Source of Radio Emissions Induced by the Galilean Moons Io, Europa and Ganymede In Situ Measurements by Juno

C. K. **Louis**[1], P. Louarn, B. Collet, N. Clément, S. Al Saati, J. R. Szalay, V. Hue, L. Lamy, S. Kotsiaros, W. S. Kurth, C. M. Jackman, Y. Wang, M. Blanc, F. Allegrini, J. E. P. Connerney, D. Gershman

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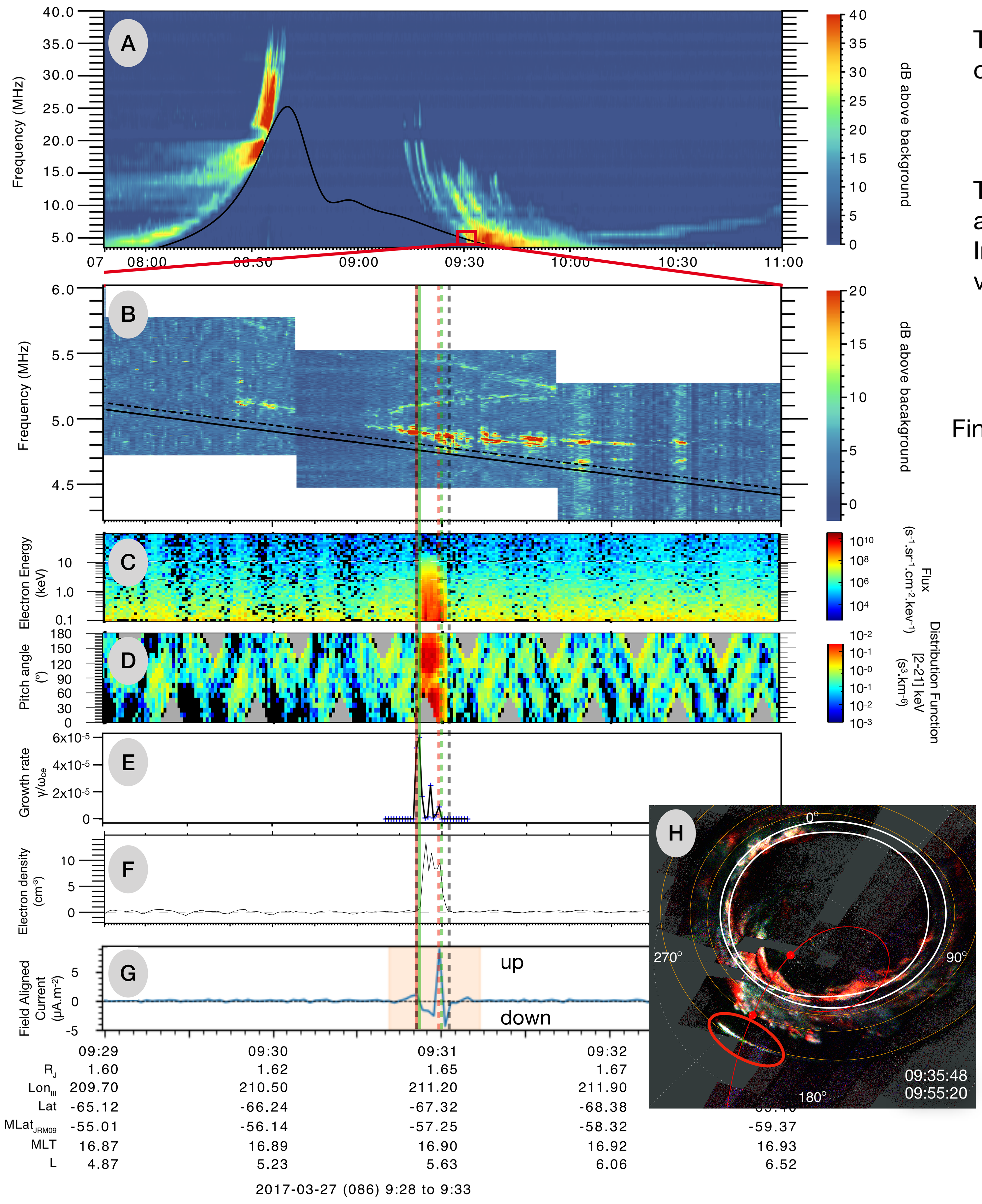
corentin.louis@obspm.fr

Abstract

At Jupiter, part of the auroral radio emissions are induced by the Galilean moons Io, Europa and Ganymede. Until now, except for Ganymede, they have been only 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 range of magnetic flux tubes which sustain the various Jupiter–satellite interactions, and in turn to sample in situ the associated radio emission regions. In this study, we focus on the detection and the characterization of radio sources associated with Io, Europa and Ganymede. Using electric wave measurements or radio observations (Juno/Waves), in situ electron measurements (Juno/JADE–E), and magnetic field measurements (Juno/MAG) we demonstrate that the Cyclotron Maser Instability (CMI) driven by a loss–cone electron distribution function is responsible for the encountered radio sources. We confirmed that radio emissions are associated with Main (MAW) or Reflected Alfvén Wing (RAW), but also show that for Europa and Ganymede, induced radio emissions are associated with Transhemispheric Electron Beam (TEB). For each traversed radio source, we determine the latitudinal extension, the CMI–resonant electron energy, and the bandwidth of the emission. We show that the presence of Alfvén perturbations and downward field–aligned currents are necessary for the radio emissions to be amplified

Observation and Analysis - The case of Io during Perijove 5 South



These emissions are believe to be produced by the Cyclotron Maser Instability (CMI) and emitted at a frequency really close to the electron cyclotron frequency $f_{ce}=eB/m_e$:

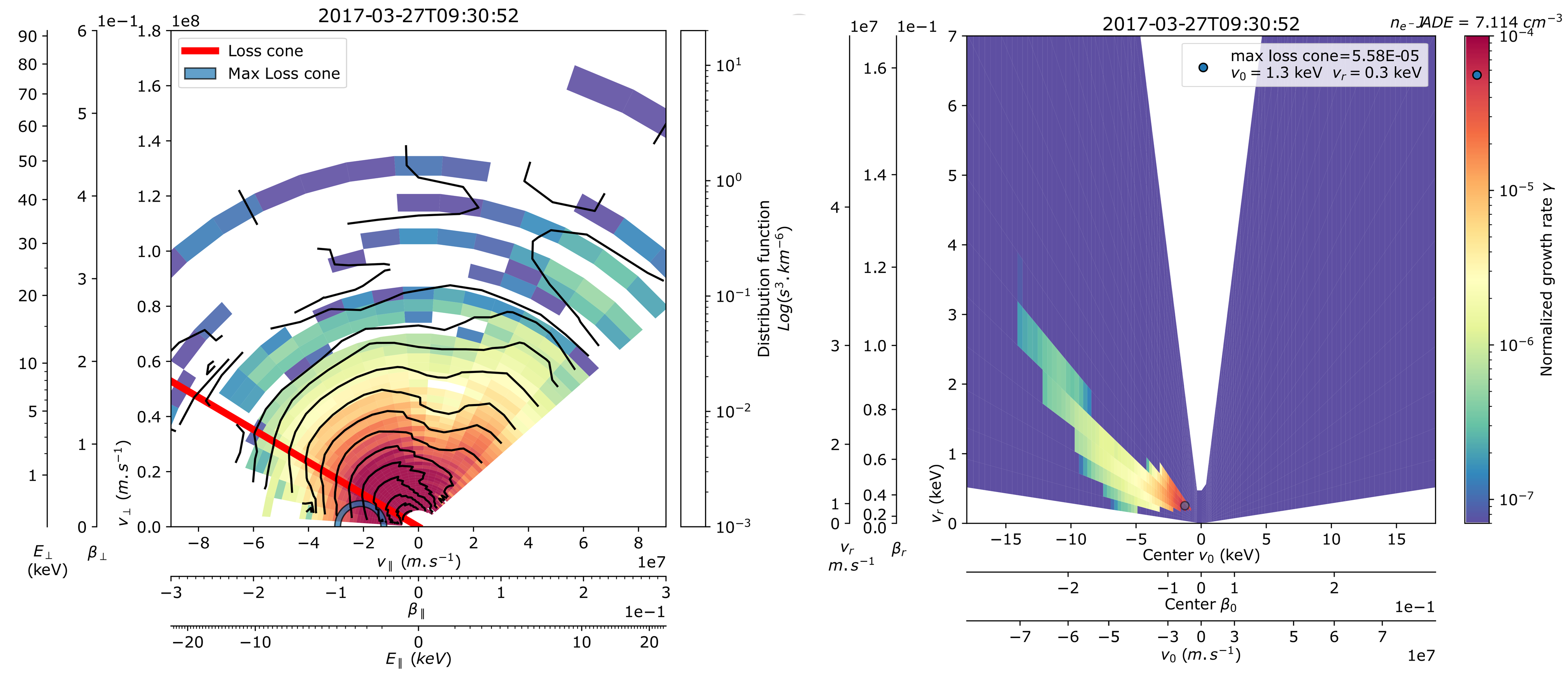
$$f_{\mathrm{CMI}} = f_{ce}\Gamma_r^{-1} + \frac{k_{||}v_{r||}}{2\pi} \quad \text{with} \quad \Gamma_r^{-1} = \sqrt{1-\frac{v_r^2}{c^2}} \quad \text{the Lorentz factor}$$

The CMI requires two conditions: (i) a magnetized plasma (where $f_{pe} << f_{ce}$) and (ii) weakly relativistic electrons previously accelerated along high magnetic field lines at typical energies of a few keV.
In the weakly relativistic case ($v_r << c$), the CMI resonance equation can be written a resonant circle equation in the velocity space

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

Find electron population that will lead to emission production: maximizing the growth rate along different resonant circles:

$$\gamma = \frac{\left(\frac{\pi}{2}\epsilon_h\right)^2}{1+\left(\frac{\epsilon_c}{2\Delta\omega}\right)^2}c^2\int_0^\pi d\phi\ v_r^2\sin^2(\phi)\frac{\partial f_h}{\partial v_\perp}(v_0 + v_r\cos(\phi), v_r\sin(\phi))$$



Results for the Jupiter-Io, Jupiter-Europa and Jupiter-Ganymede Radio Emissions Source Crossings

Moon	Io	Io	Io	Io	Europa	Ganymede	Ganymede	
Hemisphere	South	North	North	North	North	North	South	
Perijove	PJ5	PJ5	PJ6	PJ29	PJ12	PJ20	PJ30	
Date (Year–Month–Day)	2017–03–27	2017–03–27	2017–05–19	2020–09–16	2018–04–01	2019–05–29	2020–11–08	
Time interval (HH:MM:SS)	09:30:51–59	around 08:34:40	05:39:31–39	02:00:34–36	around 09:15:44	07:37:25–30	around 02:55:02	
JADE data	Yes	No	Yes	Yes	No	Yes	No	JADE data availability
f_{min} (MHz)	4.7	20.8	12.8	27.7	6.7	6.5	1.8	Minimal frequency reached by the radio emission (in MHz)
$f_{emission}$ ($\% > f_{ce}$)	3–18 × 10⁻³	3–29 × 10⁻³	2–14 × 10⁻³	5–40 × 10⁻³	7–15 × 10⁻³	5–21 × 10⁻³	5–40 × 10⁻³	Frequency bandwidth of the emission (in percentage above fce)
Intensity max. ($V^2.m^{-2}.Hz^{-1}$)	3×10^{-6}	3×10^{-6}	8×10^{-8}	2×10^{-6}	1×10^{-7}	1×10^{-6}	3.5×10^{-9}	Maximum intensity & estimated flux of the emission
Estimated flux max. ($W.m^{-2}.Hz^{-1}$)	4.0×10^{-6}	1.08×10^{-6}	2.5×10^{-7}	7.7×10^{-6}	2.4×10^{-7}	2.4×10^{-6}	7.2×10^{-9}	(based on Louis et al., 2021; Louis et al., 2023)
Electron energy (keV)	1–15	2–20	1–5	3–10	3–8	4–15	2–20	Electron energy (in keV)
Opening angle (°)	74–85°	74–85°	77–86°	73–84°	79–84°	76–83°	74–85°	Opening half–angle of the beaming cone (in °)
Radio source size (km)	360 ± 45	500 ± 100	415 ± 50	250 ± 50	200 ± 49	250 ± 50	75 ± 50	Radio source size (in km)
$\Delta\lambda_{\mathrm{Alfvén}}$ (°)	3.3°	10.8°	87.4°	7.8°	−10.5°	−1.8°	−7°	Downtail distance to the MAW (Based on Hue et al., 2023)
Associated UV emission	RAW	RAW	RAW	RAW	TEB	MAW	TEB	& associated UV emission (MAW: Main Alfvén Wing: RAW: Reflected Alfvén Wing; TEB: Transhemispheric Electron Beam)

Summary & Discussions

- **All Jupiter-moon radio emissions are shown to be similarly triggered by the CMI**
  - Only loss-cone type electron distribution functions trigger the emission
  - Electron energy: [1-20] keV
  - Half-opening angle of the beaming cone: [74°-86°]
  - Value in agreement with recent detailed remote observations with the NDA (Lamy et al., 2022, 2023)
- **The crossed radio sources are colocated with either MAW, RAW or TEB footprints**
- **The crossed radio sources coincide with downward field-aligned currents and Alfvén perturbations**
- **Flux density:**
  - In the $-1.8° < \Delta\lambda_{\mathrm{Alfvén}} < 10.8°$ interval: $[1\text{–}8] \times 10^{-6}$ W.m⁻².Hz⁻¹
  - Long distance downtail ($\Delta\lambda_{\mathrm{Alfvén}}$=87.4°): decrease of the intensity (2.5×10^{-7} W.m⁻².Hz⁻¹)
  - Emissions associated with TEB: lower intensity (7.2×10^{-9} and 2.4×10^{-9} W.m⁻².Hz⁻¹)

- **Difference in intensity: related to different type of electron distributions?**
  - For Europa: non-monotonic near-tail $<\Delta\lambda_{\mathrm{Alfvén}} \sim 4°$, broadband $>\Delta\lambda_{\mathrm{Alfvén}} \sim 4°$ (Rabia et al., 2023)
- **CMI does not trigger detectable emission every time:**
  - If f_{pe}/f_{ce} is too low: integration of the $\delta f/\delta v_\perp$ gradient gives an insufficiently high growth rate. Too low electron density in the up-going electron population due to an enhanced loss of precipitating electrons in the Jovian ionosphere?)
  - Presence of an Alfvénic acceleration process and FAC required?
    - Accelerated electron beams created by repeated Fermi acceleration by field–aligned electric fields produced by the Alfvén waves (Crary, 1997)?
    - Fraction of the electron population produces UV aurorae & fraction, is accelerated/reflected back upward --> partially empty upward loss cone in the electron distribution function with $\partial f/\partial v_\perp$ gradients --> creates the needed instability