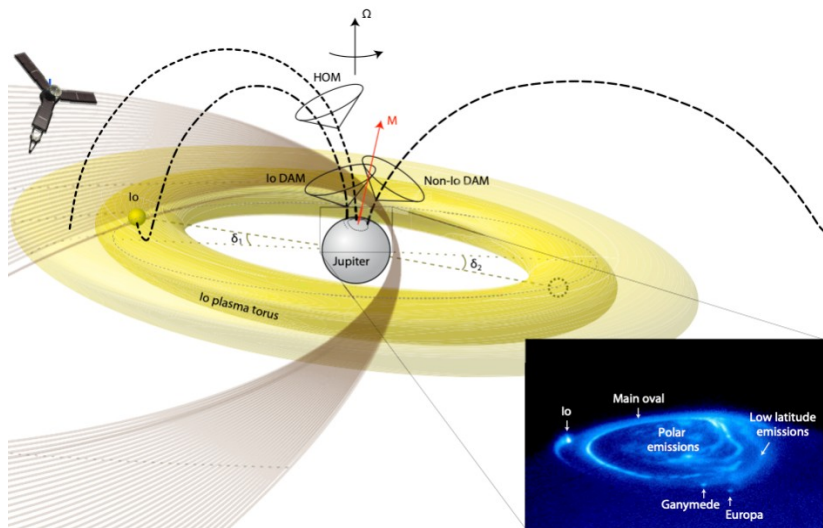


Detection of Jovian Kilometric and hectometric auroral radio harmonic with Juno/Waves

B. Collet^{1*}, L. Lamy^{2,3}, W. S. Kurth⁴, S. Wu⁵, F. Allegrini^{6,7}, and J. E. P. Connerney⁸

¹Tohoku University, Japan ²LAM, France, ³LIRA, Obs Paris, France ⁴Univ of Iowa, USA ⁵Univ of Southampton, UK ⁶SWRI, USA ⁷Univ of Texas at San Antonio, USA ⁸SPC, USA



Jovian radio auroral emissions:

- Generated by wave-particle instability (CMI)
- Jupiter's auroral acceleration region
- In situ electron and radio measurements
- Transfert of energy in a magnetosphere
- Comparative Planetology

Harmonics:

- Never clearly identified at Jupiter
- Opportunity for remote sensing
- Fundamental plasma physics

Generation Mechanism: The Cyclotron Maser Instability (CMI)

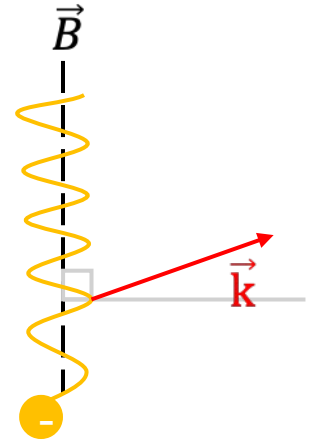
Wave-plasma instability introduced at Earth amplifies waves at :

(Wu & Lee 1979)

$$\omega = \frac{\omega_{ce}}{\Gamma} + k_{||} v_{||}$$

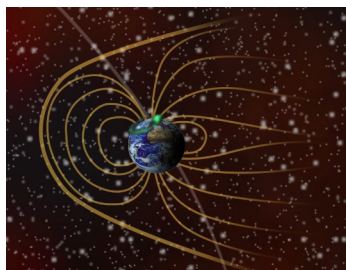
And requires:

- Depleted magnetized plasma $f_{pe}/f_{ce} \ll 1$
- Inversion of population for electrons of few keV
= **diagnostic of auroral acceleration**



Generation Mechanism: The Cyclotron Maser Instability (CMI)

Earth



Uranus? & Neptune?
Mercury??
Exoplanets?

CMI verified

(Viking:
Ergun et al. 2000)

mono energetic shell
(1-5 keV)

Source of
free energy:

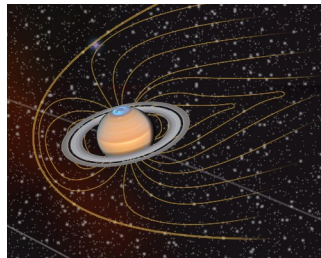
Acceleration:

Cavities+Upward
current

Connection
with aurora

UV discrete arcs

Saturn



CMI verified

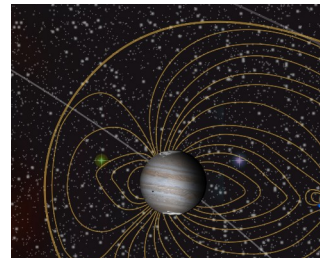
(Cassini:
Mutel et al. 2010)

mono energetic shell
+LC
(6-12 keV) (poster
PPS01-P04)

Upward current

Main oval

Jupiter



CMI verified

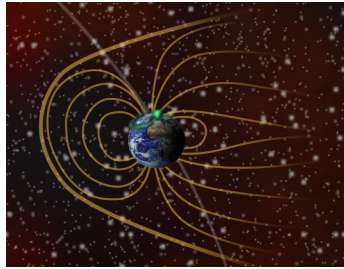
(Juno:
Louarn+ 2017 Louis+ 2023,
Collet+ 2024,2025)
Loss cone (main)
Shell (secondary)
(0.3-20 keV)

Alfven waves

Diffuse aurora +
Moon footprint

Auroral radio harmonics (ARH)

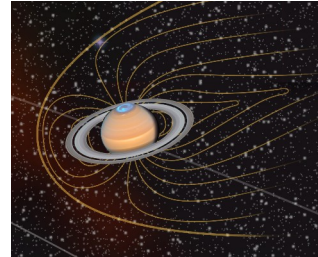
Earth



CMI verified
(Viking:
Ergun et al. 2000)

1st and 2nd
(X/O mode) harmonics
regularly observed
(Benson 1982,)

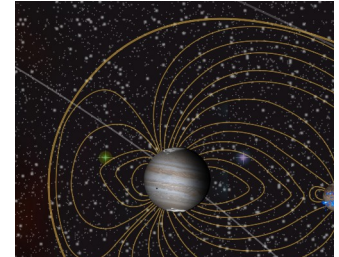
Saturn



CMI verified
(Cassini:
Mutel et al. 2010)

1st and 2nd
(X/O mode) harmonics
regularly observed
(Wu et al. 2022,)

Jupiter



CMI verified
(Juno:
Louarn+ 2017 Louis+ 2023,
Collet+ 2024,2025)

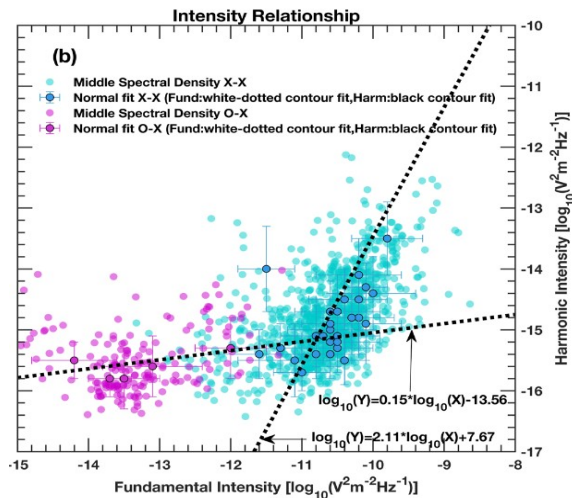
Unconfirmed
unclear reports of
Io-DAM and HOM
harmonics
(Menietti 1995,
Menietti et al. 1998)

Auroral radio harmonics (ARH)

Generation mechanism?

Saturn

(Wu et al. 2022)



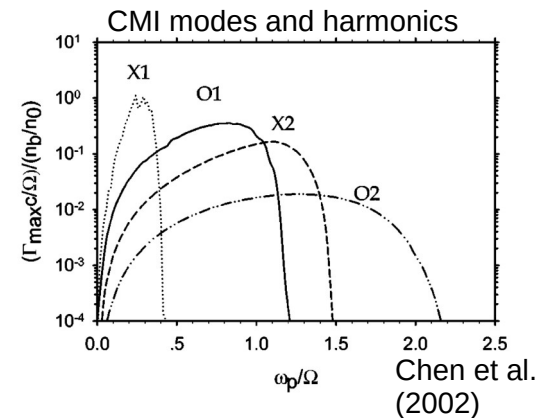
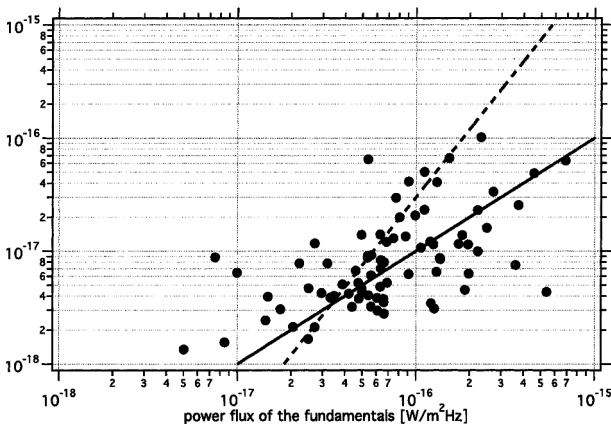
3 possible mechanisms:

- Direct CMI at 2 or 3 fce
- Inverse Landau instability driven by the electron beam
- Coalescence of X mode with Z mode emissions

Never verified but probably at least 2 coexisting

Earth

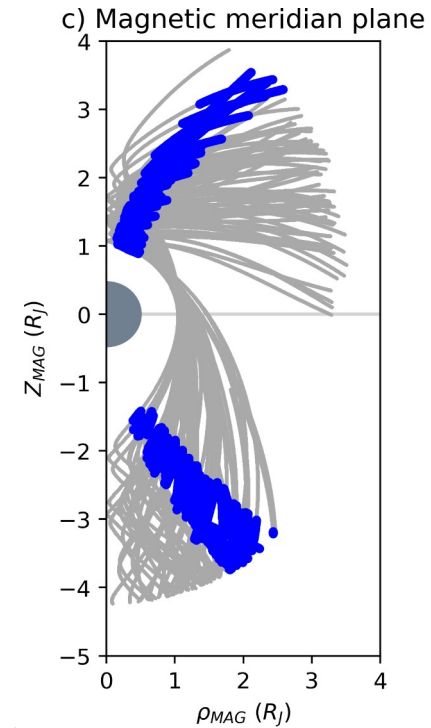
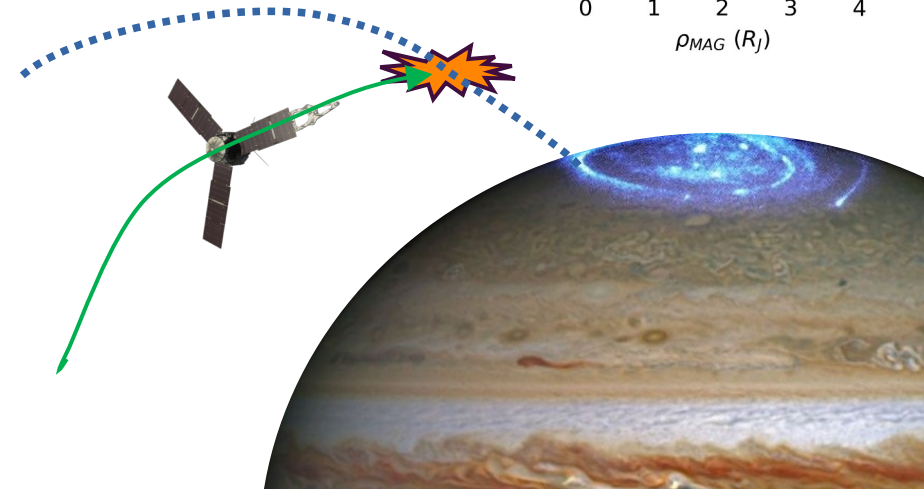
(Hosotani et al. 2003)



Chen et al.
(2002)

Juno mission

- Orbit Jupiter since 2016
- Designed to study auroral regions
- Equipped with radio (1 antenna), plasma and magnetic measurements



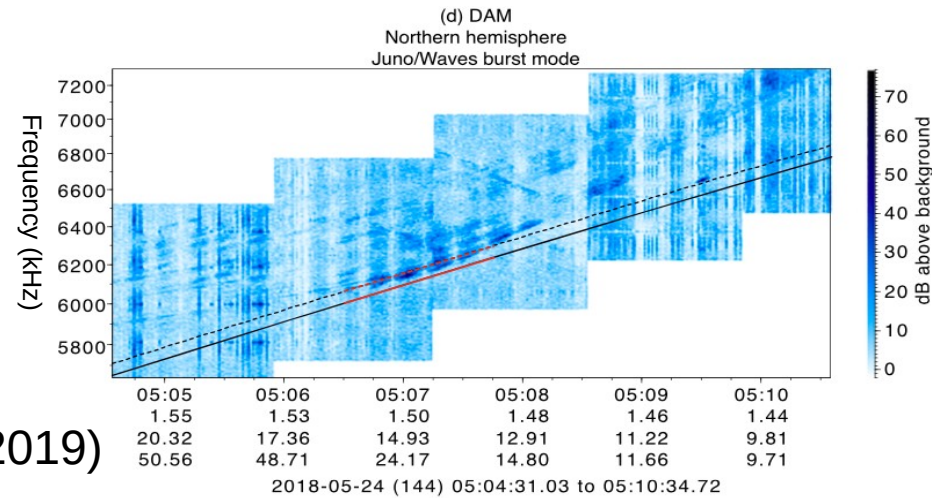
Methods:

Survey Jovian radio sources

- Harmonics probably weak emissions: need to be in **radio sources**
- Identified from radio measurements where $f < f_{ce} + 1\%$
- Survey 77 Juno orbits (2016-2025) for sources
- Identify harmonics close to 2 f_{ce} in these sources

Out of 77 orbits: we identified **124**
source crossings
(catalogue available on zenodo)

Louis et al (2019)



Methods:

Survey Jovian radio sources

High res radio not always available

4 sub receivers:

We need to have fce and 2fce on the same receiver

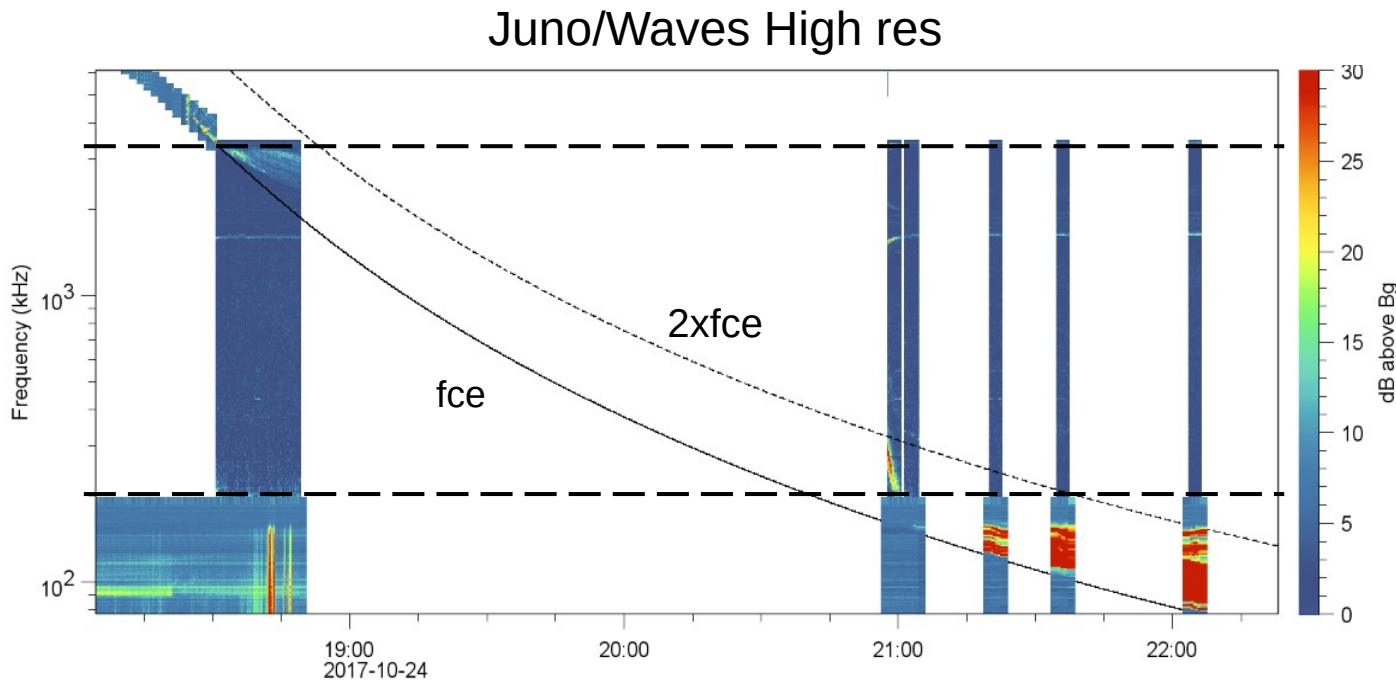
For $f_{ce} > 3\text{MHz}$ only 1 MHz band: no harmonic detection possible.

Frequency criteria:

$$10\text{ kHz} < f_{ce} < 75\text{ kHz}$$

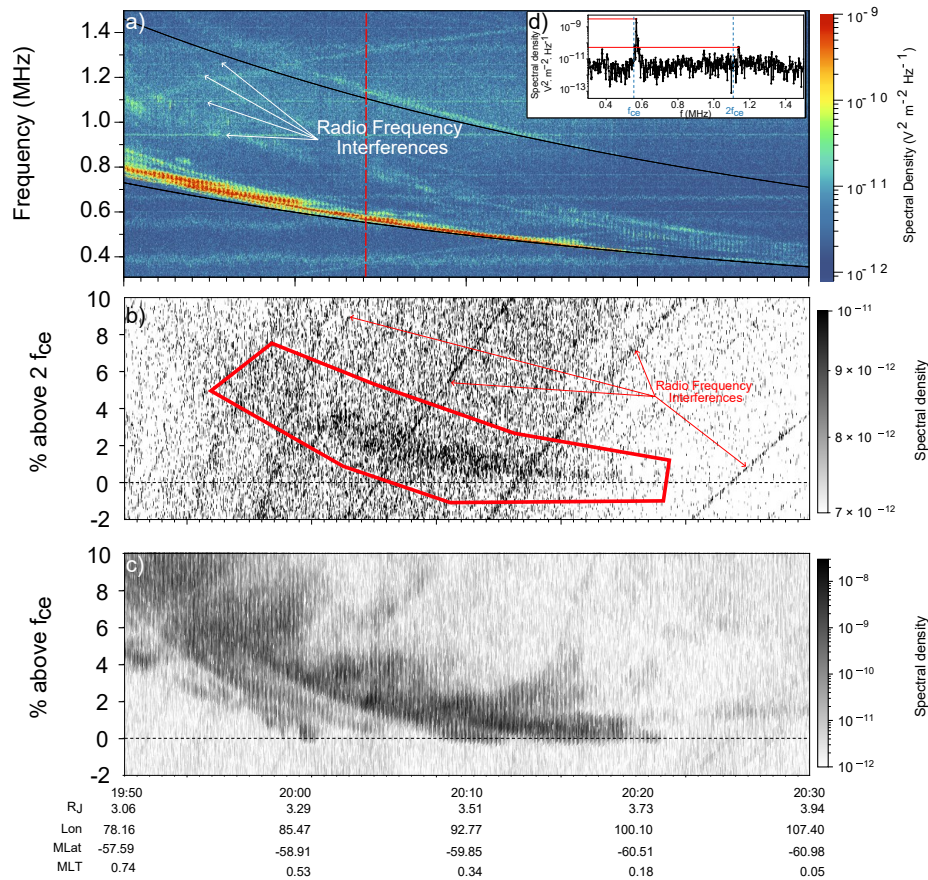
$$150\text{ kHz} < f_{ce} < 1500\text{ kHz}$$

i.e., only part of bKOM/HOM



Out of 124 source crossings,
42 validate these criteria

Results

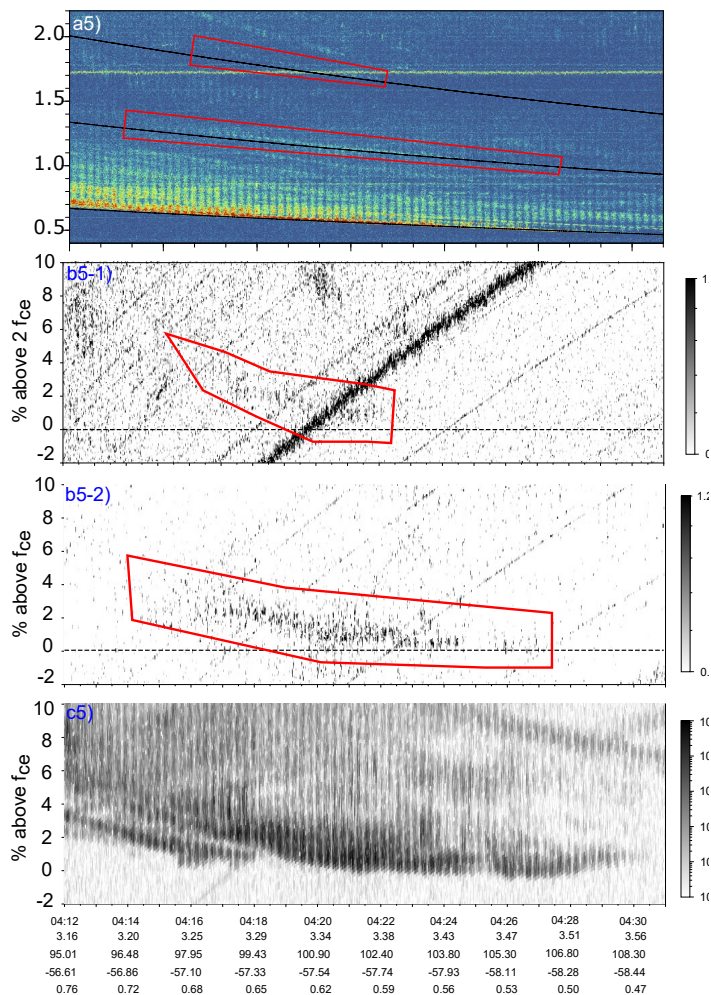


Out of these 42 source crossings,
We found **6 cases with ARH**:

- Fundamental from 200 to 700 kHz
- $f_{pe}/f_{ce} \sim 10^{-2}$
- Associated with e- monoenergetic signatures
- Intensity is 2 to 3 orders of magnitude lower (close to instrument noise)

PJ	Source crossing interval	f_F (kHz)	R (R_J)	M-SHELL (R_J)	Zone	f_{pe}/f_{ce}	I_{H1}/I_F ($\times 10^{-3}$)	I_F ($V^2 m^{-2} Hz^{-1}$)
PJ63S	2024-07-16 16:08 to 16:18	700	3.1	25	Diff. A.	10^{-2}	3	3×10^{-8}
PJ65S	2024-09-20 04:09 to 04:31	450-600	3.4	32	ZI/Diff. A.	10^{-2}	5	2×10^{-8}
PJ66S	2024-10-22 19:50 to 20:30	400-600	3.3.3-3.6	23	ZI/Diff. A.	10^{-2}	17	1×10^{-8}
PJ72S	2025-05-07 04:40:47 to 04:53:05	600	3.2	23	N/A	10^{-2}	4	2×10^{-8}
PJ73S	2025-06-08 22:20 to 23:30	300	3.6-4.2	50	N/A	$5 \cdot 10^{-2}$	2	2×10^{-8}
PJ77S	2025-10-17 19:06 to 19:15	200	4.7-5.0	20-40	ZI/Diff. A.	1.3×10^{-2}	2	1×10^{-8}

PJ65S



Results

Out of these 42 source crossings,
We found **6 cases with ARH**:

- Fundamental from 200 to 700 kHz
- $f_{pe}/f_{ce} \sim 10^{-2}$
- Associated with e- monoenergetic signatures
- Intensity is 2 to 3 orders of magnitude lower (close to instrument noise)
- 2 cases with 2nd harmonics

PJ	Source crossing interval	f_F (kHz)	R (R_J)	M-SHELL (R_J)	Zone	f_{pe}/f_{ce}	I_{H1}/I_F ($\times 10^{-3}$)	I_F ($V^2 m^{-2} Hz^{-1}$)
PJ63S	2024-07-16 16:08 to 16:18	700	3.1	25	Diff. A.	10^{-2}	3	3×10^{-8}
PJ65S	2024-09-20 04:09 to 04:31	450-600	3.4	32	ZI/Diff. A.	10^{-2}	5	2×10^{-8}
PJ66S	2024-10-22 19:50 to 20:30	400-600	3.3-3.6	23	ZI/Diff. A.	10^{-2}	17	1×10^{-8}
PJ72S	2025-05-07 04:40:47 to 04:53:05	600	3.2	23	N/A	10^{-2}	4	2×10^{-8}
PJ73S	2025-06-08 22:20 to 23:30	300	3.6-4.2	50	N/A	$5 \cdot 10^{-2}$	2	2×10^{-8}
PJ77S	2025-10-17 19:06 to 19:15	200	4.7-5.0	20-40	ZI/Diff. A.	$1-3 \times 10^{-2}$	2	1×10^{-8}

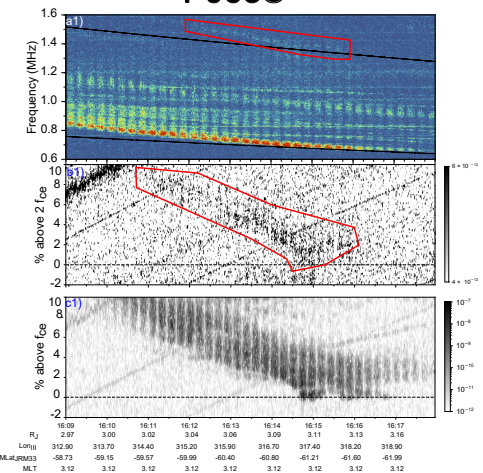
Open questions

- Source identified at relatively high **fpe/fce**: necessary condition?
- Different modes? Beaming angle? Than fundamental ?
- Jovian harmonics: **very rare or too weak?**
- **Generation mechanism** still unknown but direct CMI seems unlikely
- At Saturn ARH were observed 30-40 dB weaker than fundamental: comparable to our result
- What about **DAM** (up to 40 MHz)?
 - If harmonics: up to 80 MHz (1st harmonic) or up to 120 MHz (2nd)
 - But fpe/fce even lower

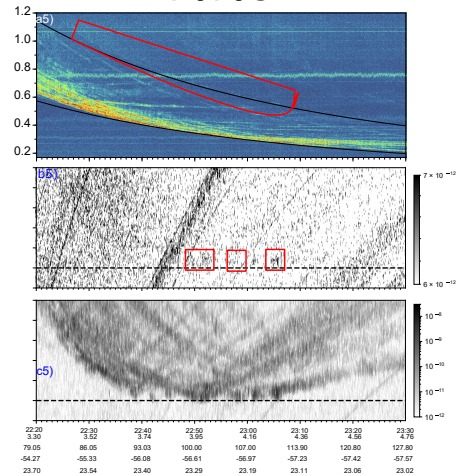
Conclusion

- Harmonic identified on only 6 bKOM/HOM cases out of 77 orbits
- Confirms previous detection with Voyager
- Confirms universality of Auroral Radio Harmonics
- Generation mechanism remains to be studied
- Opens possibility of Jovian Auroral Radio Emissions up to 120 MHz (frequency range of SKA)

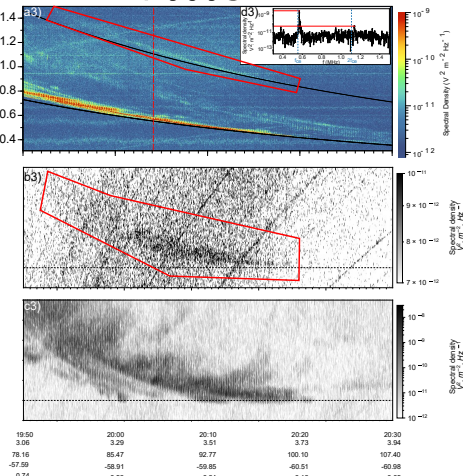
PJ63S



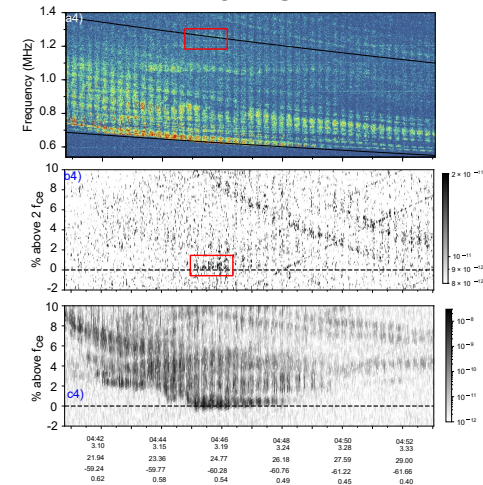
PJ73S



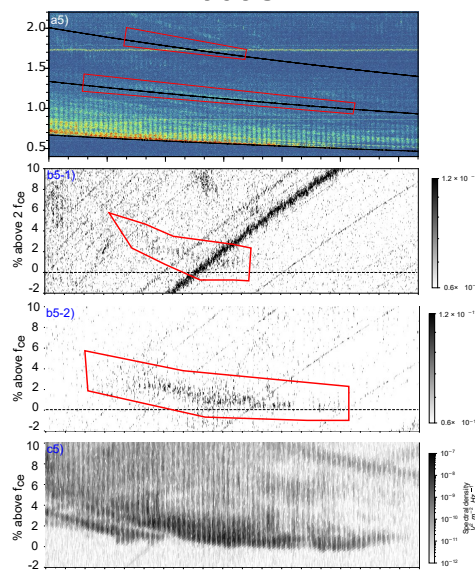
PJ66S



PJ72S



PJ65S



PJ77S

