Ganymede–induced decametric radio emission: in-situ observations and measurements by Juno

Corentin Kenel
m ${\rm LOUIS^1},$ Philippe ${\rm Louarn^1},$ Frederic Allegrini
², William S ${\rm Kurth^3},$ and Jamey R. Szalay
4

¹IRAP ²Southwest Research Institute ³University of Iowa ⁴Princeton University

November 24, 2022

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 the Ganymede flux tube. 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 growth rate of the radio emission $>3x10^{-4}$, an electron population of energy E=4-15 keV and an emission beaming angle of ϑ =76°-83°, at a frequency 1.005-1.021xf_{ce}. We also confirmed that radio emission is associated with Ganymede's down-tail far-ultraviolet emission.

Ganymede-induced decametric radio emission: in-situ observations and measurements by Juno

C. K. Louis¹, P. Louarn¹, F. Allegrini^{2,3}, W. S. Kurth⁴, J. R. Szalay⁵

¹IRAP, Universit de Toulouse, CNRS, CNES, UPS, (Toulouse), France
 ²Southwest Research Institute, San Antonio, Texas, USA
 ³Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, Texas, USA
 ⁴Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA
 ⁵Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey, USA

Key Points: 9

1

2

3

| 10 | • | First detailed wave/particle investigation of a Ganymede-induced decametric ra- |
|----|---|---|
| 11 | | dio source using Juno/Waves and Juno/JADE instruments |
| 12 | • | Confirmation that the emission is produced by a loss-cone-driven Cyclotron Maser |
| 13 | | Instability |
| 14 | • | Gany mede-induced radio emission is produced by electrons of $\sim 4\text{-}15$ keV, at a |
| 15 | | beaming angle $[76^{\circ}-83^{\circ}]$, and a frequency $1.005 - 1.021 \times f_{ce}$ |

Corresponding author: C. K. Louis, corentin.louis@irap.omp.eu

16 Abstract

At Jupiter, part of the auroral radio emissions are induced by the Galilean moons Io,

¹⁸ 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 dur-

²³ ing the crossing of the Ganymede flux tube. Using electromagnetic waves (Juno/Waves)

 $_{24}$ and in-situ electron measurements (Juno/JADE-E), we estimate the flux tube width to

be a few 100 km, a growth rate of the radio emission $> 3 \times 10^{-4}$, an electron popula-

tion of energy E = 4 - 15 keV and an emission beaming angle of $\theta = 76^{\circ} - 83^{\circ}$, 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.

²⁹ 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.

36 1 Introduction

With the arrival of Juno at Jupiter in July 2016, the probe passes above the poles 37 once per orbit, every 53 days, and acquires high-resolution measurements in the auro-38 ral regions (Bagenal et al., 2017). In particular the Waves (radio and plasma waves in-39 strument, Kurth et al., 2017), JADE (Jovian Auroral Distributions Experiment, McCo-40 mas et al., 2017, providing electron measurements) and MAG (Magnetometer experiment, 41 Connerney et al., 2017) instruments offer a unique opportunity to investigate in-situ the 42 Jovian radio emissions produced in these polar regions. These instruments enable con-43 straints on the position of the sources (Louis et al., 2019; Imai et al., 2017, 2019) and 44 the mechanism producing these emissions (Louarn et al., 2017, 2018), the Cyclotron Maser 45 Instability (CMI) which is also responsible for the production of the auroral kilometric 46 radiation at Earth and Saturn (Treumann, 2006; Wu, 1985; Wu & Lee, 1979; Le Queau 47 et al., 1984b, 1984a; Pritchett, 1986a). 48

This instability produces emissions very close to the electron cyclotron frequency 49 $f_{\rm ce}$, and requires two primary conditions : (i) a magnetized plasma, where the electron 50 plasma frequency $f_{\rm pe}$ (proportional to the square root of the electron plasma density n_e) 51 is much lower than the electron cyclotron frequency f_{ce} (proportional to the magnetic 52 field amplitude B; and (ii) a weakly relativistic electron population previously accel-53 erated along high-latitude magnetic field lines at typical energies of a few keV. The first 54 orbits of Jupiter allowed Louarn et al. (2017, 2018) to study in-situ the radio emission 55 during source crossings and determine that the auroral hectometric/decametric radio emis-56 sions are driven by the CMI with a loss cone distribution function, i.e. triggered by a 57 lack in the up-going electron population. 58

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 following Galilean moons: the best known case Io, discovered by Bigg (1964), and Europa and Ganymede (Louis, Lamy, Zarka, Cecconi, & Hess, 2017; Zarka et al., 2018, 2017). These three moons are also known to induce Far Ultraviolet (FUV) aurora above Jupiter's atmosphere (Prangé et al., 1996;
 Clarke, 1998; Clarke et al., 2002).

In the Io case, we know that FUV and radio auroral emission are produced by Alfvnic interactions, and that Io-induced radio emissions are produced on the magnetic field lines connected to the main Alfvn wing (MAW) and reflected Alfvn wing (RAW) spots (Hess et al., 2010). In the Europa and Ganymede case, 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.

78 2 Observations

On May 29th, 2019 between 07:37:14 and 07:37:32, Juno crossed the magnetic field 79 tube connected to Ganymede's tail ($\sim 8^{\circ}$ downtail from Ganymede's main auroral spot). 80 The in-situ measurements of Juno/MAG and Juno/JADE for the down-going electrons 81 and the Juno/UVS images were used by Szalav et al. (2020a) to show the presence of 82 Alfvn wave activity capable of accelerating electrons into the atmosphere and produc-83 ing FUV emissions, observed at the footprint of the crossed magnetic field lines. Here 84 we focus on the study of Juno/JADE for the up-going electrons and the radio measure-85 ments of Juno/Waves. 86

Figure 1 displays Juno measurements around the Ganymede flux tube encounter. 87 Panel (a) presents the Juno/Waves measurements (low resolution mode) around the twen-88 tieth perijove ($\sim -2/+1$ h). Panel (b) is a 5-minute zoom-in of panel (a) using the 89 Juno/Waves high-resolution mode. The solid-white line represents f_{ce} while the dashed-90 white line (panel b) represents $1.01 \times f_{ce}$ (typical frequency for a loss-cone-CMI-driven 91 emission with electron energy of ~ 5 keV, see Louarn et al., 2017). Panels (c-f) display 92 Juno/JADE-E (electrons) measurements, with panel (c) presenting the electron differ-93 ential energy flux, panels (d-e) the electron distribution functions for energy in range [2-94 21] keV for different pitch angle ranges (panel (e) showing a subset for pitch angle cor-95 responding to up-going electrons) and panel (f) the partial electron density (all the low 96 energy population (here < 0.050 keV) is not accounted for). 97

Figure 1b displays an emission very close to f_{ce} , tangent to the $1.01 \times f_{ce}$ line, between ~ 07:37:00 and ~ 07:38:10. During this time interval, and more precisely between ~ 07:37:14 and ~07:37:32 (during Ganymede's tail crossing), we observe an enhancement in the electron energy flux (panel c) at a few keV, 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 electron distribution function (panel e), i.e. the electron distribution function at low pitch angle from 0° to ~ 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).





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 $1.01 \times f_{ce}$.

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 $[0^{\circ}-60^{\circ}]$ corresponding to up-going electrons; (f) the partial electron density calculated from JADE-E 3D moments.

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 electron $(\omega_{ce}\Gamma_r^{-1})$. 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 $(v_r \ll c)$ the above resonance condition can be rewritten as the equation for a resonant circle in the $[v_{\perp}, v_{||}]$ velocity space:

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

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

$$v_0 = \frac{k_{||}c^2}{\omega_{ce}} = \frac{\omega}{\omega_{ce}}cNcos\theta,$$
(3)

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

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

125 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 127 the amplification of the wave and the production of the emission, which is done by cal-128 culating and maximizing the growth rate along different resonance circles. The simpli-129 fied version used by Louarn et al. (2017) is perfectly adapted to the amplification of X-130 mode waves propagating at frequencies close to f_{ce} , for $N \simeq 1$, in a moderately ener-131 getic ($E << m_{\rm e}c^2 = 511$ keV) and low-density ($f_{\rm pe}/f_{\rm ce} << 1$) plasma. Since the 132 electron energy is equal to a few 0.1 keV to a few keV (see Fig. 1c) and the electron den-133 sity is equal to a few particles per cm^{-3} (see Fig. 1f), we can use the simplified formula 134 of Louarn et al. (2017) to calculate the normalized growth rate of the instability along 135 resonant circles in the normalized velocity space $[\beta_{\parallel}, \beta_{\perp}]$, with $\beta = v/c$, expressed as: 136

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

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 $[\beta_{\parallel},\beta_{\perp}]$ defined by its center β_0 , radius b, and angle ϕ .



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 red-dashed 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 center $E_{0||}$ and radius b, at (e) 07:36:40, (f) $07:\overline{37}:26$, (g) 07:37:28 and (h) 07:37:43. The overplotted black lines represent the isocontours of $\Delta \omega = (\omega - \omega_{ce})/\omega_{ce} \times 10^3$.

3.1 Electron distribution function

Figures 2a-d display the distribution functions of upgoing electrons (pitch angle from 148 0° to 82.5°) measured by Juno/JADE-E at (a) 07:36:40, (b) 07:37:26, (c) 07:37:28 and 149 (d) 07:37:43. Fig. 2b,c correspond to the period of maximum increasing decametric flux 150 seen in Fig. 1b, while Fig. 2a,d correspond to time where Juno is outside the Ganymede 151 flux tube. The colors correspond to different electron distribution function iso-contours, 152 using a logarithmic scale in units of s^3/km^6 . A loss cone in each distribution is clearly 153 visible for pitch angle at least lower than 22.5° (dashed-red line), when iso-contours are 154 not following the iso-energy curves (red-circles). Note that at high pitch angle $(>75^{\circ})$, 155 the iso-contours do not follow the iso-energy circles, which is due to spacecraft shadow-156 ing (Allegrini et al., 2017, 2020). 157

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 isocontours are enlarged), which corresponds to a denser, hotter and more energized plasma.

161

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 center $E_0 = \beta_0^2 * 255.5$ and different radius *b* (taken from 0.2–0.6× β_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), with values above 3×10^{-4} (orange to red regions), sufficient for the production of radio emission.

Pritchett (1986b) performed numerical simulations of the weakly relativistic loss-172 cone maser instability, and determined (i) that the more the emission angle θ turns away 173 from the perpendicular direction the weaker the emission is, and (ii) that at $\theta < 80^{\circ}$ 174 the emission intensity drastically drops to the background noise level (and reaches it at 175 $\theta = 70^{\circ}$). This was also observed by Louis, Lamy, Zarka, Cecconi, Imai, et al. (2017), 176 for the simulated Io-decametric-induced emission not visible for $\theta < 75^{\circ} \pm 5^{\circ}$. Look-177 ing at the Juno/Waves high-resolution data during the source crossing, we can constrain 178 this limit even further, since during the source crossing (between 07:37:25 and 07:37:30), 179 no emission is observed above $f_{ce} \times 1.021$ (i.e. $\Delta \omega = 0.021$). From these considera-180 tions, we can infer that large amplifications are obtained for energies in the range \sim [6-181 15] keV at 07:37:26 and ~[4-15] keV at 07:37:28, at a frequency shift $\Delta \omega = 8.21 \times 10^{-3}$ 182 and $5-21 \times 10^{-3}$ respectively. 183

Using the equations 3-5, assuming a refractive index N very close to 1 due to the very low-density plasma ($f_{pe} \ll f_{ce}$), we can derive the propagation angle θ :

$$\theta = a\cos\left(\beta_0/(1+\Delta\omega)\right).\tag{7}$$

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

The measured B amplitude at 07:37:26 (07:37:28) gives an electron plasma frequency $f_{ce} \simeq 6484 \text{ kHz} (\simeq 6490 \text{ kHz})$. Thus, $\Delta \omega \simeq 8-21 \times 10^{-3} (5\cdot21 \times 10^{-3})$ is equivalent to an emission frequency at ~ 6535-6620 kHz (~ 6522-6626 kHz), which explains why we observe emission closer to f_{ce} at 07:37:28 in the Juno/Waves data (see Fig. 1b).

¹⁹² 4 Conclusion and Discussion

In conclusion, we analyzed the first example of in-situ particle measurements of a 193 Ganymede-induced radio emission, during the Ganymede's tail flux tube crossing (Szalay 194 et al., 2020a) connected to FUV emission. Looking at the distribution functions before during 195 and after the source crossing, we showed that the loss cone-driven CMI can explain the 196 generation of decametric radio emission. The electron population involved in this emis-197 sion has an energy of 4–15 keV, with a wave propagation angle θ varying from 83° to 198 76°, at a frequency shift $\Delta \omega = 5 - 21 \times 10^{-3}$. Furthermore, the electron distribution 199 functions show that a denser, hotter and more energized plasma (observed only during 200 the source crossing, see Fig. 2) is necessary to allow the CMI to occur. 201

Szalay et al. (2020a) showed that in this present case, Ganymede's footprint tail is sustained by Alfvnic acceleration processes. Thus, as suggested by Louarn et al. (2018), all the radio emissions seem to be triggered by Alfvnic 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 Alfvn waves originally generated at Ganymede (as is the case for Io).

Looking at the data of Fig. 1, Juno spent at least $\sim 4-6$ sec crossing the source 208 of Ganymede-induced radio emission. Juno's velocity was $\sim 50 \text{ km/s}^{-1}$ during the source 209 crossing, thus we can determine a source size of at least $\sim 250 \pm 50$ km. Taking a ra-210 dio wave propagating at the light speed, the wave spent 0.67-1 ms inside the source. 211 Since at 07:37:26 $f_{ce} = 6484$ kHz and $\gamma/\omega_{ce} = 3-4 \times 10^{-4}$, we can determine that the growth rate γ is equal to $\simeq 10 - 20 \times 10^3$ s⁻¹. At light speed, propagation of $\sim 150 - 10^{-4}$ 212 213 300 km is then sufficient to amplify the waves by a factor e^{10} , which is fully compati-214 ble with the measured size of the source and the observed intensity of the emission which 215 peaks at ~ 45 dB above the background at 07:37:28. 216

The loss-cone-driven CMI then seems to be a common way to amplify waves and 217 produce radio emissions, sustained by an Alfvnic acceleration process in the case of au-218 roral radio emissions (Louarn et al., 2017, 2018) as in the case of moon-induced radio 219 emissions (present study). The next step should be to study the more numerous radio 220 source crossings of Io's tail (Szalay et al., 2018; Louis et al., 2019; Szalay et al., 2020b) 221 in order to explain (i) how radio emission can be produced 10s of degrees away from the 222 main Alfvn Wing spot, (ii) why these radio emissions are not observed from a distant 223 point of view and (iii) how the electron distribution function and the radio emission in-224 tensity evolve with distance from the Main Alfvn Wing spot. 225

226 Acknowledgments

²²⁷ The authors thank the Juno mission team, especially the staff of the Waves and JADE

instruments. The Juno data used in this manuscript are reachable from the Planetary

- Data System at https://pds-ppi.igpp.ucla.edu/mission/JUNO in the JAD > JUNO JADE
- $_{230}$ CALIBRATED SCIENCE DATA $> {\rm DATA} > 2019 > 2019149 > {\rm ELECTRONS}$ tab for

- $UCTS > DATA > WAVES_BURST > 2019122_ORBIT_20 > WAV_2019149T071635_NBS_REC_V01$
- $_{233}$ tab for Waves burst mode data and in the WAV > JUNO WAVES SURVEY STANDARD
- $SCIENCE PRODUCTS > DATA > WAVES_SURVEY > 2019122_ORBIT_20 > WAV_2019149T000000 \pm V01$
- tab for Waves survey data. C. K. L. acknowledges funding support from the CNES, and
- thanks E. Penou, for the help with the particle analysis through the CLWeb software.
- ²³⁷ The research at the University of Iowa is supported by NASA through Contract 699041X
- ²³⁸ with the Southwest Research Institute.

239 **References**

Allegrini, F., Bagenal, F., Bolton, S., Connerney, J., Clark, G., Ebert, R. W., ...

JADE-E data, in the WAV > JUNO WAVES BURST STANDARD SCIENCE PROD-

| 241 | Zink, J. L. (2017, July). Electron beams and loss cones in the auroral |
|-----|---|
| 242 | regions of Jupiter. Geophysical Research Letters, 44 (14), 7131-7139. doi: |
| 243 | 10.1002/2017 GL073180 |
| 244 | Allegrini, F., Mauk, B., Clark, G., Gladstone, G. R., Hue, V., Kurth, W. S., Wil- |
| 245 | son, R. J. (2020, April). Energy Flux and Characteristic Energy of Electrons |
| 246 | Over Jupiter's Main Auroral Emission. Journal of Geophysical Research (Space |
| 247 | <i>Physics</i>), 125(4), e27693. doi: 10.1029/2019JA027693 |
| 248 | Bagenal, F., Adriani, A., Allegrini, F., Bolton, S. J., Bonfond, B., Bunce, E. J., |
| 249 | Zarka, P. (2017, November). Magnetospheric Science Objectives of |
| 250 | the Juno Mission. Space Science Reviews, 213, 219-287. doi: 10.1007/ |
| 251 | s11214-014-0036-8 |
| 252 | Bigg, E. K. (1964, September). Influence of the Satellite Io on Jupiter's Decametric |
| 253 | Emission. Nature, 203, 1008-1010. doi: 10.1038/2031008a0 |
| 254 | Clarke, J. T. (1998). Hubble space telescope imaging of jupiter's uv aurora during |
| 255 | the galileo orbiter mission. Journal of Geophysical Research: Planets, 103(E9), |
| 256 | 20217-20236. doi: 10.1029/98JE01130 |
| 257 | Clarke, J. T., Ajello, J., Ballester, G., Ben Jaffel, L., Connerney, J., Gérard, JC., |
| 258 | Waite, J. H. (2002, February). Ultraviolet emissions from the magnetic |
| 259 | footprints of Io, Ganymede and Europa on Jupiter. Nature, 415, 997-1000. |
| 260 | Connerney, J. E. P., Benn, M., Biarno, J. B., Denver, T., Espley, J., Jorgensen, |
| 261 | J. L., Smith, E. J. (2017, November). The Juno Magnetic Field Investiga- |
| 262 | tion. Space Science Reviews, 213, 39-138. doi: 10.1007/s11214-017-0334-z |
| 263 | Hess, S. L. G., Delamere, P., Dols, V., Bonfond, B., & Swift, D. (2010, June). Power |
| 264 | transmission and particle acceleration along the Io flux tube. Journal of Geo- |
| 265 | physical Research (Space Physics), 115, A06205. doi: 10.1029/2009JA014928 |
| 266 | Imai, M., Greathouse, T. K., Kurth, W. S., Gladstone, G. R., Louis, C. K., Zarka, |
| 267 | P., Connerney, J. E. P. (2019, Jan). Probing Jovian Broadband Kilo- |
| 268 | metric Radio Sources Tied to the Ultraviolet Main Auroral Oval With Juno. |
| 269 | Geophysical Research Letters, 46(2), 571-579. doi: 10.1029/2018GL081227 |
| 270 | Imai, M., Kurth, W. S., Hospodarsky, G. B., Bolton, S. J., Connerney, J. E. P., & |
| 271 | Levin, S. M. (2017, July). Direction-finding measurements of Jovian low- |
| 272 | frequency radio components by Juno near Perijove 1. Geophysical Research |
| 273 | Letters, 44, 6508-6516. doi: 10.1002/2017GL072850 |
| 274 | Kurth, W. S., Hospodarsky, G. B., Kirchner, D. L., Mokrzycki, B. T., Averkamp, |
| 275 | T. F., Robison, W. T., Zarka, P. (2017, November). The Juno |
| 276 | Waves Investigation. Space Science Reviews, 213, 347-392. doi: 10.1007/ |
| 277 | s11214-017-0396-y |
| 278 | Le Queau, D., Pellat, R., & Roux, A. (1984a, January). Direct generation of the au- |
| 279 | roral kilometric radiation by the maser synchrotron instability: An analytical |
| 280 | approach. Physics of Fluids, 27(1), 247-265. doi: 10.1063/1.864520 |
| 281 | Le Queau, D., Pellat, R., & Roux, A. (1984b, May). Direct generation of the auroral |
| 282 | kilometric radiation by the maser synchrotron instability: Physical mechanism |
| 283 | and parametric study. Journal of Geophysical Research, 89(A5), 2831-2841. |
| 284 | doi: 10.1029/JA089iA05p02831 |
| 285 | Louarn, P., Allegrini, F., McComas, D. J., Valek, P. W., Kurth, W. S., André, N., |
| 286 | Zink, J. L. (2017, May). Generation of the Jovian hectometric radiation: |
| 287 | First lessons from Juno. <i>Geophysical Research Letters</i> , 44, 4439-4446. doi: |
| 288 | 10.1002/2017GL072923 |
| 289 | Louarn, P., Allegrini, F., McComas, D. J., Valek, P. W., Kurth, W. S., André, N., |
| 290 | Wilson, R. J. (2018, September). Observation of Electron Conics by Juno: |
| 291 | Implications for Radio Generation and Acceleration Processes. Geophysical |
| 292 | Research Letters, 45(18), 9408-9416. doi: 10.1029/2018GL078973 |
| 293 | Louis, C. K., Lamy, L., Zarka, P., Cecconi, B., & Hess, S. L. G. (2017, September). |
| 294 | Detection of Jupiter decametric emissions controlled by Europa and Ganvmede |
| 295 | with Voyager/PRA and Cassini/RPWS. Journal of Geophysical Research |

| 296 | (Space Physics), 122, 9228-9247. doi: 10.1002/2016JA023779 |
|-----|---|
| 297 | Louis, C. K., Lamy, L., Zarka, P., Cecconi, B., Imai, M., Kurth, W. S., Levin, |
| 298 | S. M. (2017, September). Io-Jupiter decametric arcs observed by Juno/Waves |
| 299 | compared to ExPRES simulations. Geophysical Research Letters, 44, 9225- |
| 300 | 9232 doi: 10.1002/2017GL073036 |
| 301 | Louis C. K. Prangé B. Lamy L. Zarka P. Imai M. Kurth W. S. & Connerney |
| 301 | L E P (2010 November) Jovian Auroral Badio Sources Detected In Situ |
| 302 | by June /Wayes: Comparisons With Model Auroral Oyals and Simultaneous |
| 303 | UST FILV Imagon Coonducting Descendent Letters (6(21) 11.606.11.614 doi: |
| 304 | 1051 FOV mages. Geophysical Research Letters, $40(21)$, 11,000-11,014. doi: 10.1020/2010CL084700 |
| 305 | 10.1029/2019GL004799 |
| 306 | McComas, D. J., Alexander, N., Allegrini, F., Bagenal, F., Beebe, C., Clark, G., |
| 307 | White, D. (2017, November). The Jovian Auroral Distributions Experiment |
| 308 | (JADE) on the Juno Mission to Jupiter. Space Science Reviews, 213, 547-643. |
| 309 | doi: 10.1007/s11214-013-9990-9 |
| 310 | Prangé, R., Rego, D., Southwood, D., Zarka, P., Miller, S., & Ip, W. (1996, Jan- |
| 311 | uary). Rapid energy dissipation and variability of the lo-Jupiter electrody- |
| 312 | namic circuit. <i>Nature</i> , 379, 323-325. doi: 10.1038/379323a0 |
| 313 | Pritchett, P. L. (1986a, December). Cyclotron maser radiation from a source |
| 314 | structure localized perpendicular to the ambient magnetic field. Journal of |
| 315 | Geophysical Research, 91(A12), 13569-13582. doi: 10.1029/JA091iA12p13569 |
| 316 | Pritchett, P. L. (1986b, September). Electron-cyclotron maser instability in relativis- |
| 317 | tic plasmas. Physics of Fluids, 29(9), 2919-2930. doi: 10.1063/1.865492 |
| 318 | Su, YJ., Ergun, R. E., Jones, S. T., Strangeway, R. J., Chaston, C. C., Parker, |
| 319 | S. E., & Horwitz, J. L. (2007, June). Generation of short-burst radiation |
| 320 | through Alfvénic acceleration of auroral electrons. Journal of Geophysical |
| 321 | Research (Space Physics), 112(A6), A06209. doi: 10.1029/2006JA012131 |
| 322 | Szalav, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., |
| 323 | Wilson, R. J. (2020a, February). Alfvénic Acceleration Sustains Ganymede's |
| 324 | Footprint Tail Aurora. Geophysical Research Letters, 47(3), e86527. doi: |
| 325 | 10.1029/2019GL086527 |
| 326 | Szalay, J. R., Allegrini, F., Bagenal, F., Bolton, S. J., Bonfond, B., Clark, G., |
| 327 | Wilson, R. J. (2020b). A new framework to explain changes in Io's footprint |
| 328 | tail electron fluxes submitted Geonbusical Research Letters |
| 320 | Szalav J R Bonfond B Allegrini F Bagenal F Bolton S Clark G Wil- |
| 329 | son B. J. (2018) In situ observations connected to the io footprint tail |
| 330 | aurora Journal of Geonbusical Research: Planets 193(11) 3061-3077 doi: |
| 333 | 10 1029 /2018 IF005752 |
| 332 | Treumann B A (2006 August) The electron-cyclotron maser for astronomy a_{2} |
| 333 | plication Astronomy & Astronomy is Astronomy of Astronomy and Astronomy astronomy astronomy and Astronomy and Astronomy |
| 334 | _0001_v |
| 335 | -0001-y Wu C S (1085 August) Kinotic evelotron and synchrotron mesor instabilities |
| 336 | Padia amiggion processes by direct amplification of rediction - Grace Geienee |
| 337 | - Radio emission processes by direct amplification of radiation. Space Science |
| 338 | Keviews, 41, 215-296. doi: 10.1007/DF00190055 |
| 339 | wu, C. S., & Lee, L. C. (1979, June). A theory of the terrestrial knometric radia- |
| 340 | tion. Astrophysical Journal, 230, 621-626. doi: 10.1086/15/120 |
| 341 | Zarka, P., Marques, M. S., Louis, C., Ryadov, V. B., Lamy, L., Echer, E., & Cec- |
| 342 | com, b. (2017, January). Radio emission from satellite-Jupiter interactions $($ |
| 343 | (especially Ganymede). In G. Fischer, G. Mann, M. Panchenko, & P. Zarka |
| 344 | (Eds.), Planetary radio emissions viii (p. 45-58). doi: 10.1553/PRE8s45 |
| 345 | Zarka, P., Marques, M. S., Louis, C., Ryabov, V. B., Lamy, L., Echer, E., & Cec- |
| 346 | coni, B. (2018, October). Jupiter radio emission induced by Ganymede and |
| 347 | consequences for the radio detection of exoplanets. Astronomy \mathcal{B} Astrophysics, |
| 348 | 618, A84. doi: 10.1051/0004-6361/201833586 |
| | |

Figure1.



Figure2.

