Ganymede-Induced Decametric Radio Emission: In Situ Observations and Measurements by Juno

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Key Points:

- First detailed wave/particle investigation of a Ganymede-induced decametric radio source using Juno/Waves and Juno/JADE instruments
- Confirmation that the emission is produced by a loss-cone-driven Cyclotron Maser Instability
- Ganymede-induced radio emission is produced by electrons of $\sim$ 4-15 keV, at a beaming angle [76°-83°], and a frequency $1.005 - 1.021 \times f_{ce}$

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Abstract

At Jupiter, part of the auroral radio emissions are induced by the Galilean moons Io, Europa and Ganymede. Until now, they have been remotely detected, using ground-based radio-telescopes or electric antennas aboard spacecraft. The polar trajectory of the Juno orbiter allows the spacecraft to cross the magnetic flux tubes connected to these moons, or their tail, and gives a direct measure of the characteristics of these decametric moon–induced radio emissions. In this study, we focus on the detection of a radio emission during the crossing of magnetic field lines connected to Ganymede's tail. Using electromagnetic waves (Juno/Waves) and in-situ electron measurements (Juno/JADE-E), we estimate the flux tube width to be a few 100 km, a radio emission growth rate $> 3\times10^{-4}$, an electron population of energy $E = 4 - 15$ keV and an emission beaming angle of $\theta = 76° - 83°$, at a frequency $\sim 1.005 - 1.021 \times f_{ce}$. We also confirmed that radio emission is associated with Ganymede's down-tail far-ultraviolet emission.

Plain Language Summary

The Juno spacecraft crossed magnetic field lines connected to Ganymede's auroral signature in Jupiter's atmosphere. At the same time, Juno also crossed a decametric radio source. By measuring the electrons during this radio source crossing, we determine that this emission is produced by the cyclotron maser instability driven by upgoing electrons, at a frequency 0.5 to 2.1% above the cyclotron electronic frequency with electrons of energy 4-15 keV.

1 Introduction

With the arrival of Juno at Jupiter in July 2016, the probe passes above the poles once per orbit, every 53 days, and acquires high-resolution measurements in the auroral regions (Bagenal et al., 2017). In particular the instruments Waves (radio and plasma waves, Kurth et al., 2017), JADE-E (Jovian Auroral Distributions Experiment - Electrons, McComas et al., 2017) and MAG (Magnetometer , Connerney et al., 2017) offer a unique opportunity to investigate in-situ the Jovian radio emissions produced in these polar regions. These instruments enable constraints on the position of the sources (Louis et al., 2019; Imai et al., 2017, 2019) and the mechanism producing these emissions (Louarn et al., 2017, 2018), the Cyclotron Maser Instability (CMI), which is also responsible for the production of the auroral kilometric radiation at Earth and Saturn (Treumann, 2006; Wu, 1985; Wu & Lee, 1979; Le Queau et al., 1984b, 1984a; Pritchett, 1986a).

This instability produces emissions very close to the electron cyclotron frequency $f_{\rm ce}$, and requires two primary conditions: (i) a magnetized plasma, where the electron plasma frequency $f_{\rm pe}$ (proportional to the square root of the electron plasma density n_e) is much lower than the electron cyclotron frequency $f_{\rm ce}$ (proportional to the magnetic field amplitude B); and (ii) a weakly relativistic electron population previously accelerated along high-latitude magnetic field lines at typical energies of a few keV. The first orbits of Jupiter allowed Louarn et al. (2017, 2018) to study in-situ the radio emission during source crossings and determine that the auroral hectometric/decametric radio emissions are driven by the CMI with a loss cone distribution function, i.e. triggered by a lack in the up-going electron population.

The Jupiter auroral radio emission is split into three major components, depending on the emission wavelength, namely broadband kilometric, hectometric and decametric. Part of the auroral radio emissions in the decametric range are induced by the interaction between the jovian magnetosphere and the Galilean moons: the best known case Io, discovered by Bigg (1964), Europa and Ganymede (Louis, Lamy, Zarka, Cecconi, & Hess, 2017; Zarka et al., 2018, 2017) and potentially Callisto (Menietti et al., 2001; Higgins, 2007). These moons are also known to induce Far Ultraviolet (FUV) aurora above Jupiter's atmosphere (Prangé et al., 1996; Clarke, 1998; Clarke et al., 2002; Bhattacharyya et al., 2018).

In the Io case, we know that FUV and radio auroral emission are produced by Alfvénic interactions, and that Io-induced radio emissions are produced on the magnetic field lines connected to the main Alfvén wing (MAW) and reflected Alfvén wing (RAW) spots (Hess et al., 2010). In the Europa and Ganymede case, FUV emissions have been observed at the moon's footprint and along the moon's footprint tail (Bonfond, Grodent, et al., 2017; Bonfond, Saur, et al., 2017), but no simultaneous observation of FUV and radio emissions has yet been obtained.

In this study, we focus on Juno's crossing of field lines connected to Ganymede's footprint tail, which took place on May 29, 2019, where simultaneous FUV (Szalay et al., 2020a) and radio emission were observed (see Section 2). In Section 3 we present the instability leading to radio emission and the calculation to determine the different parameters of the radio emission (growth rate, electron distribution function and energy, opening of the emission cone). Finally in Section 4 we summarize and discuss the results.

2 Observations

On May 29^{th}, 2019 between 07:37:14 and 07:37:32 (20^{th} perijove) Juno crossed the magnetic field lines connected to Ganymede's tail ($\sim 8°$ downtail from Ganymede's main auroral spot). The in-situ measurements of Juno/MAG and Juno/JADE for the down-going electrons and the Juno/UVS images were used by Szalay et al. (2020a) to show the presence of Alfvén wave activity capable of accelerating electrons into the atmosphere and producing FUV emissions, observed at the footprint of the crossed magnetic field lines. Here we focus on the study of Juno/JADE for the up-going electrons and the radio measurements of Juno/Waves.

Figure 1 displays Juno measurements around the Ganymede's tail flux tube encounter. Panel (a) presents the Juno/Waves measurements (low resolution mode) around the twentieth perijove ($\sim\ -2/+1$ h). Panel (b) is a 5-minute zoom-in of panel (a) using the Juno/Waves high-resolution mode. The solid-white line represents f_{ce} while the dashed-white line (panel b) represents $1.01\times f_{\mathrm{ce}}$ (typical frequency for a loss-cone-CMI-driven emission with electron energy of ~ 5 keV, see Louarn et al., 2017). Panels (c–f) display Juno/JADE-E (electrons) measurements: panel (c) presents the electron differential energy flux; panels (d-e) display the electron distribution functions for energy in range [2-21] keV for different pitch angle ranges, panel (e) showing a subset for pitch angle corresponding to up-going electrons; panel (f) presents the partial electron density, where all the low energy population (here < 0.050 keV) is not accounted for.

Figure 1b displays an emission very close to f_{ce}, tangent to the $1.01\times f_{ce}$ line, between $\sim$ 07:37:00 and $\sim$ 07:38:10. During this time interval, and more precisely between $\sim$ 07:37:14 and $\sim$07:37:32 (during Ganymede's tail magnetic field lines crossing), we observe an enhancement in the electron energy flux (panel c) at a few keV, a strong intensification in the distribution function (panel d) and an increase of the electron density (panel f).

The maximum intensity of the radio emission (and the closest to f_{ce}) is observed between 07:37:25 and 07:37:30 (panel b), where a loss cone is observed in the up-going

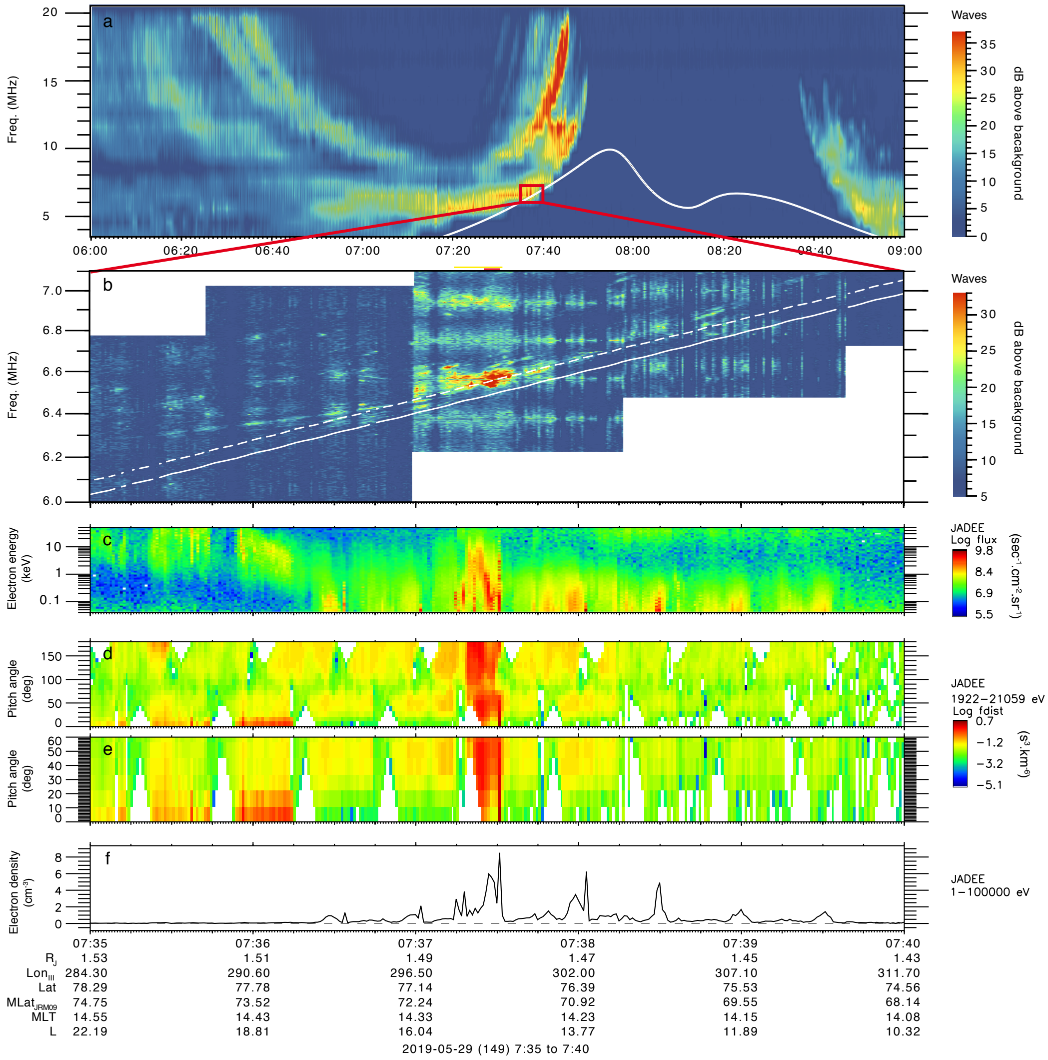

Figure 1. Juno measurements around the Ganymede's tail flux tube encounter (from 7:37:14 to 07:37:32, Szalay et al., 2020a).

Panels (a,b) display Juno/Waves data (a) in low-resolution mode and (b) in high-resolution mode. The solid-white lines represent the electron cyclotron frequency derived from the magnetic field measurements of Juno/MAG, and the dashed-white line is $1.01 \times f_{\rm ce}$.

Panels (c-f) display Juno/JADE-E measurements: (c) the electron differential energy flux; (d) the electron distribution function for energy in range [2-21] keV at all pitch angles; (e) same as panel (d) but only for pitch angles [0°-60°] corresponding to up-going electrons; (f) the partial electron density calculated from JADE-E 3D moments.

electron distribution function (panel e), i.e. the electron distribution function at low pitch angle from 0° to $\sim 25°$ is much lower than at higher pitch angle (50°–60°).

3 The Cyclotron Maser Instability: determination of the emission parameters

In this Section, we review the main details of the CMI that will be used in this study. For more details, please refer to Wu and Lee (1979); Wu (1985); Le Queau et al. (1984b, 1984a); Pritchett (1986a); Treumann (2006); Louarn et al. (2017).

The CMI is a wave-particle instability for which the resonance is reached when the Doppler-shifted angular frequency of the wave in the frame of the electron ($\omega - k_{||} v_{r_{||}}$) is equal to the relativistic gyration frequency of resonant electrons ($\omega_{ce}\Gamma_r^{-1}$). Thus, the resonance condition can be written as:

$$\omega = 2\pi f = \omega_{ce}\Gamma_r^{-1} + k_{||} v_{r_{||}}, \tag{1}$$

where the $_{||}$ index describes the component parallel to the magnetic field line, k the wave vector, v_r the resonant electron velocity and $\Gamma_r^{-1} = \sqrt{1 - v_r^2/c^2}$ the Lorentz factor associated with the motion of resonant electrons.

In the weakly relativistic case ($v_r << c$) the above resonance condition can be rewritten as the equation for a resonant circle in the [$v_\perp$,$v_{||}$] velocity space:

$$v_{r\perp}^2 + (v_{r||} - \frac{k_{||}c^2}{\omega_{ce}})^2 = c^2 \left(\frac{k_{||}^2 c^2}{\omega_{ce}^2} + 2(1 - \frac{\omega}{\omega_{ce}}) \right). \tag{2}$$

The resonance circle center v_0 (located on the $v_{||}$ axis) and its radius R are thus defined as:

$$v_0 = \frac{k_{||}c^2}{\omega_{ce}} = \frac{\omega}{\omega_{ce}} cN cos\theta, \tag{3}$$

where θ is the propagation angle of the emission with respect to the local magnetic field lines ($kcos\theta = \vec{k} \cdot \vec{b} = k_{||}$) and $N = ck/\omega$ is the refractive index value;

$$R = c \left(\frac{k_{||}^2 c^2}{\omega_{ce}^2} + 2(1 - \frac{\omega}{\omega_{ce}}) \right)^{1/2} = c \left(\frac{v_0^2}{c^2} - 2\Delta\omega \right)^{1/2}, \tag{4}$$

where

$$\Delta\omega = (\omega - \omega_{ce})/\omega_{ce} \tag{5}$$

is the frequency shift.

It is then necessary to determine the optimal electron population that will lead to the amplification of the wave and the production of the emission, which is done by calculating and maximizing the growth rate along different resonance circles. The simplified version used by Louarn et al. (2017) is perfectly adapted to the amplification of X-mode waves propagating at frequencies close to $f_{\rm ce}$, for $N \simeq 1$, in a moderately energetic ($E << m_{\rm e}c^2 = 511$ keV) and low-density ($f_{\rm pe}/f_{\rm ce} << 1$) plasma. Since the electron energy is equal to a few 0.1 keV to a few keV (see Fig. 1c) and the electron density is equal to a few particles per cm^{-3} (see Fig. 1f), we can use the simplified formula of Louarn et al. (2017) to calculate the normalized growth rate (γ/ω_{ce}) of the instability along resonant circles in the normalized velocity space [$\beta_{||}$,$\beta_{\perp}$], with $\beta = v/c$, expressed as:

$$\frac{\gamma}{\omega_{\rm ce}} \simeq 2\pi^2 \Delta\omega^2 \int_0^{\pi} d\phi \; b^2 \; sin^2(\phi) \frac{\partial}{\partial \beta_\perp} f_b(\beta_0 + b \; cos(\phi), b \; sin(\phi)), \tag{6}$$

where $\beta_0 = v_0/c$ is the center (see Eq. 3) and $b = R/c$ the radius (see Eq. 4) of the resonant circle, $\Delta\omega$ the frequency shift (see Eq. 5) and f the normalized electron distribution function ($\int f dv^3 = 1$). In practice, the factor to normalize the distribution function is $c^3 10^{-18}/n_e$, where n_e is the density (in cm^{-3}). Here $n_e \simeq 1$ cm^{-3} at 07:36:40, and $n_e \simeq 6$ cm^{-3} at 07:37:26 and 07:37:28, and $n_e \simeq 2$ cm^{-3} at 07:37:43 (see Fig. 1f), which is probably slightly overestimated (Allegrini et al., 2020), leading to underestimated growth rate.

Eq. 6 means that the growth rate is obtained by integrating $\partial f/\partial \beta_\perp$ along a resonant circle in the normalized velocity space [$\beta_{||}$,$\beta_{\perp}$] defined by its center β_0, radius b, and angle ϕ.

3.1 Electron distribution function

Figures 2a-d display the distribution functions of upgoing electrons (pitch angle from 0° to 82.5°) measured by Juno/JADE-E at (a) 07:36:40, (b) 07:37:26, (c) 07:37:28 and (d) 07:37:43. Fig. 2b,c correspond to the period of maximum increasing decametric flux seen in Fig. 1b, while Fig. 2a,d correspond to time where Juno is outside the Ganymede's tail flux tube. The colors correspond to different electron distribution function iso-contours, using a logarithmic scale in units of s^3/km^6. A loss cone in each distribution is clearly visible for pitch angle at least lower than 22.5° (bolded-dashed-red line), when iso-contours

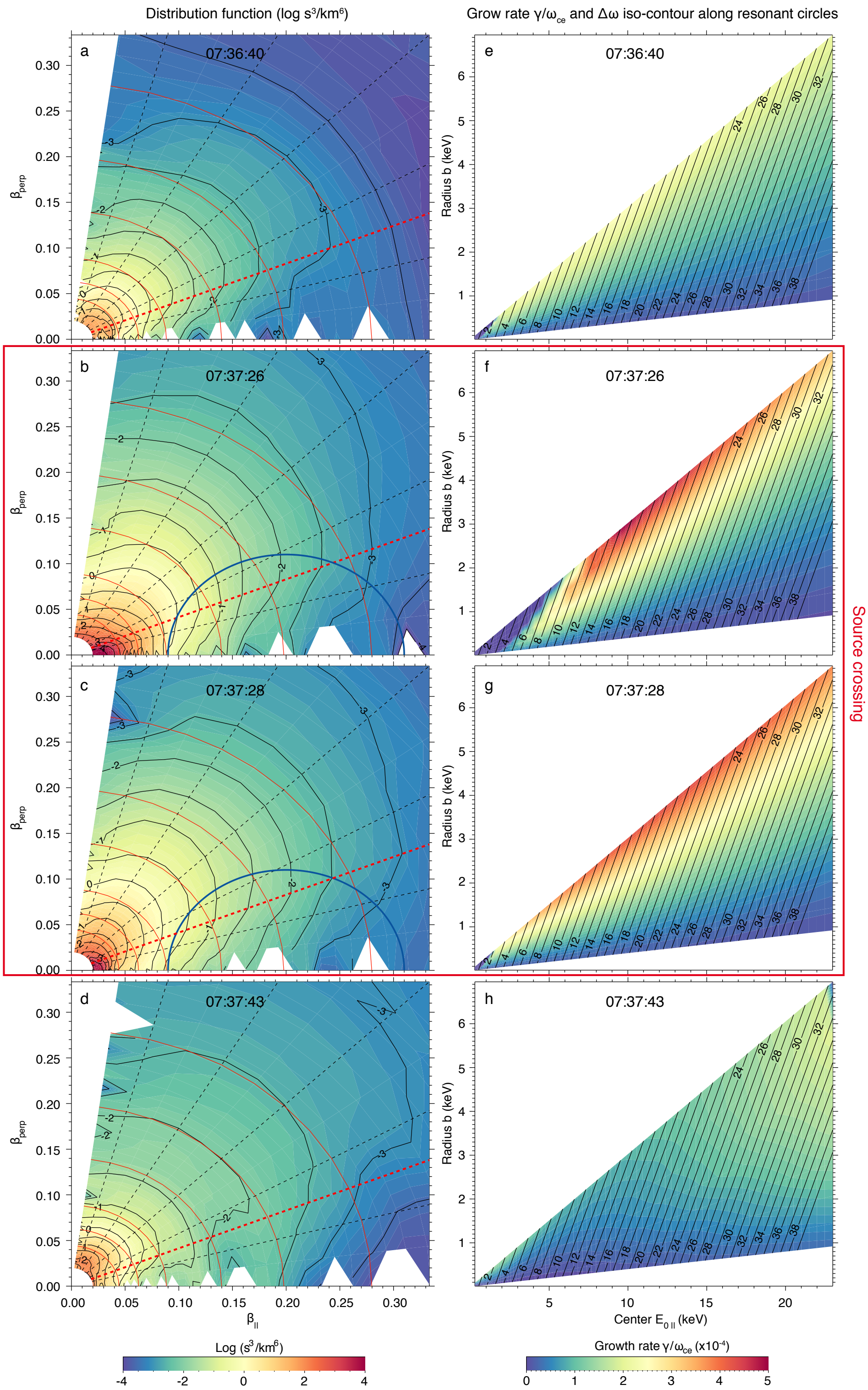

Figure 2. Panels (a-d): upgoing electron distribution function in the normalized velocity space [$\beta_{||}$,$\beta_{\perp}$] measured by JADE-E on 2019-05-29 at (a) 07:36:40, (b) 07:37:26, (c) 07:37:28 and (d) 07:37:43. The isocontours are shown using a logarithmic scale in units of s^3/km^6. The red circular arcs correspond to iso-energies of 0.5, 1, 2, 5, 10 and 20 keV and the radial black-dashed lines to pitch angles of 15°, 30°, 45°, 60° and 75°. The radial bolded-dashed-red line at pitch angle 22.5° displays the lower limit of the loss cone. An example of a resonant circle is displayed in blue in panels (b,c).

Panels (e-h): normalized growth rate γ/ω_{ce} estimates for different resonant circles at different centers $E_{0||}$ and radii b, at (e) 07:36:40, (f) 07:37:26, (g) 07:37:28 and (h) 07:37:43. The overplotare not following the iso-energy curves (red-circles). Note that at high pitch angle (> 75°), the iso-contours do not follow the iso-energy circles, which is due to spacecraft shadowing. The magnetic field strength during the Ganymedes footprint tail crossing is more than 2 Gauss and the lower energy electrons have gyro-radii of the order of the size of the spacecraft. Thus, the large solar arrays and other spacecraft structures block some trajectories before they can reach the JADE-E apertures, creating an effective shadowing. This shadowing mostly affects the electrons with large pitch angles and it also affects the lower energy more than the higher energy electrons. The shadowing was qualitatively reproduced with a simple ray-tracing simulation in (Allegrini et al., 2017, 2020).

Compared to 07:36:40 and 07:37:43, the distribution functions at 07:37:26 and 07:37:28 show larger phase space density at every energy (the spacing between the isocontours are increased), which corresponds to a denser, hotter and more energized plasma.

3.2 Estimation of growth rate and emission characteristics

From Fig. 2a-d and Eq. 6, we can calculate the normalized growth rate along different resonant circles to determine the optimal electron population. An example of a resonant circle is displayed Fig. 2b,c in blue, with a center $\beta_{0||} \simeq 0.20$ (i.e. ~ 10 keV) and a radius $b = 0.11$ (i.e. ~ 3 keV).

Figures 2e-h display the estimated normalized growth rate γ/ω_{ce} along resonant circles, calculated for different centers $E_0 = 0.5{*}m_e v_0^2 = 255.5{*}\beta_0^2$ ($m_e = 511$ kev/c^2) and different radii b (taken from 0.2–0.6$\times\beta_0$). The overplotted black lines represent the $\Delta\omega$ value at each point of the resonant circles, calculated as $\Delta\omega = (\beta_0^2 - b^2)/2$ (see eq. 4). Maximal growth rates are obtained during the source crossing (Fig. 2f,g).

Looking at the data of Fig. 1, Juno spent at least $\sim 4{-}6$ sec crossing the source of Ganymede-induced radio emission (see Section 2). Juno's velocity was ~ 50 km/s during the source crossing, thus we can determine a source size of at least $\sim 250{\pm}50$ km. To amplify a wave at a intensity of ~ 45 dB above the background (measured emission peak value at 07:37:28), by amplifying the typical radio noise, one needs amplification factors of $e^{\gamma\tau} > e^{10}$. With a wave propagating at the light speed c, and a source size $d = 250 \pm 50$ km, it gives an amplification time $\tau = d/c = 8.3 \times 10^{-4} \pm 1.6 \times 10^{-4}$ sec. To obtain $\gamma\tau = 10$, one needs a growth rate $\gamma = 12.5 \times 10^3 \pm 2.5 \times 10^3$ s^{-1}. Since $f_{ce} \simeq 6.5$ MHz, the normalized growth rate γ/ω_{ce} needs to be greater than $3{\times}10^{-4}\pm$

0.5×10^{-4}. Therefore a growth rates $\gamma/\omega_{ce} > 3 \times 10^{-4}$ (orange to red regions Fig. 2e-h) are sufficient for the production of radio emission in the present case.

Pritchett (1986b) performed numerical simulations of the weakly relativistic loss-cone maser instability, and determined (i) that the more the emission angle θ turns away from the perpendicular direction the weaker the emission is, and (ii) that at $\theta < 80°$ the emission intensity drastically drops to the background noise level (and reaches it at $\theta = 70°$). This was also observed by Louis, Lamy, Zarka, Cecconi, Imai, et al. (2017), for the simulated Io-decametric-induced emission not visible for $\theta < 75° \pm 5°$. Looking at the Juno/Waves high-resolution data during the source crossing, we can constrain this limit even further, since during the source crossing (between 07:37:25 and 07:37:30), no emission is observed above $f_{ce} \times 1.021$ (i.e. $\Delta\omega = 0.021$). From these considerations, we can infer that large amplifications are obtained for energies in the range ~[6-15] keV at 07:37:26 and ~[4-15] keV at 07:37:28, at a frequency shift $\Delta\omega$ = 8-21$\times 10^{-3}$ and 5-21 $\times 10^{-3}$ respectively.

Using the equations 3-5, assuming a refractive index N very close to 1 due to the very low-density plasma ($f_{pe} << f_{ce}$), we can derive the propagation angle θ of the emission, relative to the local magnetic field line:

$$\theta = acos\left(\beta_0/(1+\Delta\omega)\right). \qquad (7)$$

We can therefore determine that the observed emission propagates at an angle θ varying from $\sim 81°$ to $\sim 76°$ (07:37:26) and from $\sim 83°$ to $\sim 76°$ (07:37:28).

We can then calculate the emission frequency using the previously determined frequency shift $\Delta\omega$ and Eq. 5. The measured B amplitude gives an electron plasma frequency $f_{ce} \simeq 6484$ kHz at 07:37:26 and $\simeq 6490$ kHz at 07:37:28. Since $\Delta\omega \simeq 8-21 \times 10^{-3}$ at 07:37:26 and $\Delta\omega \simeq$ 5-21$\times 10^{-3}$ at 07:37:28, the emission is respectively produced at a frequency equal to $\sim 6535-6620$ kHz and $\sim 6522-6626$ kHz, which explains why we observe emission over a larger bandwidth and closer to f_{ce} at 07:37:28 than at 07:37:26 in the Juno/Waves data (see Fig. 1b).

4 Conclusion and Discussion

In conclusion, we analyzed the first example of in-situ particle measurements of a Ganymede-induced radio emission, during the Ganymede's tail flux tube crossing (Szalay et al., 2020a) connected to FUV emission. Looking at the distribution functions before, during and after the source crossing, we showed that the loss cone-driven CMI can explain the generation of decametric radio emission. From the radio waves observations and the electron distribution function, we determine that the radio source size is at least 250 ± 50 km. The electron population involved in this emission has an energy of $4-15$ keV, with a wave propagation angle θ varying from 83° to 76°, at a frequency shift $\Delta\omega = 5{-}21\times10^{-3}$. Furthermore, the electron distribution functions show that a denser, hotter and more energized plasma (observed only during the source crossing, see Fig. 2) is necessary to allow the CMI to occur.

The main limitation of our results comes from the data hole in the JADE-E measurements between 07:36:14 and 07:37:24, since these data allows us to constrain the size of the source. We can only determine that the source size is at least 250 ± 50 km, since Juno spent at least 4 to 6 seconds in the source at a velocity of ~ 50 km/s. If the size of the source is slightly larger (of a few 100s km), this would decrease the lower limit of the growth rate γ needed to produce the radio emission (e.g. $\gamma/\omega_{ce} \sim 2\times10^{-4}$), and thus slightly decreases the lower limit of the frequency shift $\Delta\omega$ (down to 2×10^{-3}) of the emission and of the resonant electron energy E (down to 1.5 keV), and slightly increase the upper limit of the emission angle θ (up to $\sim 85.5°$). However, looking at the Waves data in high-resolution (see Fig. 1b), the low-frequency limit of the observed emission ($\Delta\omega \sim 5\times10^{-3}$) is in agreement with the theoretical value determined Section 3.2 from the growth rate γ/ω_{ce} (and thus from the estimated source size of ~ 250 km). Therefore, the error on the source size and on the ensuing results (electron energy and beaming angle θ), should be very small.

Szalay et al. (2020a) showed that in this present case, Ganymede's footprint tail is sustained by Alfvénic acceleration processes. Thus, as suggested by Louarn et al. (2018), all the radio emissions seem to be triggered by Alfvénic acceleration (as at Earth, Su et al., 2007). Furthermore, we now have direct proof that radio emission is associated with a Ganymede down-tail FUV emission, likely one of the reflected Alfvén waves originally generated at Ganymede (as is the case for Io). It is interesting to note that the time spent in the source of the radio emission, 4 to 6 seconds, is lower than the time spent crossing the magnetic field lines connected to the Ganymede's tail footprint (18 seconds, Szalay et al., 2020a). The difference does not seem to be due to an underestimation of the source size (see previous paragraph), but could rather be due to the lower electron density during the first seconds of the Ganymede's tail flux tube crossing (from 07:37:14 to 07:37:24-25) than during the radio source crossing. As shown in Section 3.1, a minimum dense, hot and energetic plasma seems necessary to trigger and produce radio emissions.

The loss-cone-driven CMI then seems to be a common way to amplify waves and produce radio emissions, sustained by an Alfvénic acceleration process in the case of auroral radio emissions (Louarn et al., 2017, 2018) as in the case of moon-induced radio emissions (present study). The next step should be to study the more numerous radio source crossings of Io's tail (Szalay et al., 2018; Louis et al., 2019; Szalay et al., 2020b), in order to explain (i) how radio emission can be produced 10s of degrees away from the main Alfvén Wing spot, (ii) why these radio emissions are not observed from a distant point of view and (iii) how the electron distribution function and the radio emission intensity evolve with distance from the Main Alfvén Wing spot.

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