. On the inbound leg of the flyby, in regions where the electron density is approximately constant, the observed decay of the wave power with distance from Io roughly follows the expected distribution of neutral clouds. The presence of wave power just above the $\mathrm{SO}_2^-$ gyrofrequency suggests that there is only a small amount of $\mathrm{SO}_4^-$ in the background plasma.

Introduction

One of the major features of the data gathered by the Galileo magnetometer on the December 1995 flyby of Io was the appearance of large amplitude, highly monochromatic waves by the magnetic field experiment [Kivelson et al., 1996], starting at a radial distance of about 18 $R_{\text{Io}}$, from Io, with a peak wave power in the range of the gyrofrequencies of $\mathrm{SO}_2^-$ and $\mathrm{SO}_4^-$. While a magnetic signature of freshly ionized and picked-up particles in Io's vicinity had been expected, the onset of the waves at such a large distance from Io and their near-monochromatic nature came as a surprise.

Waves generated by gyroresonant pickup ions have been reported from the vicinity of comets in the solar wind, e.g., by Yamauchi and Smith [1986], Bame et al. [1984], and Glassmeier and Neubauer [1985]. However, at Io the conditions differ from those near comets. The background magnetic field is much larger and nearly perpendicular to the flow, and the bulk velocity is much smaller.

In this paper, after introducing the data, we will provide some basic background on ion cyclotron waves and gyroresonance with pickup ions. A simple model of the torus plasma is applied to show that this process could explain at least some of the features found in the data. Finally, we draw some conclusions on the distribution of neutral clouds and - as - the composition of the torus plasma near Io.

Observations

To study the waves, we high-pass filtered the magnetic field data by subtracting the background field, which was determined by a moving average over one minute. This, using again a moving win-

dow of one minute width for calculating the covariance matrices, we transformed the data into a coordinate system whose z axis is oriented with the direction of minimum variance. For plane waves, $\mathbf{P}_2$ direction is aligned with the wave vector $\mathbf{k}$. We define $\mathbf{r}$ as the angle between this direction and the background magnetic field. The "quality" of the minimum variance direction can be expressed by the ratio $Q$ of the intermediate to the minimum eigenvalue of the covariance matrix, which should be $> 1$.

The fact that the wave are highly monochromatic and have a well-defined plane of polarization perpendicular to $\mathbf{k}$ allows us to apply a method by Galor [1966] which replaces a time series $x(t)$ by the analytical signal $\hat{x}(t) + i \dot{\hat{x}}(t)$ (exp(i$t\hat{\omega}$), where $\hat{\omega}$ is the Hilbert transform of $x(t)$. The envelopes $x_\text{up}$ and instantaneous phases $\phi_x$, $\phi_y$ of the $x$ and $y$-components of the magnetic field, the Stokes parameters, and thus the degree of polarization $\mathbf{P}_2$, $\mathbf{P}_3$ \cite{Braun:1996}, and the ellipticity $\varepsilon = 1 - \varepsilon_2 / \varepsilon_1$ of the wave can be calculated (see Brown and Wolfe [1993]). The ellipticity is defined in such a way that a value of $\varepsilon = 1$ indicates circular left-handed polarization, $\varepsilon$ is circular linear polarization, and $\varepsilon < 1$ indicates right-handed polarization. In addition to these parameters, we define the "wave frequency" as

$$F_s(t) = \sqrt{\frac{x_\text{up}^2(t) + y_\text{up}^2(t)}{x_\text{up}^2(t) + y_\text{up}^2(t)}}$$

where the instantaneous frequency of a component is given by $2 \pi f_s(t) = \dot{\phi}_x(t)$, and the angle brackets indicate averaging over a moving window. For the results presented in this paper, the width of that moving window was 50 s.

As figure 1 shows, the timelines of $Q$ and $\mathbf{P}_3$ can be used to spectroscopically recover the source of the waves from noise: we applied the criterion $Q > 2.5$ and $\mathbf{P}_3 > 0.75$. Figure 1 also shows that the waves from mirror mode oscillations [Russell et al., 1997] which dominate in the wake region near closest approach, we used the condition $\mathbf{P}_3 < 0.37$, with the two modes clearly visible in $Q$ and $\mathbf{P}_3$. In the $\mathbf{P}_3$ panel of figure 1, the wave amplitude is plotted only when the data fulfill all three conditions imposed. The waves first occurred at a radial distance of about 18 $R_{\text{Io}}$ from Io, and their amplitude increasing to about 120 R_I before vision approach. They reappeared after Galileo left Io's wake region, then decaying faster with distance from Io and disappearing at about 7 $R_{\text{Io}}$. Figure 1 also shows that the waves are left-handed, and over long periods nearly circularly polarized, and that their frequency is close to the $\mathrm{SO}_2^-$ and $\mathrm{SO}_4^-$ gyrofrequencies. Moreover, the waves are highly field-aligned, with a typical value of $\mathbf{r} < 2$.

At the Galileo flyby, the magnetic field was tilted westward by about 10° [Kivelson et al., 1996]. Because of this tilt, freshly produced ions, which are picked up perpendicular to the local field, have a non-zero field-aligned beam velocity in the frame of the corotating torus plasma, which is not affected by the local field. Assuming a nominal corotation, this beam velocity is shown in the lowest panel of figure 1 (solid line), and can be estimated as

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\[ \omega' = \omega - k \cdot v_\infty = \omega - k r_{i\infty} \]

where \( v_{i\infty} \) is the \( z \) component (in minimum variance direction) of the spacecraft's velocity relative to the corotating plasma rest frame. \( v_{i\infty} \) is close to \( \omega_{i\infty} \), but varies with the angle \( \theta \) and can be estimated as \( v_{i\infty} \approx (0 \pm 6) \text{ km/s} \). Thus, in the spacecraft frame, the waves are observed at frequencies between those in the plasma rest frame (\( \omega \)) and those in the frame of the pickup ions.

In figure 2, power spectra of three sample time intervals are presented, with the range of gyrofrequencies during these time intervals indicated by vertical lines. They show fairly narrow-band activity in the \( \alpha \) and \( \gamma \) components: (a) and (b)—from the inbound (to lo) leg of the flyby—both above and below the \( \text{SO}_2^+ \) gyrofrequency, (c)—from the closest approach, right after leaving the wake region—just below that frequency. Though there are also a few time intervals when the spectral power is centered around the \( \text{SO}_2^+ \) gyrofrequency, the typical picture is that the power peaks sometimes at, sometimes just above or just below, and sometimes just above and just below the \( \text{SO}_2^+ \) gyrofrequency.

**Analysis**

The condition for a gyroresonance interaction between a particle with a field-aligned velocity \( \eta_i \) and an electromagnetic wave demands that the particle "see" the wave Doppler-shifted to a multiple of its gyrofrequency:

\[ \omega = \omega_i - N \Omega \]

(see Stix [1962]). The sign of \( N \) is determined by the requirement that, in the particle's frame, the wave's field must rotate in the same.
sense in which the particle gyrates around the background field. For waves propagating parallel to the magnetic field, $|N| = 1$, and for a resonance between ions and L-mode waves, $N = -1$, the resonant field aligned velocity of the particles is

$$v_r = v_{pe} \left(1 - \frac{n_e}{n_i}\right).$$

Given the beam velocity $v_b \leq 10\, \text{km/s}$ and a (small) thermal spread of the pickup ions, there is a range of possible resonant velocities $v_r \approx n_i$. Following Thorne and Tauris [1997], the sign of the linear growth rate of L-mode waves generated by a ring beam distribution of pickup ions can be calculated as

$$sgn(\gamma) = sgn \left( \frac{v_b}{v_{ri}} \left( u_b - u_i + u_i - v_{pi} \right) \right).$$

where $u_i$ and $u_b$ are the bulk ring and beam velocities of the pickup ions, and $v_{pi}$ is their thermal velocity. The magnitude of $\gamma$, as given by Thorne and Tauris [1987], is scaled by the number of particles whose field-aligned velocity equals a given $v_{pi}$. To represent this, we defined the function

$$s(\gamma) = sgn(\gamma) \cdot \frac{1}{\gamma}.$$  

for $u_i - v_{pi} \leq u_i \leq u_i + v_{pi}$

which reflects the sign of the growth rate, but also adopts a value close to zero if there are virtually no particles which fulfill the resonance condition. To evaluate $s(\gamma)$ as a function of frequency, the torus is described as a cold and homogeneous plasma. For this simple model, the phase velocity of L-mode waves (see Stix [1962]) and thus, for any given pickup species, the resonant velocity (4) can be calculated. To allow both co-streaming and counter-streaming waves, one has to consider $u_b > 0$ and $u_b < 0$, respectively.

The results shown in figure 3 were computed for SO$_3$ pickup ions, using typical conditions for the flyer ($v_{pi} = 3776$ cm/s, $\beta = 1720$), with $v_b = 10\, \text{km/s}$, $u_i = 50\, \text{km/s}$, and $v_{pi} \approx 5\, \text{km/s}$, and assuming the following composition of the background plasma:

$$\begin{align*}
\text{SO}_3^+ &\quad 1\% \quad 20\% \quad 20\% \quad 50\% \quad 9\% \\
\text{S}^+ &\quad 1\% \quad 20\% \quad 20\% \quad 50\% \quad 9\%
\end{align*}$$

The $s(\gamma)$ traces show that SO$_3$ pickup ions can generate counter-streaming waves below the SO$_3$ gyrofrequency and co-streaming waves just above the SO$_3$ cutoff frequency (which is close to the gyrofrequency, as the concentration of SO$_3$ in the background is low. It should be noted that the positive $\gamma$ just below the S$^+$ gyrofrequency (0.825 Hz) is of no physical significance because it implies an unrealistic wavelength much below the SO$_3$ gyroradius.

In the frequency range of interest, the results do not depend much on the densities of ions with a mass-charge ratio less than that of S$^+$, so the concentrations chosen for these ions are somewhat arbitrary, though they roughly agree with numbers given by Bagemal [1994]. However, the results do strongly depend on the concentration of SO$_3^+$ for $v_{pi} \approx 10\, \text{km/s}$, L-mode waves just above the SO$_3$ cutoff frequency can be excited only if the concentration of SO$_3$ in the plasma is reduced by a factor of 10. If the concentration is higher, the gap between the SO$_3$ gyrofrequency and its cutoff frequency becomes too large to be bridged by the beam velocity, and only counter-streaming waves below the gyrofrequency can be excited. It is tempting to speculate that the SO$_3$ concentration is increased during the interval shown in figure 3(c), but our result for the upper limit of the SO$_3$ concentration may change significantly if a more realistic dispersion relation is used for $v_{pi}$. In a warm plasma, the width of the SO$_3$ stop-band depends not only on the amount of SO$_3$ in the background, but also on such properties of the pickup particles as their temperature and density [Haddleston et al., 1997].

![Figure 3](image3.png)

Figure 3. The L-mode phase (solid) and group (dotted) velocities for the cold plasma model described in the text, and the SO$_3$ resonant velocity $v_r$ and growth rate function $\delta(\gamma)$ for co-streaming, $\delta(\gamma)$ for counter-streaming waves. The dotted lines in the $v_r$ panels are centered around $v_r$ with a thermal spread of about $\pm 5\, \text{km/s}$ ($T = 5\, \text{eV}$). The dashed vertical lines enclose the stop bands associated with SO$_3^+$ and S$^+$. The $\delta(\gamma)$ curves show that SO$_3$ pickup ions can generate counter-streaming waves below the SO$_3$ gyrofrequency and co-streaming waves just above the SO$_3$ cutoff frequency (which is close to the gyrofrequency, as the concentration of SO$_3$ in the background is low. It should be noted that the positive $\gamma$ just below the S$^+$ gyrofrequency (0.825 Hz) is of no physical significance because it implies an unrealistic wavelength much below the SO$_3$ gyroradius.

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![Figure 4](image4.png)

Figure 4. The ion cyclotron wave power $A_{ci}^2$ (in mT²) and the electron density $n_e$ (in cm$^{-3}$) versus radial distance $r$ from Io. On the inbound path, in the region where $n_e$ is constant, an integrated neutral cloud distribution $Z_n$ (see text) has been fitted to $A_{ci}^2$. 

$A_{ci}^2$ and $A_{ne}^2$
One can do the same analysis for a different pickup species. In the case of, e.g., $S^+$, because of the large amount of $S^+$ in the background, no co-streaming waves above the $S^+$ cutoff frequency can be excited. However, the model does allow wave growth of counterstreaming waves below the $S^+$ gyrofrequency. The same is true for $O^-$ pickup ions and waves below the $O^+$ gyrofrequency. No such waves are observed in the data. This does not mean that there is no pickup of these atomic species, but rather that their distribution functions are less unstable against wave excitation than those of the molecular species $SO_2$. The reason is that during the $\sim 13$ hours between successive encounters with Io, molecular pickup ions in the corotating torus plasma are likely to dissociate whereas atomic ions become partially thermalized. Therefore, in the plasma near Io, atomic ions are present as a relatively stable distribution of a ring superimposed on a quasi-Maxwellian, whereas molecular ions are present in a highly unstable ring distribution.

In Figure 4, the wave power $A_{2 \perp}$ and the electron density $n_e$, measured by the PWS experiment [Gurnett et al., 1994], are plotted against radial distance from Io, for the inbound and outbound legs of the flyby. The local rate of pickup given by $n_o/n_e$, where $n_o$ is the density of the neutrals and $n_e$ is the mean time for ionization. Assuming that the molecules are merely ionized by electron impact, and that the electron temperature's constant, $\tau_0$ is proportional to $1/v_e$. On the inbound path, where $n_o$ is nearly constant except very near Io, we can use the wave power to a function representing the neutral cloud density distribution. The distribution of a cloud ejected radially and uniformly from Io with a speed $v_e$ can be represented by

$$n_o = \frac{1}{4\pi} \frac{1}{v_e^2} \left( \frac{r}{v_e} \right)^2$$

(e.g. Tsunoda and Smith [1986]). Here, the timescale $\tau$ is dominated by dissociation. The wave power seen at the spacecraft is proportional to the integral of $Z_\perp$ of this function along the connecting ray path of the waves.

$$Z_\perp(r) = \int_0^t \frac{1}{4\pi} \frac{1}{v_e^2} \left( \frac{r}{v_e} \right)^2 dt$$

where $r = (x + v_e t, y, z)$ with $x$ the spacecraft position relative to Io, $v_e$ the wave's group velocity, and $v_e$ the sound velocity relative to Io. We integrated (8) numerically both for the case of co-streaming $v_e = 100$ km/s, parallel to the background field's and for counter-streaming ($v_e = 50$ km/s, antiparallel) waves (cf. Figure 3). The $\tau$ dependence of the sum of these two integrals can be fitted to the observed albedo of $A_{2 \perp}$ yielding a value of $\tau = 10000$ hr or roughly 5.5 hr. Using $v_e$'s escape velocity $v_e = 2.45$ km/s gives a mean time of dissociation of $\tau = 0.5$ hour (cf. Schaub and Smith [1994]). On the outbound path, where $n_o$ falls off with distance, the pickup rate and wave power decay faster than on the inbound leg.

Conclusions

We have presented observations of ion cyclotron waves detected by the Galileo spacecraft near Io. They can be interpreted in L-mode waves excited by gyrosionant molecular, mainly $SO_2$, pickup ions. On the inbound leg of the flyby, in a region where the electron density was constant, the decay of the wave power with radial distance from Io followed the expected distribution of neutral clouds. The mean dissociation path length for the molecular neutrals in this region is estimated to be roughly 5.5 hr. After closest approach, the more rapid decay of the waves is correlated with the falloff of the electron density. On the inbound leg of the flyby, peaks of wave power were observed not only just below, but also just above the $SO_2$ gyrofrequency. Within the framework of cold plasma theory, this can be explained only for a concentration of $SO_2$ below $\sim 2 \times 10^5$. Though the conditions in a warm plasma are far more complex, it is interesting the analysis of $Huddleston et al. [1997]$ suggests that the total amount (pickup plus background of $SO_2$) is considerably less than 1%. More thorough investigations of the evolution of the spectra with time, combined with a more realistic model of the wave dispersion relation, will add insight into the plasma compositional in the vicinity of Io.

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References


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