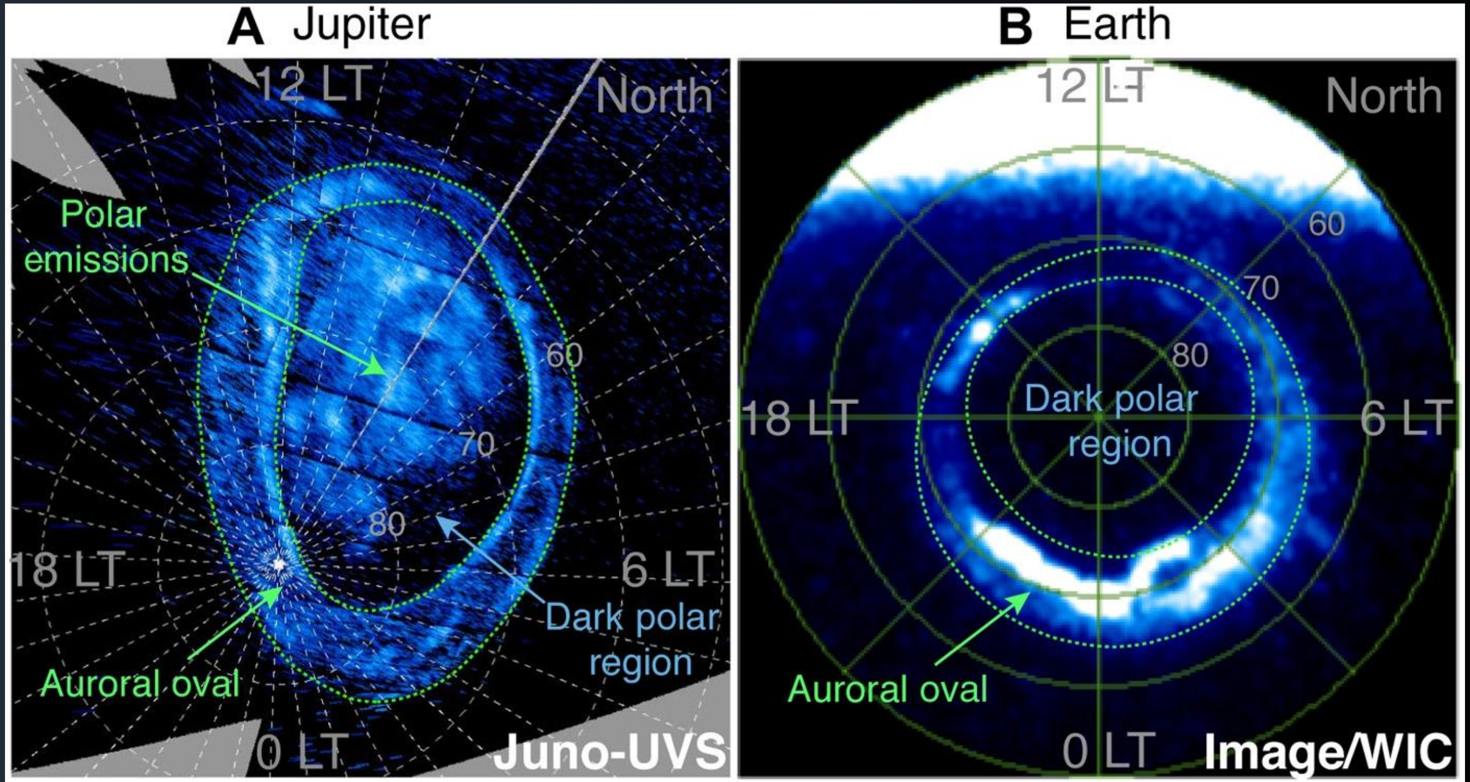
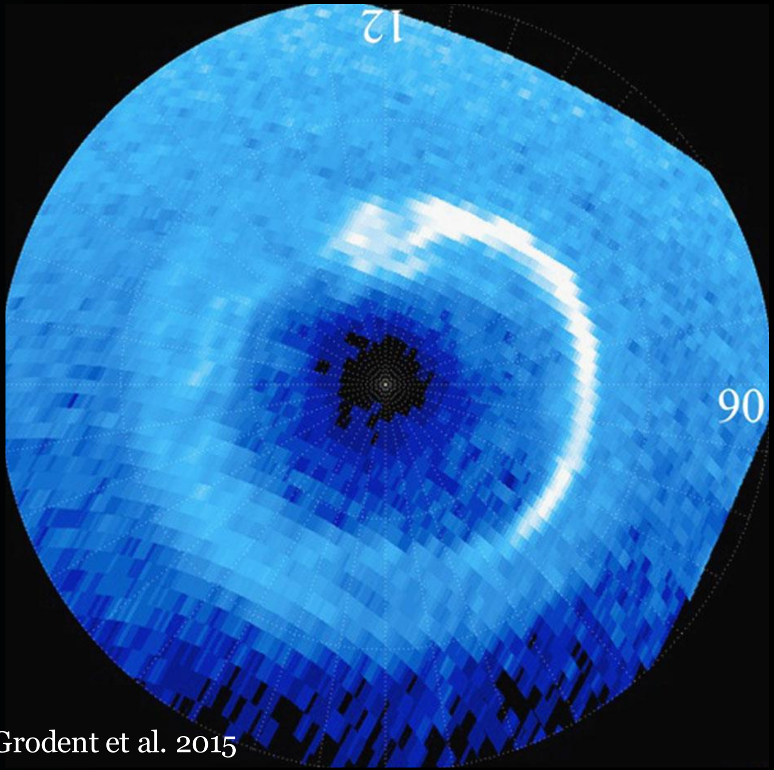
Investigating Jupiter's powerful auroras with NASA's Juno mission



Saturn



Grodent et al. 2015

George Clark
Johns Hopkins Applied Physics Lab

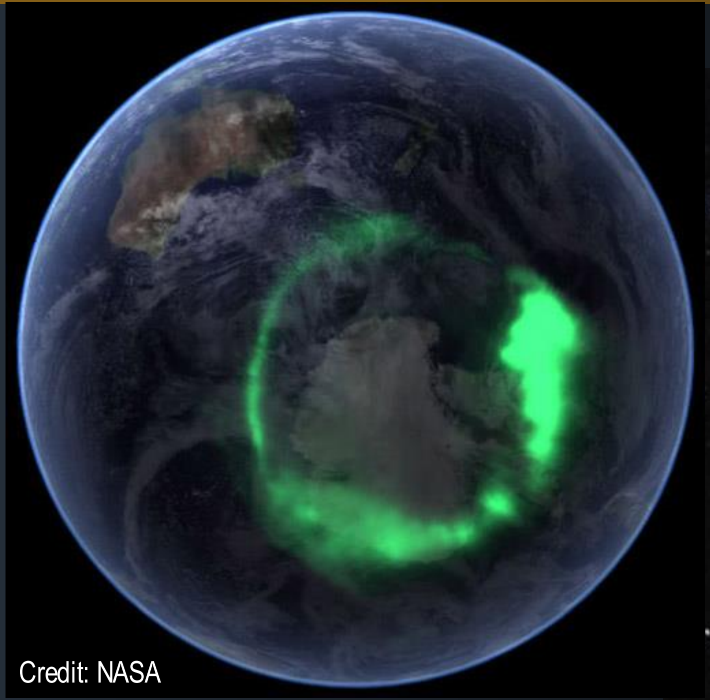
MIPSE Seminar| February 2025 | Ann Arbor, MI

Outline

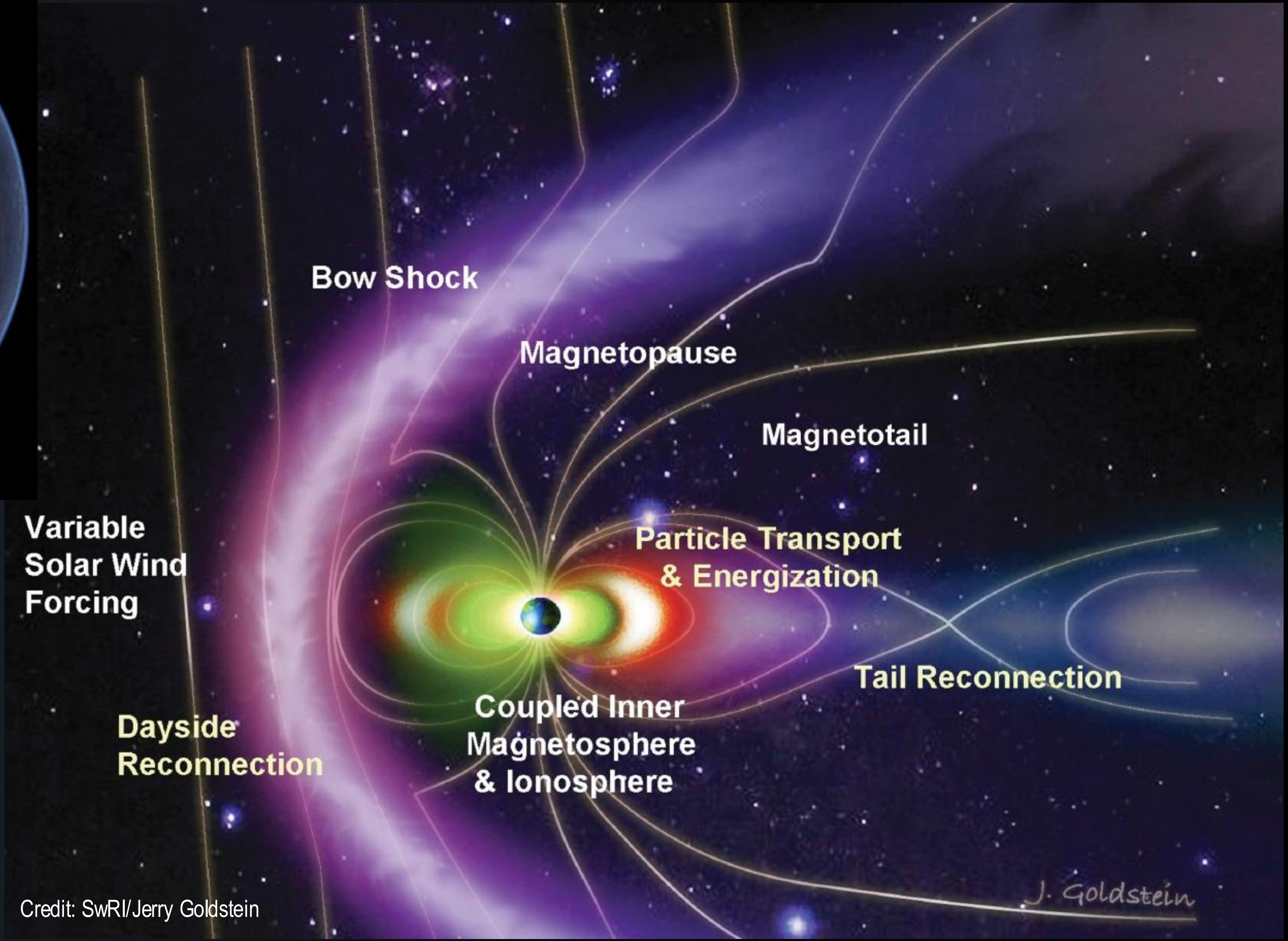
- Brief overview of auroras & Jupiter’s space environment
- NASA’s Juno mission
- Brief overview of Jupiter’s main auroral region
- Jupiter’s polar cap auroras: major discoveries and new mysteries
- Future of Jupiter exploration (if time permits)

Credit: Geraint Jones | Selfoss, Iceland | Outer Planet Moon-Magnetospheres Conference

Earth’s magnetosphere and auroras



- Particle transport and energization generates bright, discrete auroras
- Scattering of quasi-trapped particles via plasma waves generates diffuse, featureless, auroras

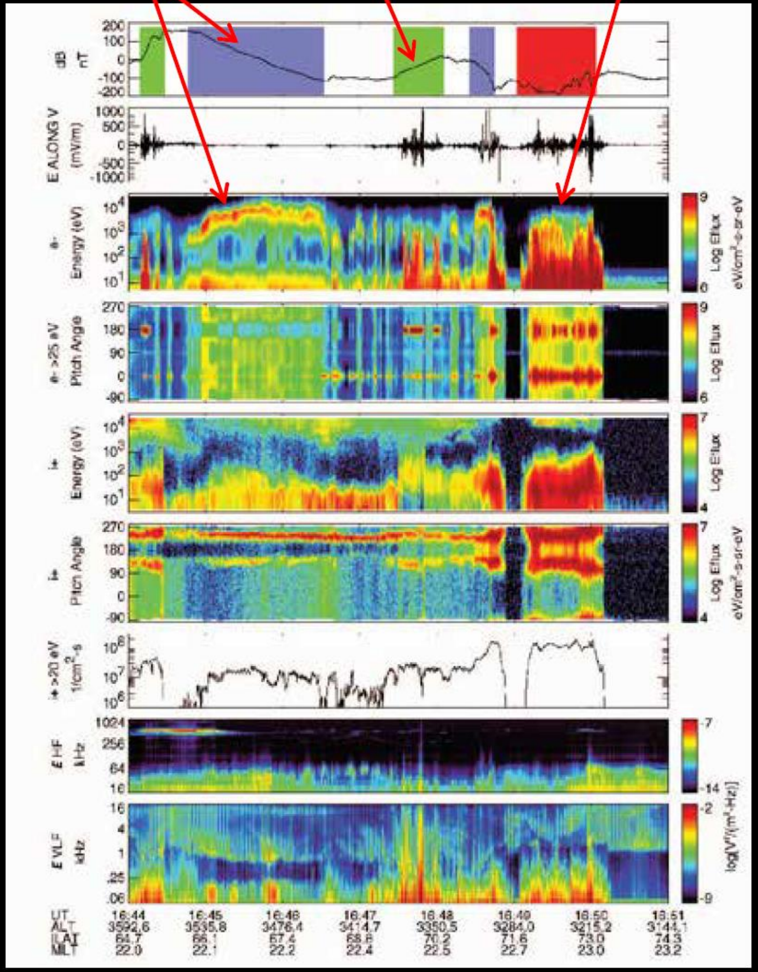


Space physicists' view of Earth's auroras

1. Upward current Peaked potential -driven aurora

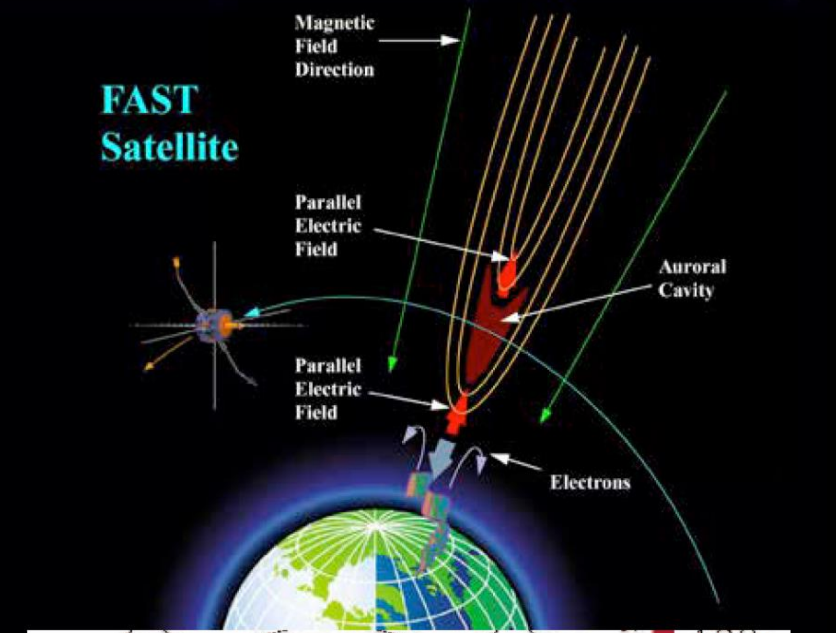
2. Downward current. "Black aurora"

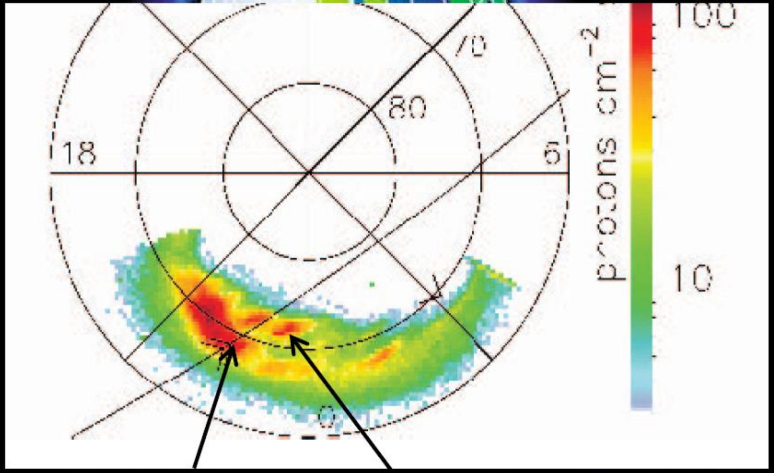
3. Broadband acceleration (Alfvénic)



Paschmann et al. ISSI book, 2002; Amm et al., 2002, SSR after Carlson et al. 1998, etc

Expectations from Earth

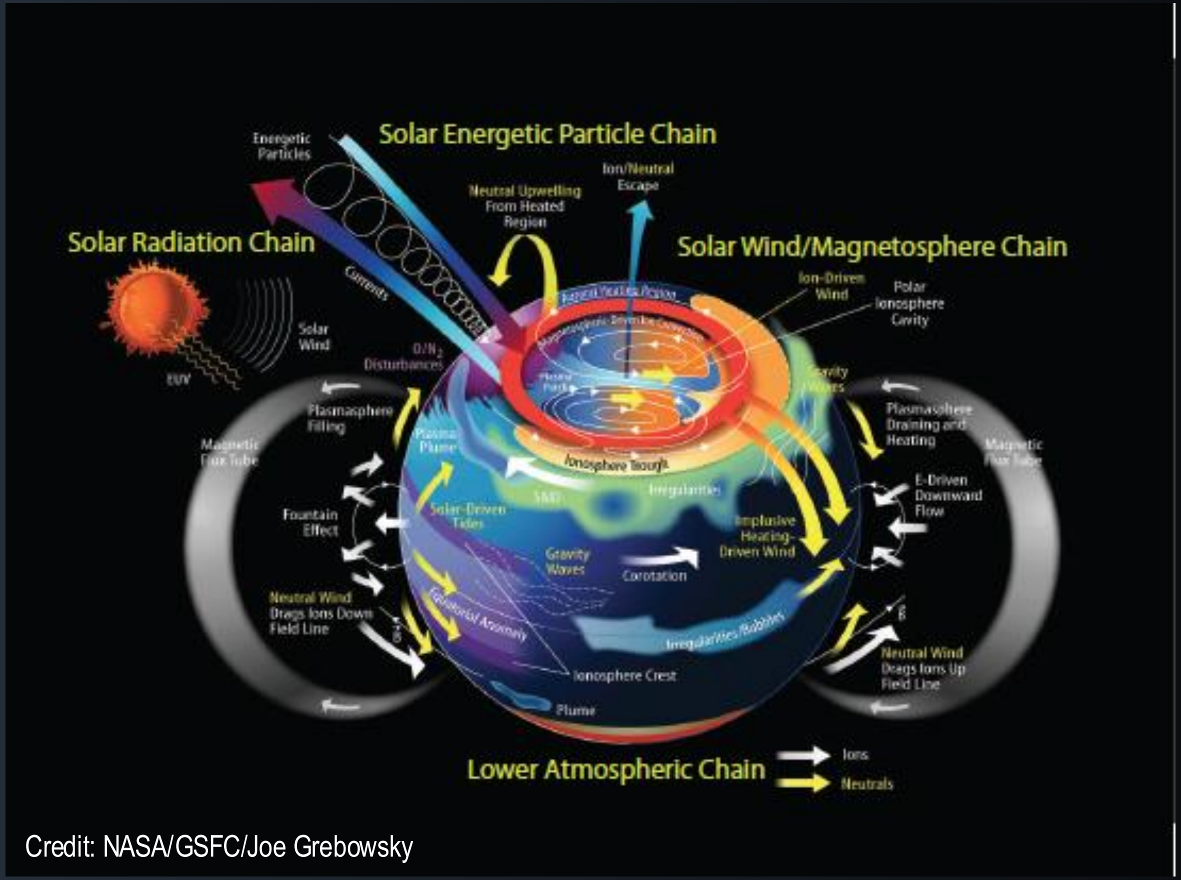




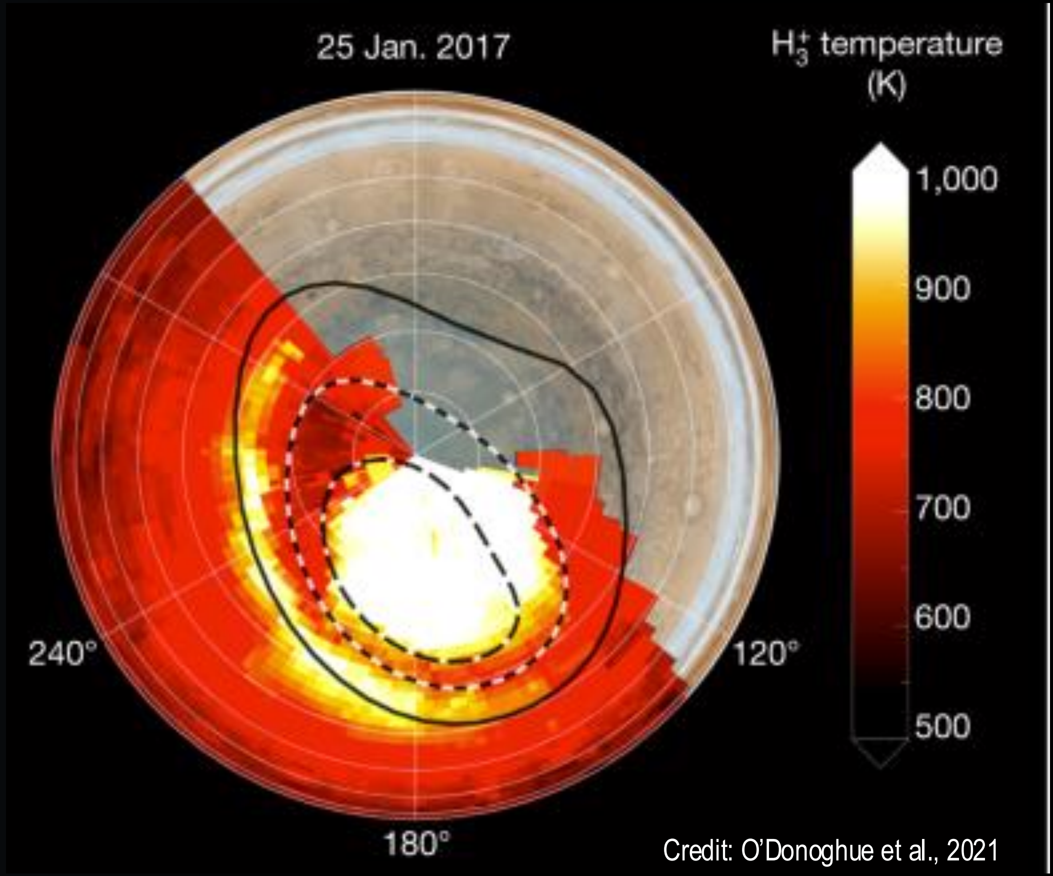
Potential-driven aurora

Broadband Alfvénic

Why study auroras?



Credit: NASA/GSFC/Joe Grebowsky



Credit: O'Donoghue et al., 2021

- Not only do auroras provide context in understanding magnetospheric processes, but they also are key in understanding the coupling between a planets atmosphere, ionosphere, and magnetosphere (left panel)

- Particle precipitation is a dominate heating mechanism for Jupiter's upper atmosphere (right panel)

Auroras are not unique to Earth

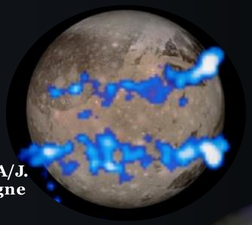
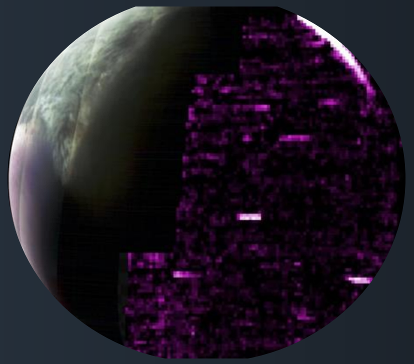
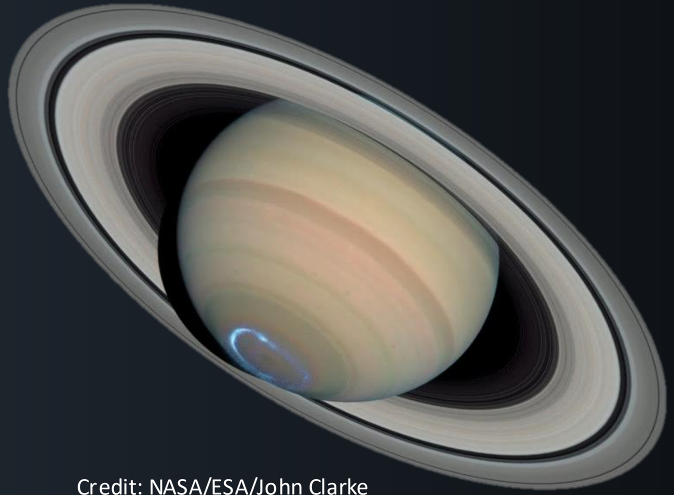


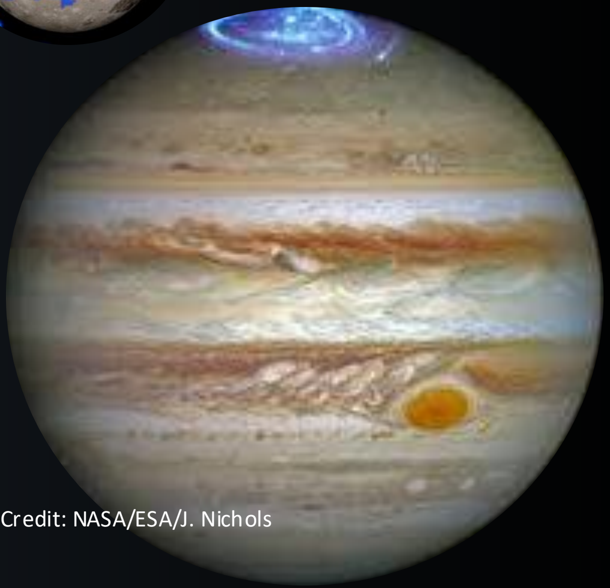
Image Credit: NASA/ESA/J. Saur/University of Cologne



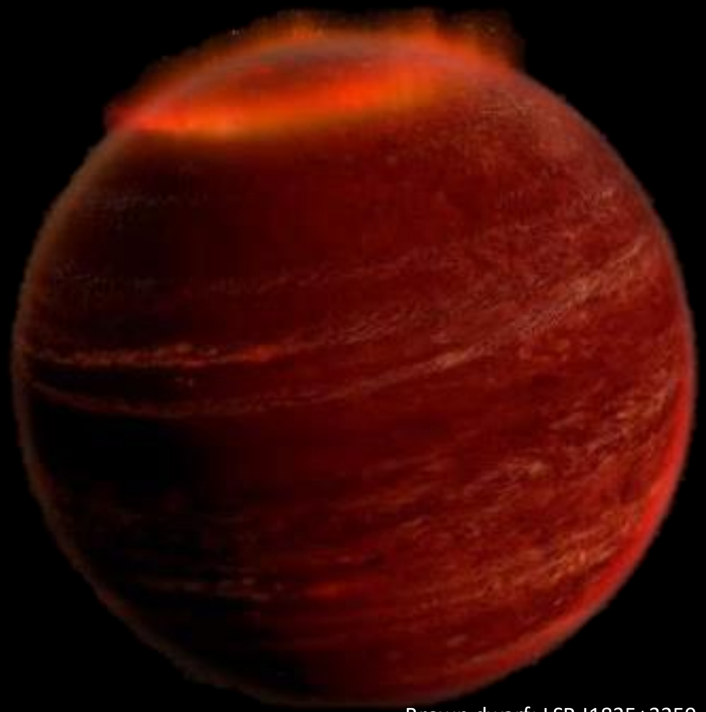
Credit: NASA/GSFC/CU



Credit: NASA/ESA/John Clarke



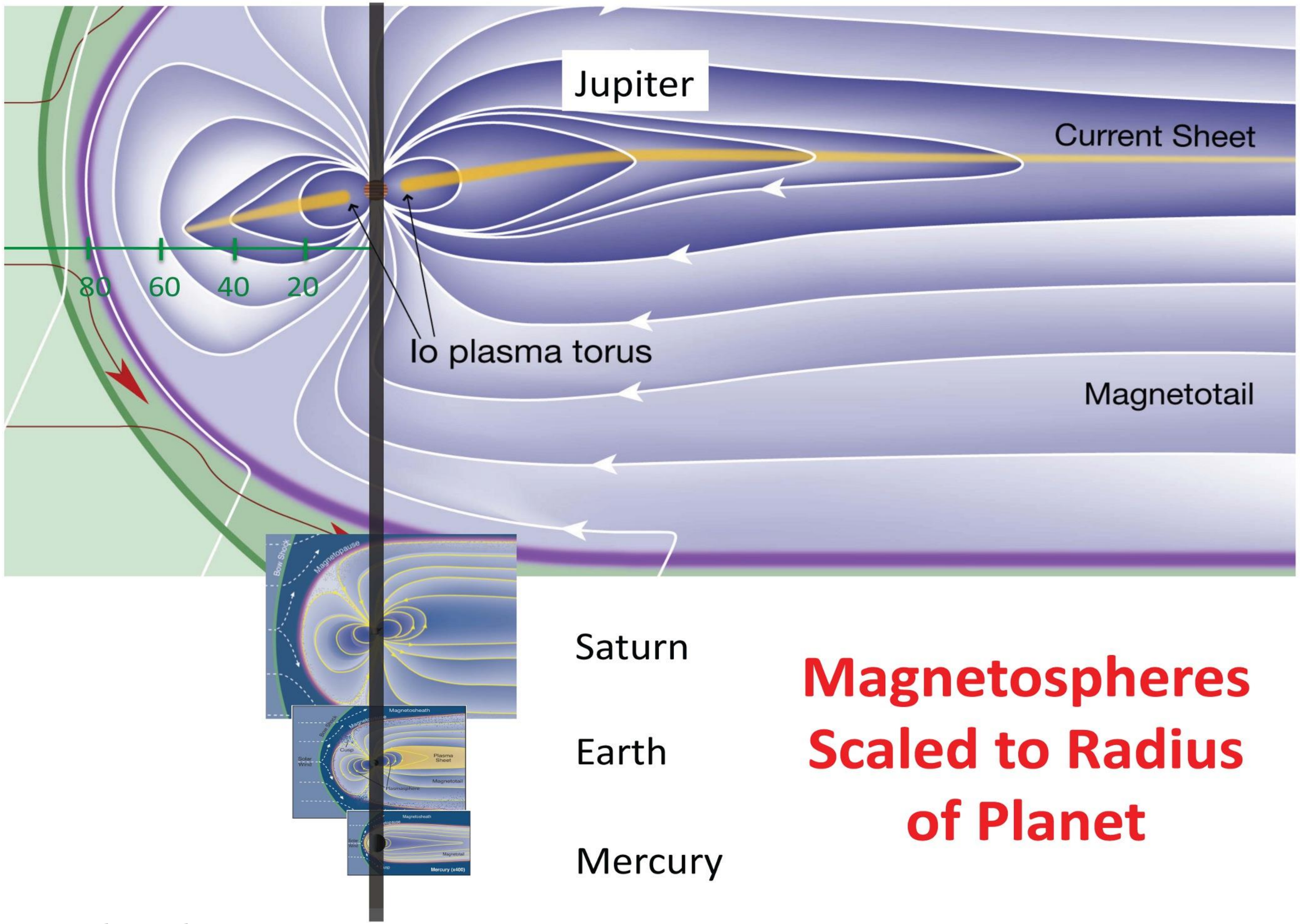
Credit: NASA/ESA/J. Nichols



Brown dwarf: LSR J1835+3259
Credit: Caltech/NASA/JPL

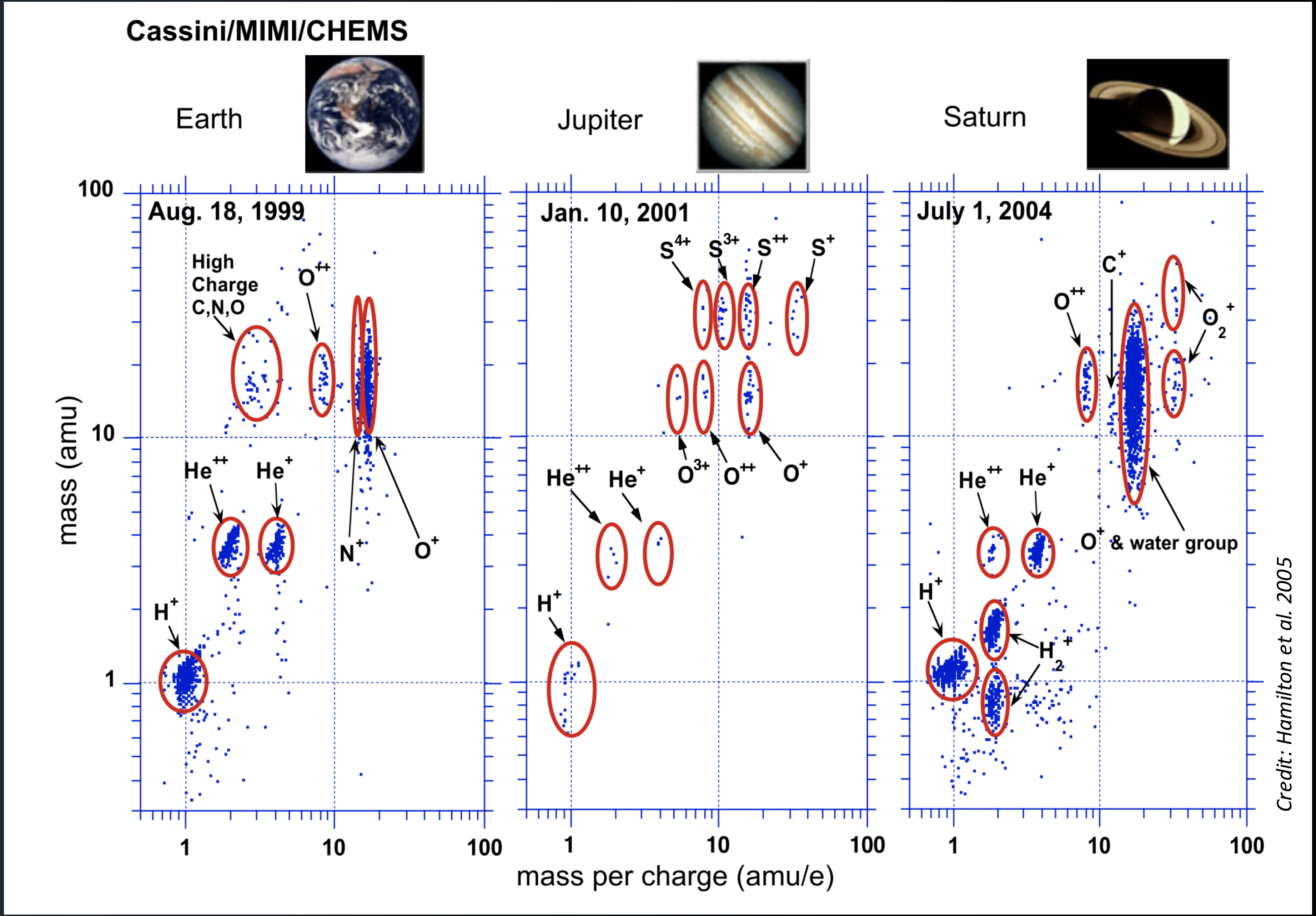
- Auroras occur elsewhere in the Solar System and cosmos
    - Magnetic field
    - Plasma
    - Atmosphere

Jupiter’s vast space environment



Credit: Bagenal & Bartlett

Jupiter is comprised of a multi-species and charge state plasma



Jupiter's inner magnetosphere: Galilean moons, corotating plasma, intense rad. belt

- Io (dominate source) and Europa supply plasma to Jupiter's magnetosphere

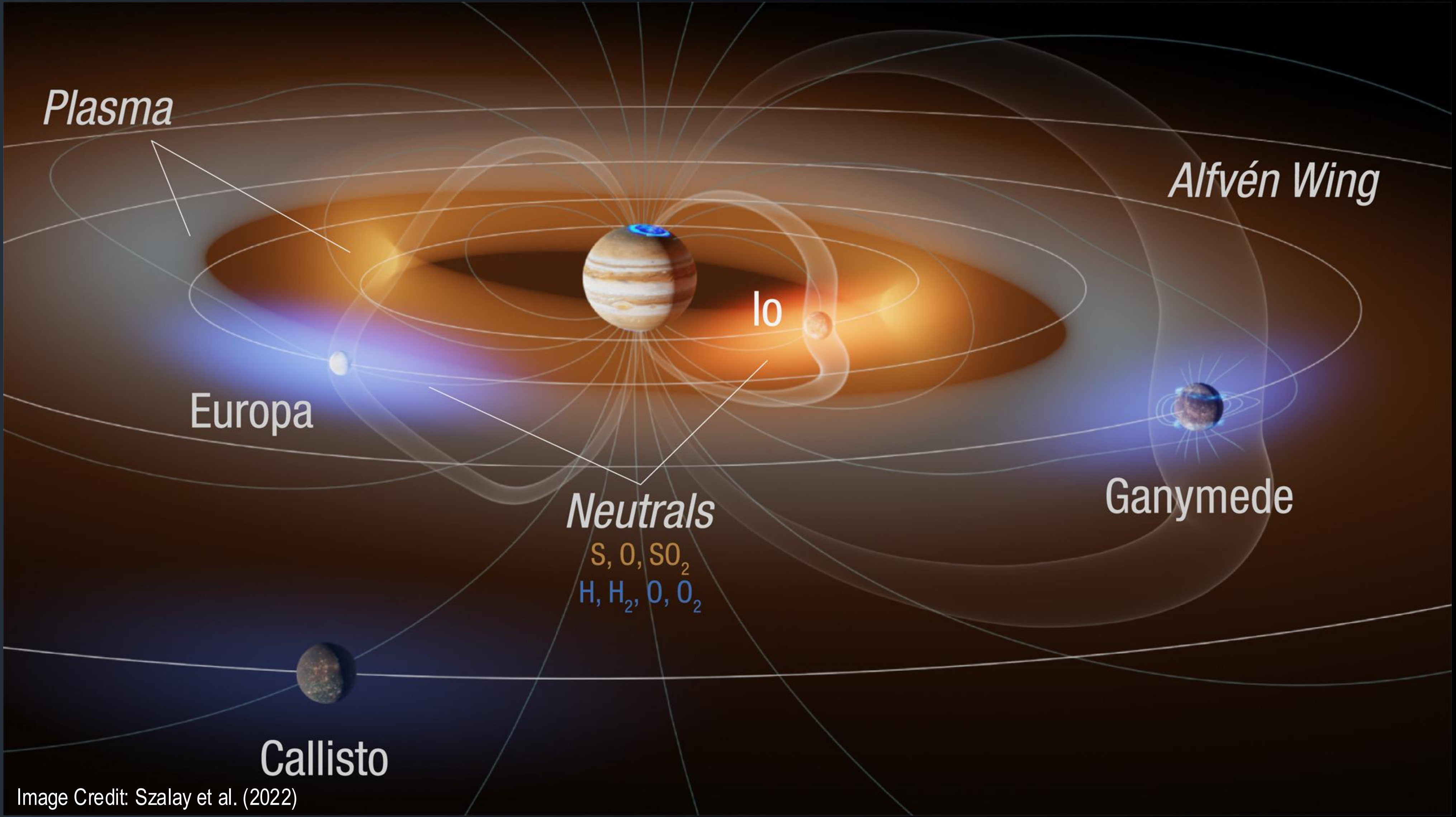


Image Credit: Szalay et al. (2022)

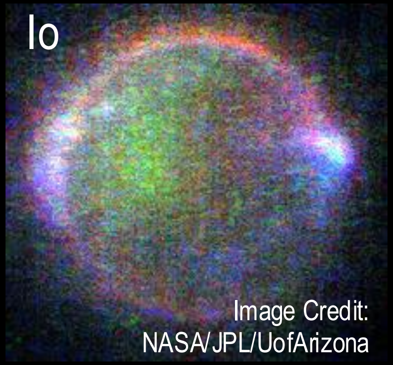


Image Credit: NASA/JPL/UofArizona

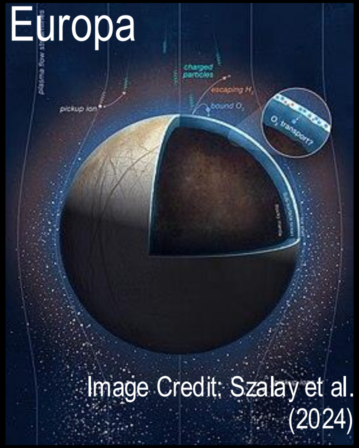


Image Credit: Szalay et al. (2024)

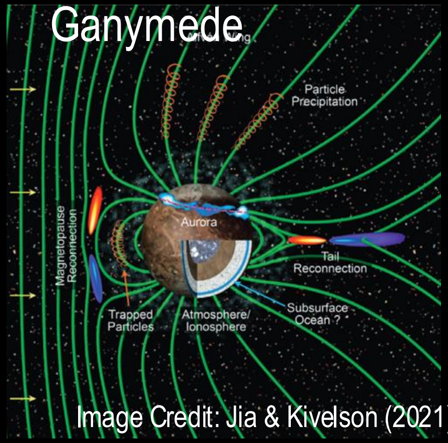
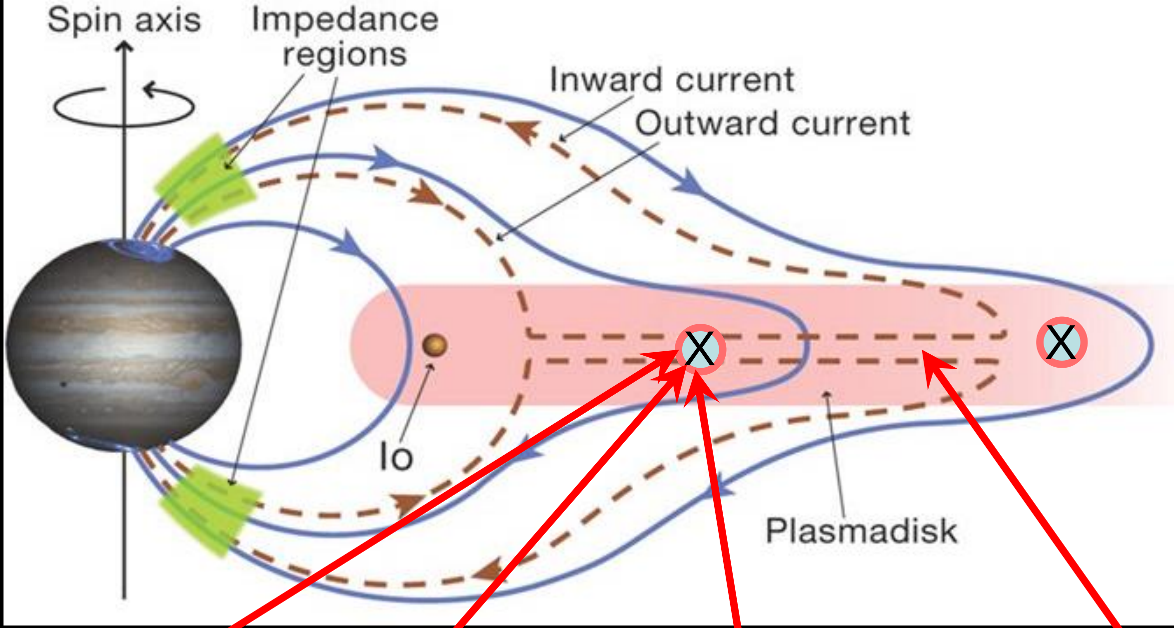


Image Credit: Jia & Kivelson (2021)

Current sources in SW vs rotationally driven systems

$$J_{\perp} = \frac{b}{B} x \nabla_{\perp}(P_{\perp}) + (P_{\parallel} - P_{\perp})\frac{b\ x\ (b \cdot \nabla) b}{B} + (m \cdot n)\frac{b}{B} x \frac{dV}{dt}$$



Pressure Gradient

Pressure Anisotropy

Centrifugal

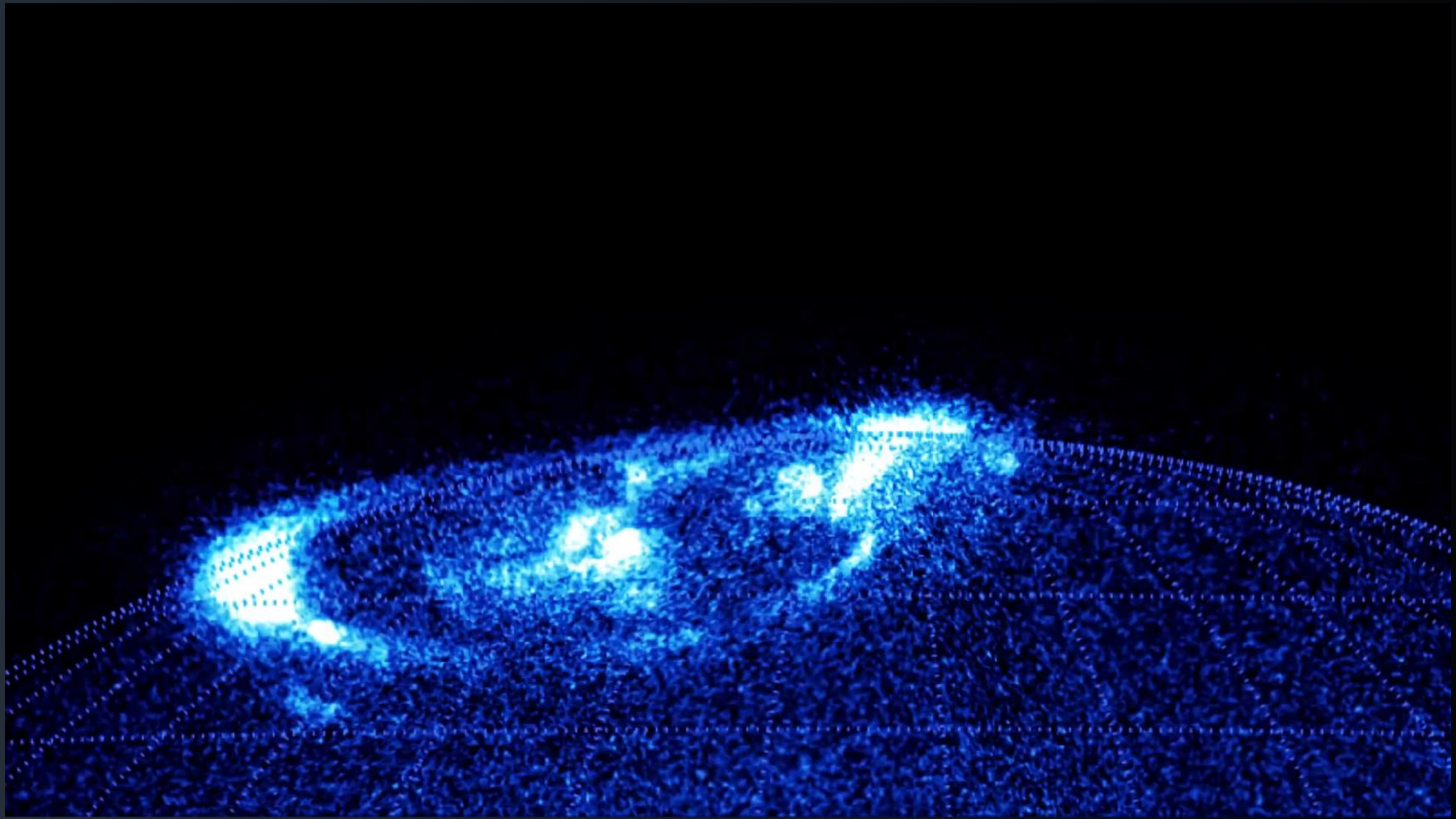
Coriolis driven

$$J_{\perp} = \frac{b}{B} x \nabla_{\perp}(P_{\perp}) + (P_{\parallel} - P_{\perp})\frac{b x (b \cdot \nabla) b}{B} + (m \cdot n)\frac{b}{B} x\left(\Omega_{pl} x\left(\Omega_{pl} x R\right)\right) + (m \cdot n)\frac{b}{B} x\left(2 \cdot \Omega_{pl} x U_{rad}\right)$$

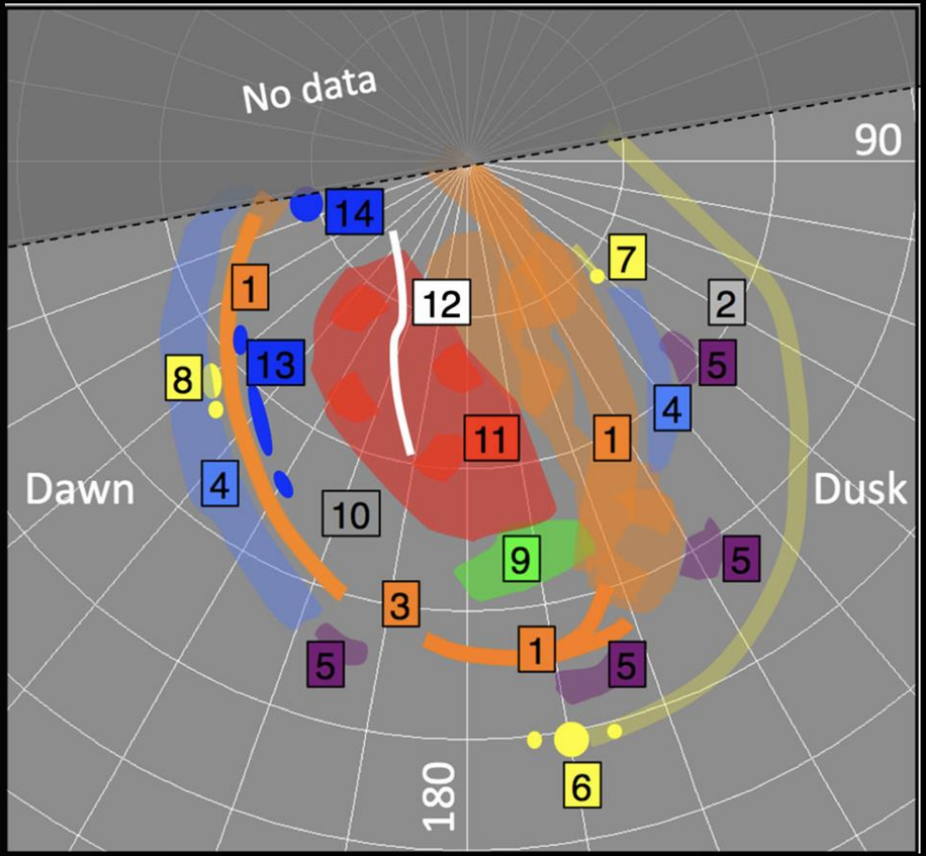
Credit: Barry Mauk

Jupiter’s complex auroral regions

- Hubble images made it possible to detail the morphology of Jupiter’s auroras (e.g., Clarke+ 2004); however, emissions were first observed with sounding rockets (Moos+ 1968) and Voyager UVS instruments (Broadfoot+ 1979) but had limited spatial resolution



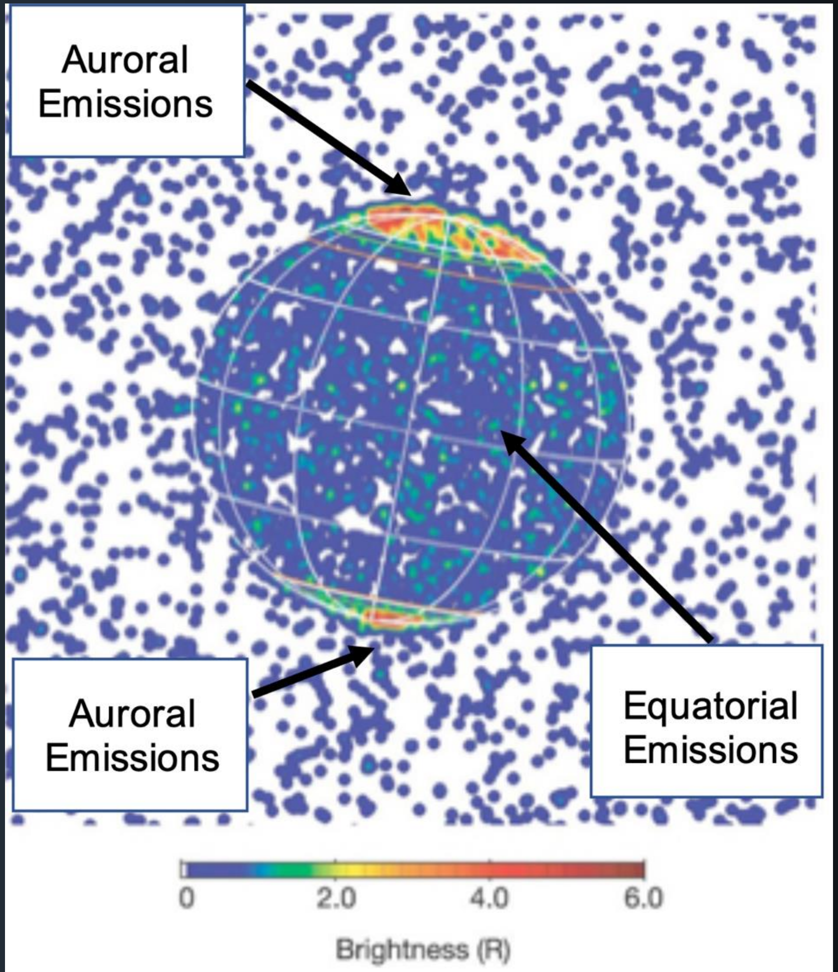
Credit: NASA/ESA/J. Nichols



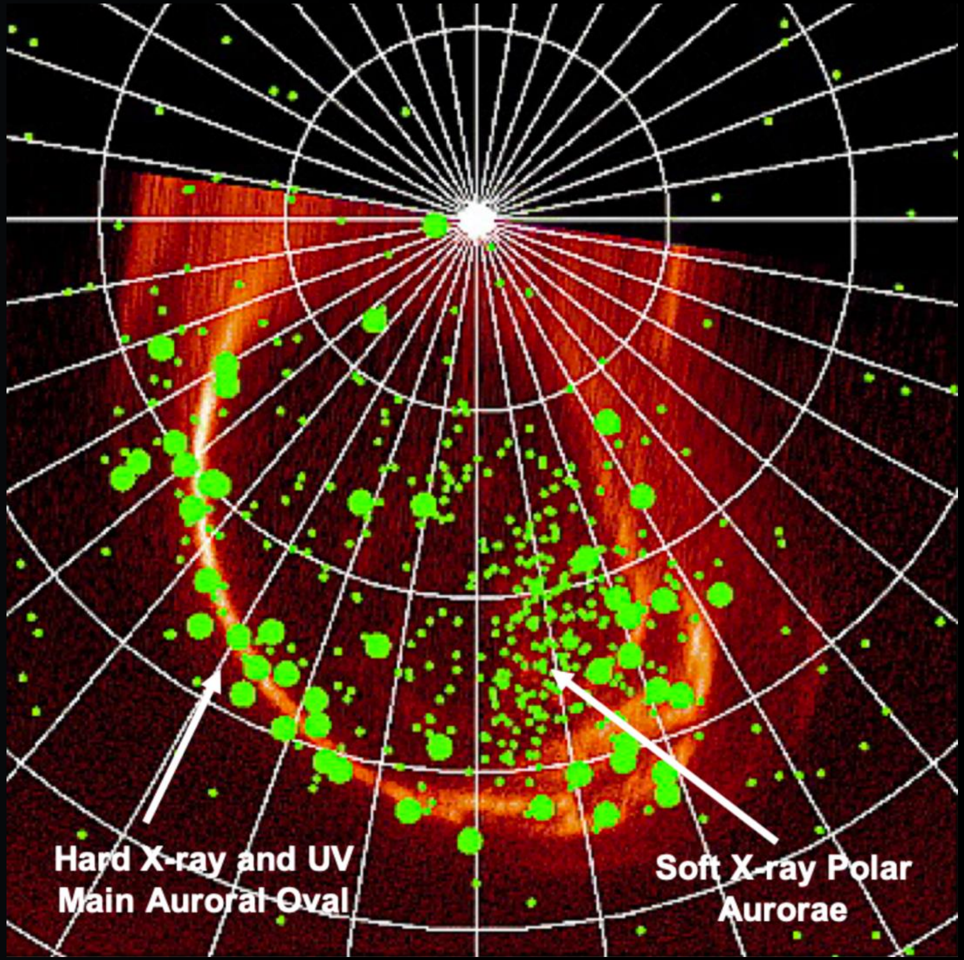
Grodent et al. (2015)

X-ray emissions in Jupiter's polar cap

- Soft (< 2 keV) and hard X-rays (> 2 keV) carried by precipitating energetic ions and electrons (e.g., Dunn+ 2022)



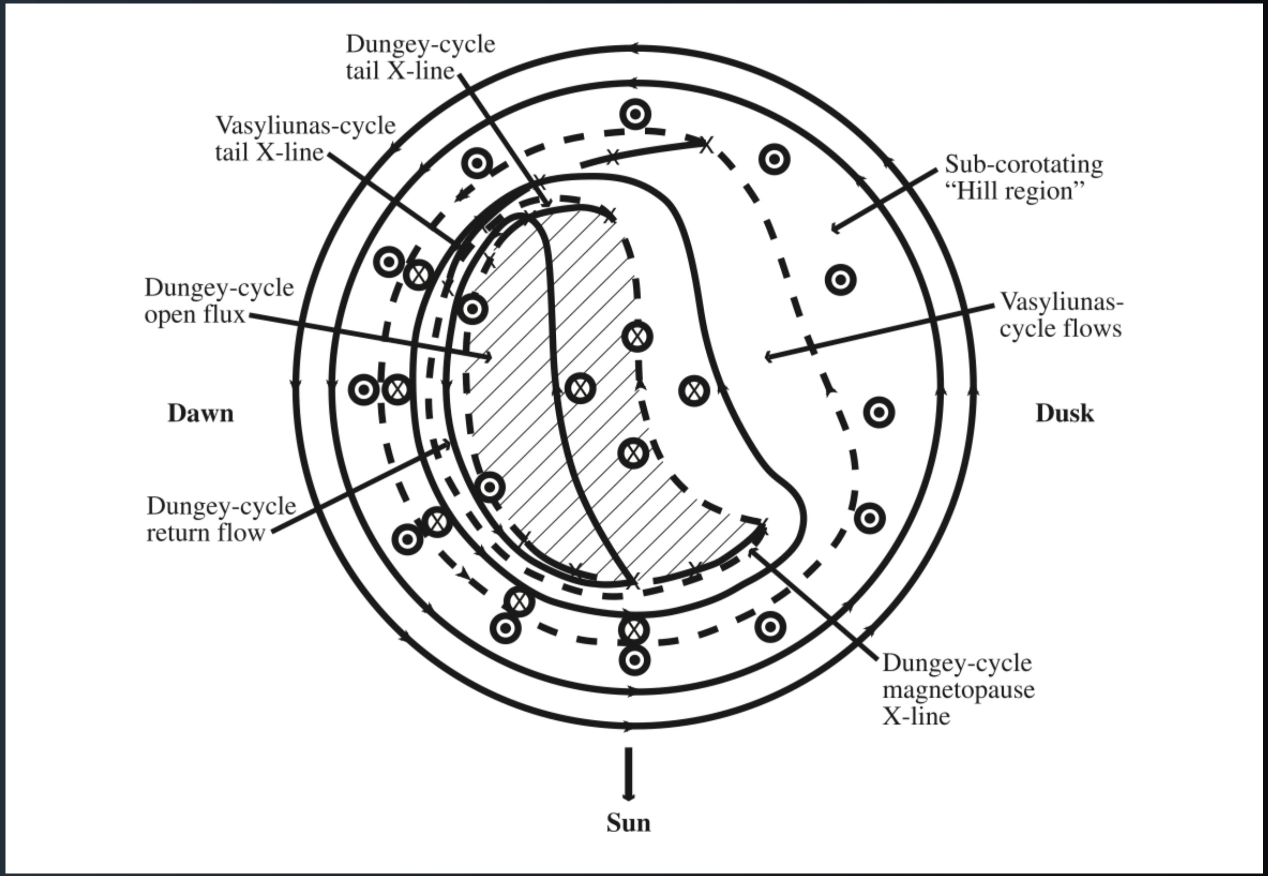
Gladstone et al. (2002)



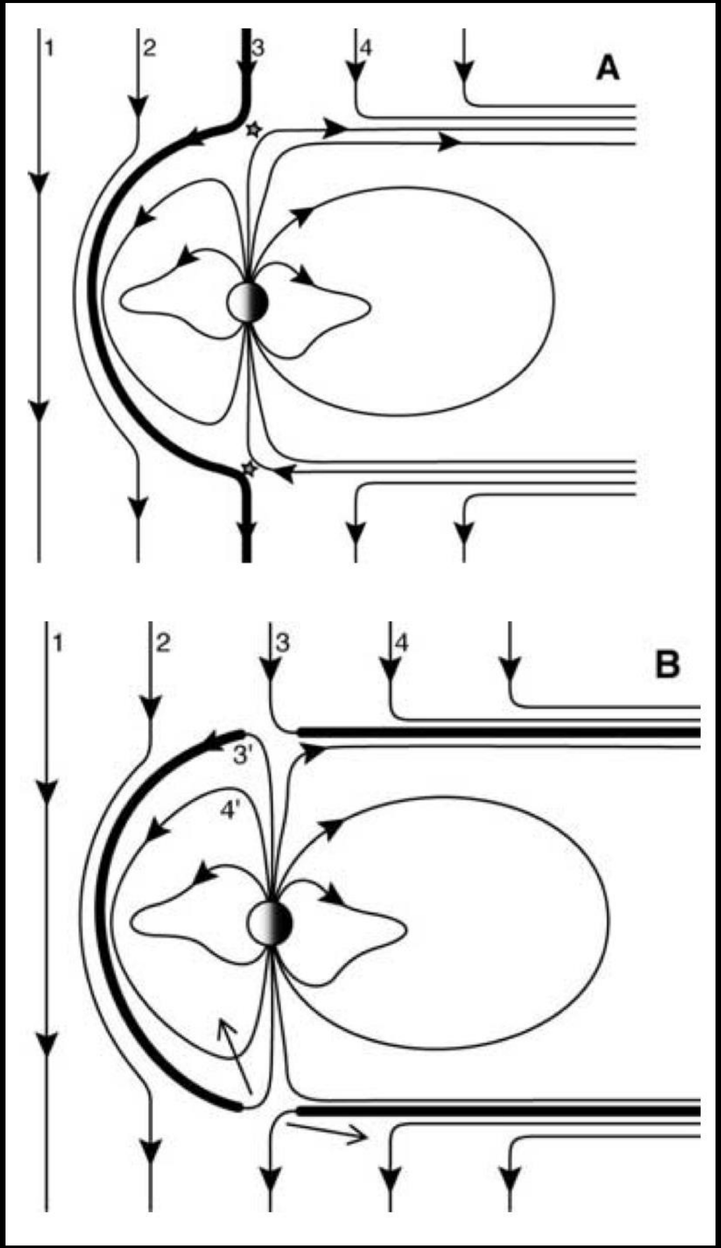
Branduardi-Raymont et al. (2008)

Where do the polar cap aurora map to in the magnetosphere?

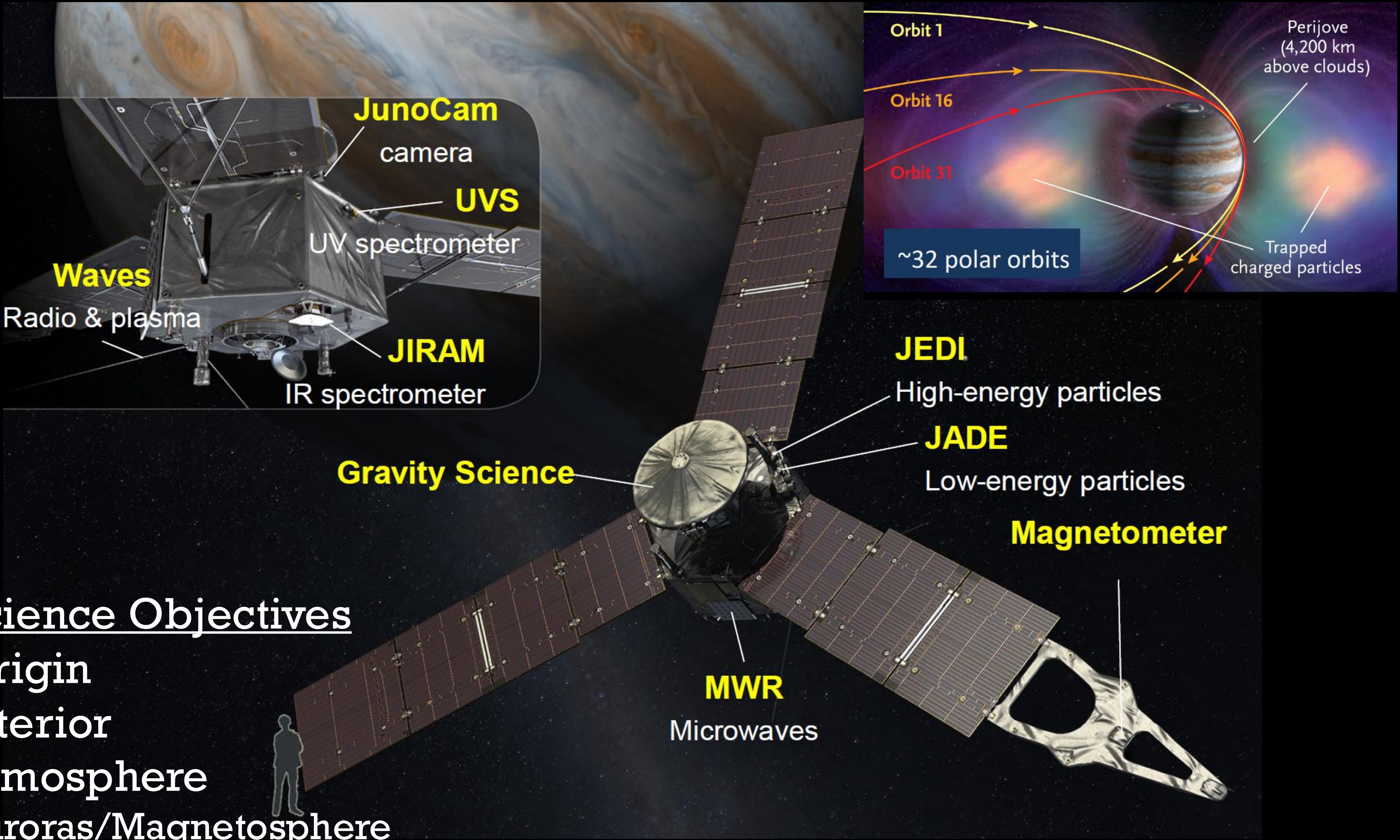
- Motivated by IR observations, Cowley et al. (2003) proposed the ionospheric flow map shown below
- Improved magnetic field mapping by Vogt+ (2011) suggested these regions were likely connected to open magnetic flux, i.e., polar cap, cusp, lobes, etc.
- Opening of magnetic flux via the IMF can close along the magnetopause (i.e., no need for a Dungey cycle)



Cowley et al. (2001)



McComas & Bagenal (2007)



Science Objectives

Origin

Interior

Atmosphere

Auroras/Magnetosphere

NASA Juno's extended mission trajectory

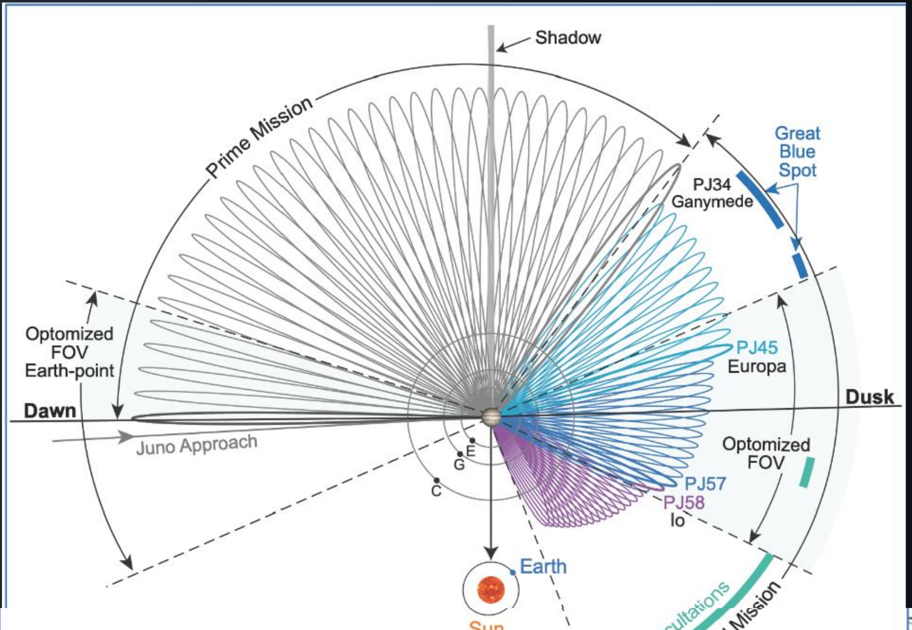
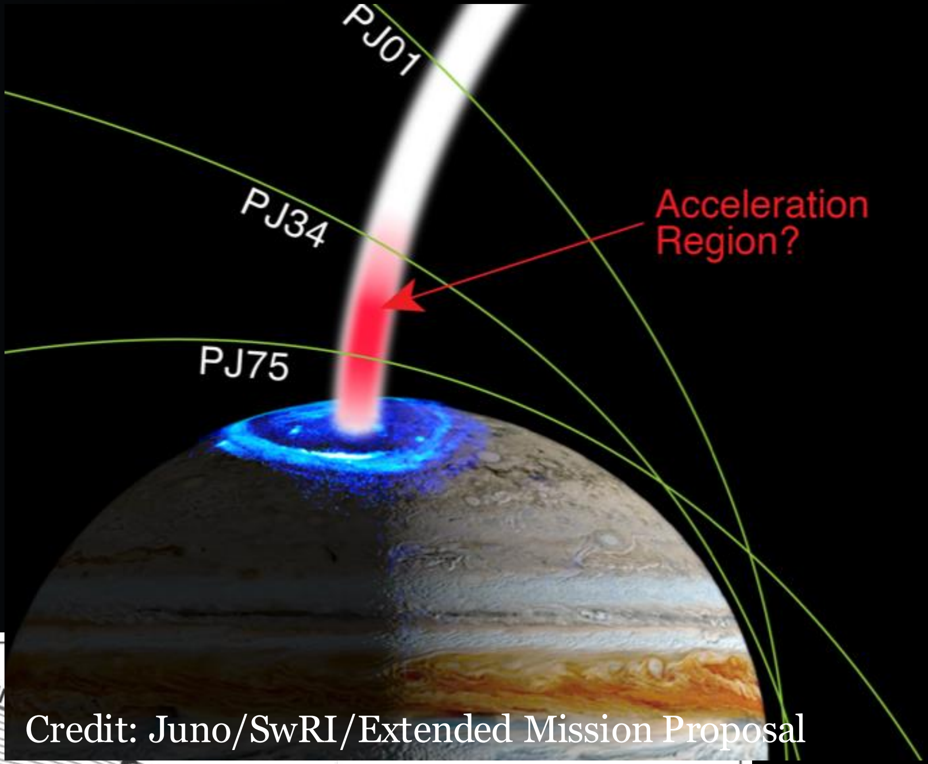
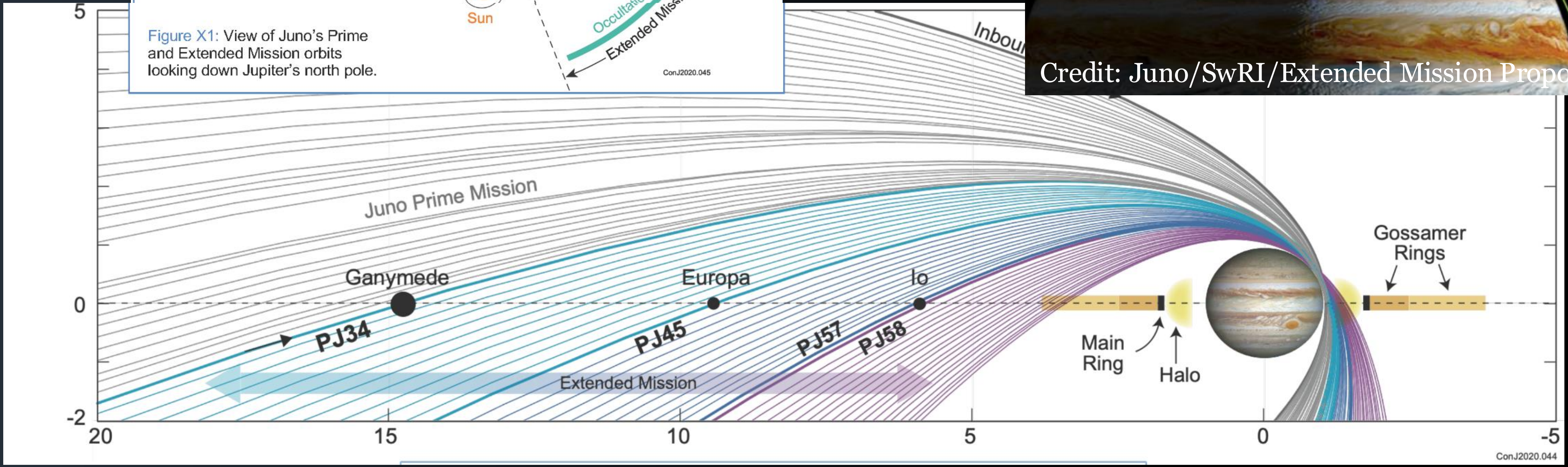


Figure X1: View of Juno's Prime and Extended Mission orbits looking down Jupiter's north pole.



Credit: Juno/SwRI/Extended Mission Proposal



Overview of Jupiter's Main Auroral Region

- The various auroral zones of Jupiter were first explicitly defined from energetic electron spectra (Mauk et al., 2020)
  - Diffuse aurora:
    - Most equatorward and broadest in latitude
    - Electron intensities greater outside the loss cone (trapped) than inside the loss cone
    - Electron intensities within the loss cone are predominantly downward (precipitating)
  - Zone-I
    - Intermediate and narrow in latitude
    - Brightest in UV
    - Electron intensities greatest in the downward loss cone
  - Zone-II
    - Poleward and narrow in latitude
    - [illegible] Saturn)
    - Electron intensities comparable in both upward and downward loss cones

General Plasma Properties (low altitude)

$|B| \sim O(10^5)$ nT

$n_e \sim O(10^{-3} – 10^{-2})$ cm^{-3}

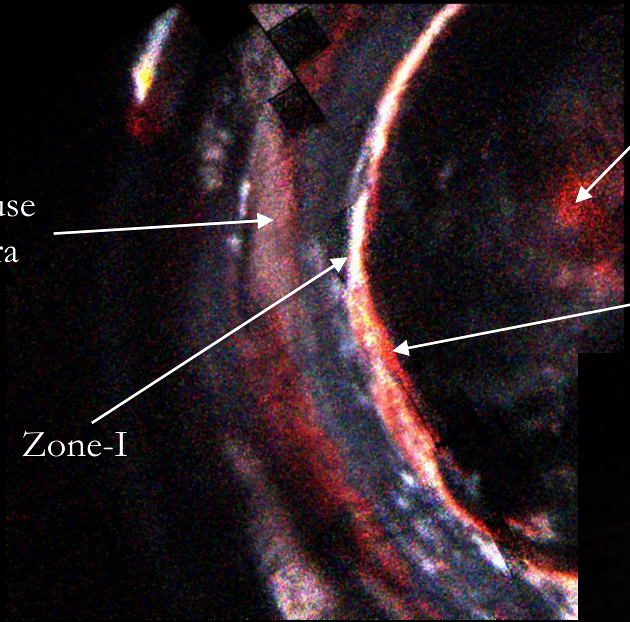
$T_e \sim O(10^3 – 10^4)$ eV

$f_{ce} \sim O(10^6)$ Hz and $f_{ci} \sim O(10^3)$ Hz

$f_{pe} \sim O(10^3 – 10^4)$ Hz

$\lambda_e \sim O(1 – 10)$ km

v_A [illegible] c

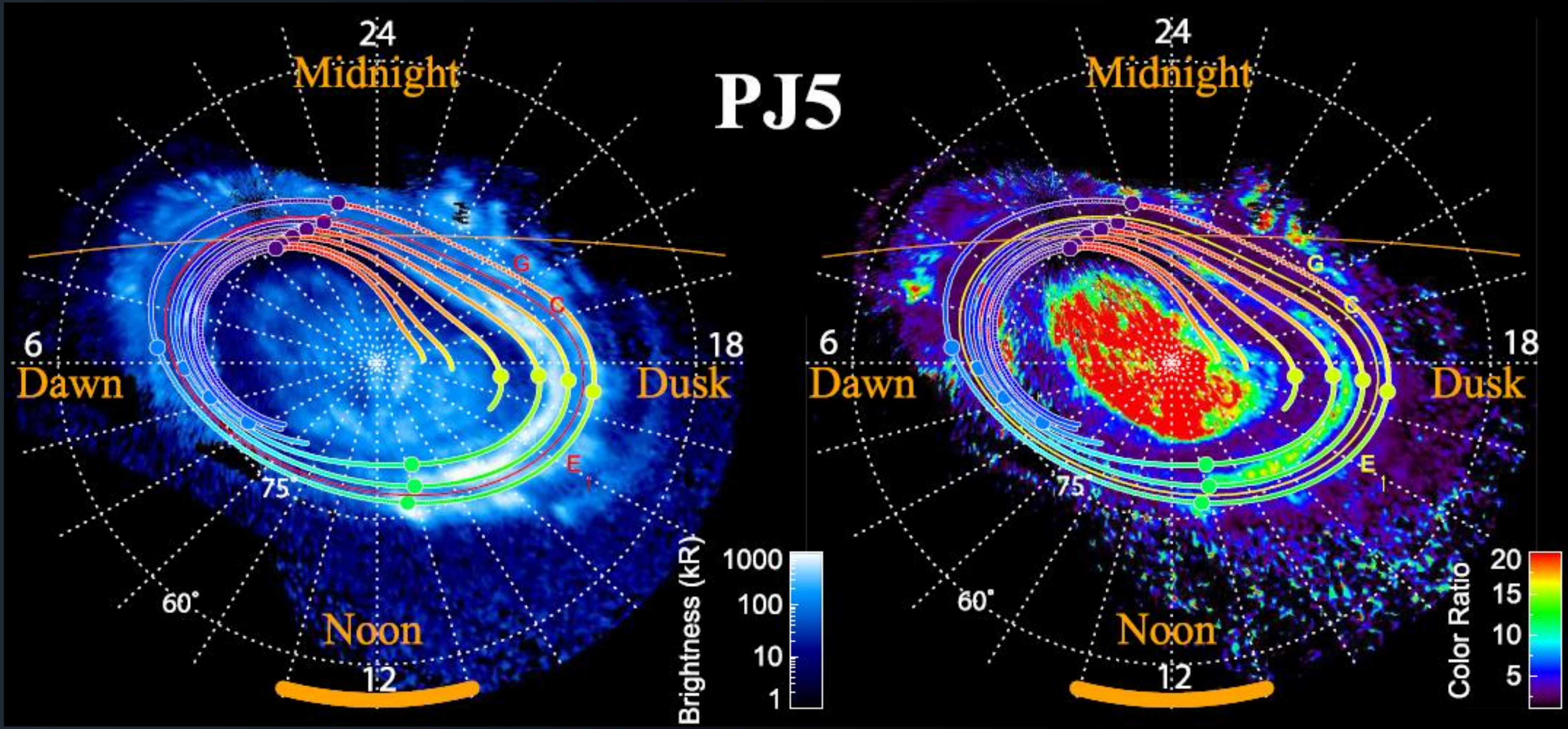


[illegible]

Credit: Ali Sulaiman, Juno Workshop, 2022

- Check out Ali Sulaiman's Fall 2023 MIPSE presentation

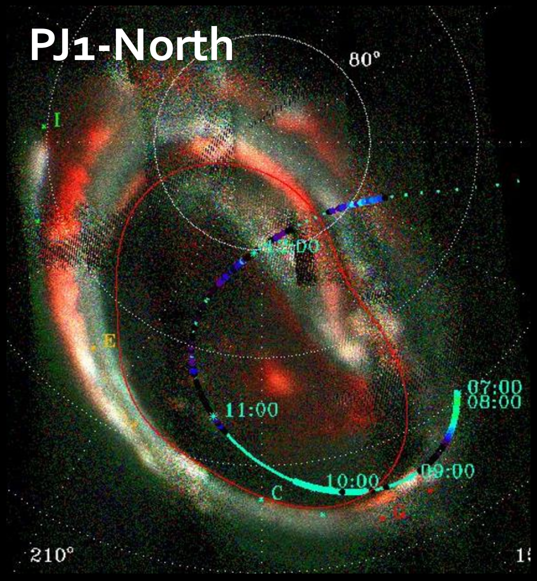
Juno observations of Jupiter's auroras

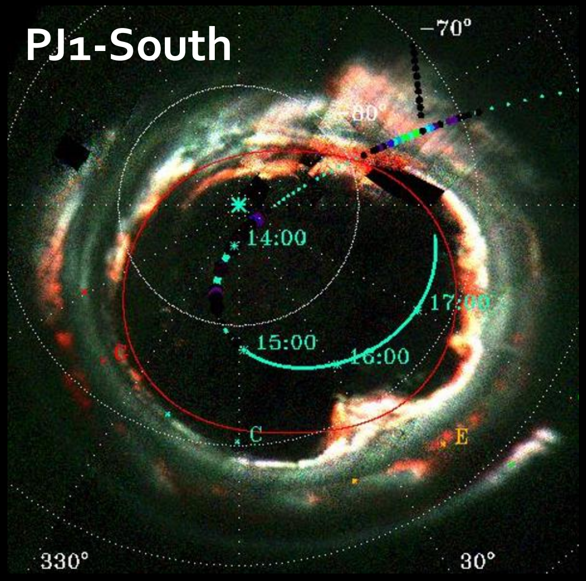


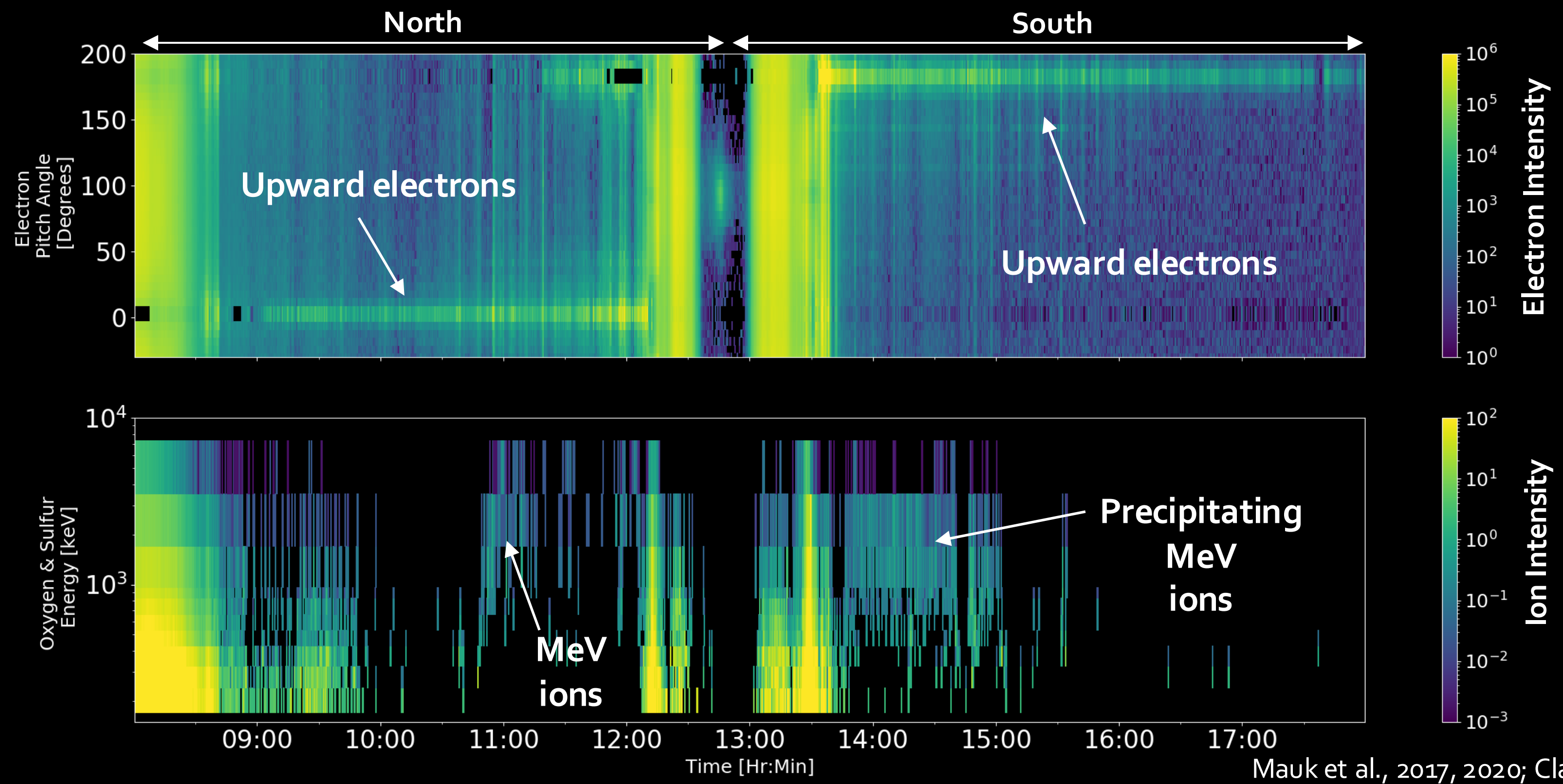
Greathouse et al. (2021)

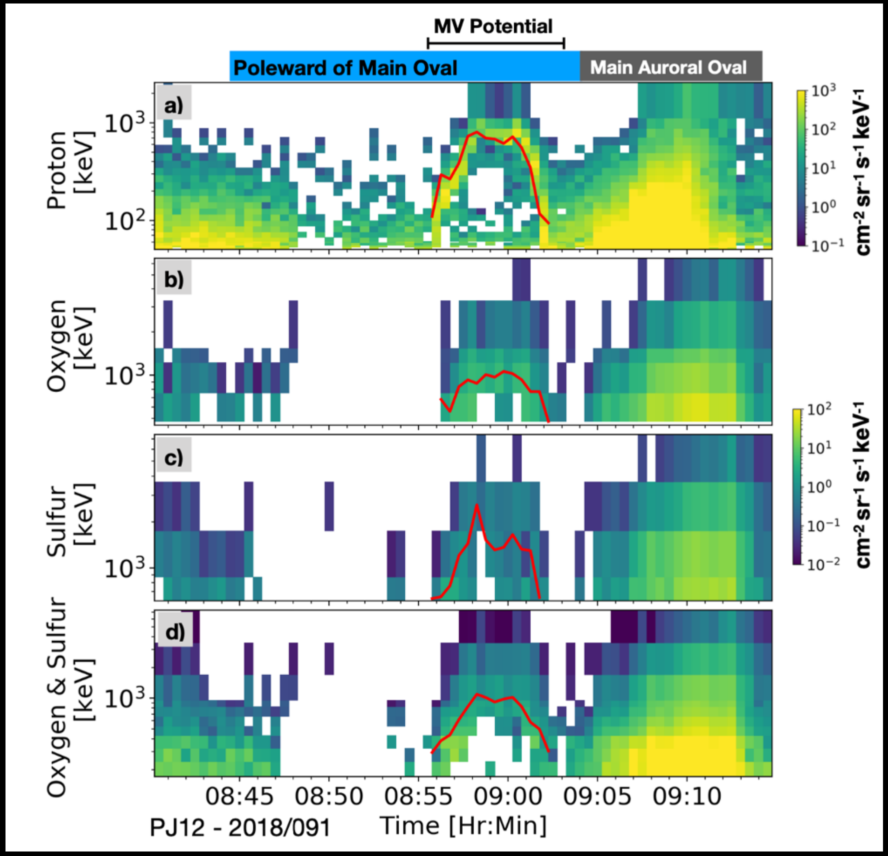
- Juno reveals that Jupiter's polar cap aurora have high "color ratios" indicating emissions coming from deeper in the atmosphere?
  - Energetic electron precipitation or another mechanism?

Energetic particle observations: upward electron beams and megavolt potentials



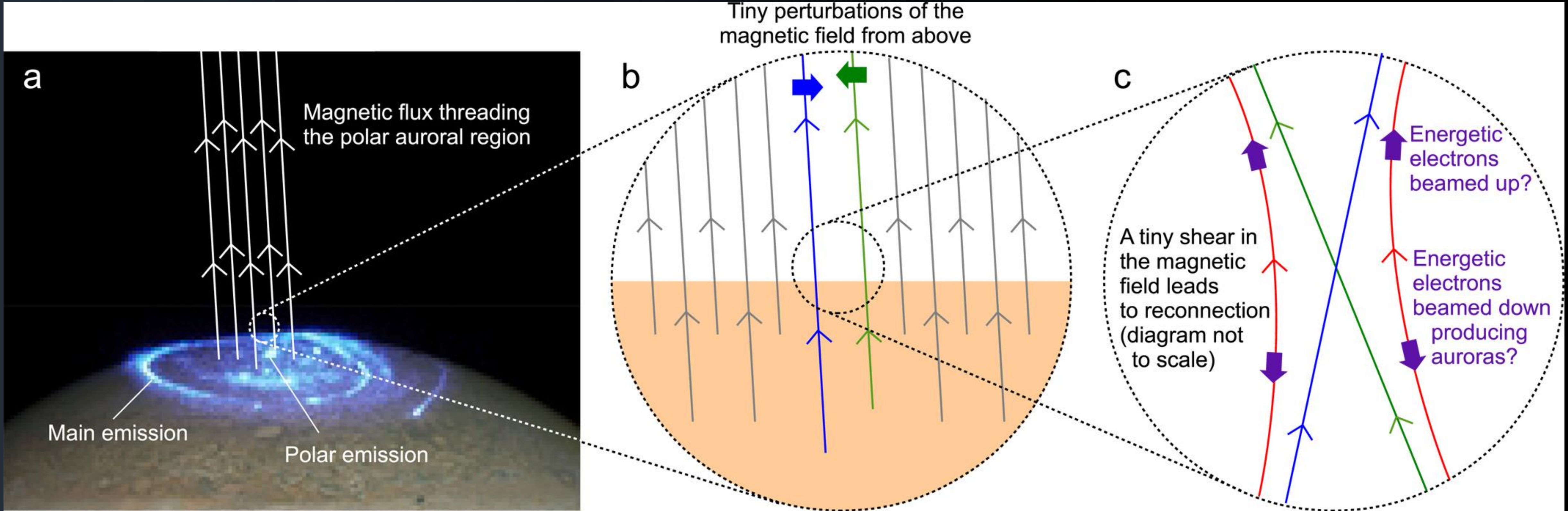






Mauk et al., 2017, 2020; Clark et al., 2017a; Clark et al., 2017b; Clark et al., 2020; Paranicas et al., 2018

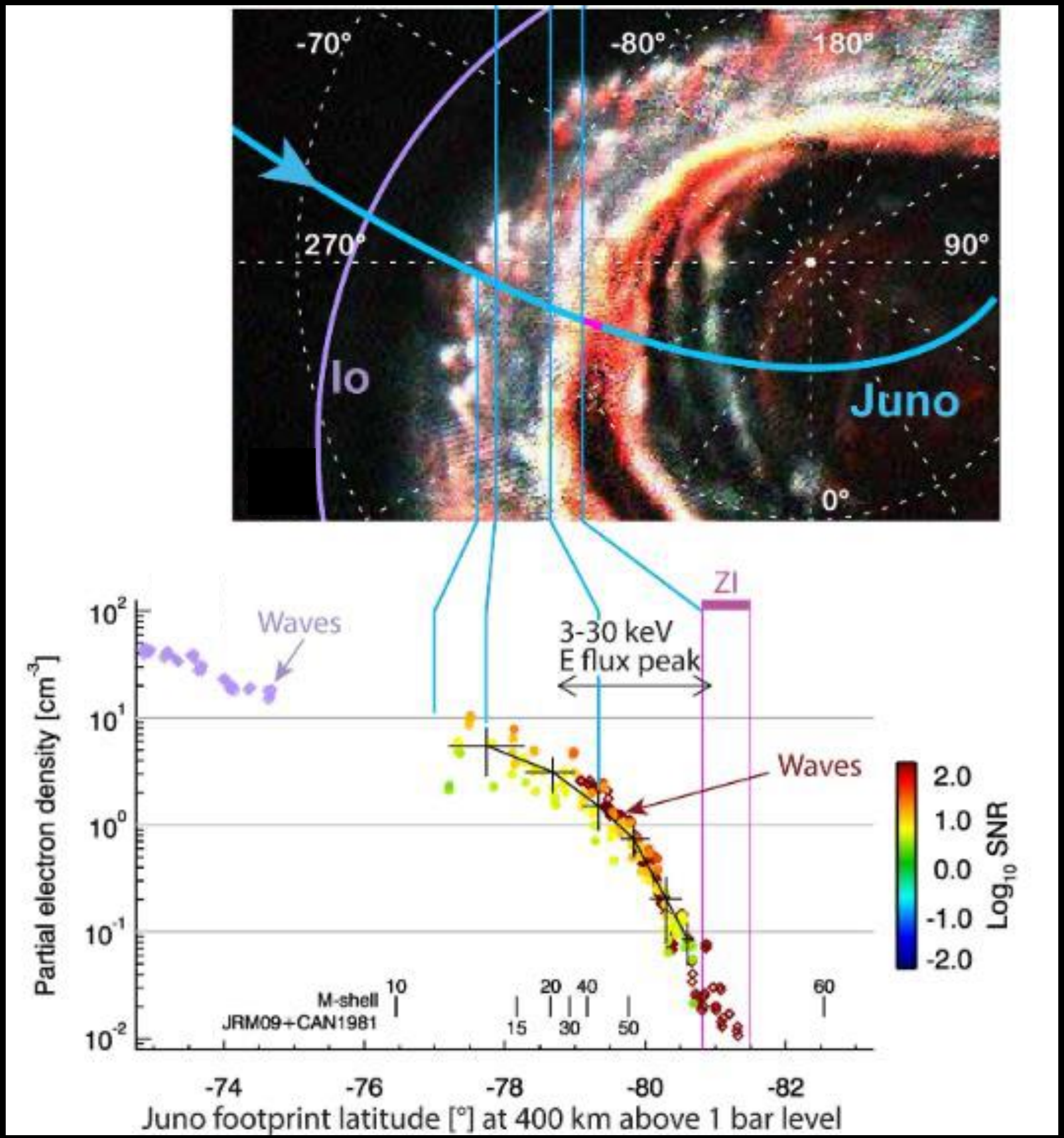
Potential Mechanism for Generating Upward Electron Beams (and downward ions?)



Masters et al., 2021

- Shear in magnetic field due to field-aligned currents leads to reconnecting fields
- Conversion of magnetic energy into particle energy can result in the observed MeV electrons
- Reconnection dynamics with a *very* large guide field is quite different from classical reconnection

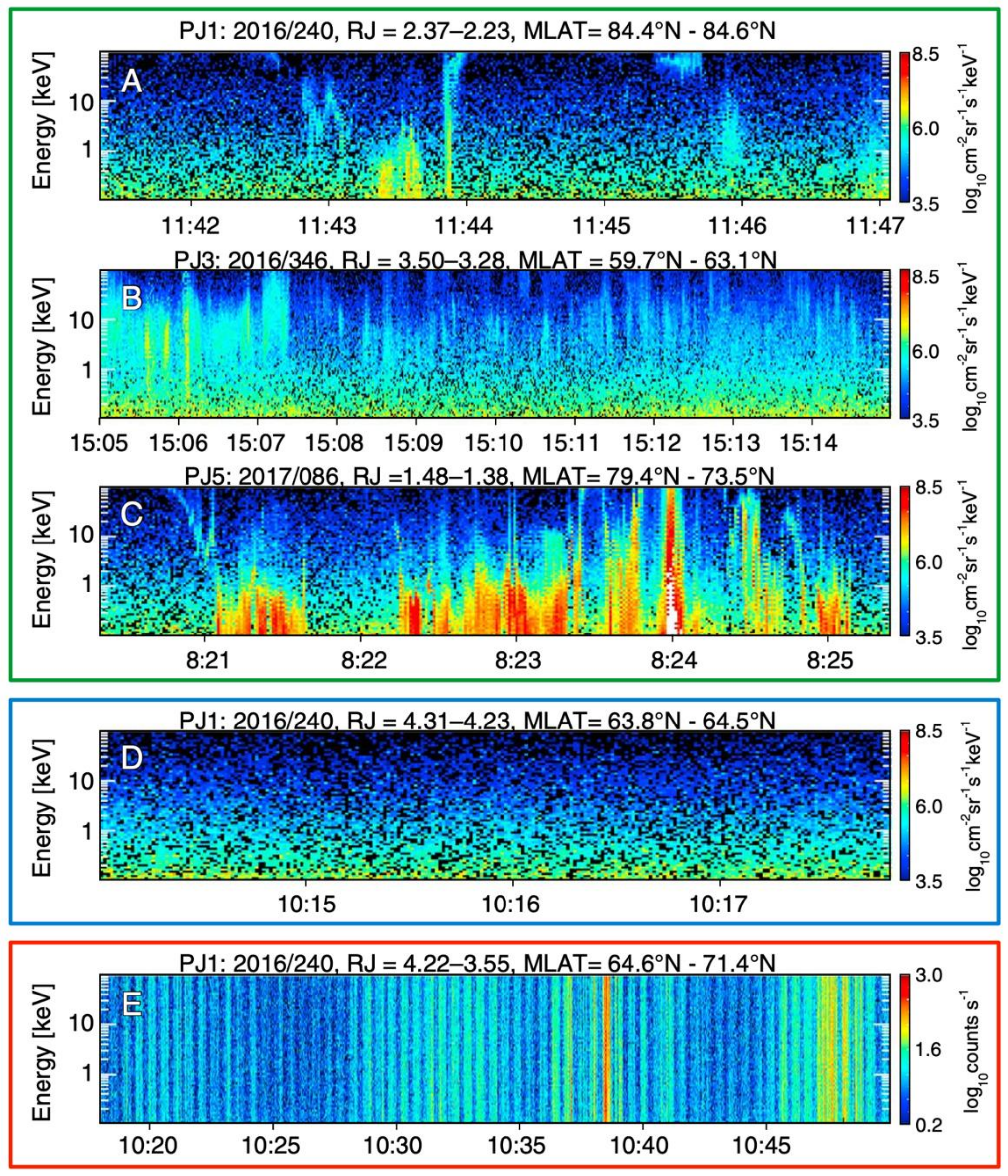
Potential mechanism for generating MV potentials?



Allegrini et al., 2021; Elliott et al., 2021; Sulaiman et al., 2022

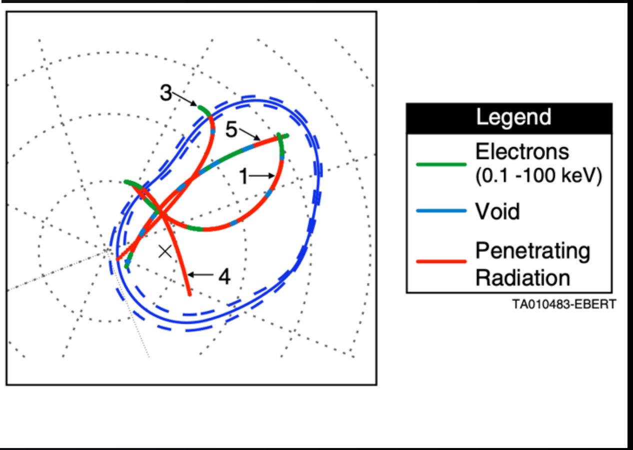
- Density cavities are one basic ingredient for auroral generation mechanisms (e.g., Persoon et al., 1998; Chaston et al., 2000, Alm et al., 2015)
- Electrostatic acceleration: Low densities require field-aligned acceleration to compensate for the shortage of charge carriers (i.e., $j \propto e n_e v$; Clark et al., 2017)
- Stochastic acceleration: Density cavities lower the threshold for Alfvénic dissipation (Saur et al., 2018).
- Ionospheric Alfvén Resonator: Formed by rapid decreases in density and causes phase mixing of Alfvén waves which enhance $E_{\parallel}$ (Lysak et al., 2021)

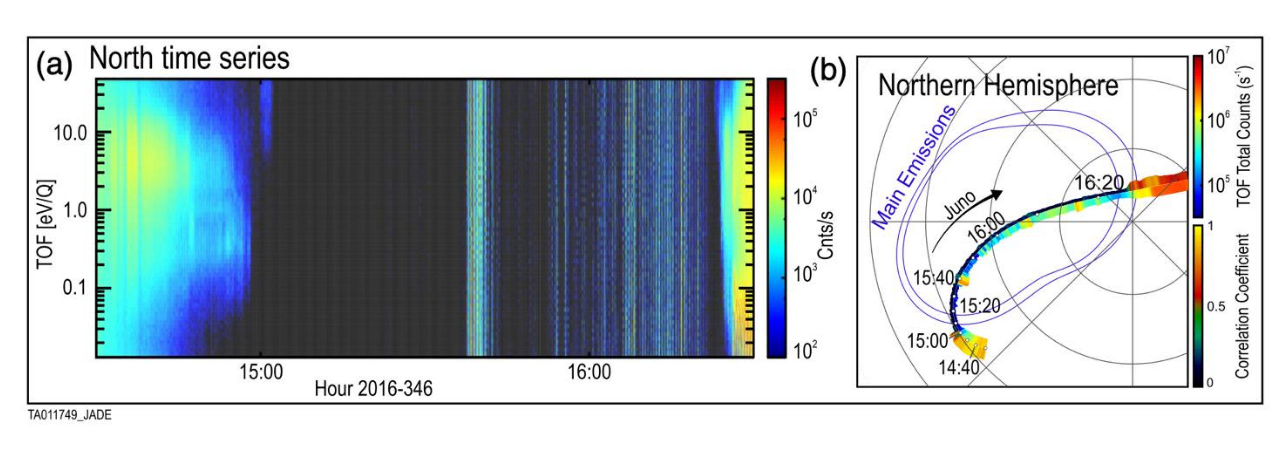
Plasma observations in the polar cap auroral region



JADE-Electron measurements

Ebert et al. (2017)

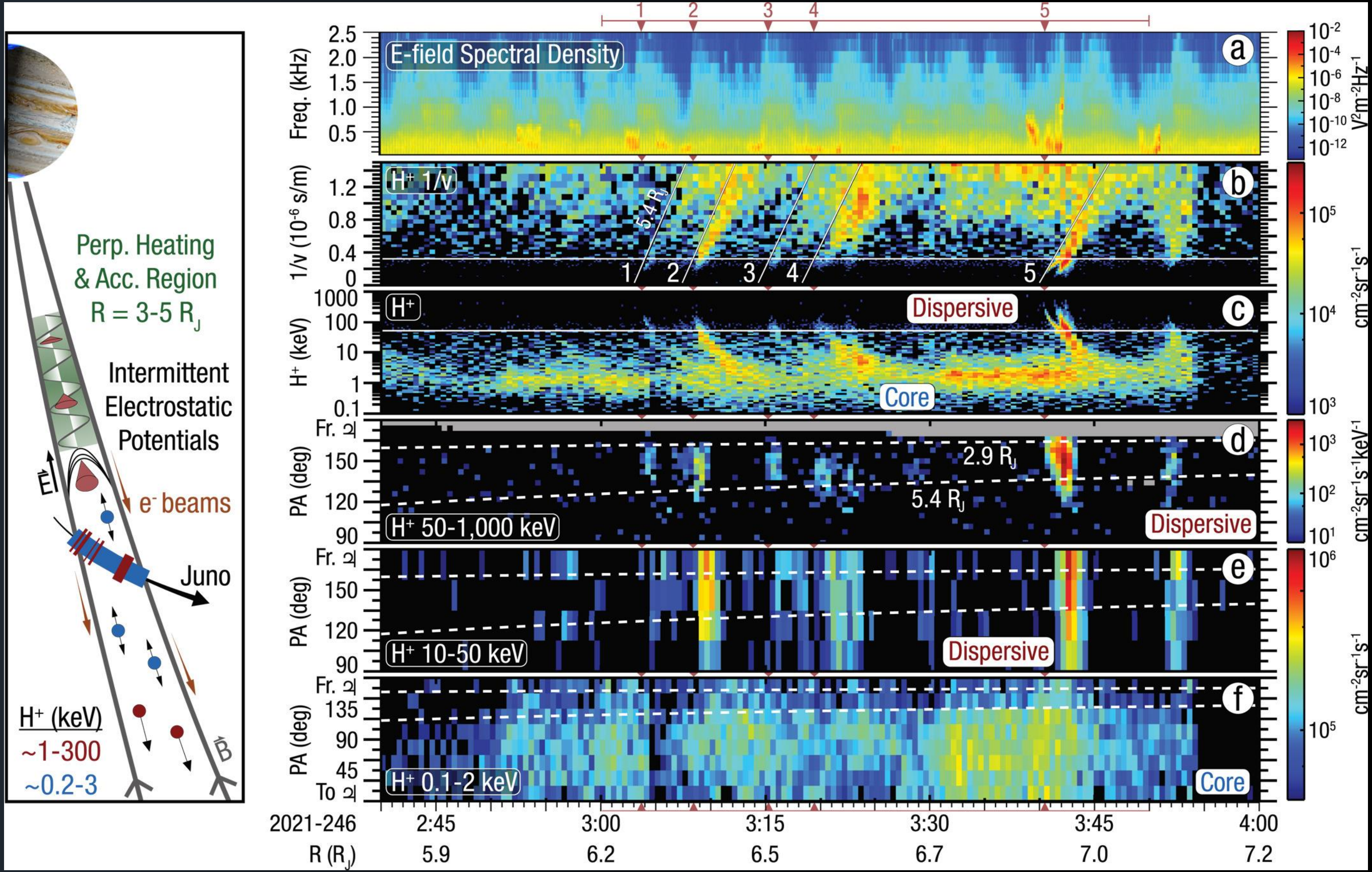




Pollock et al. (2020)

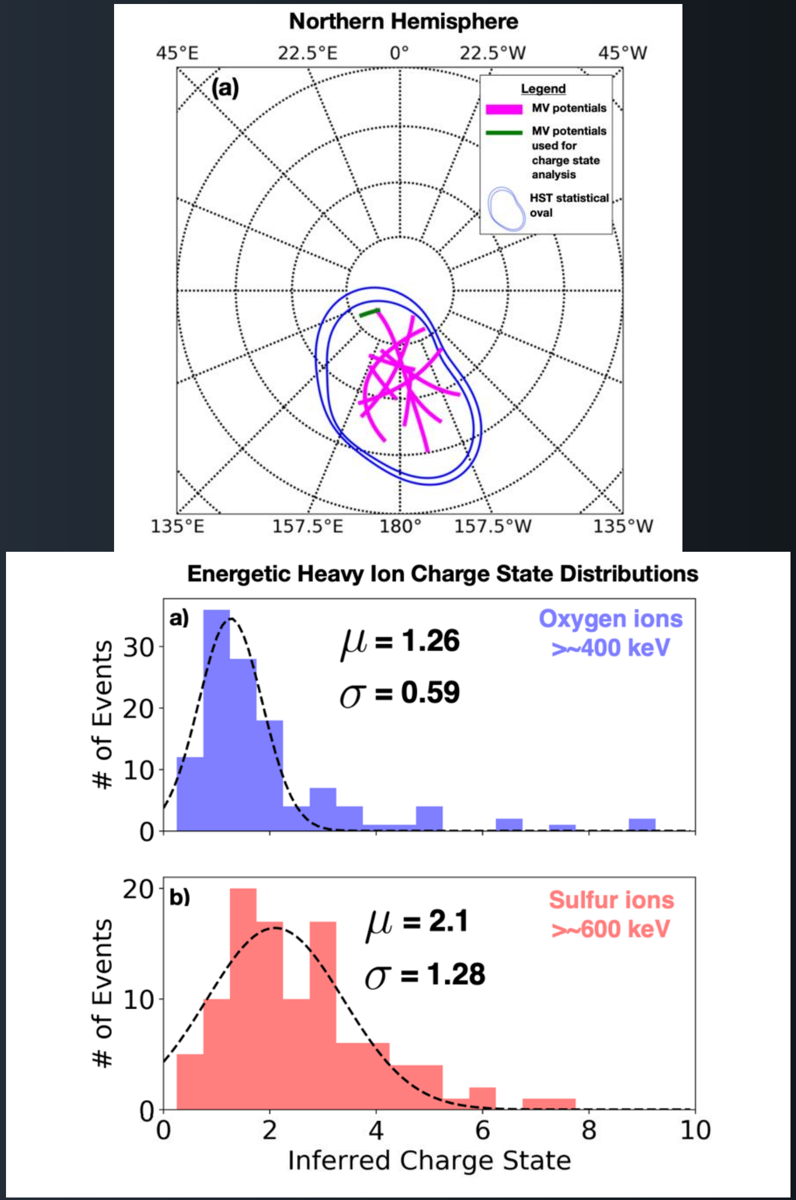
JADE-Ion measurements

Energetic particle observations: ion heating and outflow

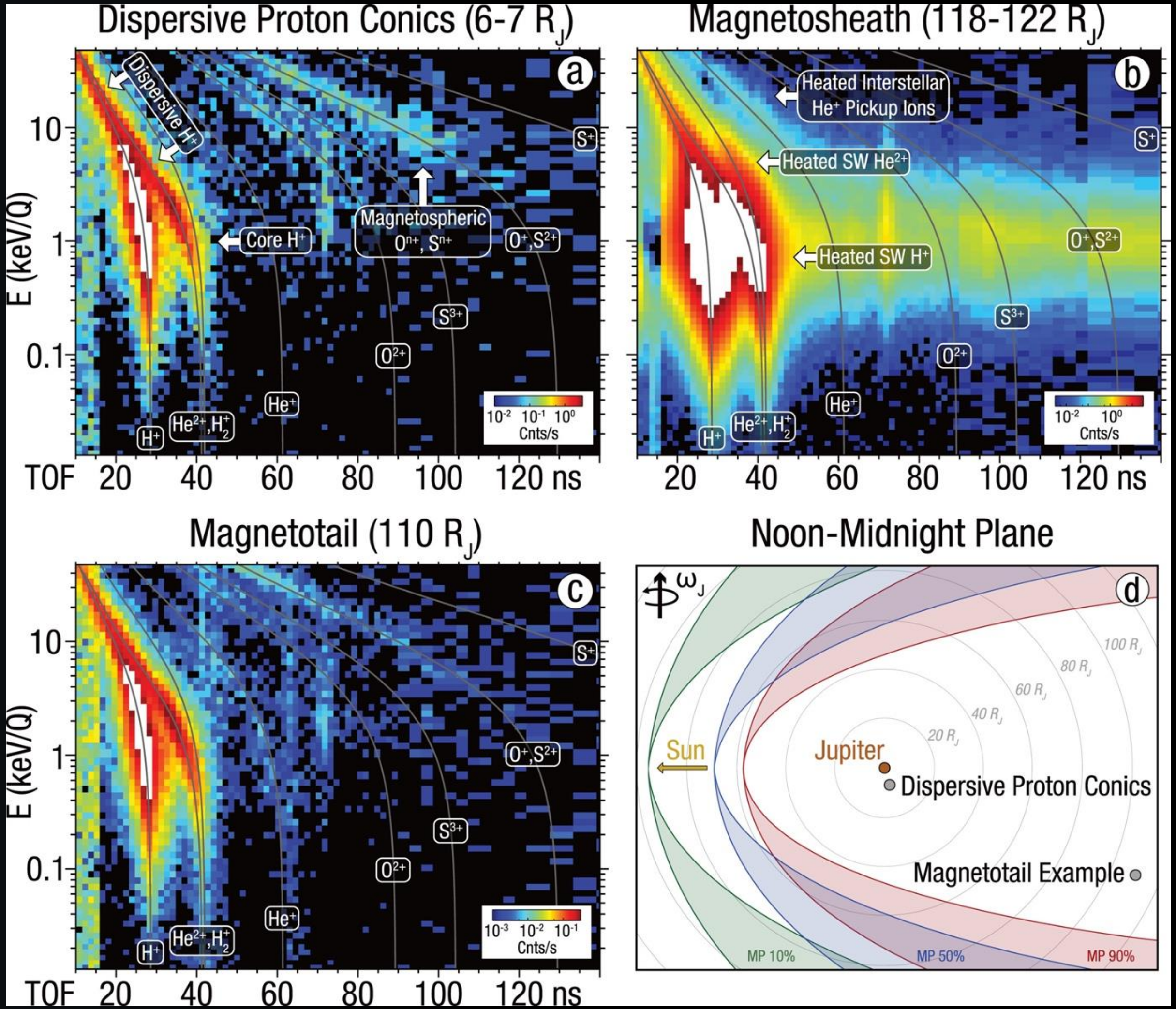


Clark et al., 2017b; Szalay et al. (2022; figure from this paper)

Magnetospheric ions appear to fill the polar cap

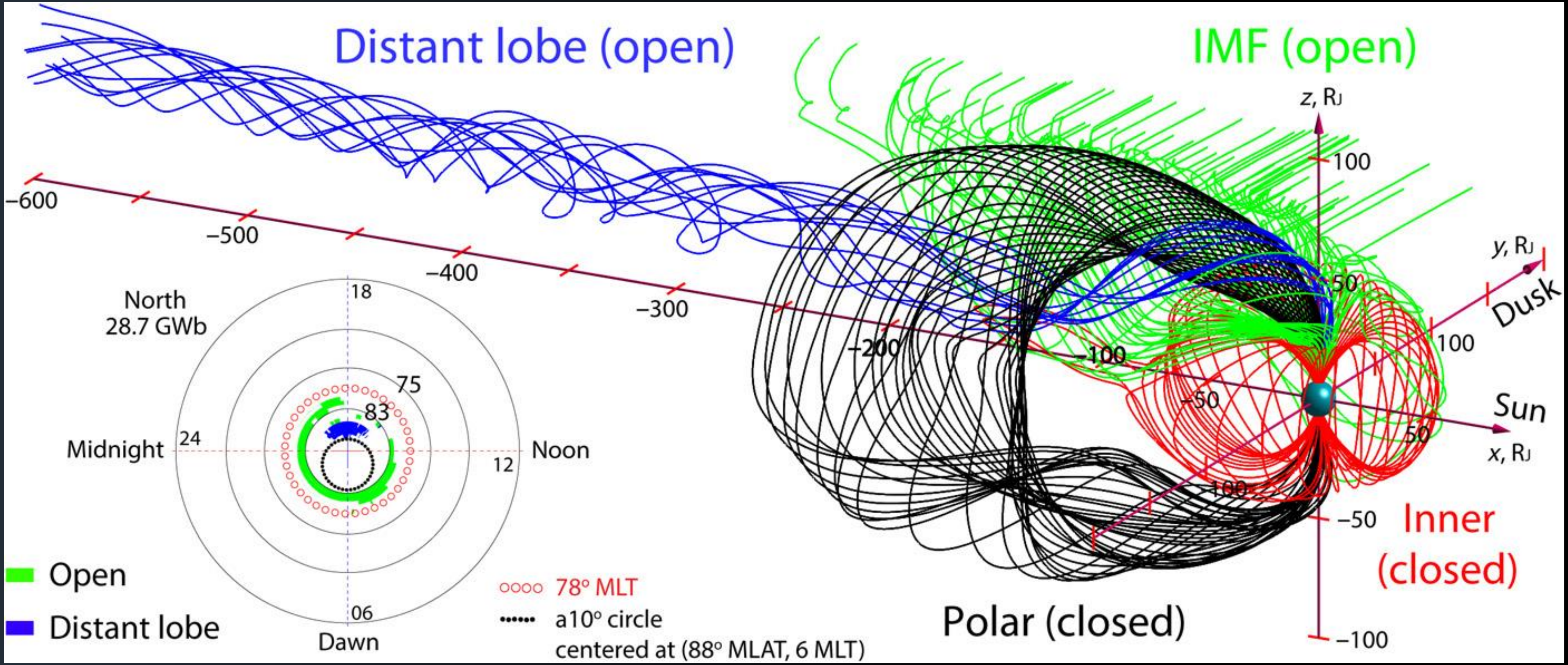


Clark et al. (2020)



Szalay et al. (2022)

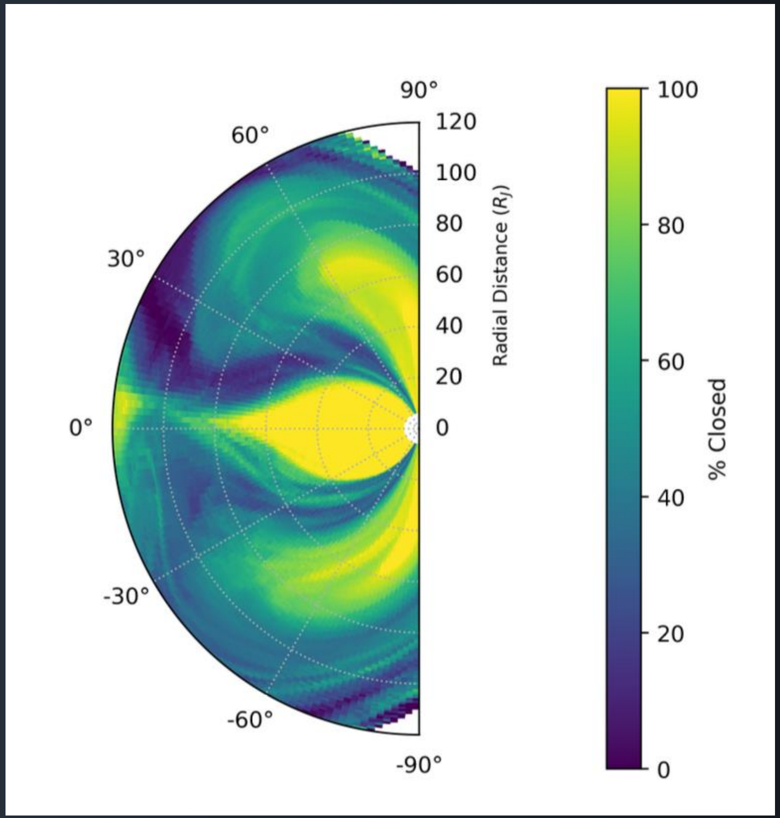
Modeling of Jupiter's open flux



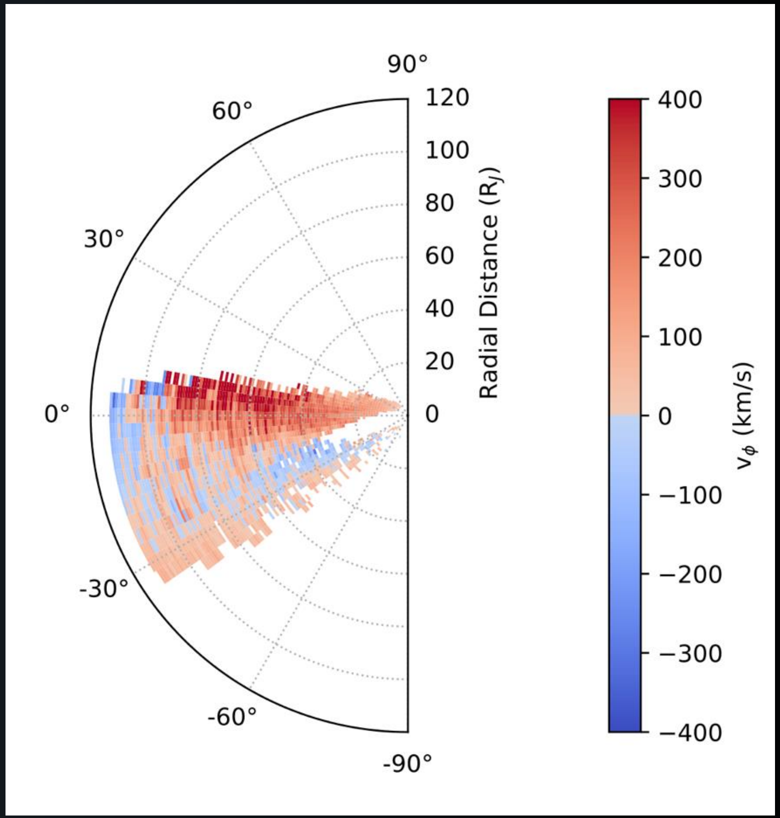
Zhang et al., 2021

Signatures of Jupiter's open magnetic flux

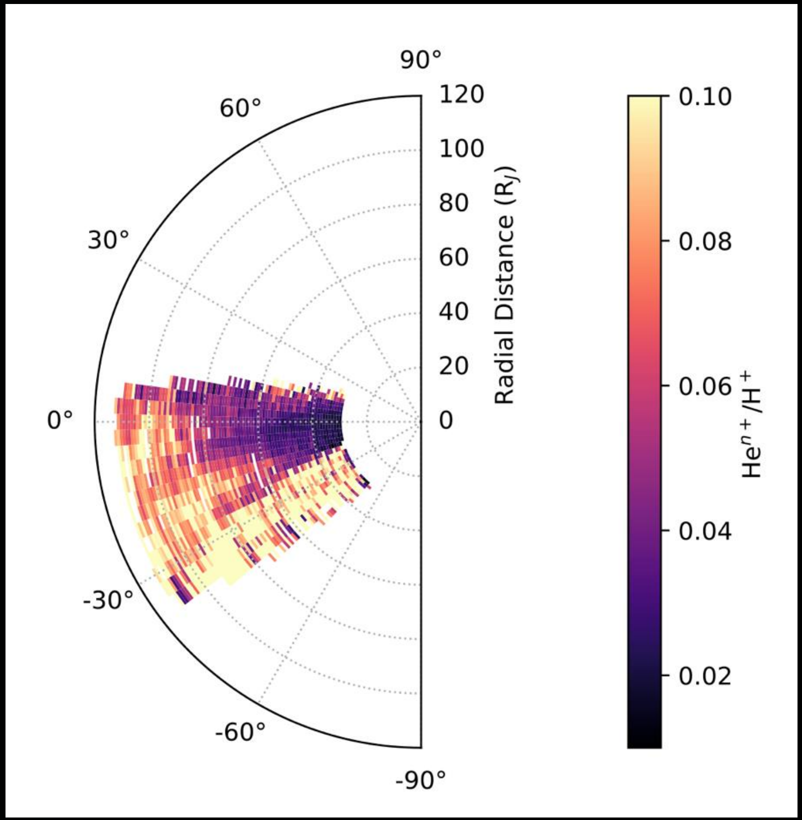
GAMERA Model



Juno/JADE Observations



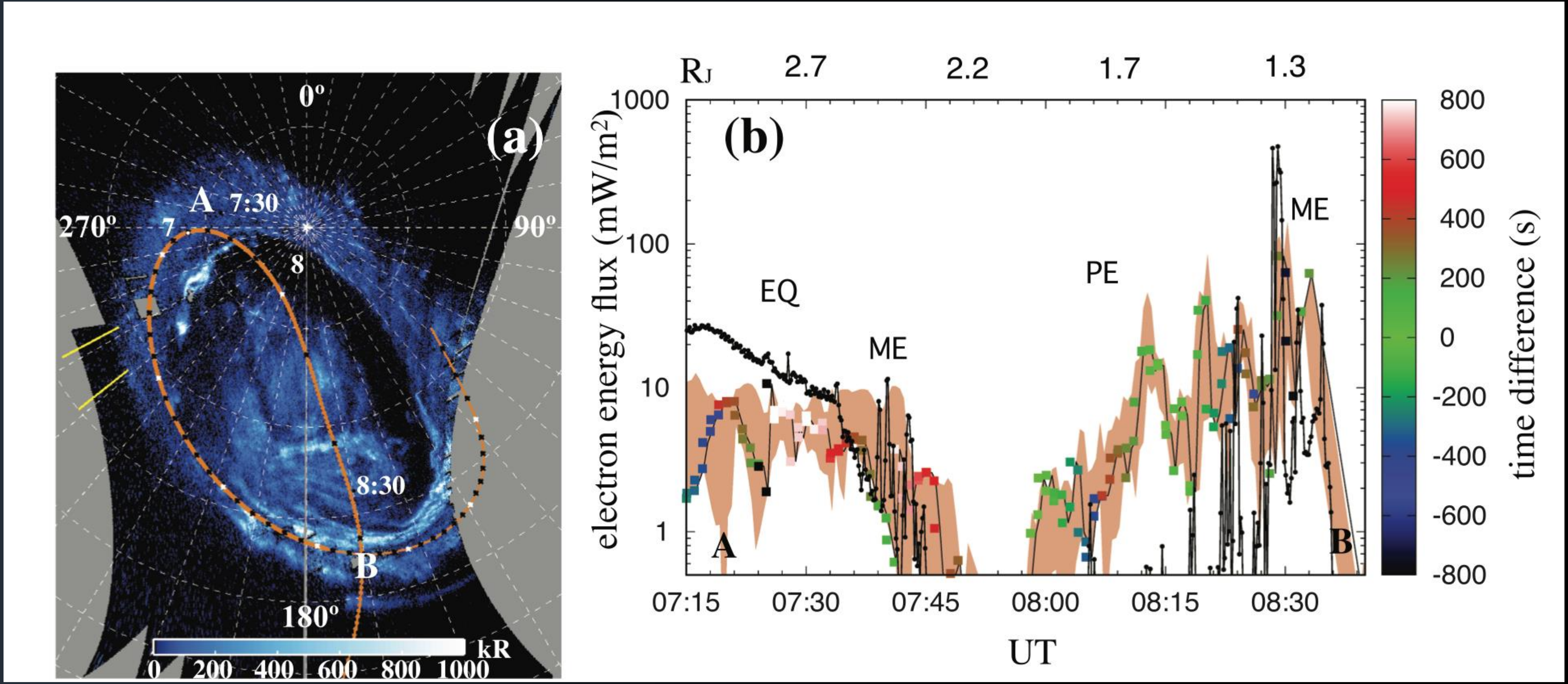
Juno/JEDI Observations



Delamere et al., 2024

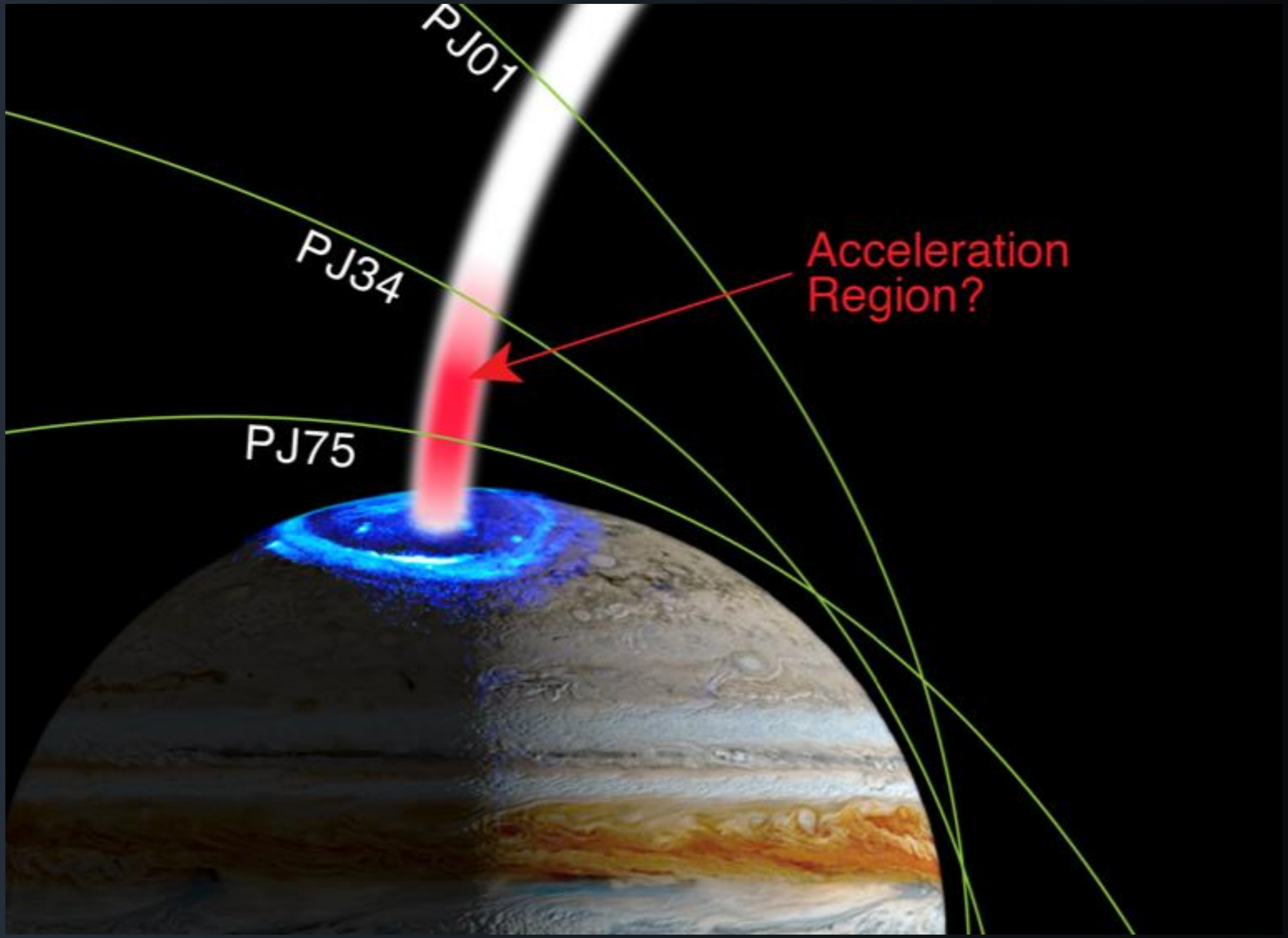
- Open field lines are confined to a narrow mid-latitude region
- Simulations show anti-corotational flows and higher He++ densities are associated with open field lines
- In situ measurements from JADE & JEDI support this idea

Comparisons between precipitating electrons and UV brightness

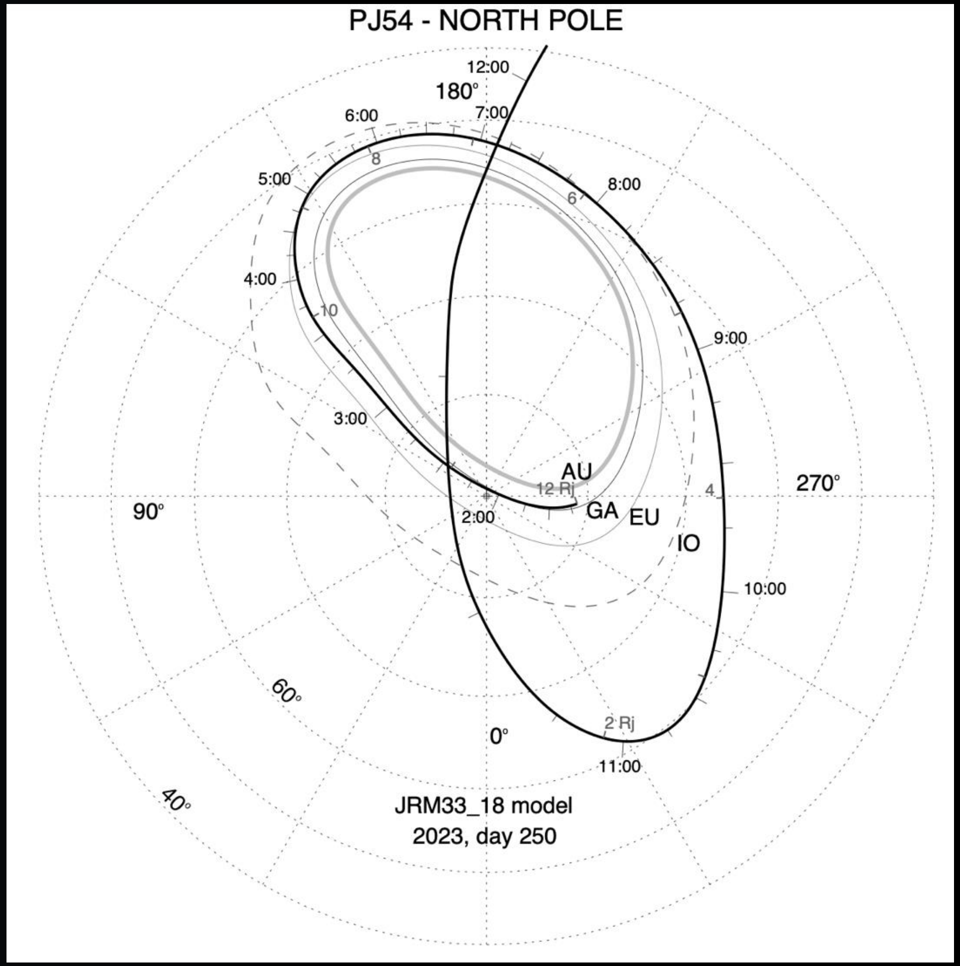


Gérard et al (2019), similar study performed by Ebert et al. (2019)

New results from Juno's extended mission

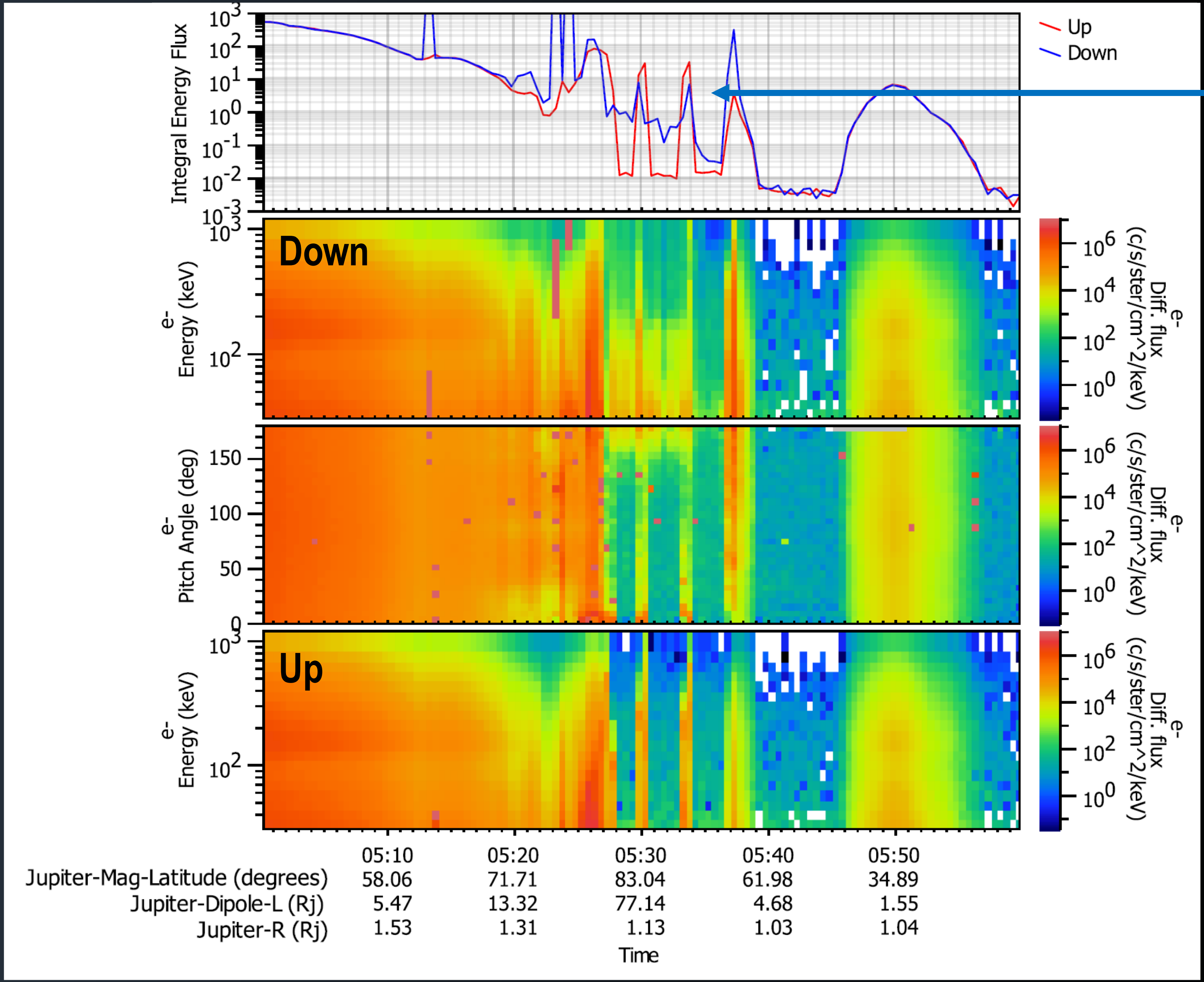


Credit: Juno/SwRI/Extended Mission Proposal

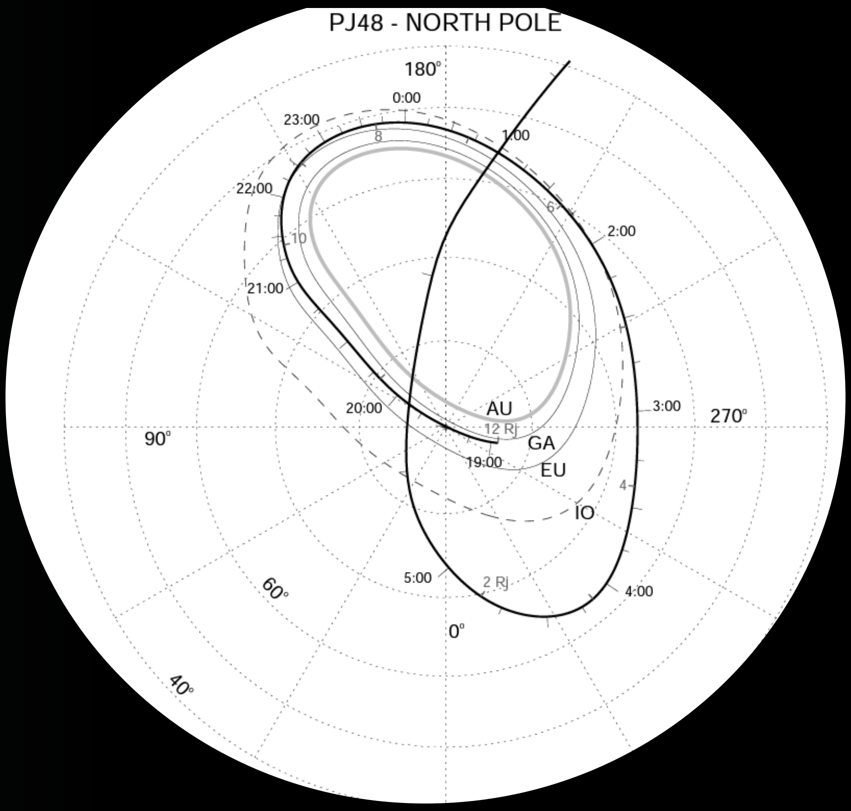


Credit: J. E. P. Connerney

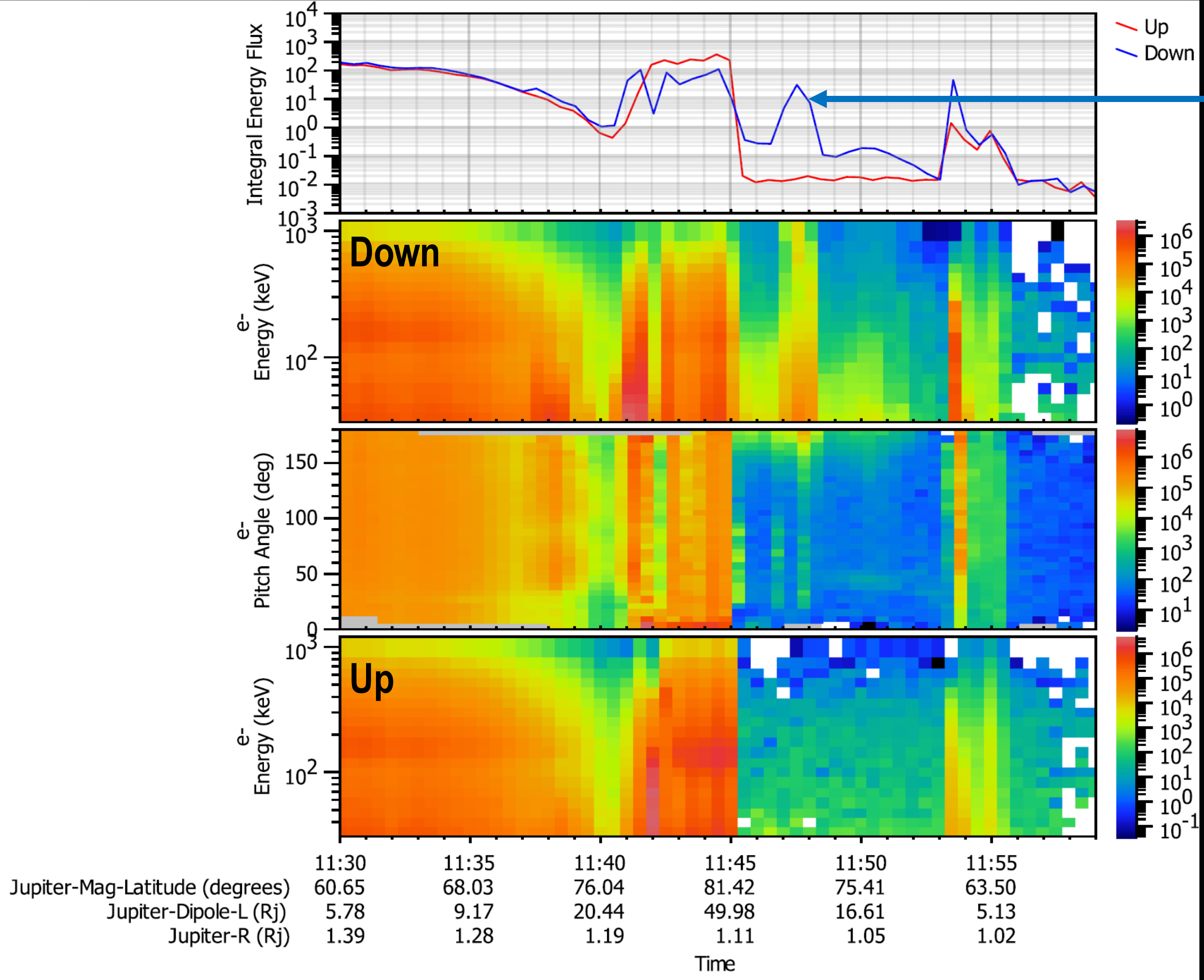
Energetic particle observations from Juno's low altitude excursions (PJ48)



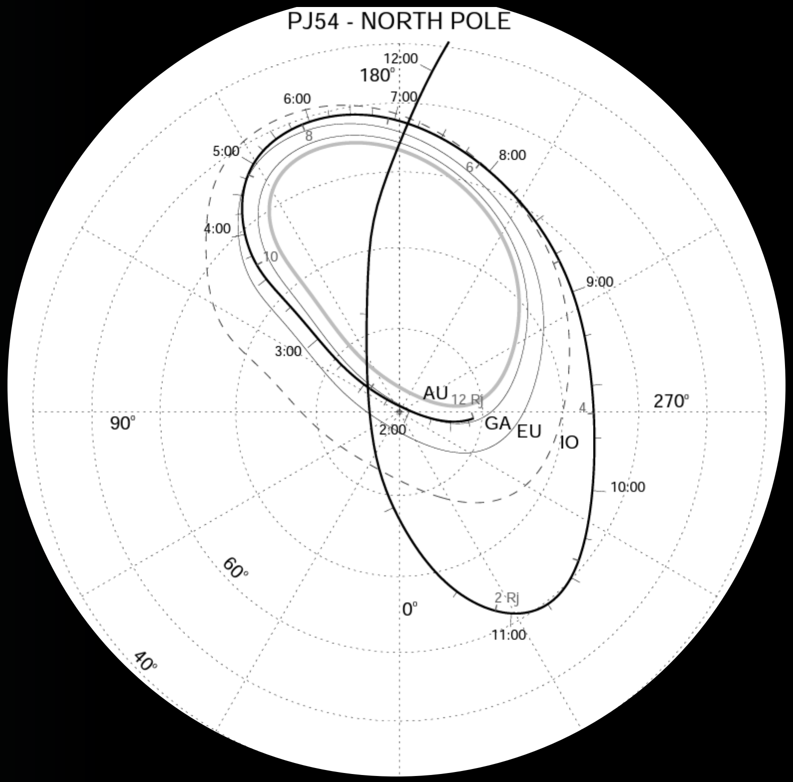
Significant precipitating energy flux



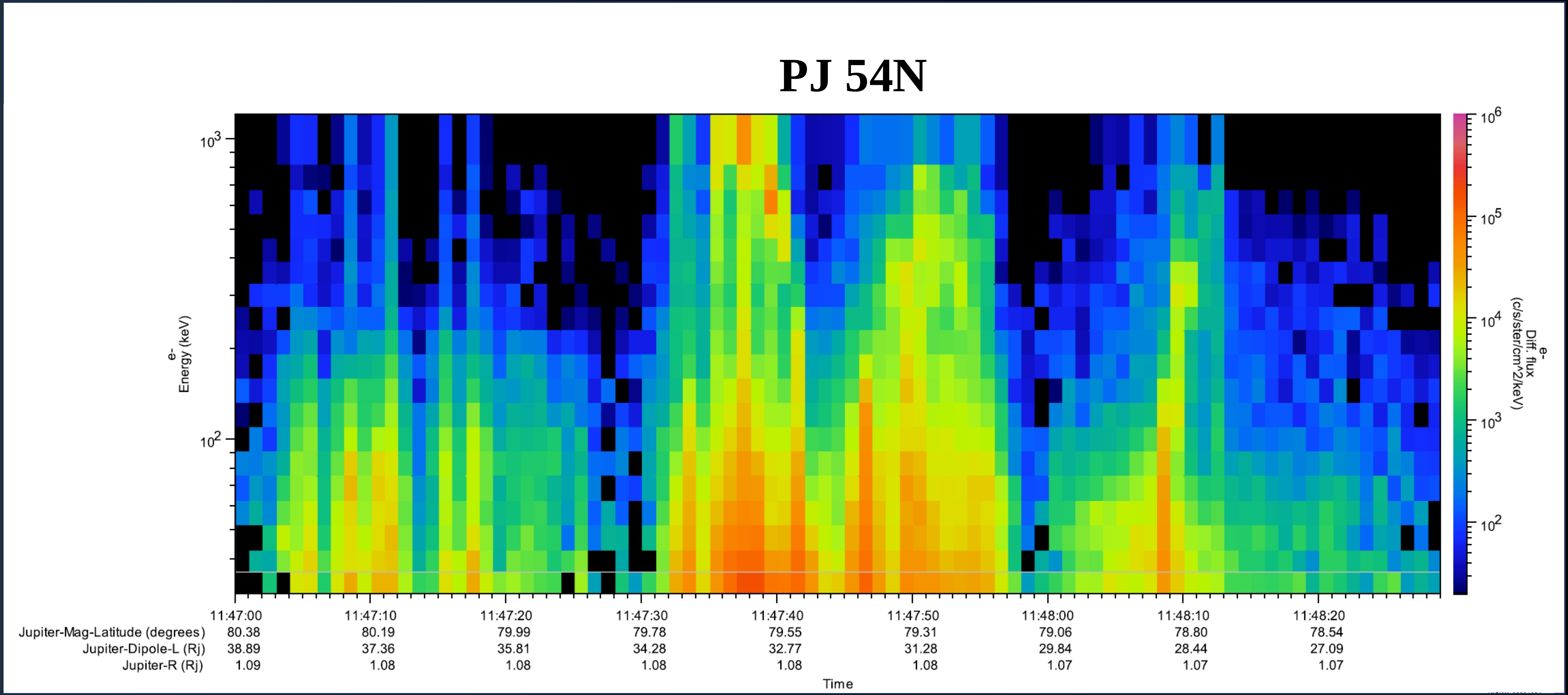
Energetic particle observations from Juno's low altitude excursions (PJ54)



Upward of 100 mW/m² (in high temporal resolution)

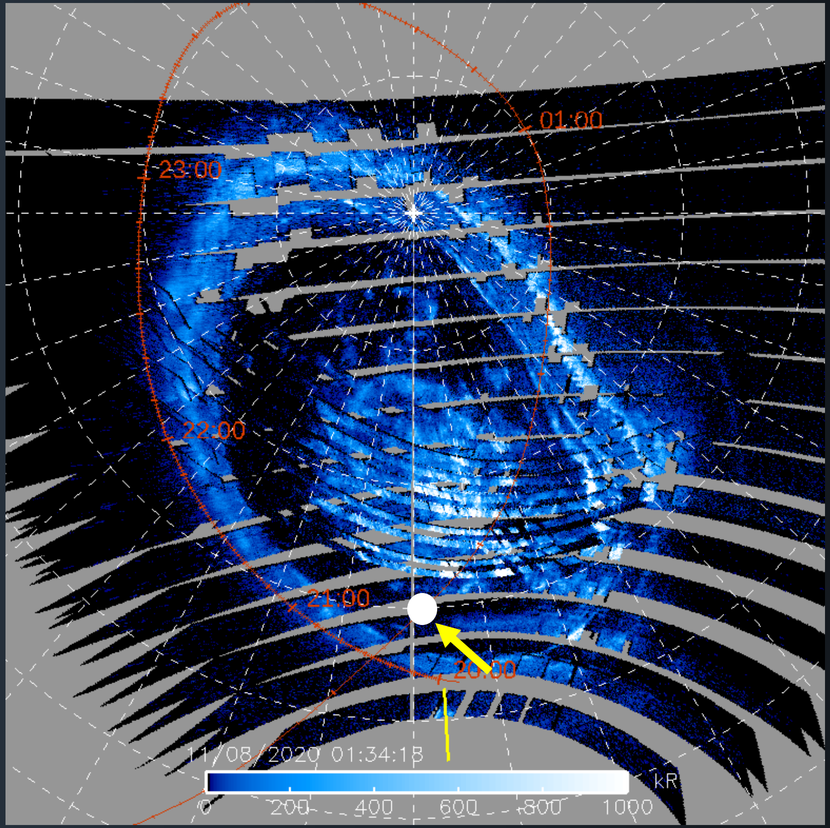


High time resolution inspection of the PJ54 down going electrons

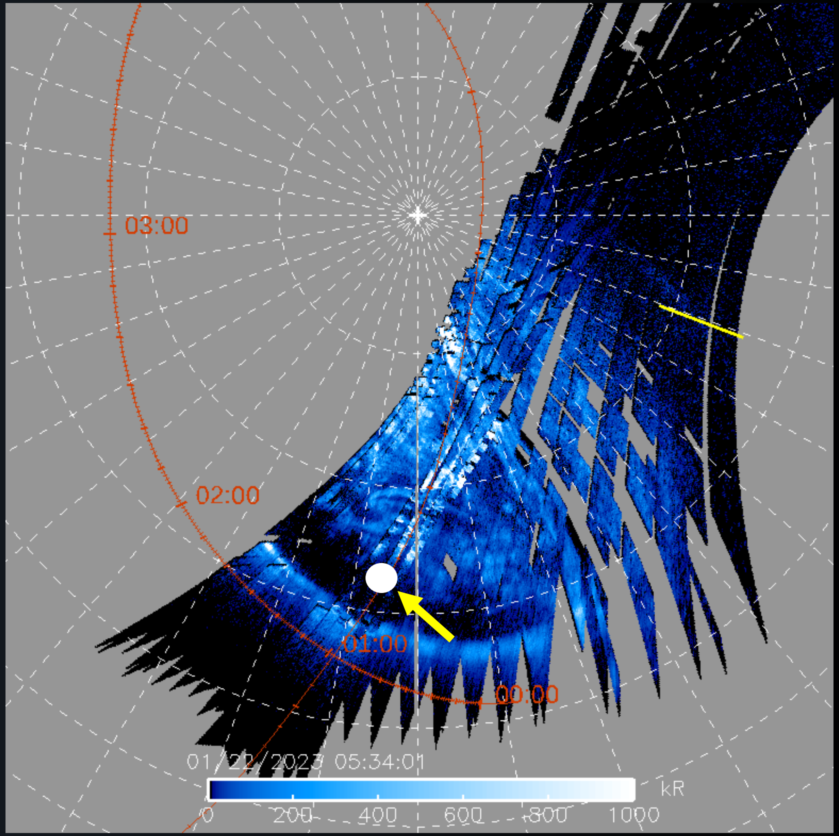


UVS observations courtesy of Bertrand Bonfond

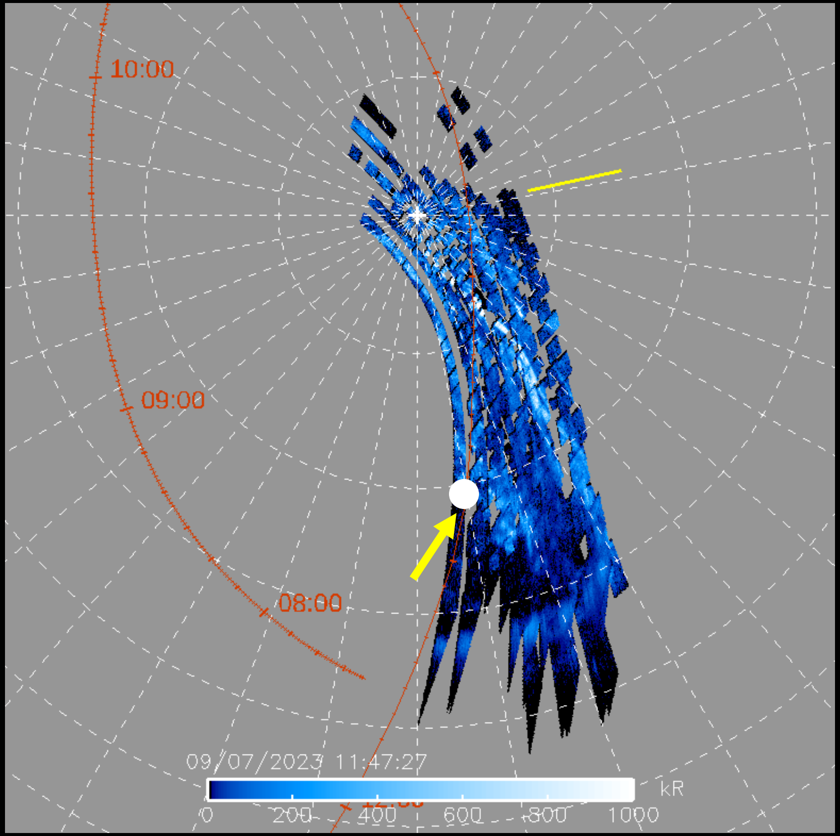
PJ 30



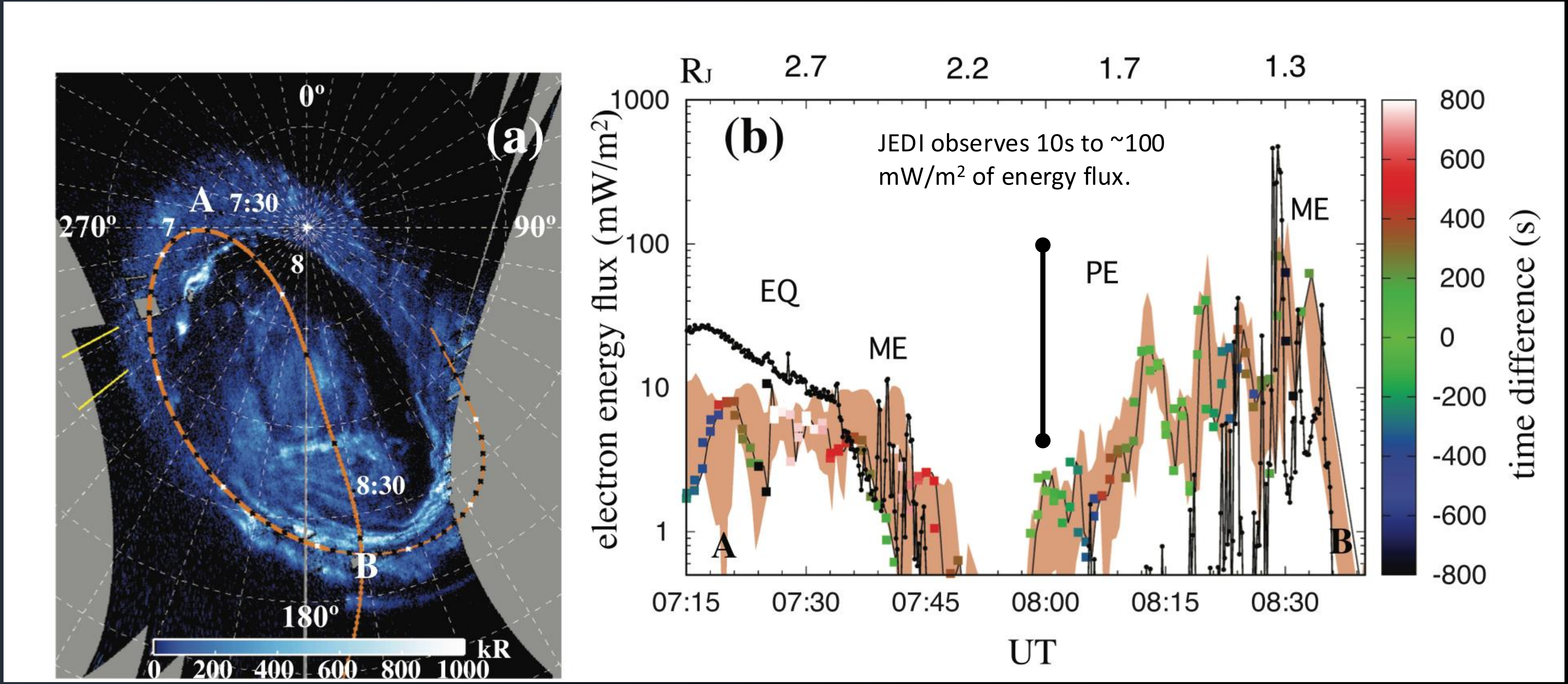
PJ 48



PJ 54



Comparisons between precipitating electrons and UV brightness

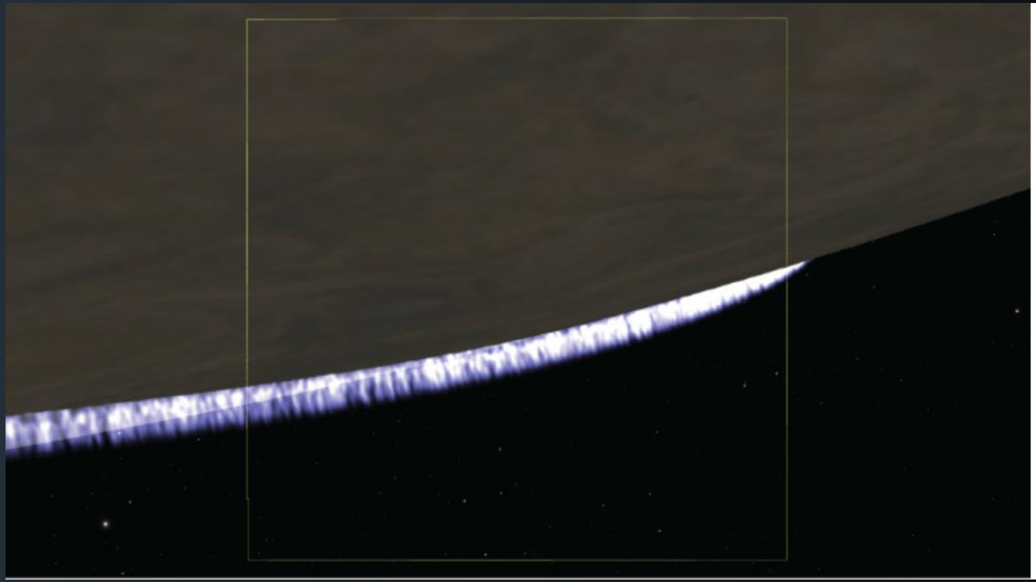


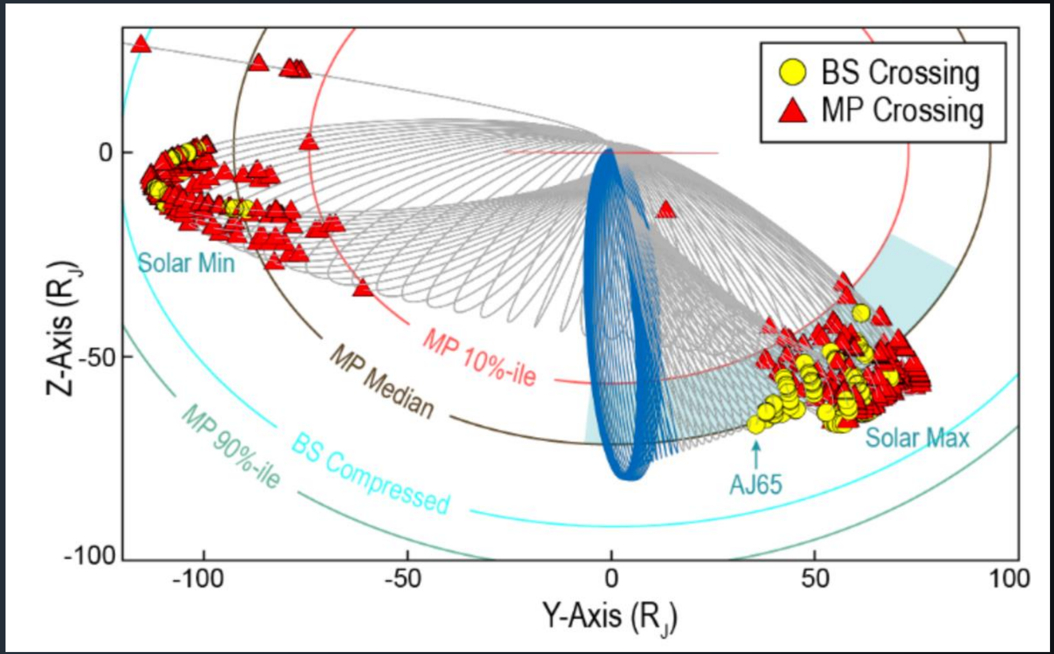
Gérard et al (2019), similar study performed by Ebert et al. (2019)

Open questions

- What powers the polar cap "red" aurora? Precipitation of very energetic electrons?
- How are MV potentials generated? Do plasma density depletions (Allegrini+ 2021, Sulaiman+ 2022) play an important role in the MI-coupling (Lysak+ 2021)? Lysak has shown that 0.01 cc can produce ~2 MV potential drops.
- How are electrons accelerated to multi-MeV energies over the polar cap? Wave-particle interactions via whistler mode waves (Elliott+ 2018, 2020)? Component reconnection in Jupiter's low-altitude polar cap (Masters+ 2021)?
- Can we bring closure to the open/closed polar cap problem (Delamere et al., 2024)?
- Juno appears to have found the low-altitude acceleration region (~0.2 R_J altitude) and the energy flux is commensurate with measured UV brightnesses. Is this the process creating Jupiter's patchy polar UV emissions (Clark et al., in prep)?

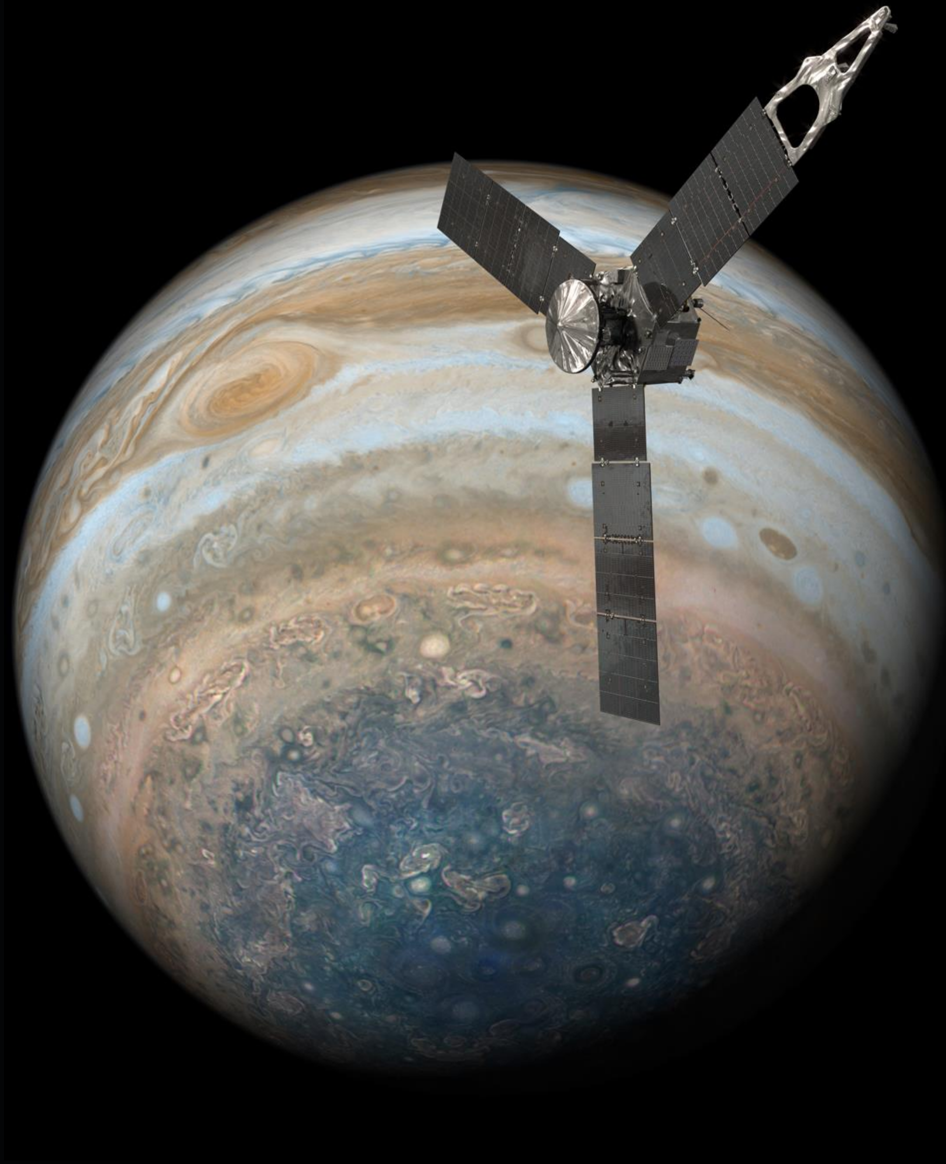
Another Juno extended mission can visit unexplored regions





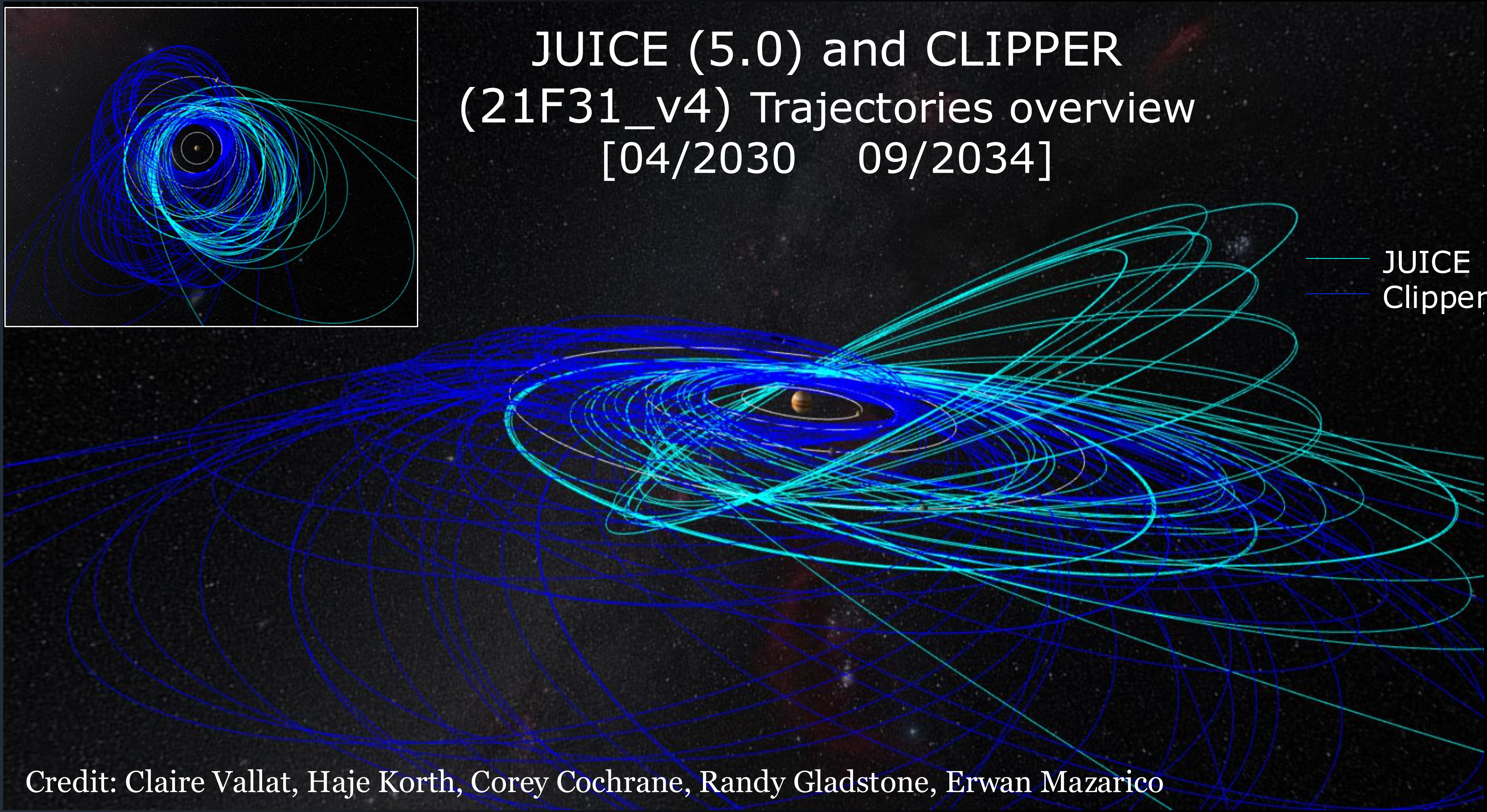
- Understanding the vertical extent of the auroral curtain

- Revealing boundary processes and the nature of solar wind-magnetosphere coupling at Jupiter



Joint JUpiter ICy moon Explorer (JUICE) and Europa Clipper Science Opportunities

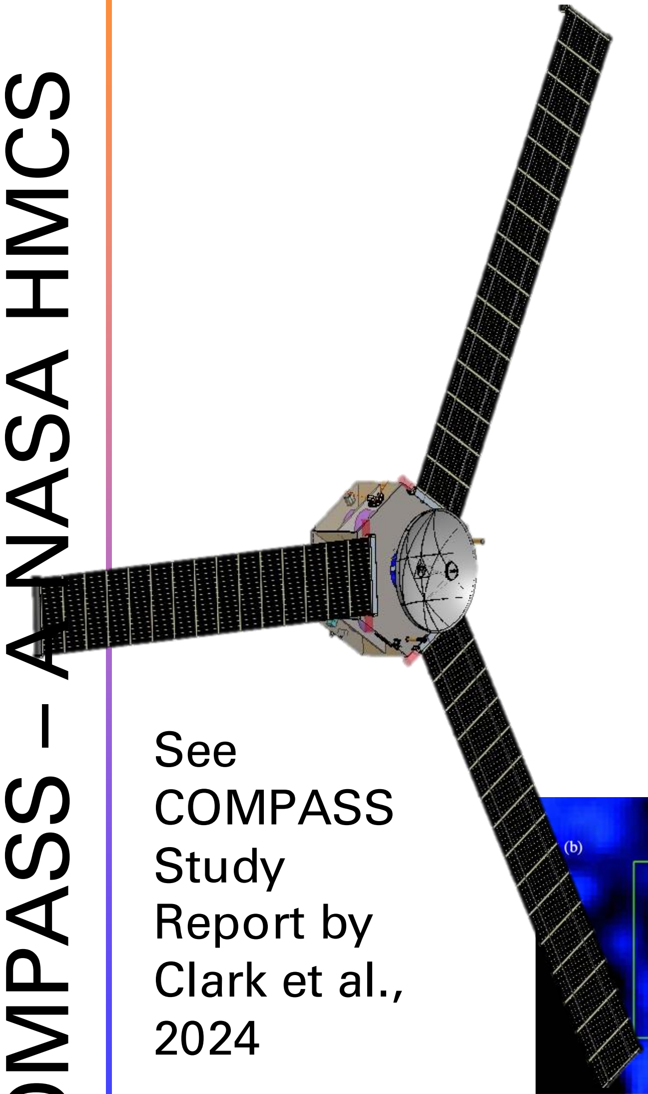
JUICE (5.0) and CLIPPER (21F31_v4) Trajectories overview [04/2030 09/2034]



Credit: Claire Vallat, Haje Korth, Corey Cochrane, Randy Gladstone, Erwan Mazarico

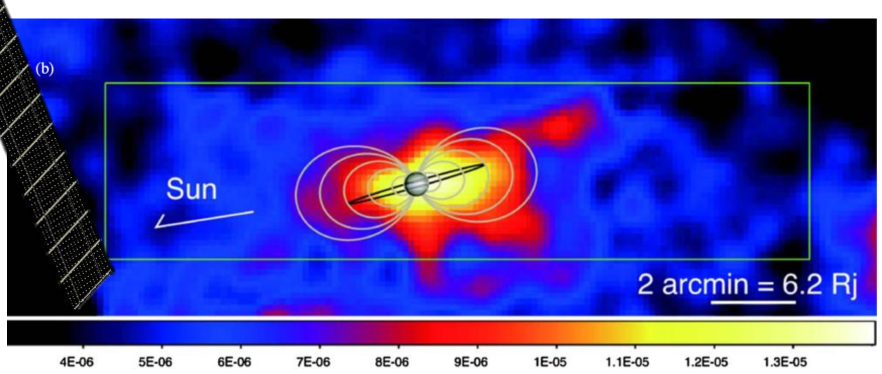
COMPASS – A NASA HMCS

Comprehensive Observations of Magnetospheric Particle Acceleration, Sources and Sinks (COMPASS)



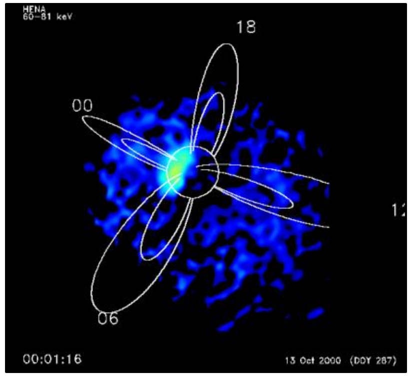
- COMPASS is a Solar Terrestrial Probes-class mission concept to **Jupiter's radiation belts**
- COMPASS was recommended in the 2024-2033 Solar and Space Physics Decadal Survey as a potential mission to achieve NASA Heliophysics' longer term goal of exploring other planetary magnetospheres
- Outfitted with an unprecedented scientific payload to reveal the mysteries associated the in situ fields and particles (e.g., energy-resolved >> 1 MeV electron and ion populations) environment as well as an X-ray imager to monitor the dynamics and emissions associated with loss processes
- Perform several deep dives into the heart of Jupiter's radiation belt

See COMPASS Study Report by Clark et al., 2024



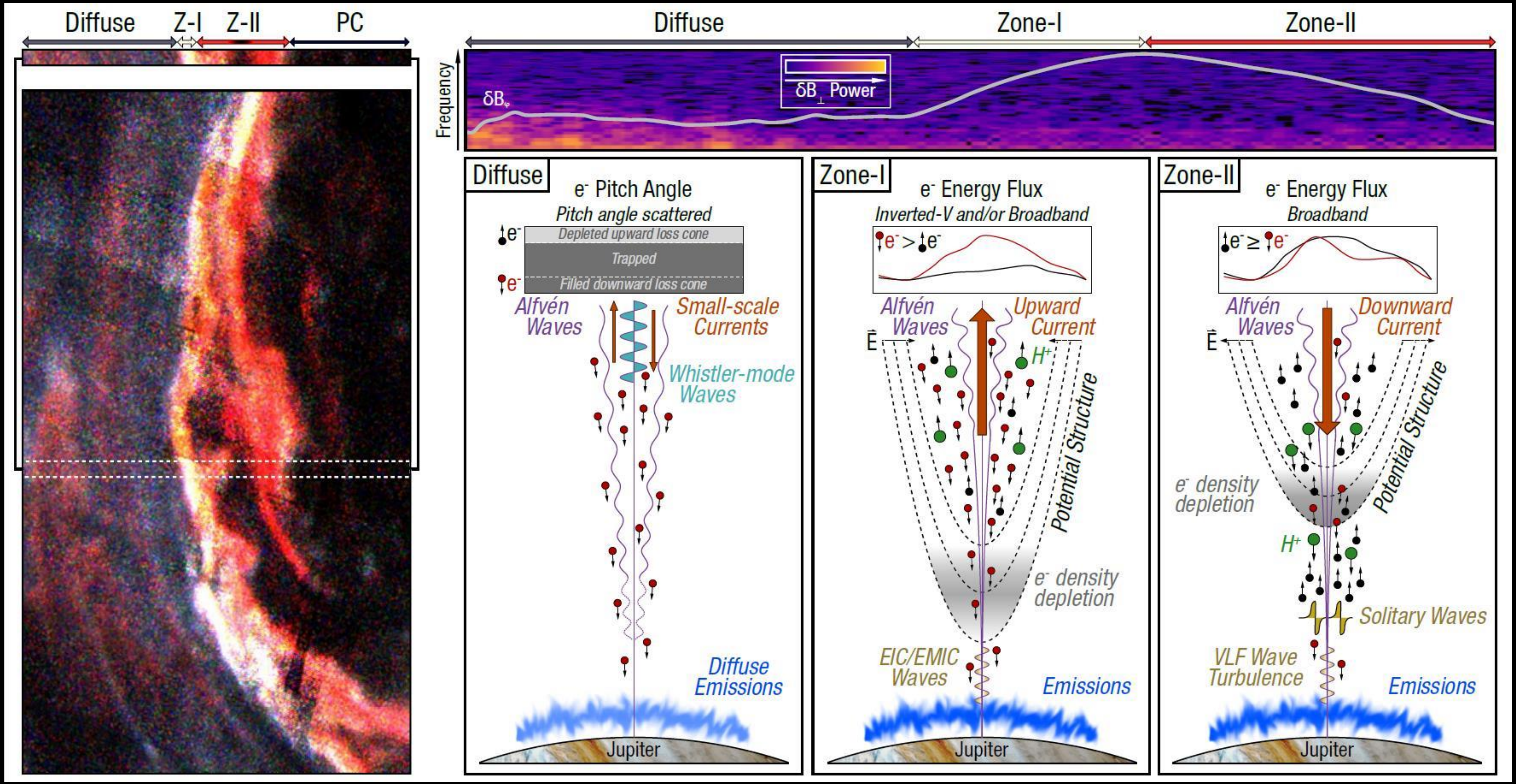
Ezoe et al. (2010); X-rays via inverse-Compton scattering with Suzaku

Global imaging of X-rays–similar to global perspective offered by ENAs



Credit: Image/HENA

Overview of Jupiter's Main Auroral Region



Sulaiman et al., 2022 [Credit: Szalay and Bagenal]