Resolving Global Geospace Processes: What ENA Imaging Can and Cannot do

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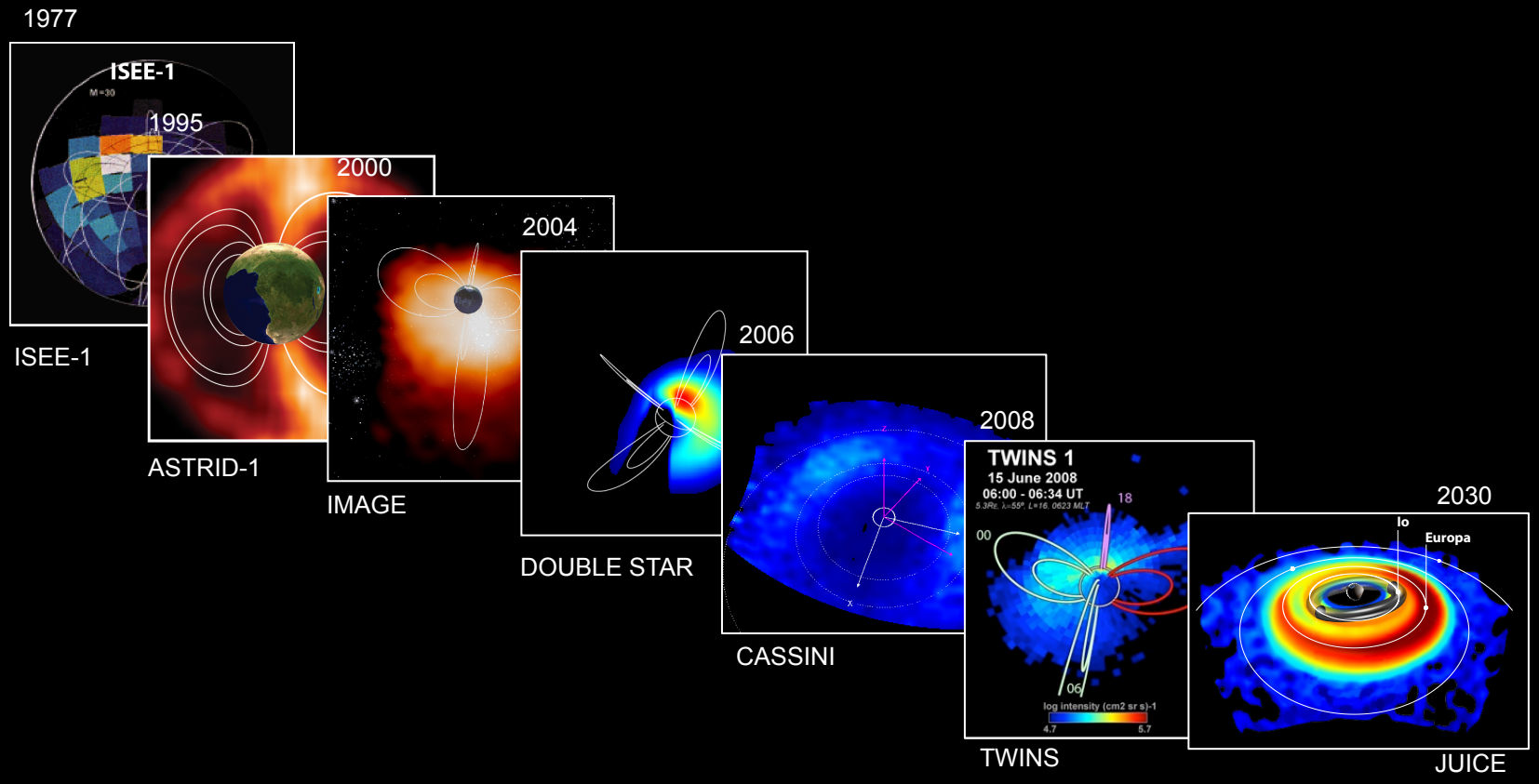

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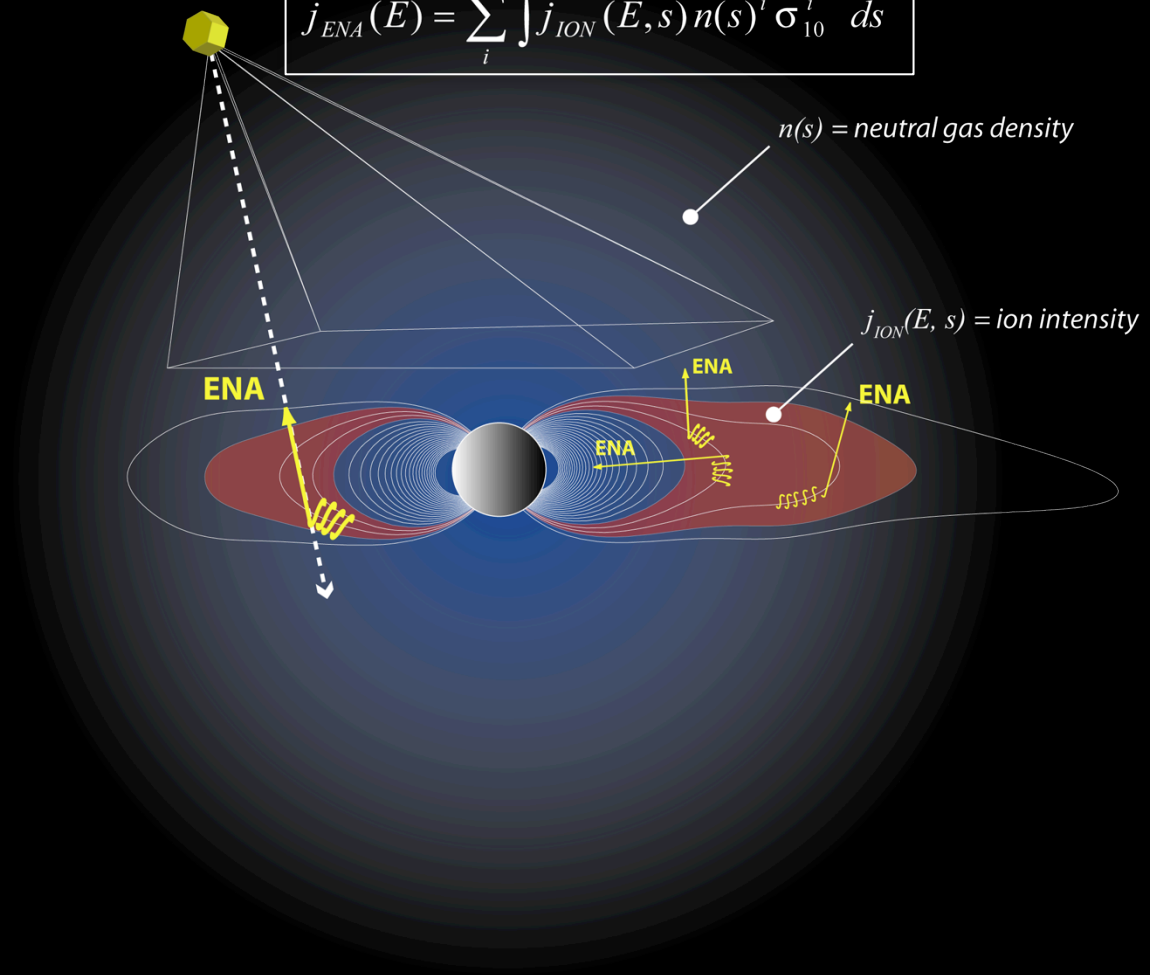
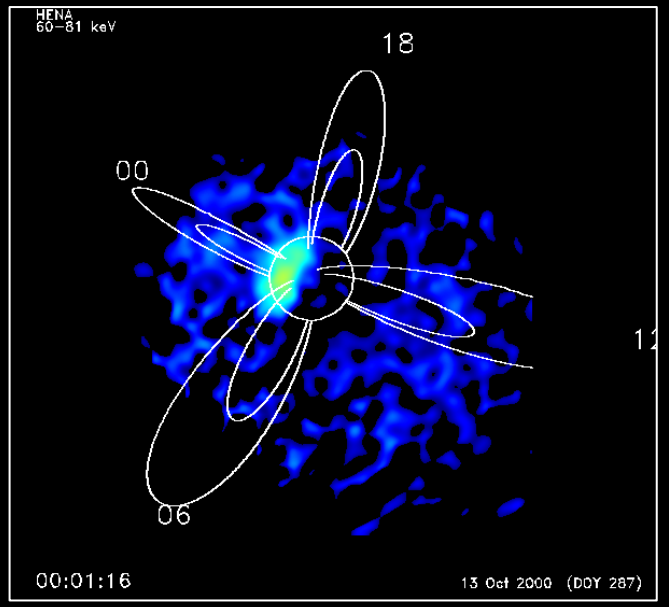
Outline

1. **What is ENA imaging?**
2. **Examples Observations and Achievements**
3. **Inversion of the terrestrial ring current**
4. **Electrical current and magnetic field structure**
5. **Summary**

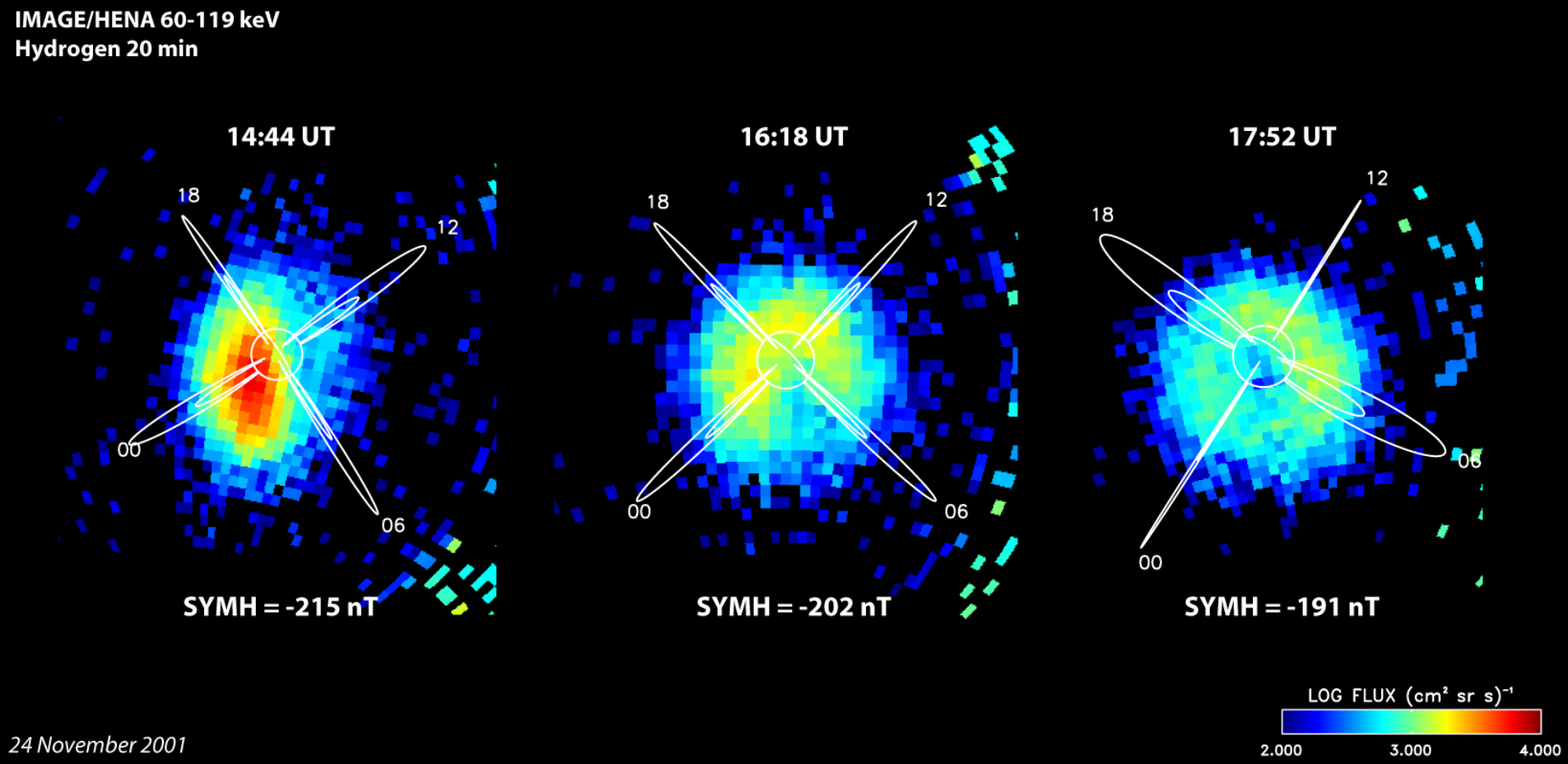
Basics

$$j_{ENA}(E) = \sum_i \int j_{ION}(E,s)\, n(s)^i \sigma_{10}^i \; ds$$

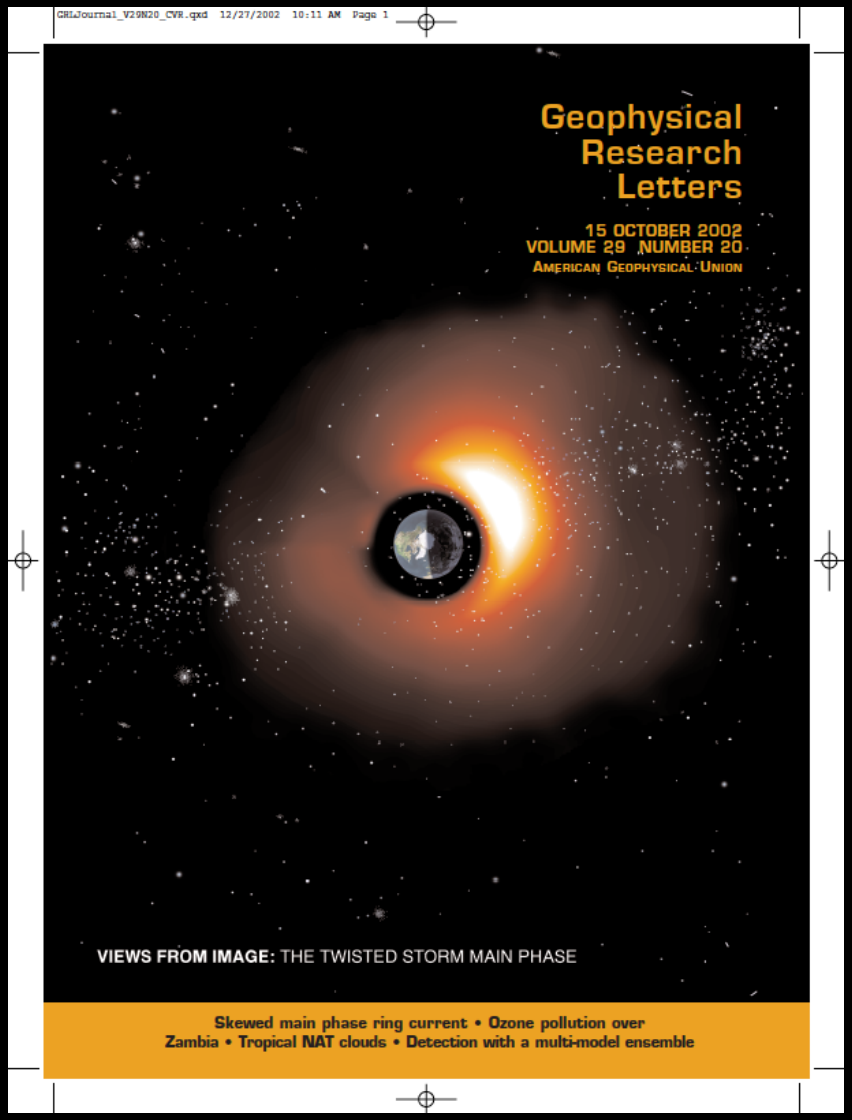


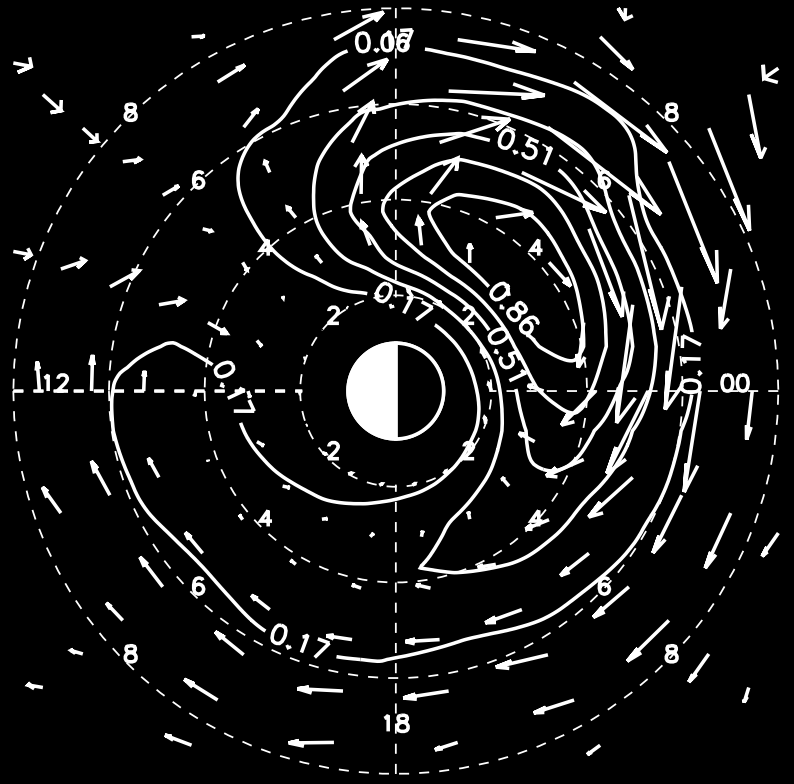


Earth: *Storm Dynamics (HENA)*



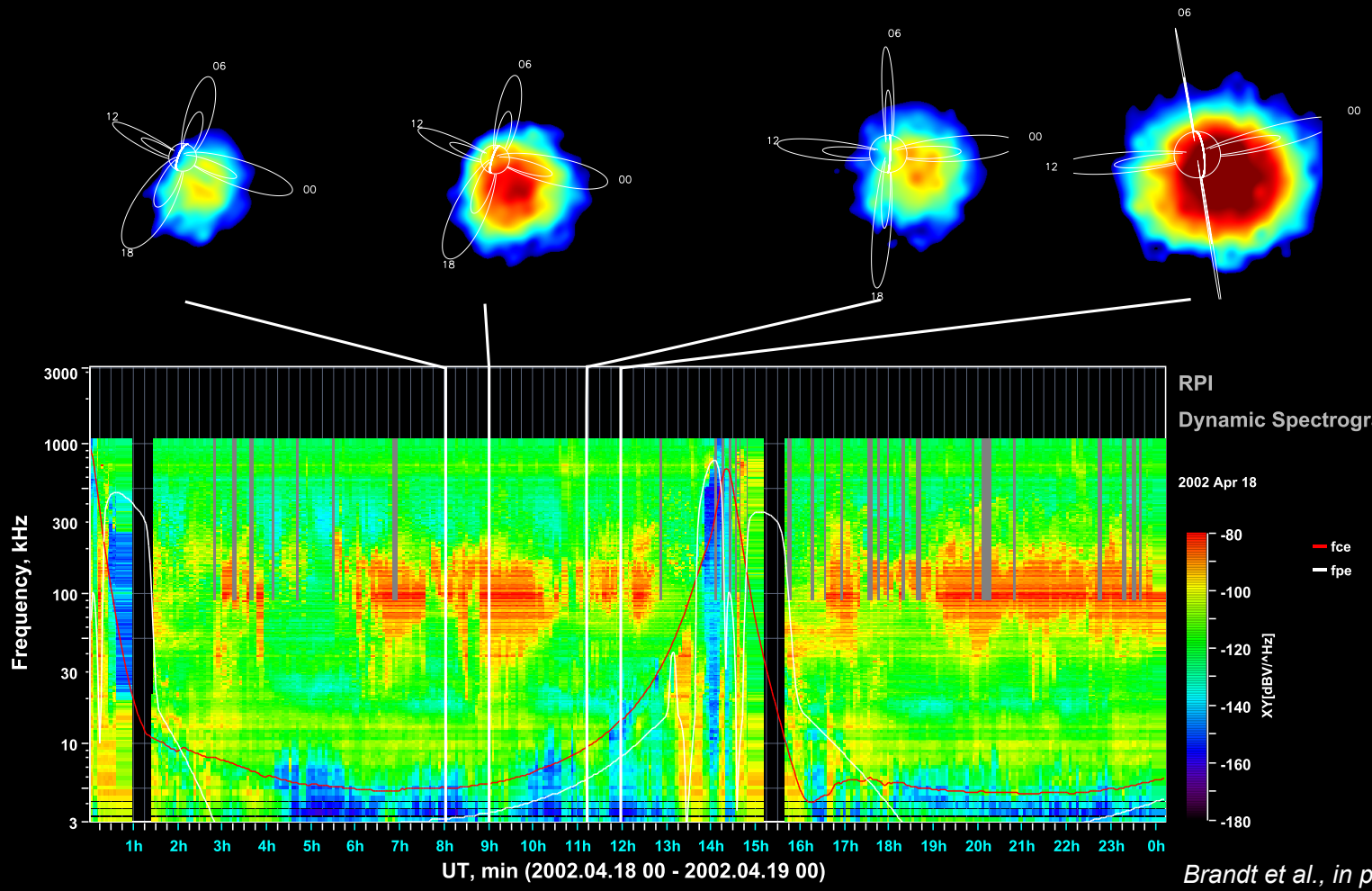
Earth: Sudden Enhancement due to Solar Wind Pressure Pulse (HENA)





(a) Early IMAGE/HENA images showed a post-midnight enhancement in ENAs up to 150 keV (Brandt et al., 2002).**(b)** Estimations of the pressure-driven ring current density displayed a dawn-dusk asymmetry (Brandt et al., 2004).

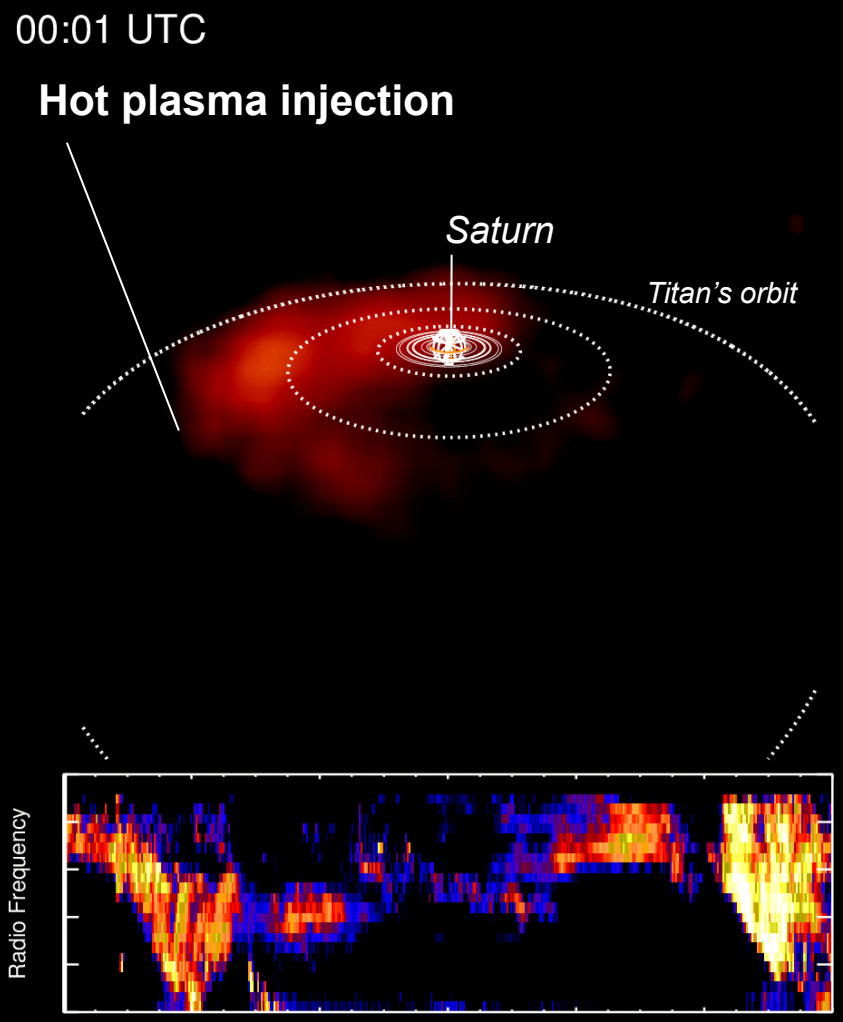
Earth: AKR and Substorm Injections (IMAGE/HENA)



Brandt et al., in preparation.

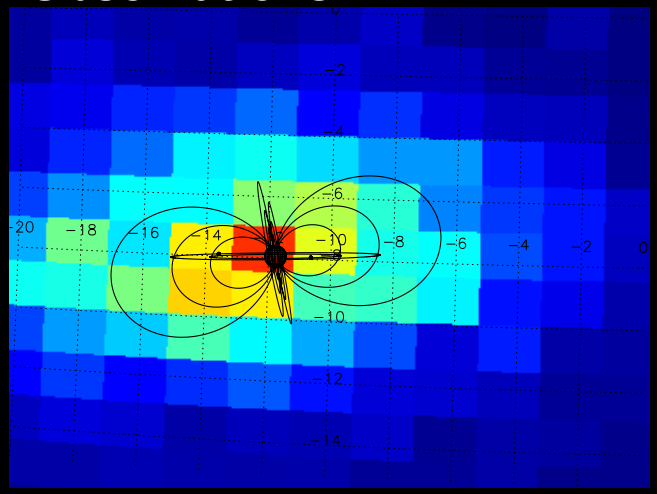
At Earth, substorms are not periodic but can appear quasi-regular intervals during steady convection. There is a well-known 0.99 correlation with AKR, but magnetospheric engine is still under debate.

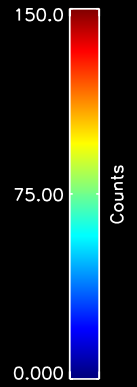
Saturn: SKR and Injections (Cassini/INCA)



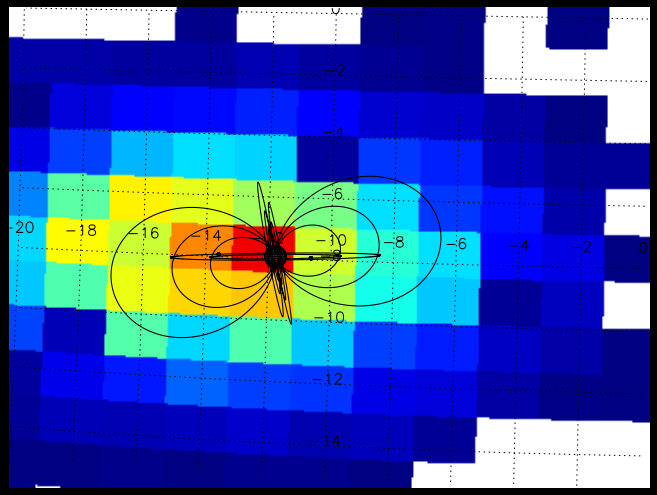
Jupiter: Europa Torus Imaging (Cassini Flyby 2001)

Observations

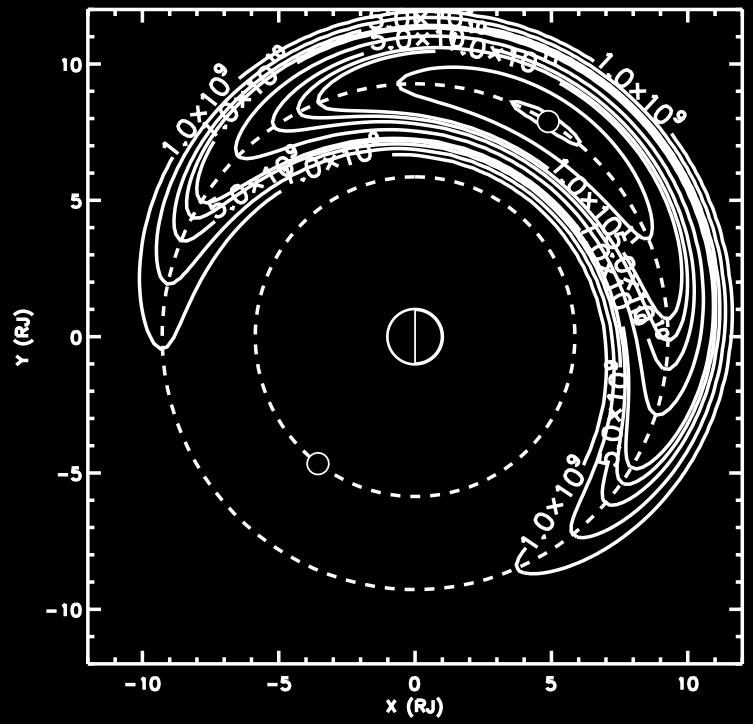




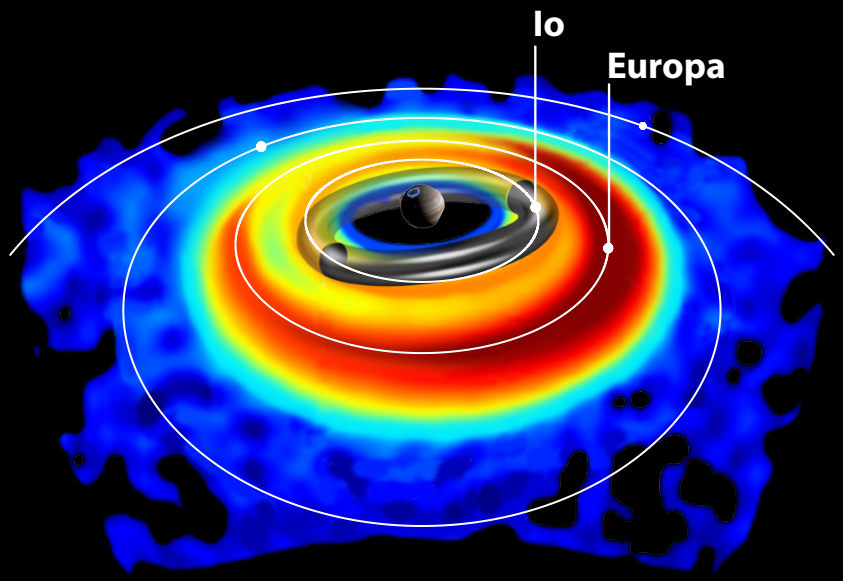
Simulations

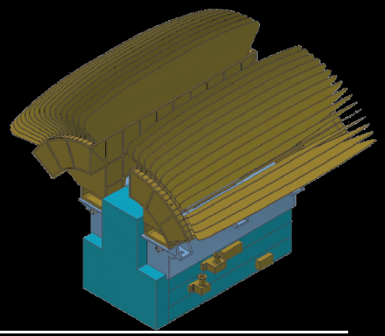


Model Europa Neutral Gas (H_2 or O)



Jupiter: Europa Torus Imaging (JUICE/JENI)





INCA/HENA Measurement Capabilities	
Species	H and heavies (ENA, ions)
Energy range	5 – 5.0 MeV
ΔE/E	<30%
FOV	90°x120°
Angular resolution	~10° (E ≥ 10 keV H)
G-factor	0.45 cm² sr

JENI Measurement Capabilities	
Species	H, He, O, S (ENA, ions)
Energy range	0.5 – 5.0 MeV
ΔE/E	<14%
FOV	90°x120°
Angular resolution	2° (E ≥ 10 keV H)
G-factor	0.013 – 1.80 cm² sr

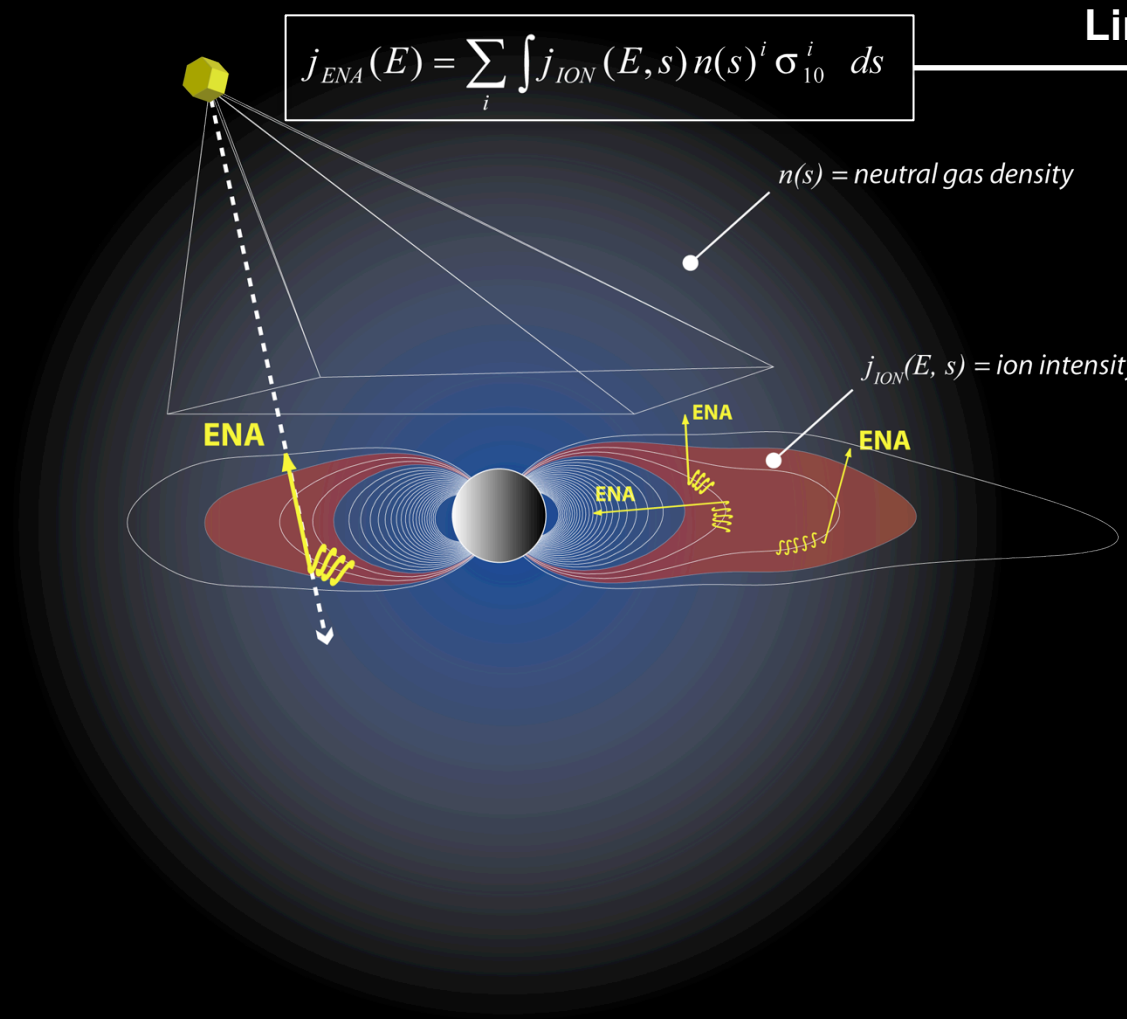
Inversion Methodology

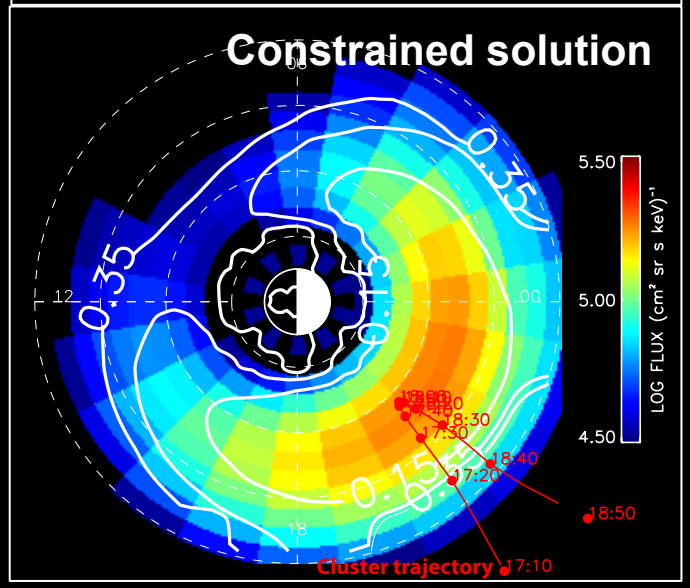
$$j_{ENA}(E) = \sum_i \int j_{ION}(E,s)\, n(s)^i \sigma_{10}^i \, ds$$

Linearize

$$C_i = \sum_{pkl} b_{ikl}^p \, j_{ION}^p(L_k, \varphi_l)$$

$$\mathbf{J_{ION}} = (\mathbf{K}^T \sigma_c^{-2} \mathbf{K} + \gamma \mathbf{H})^{-1} \mathbf{K}^T \sigma_c^{-2} \mathbf{C}$$





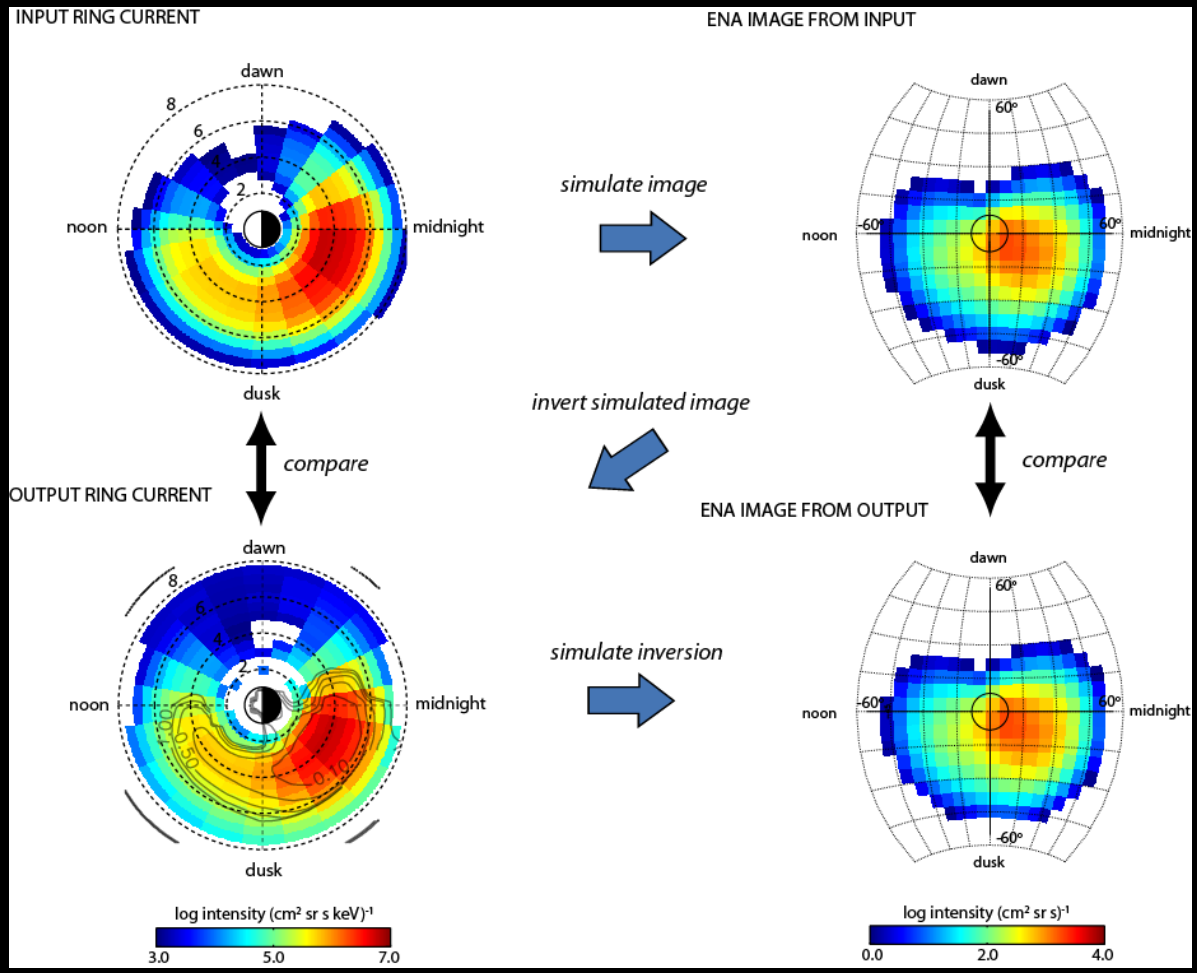
Inversion Optimization: Choosing the correct solution

$$\mathbf{J}_{\mathrm{ION}} = (\mathbf{K}^{\mathrm{T}}\sigma_c^{-2}\mathbf{K} + \gamma\mathbf{H})^{-1}\mathbf{K}^{\mathrm{T}}\sigma_c^{-2}\mathbf{C}$$

Constraint strength ("smoothness")

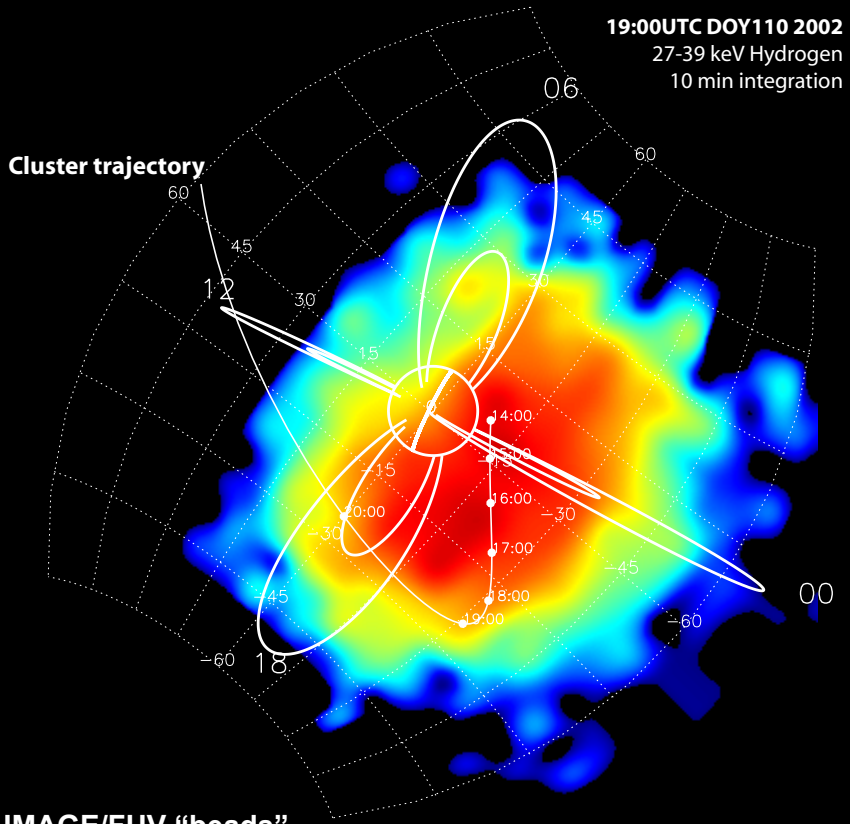
Two ways of optimizing constraints:

- **In-situ validation**
- **Simulate synthetic data**

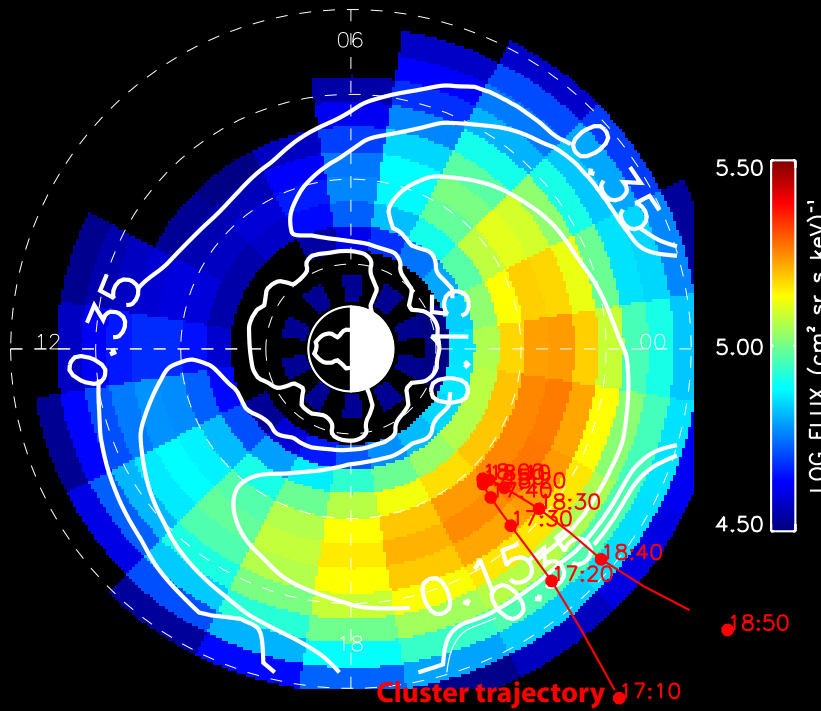


Inversion Validation: Main phase ring current 2002 DOY 110

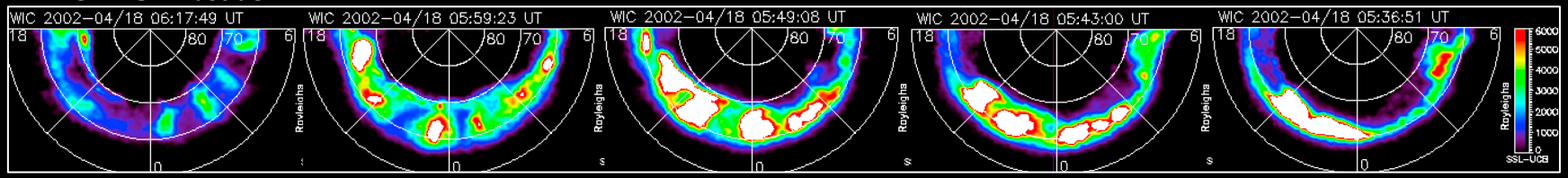
Hydrogen ENA intensity
27-39 keV



Perpendicular equatorial proton intensity
27-39 keV

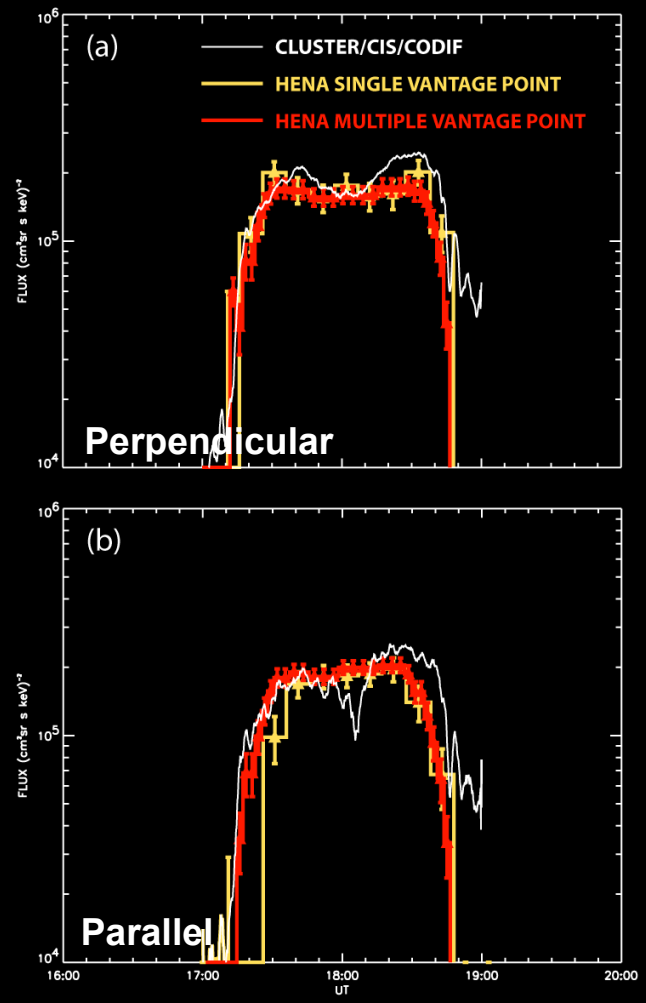


IMAGE/FUV "beads"

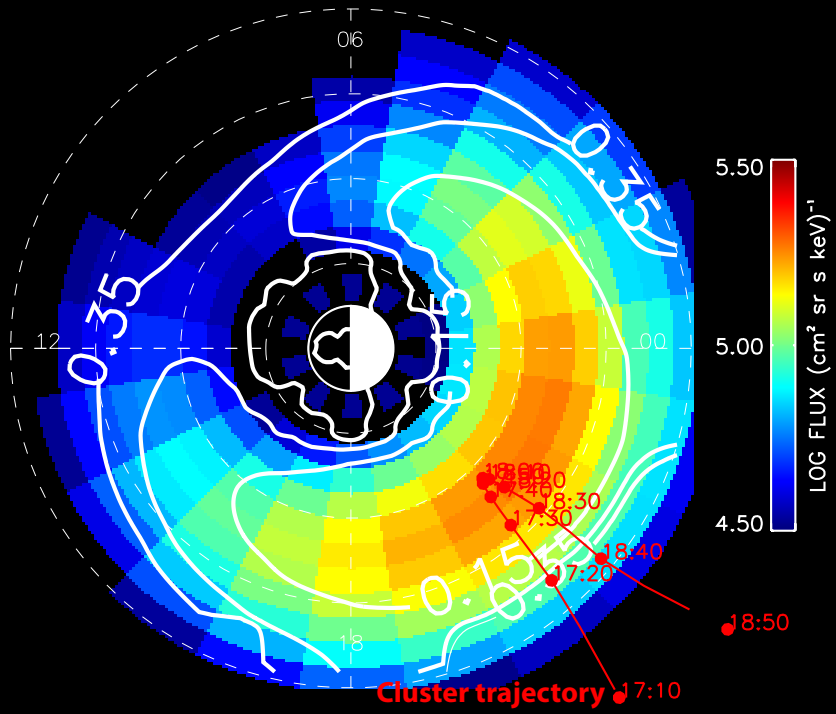


Inversion Validation: Main phase ring current 2002 DOY 110

Validation against Cluster/CODIF
27-39 keV protons

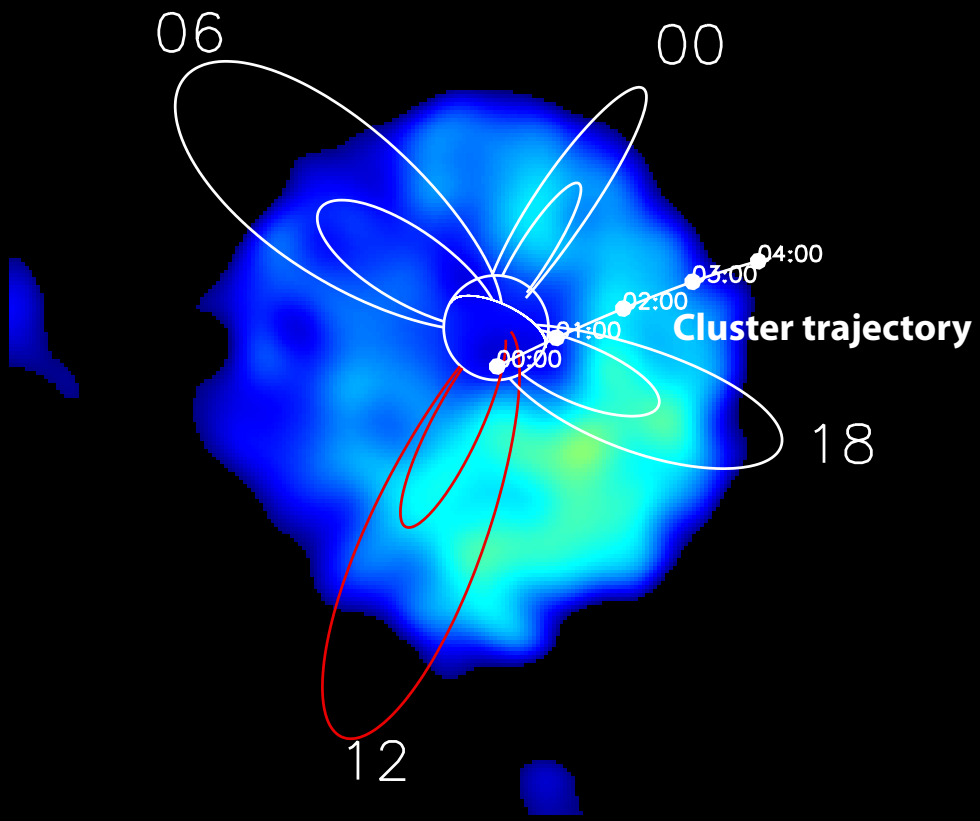


Perpendicular equatorial proton intensity
27-39 keV

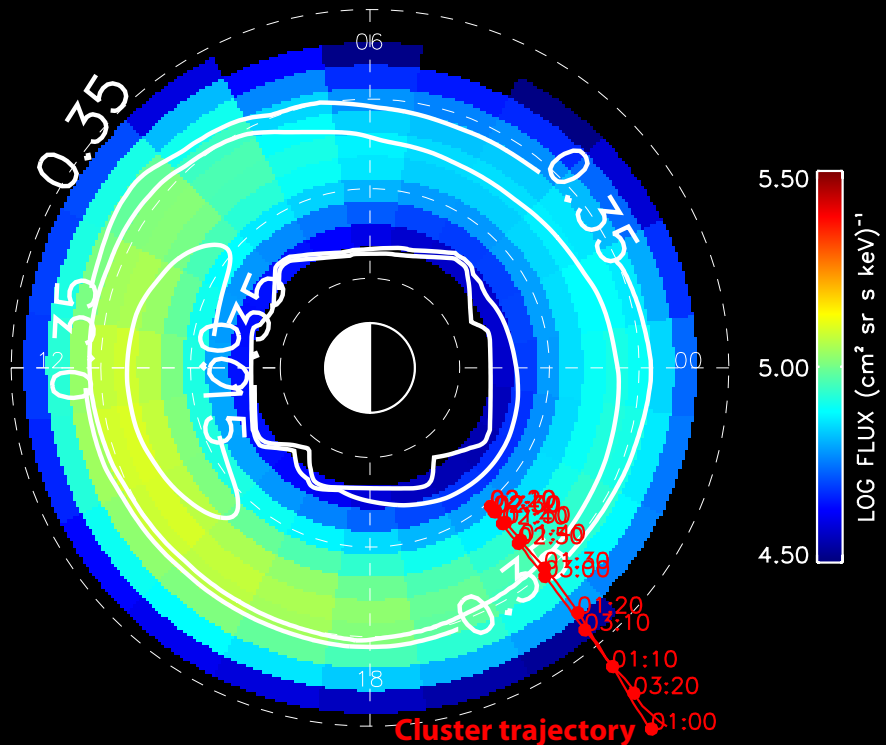


Inversion Validation: Recovery phase ring current 2001 DOY 114

Hydrogen ENA intensity
27-39 keV



Perpendicular equatorial proton intensity
27-39 keV



Inversion Validation: Recovery phase ring current 2001 DOY 114

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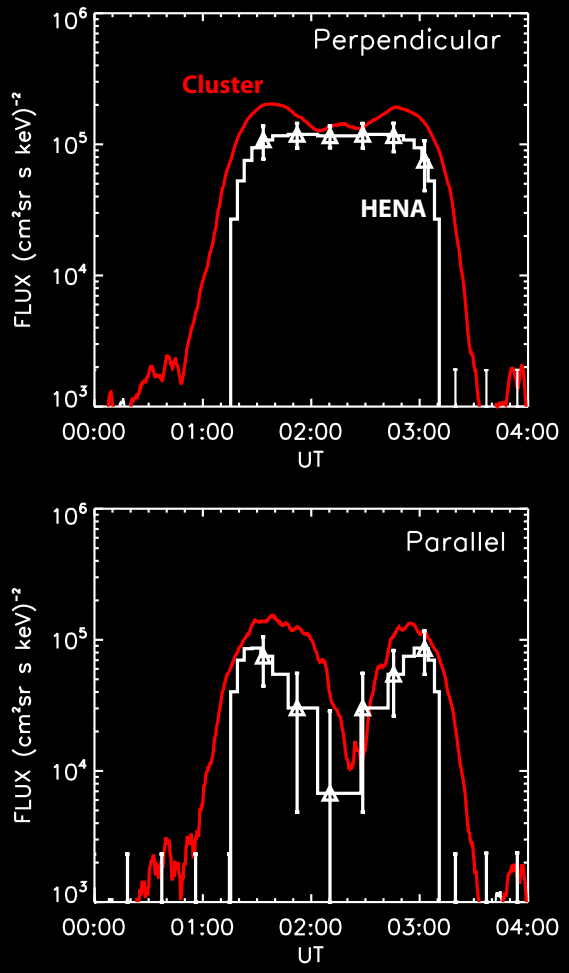
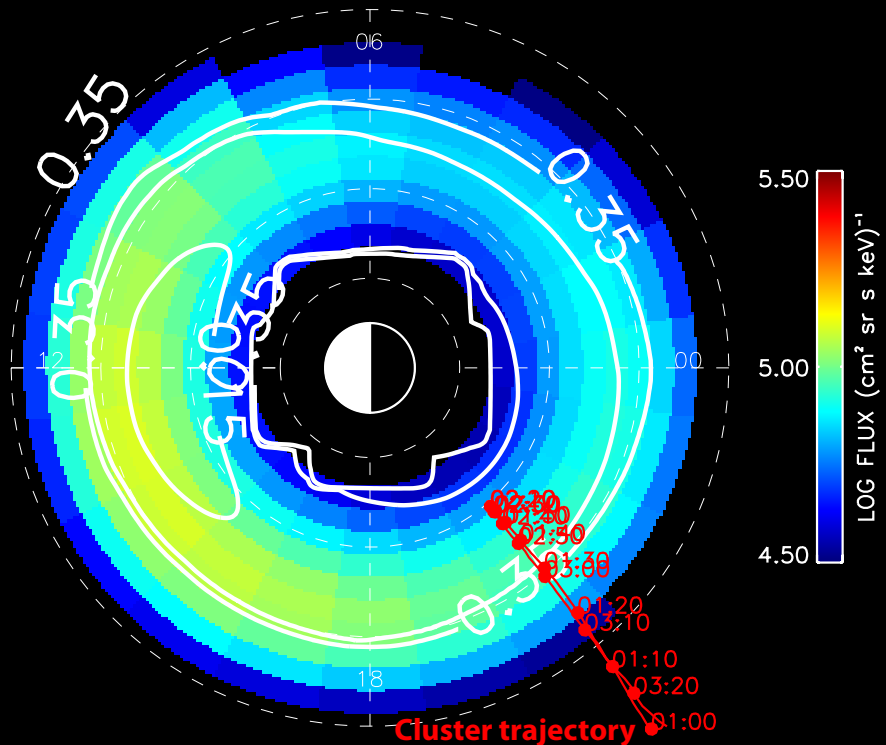
27-39 keV protons



Perpendicular equatorial proton intensity
27-39 keV



Pressure, Currents and Fields

Pressure

$$P_{\perp} = \pi\sqrt{2m}\int\int\sqrt{E}\,j_{ION}(E,\alpha,L)\sin^3\alpha\,d\alpha\,dE$$

$$P_{\parallel} = 2\pi\sqrt{2m}\int\int\sqrt{E}\,j_{ION}(E,\alpha,L)\sin\alpha\cos^2\alpha\,d\alpha\,dE$$

Current continuity and force-balance

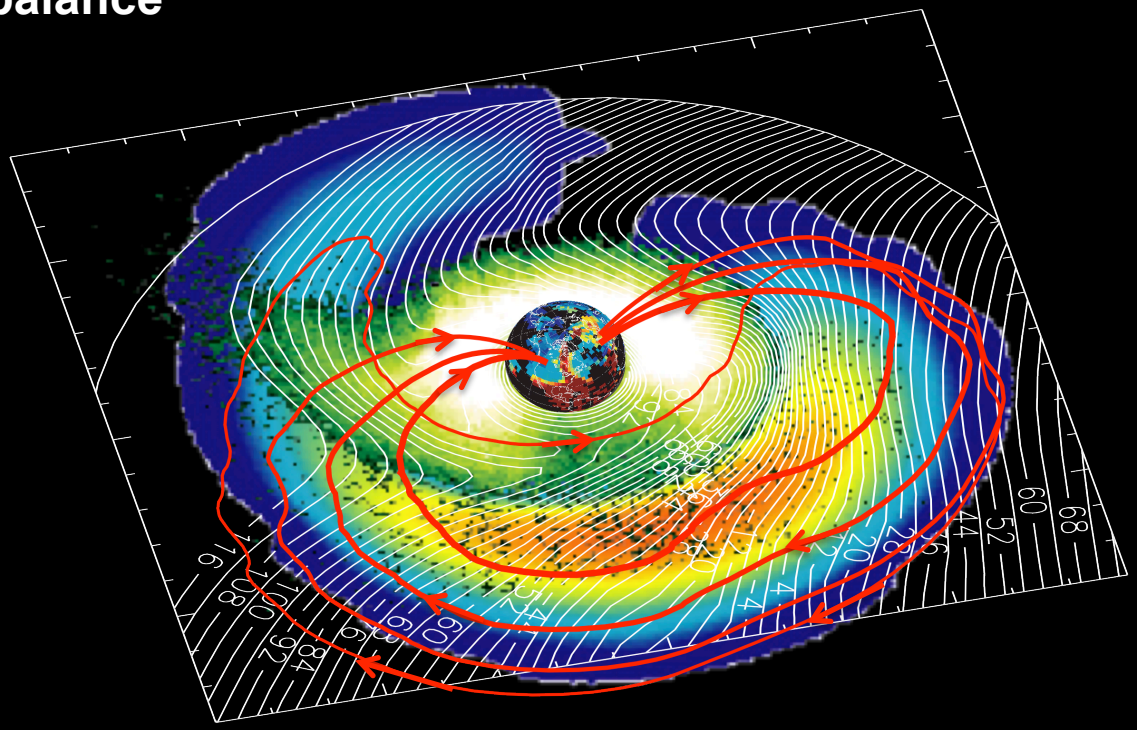
$$\nabla\cdot\mathbf{J} = 0$$

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

Solution

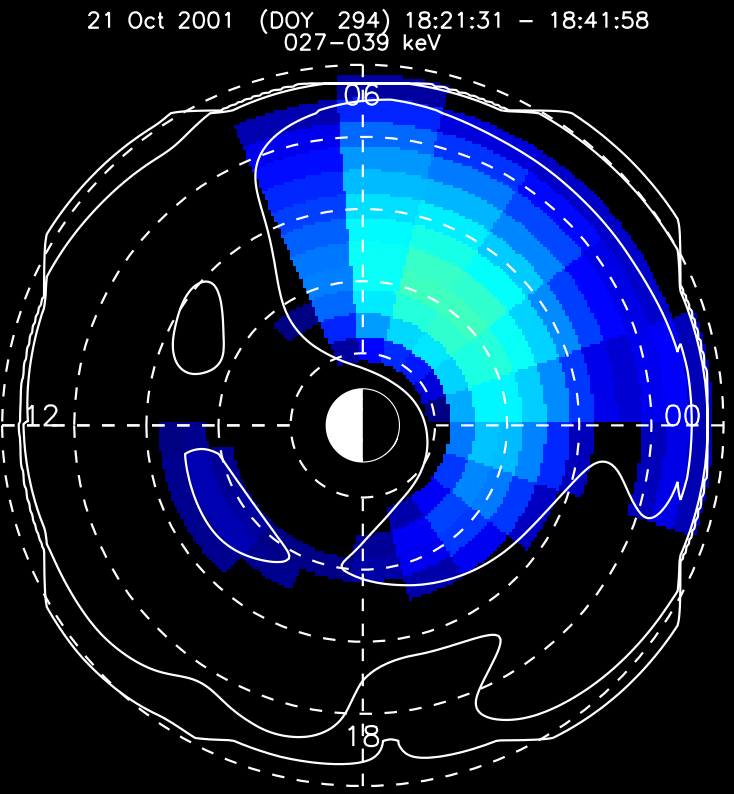
$$\mathbf{J}_{\perp} = \frac{\mathbf{B}}{B^2}\times\left[\nabla P_{\perp} + (P_{\parallel} - P_{\perp})\frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{B^2}\right]$$

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

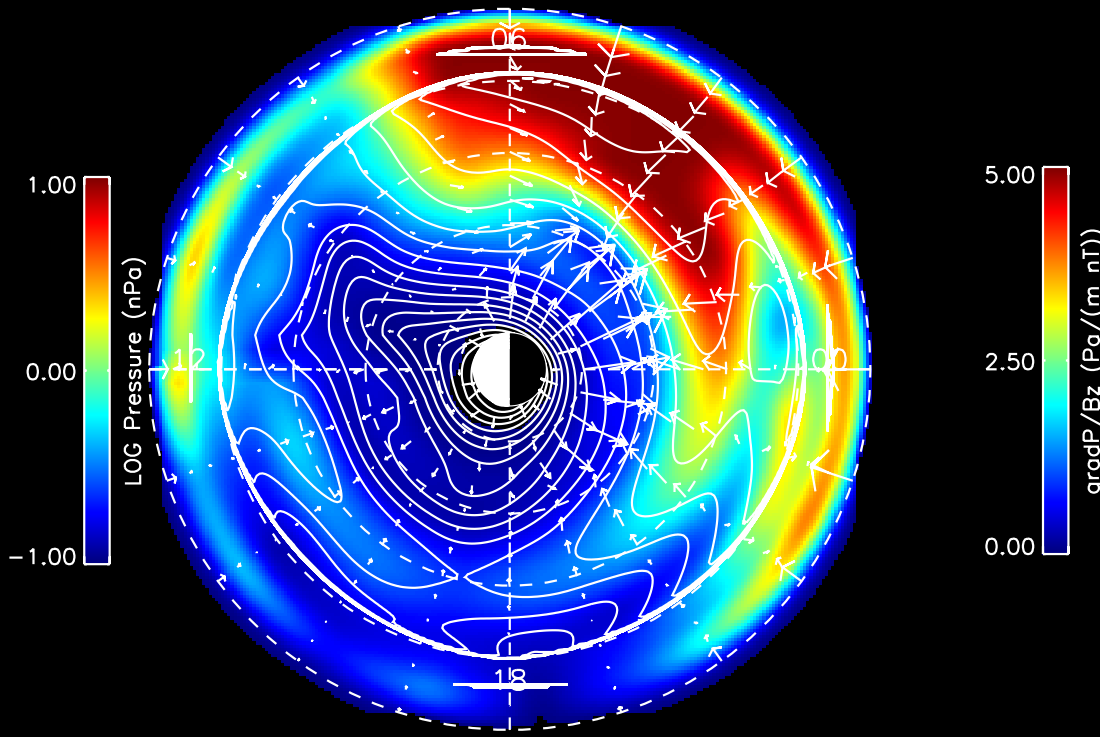


How well do we know the force balance in the inner magnetosphere?

Proton pressure
27-39 keV



Perpendicular gradP
Normalized by Bz



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Proton pressure
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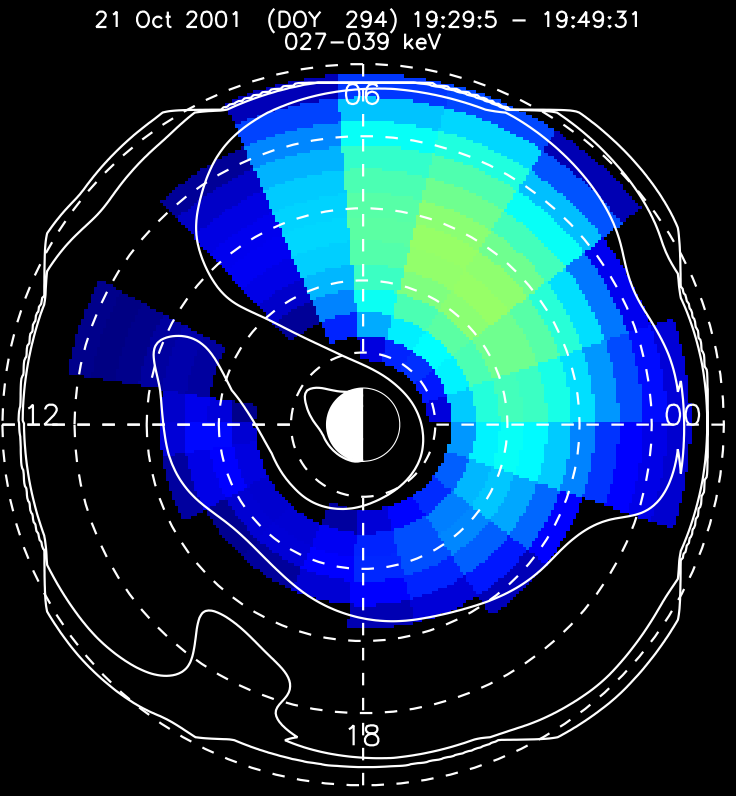
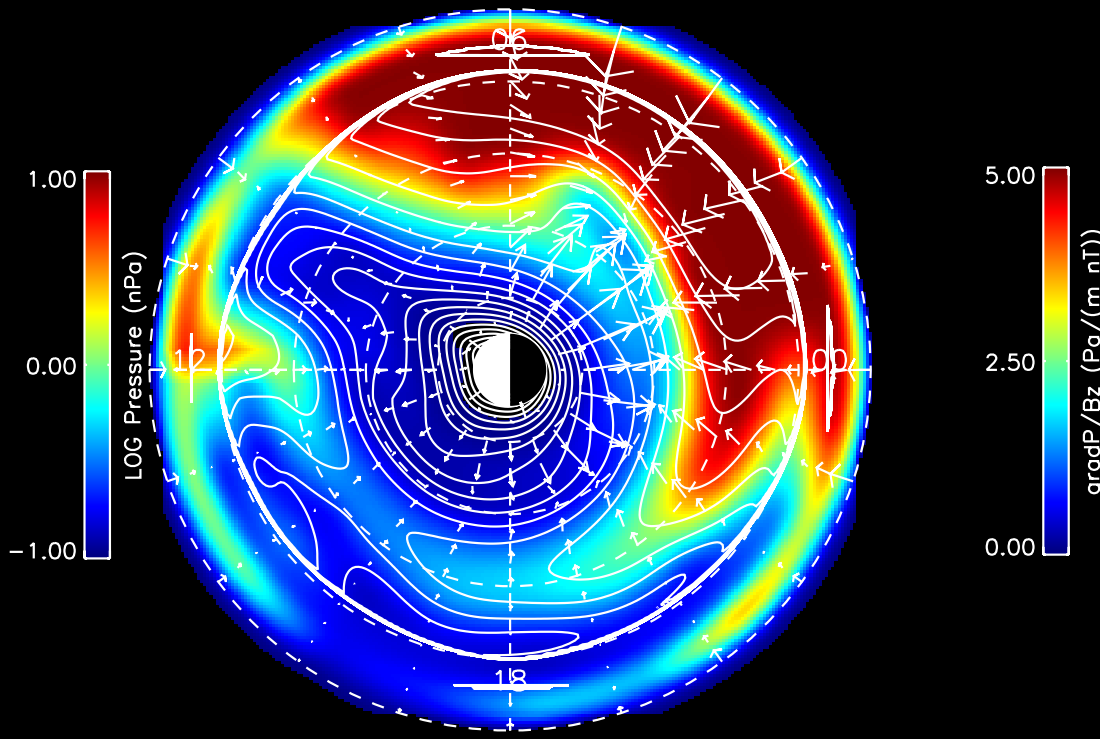
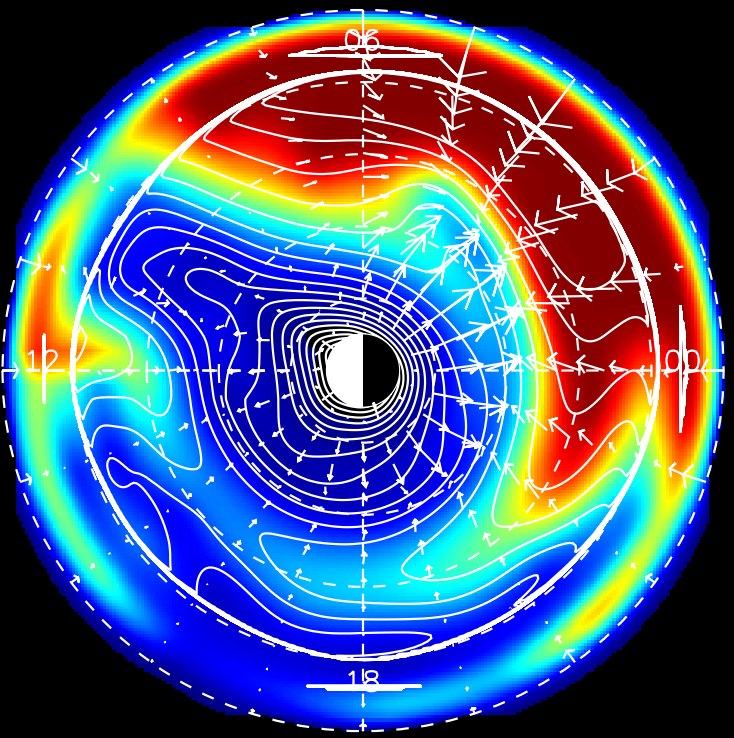


Perpendicular gradP
Normalized by Bz

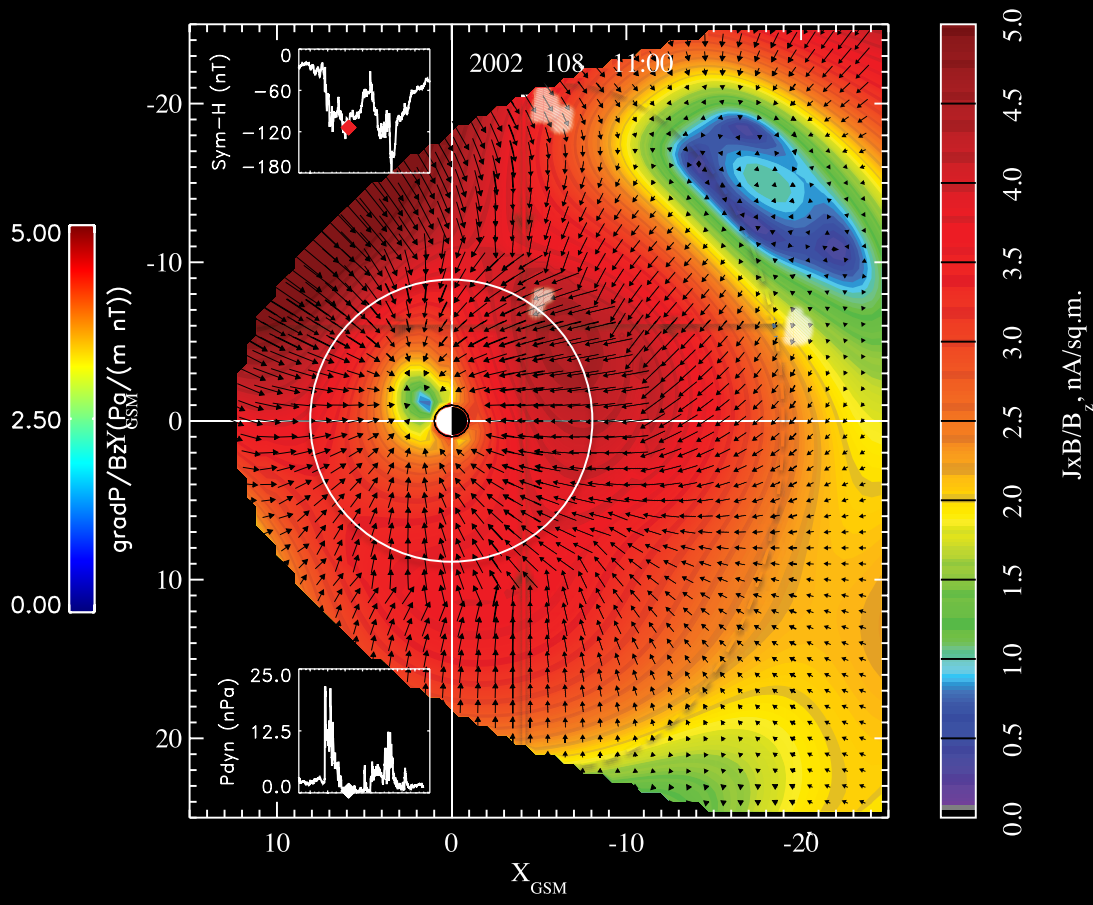


How well do we know the force balance in the inner magnetosphere?

Perpendicular gradP
Normalized by Bz



JxB
Normalized by Bz

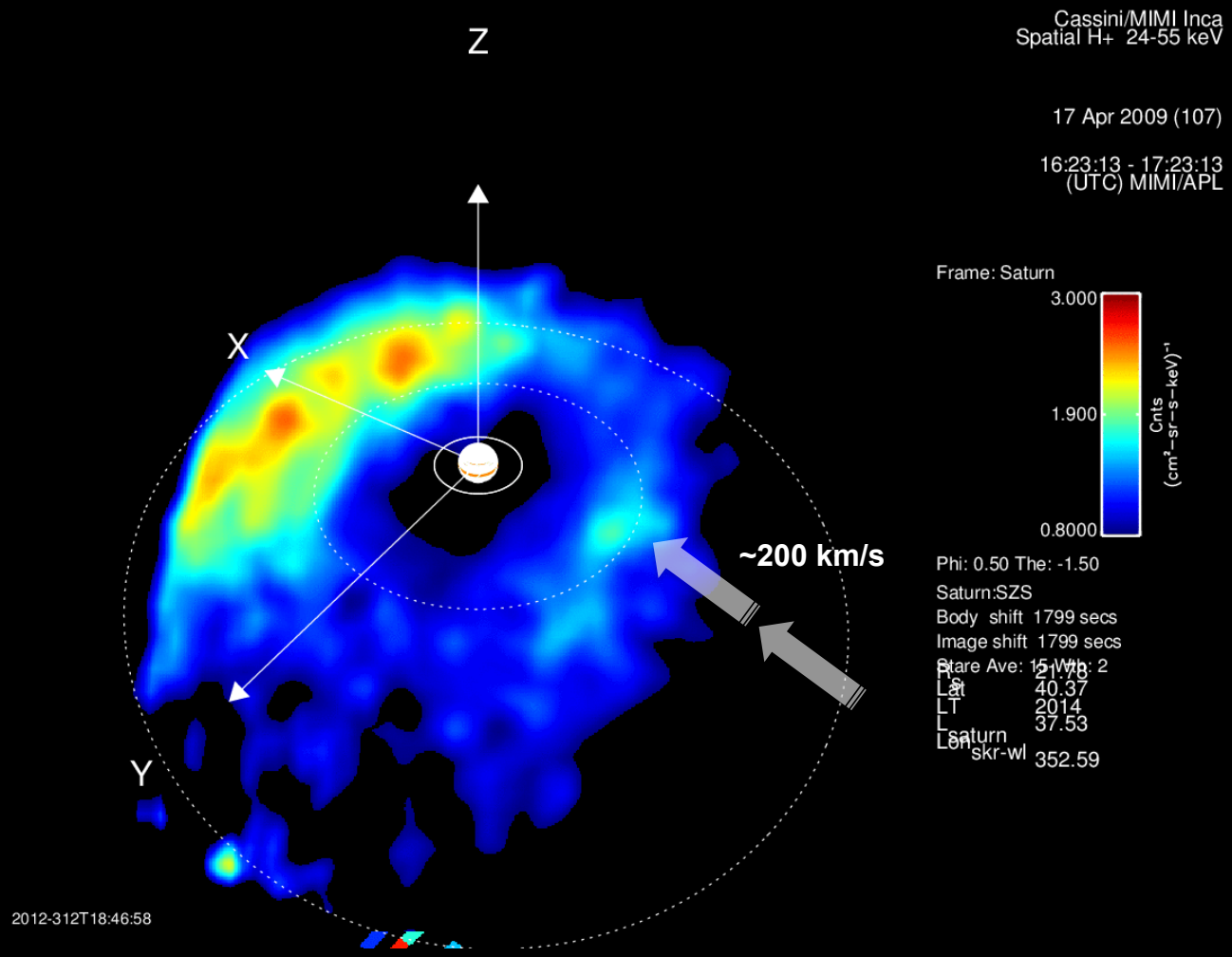


Summary

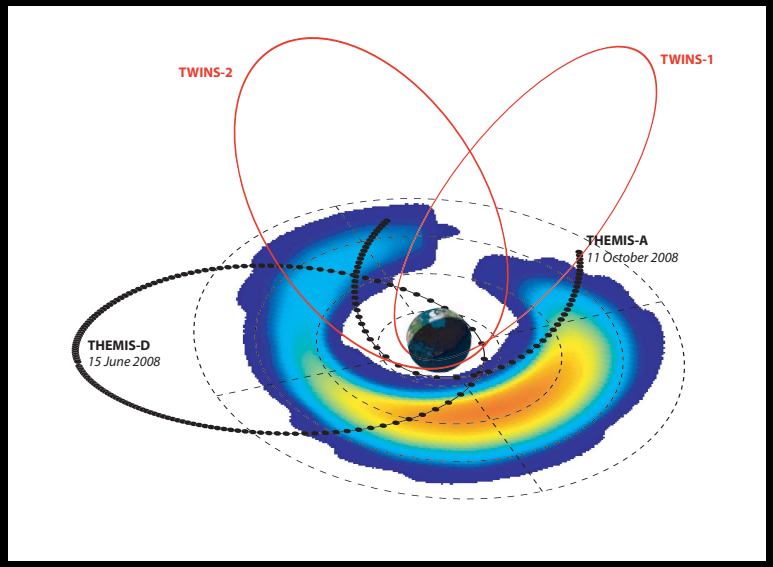
- **The terrestrial ring current vary globally on ~10 min time scales**
- **During storm main phases, the terrestrial ring current is asymmetric**
- **Substorms injections are dramatic for Oxygen ENA images and correlate well with AKR**
- **A post-midnight enhancements in intensity and (partial) pressure gradients are observed during strong storms consistent with results from TS07d modeling (Sitnov et al., 2008)**
- **Constrained linear inversion can provide large-scale distributions of perpendicular and parallel intensities to within a factor of 2-3.**
- **Other examples (not shown):**
  - *Substorm and plasmasheet dynamics*
  - *Pressure pulse ring current enhancements*

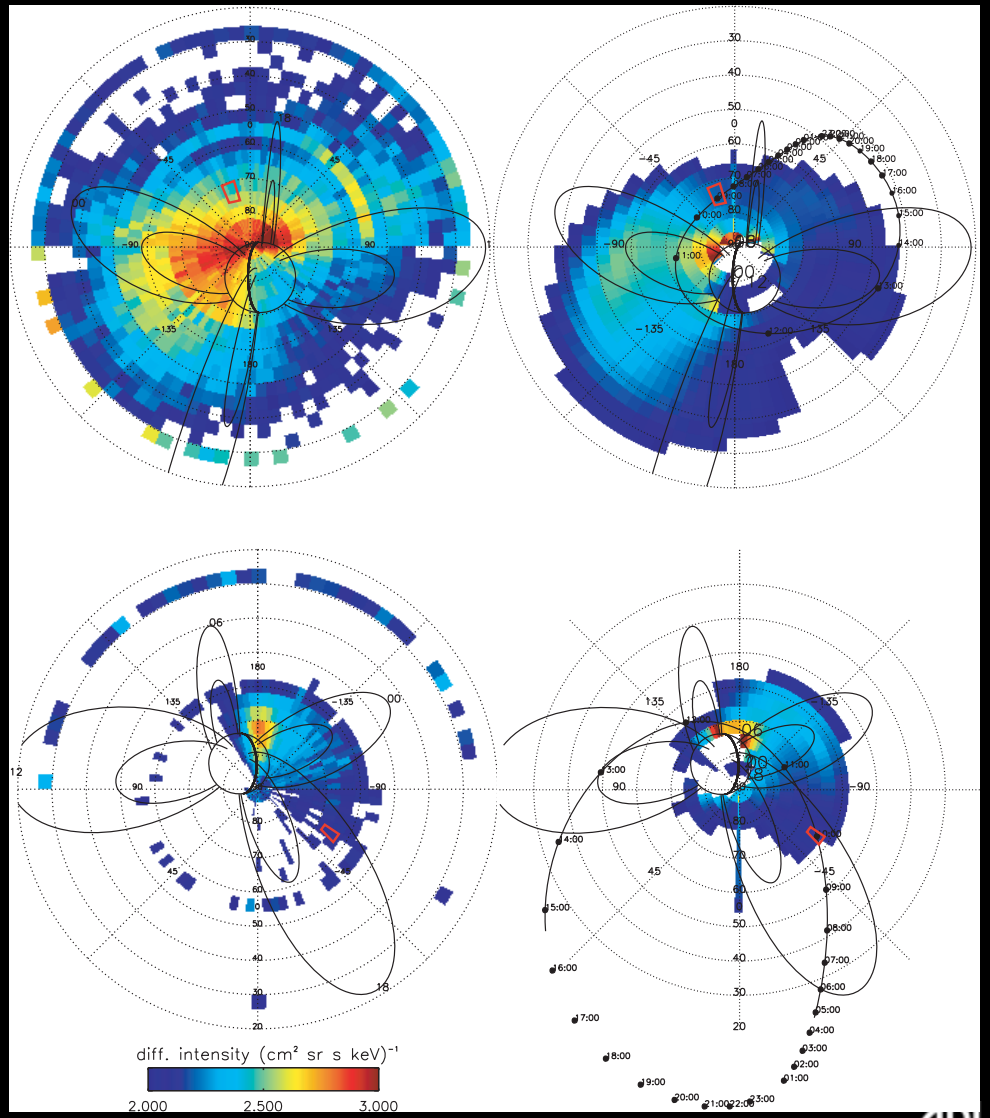
Back-up Slides

Saturn: Ring Current Injection (Cassini/INCA)



Earth: Ring Current/Plasmasheet Imaging (TWINS)





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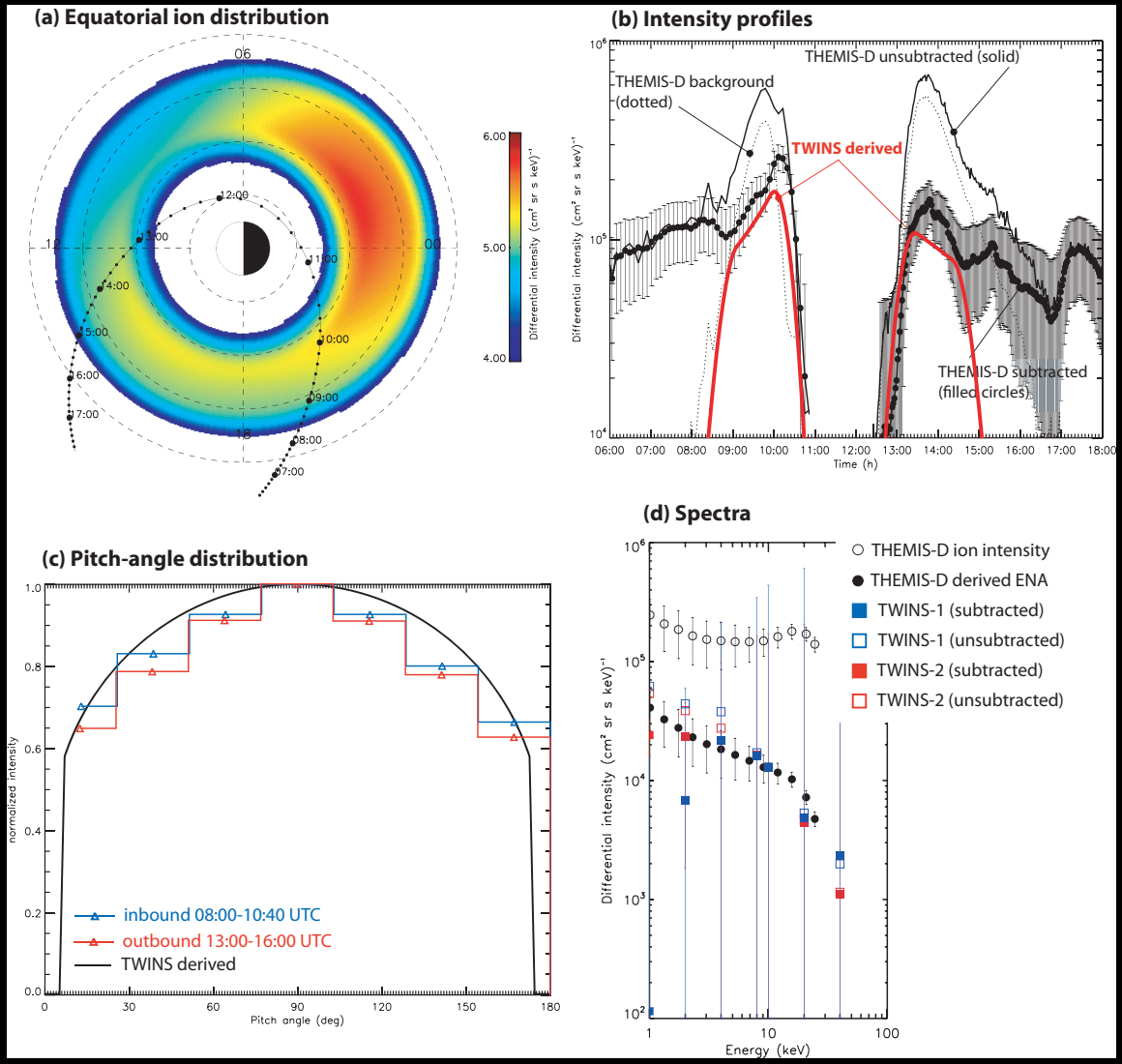
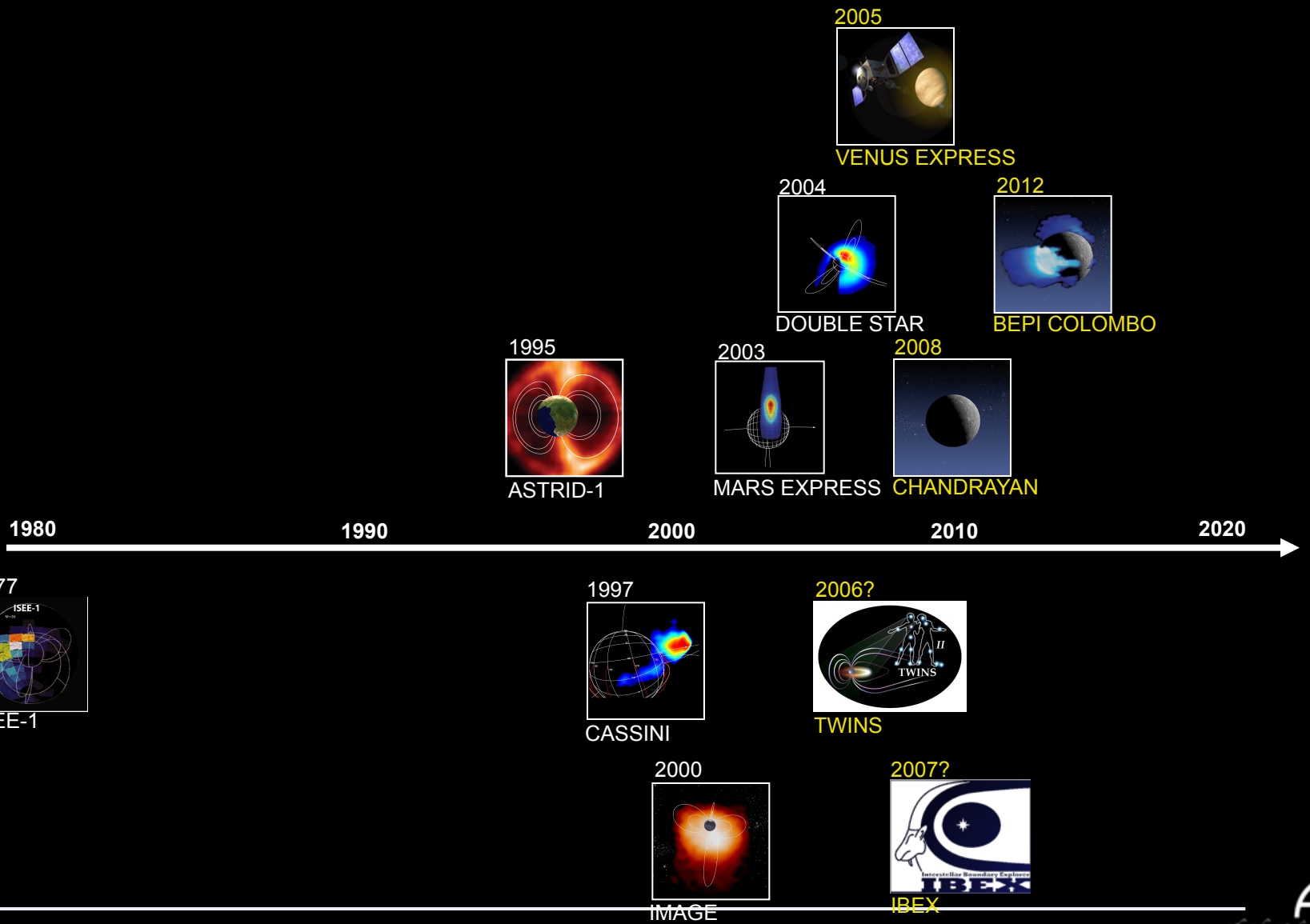
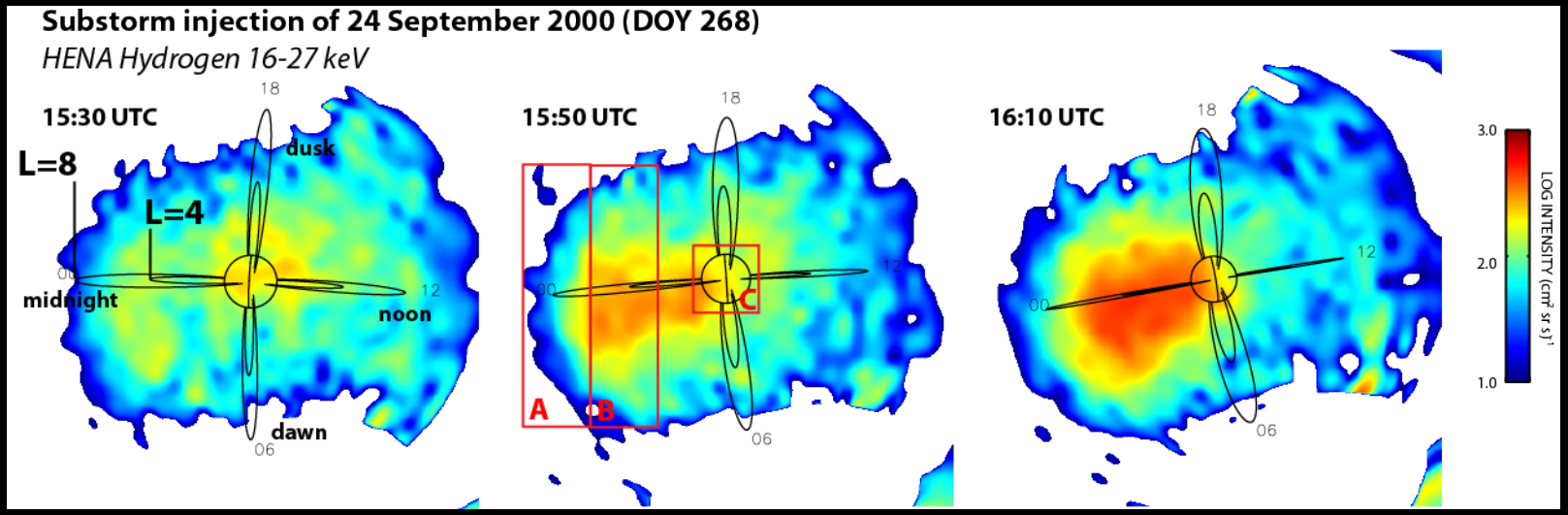


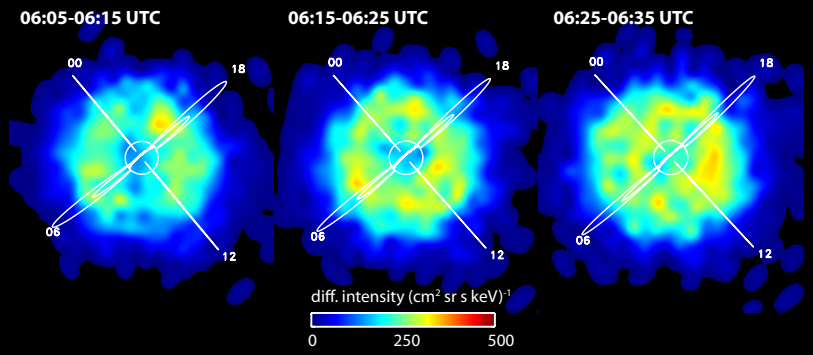
ENA History

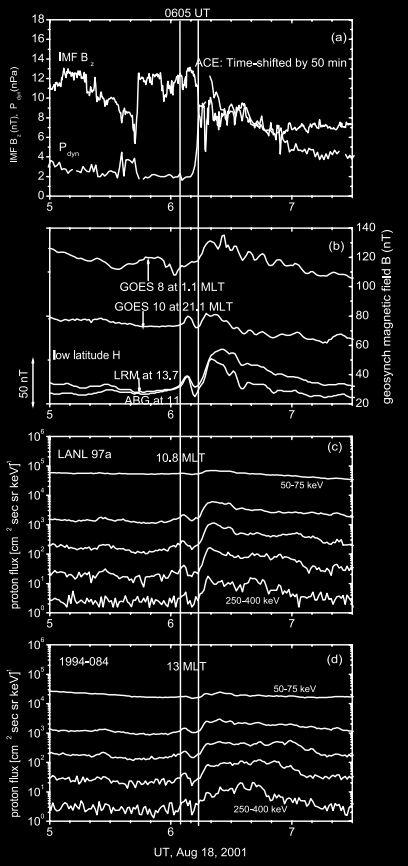

2005
VENUS EXPRESS
2004
DOUBLE STAR
2012
BEPI COLOMBO
1995
ASTRID-1
2003
MARS EXPRESS
2008
CHANDRAYAN
1980
1990
2000
2010
2020
1977
ISEE-1
ISEE-1
1997
CASSINI
2006?
TWINS
TWINS
2000
IMAGE
2007?
IBEX
IBEX

"Non-Storm" Substorm

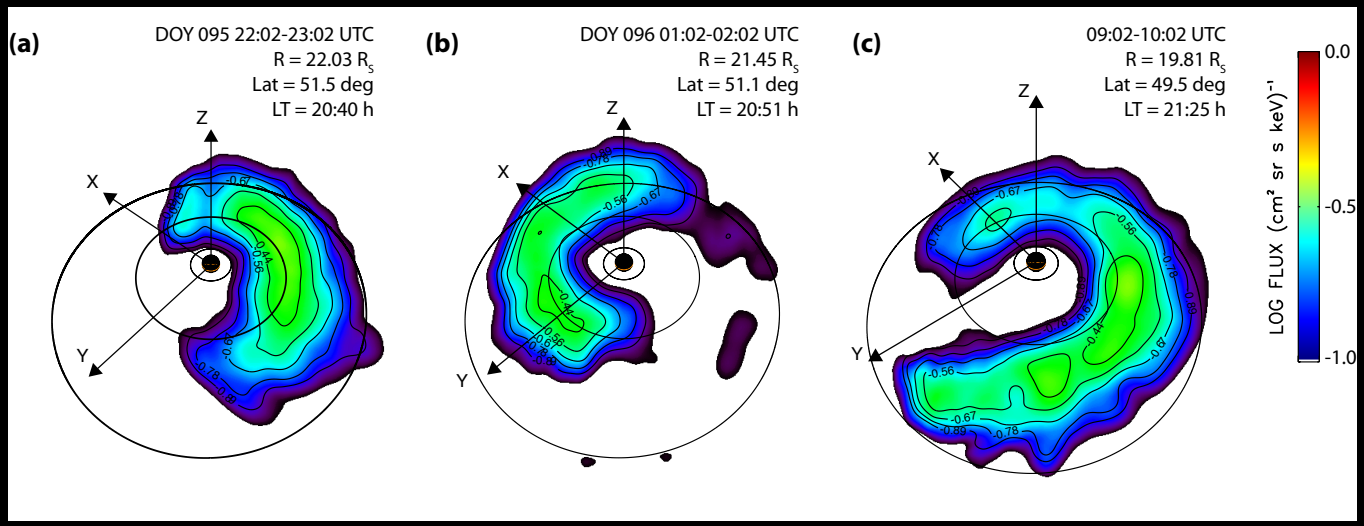


Earth: Sudden Enhancement due to Solar Wind Pressure Pulse (HENA)





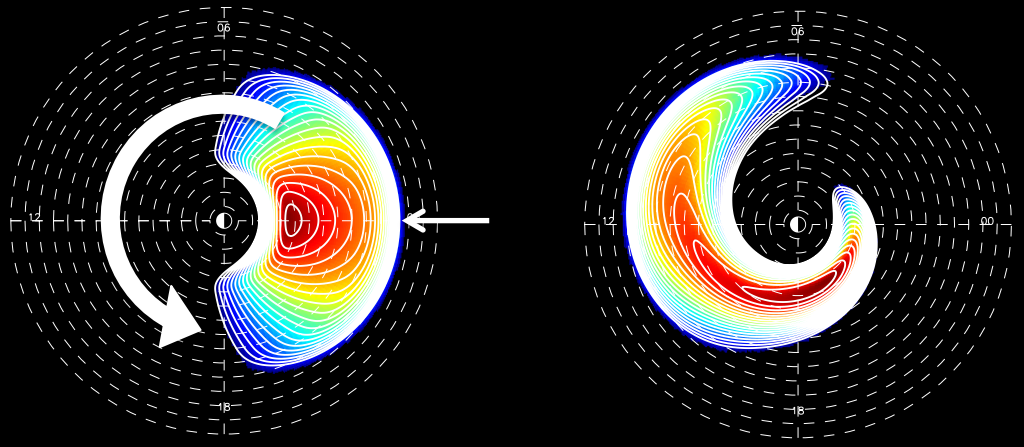
Saturn: Ring Current Drifts and Dispersion (Cassini/INCA)



Brandt et al., 2008.

$$v_{grad-curv}(W,L) = k\frac{q_0}{q}W\frac{W/2+m_0c^2}{W+m_0c^2}L$$

$$\frac{v_{rot}(L)}{v_{rigid}(L)} = f_r + (1-f_r)\frac{1}{1+(L/L_0)^N}$$



Saturn: Imaging of Ion Injections (Cassini)