HEAVY-ION PLASMA PROPERTIES DURING ROTATIONALLY-DRIVEN INTERCHANGE EVENTS: INSIGHTS FROM JUNO OBSERVATIONS AT JUPITER

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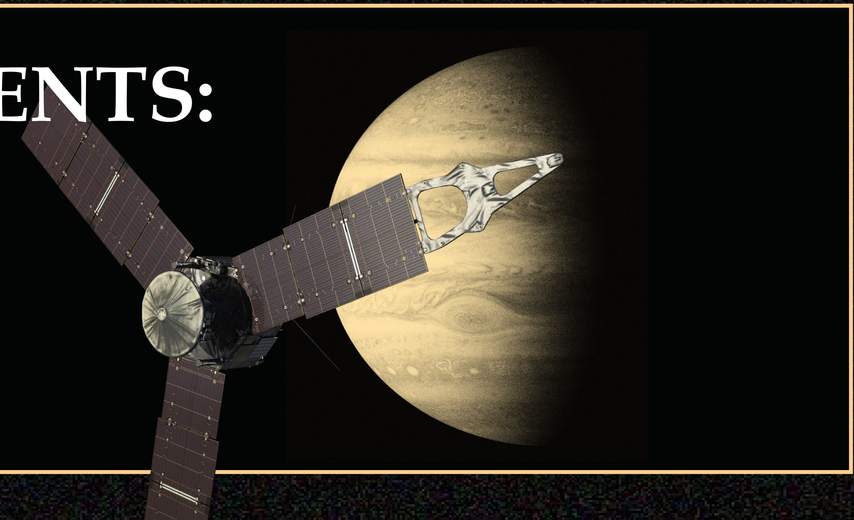
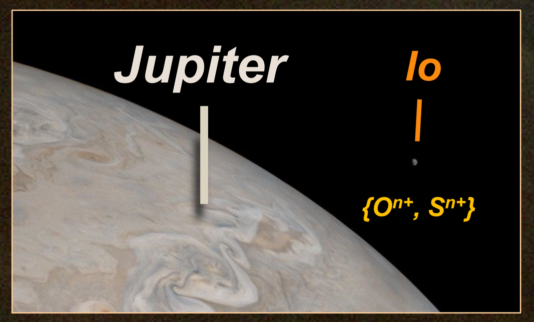


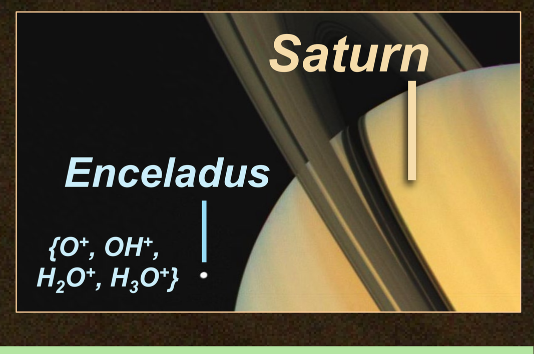
A ROTATIONALLY-DRIVEN INSTABILITY

What is the interchange instability?

→ A "Rayleigh-Taylor-like" plasma instability in the gas-giant magnetospheres, caused by a dense torus of moon-origin ions radially overlying an outer region of hot, lower-density plasma

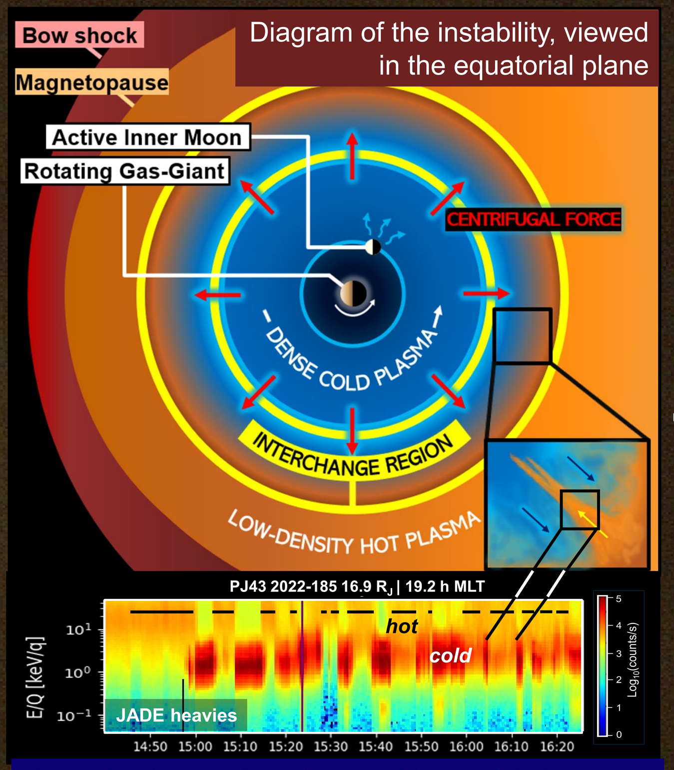
- Moon-origin plasma is coupled to the planets' magnetic field
- The plasma corotates rapidly, producing centrifugal forces
- Outward force ("heavy over light fluid") drives instability





What are interchange events (IEs)?

Rapid transport events through which the instability dynamically manifests itself; IEs carry in outer-magnetospheric plasma and magnetic flux, replacing the inner-magnetospheric plasma/flux



Example observation of several in-situ IE signatures

How do we observe interchange?

→ IEs are seen as **injection-like inflows**, featuring

- Enhancement of higher energy ions
- Depletion of lower energy ions
- Jump in magnetic field (B) and wave activity

Why are interchange events important?

→ Heavy, moon-origin ions dominate plasma density throughout the entire magnetospheric system

- **IEs play major role in global plasma circulation**

However, many questions remain regarding IEs:

→ What conditions **trigger** interchange onset?

→ What is the **structure** or **shape** of individual IEs?

→ What is the **global distribution** IE occurrence?

DATASETS & METHODOLOGY

The magnetosphere is **locally unstable** to interchange if transport causes a **decrease of potential energy, U:**

STABILITY CRITERION [Hill, 1976]

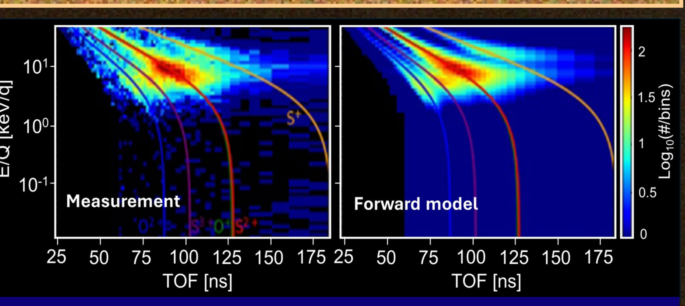
$$\Sigma \Delta U < 0$$

$$U = \int \frac{ds}{B}\left[\frac{\gamma}{\gamma - 1}P - \rho\frac{GM}{R} - \frac{1}{2}\rho\omega^2 r^2\right]$$

Interchange formation would thus depend on:

- total mass density ρ (thus: plasma composition)
- number density **n** (P=nkT)
- temperature **T** (P=nkT)

These parameters provide a means for identifying events and evaluating what conditions may trigger interchange.



Example FM fit of JADE (0.01–46.2 keV/q) TOF data

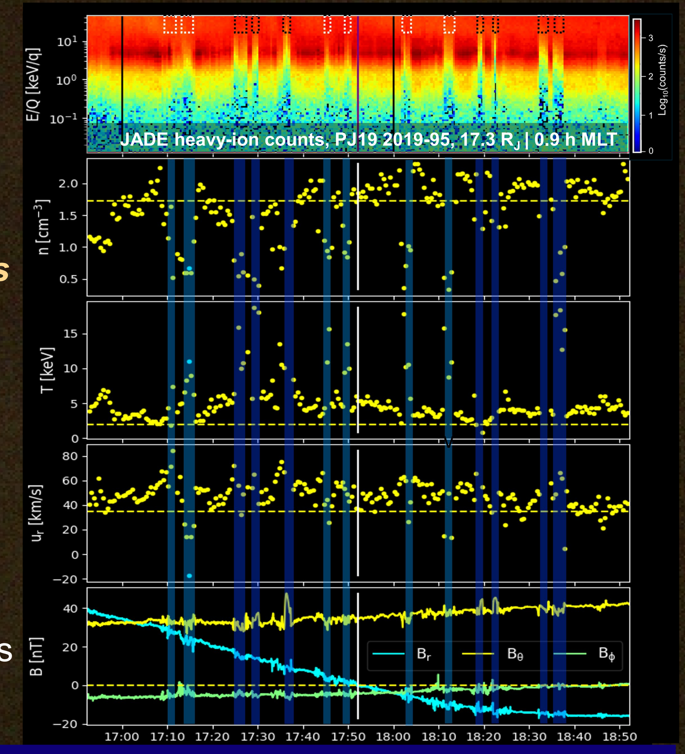
What's the approach for our analysis?

New **forward-modeling** (FM) techniques using time-of-flight (TOF) data can disambiguate the different heavy-ion species, as well as 3D bulk-flow velocity and temperature

→ Use Wang+ 2024 FM ion dataset (Juno JADE)

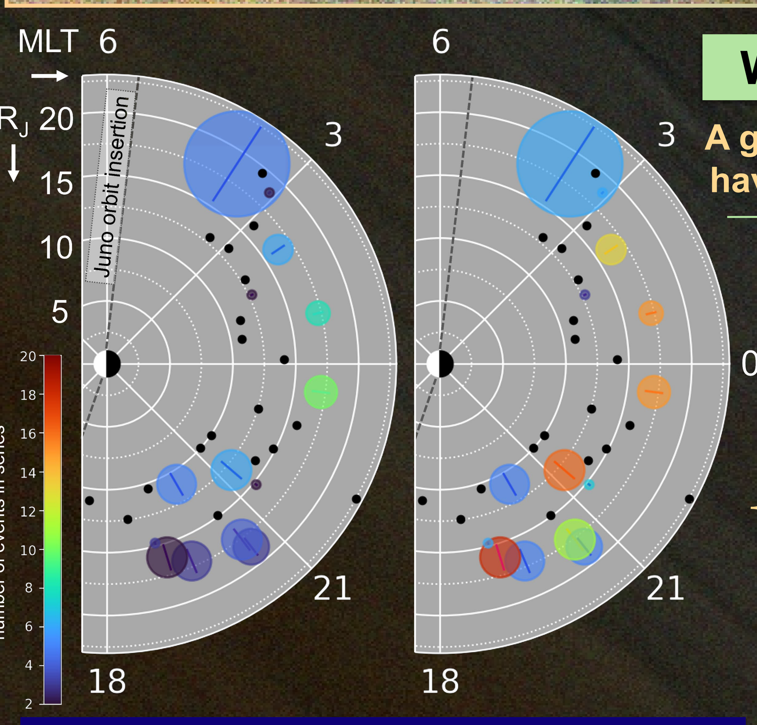
→ Use Daly+ 2024 (D24) Jupiter IE list as base set of events

- Analyze plasma properties in already identified IEs
- Identify additional events using **n**, **T** excursions
- Focus on Jupiter; compare insights with Saturn



Example 2-hr period of interchange; identified events are highlighted (D24 = dark blue; this study = light blue)

RESULTS: JOVIAN INTERCHANGE CLUSTERS AND THEIR PROPERTIES



Map of isolated IEs and clusters in R-MLT plane. Left: D24 events only; Right: D24 & n, T jump events

What do we mean by an interchange "cluster"?

A group of consecutive IEs; here we arbitrarily define a cluster as having 4 or more events observed within < 1 hour of one another

D24 list: **107** identified events (**70** events with FM ion data):

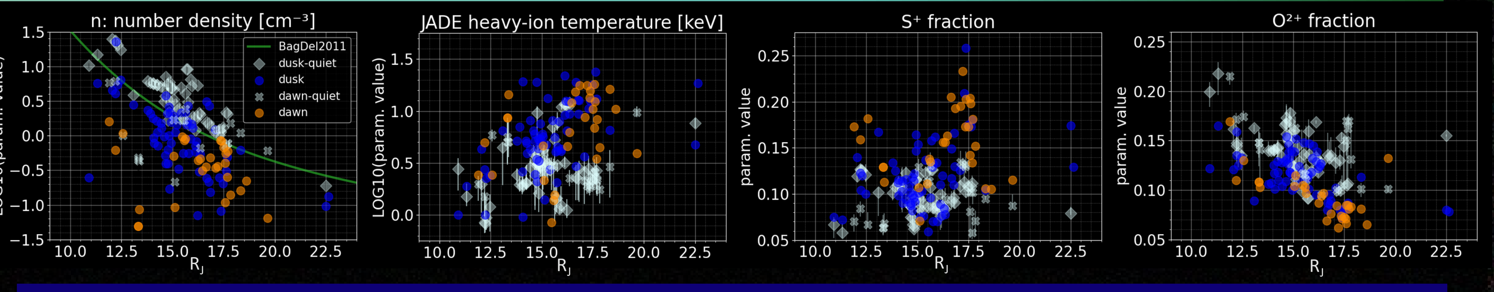
- **33** events (47%) occurred in a **cluster**
  - **6 clusters total** • **average ~6 events/cluster**

For current study, located ***n, T*** jumps in vicinity of D24 IEs:

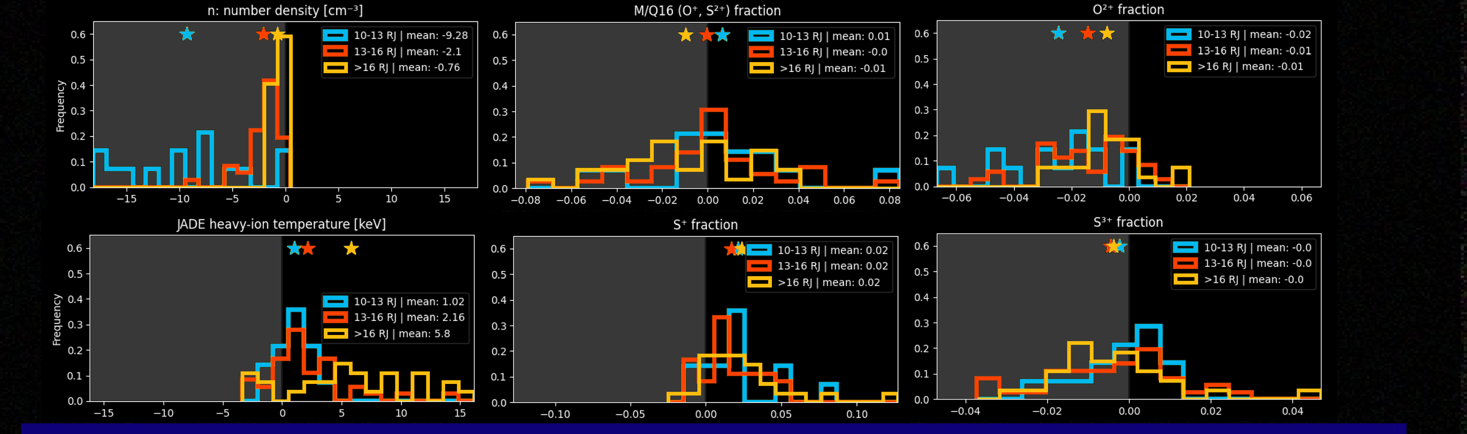
- **~73 additional IEs manually identified**
- Majority (~97%) within larger IE cluster
- With these new interchange events included:
  - **12 clusters total** • **average ~10 events/cluster**

Analysis of properties in all 143 events with FM ion data:

- Greater jumps in T (n) for events at larger (smaller) R
- Composition jumps (↑ S^+, ↓ O^{2+}) also depend on R

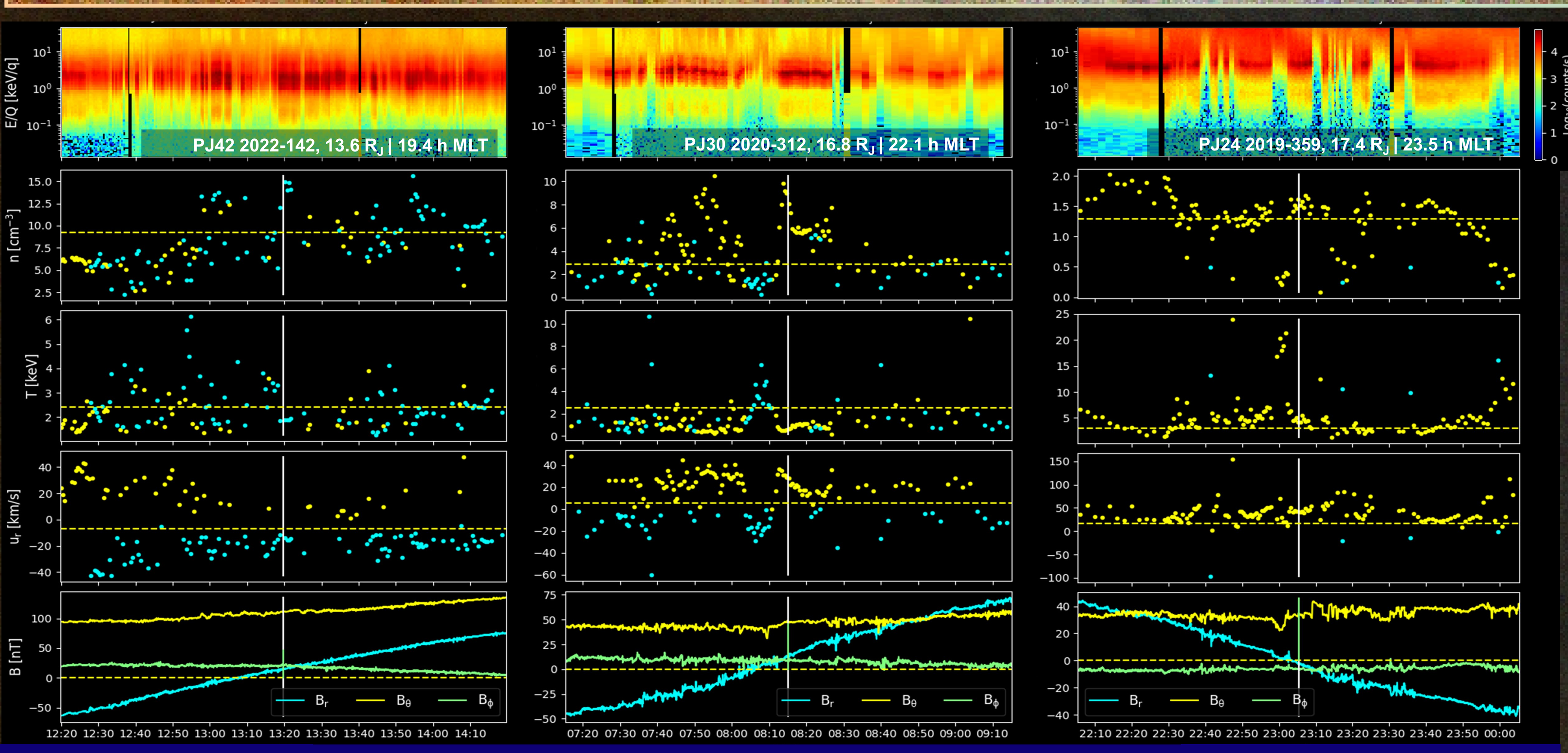


IE properties as a function of radial distance (colored), compared against comparable quiet time values (white)



Distributions of density, temperature, and composition anomalies during all (D24+this study) identified IEs

TWO DISTINCT JOVIAN INTERCHANGE-INTERVAL BEHAVIORS



MORE TYPE-1 LIKE ← **behaviors seen in IE-like clusters** → **MORE TYPE-2 LIKE**

Cluster behavior type 1

→ Many short-lived or narrow IEs

- Fine IE "striping" of plasma spectra

→ IE-signatures in spectra most organized in u_r

- Many sharp jumps between negative (inflow) and positive (outflow), coincide with IE "stripes"
- Inflows rarely more than 50 km/s

→ Density and temperature highly fluctuating

- Neither clearly dependent on sign of u_r

Cluster behavior type 2

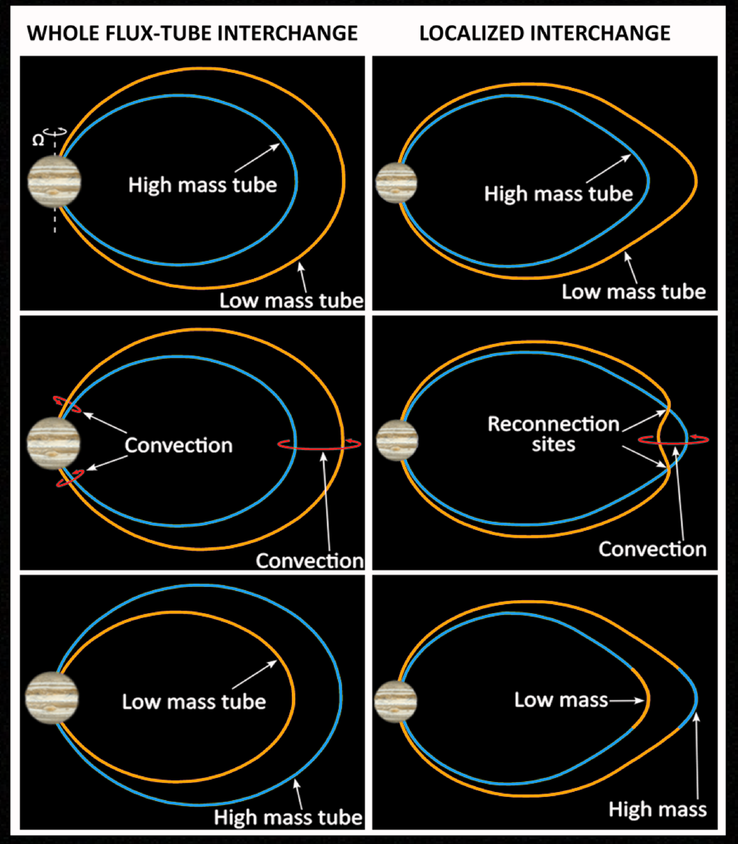
→ Longer and/or wider individual IEs

→ IE-signatures in spectra organized in **n, T**

- Often coincident drop in n and jump in T, but sometimes only one will markedly change

→ u_r displays non-uniform behavior

- Can be extremely strong inflow or outflow (>100 km/s speed), or not change at all…

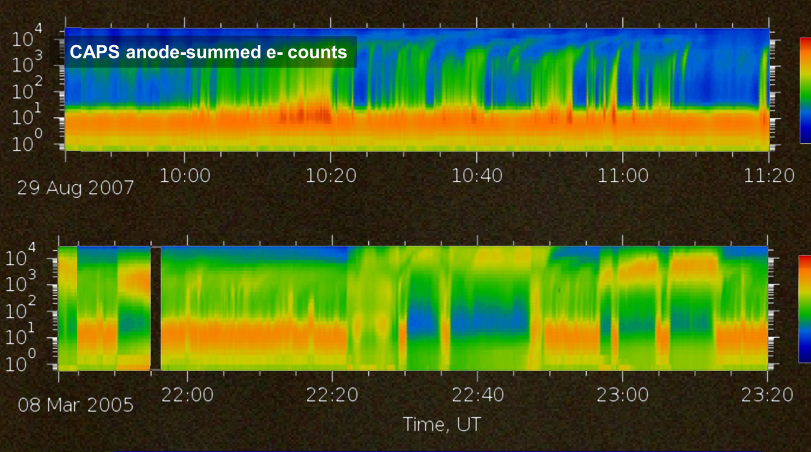


Two possible interchange mechanisms that may cause different cluster behaviors (Wang et al. 2025)

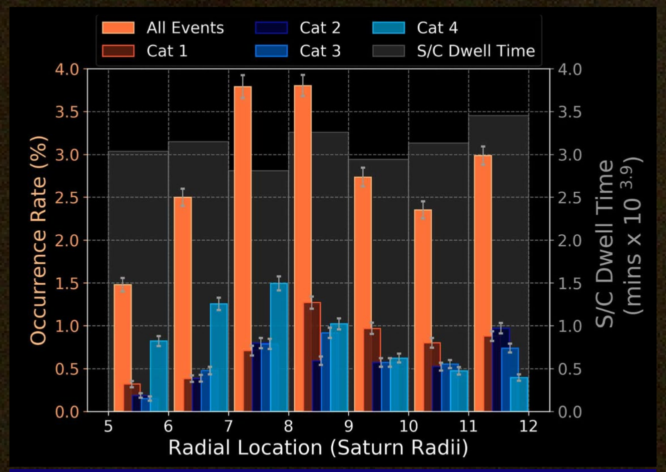
SIMILARITIES AT SATURN

At Saturn, IEs have also been extensively observed and statistically evaluated with in-situ data

- Interchange events often occur in clusters, similar to what is seen at Jupiter
- Different clusters show different individual IE intensities and widths; some of these clusters align with the type-1 and type-2 classifications discussed above
- Unique to Saturn, older IE flows can be identified as high-energy dispersions in the spectra



Examples of more type-1-like (top) and more type-2-like (bottom) spectral signatures for two different interchange clusters observed by Cassini CAPS



Radial distribution of different intensity IEs (cat. 1 = category 1 = least intense) registered by Cassini in Saturn's magnetosphere (from Azari et al. 2018)

What are the main takeaways?

1) **Density and temperature excursions may be used as a method to expand IE datasets**
2) **The plasma properties within Jovian interchange events depend strongly on R, including how certain heavy-ion species (S^+, O^{2+}) become more or less prominent**
3) **Interchange clusters show distinct types of behaviors; classifying the exact aspects and occurrence rates of these IE "types" may elucidate different instability modes**

What are the next steps?

→ **Carry out this analysis for Saturn with newly released FM dataset; compare with Jupiter**

→ **Go through all plasma-disk crossings to develop holistic, standardized IE-ID procedure**

→ **Evaluate spatialization of IE intervals with different characteristics (e.g., type 1 vs type 2)**

References:

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Acknowledgements: A. Roosnovo thanks Dr. Mike Liemohn for primary science feedback, as well as Dr. Fran Bagenal, Dr. Jian-Zhao Wang, and Alec Daly for support in dataset usage. This research was conducted with support from the University of Michigan Rackham Merit Fellowship program and continues to be developed with support from the NASA FINESST Fellowship.

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