

Can we observe the effects of gradient drift on convecting plasma using ENA imagery?

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1 Introduction

The Cassini Ion-Neutral Camera (INCA) captured wide-area energetic neutral atom (ENA) emissions from Saturn's magnetosphere, typically showing diffuse enhancements linked to magnetotail reconnection and injected plasma subsequently interacting with the extended neutral water cloud. These ENA features often correspond with ultraviolet auroral and kilometric radio emissions and can persist for days.

We utilize a newly re-calibrated and re-projected INCA dataset to superpose high energy (90-230 keV) Oxygen and lower energy Hydrogen bands. This superposition may resolve energy-dependent gradient drifts from imagery, complementing in situ-based estimates. We segment the imagery and track the morphology and spatial extent of the ENA emission at each INCA energy range for the most intense events observed.

2 Dispersion drift of injected plasma

Saturn's inner magnetosphere has low flux of trapped energetic ions due to charge exchange with the water neutral cloud. Instead, in situ observations (e.g., Figure A) reveal signatures of plasma injections that move inward and spread azimuthally via radial flow shears and dispersive drift. Estimating their age by back-tracing drift paths is complex. It requires assumptions about the bulk plasma's drift rate, which varies with distance, and is complicated by the spacecraft being immersed in multiple, evolving flow channels of varying ages e.g., Paranicas et al., 2007.

High-latitude INCA imagery uniquely captures the global azimuthal flow patterns of the plasma via the ENA emissions. We want to assess the amount of dispersion resolvable in the INCA image energy ranges. **What's the expectation at these ion energies?** The total azimuthal drift rate for a given particle species, ω , is the sum of the plasma rotation rate, Ω , and the gradient-curvature drift rate,

$$\omega = \Omega + \omega_D \quad (1)$$

We estimate the bounce-averaged gradient drift speed (in rad/s) of ions mirroring in the equatorial plane of a dipole field following Mauk et al. (2005), and references therein:

$$\omega_D = 3.94 \cdot 10^{-5} \left(\frac{q_0}{q} \right) E_{MeV} \frac{(E_{MeV}/2 + m_0 c^2)}{E_{MeV} + m_0 c^2} L \quad (2)$$

Figure B illustrates the dispersion effect on ion energies at a range of $L = 7 R_S$, in steps of 3 hours after a hypothetical injection at $T = 0$. Figure C illustrates this in the frame of Saturn's magnetosphere and ENA image capture (from Mitchell et al. 2009).

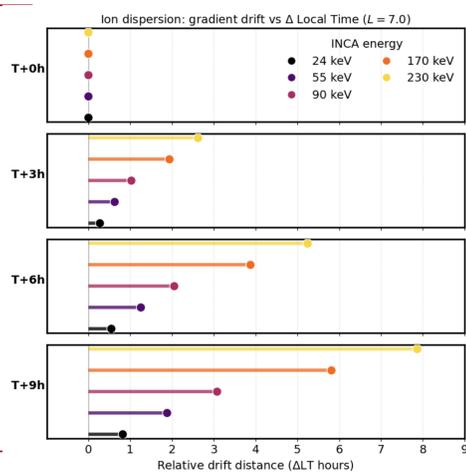


Figure B: Gradient drift developing $T + n$ hours after a coherent injection at $L = 7 R_S$ in a dipole field, for the INCA energy range. These energy-dependent drifts add to the plasma's bulk angular velocity under $E \times B$ drift, and result in a spatial 'fanning out' of the injection channel in LT and radial distance. After Mauk et al. (2005) for pitch angles of 90° .

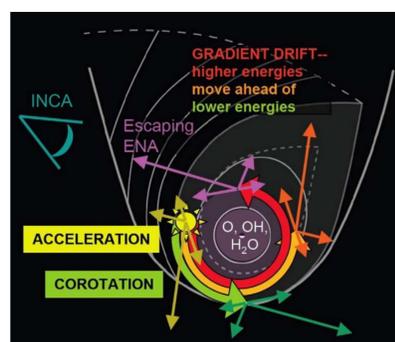


Figure C: Illustration of how energetic ions spread azimuthally in Saturn's magnetosphere under gradient-curvature drift. The dispersion pattern of an injection event develops within the frame of the bulk plasma flow. Adapted from Mitchell et al. (2009).

The statistical ENA tori show that injected ions have asymmetric trajectories around Saturn under the influence of a global noon-midnight E-field. The ions transect a range of radial distances and associated azimuthal shear flows, as well as the L-dependent dispersion drift. Higher energy ions reach deeper into the magnetosphere, further complicating the picture.

Figure D: Statistical ENA tori resulting from a re-calibration and re-projection of the entire INCA dataset. Adapted from Kinrade, Bader et al. (2021).

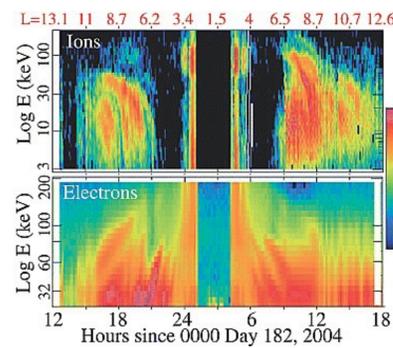
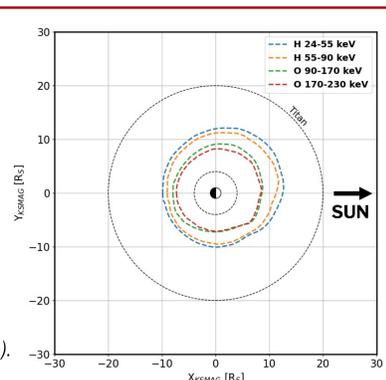


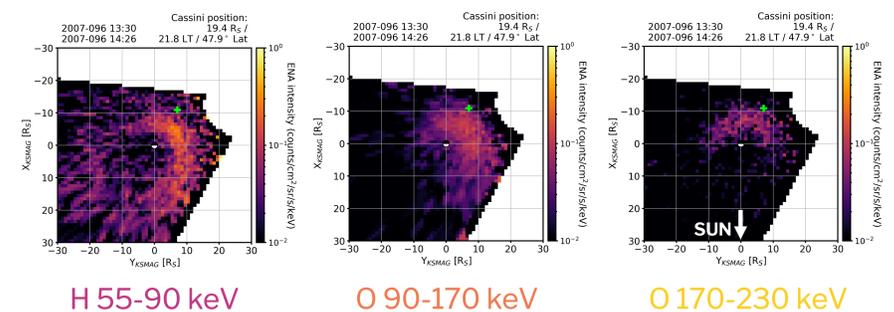
Figure A: In situ particle signatures of plasma injection from Cassini CHEMS (top, ions) and LEMMS (bottom, electrons). Higher energy ions typically reach the spacecraft ahead of those at lower energies. Adapted from Mauk et al. (2005).

3 Open questions

- How much dispersion is resolvable in Cassini INCA imagery?
- The ENA signal lags planetary rotation speeds; why is the plasma lagging?
- Is there a recurrent re-energization process around midnight? e.g., Mitchell+ 2009.
- How does this re-energization change the dispersion pattern of existing plasma injection flows?
- How much does the global E-field asymmetry influence ENA morphology?

4 Dispersive drift in ENA imagery?

Examining INCA image projections across different energy bands reveals differences in the captured ENA morphology. These three images, showing a typical rotating injection enhancement, are averaged over the same ~ 60-minute window, each representing an energy 'sub-population' of the full plasma distribution.



The ENA enhancement appears at later local times with increasing energy. But how do we decouple dispersive drift effects from the global plasma circulation? i.e., can we quantify the enhancement spreading in local time as it evolves? The signal-to-noise ratio of the intensity also varies with INCA's energy bands, making this non-trivial.

5 Motion tracking

We use an image processing method called Voronoi segmentation, inspired by the VOISE algorithm developed by Guio & Achilleos (2009). INCA images are initially segmented randomly, and cells are then recursively merged or further segmented after comparison with their neighbours. We repeat this many times on each image, and the result is a seed cloud showing images areas of persistent structure. The centroid of the cloud lets us track bulk plasma flow at a certain energy, while the radial and azimuthal extents are a measure of cloud size at it develops in time.

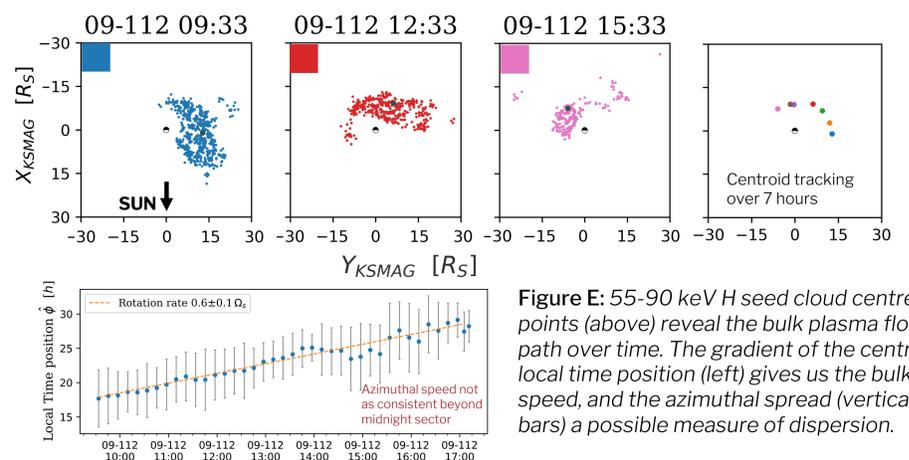


Figure E: 55-90 keV H seed cloud centre points (above) reveal the bulk plasma flow path over time. The gradient of the centroid local time position (left) gives us the bulk drift speed, and the azimuthal spread (vertical error bars) a possible measure of dispersion.

6 Summary

- Injected plasma at Saturn undergoes both $E \times B$ drift and energy-dependent dispersive drift, making the back-tracing of injection ages from in situ data complex.
- By tracking the evolving morphology of ENA emissions across INCA's full energy range, we aim to decouple the dispersive spread of plasma injections from the bulk plasma rotation.
- After a Saturn rotation, expect ~8 h LT gradient drift between INCA's lower and upper energy imagery at $7 R_S$.
- Energetic Oxygen ion gradient drift rates up to ~ 40-55% of rigid corotation at peak ENA intensity distances of $7-10 R_S$.

7 Implications for Jupiter

- Enhanced capability:** JUICE mission is flying with an advanced ENA imager, JENI, that has wider energy range (0.5-300 keV) and improved spatial resolution compared to INCA.
- Complex dispersion patterns:** Jovian system strongly plasma-dominated, resulting in longer ion lifetimes (Bagenal & Delamere, 2011) and potentially more extensive and complex dispersion patterns that JENI may be able to resolve and track. Strong magnetospheric stretching may significantly enhance localized gradient-curvature drifts.
- Quantifying global dynamics:** This technique could provide novel, global constraints on the drift rates of high-energy ions, key to understanding Europa & Io as neutral sources.

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Acknowledgements

- Cassini MIMI instrument team.
- Nick Achilleos for chats about the VOISE algorithm.
- STFC funding grant ST/Y002393/1.

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