

A new type of Jovian hectometric radiation powered by monoenergetic electron beams

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Key Points:

- A survey of Juno/Waves in situ measurements from 2016 to 2022 reveals 15 hectometric sources observed below the local electron cyclotron frequency.
- We show with a Cyclotron Maser Instability growth rate analysis using Juno/JADE-E data that they are generated by 0.2-5 keV shell electrons.
- This new source of Jovian auroral radio emission is reminiscent of the auroral kilometric radiations of Earth and Saturn.

Abstract

In this study, we statistically analyze the Jovian auroral radio sources detected in situ by Juno/Waves at frequencies f below the electron cyclotron frequency f_{ce} . We first conduct a survey of Juno/Waves data over 1–40 MHz from 2016 to 2022. The 15 detected HectOMetric (HOM) sources all lie within 1–5 MHz and are both less frequent than the radio sources commonly observed slightly above f_{ce} and clustered in the southern hemisphere, within $\sim 90 - 270^\circ$ longitudes.

We analyze these emission regions with a growth rate analysis in the framework of the Cyclotron Maser Instability (CMI), which we apply to JADE-E high cadence electron measurements. We show that the $f < f_{ce}$ emissions correspond to crossed radio sources, ~ 300 km wide. They are located in a hot and highly depleted auroral plasma environment, along flux tubes colocated with upward field-aligned current and at the equatorward edge of the main auroral oval. The wave amplification is consistent with the CMI and its free energy source consists of a shell-type electron distribution function (EDF) with characteristic energies of 0.2–5 keV. More energetic, 5–50 keV, shell-type EDFs were systematically observed at higher latitudes but without any radio counterpart. Various parameters for the $f < f_{ce}$ HOM sources, reminiscent of the ones at Earth/Saturn, are compared.

Other CMI-unstable EDFs, primarily loss cone ones, are systematically observed during the same intervals, giving rise to emission observed at $f_{ce} < f < f_{ce} + 0.5\%$. Our analysis thus reveals that different portions of the same EDF can be CMI-unstable and simultaneously amplify radio waves below and above f_{ce} .

Plain Language Summary

Taking advantage of Juno radio, electron and magnetic measurements within the source of Jupiter’s auroral radio emissions, we analyze a new type of HectOMetric (HOM, a wavelength of 1 hectometer matching a frequency of 3 MHz) emissions observed in situ by Juno/Waves at frequencies f below the electron cyclotron frequency f_{ce} . We first survey the Juno/Waves radio observations over 1–40 MHz between 2016 and 2022, covering the first 45 orbits. The 15 detected cases of $f < f_{ce}$ emissions are much less frequent than the usual HOM emissions observed slightly above f_{ce} and their sources are inhomogeneously distributed. We then analyze these events in the framework of the Cyclotron Master Instability (CMI) by calculating their theoretical growth rate from electron distribution functions simultaneously measured by the Juno/JADE-E spectrometer. We show that the $f < f_{ce}$ HOM sources are definitely consistent with the CMI powered by electron beams of 0.2–5 keV. This new type of Jovian auroral radio emission is reminiscent of the ones prominently observed at Earth and Saturn. These $f < f_{ce}$ sources co-exist with HOM emission at $f_{ce} < f < f_{ce} + 0.5\%$, which is also driven by the CMI based on different well-known sources of free energy.

1 Introduction

Jupiter is the brightest planetary radio emitter in the solar system. The auroral regions of its magnetosphere radiate intense, non thermal, radio emissions at frequencies ranging from a few kHz to 40 MHz. This spectral range encompasses various radio components, which have been historically classified by wavelength as DecAMetric (DAM, ~ 10 –40 MHz), HectOMetric (HOM, ~ 500 kHz–10 MHz), and broadband-KilOMetric (bKOM, a few kHz up to 1 MHz) (Zarka, 1998, and references therein). These emissions, the most intense of which are induced by Io, are produced at frequencies close to the electron cyclotron frequency $f_{ce} = \frac{eB}{2\pi m_e}$ (with e and m_e the electron charge and mass, B the magnetic field amplitude). They are beamed along a thin hollow-cone at large angles from

67 the local magnetic field, which is responsible for the arc-shaped structures observed in
 68 time-frequency radio spectrograms, they propagate in the Right-handed eXtraordinary
 69 (R-X) mode and are associated with the powerful Jovian aurorae. They were thus early
 70 suspected to be driven by energetic auroral electrons through the Cyclotron Master In-
 71 stability (CMI).

72 This electron-wave resonant instability was first proposed by Wu and Lee (1979) to ac-
 73 count for Auroral Kilometric Radiation (AKR) at Earth. It amplifies waves at frequen-
 74 cies close to f_{ce} in low density plasma regions where $f_{pe} \ll f_{ce}$, with f_{pe} the electron
 75 plasma frequency (proportional to $\sqrt{n_e}$, with n_e the electron density) from a weakly rel-
 76 ativistic, out-of-equilibrium, Electron Distribution Function (EDF). The AKR free en-
 77 ergy source was first thought to reside in the loss cone portion of the auroral EDF, which
 78 results from the loss of electrons precipitating into the atmosphere (Treumann, 2006, and
 79 references therein). In situ measurements performed within AKR sources by terrestrial
 80 polar orbiters such as *Viking* and *FAST* later showed that AKR waves display charac-
 81 teristics inconsistent with a loss cone free energy source: the radiation is primarily pro-
 82 duced in the R-X mode perpendicularly to the magnetic field, at frequencies 1-2% be-
 83 low f_{ce} and with too high flux densities. Electron measurements instead revealed that
 84 the AKR primary source of free energy resides in a shell-type EDF produced by the adi-
 85 abatic motion of electrons accelerated at 1-10 keV along auroral magnetic flux tubes (Louarn
 86 et al., 1990; Pritchett et al., 1999; Delory et al., 1998; Ergun et al., 2000). The radio sources
 87 themselves are embedded within auroral density cavities collocated with layers of upward
 88 field-aligned current along magnetic flux tubes mapping to the auroral oval (Hilgers, 1992;
 89 Roux et al., 1993).

90 The magnetosphere of Jupiter largely differs from those of the Earth and Saturn, with
 91 a large magnetic field, Io as a prominent plasma source, auroral acceleration processes
 92 of different natures. Jupiter’s rapid rotation was for instance long thought to drive the
 93 main aurorae through a field-aligned current system driven by the plasma corotation break-
 94 down in the middle magnetosphere (Cowley & Bunce, 2001). The remote properties of
 95 Io-DAM emissions, such as a strongly oblique apparent beaming, were interpreted as the
 96 signature of loss cone driven CMI (Zarka et al., 1996; Hess et al., 2007b, 2008; Mottez
 97 & Génot, 2011), while the free energy sources of the other Jovian auroral radio compo-
 98 nents remained open. The Juno spacecraft, which has been in polar orbit around Jupiter
 99 since mid-2016, aims at understanding the auroral acceleration and radio emission pro-
 100 cesses with in situ measurements (Bagenal et al., 2017).

101 The first results obtained by Juno challenged our view of the Jovian auroral physics. The
 102 auroral regions host three main zones: a layer of upward field-aligned current associated
 103 with the main auroral oval (called zone I, or ZI) equatorward of a layer of downward field-
 104 aligned current (called zone II or ZII) (Mauk et al., 2020). Both regions are dominated
 105 by highly energetic (50-1000 keV) bidirectional electrons. A third region, equatorward
 106 of ZI is collocated with the Diffuse Aurora (Diff. A.). It is characterized by a peak in the
 107 3-30 keV electron energy flux and Alfvénic fluctuations (Mauk et al., 2017; Allegrini et
 108 al., 2020a; Gershman et al., 2019). Overall, the EDFs observed in the auroral regions
 109 are prominently composed of broadband distributions rather than of mono-energetic struc-
 110 tures (Salveter et al., 2022). The specific analysis of radio sources encountered by Juno
 111 also yielded unexpected results. The spatial distribution of DAM, HOM, and bKOM sources
 112 identified between f_{ce} and $f_{ce}+1\%$ first revealed that they all lie along a common set
 113 of magnetic flux tubes. Also, when compared to the position of UV aurorae imaged si-
 114 multaneously on 3 occasions, the radio sources map to the equatorward edge of the main
 115 UV oval (Louis et al., 2019). A growth rate analysis applied to case studies of HOM sources
 116 (near a few MHz) showed that these are driven by the CMI with a loss cone EDF as the
 117 prominent source of free energy (Louarn et al., 2017; Louis et al., 2020) and a conics EDF
 118 as a second one (Louarn et al., 2018). In a recent study, we have checked those first re-
 119 sults with a more statistical approach (Collet et al., 2023). In a survey of the HOM source

120 crossings observed near the 10 first perijoves, we have confirmed their systematic col-
 121 location with the polar edge of the Diff. A. zone (see also Al Saati et al., 2022). We dis-
 122 covered one case of HOM emission observed at $f < f_{ce}$, which we showed with an im-
 123 proved CMI growth rate analysis to be unambiguously driven by a shell-type EDF, as
 124 at Earth and Saturn.

125 In this article, we build up on this approach to exhaustively identify and analyze all the
 126 HOM sources (the most frequently encountered) observed at frequencies $f < f_{ce}$ over
 127 the first 45 perijoves, sampling the 2016-2022 interval. Section 2 describes the Juno ra-
 128 dio, electron and magnetic datasets used. In Section 3, we review the basics of the CMI
 129 and the principles and limitations of our updated growth rate analysis. The influence
 130 of biased EDF measurements onto the calculated growth rates is assessed in Appendix
 131 A. The survey of the 15 $f < f_{ce}$ radio source crossings identified solely from radio ob-
 132 servations is described in Section 4. We then apply in Section 5 our growth rate anal-
 133 ysis to two representative source crossings, unraveling three different CMI-unstable, co-
 134 existing, sources of free energy. We finally discuss these results in the context of the Jo-
 135 vian auroral acceleration processes in Section 6.

136 2 Dataset

137 Since its arrival at Jupiter, the Juno spinning spacecraft (2 rotations per minute) has
 138 sampled its polar magnetosphere with 53 days-long (up to mid 2021, 43 days-long af-
 139 ter), highly elliptical, orbits. Late Sept. 2022, it had completed 45 orbits, labeled by per-
 140 ijove (hereafter PJ). The spacecraft trajectory is such that it successively crosses the north-
 141 ern and southern auroral regions (before/after each PJ, hereafter referred to as PJN or
 142 PJS for simplicity) at low enough altitudes to intercept auroral magnetic flux tubes host-
 143 ing auroral radio emissions. In this study, we have used observations acquired from within
 144 such radio sources by three instruments, namely the (radio and plasma) Waves exper-
 145 iment (Kurth et al., 2017), the JADE-E electron spectrometer (McComas et al., 2017)
 146 and the MAG flux gate magnetometer (Connerney et al., 2017), whose characteristics
 147 are briefly reminded below.

148 2.1 Waves

149 Waves measures electric fields between 50 Hz and 41 MHz with an electric dipole antenna
 150 made of two 2.8 m monopoles and two Low and High Frequency Receivers (LFR and HFR,
 151 resp.). Both receivers sample two bands: LFR-Low from 50Hz to 20 kHz and LFR-High
 152 from 20 kHz to 140 kHz, HFR-Low from 140 kHz to 3.5 MHz, and HFR-High from 3.5
 153 MHz to 41 MHz. Waves operates either in the so-called survey or burst mode. Survey
 154 observations provide time-frequency measurements, sweeping the full Waves spectral range
 155 at a cadence varying between 1 and 30 sec. The 1 sec cadence is used near perijoves for
 156 the sampling of auroral regions.

157 In this study, we focused on Burst mode HFR-Low and -High measurements between
 158 1 and 40 MHz, covering the HOM and DAM spectral ranges. The electric field is sensed
 159 with 4096 12-bit samples at a cadence of 7 Msps (HFR-Low) and 1024 12-bit samples
 160 at a cadence of 1.3 Msps (HFR-High). These measurements can be processed by Fast-
 161 Fourier Transforms (FFT) to produce high resolution $1 \text{ s} \times 1.709 \text{ kHz}$ (HFR-Low) and
 162 $1 \text{ s} \times 1.270 \text{ kHz}$ (HFR-High) time-frequency spectrograms. Note that in HFR-High, data
 163 are only measured in snapshots of $1 \text{ s} \times 1 \text{ MHz}$ encompassing the local f_{ce} value (as mea-
 164 sured by MAG, see below). We used these high resolution dynamic spectra to track en-
 165 countered radio sources, namely emissions observed near f_{ce} , and to characterize the wave
 166 properties (frequency, duration, intensity). Whenever necessary, we estimated the phys-
 167 ical wave flux density by cross-calibrating the burst mode spectrograms onto the survey
 168 mode observations already properly calibrated by Louis et al. (2021, 2023).

169 We noticed on some occasions that the radio emissions tracked throughout successive
 170 HFR-High high resolution spectrograms display a discontinuity when the central frequency
 171 of the tracked 1 MHz bandwidth changes. We suspect that, in such cases, the frequency
 172 ramp of the spectrograms is not reliable, which prevents us from confidently tracking emis-
 173 sion below f_{ce} . The corresponding time intervals were therefore avoided in this study.

174 2.2 JADE-E

175 JADE-E is a swept-energy electron spectrometer that measures electrons at energies log-
 176 arithmically spaced from 0.1 to ~ 100 keV. The spatial coverage was originally ensured
 177 by 3 sensors measuring the full sky EDF, out of which 1 failed during the Juno cruise
 178 phase. The EDF is measured since then by the 2 remaining sensors, with a total of 64
 179 anodes each sampling a 7.5° field-of-view. During the auroral passes, JADE-E operates
 180 in high resolution mode, in which the EDF is measured every second. As Juno completes
 181 a rotation in 30 s, JADE-E samples all directions within this time interval. The signal
 182 is recorded successively by adjacent energy channels with a time delay of ~ 0.1 s. It can
 183 therefore significantly change whenever the EDF varies at sub-second timescales, pro-
 184 ducing a characteristic saw tooth profile (Louarn et al., 2018). The maximal energy sam-
 185 pled by JADE-E is lower when the spacecraft spin axis is not parallel to the magnetic
 186 field (down to 40 keV when the angle is about 35°).

187 The measured EDF can nonetheless be biased. Electron measurements are significantly
 188 depleted for pitch angles $\theta = (\mathbf{v}, \mathbf{B})$ (with \mathbf{v} the electron velocity and \mathbf{B} the local mag-
 189 netic field) near 90° in strong magnetic field regions because of an instrumental, energy-
 190 dependent, masking of incident electrons (McComas et al., 2017; Allegrini et al., 2017,
 191 2020b).

192 For our purpose, we used calibrated measurements of EDF together with values of n_e
 193 inferred from these (Louarn et al., 2017, 2018) to derive f_{pe} . Because of the missing sen-
 194 sor, the instrumental shadowing, and the non-sampling of electrons with energies falling
 195 outside the JADE-E range, the derived values of f_{pe} are a lower limit of the real instan-
 196 taneous electron plasma frequency.

197 2.3 MAG

198 The radio/electron observations introduced above are complemented by MAG high res-
 199 olution measurements of the magnetic field amplitude B and of its components. f_{ce} can
 200 thus be derived directly from the measured B , and the direction of encountered field-
 201 aligned currents (FAC) by the derivative of the azimuthal component B_ϕ (Kotsiaros et
 202 al., 2019).

203 3 Growth rate analysis

204 3.1 Basics of the electron cyclotron maser instability

205 As mentioned above, the CMI was developed to account for the terrestrial AKR (see the
 206 reviews of Wu, 1985; Treumann, 2006). It requires a tenuous and magnetized enough plasma
 207 ($f_{pe} \ll f_{ce}$) and hot, weakly relativistic, unstable electrons (of density n_h) generally
 208 embedded within a cold, prominent, electron population (of density n_c). The CMI am-
 209 plifies waves near the electron gyrofrequency $\omega_{ce} = 2\pi f_{ce}$ along the resonance equation:

$$\omega = \frac{\omega_{ce}}{\Gamma} + k_{\parallel} v_{\parallel} \quad (1)$$

210 where $\omega = 2\pi f$ is the wave angular frequency, $\Gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor
 211 and k_{\parallel} and v_{\parallel} are the projection of the wave vector \mathbf{k} and the electron velocity \mathbf{v} onto

212 the direction of the local magnetic field. In the weakly relativistic assumption, when v/c
 213 is low, $\Gamma^{-1} \approx 1 - \frac{v^2}{2c^2}$ and the resonance equation 1 transposes into the equation of a
 214 circle in the $(v_{\parallel}, v_{\perp})$ phase space. This resonance circle is defined by a center $(v_0, 0)$ and
 215 radius v_r such that:

$$v_0 = \frac{k_{\parallel} c^2}{\omega_{ce}}$$

$$v_r = c \sqrt{\frac{k_{\parallel}^2 c^2}{\omega_{ce}^2} - 2\left(\frac{\omega}{\omega_{ce}} - 1\right)} = \sqrt{v_0^2 - 2c^2 \Delta\omega}$$
(2)

216 with $\Delta\omega = \frac{\omega - \omega_{ce}}{\omega_{ce}}$ (e.g. Galopeau et al., 2004). These two parameters determine the
 217 properties of the amplified waves: the wave number k_{\parallel} , which defines the emission angle,
 218 is directly linked to v_0 , and the wave emission frequency f is linked to v_r . Equations
 219 1 and 2 imply in particular that emission perpendicular to the magnetic field ($k_{\parallel} = 0$)
 220 corresponds to waves radiated at frequencies strictly below f_{ce} from resonance circles centered
 221 on $v_0 = (0, 0)$ which, as we will see, can amplify waves from shell structures present
 222 in the EDF. Conversely, oblique emission corresponds to waves radiated at frequencies
 223 slightly above f_{ce} from non-centered circles associated for instance with the loss cone part
 224 of the EDF (Hess et al., 2007a).

225 Waves are amplified at large angles from the magnetic field, most efficiently in the Right-
 226 handed eXtraordinary (RX) mode, whenever the wave growth rate (the imaginary part
 227 of the wave angular frequency ω_i) computed from the EDF along the resonance circle
 228 is positive.

229 3.2 Growth rate

230 The analytical expression of the growth rate results from the RX mode dispersion equa-
 231 tion, which itself depends on the nature of the ambient plasma. Various expressions of
 232 the growth rate can be found in the literature, most of which assume that the auroral
 233 plasma is dominated by cold electrons. A general expression of the normalized growth
 234 rate $\gamma = \frac{\omega_i}{\omega_{ce}}$ can be written as:

$$\gamma = A \int_0^{\pi} d\alpha c^2 v_r^2 \sin^2(\alpha) \frac{\partial F_h}{\partial v_{\perp}}$$
(3)

235 where c is the speed of light, F is the EDF with the subscript h standing for the hot, and
 236 unstable, electron population, the integral is computed along the resonance circle, α is
 237 the angle formed by a radius and the v_{\parallel} axis, and A is a coefficient whose expression varies
 238 among the authors. Wu and Lee (1979) and Wu (1985) for instance used $A = \frac{\pi^2}{4} \epsilon_h^2$,
 239 with $\epsilon_h = \frac{\omega_{ph}}{\omega_{ce}}$. A similar expression was later reused to study in situ the AKR source
 240 region (Mutel et al., 2007), the SKR one (Mutel et al., 2010), and to remotely investi-
 241 gate the wave properties of Jovian DAM emissions (Galopeau et al., 2004; Hess et al.,
 242 2007a).

243 Focusing on the Jovian HOM sources, Louarn et al. (2017) introduced a new expression
 244 of the growth rate, aimed at better considering the effect of hot electrons in a prominent
 245 cold plasma, with $A = 2\pi^2 \frac{\epsilon_h^2}{\epsilon_c^2} \Delta\omega^2$, where the subscript c stands for the cold thermal elec-
 246 tron population.

247 In Collet et al. (2023), we derived a more general expression of the RX mode growth rate
 248 (Eq. 4):

$$\gamma = \frac{\left(\frac{\pi}{2}\epsilon_h\right)^2}{1 + \left(\frac{\epsilon_c}{2\Delta\omega}\right)^2} c^2 \int_0^\pi d\alpha v_r^2 \sin^2(\alpha) \frac{\partial F_h}{\partial v_\perp} (v_0 + v_r \cos(\alpha), v_r \sin(\alpha)) \quad (4)$$

249 This formula simplifies to the growth rate expression of Louarn et al. (2017) (that of Mutel
250 et al. (2010), respectively) whenever $\Delta\omega \ll \frac{\epsilon_c}{2}$ ($\Delta\omega \gg \frac{\epsilon_c}{2}$, respectively).

251 Overall, the growth rate is proportional to the integral of the perpendicular gradient of
252 the hot EDF $\frac{\partial F_h}{\partial v_\perp}$ along the CMI resonance circle in the velocity space.

253 The CMI free energy source thus lies in the EDF portion where $\frac{\partial F_e}{\partial v_\perp}$ is positive (popu-
254 lation inversion). Loss cone and shell structures both fulfill this condition and are thus
255 CMI unstable. The angle of the loss cone θ_{LC} can be estimated from the expression:

$$\sin^2(\theta_{LC}) = \frac{B_o}{B_{max}} \left(1 - \frac{e\Delta\phi}{E_o}\right) \quad (5)$$

256 where B_o and $E_o = \frac{m_e v^2}{2}$ are the magnetic field amplitude and energy at the observa-
257 tion point and B_{max} is the magnetic field amplitude for a mirror point at the bound-
258 ary between the atmosphere and the magnetosphere. $\Delta\phi = \phi_o - \phi_m$ account for any
259 electric potential difference between the atmosphere and the observation point. When-
260 ever needed, θ_{LC} was derived by using the JRM33 internal magnetic field model (Connerney
261 et al., 2022) combined with the most recent current sheet model (Connerney et al., 2018)
262 assuming $\Delta\phi = 0$ and B_{max} derived at a precipitation altitude of 300 km above the
263 1 bar level. A variety of resonance circles can be fitted to the loss cone, corresponding
264 to a wide range of electron energies. They generally match positive but also negative gra-
265 dients, so that the associated growth rates can remain modest.

266 A shell structure (also referred to as a horseshoe in 2D) consists of an EDF intensifica-
267 tion at constant velocity. It results from parallel acceleration and conservation of the first
268 adiabatic invariant of electrons moving along field lines (Pritchett, 1984). It is highly CMI-
269 unstable: for an idealized shell, the resonance circle fitting the inner shell boundary con-
270 tinuously matches positive gradients out of the loss cone, yielding high growth rates.

271 3.3 Search for CMI-unstable electrons

272 Electron measurements have been regularly investigated at Earth (Louarn et al., 1990;
273 Ergun et al., 2000) and Saturn (Mutel et al., 2007; Menietti et al., 2011) to check their
274 CMI-instability and unambiguously confirm auroral radio emission sites. This approach
275 has been first applied to Jupiter with Juno in situ measurements by Louarn et al. (2017),
276 who analyzed a southern HOM source crossed after PJ1.

277 Assuming a cold plasma environment, the authors derived CMI growth rates from JADE-
278 E measurements of the EDF. The perpendicular gradient was derived from $\frac{\partial F_e}{\partial \alpha}$. This
279 approximation is only valid for small pitch angles, thus for circles with finite centers and
280 small radius. It was later reused by Louarn et al. (2018) and Louis et al. (2020) to study
281 another HOM source and a higher frequency one associated with Ganymede, respectively.
282 Overall, these authors identified both loss cone and conics-type EDF as CMI free energy
283 sources.

284 As an attempt to improve this approach, we developed the following systematic method.
285 We used the CMI growth rate expression given in equation 4, which we computed from
286 JADE-E data (assuming $\frac{\partial F_h}{\partial v_\perp} \approx \frac{\partial F_e}{\partial v_\perp}$) treated as follows. Each measurement of EDF
287 was first bi-linearly interpolated over 8 adjacent pixels in both velocity (v) and pitch an-
288 gle (θ) directions to achieve robust estimates of $\frac{\partial F_e}{\partial \alpha}$ and $\frac{\partial F_e}{\partial v}$.

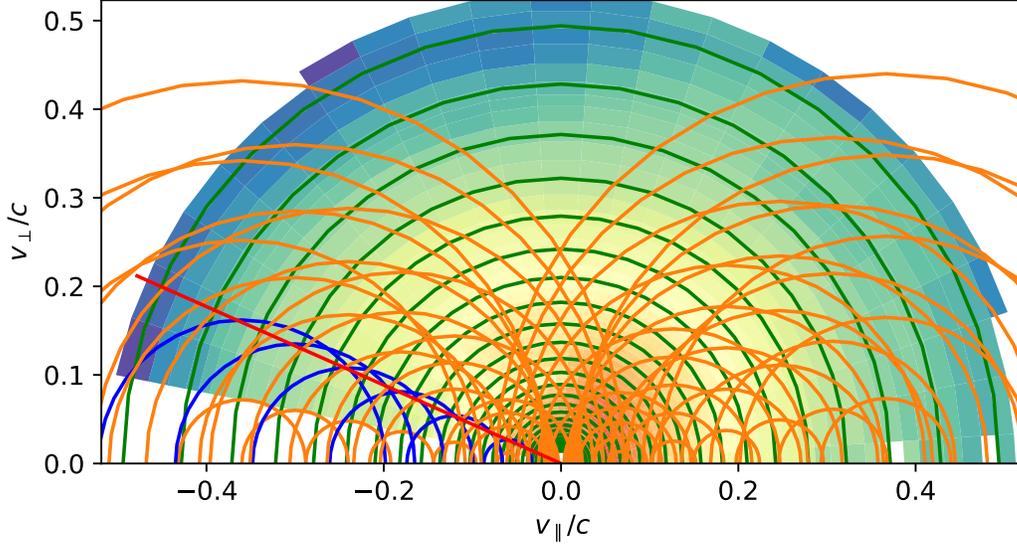


Figure 1. JADE-E measurement of an electron distribution function displayed in the velocity space, once smoothed over 3 consecutive pitch angle and energy channels. The red line shows the expected loss cone aperture angle. The colored circles display a subset of centered (green) and non-centered (orange, blue) CMI resonance circles. Only the blue circles are consistent with loss cone EDF.

289 We then tested the CMI-instability of the distribution with a total of ~ 4000 resonance
 290 circles, yielding the same number of growth rates. A subset of these circles is illustrated
 291 by the example provided by Figure 1. A series of 128 circles with $v_0 = (0,0)$ and loga-
 292 rithmically distributed radii v_r ranging on the whole JADE-E energy interval (green cir-
 293 cles), was specifically chosen to test shell-type EDF fulfilling the weakly relativistic as-
 294 sumption. A second series of 4200 non-centered resonance circles, exploring the ranges
 295 $v_0 = 0.033 c$ to $0.367 c$ (0.28-38.3 keV) and $v_r = 0.2 v_0$ to $1.25 v_0$, were aimed at test-
 296 ing loss cone EDFs (blue circles) and any other unstable part of the EDF with $\frac{\partial F_e}{\partial v_\perp} \geq$
 297 0 (orange circles).

298 More precisely, resonance circles were considered as consistent with the theoretical loss
 299 cone aperture angle θ_{LC} whenever $|\theta_{chara} - \theta_{LC}| < 7.5^\circ$, where $\theta_{chara} = \arcsin(v_r/v_0)$
 300 is the characteristic pitch angle of non-centered circles (see Fig. 2 and Hess et al., 2008).
 301 We also define the kinetic characteristic energy of a circle as $E_{chara} = \frac{mv_{chara}^2}{2}$ with $v_{chara} =$
 302 $\sqrt{|v_0^2 - v_r^2|}$ for non centered circles and $v_{chara} = v_r$ for centered circles. E_{chara} corre-
 303 sponds to the energy of the hot electron population where the resonance circle is tan-
 304 gent to the loss cone, where the wave amplification is in principle maximal.

305 Resonance circles intercepting less than 20 (v_\parallel, v_\perp) data points or more than 13% un-
 306 physical data points with $F_e \leq 0$ (resulting from background subtraction and low SNR)
 307 were not considered. Also, to deal with sub-second variations of instrumental origin pro-
 308 ducing a saw tooth profile able to erroneously yield positive growth rates for centered
 309 circles, we additionally imposed the condition that centered resonance circles must yield
 310 positive growth rates for at least two consecutive circles in radius/energy.

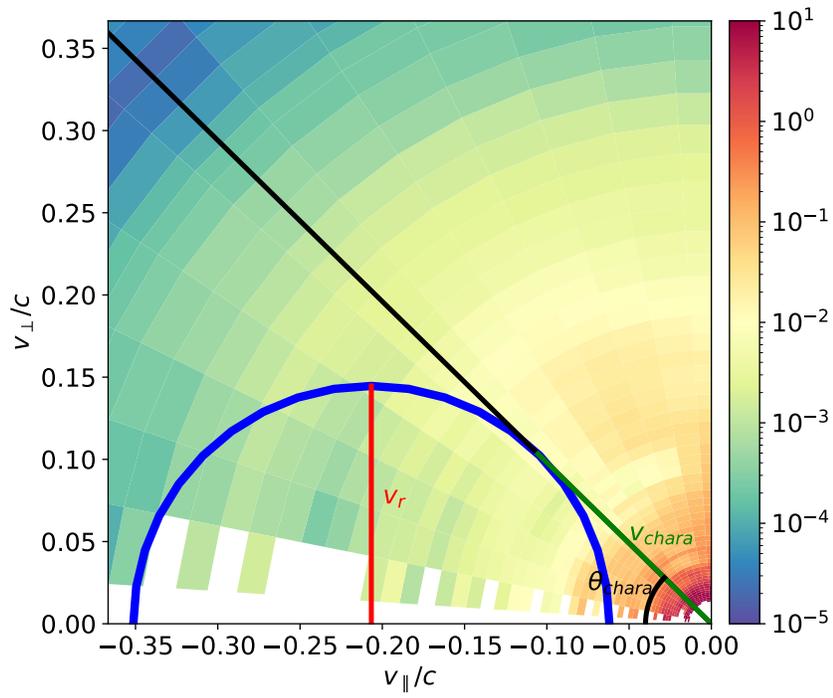


Figure 2. Same as Figure 1 with a single resonance circle defined by its coordinates v_0 and v_r , yielding the characteristic electron speed v_{chara} (green line) and angle θ_{chara} (black angle). The tested circle is consistent with a loss cone type EDF whenever $|\theta_{chara} - \theta_{LC}| < 7.5^\circ$.

3.4 Wave intensity

From the growth rate, we can derive the expected spectral flux density S in $\text{W.m}^{-2}.\text{Hz}^{-1}$ and compare it to the one measured by Waves. S can be expressed as $S = G S_0$ with S_0 the amplitude of source radio waves and G the gain factor associated with the wave growth. The expression of G can be written as:

$$G = \exp\left(\frac{4\pi f_{ce}\gamma L_c}{v_g}\right) \quad (6)$$

where L_c is the convective length and v_g is the RX mode wave group velocity (Mutel et al., 2010).

For the sake of simplicity, we chose a constant group velocity $v_g = 0.1 c$, as derived for the auroral region of Saturn by Mutel et al. (2010). A more precise estimate of v_g would require to solve the dispersion relation with a relativistic analytical model of the EDF - such as delta ring or DGH distributions (Pritchett, 1984; Wu, 1985) - in the observed Jovian hot and highly depleted auroral plasma environment, which is beyond the scope of this paper.

We use the galactic background radio spectrum as a source term, $S_0 \sim 10^{-19} \text{ W.m}^{-2}.\text{Hz}^{-1}$ for frequencies of a few MHz (Dulk et al., 2001). We note that an alternate source term could be the incoherent noise from hot electrons (Zarka et al., 1986).

This growth rate analysis will be illustrated on two representative cases of encountered radio sources in Section 5.

4 Survey of $f < f_{ce}$ radio emissions

A straightforward approach to identify radio sources encountered along the Juno trajectory is to search for emissions observed at frequencies near f_{ce} by Waves. Louis et al. (2019) led a survey of bKOM, HOM, and DAM sources over the 15 first perijoves by tracking emission between f_{ce} and $f_{ce}+1\%$, an empirical detection criterion chosen from the early results of Louarn et al. (2017). This *ad hoc* criterion is not unambiguous though, as emission $f > f_{ce}$ can correspond to either a really crossed source or a nearly distant one since the CMI emission frequency depends on the velocity of resonant electrons.

In a recent re-analysis of candidate radio sources observed over the first 10 perijoves with high resolution Waves observations, we unexpectedly identified several cases of HOM and DAM emission at frequencies strictly below f_{ce} reminiscent of the AKR and SKR sources observed in situ at Earth and Saturn (Collet et al., 2023). Interestingly, $f < f_{ce}$ emission can only be driven by the CMI from shell-type EDF, which had not been reported at Jupiter to date. The case of the southern HOM source observed during PJ6S and studied in detail in (Collet et al., 2023) is illustrated in the Waves time-frequency spectrogram of Figure 3.

In this follow-up study, we extend our survey to perijove 45, covering a 6 years-long time interval ranging from mid-2016 to Sept. 2022, to achieve an exhaustive list of $f < f_{ce}$ candidate radio sources. Out of these, we identified 13 events with $f < f_{ce}$ between 1 and 3 MHz in the HFR-Low band and 2 events between 4 and 5 MHz in the HFR-High band, resulting in a total of 15 candidate sources with $f < f_{ce}$, all corresponding to the HOM range. Table 1 lists these candidate sources together with their properties. We rejected 8 ambiguous cases of $f < f_{ce}$ emissions observed by HFR-High.

For comparison purposes, we also compiled a list of $f_{ce} < f < f_{ce}+1\%$ candidates radio sources, provided in supplementary material (Collet et al., 2024), which includes both HOM and DAM emissions.

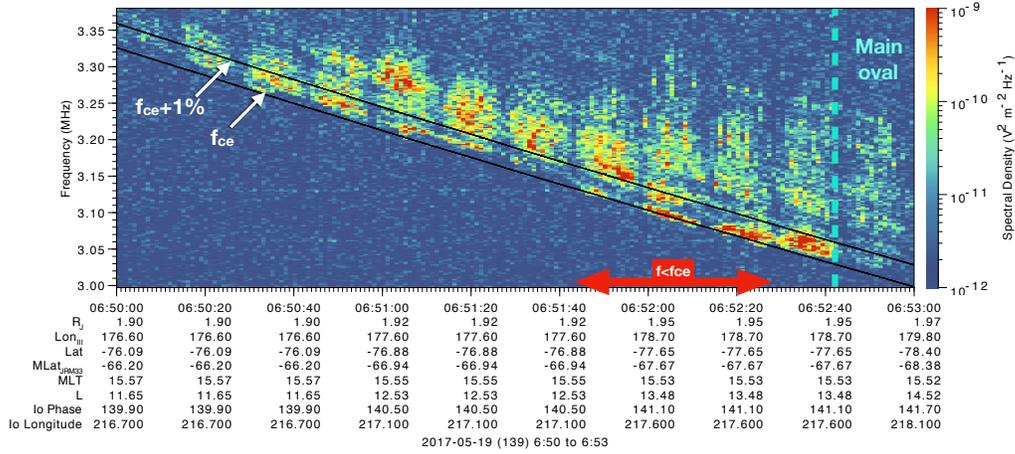


Figure 3. High resolution time-frequency spectrogram during the southern auroral pass following PJ6. The two black solid lines plot f_{ce} and $f_{ce}+1\%$. HOM emissions are observed near 3 MHz below $f_{ce} + 1\%$ over the full 3 min-long interval and strictly below f_{ce} from 06:51:45 to 06:52:27 UT. Both radio sources are colocated with the Diff. A. zone, equatorward of the main UV auroral oval (Collet et al., 2023).

355 The modest but significant number of $f < f_{ce}$ HOM events provides the opportunity
 356 to assess their average spatial distribution. First of all, out of the 15 events, only 3 were
 357 observed in the northern hemisphere and 12 in the southern one. Their footprints are
 358 plotted (green symbols) together with those of $f_{ce} < f < f_{ce} + 1\%$ events (orange
 359 symbols) in the southern polar projections of Figure 4, on top of the Juno footpath with
 360 M-Shell between $\sim 70R_J$ and $\sim 5R_J$ (gray lines). The northern (Fig. 4a1 and b1) and
 361 southern (Fig. 4a2 and b2) polar projections are displayed in planetocentric coordinates
 362 (Fig. 4a1 and a2) and as a function of magnetic latitude and magnetic Local Time (MLT,
 363 Fig. 4 b1 and b2). The magnetic footprints of field lines mapping to 15 and 60 R_J ($1 R_J$
 364 = 71492 km = a jovian radius) at the magnetic equator are indicated by the blue dashed
 365 lines and taken as boundaries of the main auroral oval.

366 Overall, the $f < f_{ce}$ HOM emissions are not homogeneously distributed, as opposed
 367 to the $f_{ce} < f < f_{ce} + 1\%$ HOM/DAM ones. Altogether, the former are roughly dis-
 368 tributed at all MLTs, except in the 11-16 sector. Nonetheless, we note that 9 events out
 369 of 15 (60%) are confined in the 02-11 MLT dawn side. Looking at longitudes, the emis-
 370 sion regions all lie between 80° and 270° , with the exception of a single one observed near
 371 330° . The $f < f_{ce}$ radio sources are located along flux tubes with M-shells between 17
 372 and 50 R_J , consistent with the average location of the main auroral oval. We compare
 373 the relative locus of radio and UV auroral emissions in more detail in Section 5.3.

374 5 Multi-instrumental analysis of $f < f_{ce}$ radio sources

375 To unambiguously validate and characterize the $f < f_{ce}$ HOM source candidates listed
 376 in table 1, we study all cases with Juno multi-instrumental observations and our CMI
 377 growth rate analysis described in Section 3.3 and show below two representative south-
 378 ern cases.

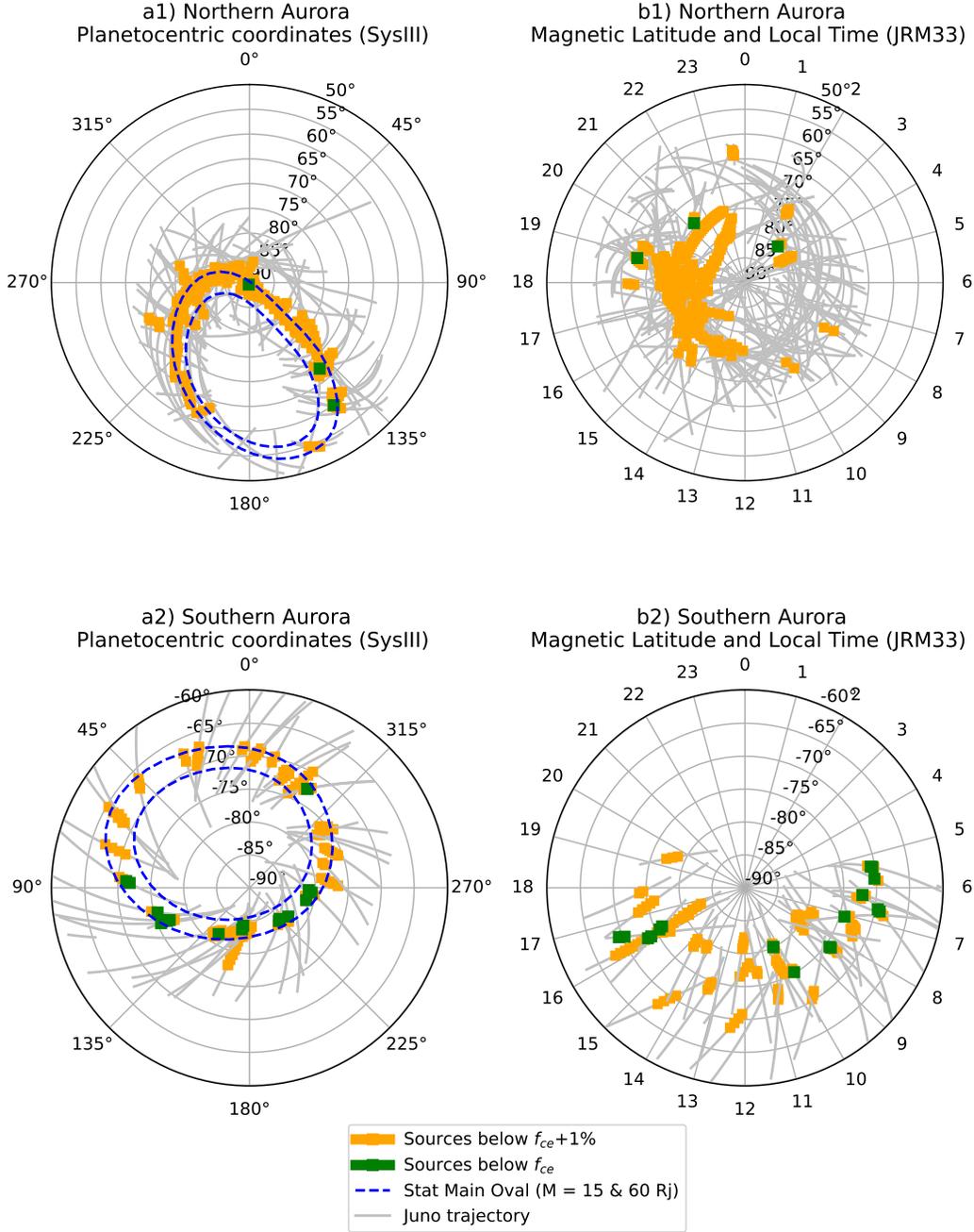


Figure 4. (a_1, b_1) Northern and (a_2, b_2) southern magnetic polar projections displayed in (a_1, a_2) planetocentric SIII coordinates and (b_1, b_2) as a function of the magnetic latitude and the magnetic local time. The Juno footpath (gray lines), together with the magnetic footprints of $f_{ce} < f < f_{ce} + 1\%$ (orange symbols) and $f < f_{ce}$ (green symbols) radio emission regions, have been derived from magnetic projection based on the Juno JRM33 and current sheet model (Connerney et al., 2022, 2020) at 300 km altitude above the 1-bar level (Gustin et al., 2016). The inner and outer blue dashed lines indicate field lines with magnetic apex (M-shell) located at 15 and 60 R_J , respectively.

Table 1. Catalog of $f < f_{ce}$ HOM emissions identified from Waves observations over PJ1-45. Columns 1 and 2 indicate the perijove and the event time interval. Columns 3, 4, and 5 give the absolute and relative emission frequency at the point where the emissions are the lowest below f_{ce} , together with the $\frac{\omega_{pe}}{\omega_{ce}}$ ratio. Column 6 indicates whether Juno was magnetically collocated with the main auroral oval or with the Diff. A. zone located from UVS images, column 7 whether the JADE-E spectrum exhibited a mono-energetic signature, column 10 whether we identified Alfvénic perturbations from MAG measurements, and column 9 the upward/downward sense of FAC (not identified on PJ35N). Column 8 indicates the ratio of hot to total electron density. Columns 12-14 provide the radio wave properties derived from our CMI growth rate analysis and the source size along the spacecraft trajectory. The last column gives the source peak spectral flux density as observed by Waves.

PJ	Interval	f (MHz)	$\frac{f-f_{ce}}{f_{ce}}$	$\frac{f_{pe}}{f_{ce}}$	UV aurorae	Mono energetic signature	$\frac{n_h}{n}$	FAC direction	Alfvén waves	Shell energy (keV)	Enlargement of LC	Normalized growth rate ($\times 10^{-4}$)	Size (10^3 km)	Estimated intensity ($\text{W}\cdot\text{m}^{-2}\cdot\text{Hz}^{-1}$)
1S	2016-08-27 13:29:29-30:51	5	-0.6 %	4×10^{-3}	Poleward.		0.5	↑	X	0.2	X	0.3-0.8	0.25	7.9×10^{-10}
6S	2017-05-19 06:51:45-52:27	3	-0.2%	10^{-3}	Diffuse	X	0.8	↑		0.5-3	X	0.2 – 2	2	8.02×10^{-12}
11N	2018-02-07 12:57:24-36	2.5	-0.3%	2×10^{-3}	Main Oval		0.8	↑	X	1	X	0.5 – 1	0.6	1.85×10^{-11}
11S	2018-02-07 14:44:54-45:19	2.8	-0.25%	3×10^{-3}	Main Oval		0.8	↑	X	2	X	0.5 – 3	1.25	2.56×10^{-11}
21N	2019-07-21 03:08:05-29	2.6	-0.25%	2×10^{-3}	Diffuse	X	0.7	↓		3	X	0.2 – 2	1.2	1.20×10^{-11}
24S	2019-12-26 19:04:04-54	1	-0.3%	3×10^{-3}	Diffuse	X	0.15	↑		1	X	0.2 – 0.8	2.5	2.69×10^{-11}
25S	2020-02-17 19:11:43-57	1.2	-0.2%	3×10^{-3}	Poleward		0.5	↑		0.2-0.7	X	2-3	0.75	4.13×10^{-11}
28S	2020-07-25 07:14:06-51	2.2	-0.3%	2×10^{-3}	Main Oval	X	0.5	↑		2	X	0.5	2	4.00×10^{-12}
31S	2020-12-30 23:08:24-09:20	1.1	-0.25%	2×10^{-3}	Main Oval	X	0.6	↑↓		2-3	X	0.3 – 3	2.5	8.27×10^{-12}
32S	2021-02-21 18:42:13-43	2.2	-0.55%	10^{-3}	Diffuse	X	0.7	↑	X	1.5	X	0.1 – 1	0.8	1.5×10^{-11}
35N	2021-07-21 7:27:30-40	4.0	-0.2 %	2×10^{-3}	Diffuse		0.7	*	*	0.2	X	0.5	1-10	6×10^{-10}
37S	2021-10-16 18:22:33-25:39	1.6	-0.4%	3×10^{-3}	Main Oval		0.4	↓		3	X	2 – 20	(1+) 3	1.29×10^{-11}
38S	2021-11-29 15:34:35-36:34	1.1	-0.4%	2×10^{-3}	Diffuse		0.5	↑		4	X	1 – 20	(0.5+)1.5	8.27×10^{-12}
41S	2022-04-09 17:05:40-06:35	1.3	-0.3%	5×10^{-3}	Diffuse		0.6	↑		5	X	2 – 10	2.75	3.50×10^{-11}
44S	2022-08-17 16:17:14-34	0.9	-0.8%	4×10^{-3}	Diffuse	X	0.5	↑		5	X	0.2 – 1	1.0	2.69×10^{-10}

5.1 The case of PJ32S

5.1.1 Radio source and auroral context

The case of PJ32S stands as a typical illustration of $f < f_{ce}$ southern HOM sources. Figure 5 provides a summary of radio and particle measurements observed between 18:40:00 to 18:45:00 UT on day 2021-02-21. Figure 5a shows a high resolution radio dynamic spectrum ranging from 1.9 to 2.4 MHz. We observe emissions between f_{ce} and $f_{ce}+1\%$ from 18:40:10 to 18:43:45 UT (black dashed rectangle) and emissions strictly below f_{ce} , down to $f_{ce} - 0.5\%$, from 18:42:30 to 18:43:00 UT (red dashed rectangle).

Figure 5b shows the electron plasma frequency f_{pe} (left-handed y-axis) derived from JADE-E measurements of the total electron density n_e (right-handed y-axis) with black crosses. The contribution of energetic electrons n_h (we assume their density is the one from electrons with energy above 1 keV) is displayed by red crosses. The solid lines plot the upper envelope of both series of symbols to remove unphysical drops resulting from instrumental shadowing/spacecraft spin. Overall, f_{pe} is sharply decreasing between 18:42:00 and 18:43:00 from 10 kHz ($n_e \sim 1.5 \text{ cm}^{-3}$) to 2 kHz ($n_e \sim 0.05 \text{ cm}^{-3}$) resulting in f_{pe}/f_{ce} ratios as low as 1×10^{-3} . Energetic electrons become prominent after 18:42:00 with $n_h \sim 0.7n_e$.

Figures 5c and d show time-energy electron spectrograms in the downward ($\theta < 30^\circ$) and upward ($\theta > 150^\circ$) direction, respectively, while Figure 5e displays the time pitch-angle spectrogram for 3-30 keV electrons. On top of Figure 5c is superimposed the azimuthal magnetic field, whose blue and red portions indicate downward and upward FAC. Clear signatures of downward monoenergetic electrons between 1 and 20 keV form inverted Vs observed between 18:42:45 to 18:44:15, overlapping both the upward FAC layer starting equatorward of the main UV oval and the $f < f_{ce}$ HOM emission. The density of this monoenergetic population (unseen for upgoing electrons) is decreasing with increasing energy. Figure 5f shows a time-frequency spectrogram of transverse magnetic field fluctuations (as defined in Gershman et al. (2019)) as the spectrogram of the normalized trace of the power spectral matrix). Alfvénic fluctuations are visible equatorward of the main oval, from 18:40:00 to 18:42:00 (orange dashed rectangle), reminiscent of those identified by Gershman et al. (2019).

From the above results, we can infer the position of the auroral zones. Alfvénic fluctuations are characteristic of the Diff. A. region. However, since their amplitude is known to decrease with increasing 3-30 keV electron flux (hereafter 18:41:30), the Diff. A. region plausibly ends between 18:42:00 and 18:42:30. The $f < f_{ce}$ HOM emission lies strictly equatorward of the main UV auroral oval while coinciding with a depletion of the total electron density and with the upward FAC layer consistent with region ZI.

5.1.2 Growth rate analysis

Figure 6 illustrates our growth rate analysis on the example of the EDF sampled by JADE-E at 18:42:46 UT, chosen middle in the $f < f_{ce}$ HOM emission region. Figure 6a shows the EDF in the velocity plane, with the red line indicating the loss cone aperture θ_{LC} . The plotted resonance circles are those maximizing the growth rate for the shell (green), loss cone (blue), and "other" (orange, neither shell nor loss cone) categories. Figure 6b replicates Figure 6a while plotting $\frac{\partial F_e}{\partial v_\perp}$ instead of F_e . The blue circle indeed intercepts gradients close to the theoretical loss cone whereas the orange circle intercepts gradients at pitch angles slightly larger than $\theta_{LC} + 7.5^\circ$ ($\sim 10^\circ$). The green circle is tangent to a partial shell best visible for downgoing electrons and peaking near $v \sim 2.10^7 \text{ m.s}^{-1} = 0.06 c$ (1.1 keV).

Figures 6c-d plot all the calculated growth rates as a function of (v_0, v_r) and as a function of $\Delta\omega$. In Figure 6c, the black lines delimit the area of resonant circles consistent

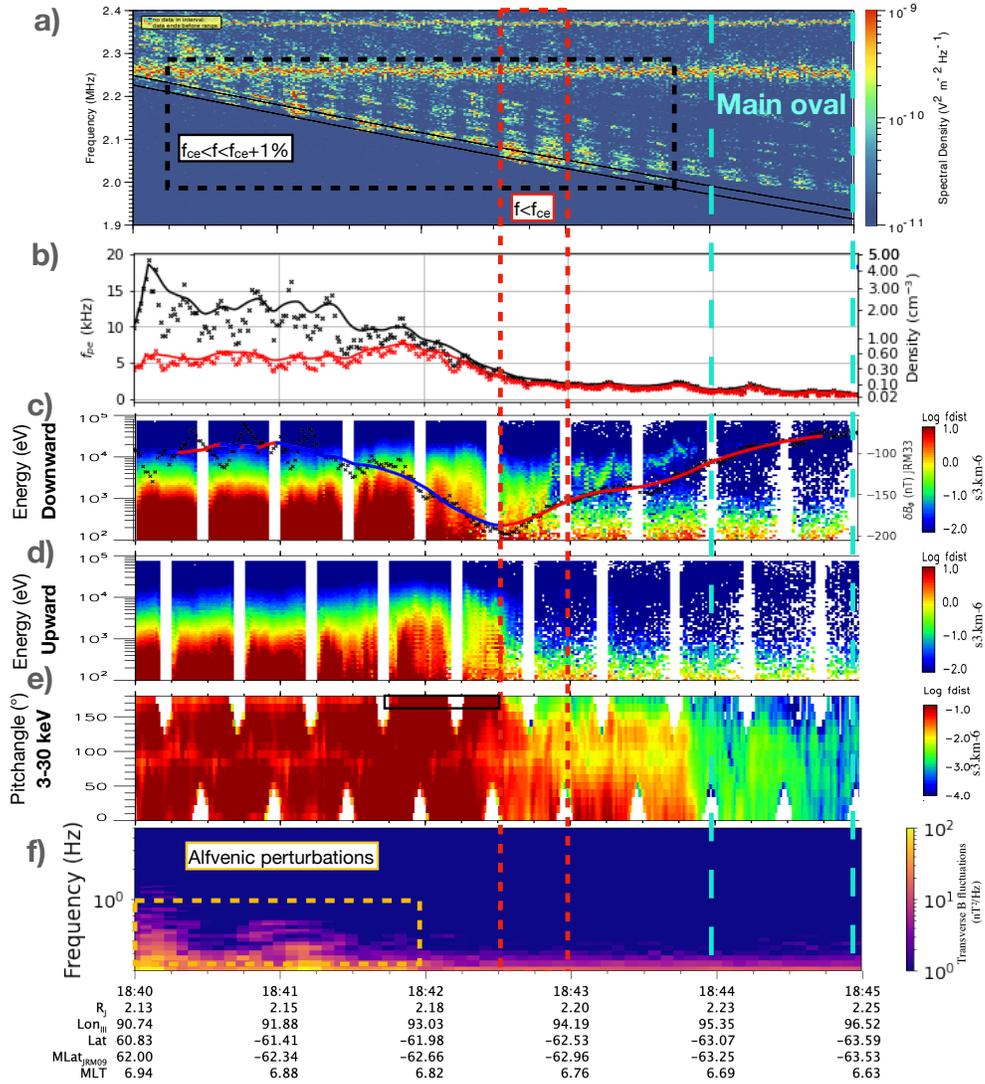


Figure 5. Juno radio and particle measurements obtained during PJ32S on day 2021-02-21. (a) Waves high resolution time-frequency spectrogram. The two solid black lines plot f_{ce} and $f_{ce}+1\%$. The dashed red (black, resp.) boxes indicate emission at frequencies $f < f_{ce}$ ($f < f_{ce} + 1\%$, resp.). The vertical blue dashed line marks the timing after which Juno was collocated with the main UV auroral oval. The horizontal signal seen near 2.27 MHz is an instrumental radio frequency interference. (b) Electron plasma frequency f_{pe} (left-handed y-axis) or electron plasma density n_e (right-handed y-axis) plotted as a function of time, as derived from JADE-E for all electrons (black crosses) and for those above 1 keV only (red crosses). The solid lines plot the upper envelope of the density. (c) Time-energy spectrogram of the downward electron flux ($\theta < 30^\circ$). The azimuthal magnetic field is superimposed on the panel with the right-handed y-axis. Its blue and red portions indicate downward and upward FAC. (d) Same as (c) for the upward electron flux ($\theta > 150^\circ$). (e) Time-pitch angle spectrogram of the electron flux integrated between 3 and 30 keV. (f) Time-frequency spectrogram of the transverse perturbations of the magnetic field. The yellow box indicates Alfvénic fluctuations (during which no compressive perturbations were observed, supporting their Alfvénic nature).

with the loss cone aperture. The associated growth rates are displayed by blue dots in Figure 6d. The shell and other resonance circles are displayed with green diamonds and orange crosses (sub-dividing into 'X' for circles associated with upward electrons and '+' for downward ones), respectively. The maximal growth rate for each of the 3 categories of circles is marked by a symbol in Figure 6c and by its associated resonance circle in Figures 6a-b.

Overall, two portions of the investigated EDF yield $\frac{\partial F_e}{\partial v_\perp} > 0$ and are therefore simultaneously CMI-unstable. The maximal growth rate $\gamma = 5.4 \times 10^{-5}$ is obtained for the shell-centered resonance circle associated with a weakly energetic electron horseshoe feature at 0.9 keV and expected emission frequency slightly below f_{ce} . The loss cone and other categories yield lower maximal growth rates of 1.2 and 1.1×10^{-6} , respectively, associated with electrons of 5.3 and 4.6 keV characteristic energies and expected emission near $f_{ce} + 1\%$.

Figure 5a displays distinct radio emissions both below and above f_{ce} consistent with predictions, thus supporting simultaneous CMI wave amplification by both parts of the EDF. The comparison between the observed and predicted spectral flux densities is addressed at the end of this Section.

5.1.3 Sources of free energy

Figure 7 shows the results of our growth rate analysis applied to the full time interval of Figure 5. Figure 7a displays the maximal growth rate for each category of resonance circle as a function of time. Figure 7b plots the associated characteristic electron energy. Figure 7c shows a high resolution radio dynamic spectrum, here plotted as a function of $\Delta\omega = (f - f_{ce})/f_{ce}$, on top of which are plotted the emission frequencies derived from the radius of resonance circles yielding large enough growth rates (we arbitrarily chose the condition $\gamma > 10^{-5}$, found below to be a good compromise).

The 3 categories of circles simultaneously display positive growth rates, with γ ranging from 10^{-7} to a few 10^{-4} , over the whole interval, thus extending the results of the example EDF presented above. Before 18:42:20, the loss cone growth rates (blues dots) are prominent, gradually rising from 10^{-7} to 10^{-4} . They correspond to 0.3-30 keV electrons and emission frequencies of a few 0.1% above f_{ce} consistent with the HOM low frequency envelope observed below $f_{ce} + 1\%$. We note at this occasion that the cone emission angle ranges from 92° to 96° for the most unstable loss cone circles.

Positive shell growth rates (green diamonds) appear after 18:42:10, peaking at a few 10^{-4} before monotonically decreasing down to 10^{-6} at 18:45:00. They correspond to electron energies increasing from 0.2 to 26 keV, and emission frequencies below f_{ce} . The latter matches the $f < f_{ce}$ HOM low frequency cutoff observed down to $f_{ce} - 0.5\%$ between 18:42 and 18:43 (for 1-3 keV electrons). Within this interval, electron energies vary similarly to the inverted Vs identified in Figure 5c, with energy increasing with time. After 18:43:00, shell growth rates predict radio emission below $f_{ce} - 0.5\%$ which is unobserved by Waves.

We now focus on the third type of resonance circles. Figure 8 displays the characteristic aperture of both the other and loss cone circles with crosses and dots, respectively, for upgoing (top, $v_\parallel < 0$) and downgoing (bottom, $v_\parallel > 0$) portions of the EDF. As reminded above, the circles associated with upgoing electrons were classified as loss cone whenever $|\theta_{chara} - \theta_{LC}| < 7.5^\circ$, lying within the two black dashed lines on Figure 8a. This condition left circles consistent with an enlarged loss cone, well visible between 18:42:30 and 18:43:50. This enlargement might probe a downward acceleration experienced by the EDF consistent with the upward FAC layer encountered during this interval and/or a downward potential drop located below the spacecraft. These circles generate emissions between 92° and 98° to the direction of the magnetic field. Figure 8b also reveals

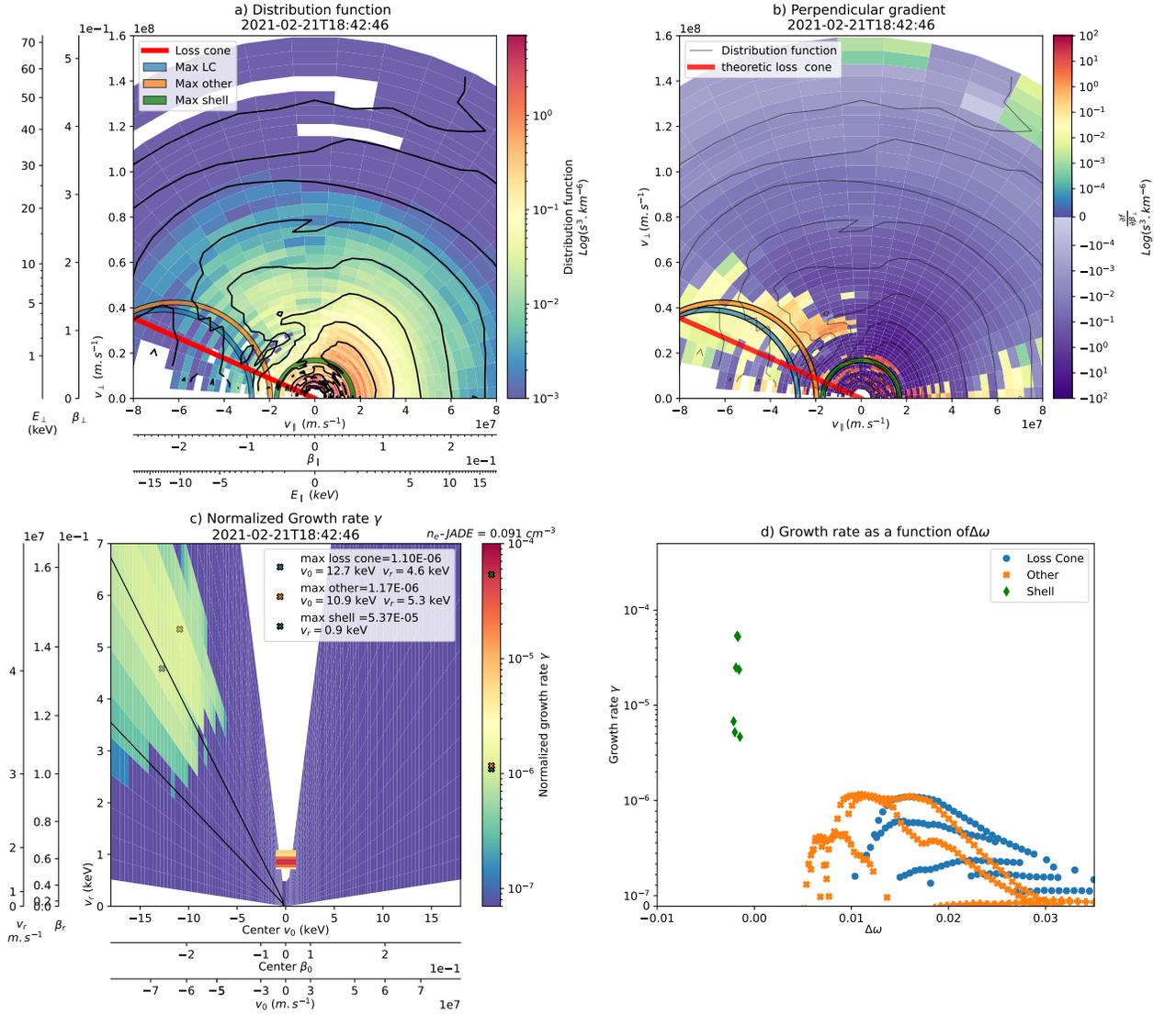


Figure 6. CMI growth rate analysis of the EDF measured by JADE-E on 2021-02-21 18:42:46 UT (PJ32S). a) EDF displayed in the $(v_{\parallel}, v_{\perp})$ phase space. For the sake of clarity, each axis displays velocities v in m/s, relative velocities $\beta = \frac{v}{c}$, and associated energies $E = \frac{1}{2} m_e v^2$ in keV. The black lines map isocontours of the EDF smoothed over 3 consecutive energy and pitch angle channels. The red line plots the theoretical loss cone aperture angle. The green, blue, and orange circles correspond to those yielding the maximal growth rates for the categories of CMI resonance circles testing shell-type, loss cone-type, and other (neither shell nor loss cone) unstable electrons. b) Same as a) with $\frac{\partial F_e}{\partial v_{\perp}}$ plotted instead of F_e . c) CMI growth rate displayed as a function of the center v_0 and the radius v_r . The 2 black lines enclose the area corresponding to loss cone-type resonance circles. d) CMI growth rate displayed as a function of $(\Delta\omega = \frac{1}{2c^2}(v_0^2 - v_r^2))$. The green, blue, and orange symbols again correspond to shells, loss cones, and other types of resonance circles. For the latter category, the '+' and 'x' symbols distinguish between circles intercepting positive $\frac{\partial F_e}{\partial v_{\perp}}$ for electrons propagating downward or upward, respectively. For this time interval, the largest growth rates were obtained for upward electrons, such as for the loss cone resonance circles.

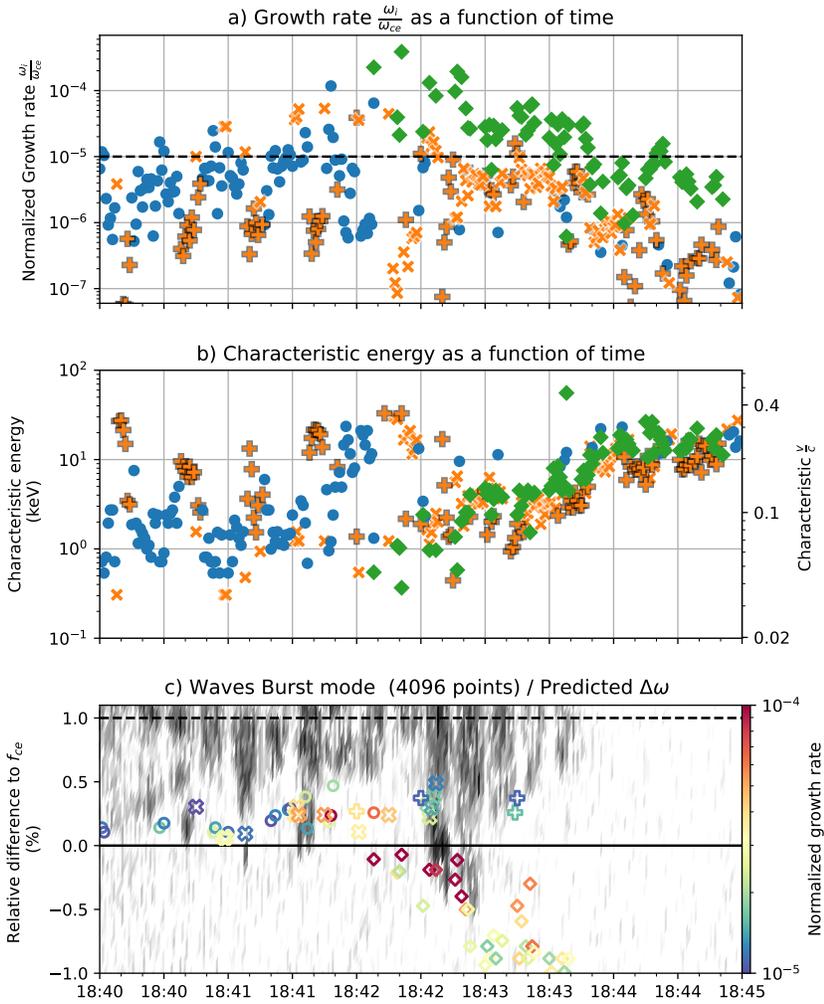


Figure 7. CMI growth rate analysis applied to the full-time interval of Figure 5. a) Maximum growth rate as a function of time for each EDF measurement (1-sec cadence) for the shell (green diamonds), loss cone (blue circle), upward other (orange 'x' crosses), and downward other (orange '+' crosses) types of resonance circles. b) Associated electron characteristic energy as a function of time. c) Waves high resolution dynamic spectrum plotted as a function of time and frequency relative to f_{ce} . The colored symbols map the predicted wave emission frequency for positive growth rates $\geq 10^{-5}$.

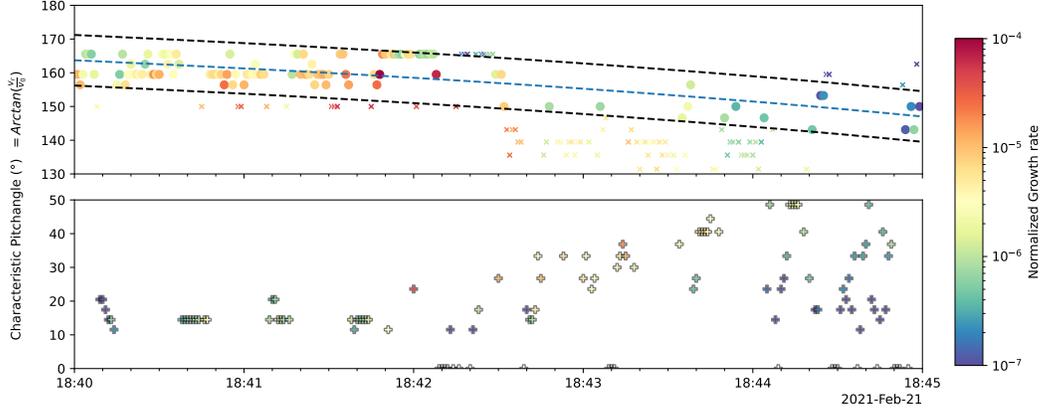


Figure 8. Characteristic pitch angle $\theta_{chara} = \arcsin(v_r/v_0)$ of the loss cone-type (filled circle) and other-type (crosses) resonance circles yielding the maximum growth rate displayed in Figure 7a as a function of time for (top) up going and (bottom) downgoing electrons. The blue dashed line on the top panel indicates the theoretical loss cone aperture angle, and the black lines its $\pm 7.5^\circ$ uncertainty. Loss cone (other) resonance circles therefore lie within (outside) these black lines. The blue-to-red color scale corresponds to increasing growth rates.

478 a significant amount of other circles associated with the downgoing portion of the EDF,
 479 where $\frac{\partial F_e}{\partial v_\perp} > 0$ (well visible on the right-hand side of Figure 6b). The population in-
 480 version probed by those circles is reminiscent of the conics-type EDF identified by Louarn
 481 et al. (2018). These circles generally yielded modest growth rates, corresponding to ex-
 482 pected emission near $f_{ce} + 0.2 - 0.3\%$ with emission angles from 84° to 86° , for instance,
 483 observed at 18:42:30 and 18:43:20.

484 The non-observation of radio waves expected to be amplified below $f_{ce} + 0.5\%$ from 18:41:40
 485 and 18:42:30 and below $f_{ce} - 0.5\%$ after 18:43:00 from 2-20 keV electrons may be ex-
 486 plained by transient, smaller sized, sources resulting in lower wave spectral flux den-
 487 sities, below the Waves' sensitivity threshold. From 18:42:00 to 18:42:30, the loss cone was
 488 generally filled in (black rectangle in Figure 5e), and unstable loss cone EDF were not
 489 detected continuously.

490 Overall, our growth rate analysis validated shell-type EDF as the CMI free energy source
 491 for $f < f_{ce}$ HOM emissions, in addition to the already known prominent loss cone EDF
 492 being responsible for HOM emission observed between f_{ce} and $f_{ce} + 0.5\%$. HOM emis-
 493 sion observed between $f_{ce} + 0.5\%$ and $f_{ce} + 1\%$ in turn most likely corresponded to a
 494 slightly distant (uncrossed) emission region.

495 5.1.4 Wave intensity

496 As described above, the wave spectral flux density can be derived from the growth rate,
 497 along with Equation 6, assuming $v_g = 0.1c$.

498 The convective length can be derived from the overall time interval τ_{cross} during which
 499 $f < f_{ce}$, which yields $1000km$. We then transpose this source length along the space-
 500 craft trajectory to its equivalent latitudinal extent as a more realistic estimate, so that
 501 $L_c \approx 350km$.

502 We then derive a gain $G \approx 10^{27}$. This tremendous value is unrealistic and may result
 503 from either an overestimated convective length, or an underestimated group velocity, or
 504 a combination of both.

505 The former possibility can be explored by a refined analysis of the crossed sources. Sec-
 506 tion 5.1.2 pointed out that unstable shell-type electrons at energies consistent with the
 507 observed emissions last for about 8 seconds. This reduced time interval corresponds to
 508 a latitudinal extent of ≈ 100 km. This yields a more realistic gain $G = 10^9$, which in
 509 turn provides a theoretical wave intensity of $S = 10^{-10}$ W.m⁻².Hz⁻¹ which well com-
 510 pares to the observed $S_{Waves} = 10^{-11}$ W.m⁻².Hz⁻¹.

511 Suppose we alternately consider the $L_c = 350$ km value as reliable and use the observed
 512 wave intensity as a reference observable to infer v_g . By inverting Equation 6, we obtain
 513 a necessary gain of $G = 10^8$, requiring $v_g = 0.34$ c.

514 The respective role of these two free parameters is discussed in more details in Section
 515 6.

516 5.2 The case of PJ28S

517 Hereafter, we similarly investigate a second representative case of a $f < f_{ce}$ HOM event
 518 observed on day 2020-07-25 during PJ28S.

519 5.2.1 Radio source and auroral context

520 Figure 9 provides the auroral context between 07:12:00 and 07:15:30 UT in a format iden-
 521 tical to Figure 9. HOM emissions at $f < f_{ce}$ ($f < f_{ce} + 1\%$, resp.) are visible in Fig.9a
 522 between 07:14:05 and 07:14:50 (between 07:13:30 and 07:15:05, resp.). The $f < f_{ce}$ HOM
 523 emission region coincides with a prominent hot plasma in Figure 9b and with inverted-
 524 V shaped mono-energetic downward electron beams, visible in Fig.9 c, labeled A (from
 525 07:14:30 to 07:15:00) followed by a second interval labeled B (from 07:15:00 to 07:15:30).
 526 The latter does not coincide with $f < f_{ce}$ emissions. Similarly, weaker, signatures are
 527 simultaneously visible for upgoing electrons in Figure 9d, suggesting bidirectional accel-
 528 eration. Upward and downward FAC signatures alternate during the interval, the $f <$
 529 f_{ce} event overlapping with the upward FAC layer visible between 07:13:51 and 07:15:00.
 530 Figure 9e provides the JADE-E pitch angle coverage for 3-30 keV electrons and addi-
 531 tionally shows that the loss cone (indicated by the horizontal line) was sporadically filled
 532 in (black rectangles). Alfvénic fluctuations characteristic of the Diff. A. are clearly vis-
 533 ible from 07:12:10 to 07:14:15, overlapping the first half of the $f_{ce} < f < f_{ce} + 1\%$
 534 HOM emission region. The locus of the main UV auroral oval during this interval was
 535 unclear. However, we notice upward FAC from 07:13:45 to 07:14:45. We then infer that
 536 the Diff. A. spans the time interval associated with Alfvénic fluctuations from 07:12:15
 537 to 07:14:10 and ZI from 07:14:10 to 07:14:45. The emissions below f_{ce} were thus detected
 538 mostly in ZI.

539 5.2.2 Growth rate analysis and sources of free energy

540 Figure 10 displays the results of our growth rate analysis in a format identical to Fig-
 541 ure 7. In Figure 10a, the 3 types of circles again yield positive growth rates between $\sim 10^{-7}$
 542 and $\sim 10^{-4}$.

543 The most intense ones are obtained for shell EDFs associated with electrons of 0.5 to
 544 2 keV (Figure 10b) consistent with both monoenergetic electron signatures A and B ob-
 545 served in Fig.9c. Figure 10c illustrates the excellent correspondence between the predicted
 546 and observed wave emission frequencies below f_{ce} for event A only.

Throughout the interval, we observe modest growth rates associated with the loss cone resonance circles. These maximize at the middle of the interval with $\gamma \sim 10^{-5}$. The expected emissions near $f_{ce}+0.1\%$, corresponding to weakly energetic electrons ≤ 1 keV, were generally not observed. We note some episodes during which the loss cone is filled in and other ones during which JADE-E did not sample upward electrons, though.

Other circles associated with both downgoing and upgoing electrons are observed. The latter again displays a slightly larger aperture than the loss cone circles, indicating here again a loss cone enlargement (and the same emission angles range as PJ32S). They coincide with the monoenergetic structures with maximal growth rates $\sim 5 \times 10^{-5}$ during event B. The expected emission near $f_{ce}+0.15\%$, associated with electrons of ~ 2 keV, is observed. The rest of other circles associated with downward electrons display growth rates as modest as the loss cone ones, peaking at $\sim 10^{-5}$ at the start of event A. The predicted emission near $f_{ce} + 0.1$ to 0.2% , with electrons ranging from 0.4 to 2 keV, corresponds to the most intense HOM emission observed throughout the interval.

5.2.3 Wave intensity

Computing the wave intensity requires a precise estimation of γ . In this case, EDFs used for calculation were significantly affected by shadowing near $\theta \sim 90^\circ$, thus biasing the growth rate toward a lower value. We show in Appendix A that this instrumental bias can be corrected by multiplying shell growth rates by a correcting factor, here estimated to be 1.85.

Similarly to PJ32S, we can compute from the source crossing a source size of 2500 km along the spacecraft path which is equivalent to a latitudinal extent $L_c = 1100\text{ km}$. Using $v_g = 0.1\ c$ and $\gamma \sim 9 \times 10^{-5}$, we obtained a gain $G = 10^{40}$.

Once again, this value is tremendous compared to the observed emission intensity of $4 \times 10^{-12}\ \text{W.m}^{-2}.\text{Hz}^{-1}$.

We have found that, together with $f < f_{ce}$ radio emissions, unstable shell-type EDFs are detected for only 7 seconds. This corresponds to a latitudinal convective length $L_c \approx 200\text{ km}$ which in turn results in $G \approx 10^{7.4}$ and $S = 2 \times 10^{-12}$. This source size seems then to be consistent with the observations.

Conversely, since there is a factor of 5 between the exponents of the gain deduced from JADE-E and the one deduced from Waves, we could also deduce an adjustment in the group velocity to $v_g = 0.5\ c$.

5.3 Statistical study

To achieve a more comprehensive view of the $f < f_{ce}$ HOM sources, we applied our growth rate analysis to all the events from our survey, frequencies ranging from 1 to 3 MHz, whose characteristics are listed in Table 1.

We have identified CMI-unstable shell EDF for all of these events, with predicted emission properties in excellent agreement with those simultaneously observed below f_{ce} . This validates shell EDF as a new, third, CMI source of free energy driving HOM emission at Jupiter and the robustness of the $f < f_{ce}$ criterion to unambiguously track in situ crossed radio sources. Coincident signatures of monoenergetic electron structures were seen on JADE-E spectra in 7 cases.

The plasma region hosting the $f < f_{ce}$ HOM sources is hot and tenuous with $n_h/n_{tot} \sim 0.6$ and $\frac{\omega_{pe}}{\omega_{ce}} \sim 2 \times 10^{-3}$ on average. The radio sources were hosted along flux tubes with magnetic apex (M-shell) ranging from 17 to 50 R_J . The magnetic footprints of 8 sources are collocated with the diffuse UV auroral emissions, 5 with the main oval and 2 poleward of it. As opposed to the case study of (Collet et al., 2023), only 4 sources coincide

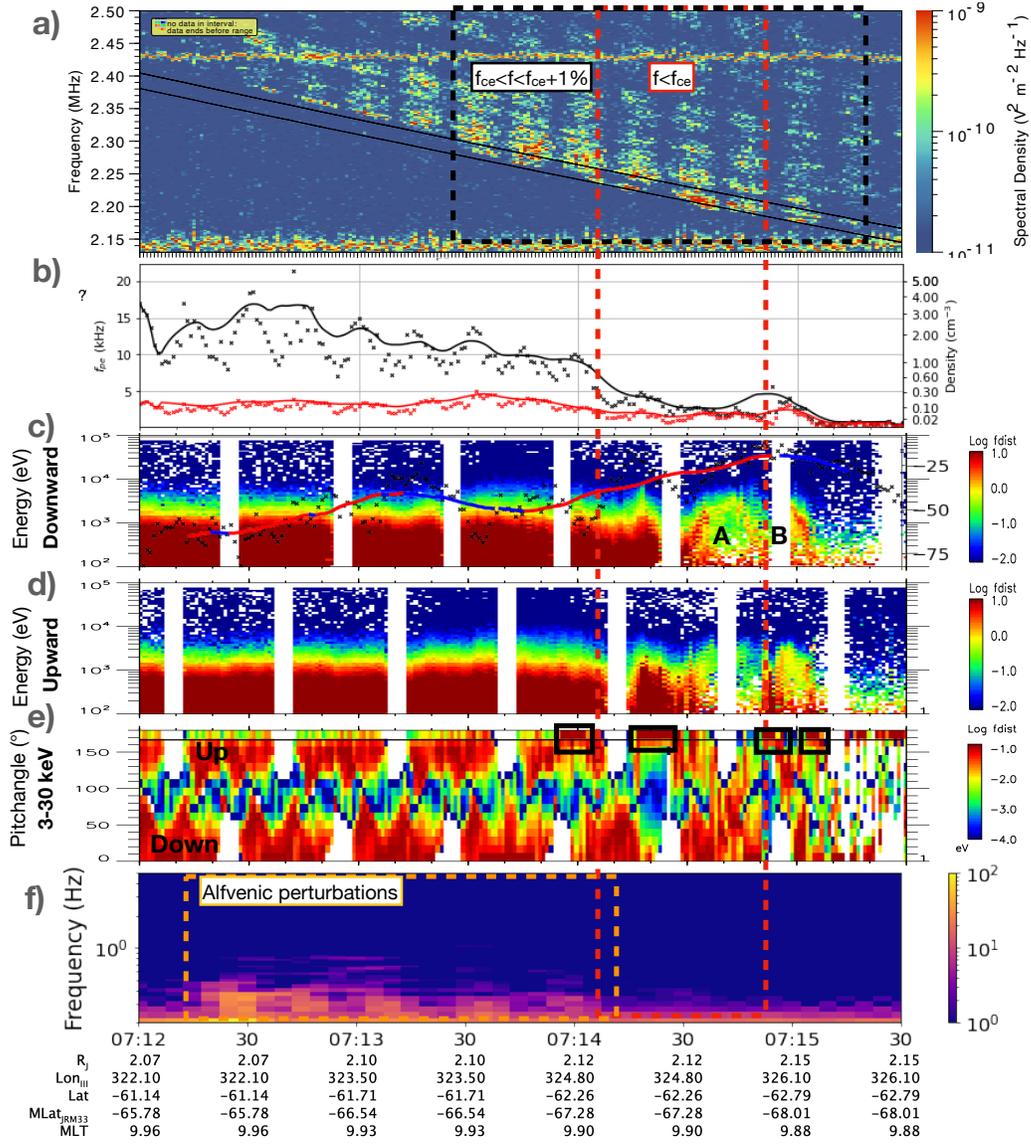


Figure 9. Same as Figure 5 for PJ28S.

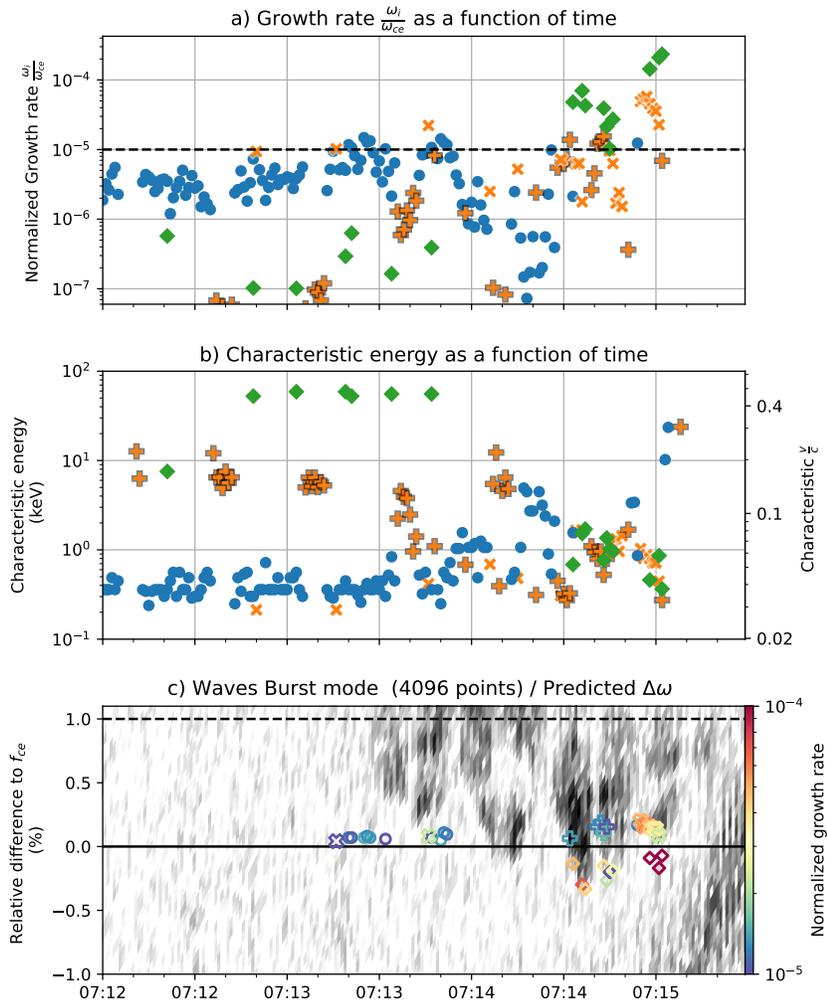


Figure 10. Same as Figure 7 for PJ28S.

594 with Alfvénic fluctuations. 12 sources lie within an upward FAC layer and match a grad-
 595 ual electron depletion. According to the criteria proposed in Mauk et al. (2020); Sulaiman
 596 et al. (2022), the sources are located near the boundary between Diff. A. and ZI (a def-
 597 inite identification of which would have required the analysis of highly energetic electrons
 598 sampled by Juno/JEDI, which we did not include in this study). We only found obvi-
 599 ous monoenergetic structures in JADE-E energy spectra for 7 events.

600 The most unstable shell resonance circles correspond to growth rates up to a few 10^{-4}
 601 associated with weakly energetic electrons of 0.2 to 5 keV. The observed wave spectral
 602 flux densities S_{obs} range from 4×10^{-12} to 7.9×10^{-10} $\text{W.m}^{-2}.\text{Hz}^{-1}$. The latter, largest,
 603 value (observed at 5 MHz during PJ1S) transposes to 4.0×10^{-20} $\text{W.m}^{-2}.\text{Hz}^{-1}$ at 1 as-
 604 tronomical unit (AU), slightly below the median (50% occurrence level) intensity derived
 605 from statistical Waves observations (Louis et al., 2021). In other words, the crossed HOM
 606 sources corresponded to weak emissions, as observed remotely on average by Waves.

607 Poleward of the $f < f_{ce}$ detected sources, we regularly identified CMI-unstable shell
 608 EDF with large growth rates associated with more energetic, 2-20 keV, electron beams
 609 but, surprisingly, without any visible radio counterpart. We have also identified at some
 610 occasions unstable shell resonance circles at larger (up to 30 keV) energies, unrelated to
 611 the $f < f_{ce}$ observed HOM sources, yielding growth rates $\gamma \lesssim 10^{-6}$, likely too low to
 612 amplify radio waves above the Waves sensitivity threshold.

613 Loss cone and other CMI-unstable EDFs are always present during the $f < f_{ce} + 1\%$
 614 source crossings and encompass the $f < f_{ce}$ ones. We noticed a systematic enlargement
 615 of the loss cone similar to the one discussed in the two above case studies.

616 6 Discussion

617 The statistical identification of previously unreported shell-driven CMI Jovian HOM emis-
 618 sions reminiscent of AKR at Earth and SKR at Saturn provides a new basis for com-
 619 parative discussion.

620 The $f < f_{ce}$ HOM source region corresponds to a hot, highly depleted, plasma with
 621 $\frac{\omega_{pe}}{\omega_{ce}} \sim 10^{-3}$, 1 order of magnitude less than at Earth and Saturn. As for Saturn, such
 622 values are low enough to drive the CMI whenever any type of unstable EDFs are present,
 623 and the radio sources were not coinciding with Earth-like cavities characterized by sud-
 624 den drops of the total electron density.

625 The normalized growth rates derived in this study range from 0.2 to 20×10^{-4} what-
 626 ever the free energy source. These values are typically 1 order of magnitude less than
 627 those previously published at Jupiter (Louarn et al., 2017; Louis et al., 2020), which we
 628 attribute to our different expressions of the CMI growth rate.

629 The large contribution of hot electrons to the total density challenges the cold plasma
 630 approximation. Determining growth rates in a hot plasma requires the use of numeri-
 631 cal methods (Pritchett et al., 1999; Pritchett, 1984, and references therein) or to ana-
 632 lytically derive the dispersion relation by assuming a specific hot plasma population (Wong
 633 et al., 1982). Such complex calculations are beyond the scope of this study.

634 The vast majority of $f < f_{ce}$ HOM sources coincide with upward current layers, like
 635 AKR and SKR, but they were generally located along flux tubes equatorward of the main
 636 auroral oval which stands as a major difference with the terrestrial and kronian cases.
 637 The poor matching between the position of the main oval and upward FAC or the spo-
 638 radic unexpected coincidence between the main oval and Alfvénic fluctuations renders
 639 the identification of auroral zone I and the region of diffuse aurora ambiguous. However,
 640 there is no obvious reason that these regions do not overlap.

Our survey of $f < f_{ce}$ HOM sources revealed a strong north/south asymmetry with only 3 unambiguous sources detected in the north. The northern auroral region proved to host more complex and dynamical FAC systems (Al Saati et al., 2022) which may result in less frequent and/or more transient electron beams producing shell EDF than in the southern auroral region.

The source electrons of the $f < f_{ce}$ observed HOM sources display lower energies, typically within 0.2 – 5 keV, than at Earth (1 – 10 keV) and Saturn (1 – 20 keV). The associated emission frequencies are therefore close to f_{ce} (0.2 – 0.8% to be compared to 1 – 2% for AKR/SKR). Indeed, according to Equation 1, for shell-driven CMI, the larger the electron energy, the lower the emission frequency. Weakly energetic electrons of a few keV were to be expected, as the CMI equation transposes into a resonance circle in the velocity space in the weakly relativistic assumption. Nonetheless, it is interesting to note that more energetic (5–50 keV) CMI-unstable shell EDF with large growth rates were systematically detected poleward of the tracked $f < f_{ce}$ sources, but without any radio counterpart. Smaller sources might be a plausible reason for preventing wave amplification beyond the Waves’ sensitivity threshold. The increase in energy of the shell EDF toward the pole was correlated with a decrease in the total electron density, as expected from a static current system (Knight, 1973).

The detected shell EDF results from the adiabatic evolution along auroral flux tubes of mono-energetic electrons beams, which are much less frequently observed than broadband distributions along high latitude flux tubes (Salveter et al., 2022). The reason why no radio emission is detected along flux tubes mapping to the main auroral oval and populated by highly energetic electrons of several hundreds of keV (Gérard et al., 2019), together with the validity of the CMI in strongly relativistic conditions, is left for future studies.

The wave intensity values derived for the two perijoves studied above strongly depend on the chosen group velocity and convective length. v_g has been considered to be equal to the speed of light in recent studies on DAM and HOM as a first approximation (Louarn et al., 2017, 2018; Louis et al., 2021). We chose instead the $v_g = 0.1c$ value derived in the cold plasma approximation for the SKR source region by Mutel et al. (2010). The results presented in Sections 5.1.4, 5.2.3 suggest that v_g might be larger. A definite answer requires to solve the dispersion relation for the hot and low $\frac{f_{pe}}{f_{ce}}$ Jovian hectometric source region. Recently, Ning et al. (2023) updated the results of Mutel et al. (2010) for Saturn by solving the dispersion relation by taking into account the relativistic effect of the hot population. Unexpectedly, the authors found that the emissions driven by shell-type EDF should be produced on an unstable trapped mode (named R1 in their study). Assuming that HOM electromagnetic waves are trapped, their escape from the source region as RX free-space mode waves would remain to be explained. We point out here that this specific R1 mode was already theoretically derived by Le Queau and Louarn (1989) from a parametrical analysis of the X mode dispersion relation using DGH functions. These authors identified the different regimes of X mode CMI and showed in particular that this specific mode connects to the usual escaping X mode when hot electrons dominate and that the cold electron component is negligible whenever $\frac{n_{cold}}{n_{hot}}\tau^2 < 3/5$ (with τ the ratio of the thermal speed of hot electrons to that of cold ones). They also showed that the $\frac{f_{pe}}{f_{ce}}$ ratio plays a crucial role in the determination of the wave propagation conditions. The low values observed in the Jovian auroral region therefore appear as a key parameter to consider.

Similarly, the source convective length was here first estimated from the latitudinal extent of the overall source identified with Waves as a realistic source size, as opposed to the expression $L_c = \tau_{cross}v_{Juno}$ used by Louarn et al. (2017). We then refined the value of L_c by considering the effective duration for unstable JADE-E data matching the source region, which turned out to be ~ 3 times lower. The effective median duration of all $f < f_{ce}$ HOM/DAM sources reaches ~ 300 km. This is only slightly larger than the typi-

cal 100 km length of individual AKR sources (Hilgers et al., 1991) and compares to the size of SKR sources of a few 100 km, also found to be filamented (Lamy et al., 2018).

To derive the expected wave intensity, we supposed that the emission is not saturated. We can check this assumption from the AKR study of Pritchett (1984), who estimated a saturation time of about $50 \omega_{pe}^{-1}$ in the case of 5 keV shell-type EDF with $\frac{\omega_{pe}}{\omega_{ce}} = 0.05$. Assuming that the 50 times lower $\frac{\omega_{pe}}{\omega_{ce}}$ ratio observed in the HOM source region would not significantly change this expression, we obtain a mean theoretical saturation time of ~ 3 ms at Jupiter. Here, with a median convective length of 300 km, and assuming a group velocity $v_g = 0.3 c$, we obtain a typical wave interaction time of 4 ms. This result either shows that in the particular case of $f < f_{ce}$ HOM, saturation is an important aspect of the intensity computation or that the source size is overestimated.

Apart from shell EDF responsible for $f < f_{ce}$ emission, we noticed the presence of other CMI-unstable circles probing upgoing electrons near the loss cone or downgoing ones over time periods longer than the $f < f_{ce}$ studied sources and consistent with wave emission observed slightly above f_{ce} . During the $f < f_{ce}$ sources, different portions of the same EDF could therefore amplify radio emission below and above f_{ce} simultaneously. The systematic enlargement of the loss cone likely results from downward electron acceleration consistent with upward FACs and/or kinetic Alfvén waves. These phenomena are also known to be able to generate shell-type EDFs (Hess et al., 2007a). We then hypothesize that this enlargement of the loss cone and the shell feature are generated by the same structures.

The maximal frequency reached by $f < f_{ce}$ HOM sources of our survey was about 5 MHz. The reason why we did not detect DAM sources beyond 5 MHz likely relates to the altitude at which the auroral flux tubes were crossed, favoring the HOM range. Still, the Jovian auroral radio spectrum peaks in the hectometric range, and HOM/DAM sources are spatially colocated, so that the studied HOM sources can be taken as representative of both HOM/DAM components. As the mission progresses the northern altitudes sampled decrease while the southern ones increase.

7 Summary and conclusions

In this work, we have surveyed Juno/Waves high resolution observations acquired near Juno perijoves from PJ1 to PJ45, covering the time period from mid-2016 to late 2022, to identify all the radio sources within 1–40 MHz observed strictly below f_{ce} . We detected 15 such sources between 1 and 5 MHz corresponding to HOM emissions only, at frequencies 0.2 to 0.8% below f_{ce} . A vast majority of these were sampled in the southern hemisphere, located along flux tubes mapping to 17–50 R_J and clustered within 80–270° longitude.

We have then analyzed these sources with an improved CMI growth rate analysis based on EDF in situ measurements by JADE-E. This analysis confirmed the CMI as a generation mechanism and a shell-type EDF involving weakly energetic electrons of 0.2–5 keV as the source of free energy of $f < f_{ce}$ HOM emissions. This statistically confirms and extends the discovery and analysis of a HOM source with $f < f_{ce}$ by (Collet et al., 2023).

The Jovian $f < f_{ce}$ HOM sources exhibit similarities and differences with the AKR observed at Earth and the SKR at Saturn.

As at Earth and Saturn, the sources are located in a hot and depleted plasma ($\frac{\omega_{pe}}{\omega_{ce}} \sim 2 \times 10^{-3}$ on Jupiter, 6×10^{-2} at Saturn (Mutel et al., 2010) and 0.1 at Earth), coinciding with upward field-aligned currents, and displaying a typical size of ~ 300 km. The shell electrons correspond to inverted-V monoenergetic structures.

As opposed to the terrestrial case, the emission region does not coincide with large-scale auroral cavities. Contrary to the AKR/SKR cases, $f < f_{ce}$ HOM sources are generally not connected with the main auroral oval. They are driven by slightly less energetic electron beams ($\sim 0.2 - 5$ keV) and lead to CMI growth rates as large as a few 10^{-4} . More energetic (5–50 keV) shell EDFs were systematically observed poleward but without any detected radio counterpart.

Other CMI-unstable EDF, such as loss cone or conics ones, previously identified as primary sources of free energy for HOM sources, were also systematically observed to produce high enough growth rates to drive HOM emissions between f_{ce} and $f_{ce} + 5\%$, so that different portions of the same EDF can be simultaneously CMI-unstable and amplify waves below and above f_{ce} . The loss cone aperture was found to be systematically larger than expected, indicating the presence of auroral potential structures leading to additional acceleration of electrons into the ionosphere.

A pending important question concerns the eventual generation of radio waves by the prominent highly energetic electrons of a few 100 keV found above the auroral oval (Allegrini et al., 2020b). Clues for such a CMI amplification have yet to be identified whether below or above f_{ce} (Collet et al., 2023). This analysis will require the analysis of Juno/JEDI electron measurements. The growth analysis method developed in this study also aims to be extended to the study of bKOM sources at lower frequencies/larger altitudes. Beyond Jupiter, this approach could also be redeployed for the re-analysis of auroral radio sources crossed at Earth by various polar orbiters, at Saturn by Cassini, and soon at Mercury by Bepi-Colombo.

Appendix A Influence of biased EDF onto the calculated growth rate

In this Section, we investigate the influence of instrumental shadowing of JADE-E EDF measurements at pitch angles near 90° (McComas et al., 2017) on the determination of shell-driven CMI growth rates. Figure A1a shows the EDF measured on 2020-07-25 at 07:14:45, once smoothed over 3 consecutive energy and pitch angles channels, and corresponding to the PJ28S case dealt with in Section 5.2. The green circle indicates the centered resonance circle yielding the maximal growth rate, fitting a partial shell structure. The shadowing is well visible for anodes sampling pitch angles between 52.5° and 97.5° with low values of F_e .

To fill in the biased region (considered as a data gap), we suppose that the shell was isotropic and we populated the $52.5-97.5^\circ$ region (between red lines) with the median value of EDF measured between $\theta = 97.5^\circ$ and $\theta = 135^\circ$. We chose to only take into account the downward part of this shell distribution as it would be difficult to estimate, for the upward part of it, to what extent the shell structure has propagated and where it is interrupted by the loss cone. This corrected distribution is shown in Figure A1b. Figure A1c compares the maximal growth rates obtained for the original distribution (in blue) and for the corrected one (in orange). We observe here that in contrast to the originally obtained growth rates, the corrected curve displays 2 local maxima: the first one is close to the original maximum while the second one is at slightly higher energy ($0.068c/1.18$ keV instead of $0.058c/860$ eV). This difference in energy results in an emission frequency change of less than 0.1%.

We note here that this second peak could either be related to the shadowing itself impacting more on this part of the gradient or that it could be due to variation below the 1s time resolution of JADE E, causing a sawtooth profile. From the growth rate corresponding to these peaks, we estimate that the factor between the maximum growth rate affected by the shadow and the corrected growth rate is between 1.85 and 4.8. While this interval is quite large for a correction factor, it gives us a better estimate of the growth rate estimation than using the biased JADE-E data. Further work is needed to overcome

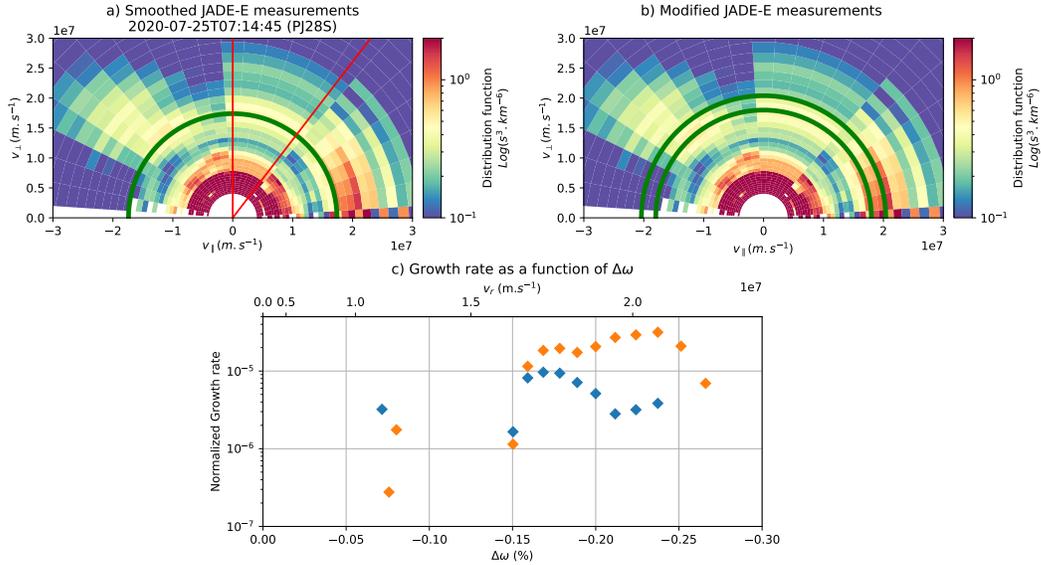


Figure A1. Original (a) and corrected (b) JADE-E EDF measurement on 2020-07-25 07:14:45 (PJ28S). c) Growth rates computed for both distributions.

792 this shadowing, one could work on a statistical study of this shadowing impact or use
 793 simulations to reproduce the shadowing as Allegrini et al. (2017) did. Such a precise study
 794 is beyond the scope of this work.

795 Appendix B Open Research

796 The Juno data used in this manuscript are reachable from the Planetary Data System
 797 at <https://doi.org/10.17189/1522461> (Kurth, W. S., 2021) for Waves data, at <https://doi.org/10.17189/1519715>
 798 (Wilson,R.J, 2020) for JADE-E data and at <https://doi.org/10.17189/1519711> (Connerney,
 799 J., 2017) for MAG data.

800 The Juno/Waves estimated flux density Collection (Version 02) (Louis et al., 2023, 2021)
 801 is available at <https://doi.org/10.25935/fwtq-v202>

802 Fig.4 was produced using a list of HOM/DAM source crossings in Supplementary Infor-
 803 mation (Collet et al., 2024).

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