Global Magnetospheric Dynamics of Jupiter and Saturn Revealed by ENA Imaging

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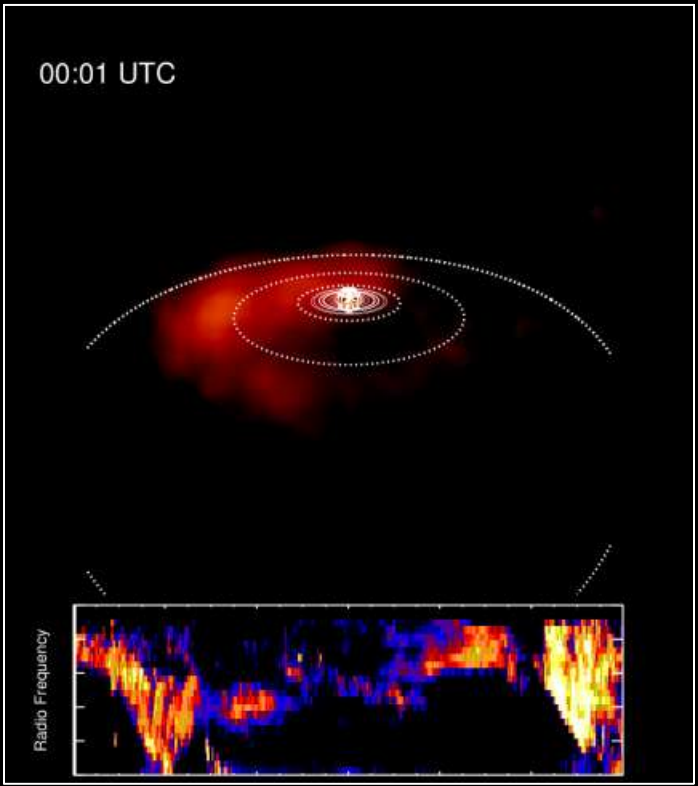
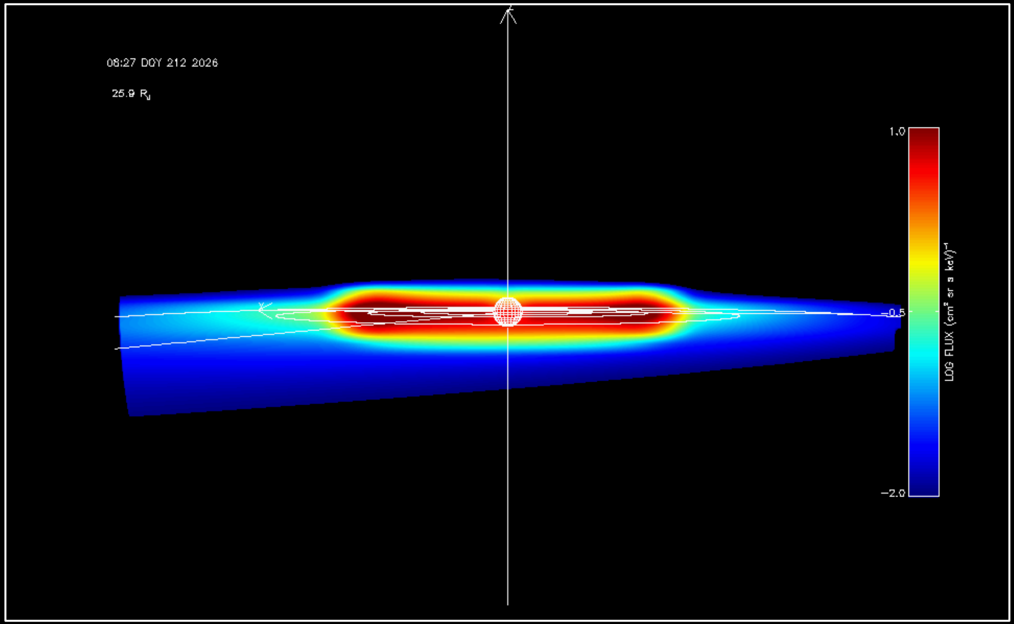
Saturn

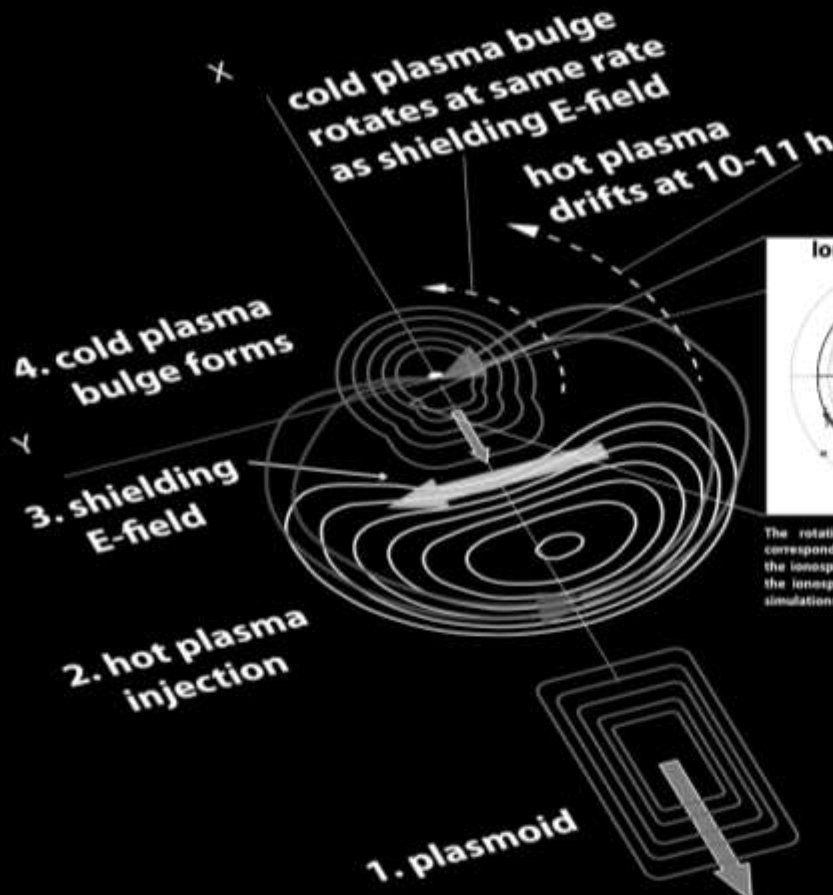


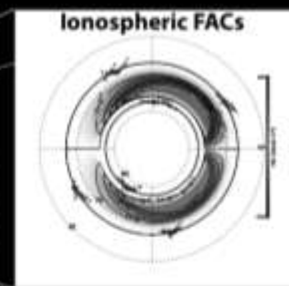
Jupiter



POSTER: In Search for a Self-Consistent Hypothesis for Magnetospheric Periodicities: Effects of the Shielding E-field Produced by the Partial Ring Current

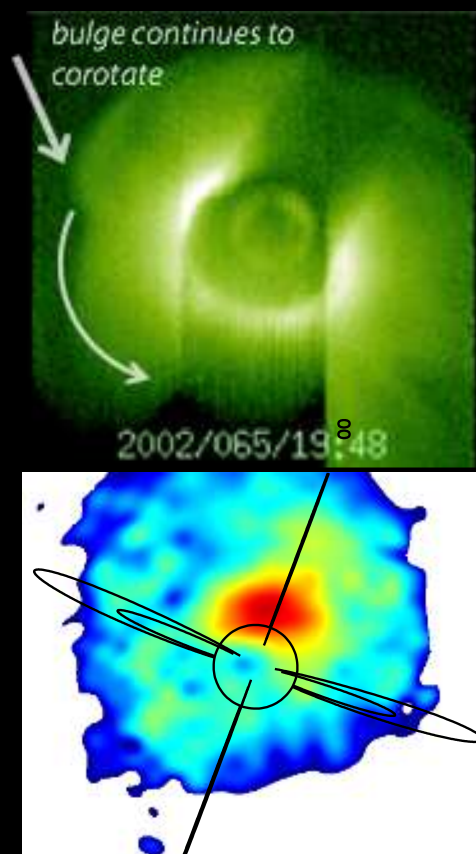
Pontus C. Brandt, D. G. Mitchell,Y. Ebihara



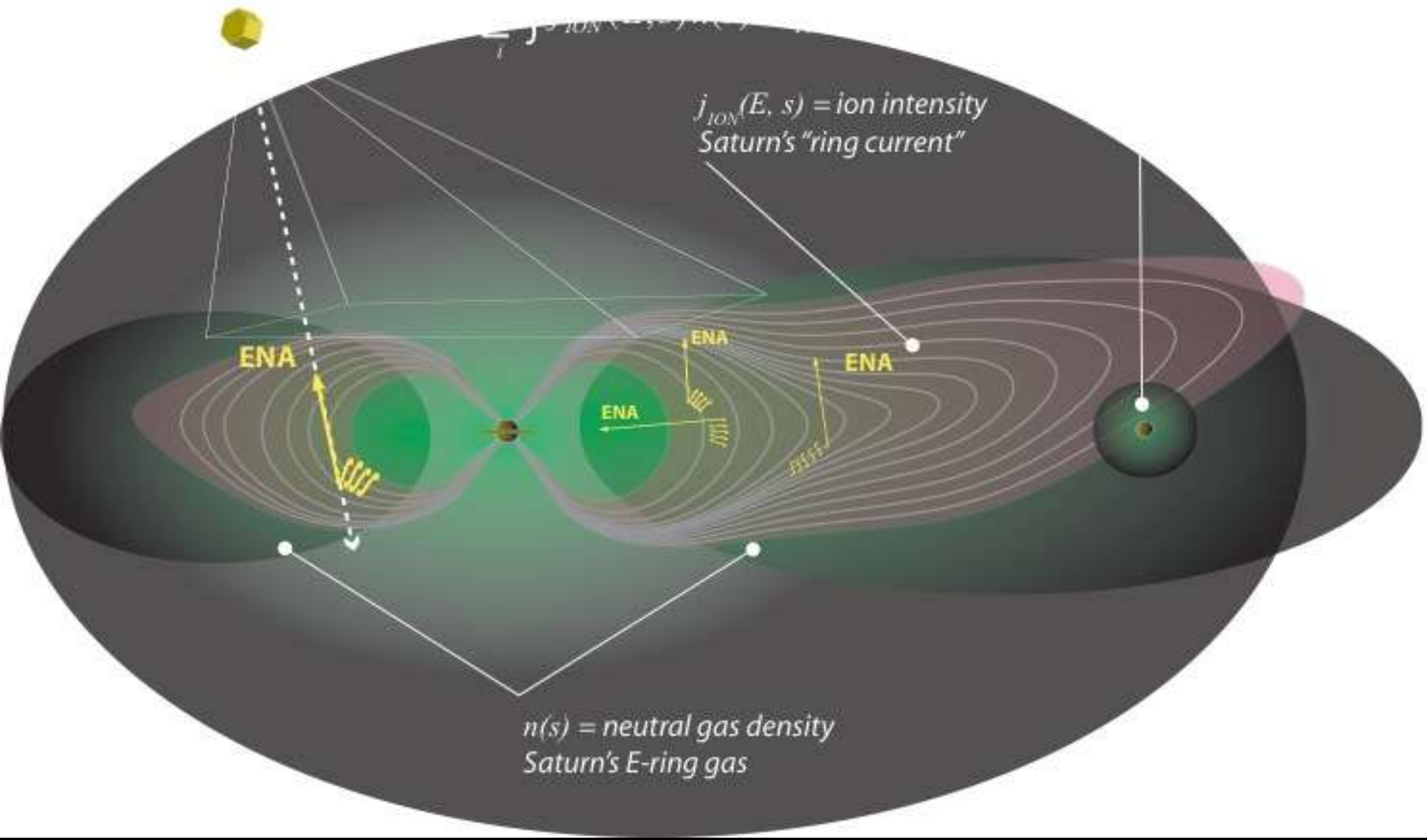


The rotating, asymmetric PRC drives a corresponding rotating FACs in and out of the ionosphere that can fill the purpose of the ionospheric vortices prescribed in the simulations of Jia et al. [2011].

Shielding effects on the terrestrial plasmasphere

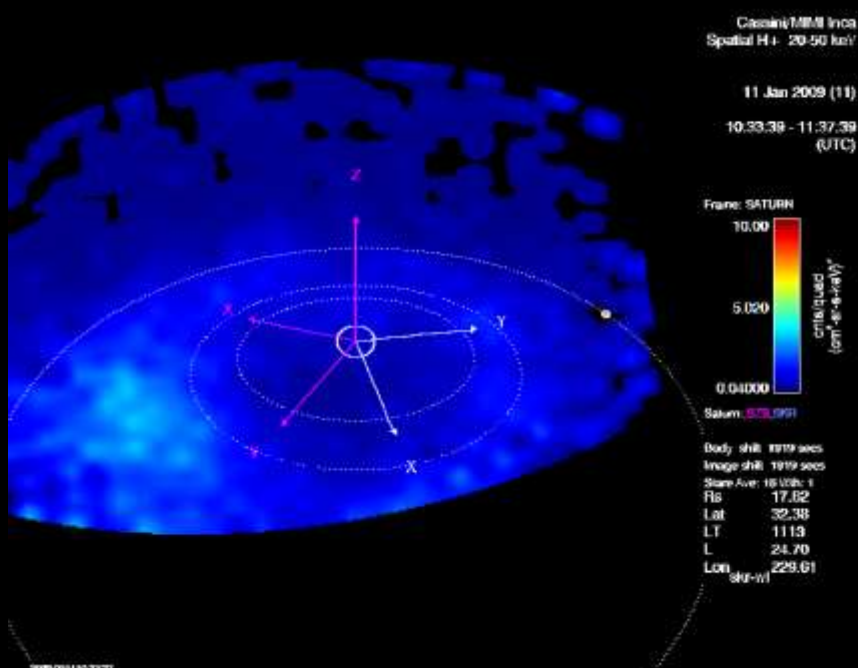


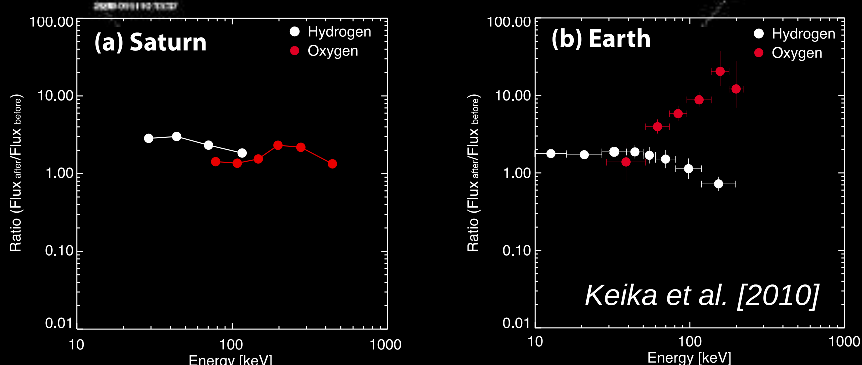
ENA imaging



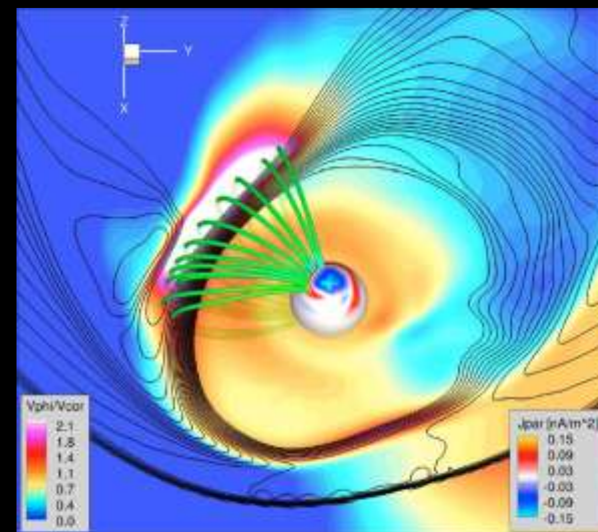
$j_{ION}(E, s)$ = ion intensity
Saturn's "ring current"
ENA
ENA
ENA
ENA
$n(s)$ = neutral gas density
Saturn's E-ring gas

Energization





Keika et al. [2010]

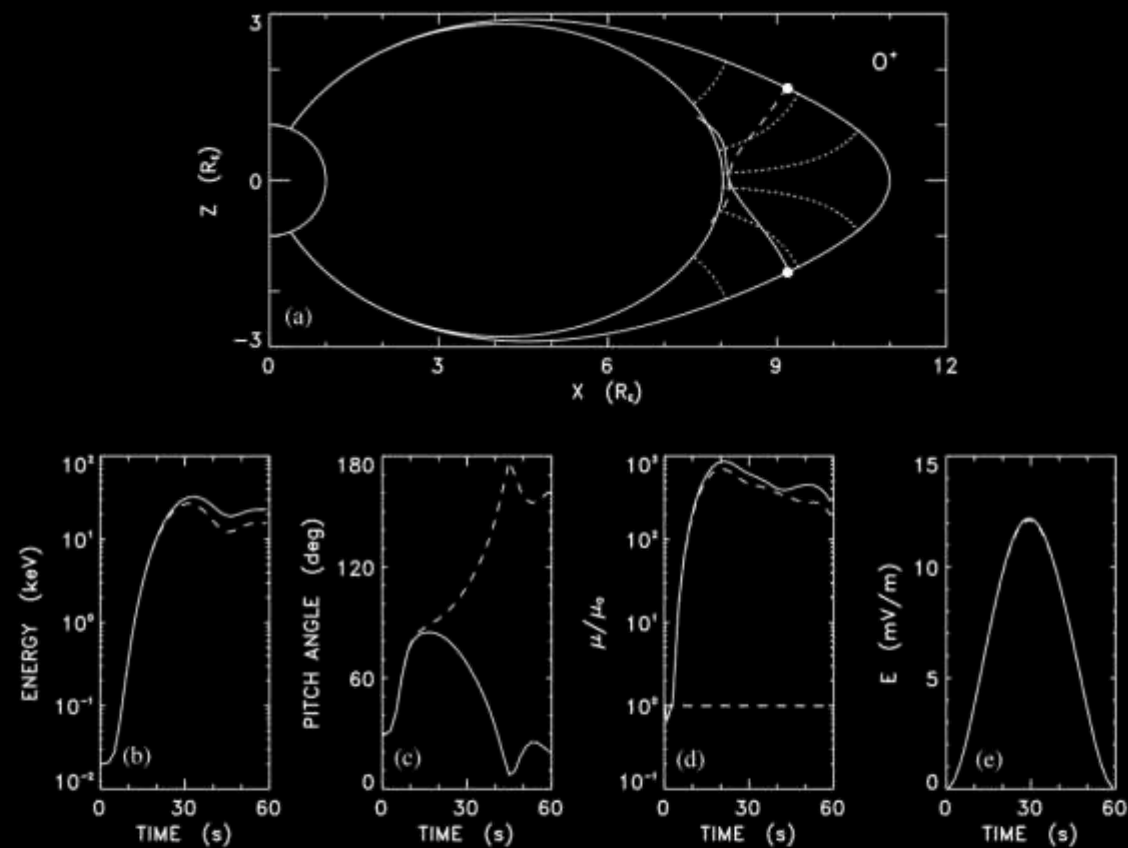


Jia et al., MAPS, [2011]

- **Large-scale injections appear in the night side magnetosphere**
- **Energization most likely caused by the "dipolarizations" following plasmoid releases**
- **Heavy ions are more effectively energized than lighter**

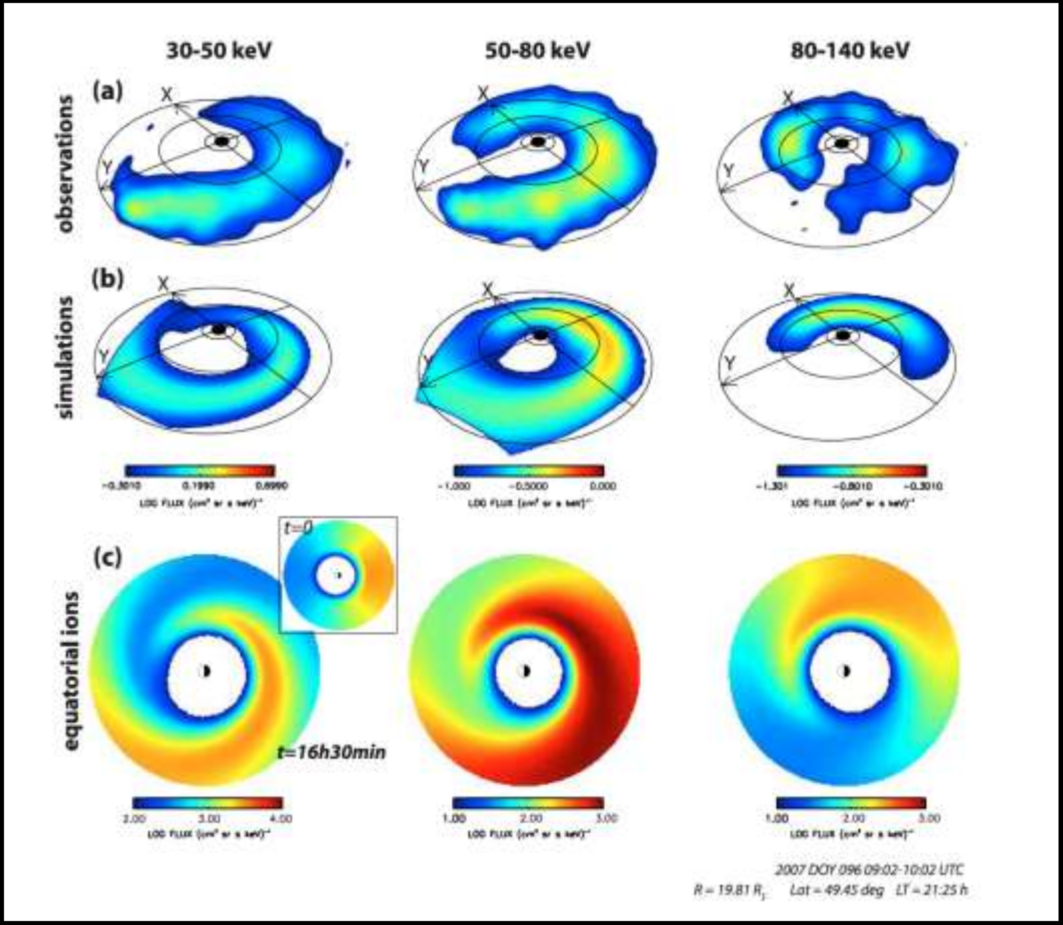
Energization: Earth comparison

D.C. Delcourt / Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 551–559



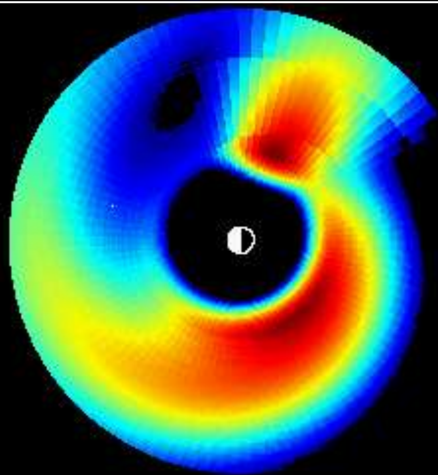
Ions are efficiently energized during rapid magnetic field reconfigurations. Shown are model results of O^+ for terrestrial substorms. Similar mechanisms are probably at work also at Mercury and Saturn.

Transport

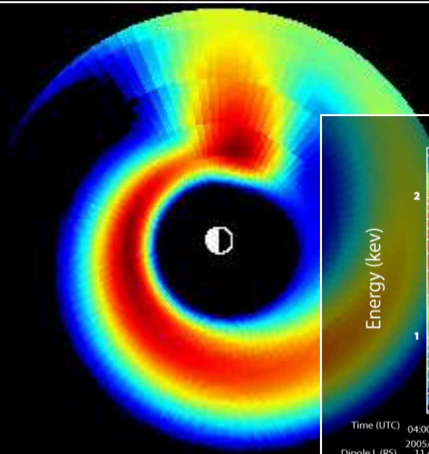


Brandt et al. [2008]

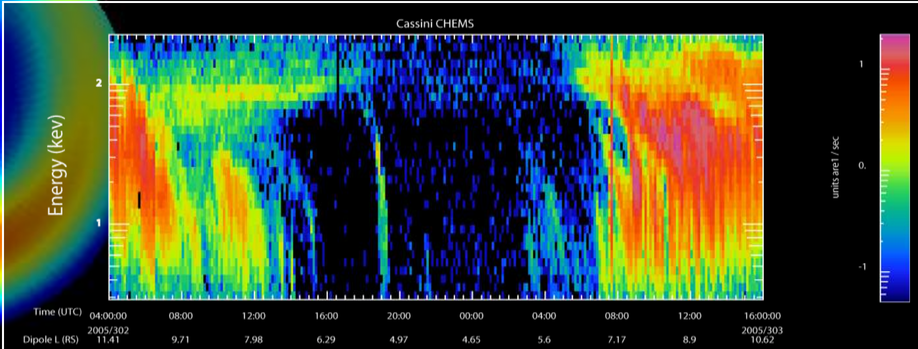
Transport



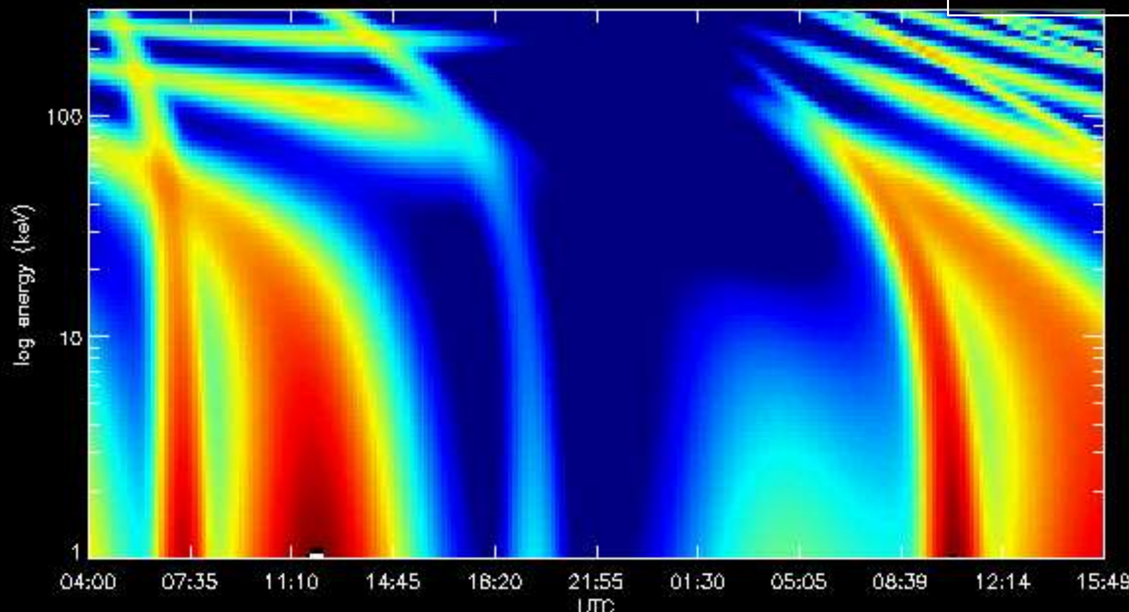
10 keV



100 keV



Typical in-situ dispersion signatures indicating injections of different ages and sizes.



Simulation showing <u>one possible</u> global distribution that reproduces the dispersion observed in-situ.

Force Balance: 3D Current System

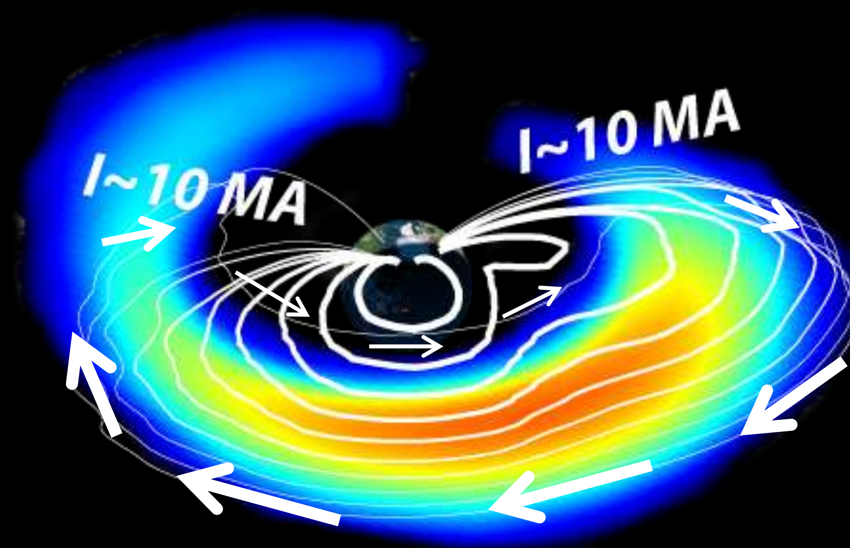
force balance $\mathbf{J} \times \mathbf{B} = \nabla \cdot \mathbf{P}$

current continuity $\nabla \cdot \mathbf{J} = \mathbf{0}$

$$\mathbf{J}_\perp = \frac{\mathbf{B}}{B^2} \times \left[\nabla P_\perp + (P_\parallel - P_\perp) \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{B^2} \right]$$

$$B \frac{\partial}{\partial s} \left(\frac{J_\parallel}{B} \right) = -\nabla \cdot \mathbf{J}_\perp$$

particle motion [*Parker, 1957*]

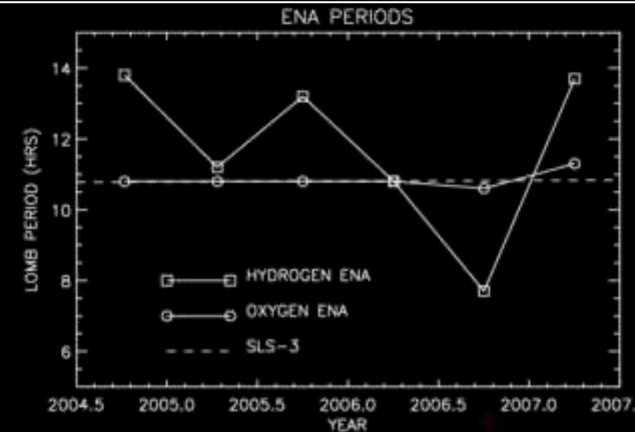


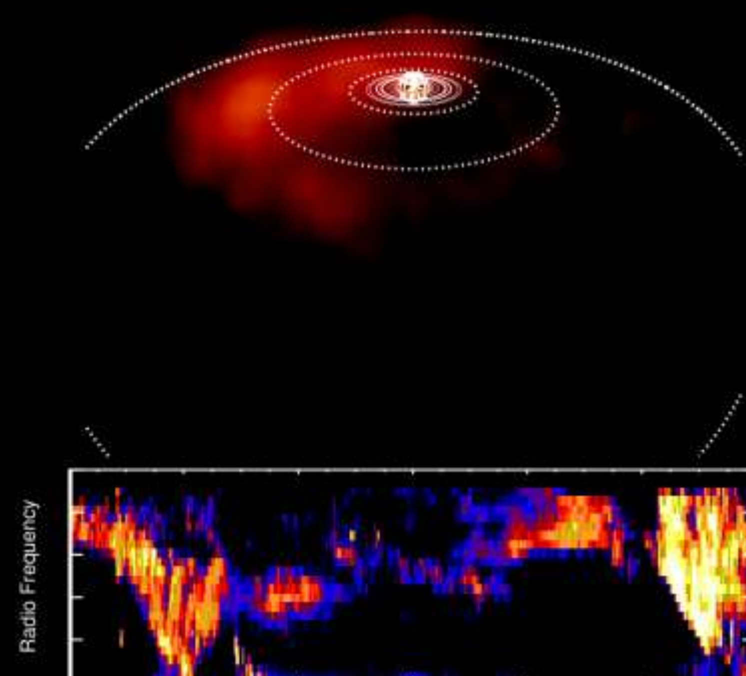
The main phase ring current system ("Region-2") is highly asymmetric and is driven by the pressure of the inner magnetosphere.

Periodicity: ENA and SKR

- **"ENA injections " simultaneous with SKR [Mitchell et al., 2009]**
- **ENA injections simultaneous with in-situ observation of a plasmoid release [Hill et al., 2008]**
- **SKR most likely driven by (1) pressure-driven currents from energetic particles and/or (2) flow-shear in the fast-flow region**
- **Lifting the veil:**
  - *Periodic plasmoid release the most likely driver of the magnetospheric periodicities*
- **Dual periodicities in ENA data?**
  - *Not clear yet…see Carbary's talk!*

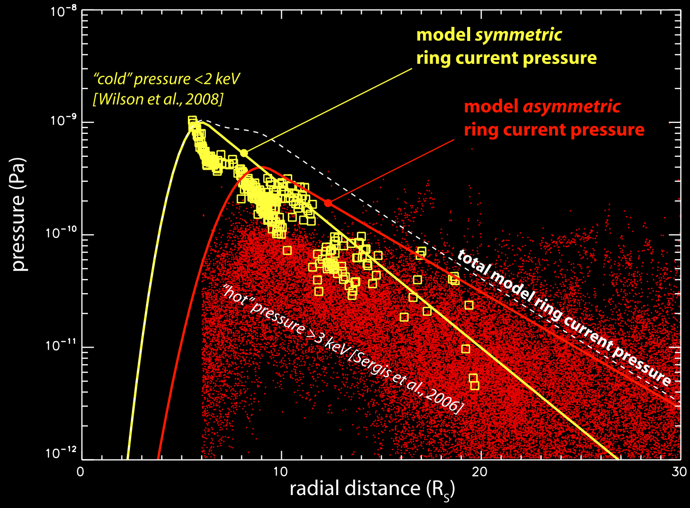
00:01 UTC

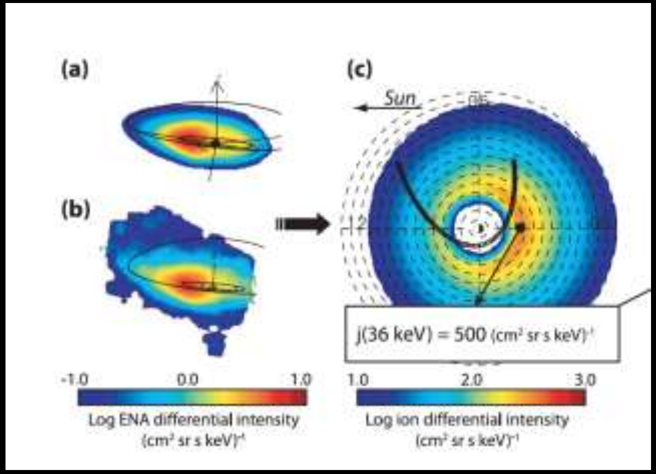




Periodicity: Magnetic field

- **Preliminary estimations demonstrate that the injected plasma pressure and subsequent drift can account for the field perturbations, at least around the equator [Brandt et al., 2010]**
- **More rigorous effort under way, where the field perturbations from a rotating PRC is added to a bkgrd field model**
- **The background field model is an updated version and faster version of KMAG06 including all data [Tsyganenko, Khurana and Brandt]**





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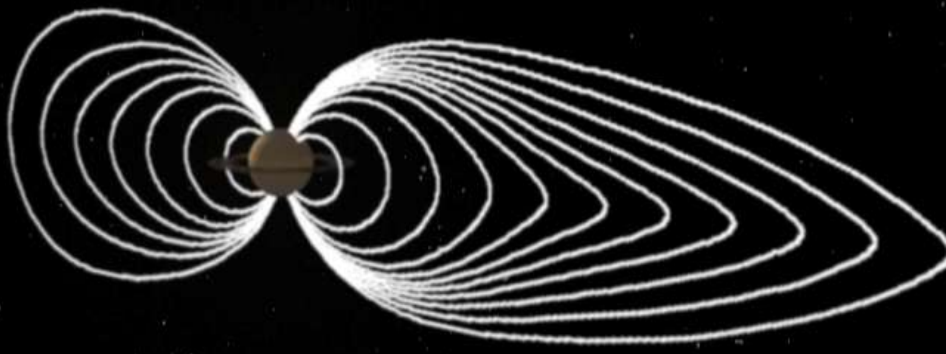
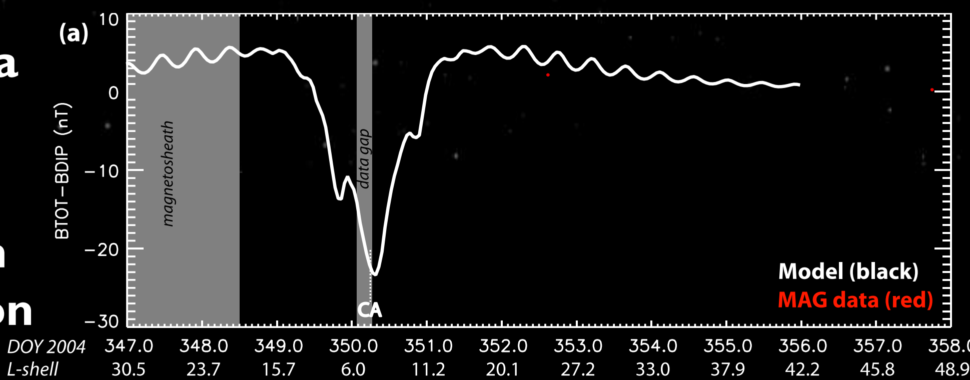
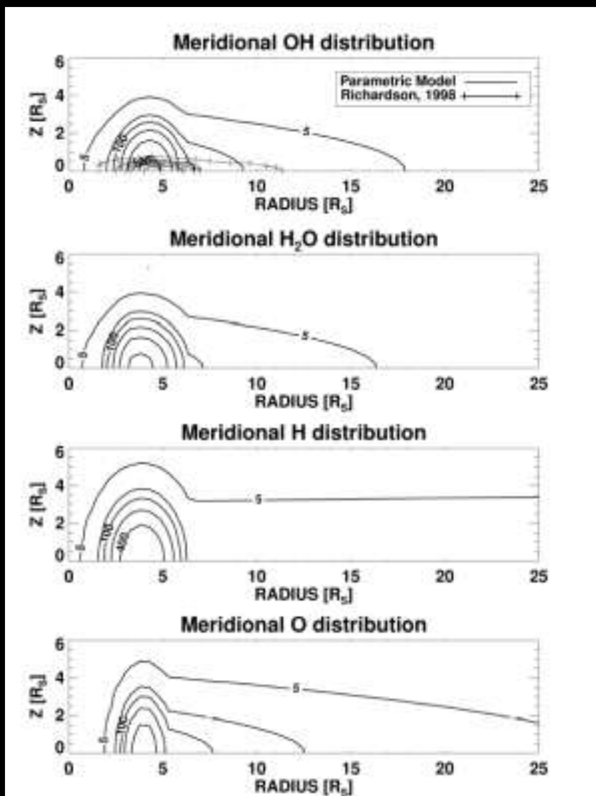


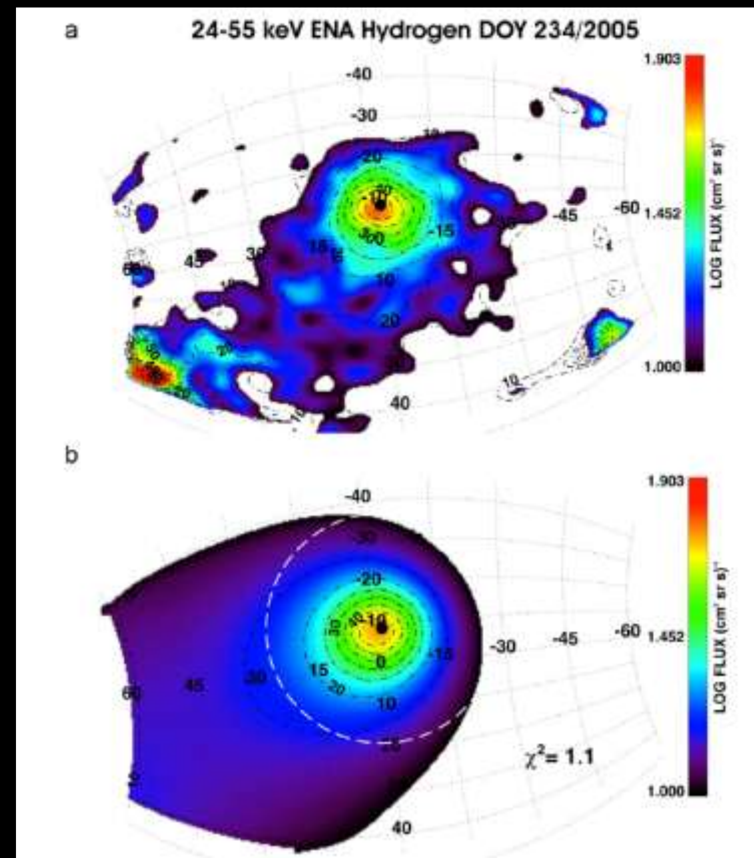
Brandt et al., Geophys. Res. Letters, 2010



Neutral gas

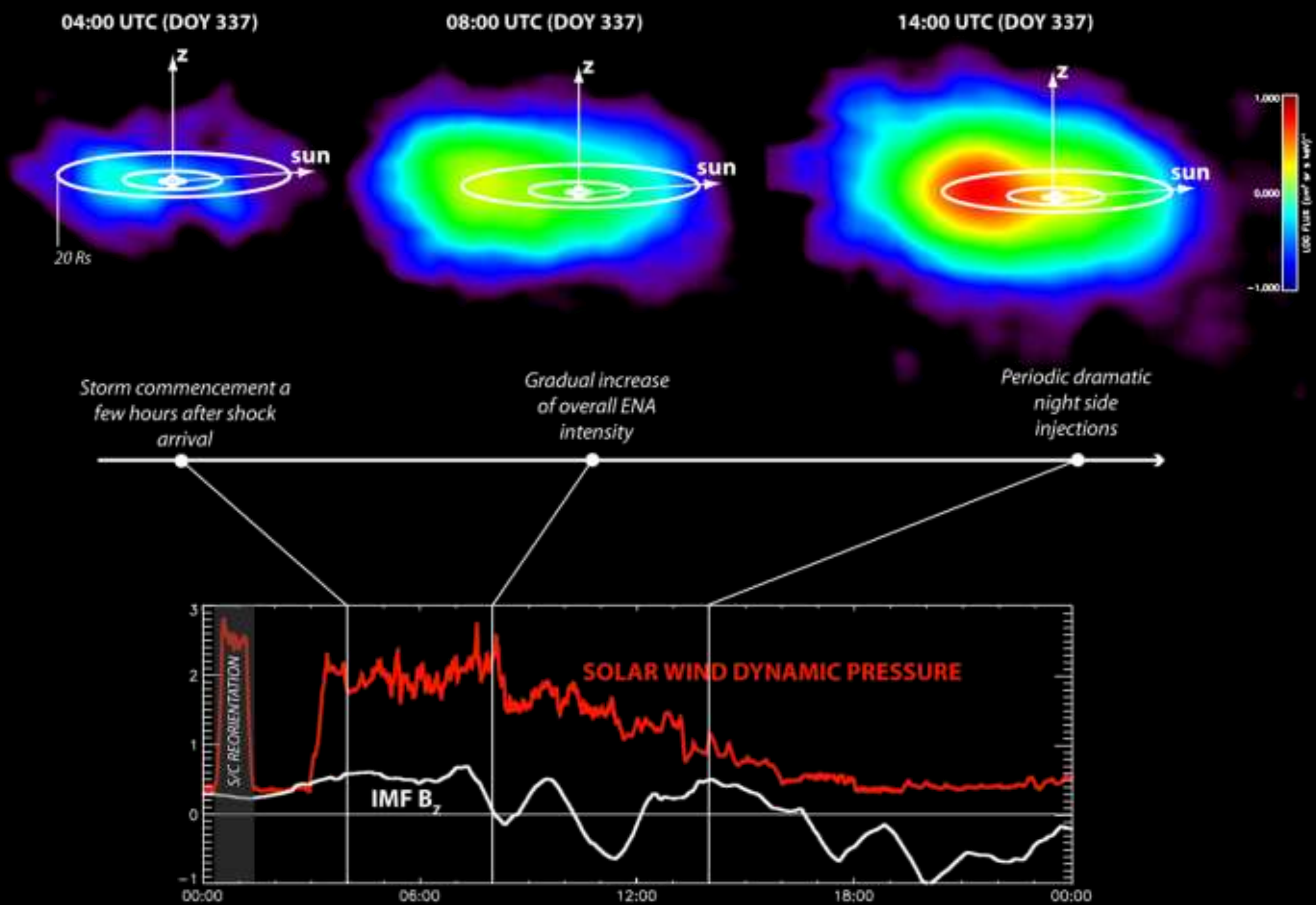


Dialynas et al., in preparation, 2011.



Brandt et al., PSS, 2011.

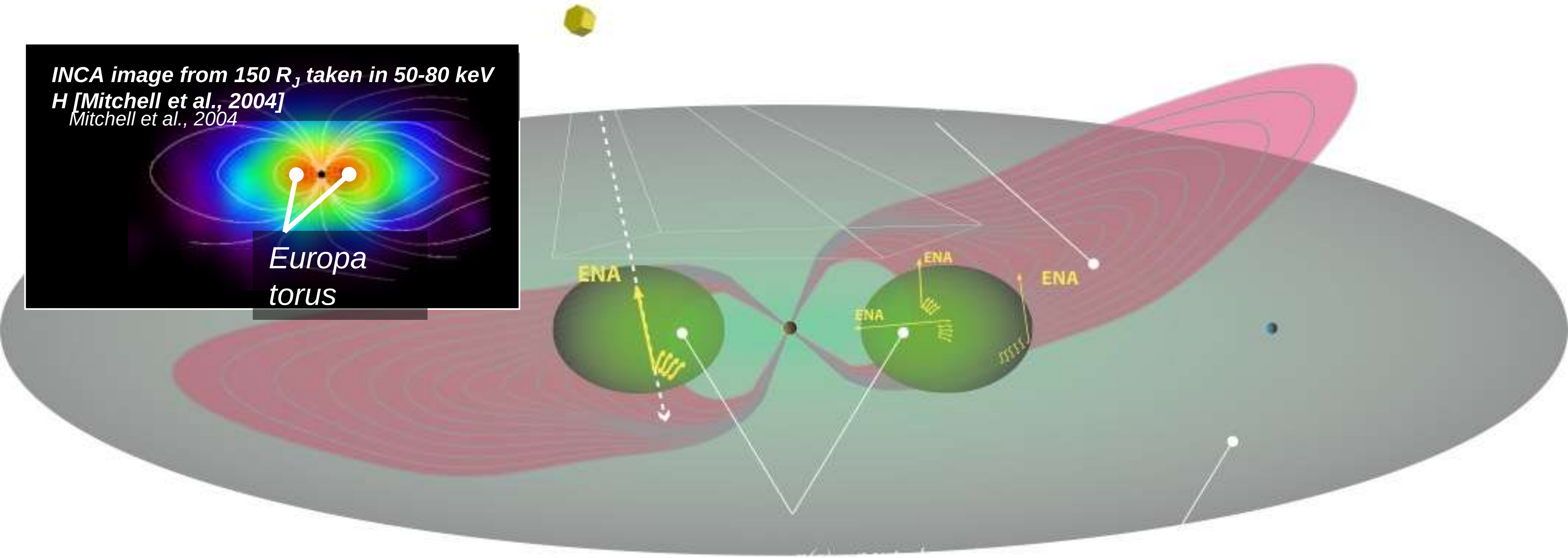
Solar wind control

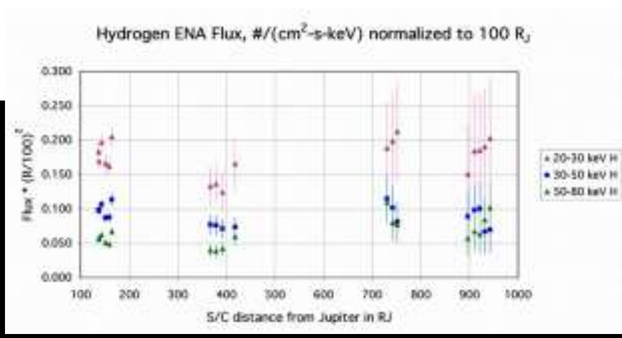


Brandt et al., AGU, 2006.

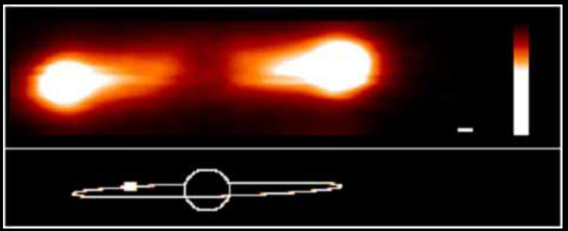
ENA imaging

INCA image from 150 R_J taken in 50-80 keV H [Mitchell et al., 2004]





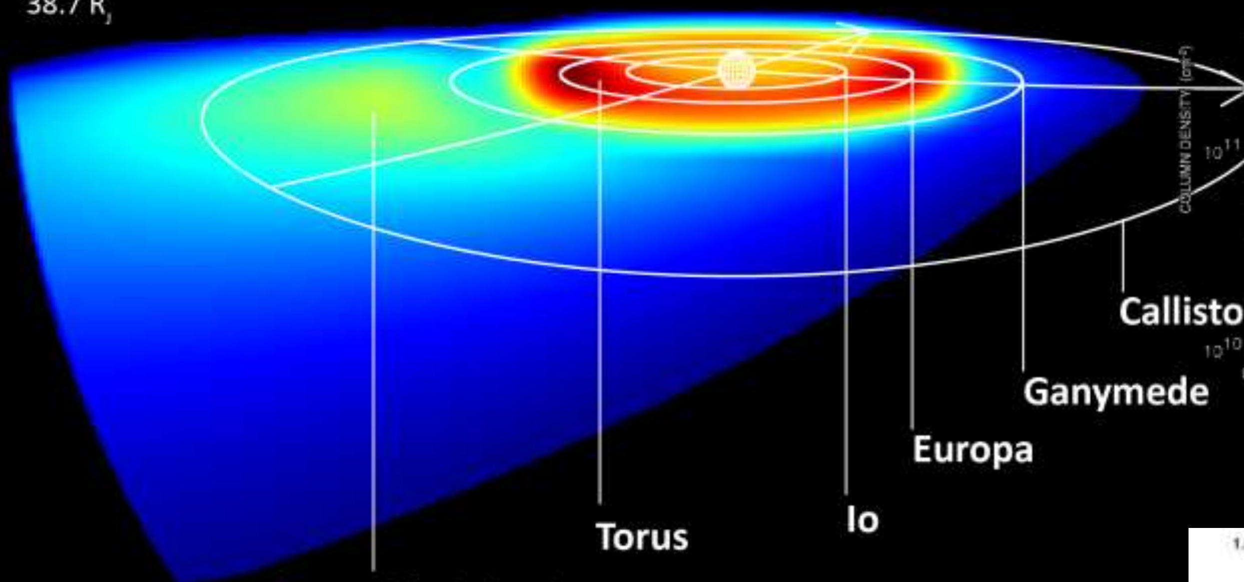
Cassini/UVIS (S-band emissions)



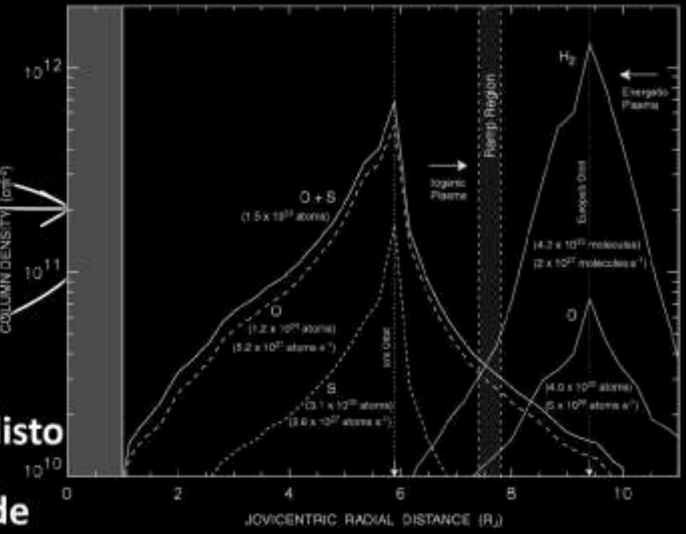
ENA imaging: Simulations

ENA image of the Jovian magnetosphere (40 keV H)

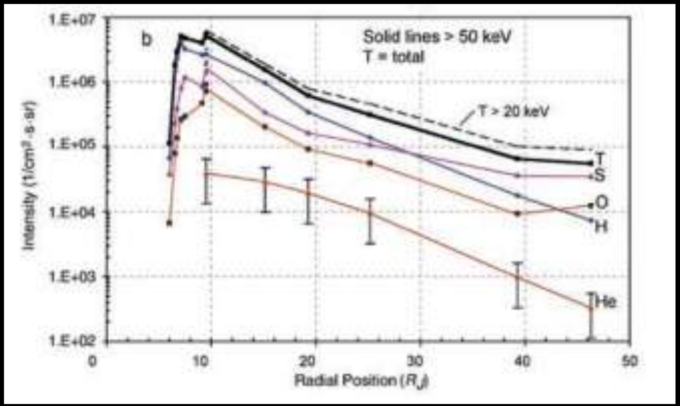
JGO Orbit Insertion
DOY 198 2026
38.7 R_J



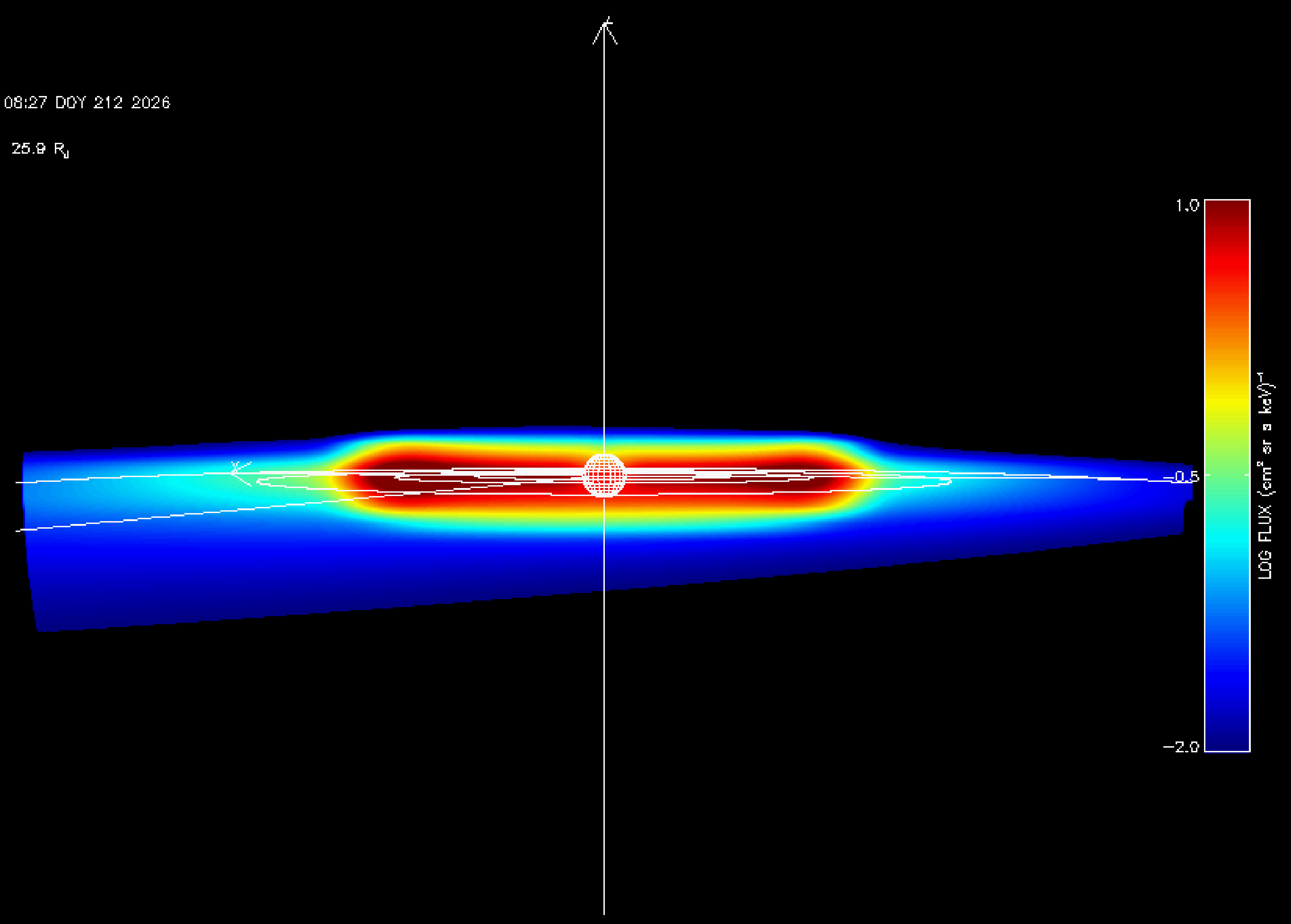
Neutral gas [Smyth et al., 2005]



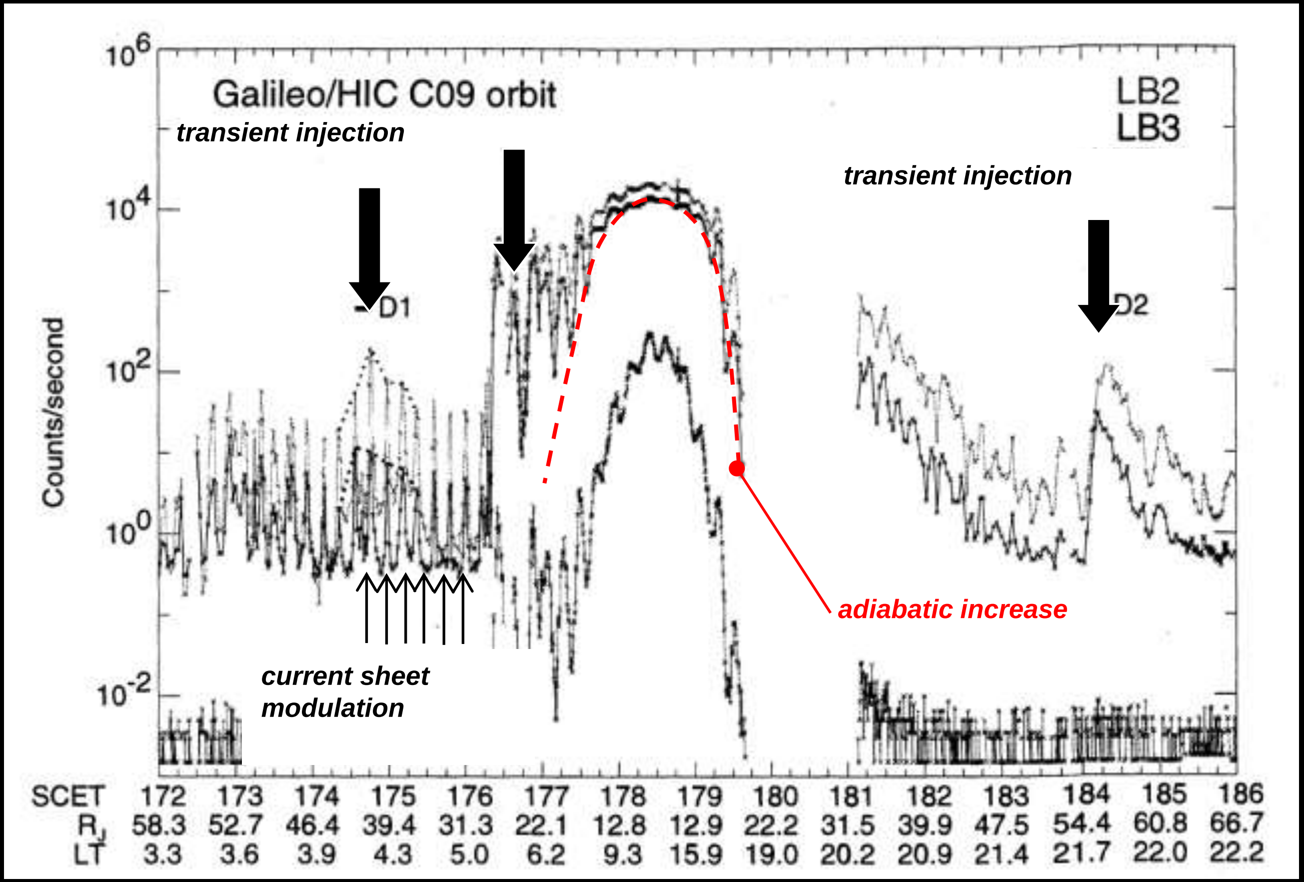
Energetic ions [Mauk et al., 2004]



ENA imaging: Simulations



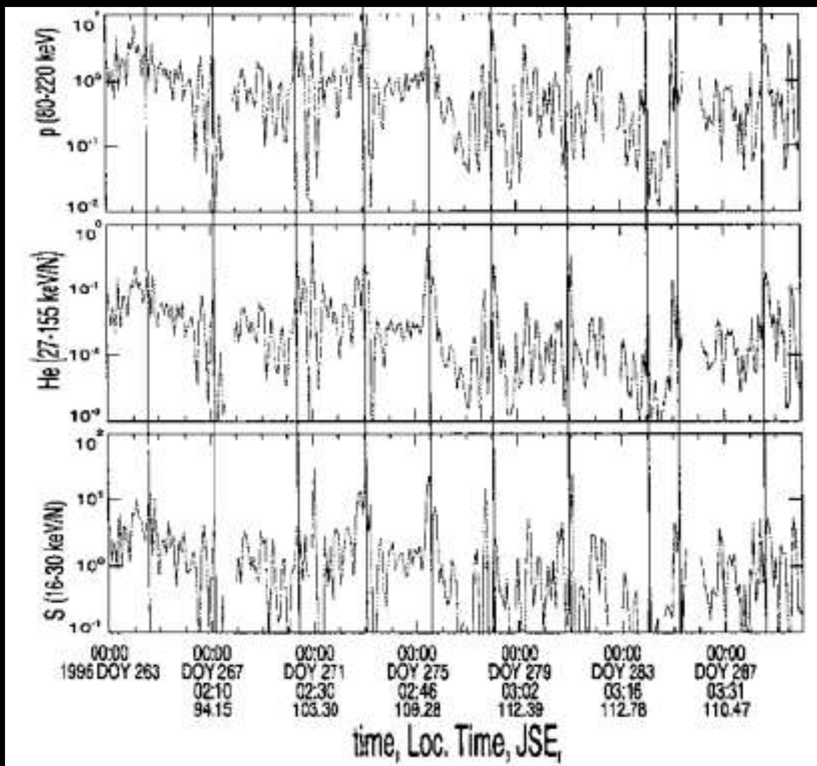
Energization



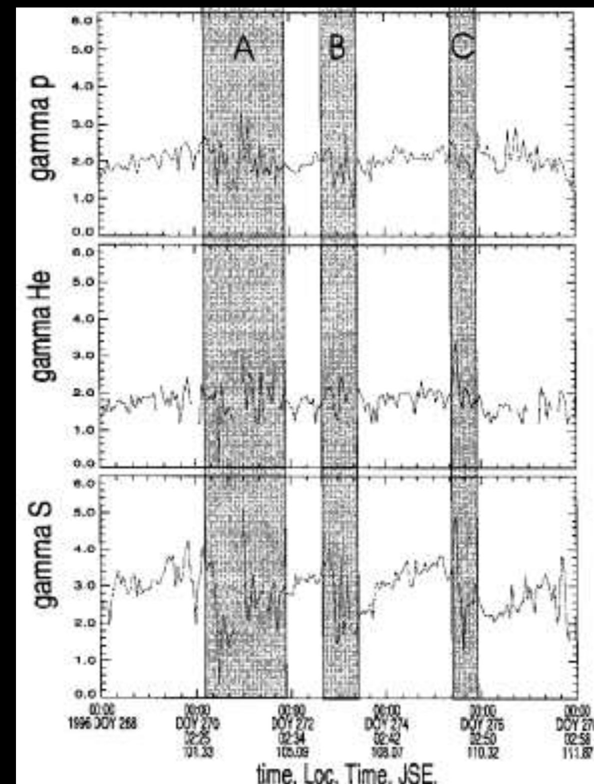
Transient, quasi-periodic injections are seen in in-situ data, but it is nearly impossible to discern their global spatial and temporal distribution and evolution. Data taken from Selesnick et al. [2001].

Energization

Intensities



Spectral slope



Intensities and spectral slopes of heavies increase more than for lighter ions every ~3 days. Is this the same non-adiabatic mechanism that is at work at Earth?

Krupp et al. [1998]

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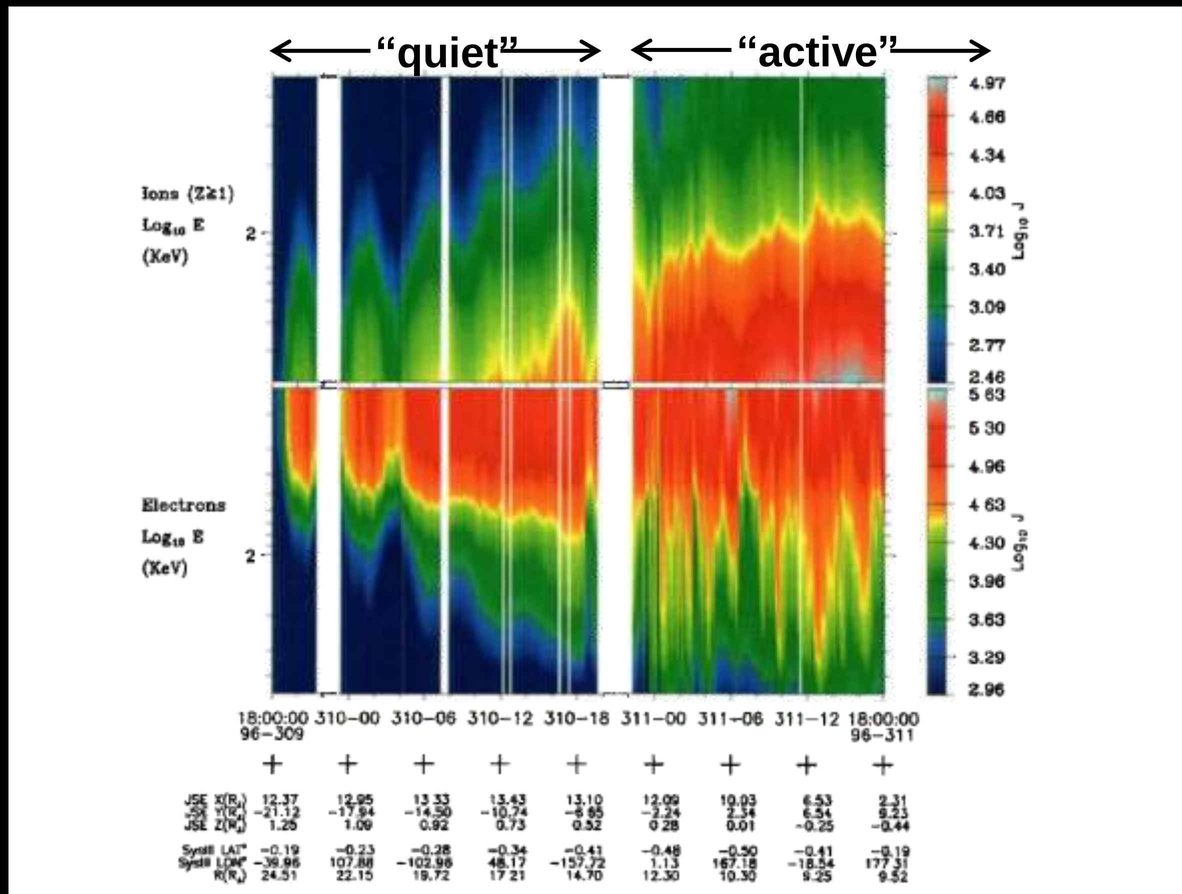
APPLIED PHYSICS LABORATORY

Solar wind control?



Galileo measurements strongly indicate that "storms" occur in Jupiter's magnetosphere. Particle signatures similar to response of solar wind pressure increase [Mauk et al., 1999].

Summary

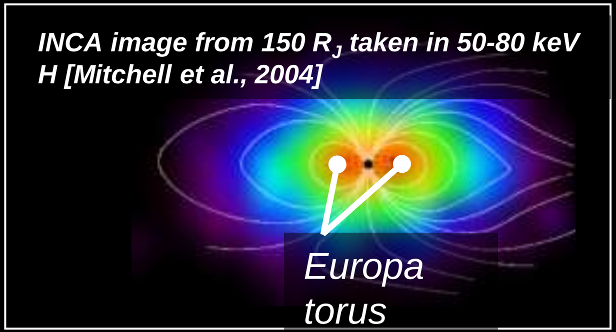
- **Saturn**
  - *Evidence for efficient energization of heavy ions….just like at Earth and Jupiter*
  - *ENA and SKR intimately related. Link is probably (1) pressure-driven currents, and/or (2) flow-shear driven currents in the fast flow in the post midnight sector seen in Jia et al. model.*
  - *Field periodicities caused by rotating partial ring current (hot and/or cold)*
  - *Solar wind control apparent (Pressure or speed)*
- **Jupiter**
  - *Strongest ENA intensities from Torus region*
  - *ENA imaging potentially resolve large-scale injections. Are they quasi-periodic? How do they relate to radio emissions?*
  - *Evidence for efficient energization of heavy ions….just like at Earth and Saturn*
  - *Solar wind control not known, but could be addressed by ENA imaging*

Extra Slides

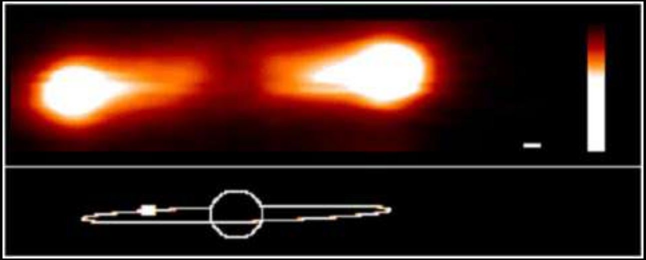
Neutral Gas

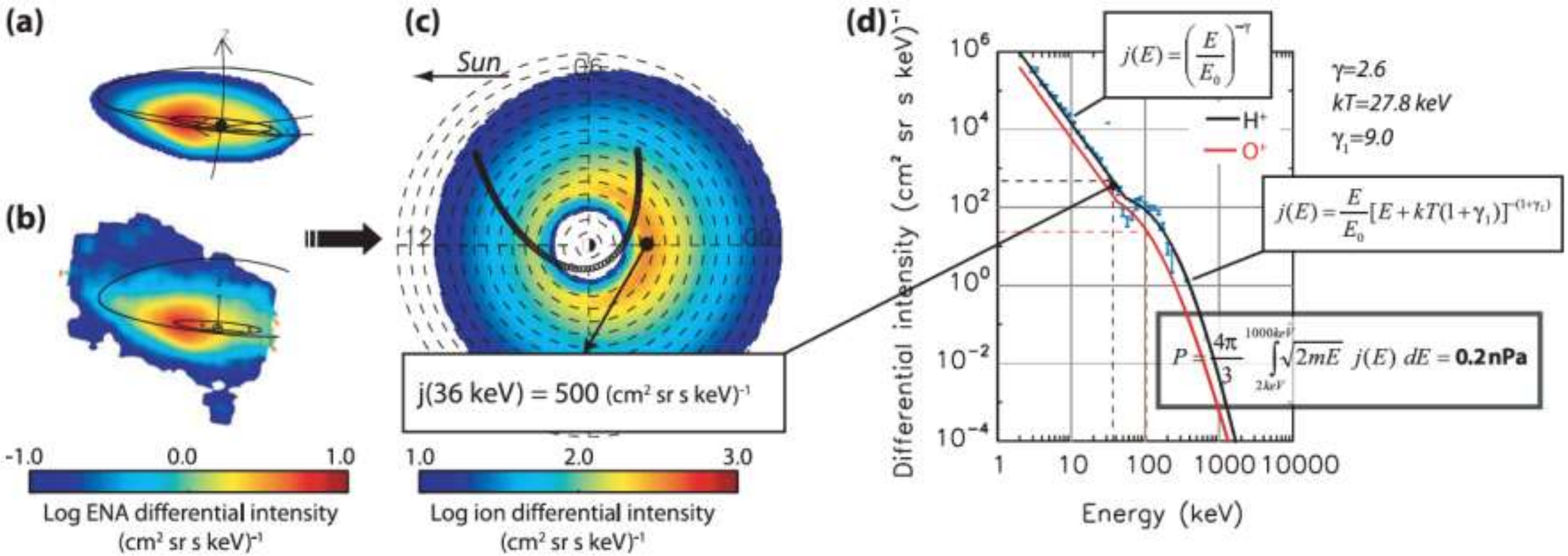
Europa/Io Torus Region

- ENA intensities strongest from Europa torus
  - *Spatial distribution of neutral gas in Europa torus and its long-term evolution (~months)*
  - *Short-term variations (hours) include 5.5 h disc wobble and energetic particle injections*
- Synergy with EUV observations
  - *EUV: Io torus (O, S bands), but Europa torus is very, very weak (H2)*
  - *ENA: Europa torus, but not Io torus (lack of energetic ions)*



Io Torus
Cassini/UVIS (S-band emissions)





(a)
(b)
(c)
Sun
06
12
00
j(36 keV) = 500 (cm² sr s keV)⁻¹
(d)
$j(E) = \left(\frac{E}{E_0}\right)^{-\gamma}$
γ=2.6
kT=27.8 keV
γ₁=9.0
H⁺
O⁺
$j(E) = \frac{E}{E_0}[E + kT(1+\gamma_1)]^{-(1+\gamma_1)}$
$P = \frac{4\pi}{3}\int_{2keV}^{1000keV}\sqrt{2mE}\ j(E)\ dE = \mathbf{0.2\,nPa}$
Differential intensity (cm² sr s keV)⁻¹
Energy (keV)
-1.0
0.0
1.0
Log ENA differential intensity
(cm² sr s keV)⁻¹
1.0
2.0
3.0
Log ion differential intensity
(cm² sr s keV)⁻¹

Force Balance

pressure gradient

JxB

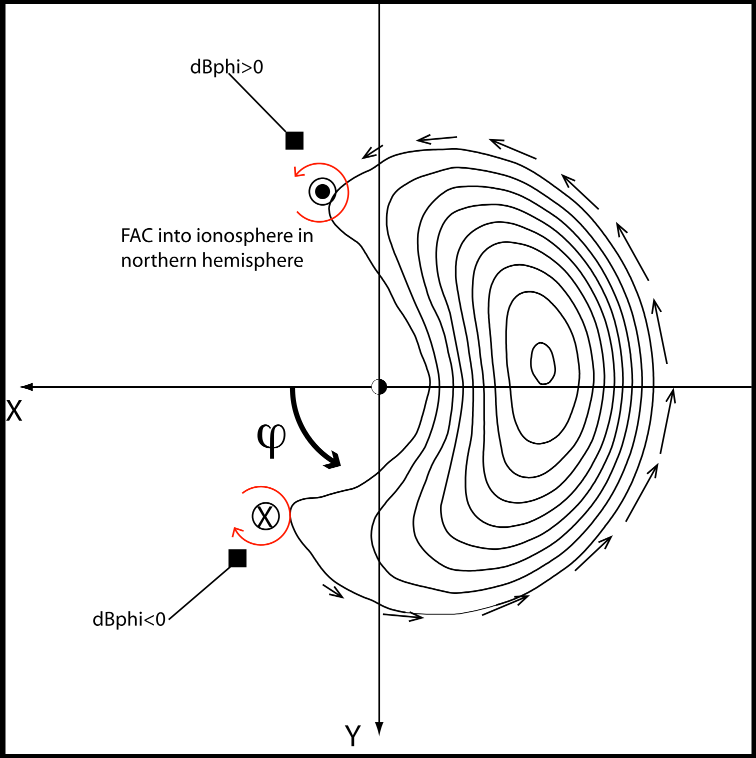
curvature

$$-\nabla_{\perp}\left(\frac{B^2}{8\pi}\right)+\boldsymbol{\kappa}\left(\frac{B^2}{4\pi}\right)=\nabla_{\perp}P_{\perp}+\boldsymbol{\kappa}(P_{\parallel}-P_{\perp})$$
$$+\frac{M^2}{\rho}\left(\frac{B^2}{4\pi}\right)[(\hat{\rho}\cdot\hat{\kappa})\hat{\kappa}+(\hat{\rho}\cdot\hat{\xi})\hat{\xi}]$$

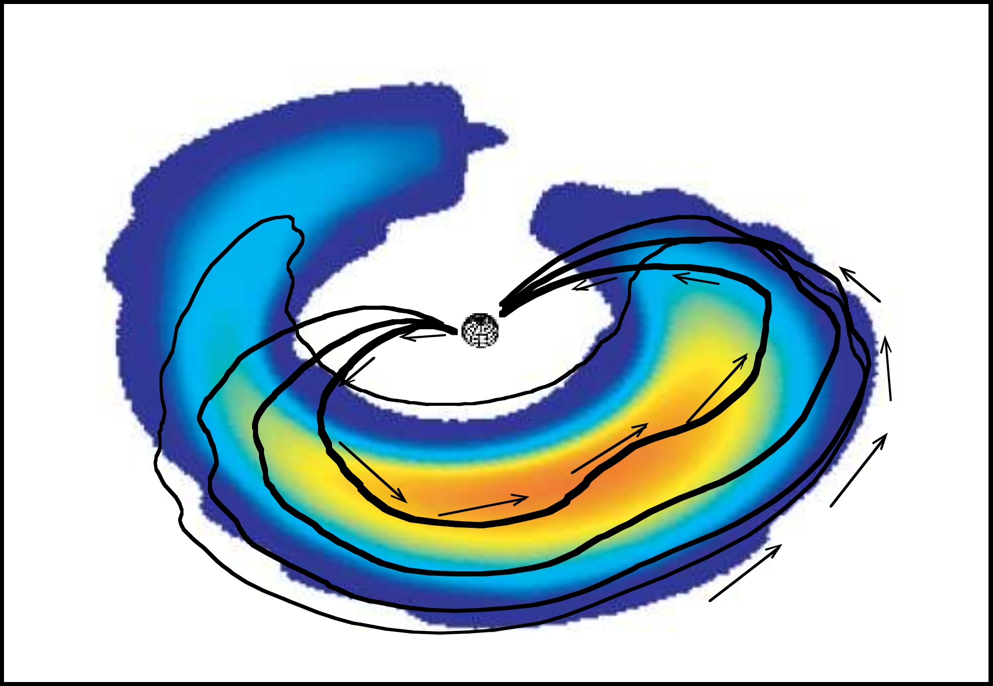
centrifugal

The Pressure-Driven Current System

Equatorial current system

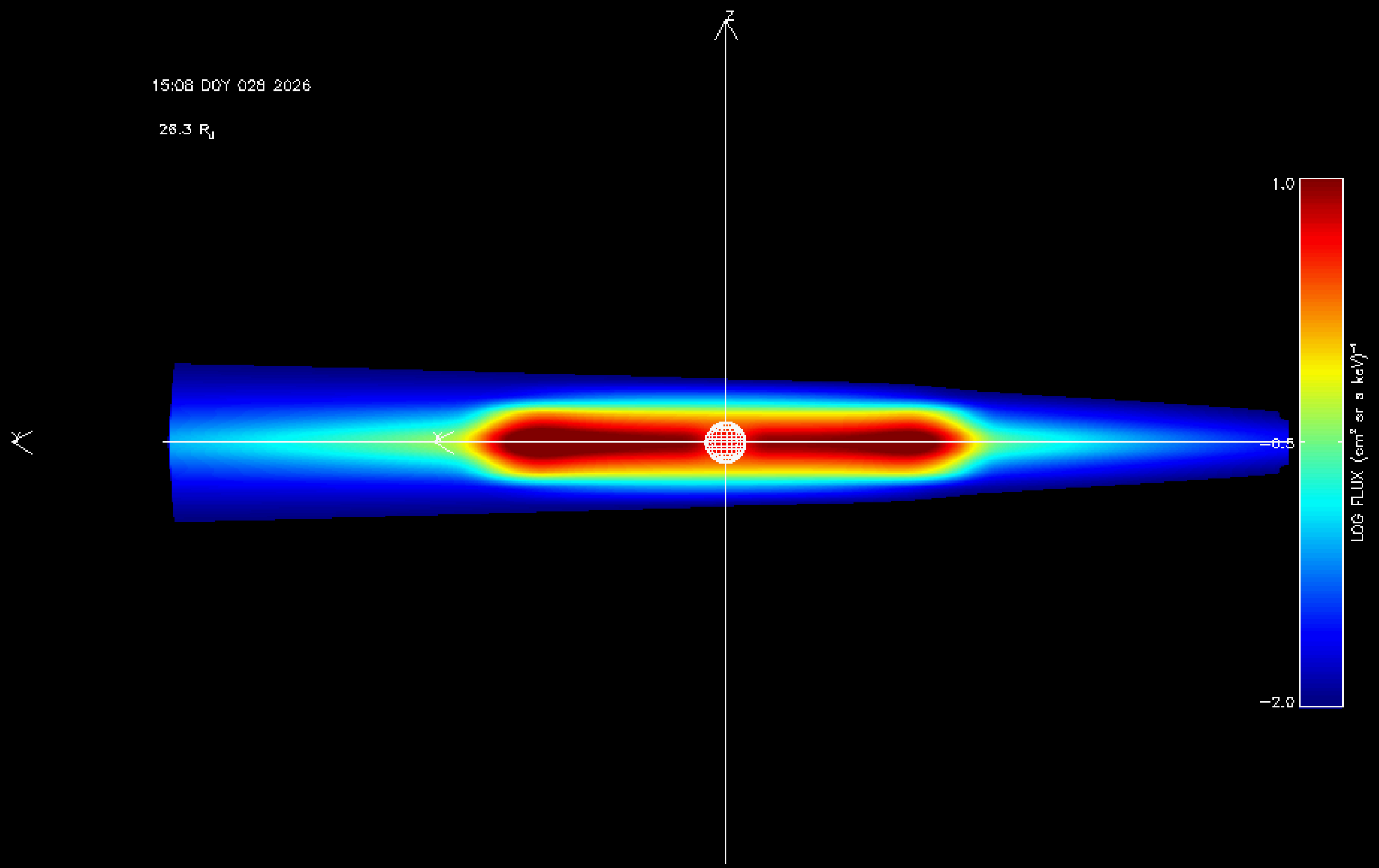


3D current system



ENA Simulations

Inclination 6 deg

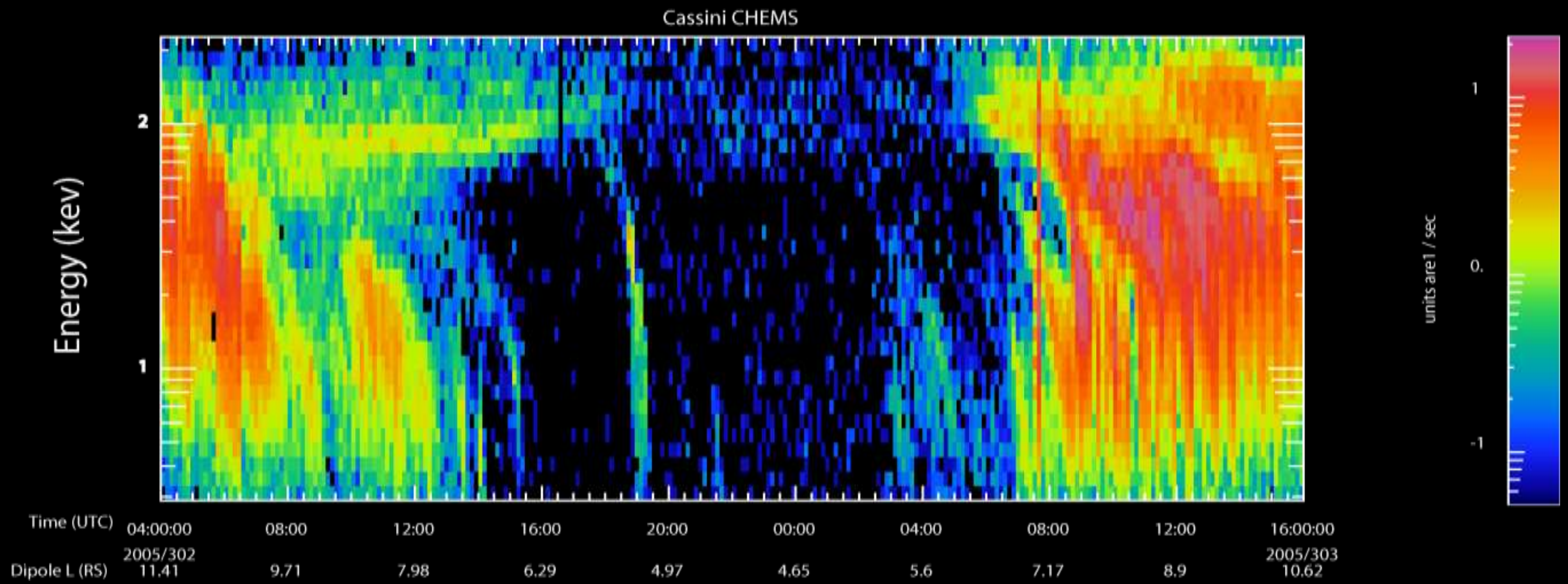


Summary

- **Orbit**
  - *Equatorial orbits resolve radial and vertical structures well such as thickness and structure of magnetodisc and torus, but very limited azimuthal resolution*
  - *>20 deg inclination achieves drastically better azimuthal resolution but maintains also vertical resolution and avoid most of the harsh radiation*
  - *Higher inclination → better for simultaneous radio observations?*
- **Europa torus**
  - *Morphology and long-term variations of neutral gas in torus region*
  - *Simultaneous EUV observations of O, S plasma torus nice complement*
  - *Short-term variations and distribution of energetic particles (H+, O+, S+)*
  - *Characterizes Europa's ion sputtering environment remotely [Leblanc et al., 2005] + remote backscatter*
- **Giant accelerator**
  - *Location and evolution of energetic particle injections (H+, O+, S+) in 3-300 keV range*
  - *Acceleration mechanisms determined through spectral evolution of different masses*
- **Magnetodisc**
  - *Thickness, shape and modulations*
- **Relation to radio emissions**
  - *Correlate global configuration and evolution of magnetodisc and energetic particles, and moons with radio emissions*

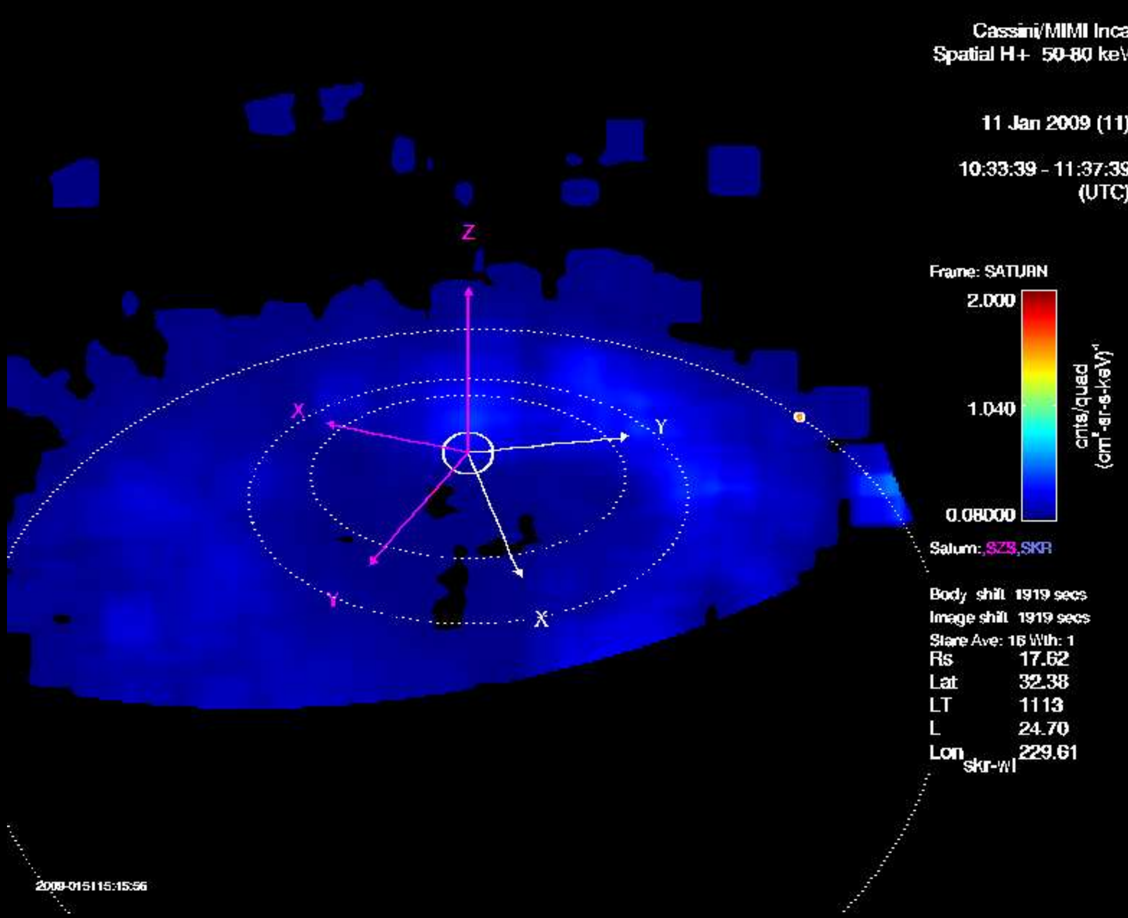
The In-Situ View

Knowing the details, but not seeing the global picture



In-situ particle measurements have long been our only tool for probing magnetospheric dynamics. Although it provides detailed information of particle distributions, it is at best difficult to retrieve the global dynamical behavior of the particle distributions. Typical proton spectrogram in the 3-300 keV range taken from a pass through the equatorial region of Saturn's magnetosphere.

Seeing the Invisible



ENA imaging enables us to "see" the global dynamics of energetic ions. This movie was obtained by Cassini/INCA in orbit around Saturn and is only one of many, many compelling dynamical events that have been revealed. Can this success be repeated for Jupiter?

What is ENA imaging?

- **ENA simulation**
  - *Measured profiles of ion intensities [Mauk et al., 2004]*
  - *Neutral Europa and Io torus model of Smyth et al., [2006]*
  - *Extended neutral H gas from Cheng et al. [1998]*
  - *Compute LOS integral*
  - *Convolve with camera response function*

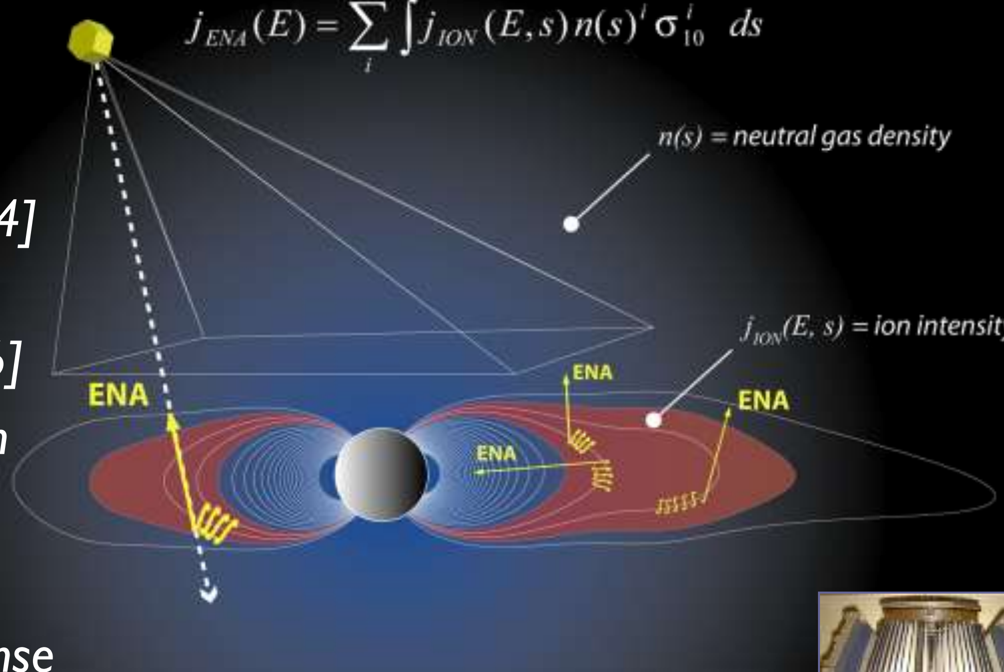
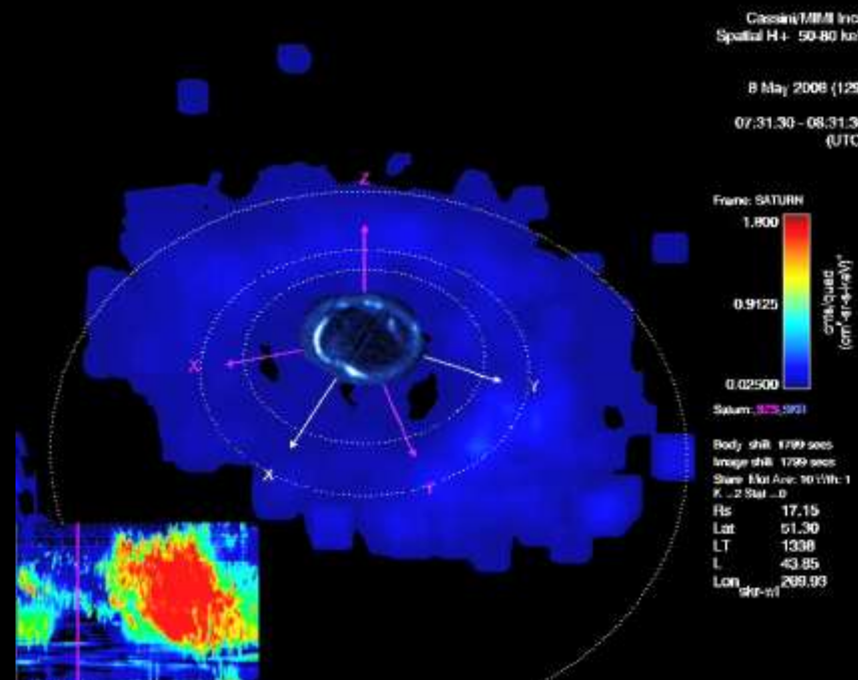


Table 1: Cassini/INCA specifications	
Field of View	***90x120 deg***
Angular resolution	***3x3 deg***
Mass resolution	***H, O (with SSD H, He, O, S)***
Energy resolution	***ΔE/E=100%***
Energy range	***~10-300 keV/nucleon***

ENA Imaging at Saturn

- Discovery of periodic, global injections and acceleration [Paranicas et al., GRL, 2005; Mitchell et al., GRL, 2005, PSS, 2009; Carbary et al., JGR, 2008]
- Global transport and dispersion [Brandt et al., GRL, 2008]
- Periodic field perturbations from a rotating partial ring current [Khurana et al., JGR, 2008; Provan et al., 2009; Brandt et al., GRL, 2010]
- Interaction with Titan [Mitchell et al., Science, 2005]
- Solar wind control [Brandt et al., AGU, 2006]

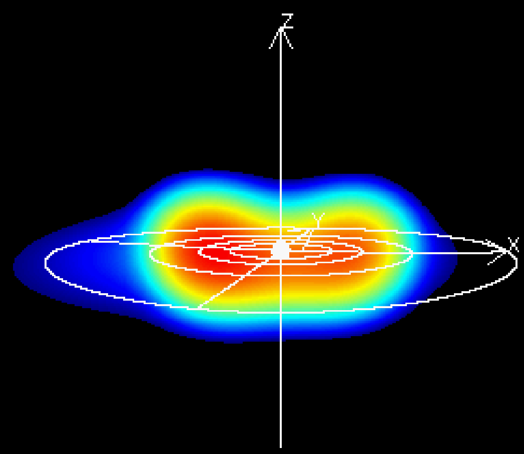


Science Target 1 – Global Magnetospheric Dynamics

JGO Orbit Insertion

19:59 DOY 195 2026

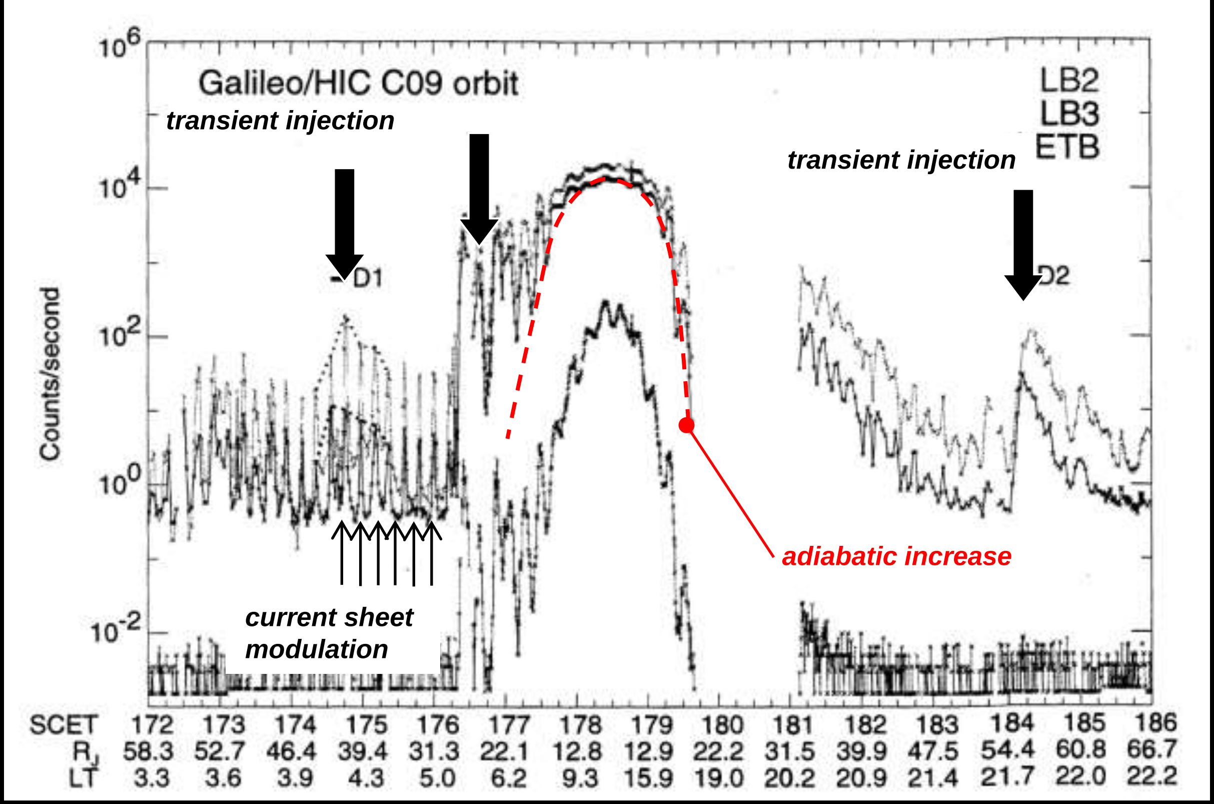
55.32 R_J



ENA intensities are dominated by emissions from the torus region. INCA has no problems resolving those at a resolution <1h. Transient injections in the outer (~20RJ) region are weaker due to the lower neutral gas densities (~0.1 cm^{-3} assumed here) and will probably require several hours of time integration depending on neutral gas density and geometry factor.

Jupiter

Hectometric Auroral Radiation (HOM)



Transient, quasi-periodic injections are seen in in-situ data, but it is nearly impossible to discern their global spatial and temporal distribution and evolution [Selesnick et al., 2001]. Do these correspond to terrestrial substorms?