Dynamic Planetary Magnetospheres: Gas-Plasma Interactions at their Best

by

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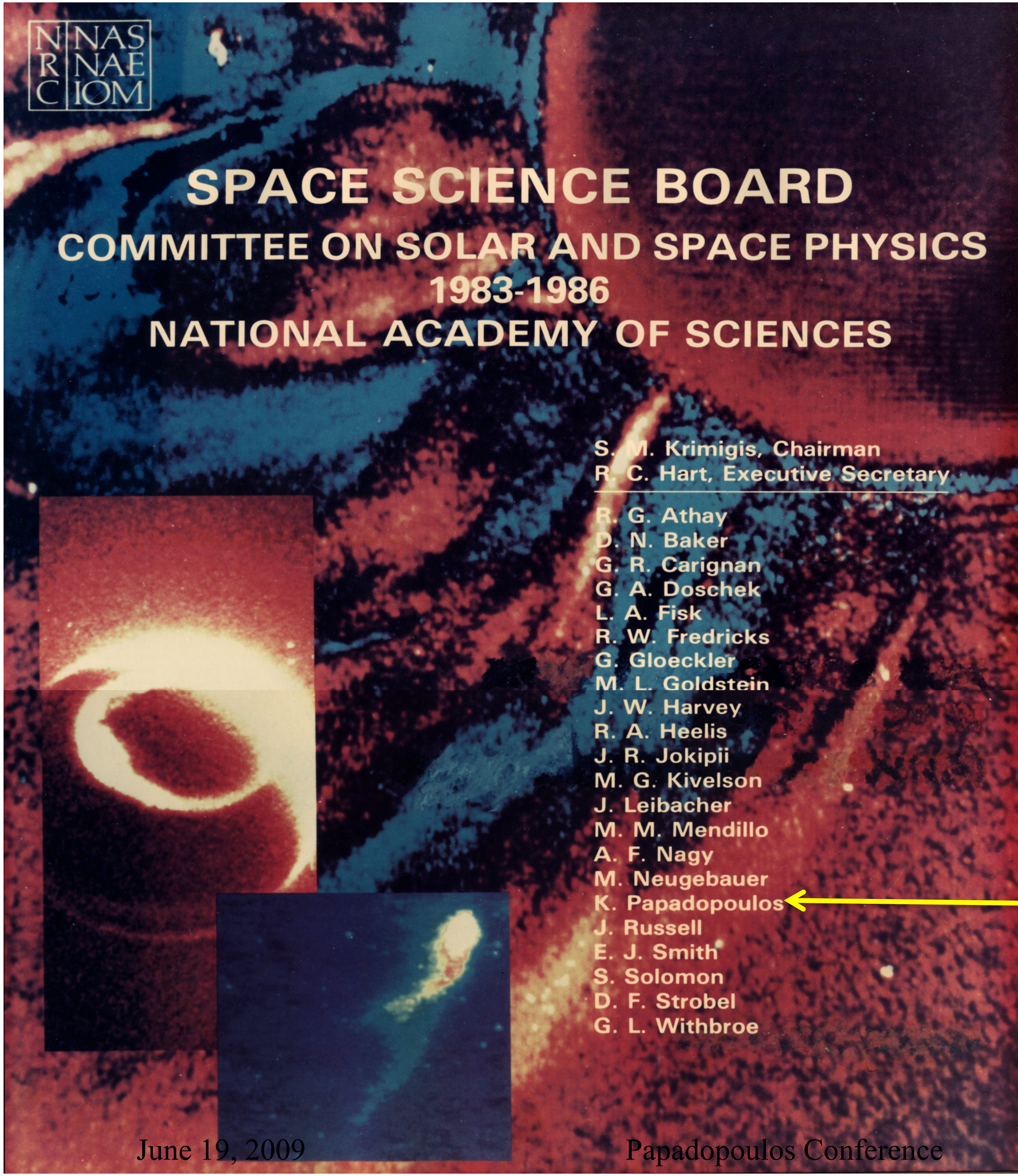
Modern Challenges in Non-linear Plasma Physics

Honoring the career of Dennis Papadopoulos

June 15-19, 2009 Halkidiki, Greece



An implementation Plan for Solar and Space Physics

An SSB Report, 1986

Theory section of report

Forty years ago, the magnetosphere was simple…

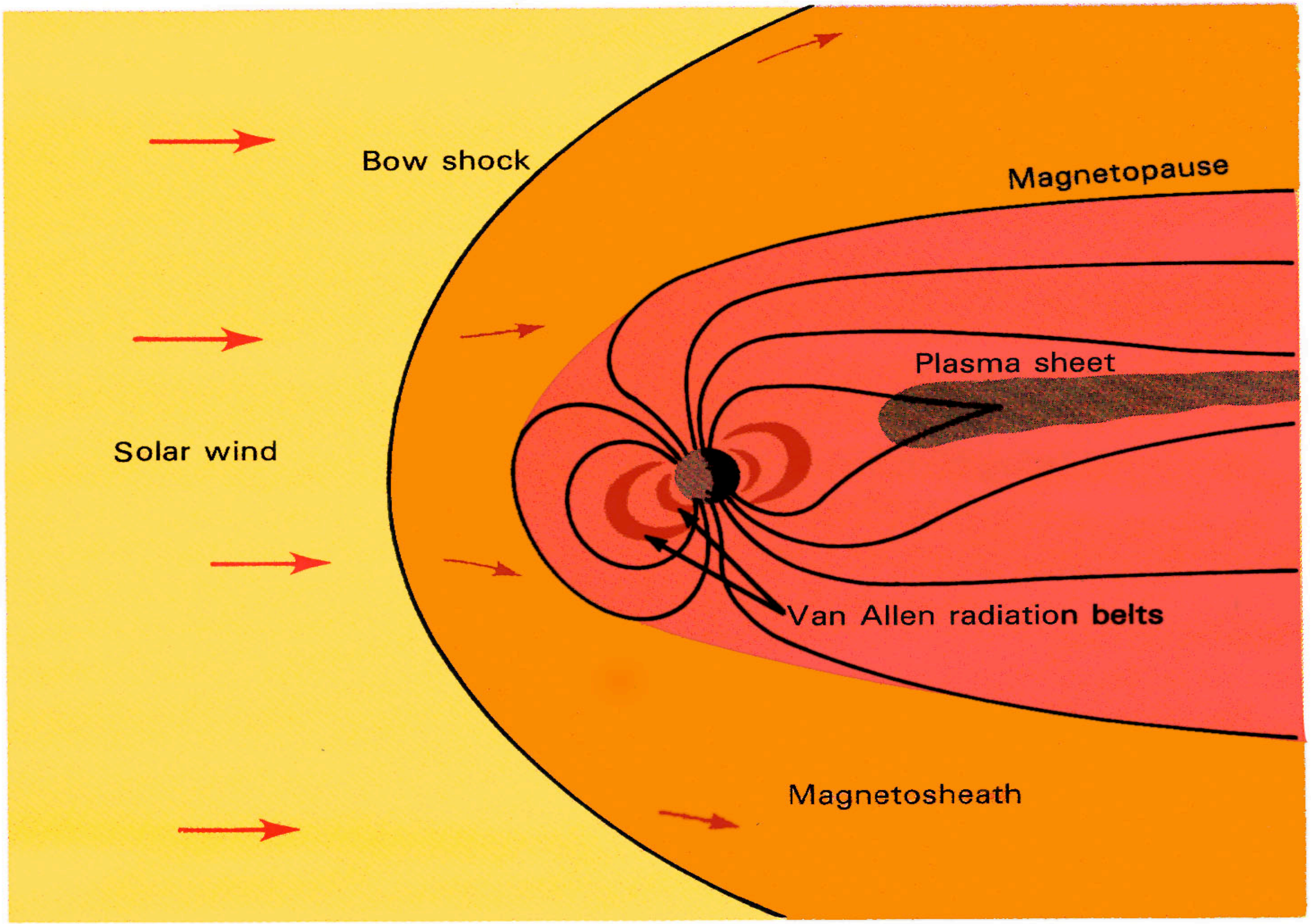


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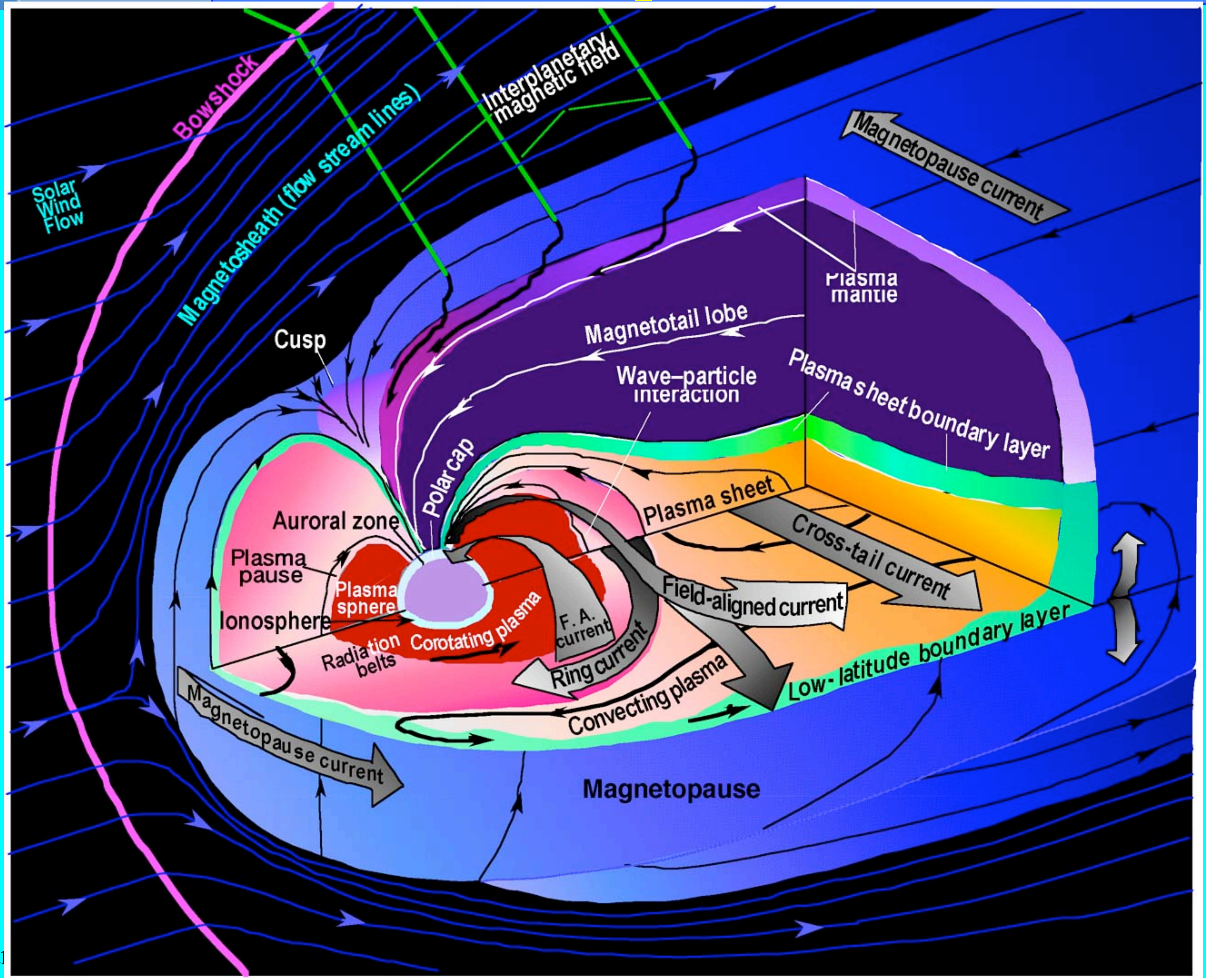
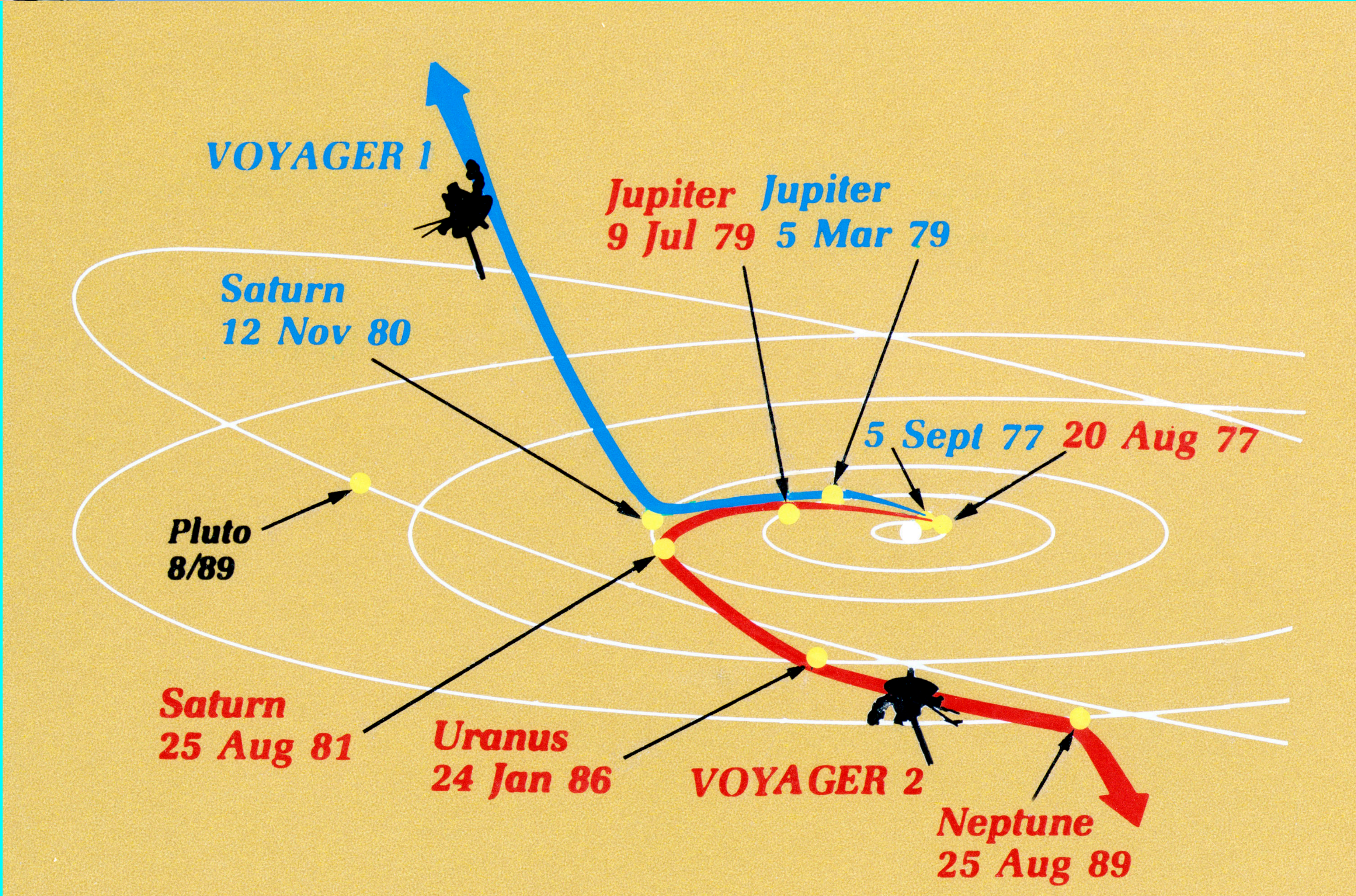
Figure 1—Earth's magnetosphere. The sketch shows important features of the plasmas and waves in the magnetic fields that surround Earth. (Lanzerotti and Krimigis, Physics Today, 1985)

James Van Allen at 90
October 9, 2004, Iowa City, IA

Now Earth's Magnetosphere is more complicated…

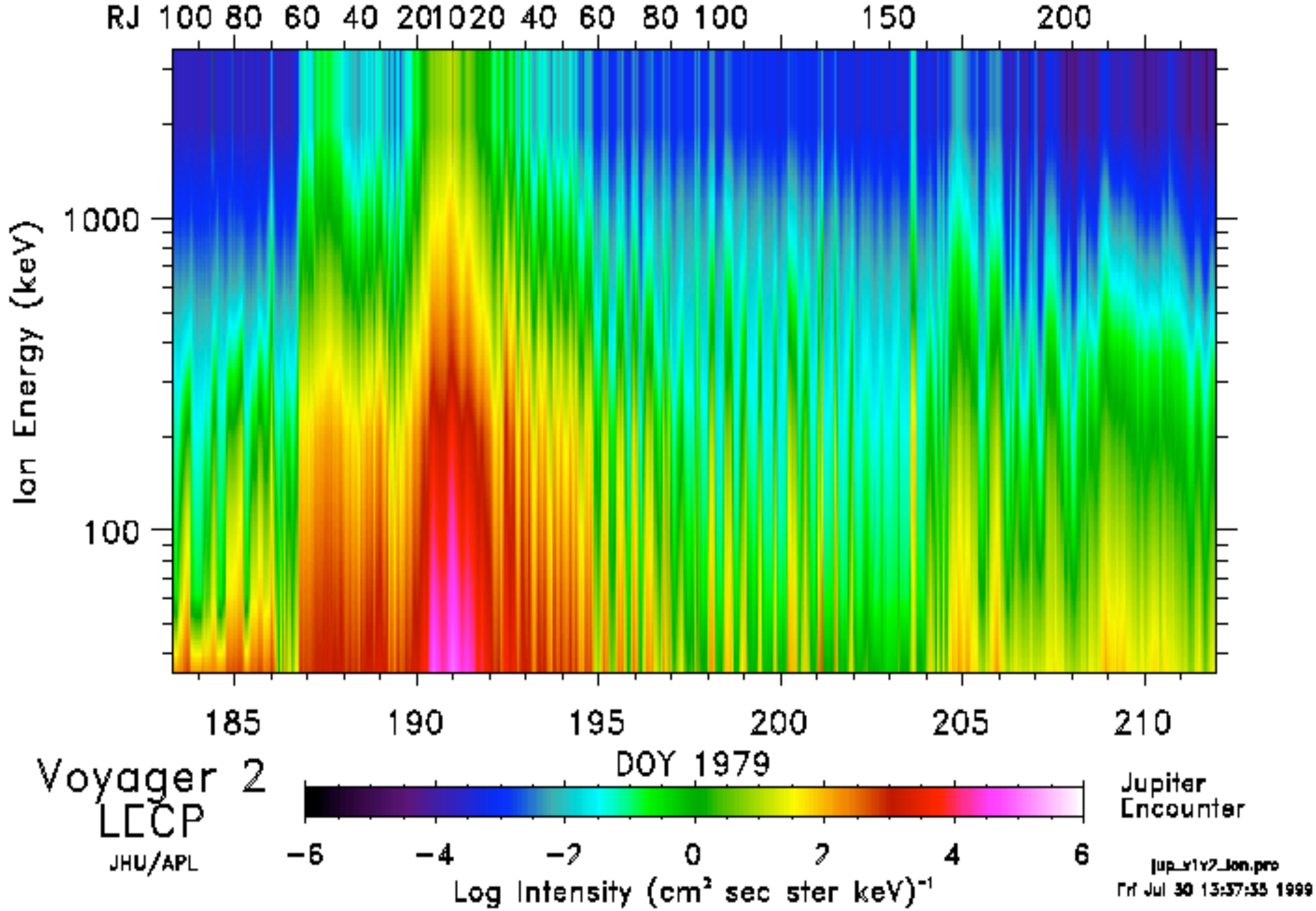


Voyagers showed that Outer Planet magnetospheres are most dynamic



Ion Intensities in Jupiter's Magnetosphere

Voyager 2, 1979 (Krimigis et al, JGR, 86, 8227, 1981)



Jovian plasma flows in the corotation direction (Krupp et al., JGR, 2001)

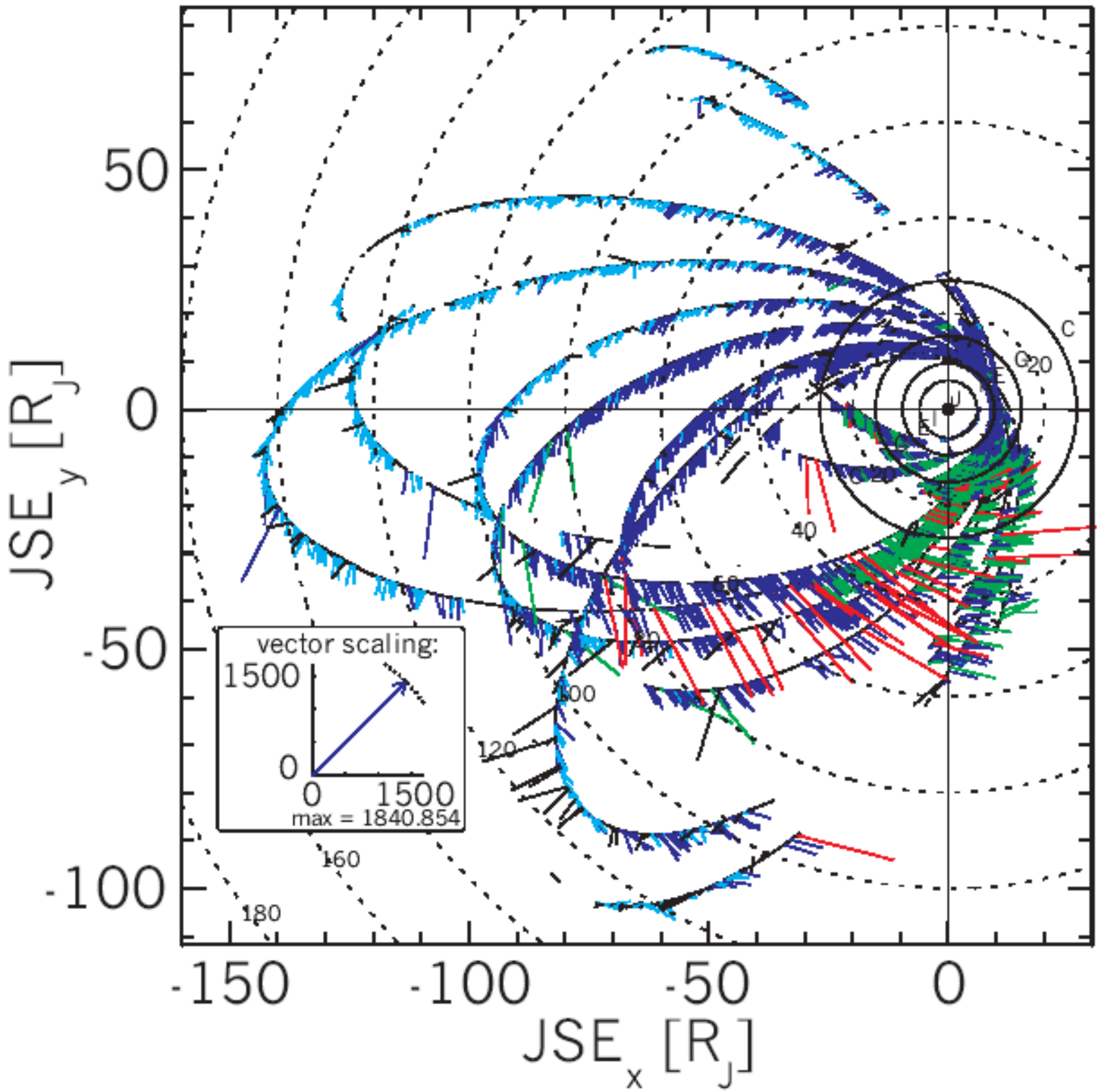


Figure 6. Flow velocity vectors of sulfur ions (16-30 keV/nucleon) in the Jovian equatorial plane. Data are dynamically time-averaged (T = 3 min · distance [R_J]). The colors distinguish between certain values of the ratio between the velocity values and the rigid corotation velocity v_{rigid}:

cyan: $v_{10}/v_{rigid} < 0.2$ (sub-corotational flow < 20%);

blue: $0.2 < v_{10}/v_{rigid} < 0.8$ (sub-corotational flow between 20 and 80%);

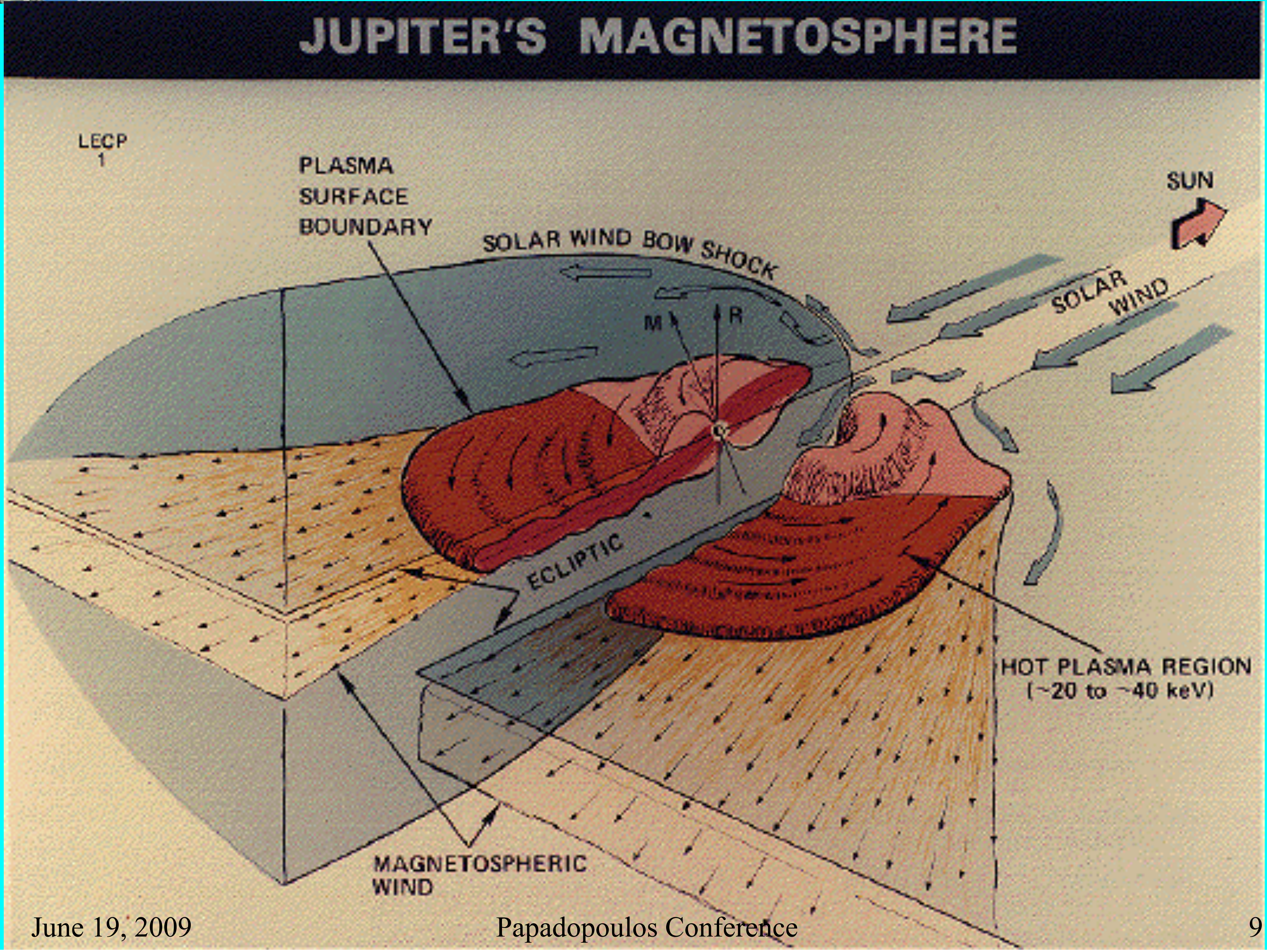
green: $0.8 < v_{10}/v_{rigid} < 1.2$ (corotational flow $\pm$ 20%);

red: $v_{10}/v_{rigid} > 1.2$ (super-corotational flow).

Black vectors indicate those time periods where the radial components are larger than the components in corotation direction (radial inward and outward bursts).

Jupiter's rotation-dominated magnetosphere

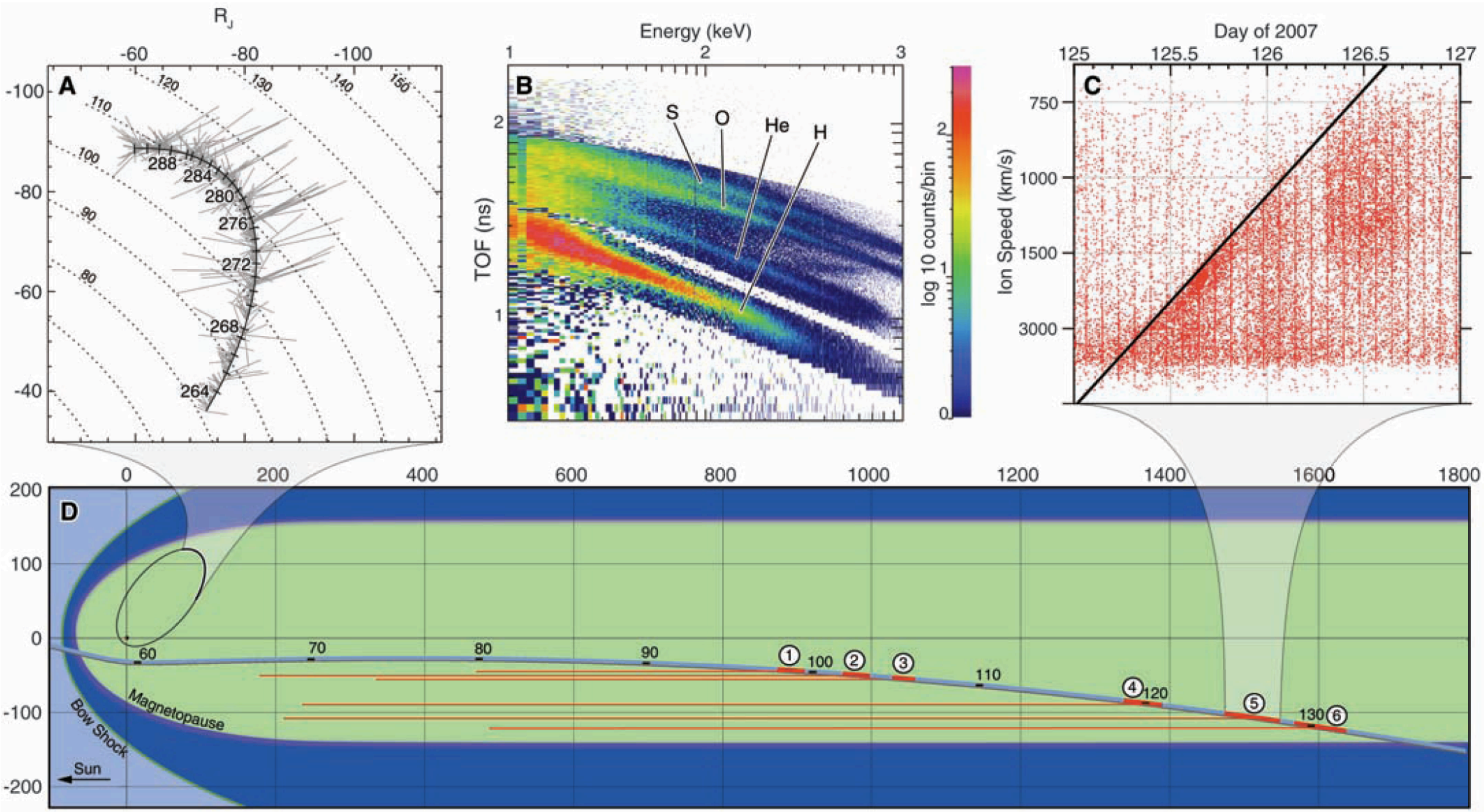
(Krimigis et al, JGR, 86, 8227, 1981)



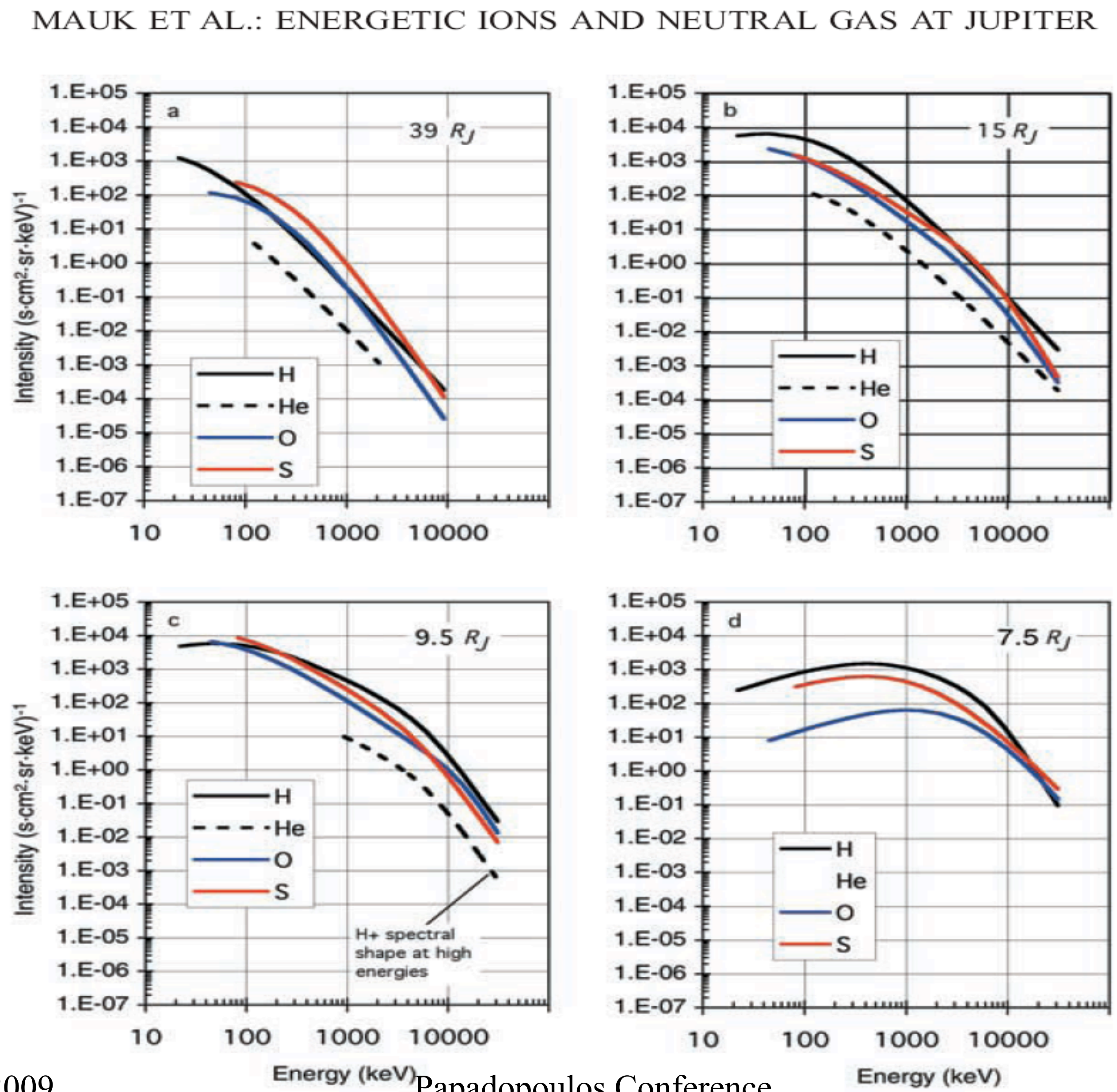
Jupiter's magnetotail explored by ***New Horizons*** *in 2007 extends to > 1 AU*

(McNutt et al, Science 318, 220, 2007)

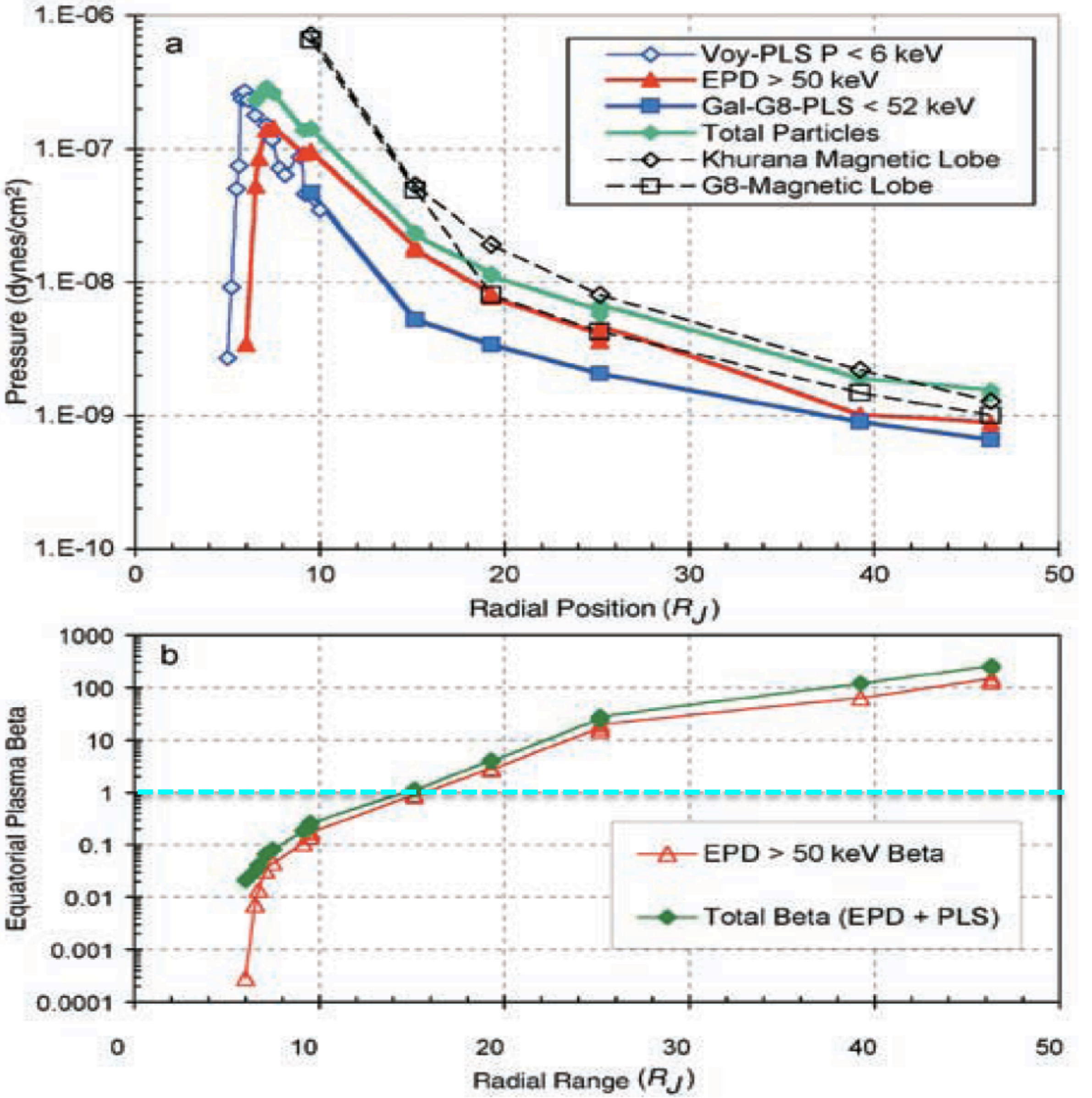
New Horizons at Jupiter



Jupiter's plasma is dominated by heavy ions (O, S) {Mauk et al, 2004}



Jupiter's Magnetosphere: High β regime (Mauk et al, 2004)



Stochastic acceleration of large M/Q ions by hydrogen cyclotron waves in the magnetosphere

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It is shown that in hydrogen dominated multi-ion plasmas supporting coherent hydrogen cyclotron waves, the minority ion species with large M/Q are preferentially accelerated and the maximum energy achieved scales as $(M/M_{H^+})^{5/3}$. The importance of this scaling to O^+ acceleration in the auroral zones and to other high energy heavy ion observations in the earth's and Jupiter's magnetospheres is discussed.

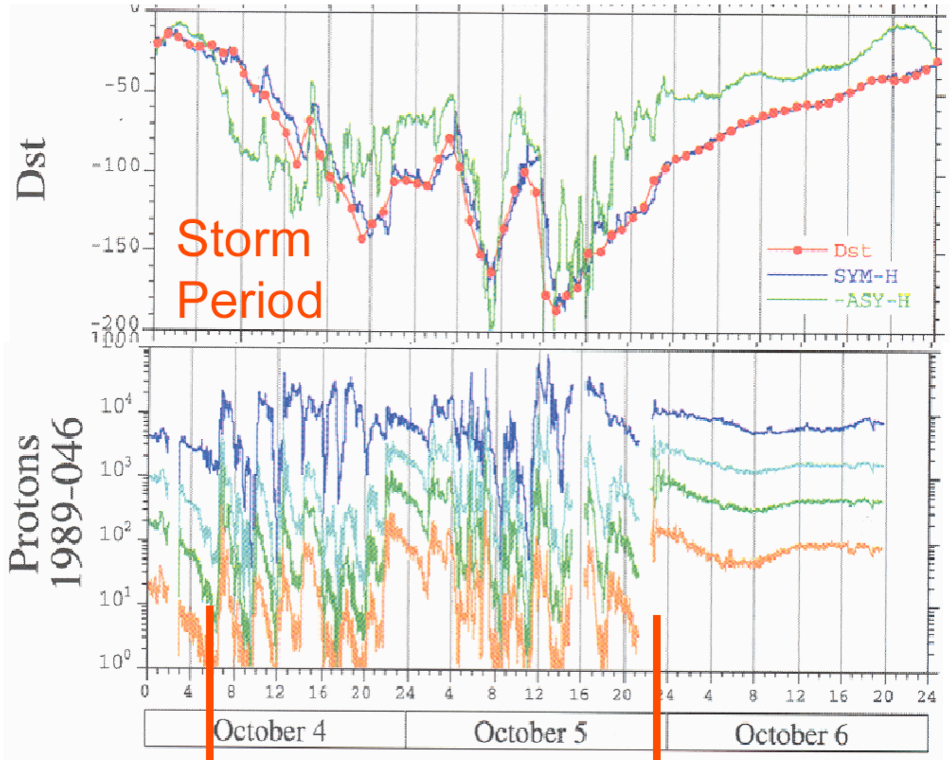
Received 16 June 1980; accepted 1 August 1980; .

Citation: Papadopoulos, K., J. D. Gaffey Jr., and P. J. Palmadesso (1980), Stochastic acceleration of large M/Q ions by hydrogen cyclotron waves in the magnetosphere, *Geophys. Res. Lett.*, *7*(11), 1014–1016.

Like Earth, Jupiter has quiet and active periods of injections

At Earth:

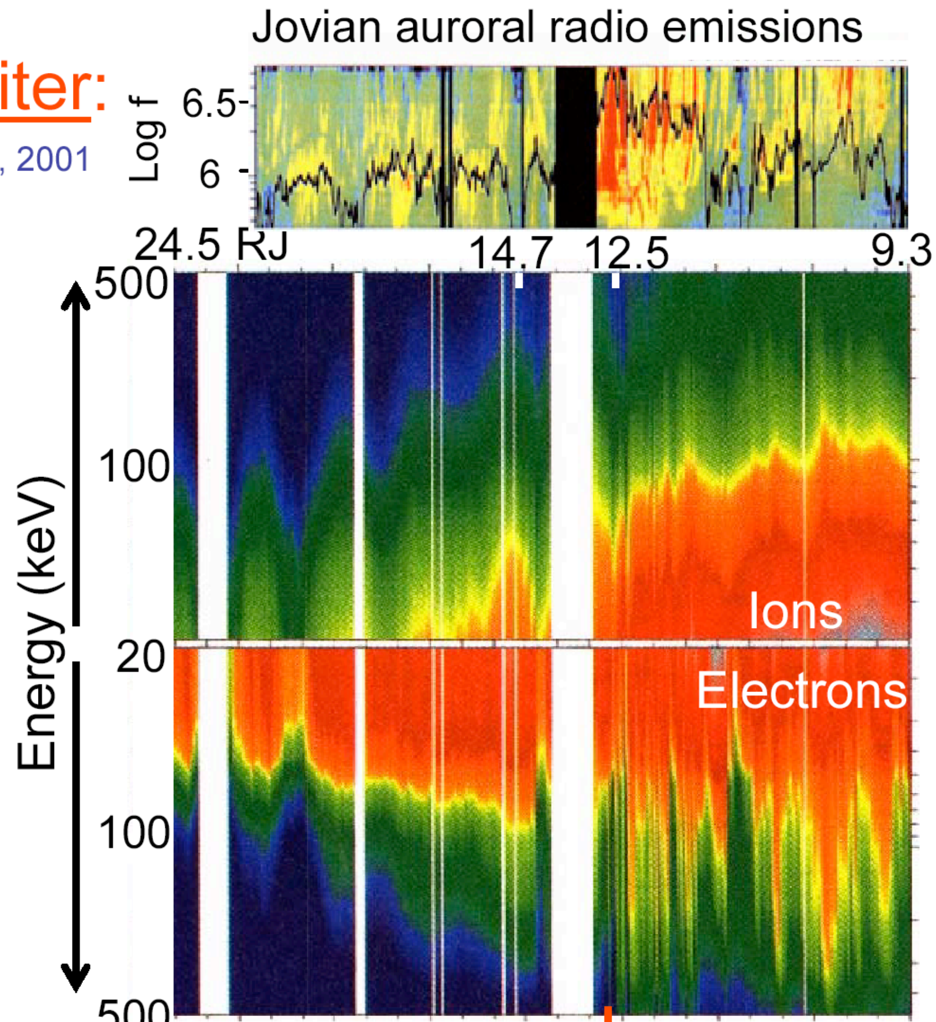
Reeves et al., 2003



Storm
Associated
Injections

At Jupiter:

Louarn et al., 2001

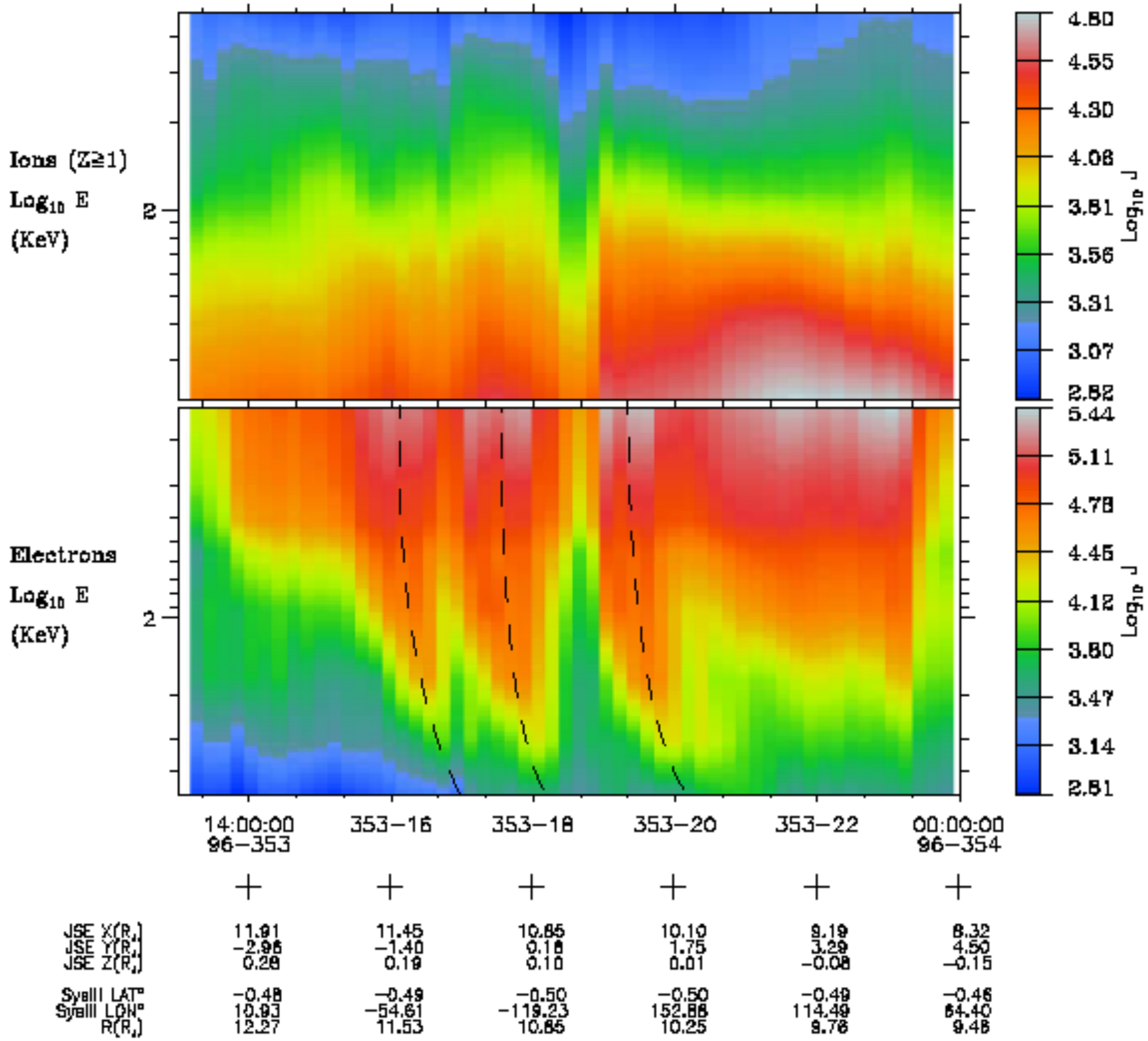


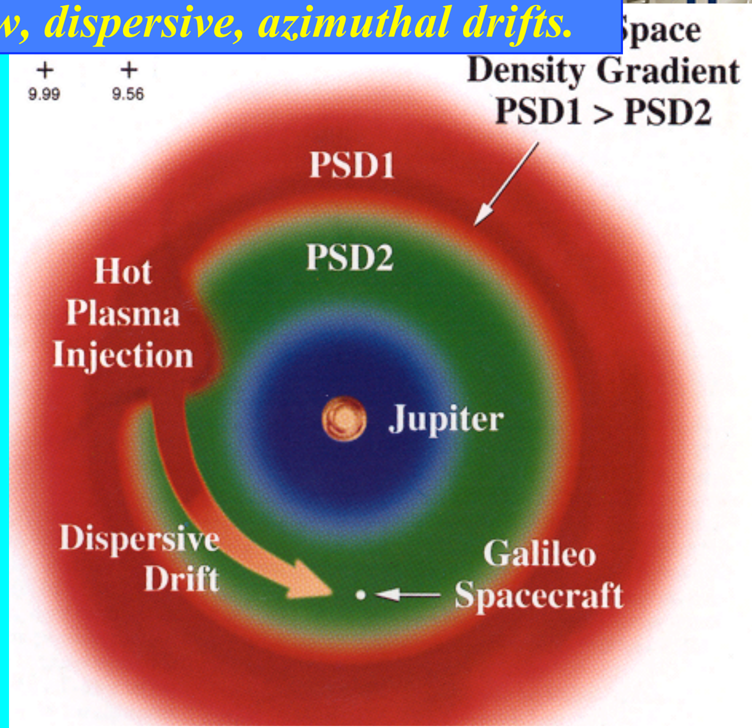
"Quiet" Period

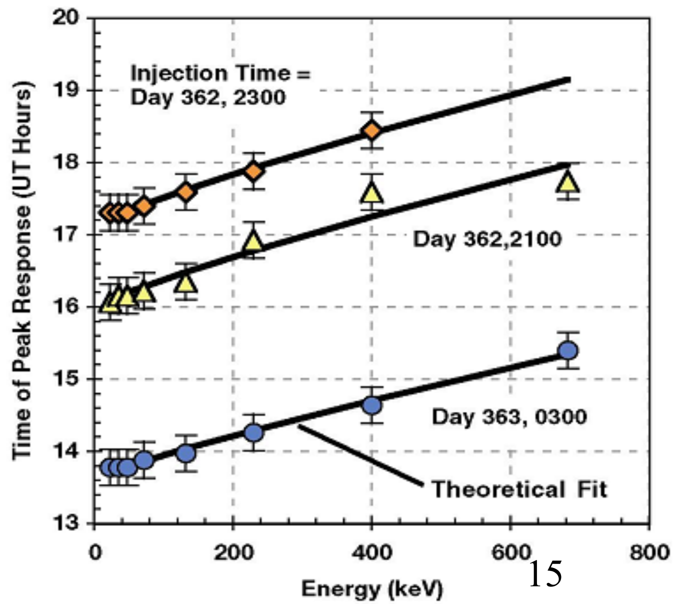
"Storm" Period

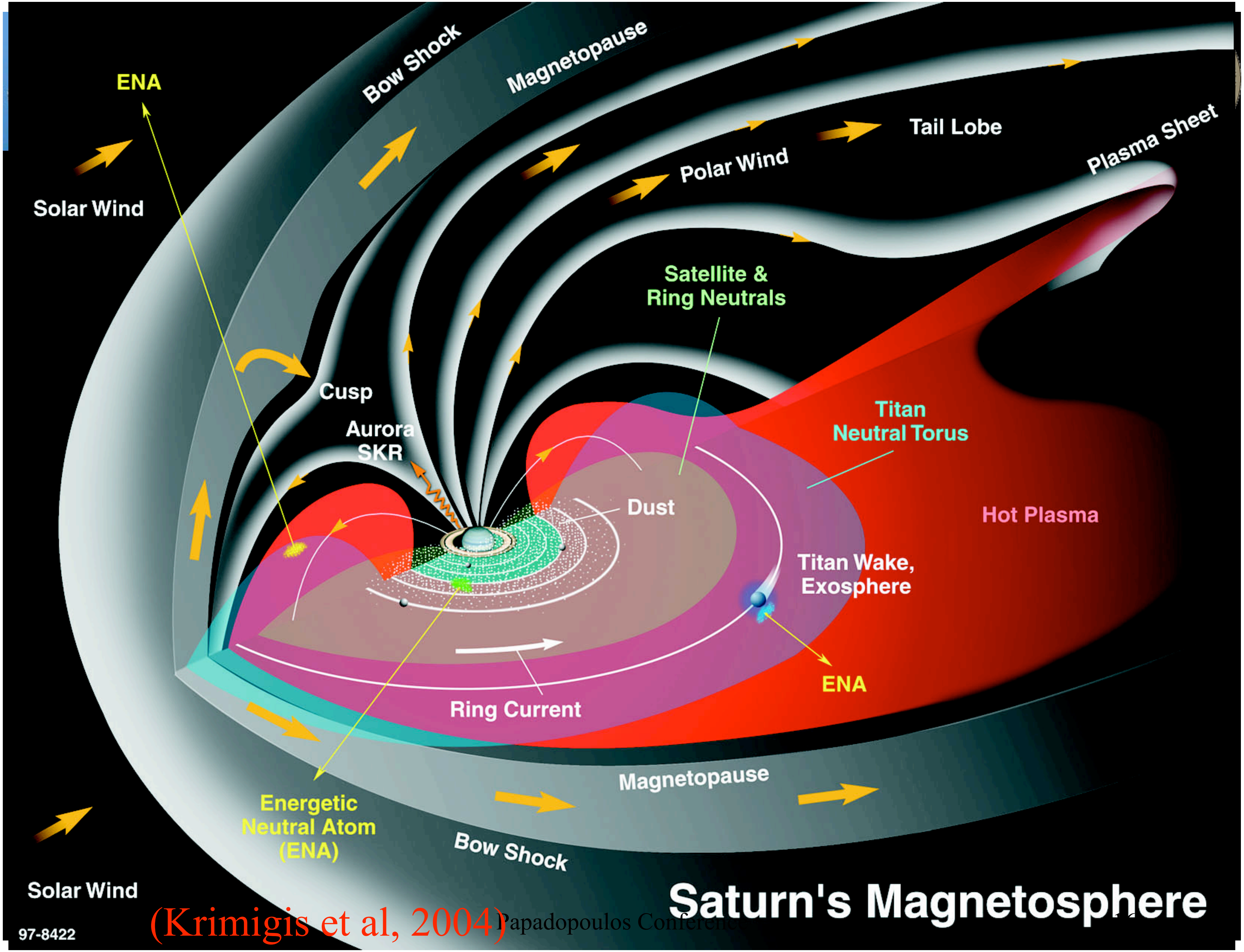
The behaviors of Jupiter magnetosphere injections were understood by invoking sudden radial injections over confined regions in azimuth followed by slow, dispersive, azimuthal drifts.

Mauk et al, 2004)





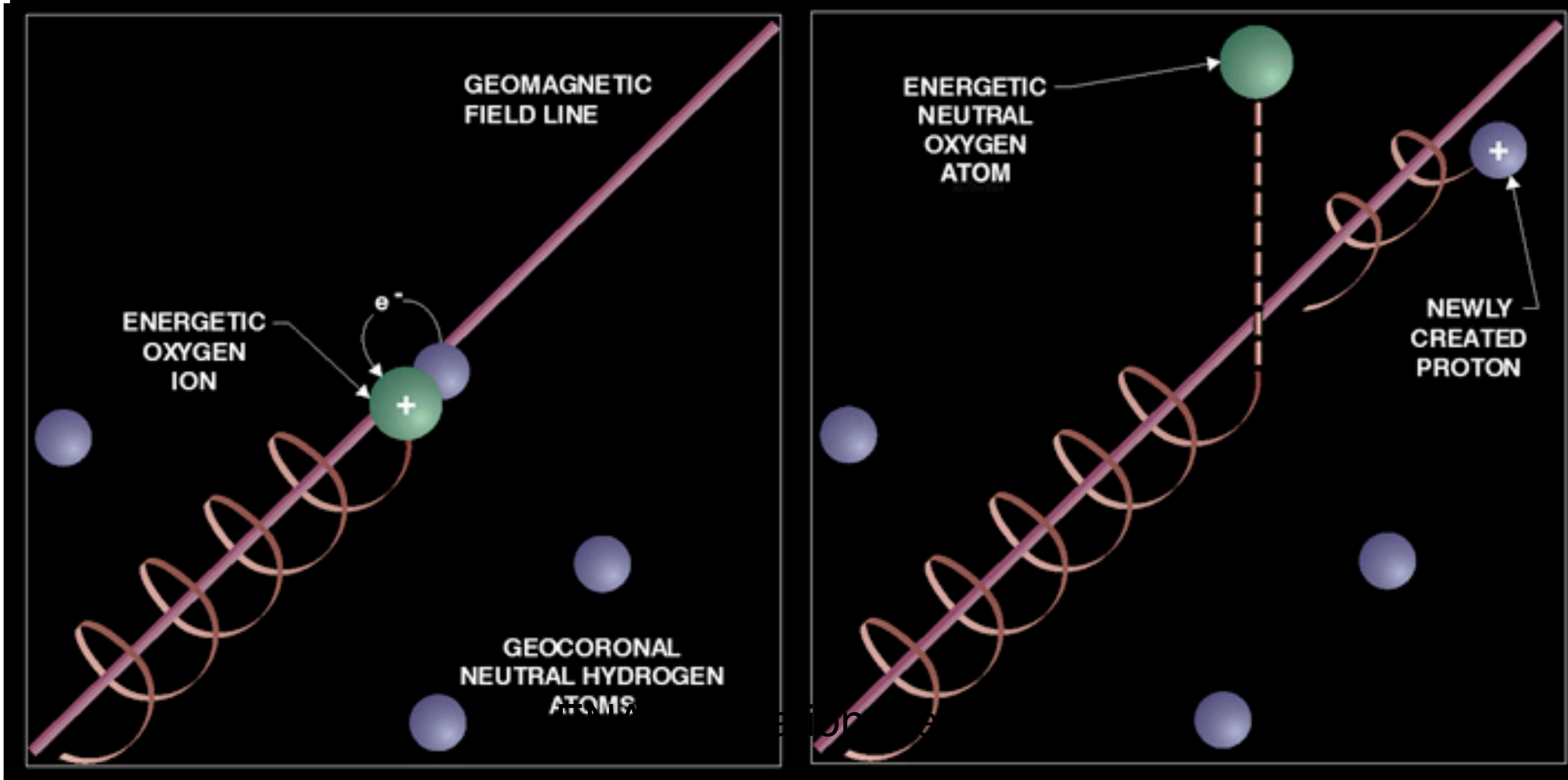




(Krimigis et al, 2004)

Energetic Neutral Atom (ENA) Imaging

$$O^{+}_{fast} + H \rightarrow O_{fast} + H^{+}$$



ENA (Energetic Neutral Atoms) production principle

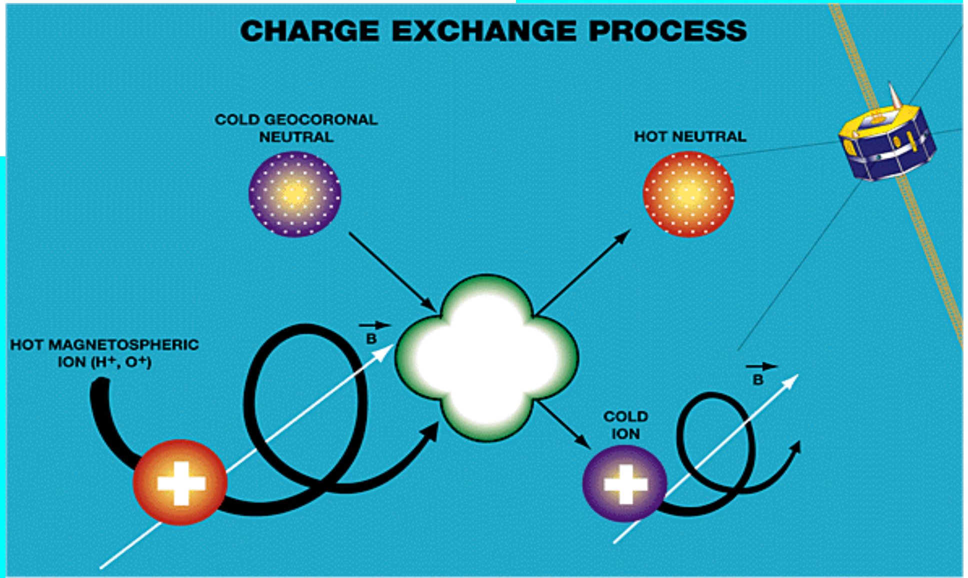
$$j_{ENA}(E) = \Sigma_k \, \sigma_{ik}(E) \int j_i(E) \, n_k(l) \, dl$$

$j_{ENA}(E)$: Energetic Neutral Atoms (ENA) Flux

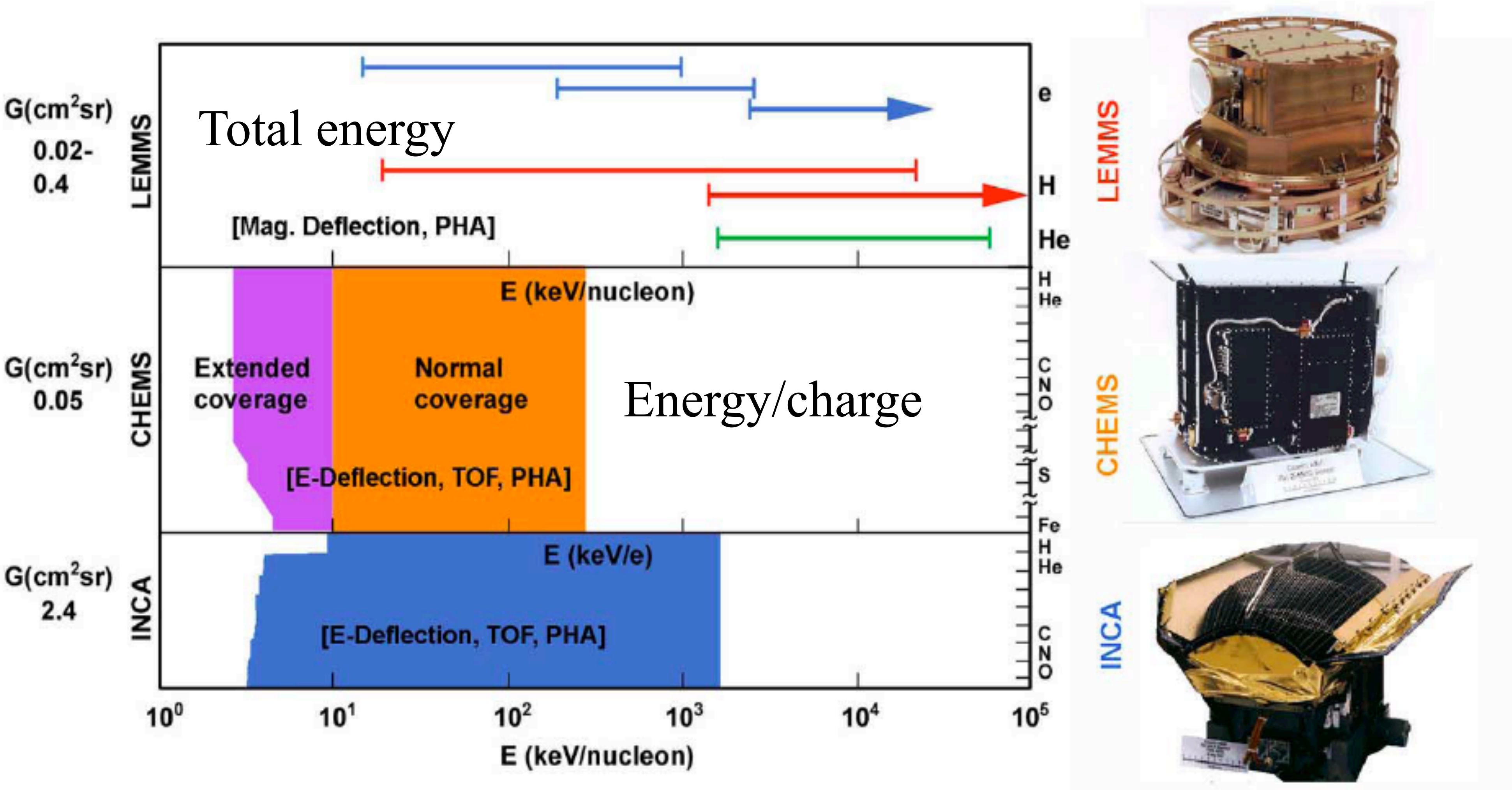
$j_i(E)$: Ion Flux (*i* species)

$n_k(l)$: Exospheric Density (*k* species)

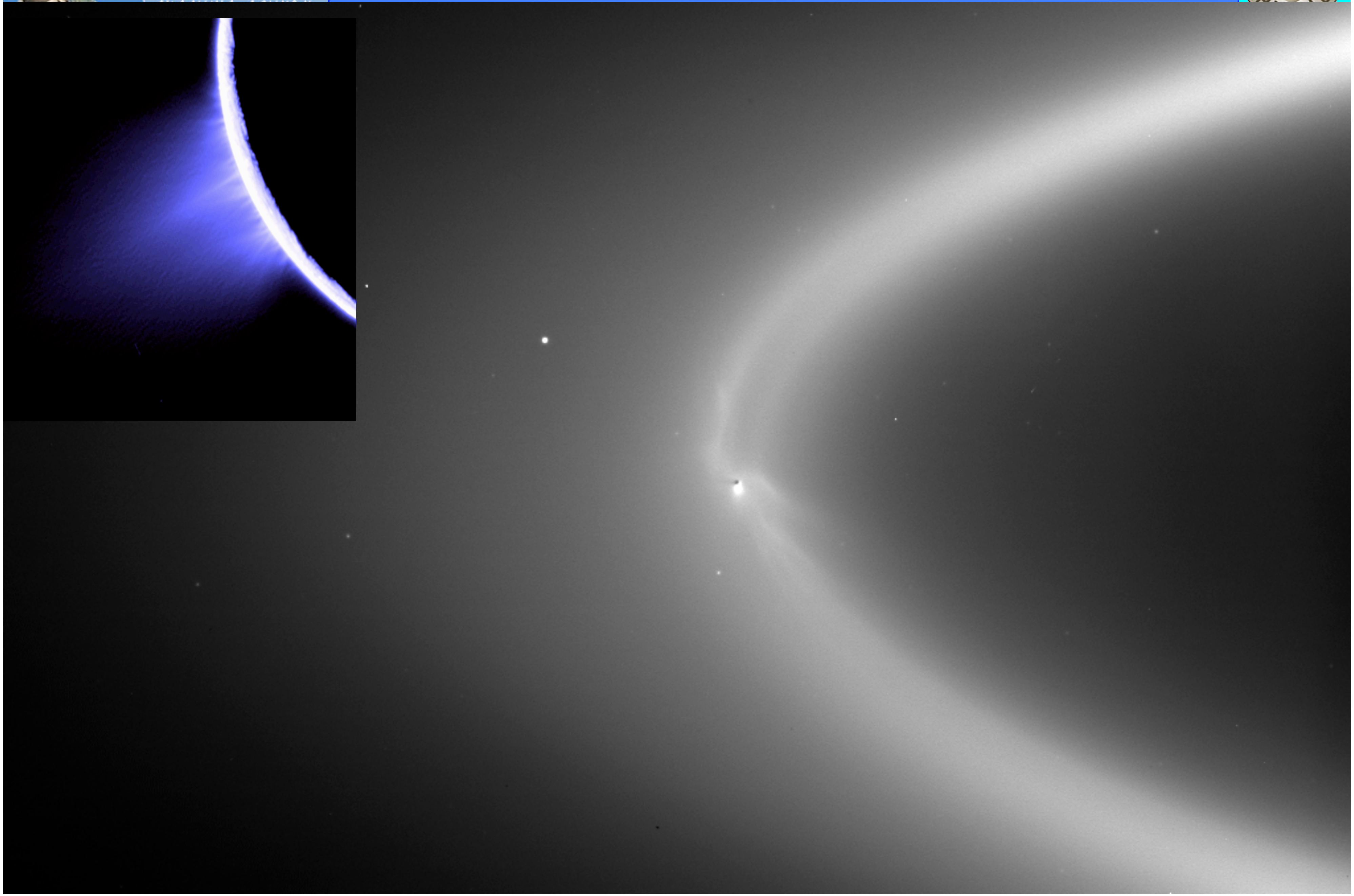
$\sigma_{ik}(E)$: Charge Exchange Cross-Section between Ions *i* and Exospheric Atoms *k*



Magnetospheric Imaging Instrument (MIMI) On the Cassini Mission to Saturn/Titan



Enceladus icy material feeds Saturn's E-ring at rate ~ 100 kg/s



Composition of plasma is mostly Water group (W^+) and H^+ ions, but W^+ dominate during active periods (Hamilton et al, 2008)

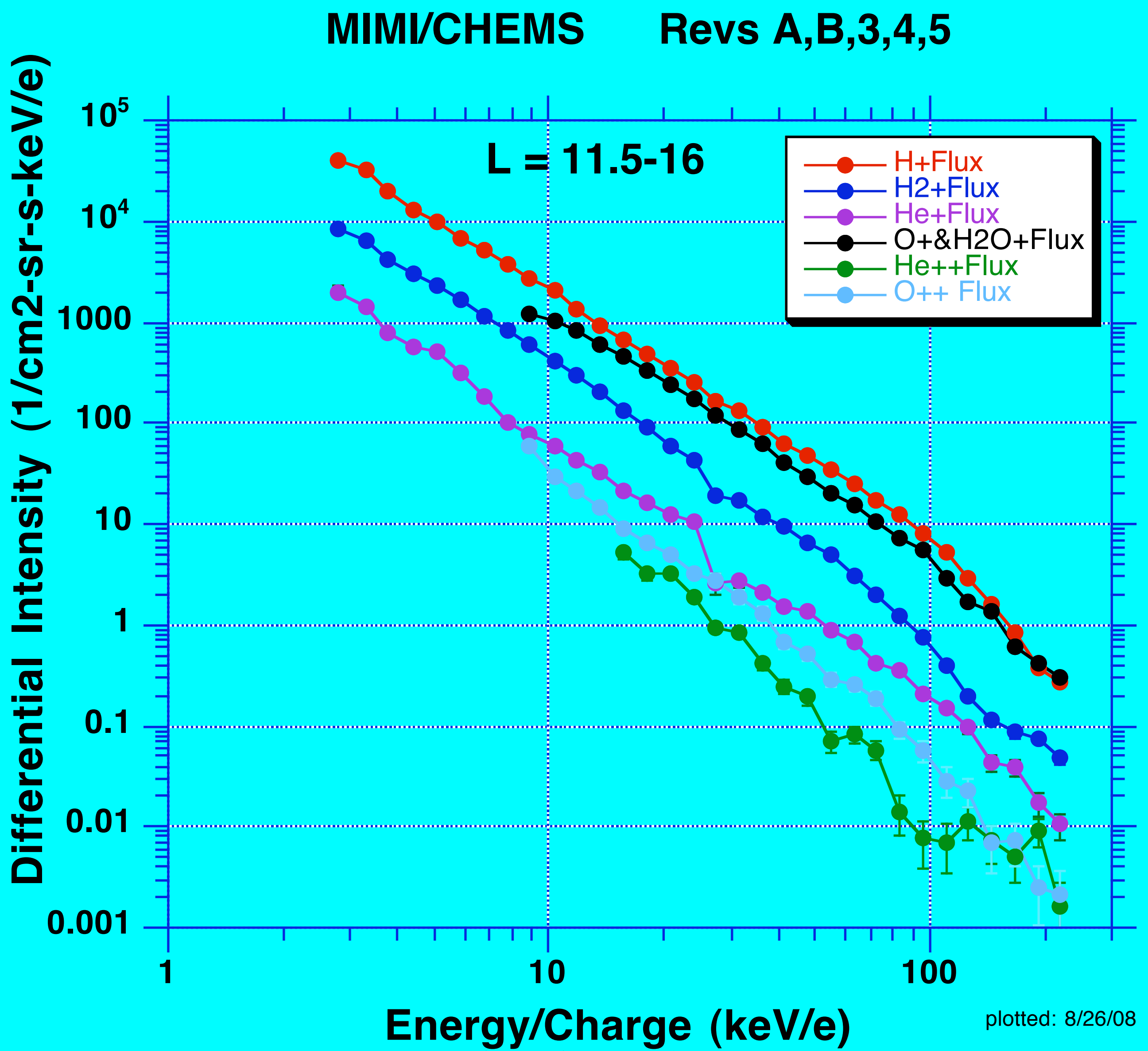
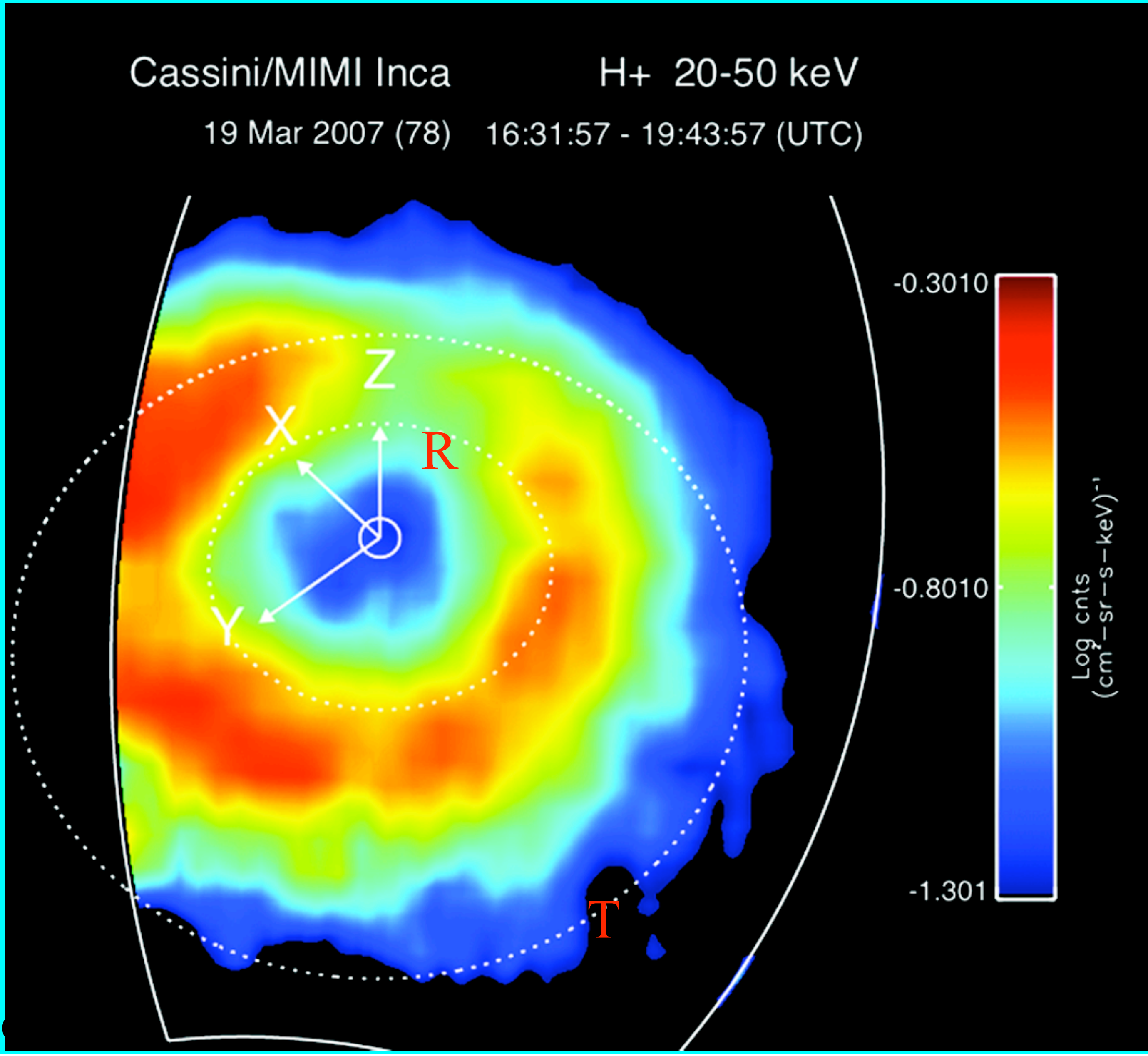


Image of Saturn's Ring Current through ENAs

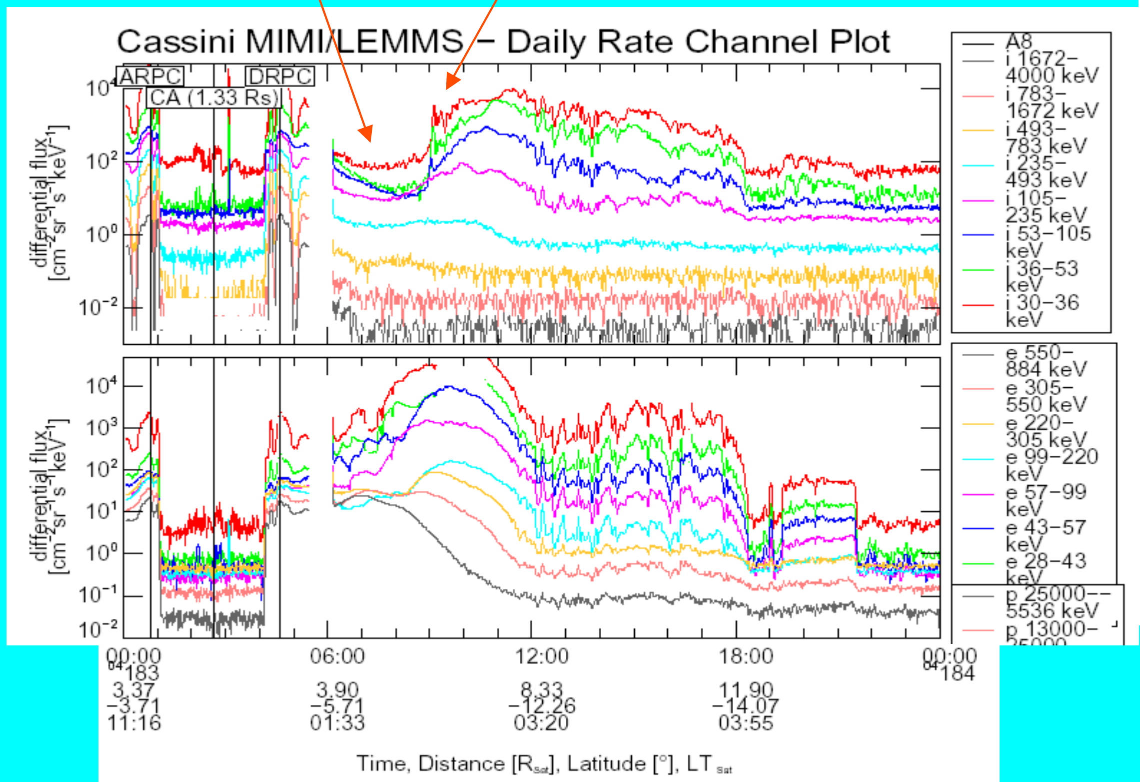
(Krimigis et al, Nature, 450, 1050-1053, 2007)

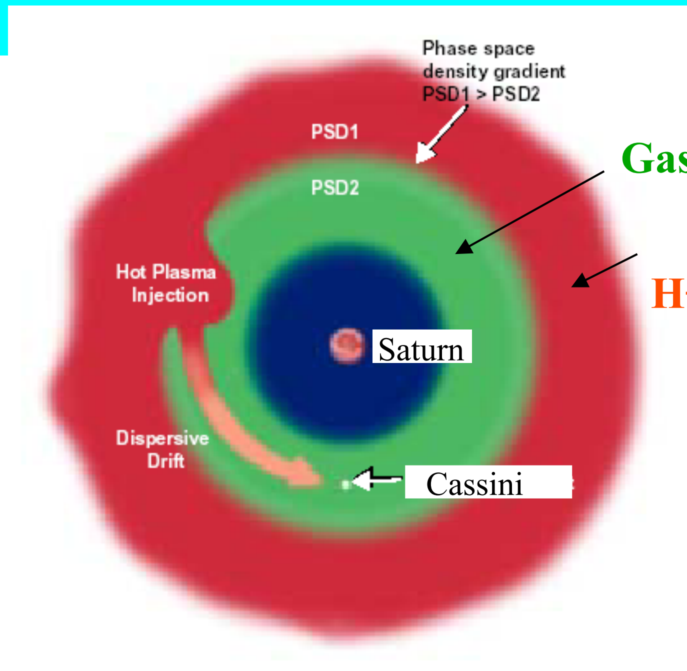


Hot plasma injections (revealed as ion dispersion events) into the neutral gas reservoir may explain some Saturn ENA emission dynamics

Neutral Gas?

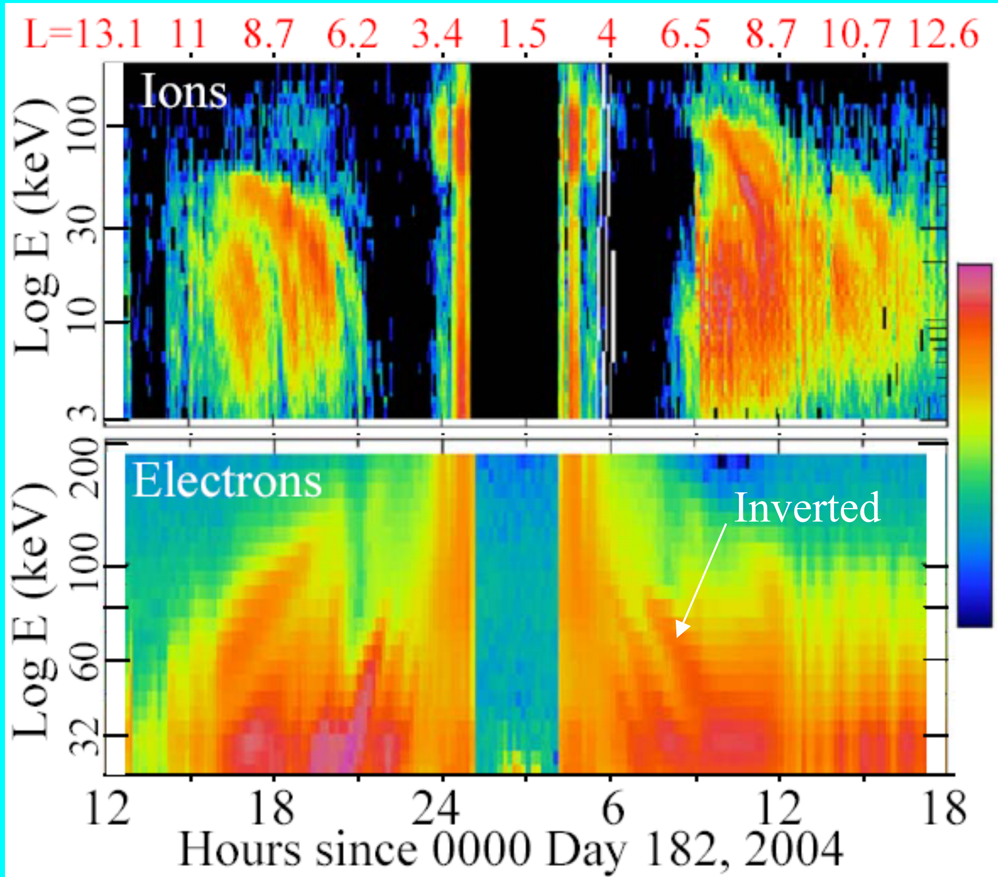
Ion Dispersion Event

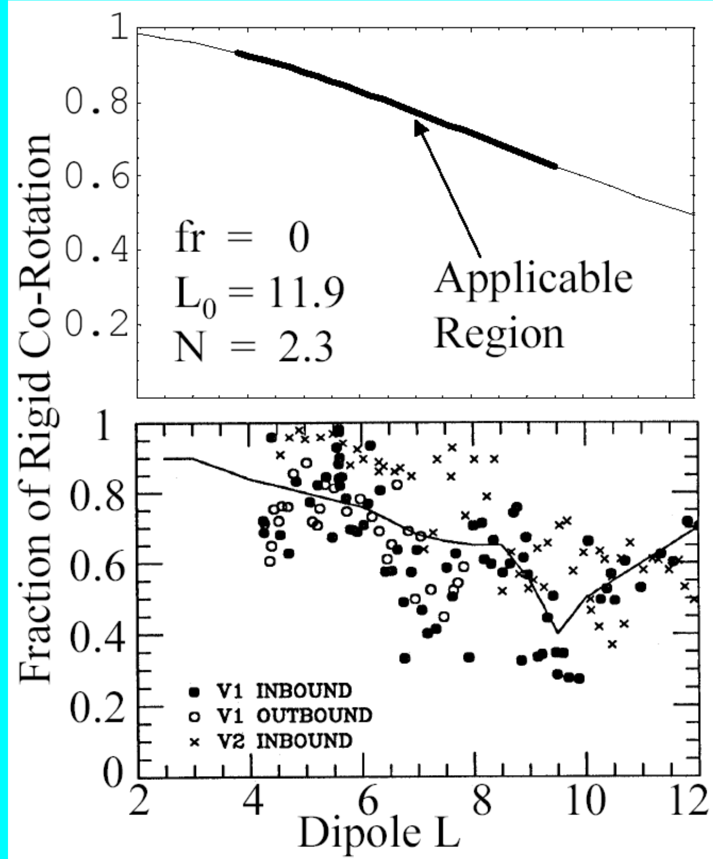




Mauk et al., 1997

Energetic Particle Injections are as pervasive at Saturn as they are at Jupiter



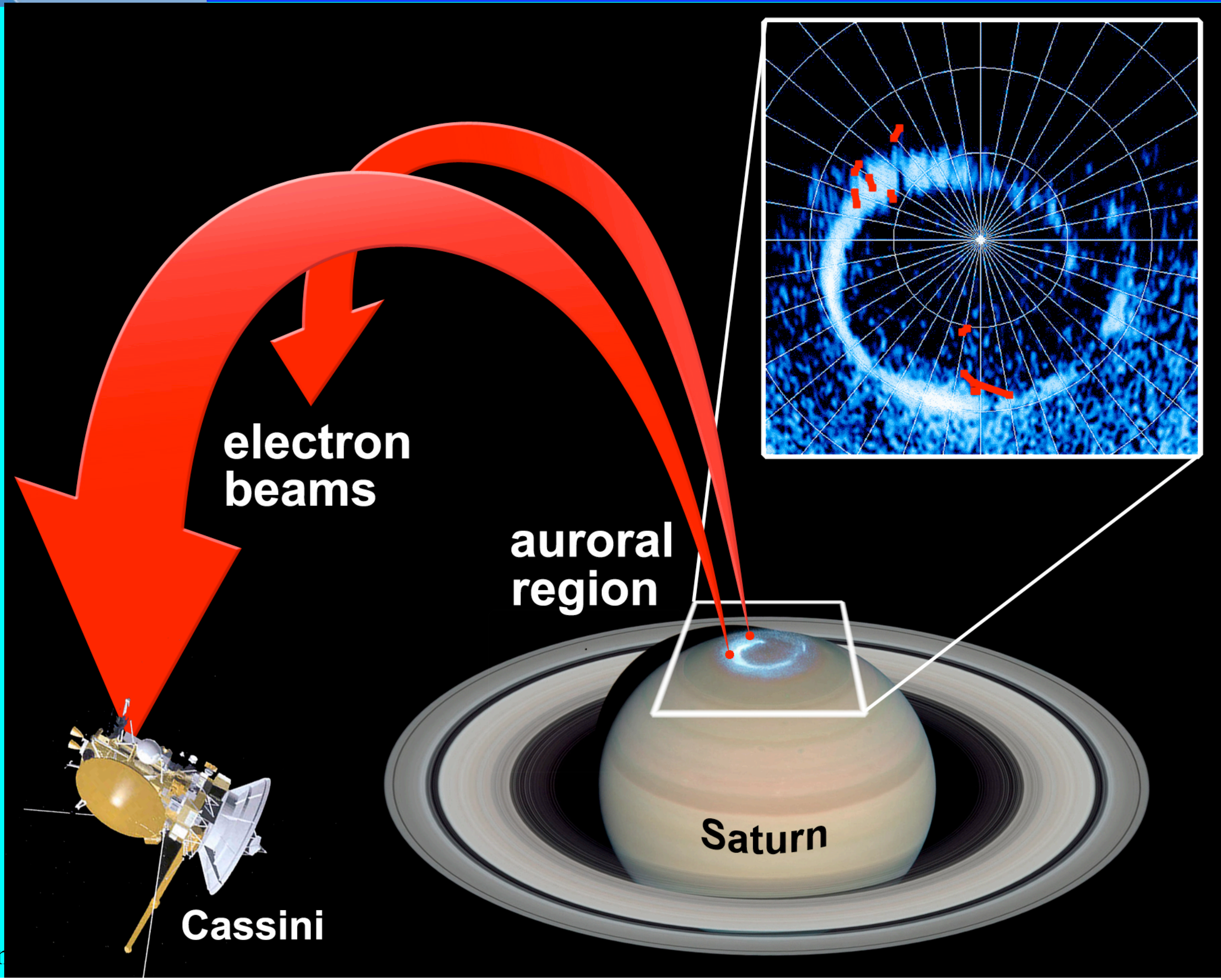


A. Dispersion features are sometimes inverted from expectations. The explanation is shear in the radial flow profile

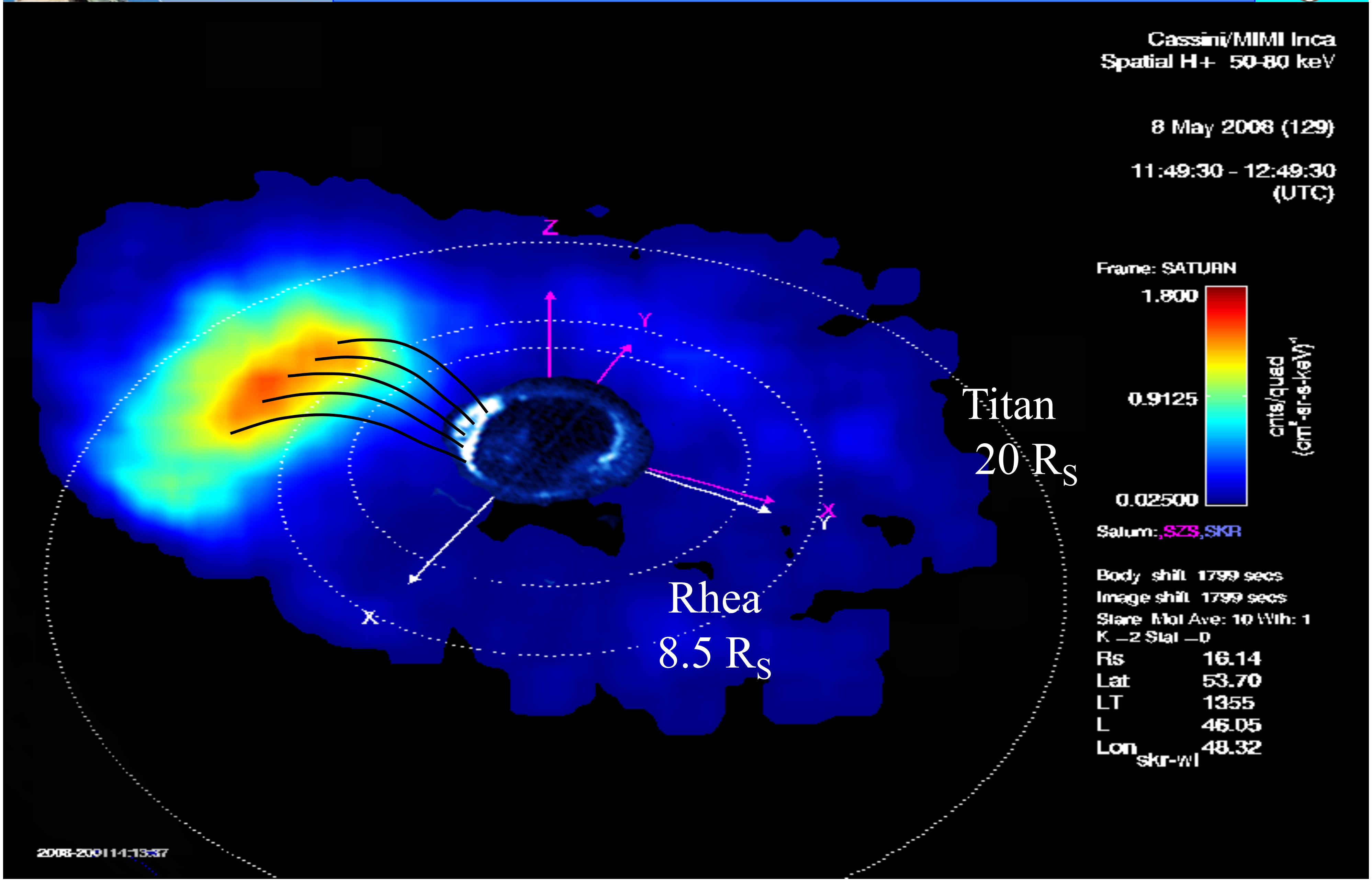
B. Injection-derived radial flow profile is commensurate with Voyager flow measurements

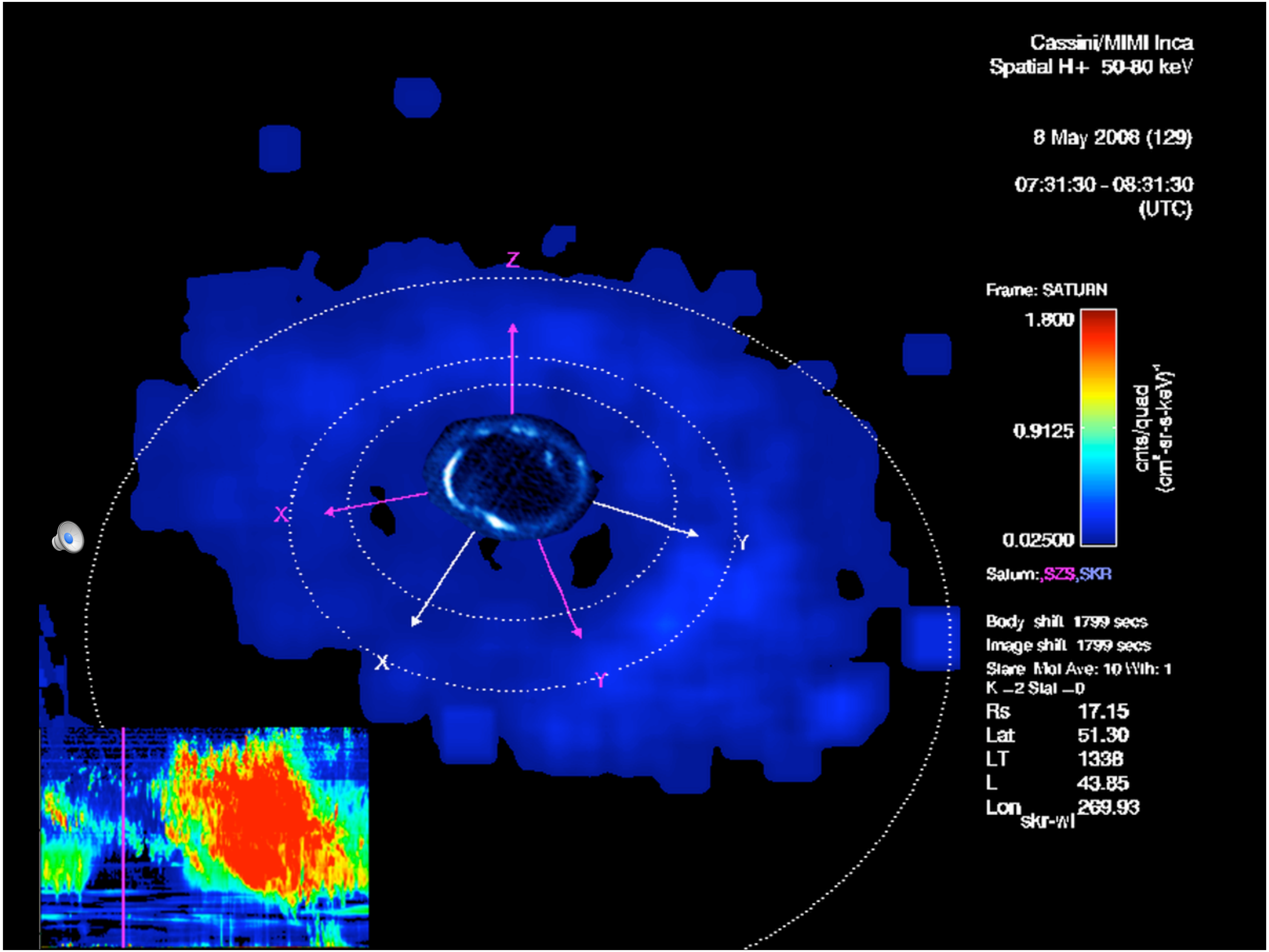
Mauk et al., GRL Cassini Issue, 2005

Electron Beams moving away from Saturn (Saur et al, Nature, 439, 699, 2006)

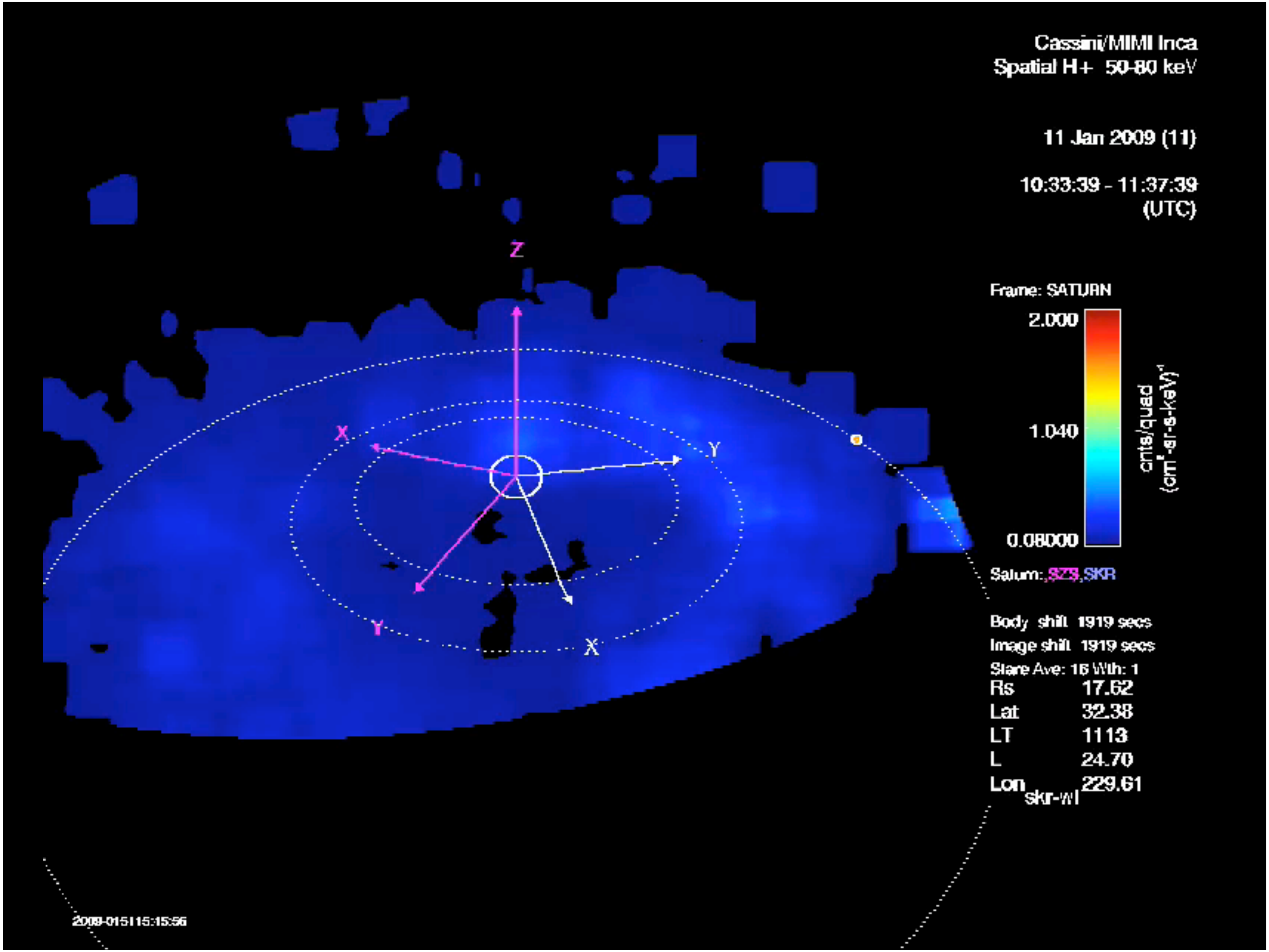


Acceleration event at equator connects to aurora through field-aligned currents (FAC)



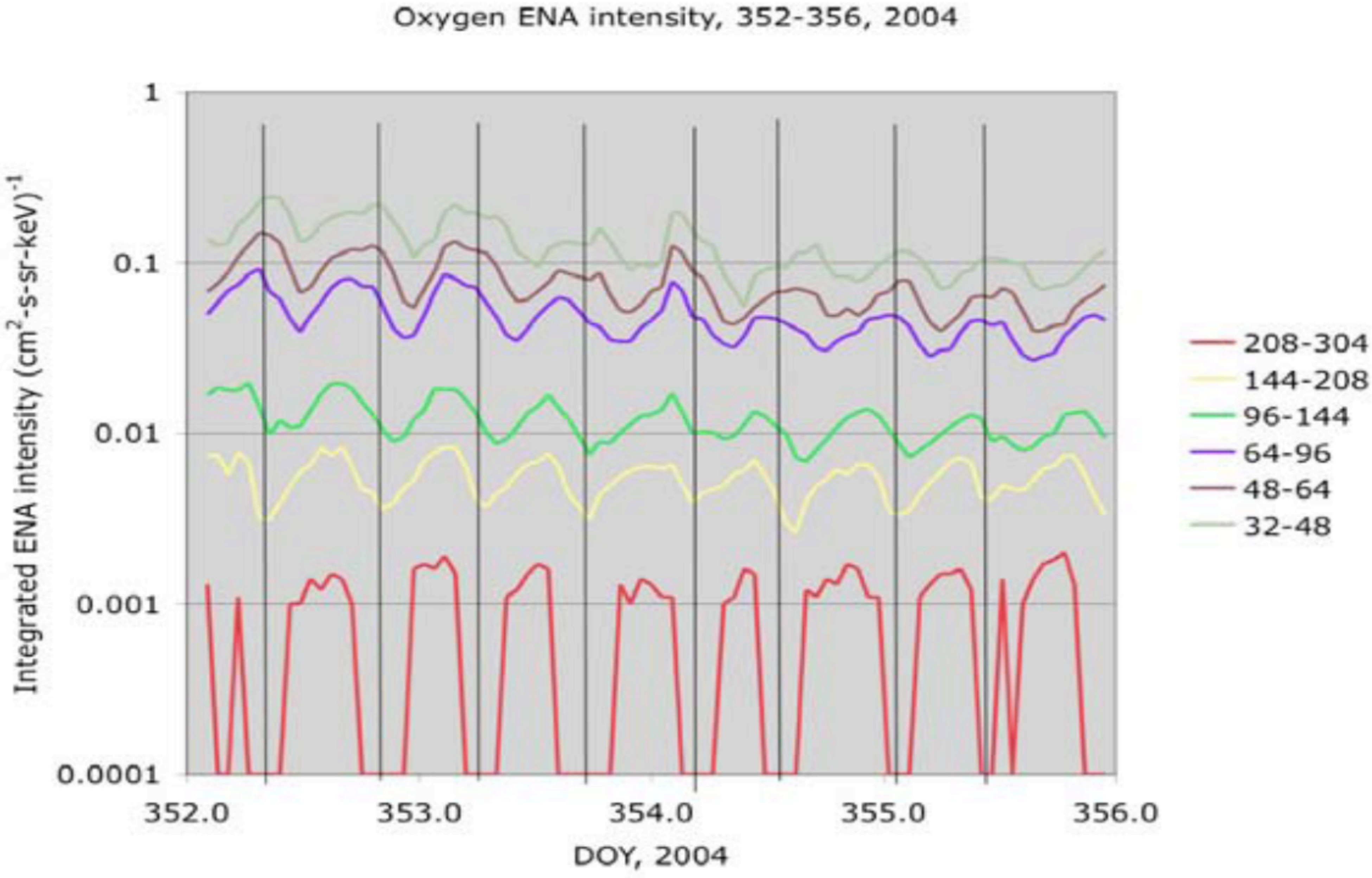


Cassini/MIMI Inca
Spatial H+ 50-80 keV
8 May 2008 (129)
07:31:30 - 08:31:30
(UTC)
Frame: SATURN
1.800
0.9125
0.02500
cnts/quad
(cm²-sr-s-keV)⁻¹
Saturn:,SZS,SKR
Body shift 1799 secs
Image shift 1799 secs
Stare Mot Ave: 10 Wh: 1
K =2 Stat =0
Rs 17.15
Lat 51.30
LT 1338
L 43.85
Lon skr-wl 269.93
Z
X
Y
X
Y

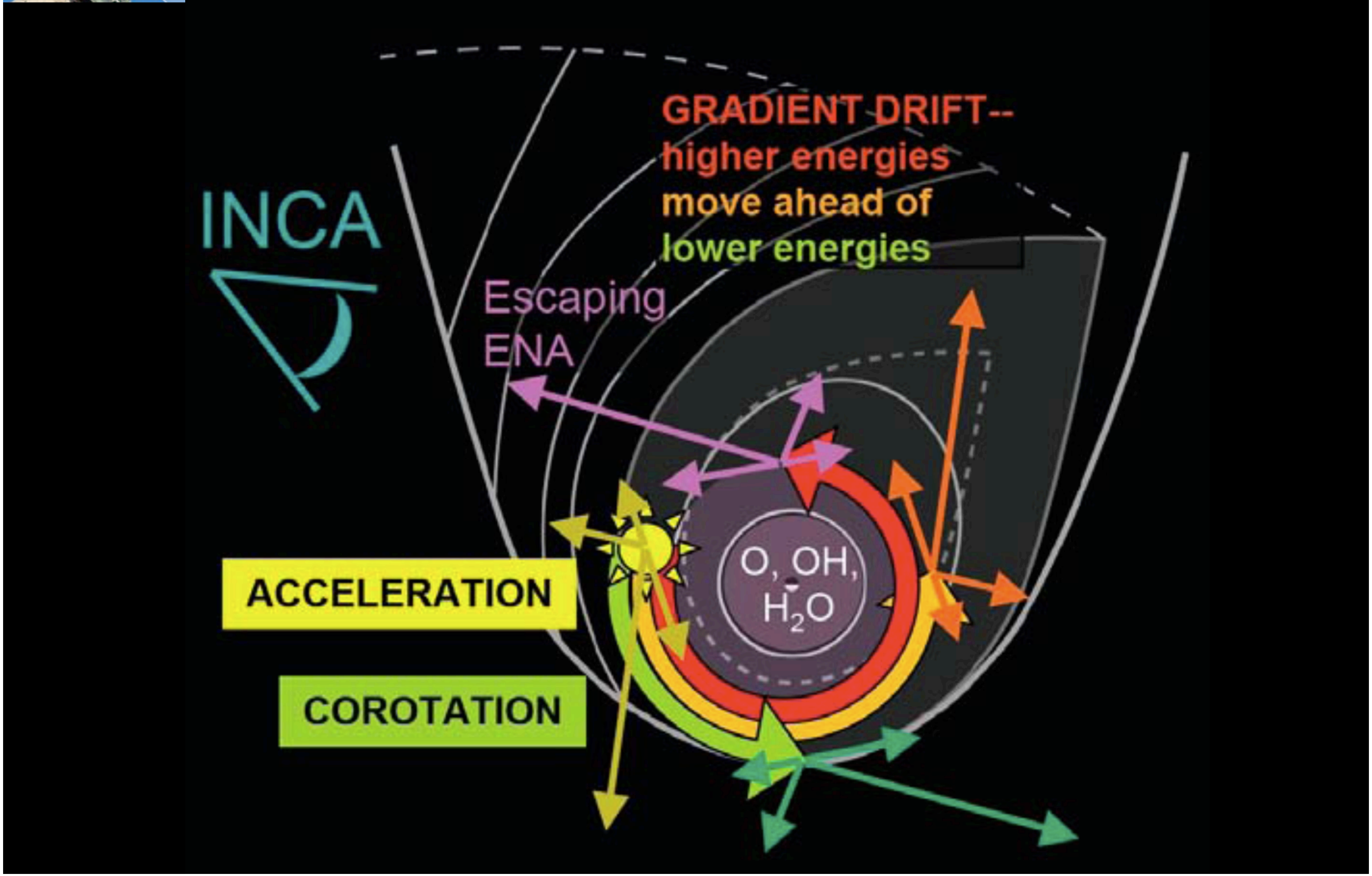


Cassini/MIMI Inca
Spatial H+ 50-80 keV
11 Jan 2009 (11)
10:33:39 - 11:37:39
(UTC)
Frame: SATURN
2.000
1.040
0.08000
cnts/quad
(cm²-sr-s-keV)⁻¹
Saturn:,SZS,SKR
Body shift 1919 secs
Image shift 1919 secs
Stare Ave: 16 Wth: 1
Rs 17.62
Lat 32.38
LT 1113
L 24.70
Lon skr-w 229.61
Z
X
Y
Y
X
2009-015115:15:56

Oxygen injections over 4-day period: lower energies lag due to curvature and gradient drifts (Mitchell, Krimigis et al, PSS, 2009)

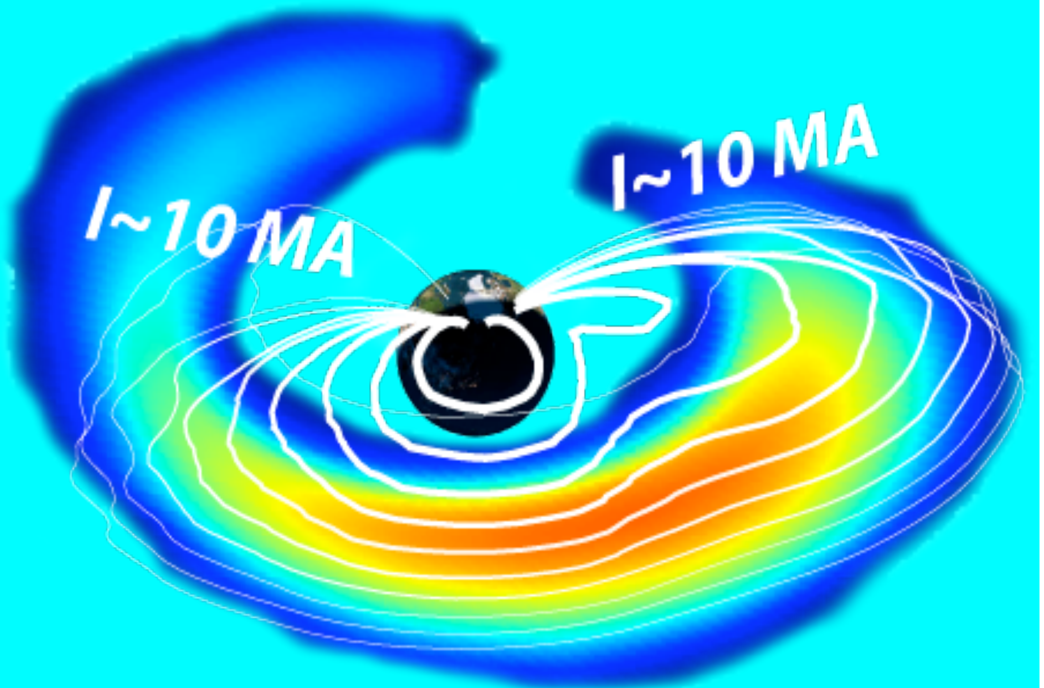


Acceleration and corotation in Saturn's magnetosphere (Mitchell et al, 2009)



Injections Cause SKR (Brandt et al, EGU, 2009)

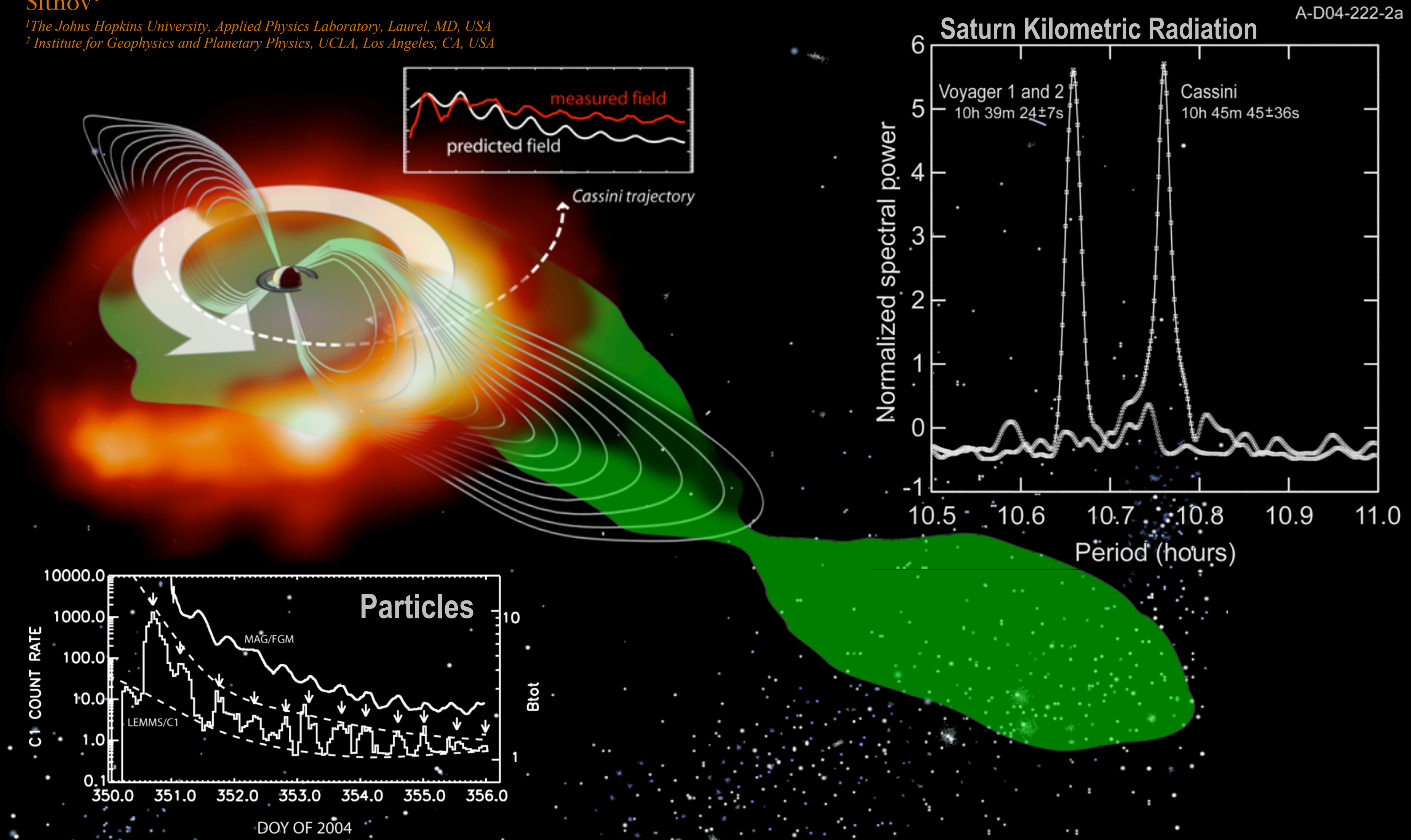
- The energized H^+ and O^+ of the injection results in an *azimuthally asymmetric* pressure
  - Hot pressure can dominate cold pressure in this region [Sergis et al., 2007; Wilson et al., 2008; Brandt et al., 2009]
- The azimuthal gradients "drive" currents in and out of the ionosphere
- The field-aligned currents trigger the maser instability responsible for the SKR emission
- OBSERVATIONS: SKR onset together with INCA onset.



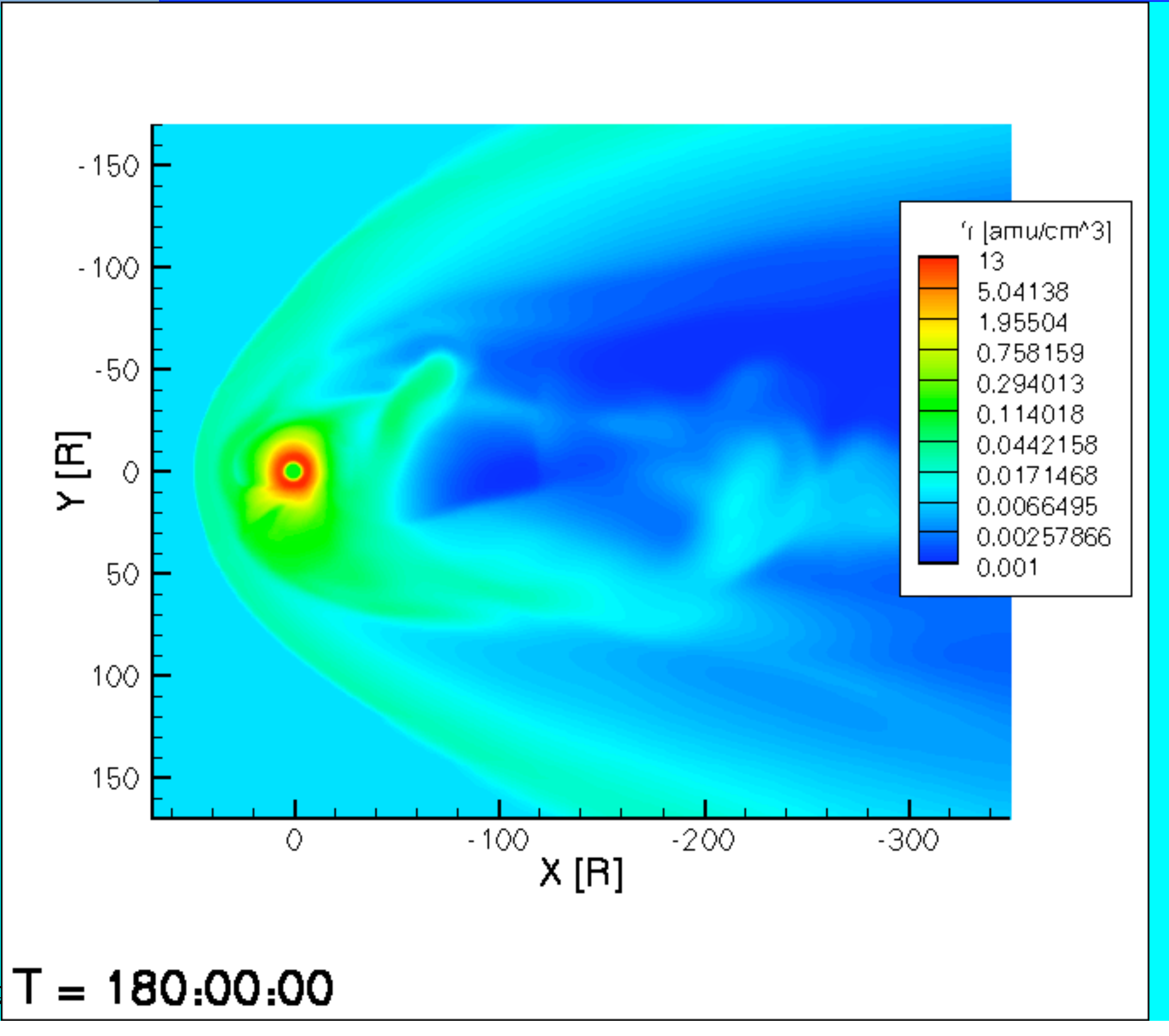
The asymmetric plasma pressure drives currents connecting to the ionosphere, which triggers SKR and perturbs the magnetic field. Example from Earth is shown [Brandt et al., 2008].

On How Plasma Transfers its Rotational Energy into Acceleration of Particles

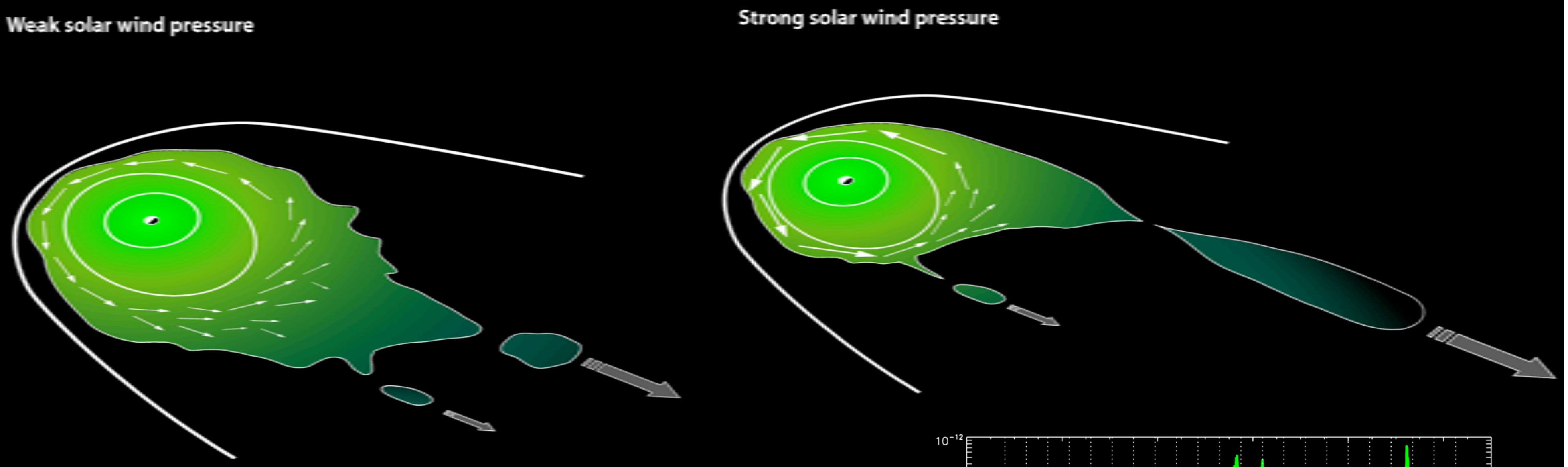
- P. C. Brandt[1], D. G. Mitchell[1], C. P. Paranicas[1], K. K. Khurana[2], J. F. Carbary[1] , M. Sitnov[1]
- [1]The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD, USA
- [2] Institute for Geophysics and Planetary Physics, UCLA, Los Angeles, CA, USA

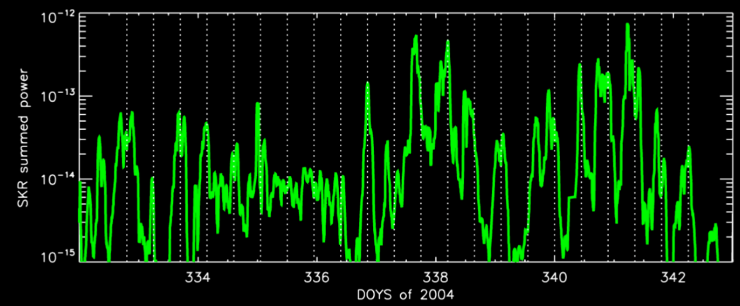


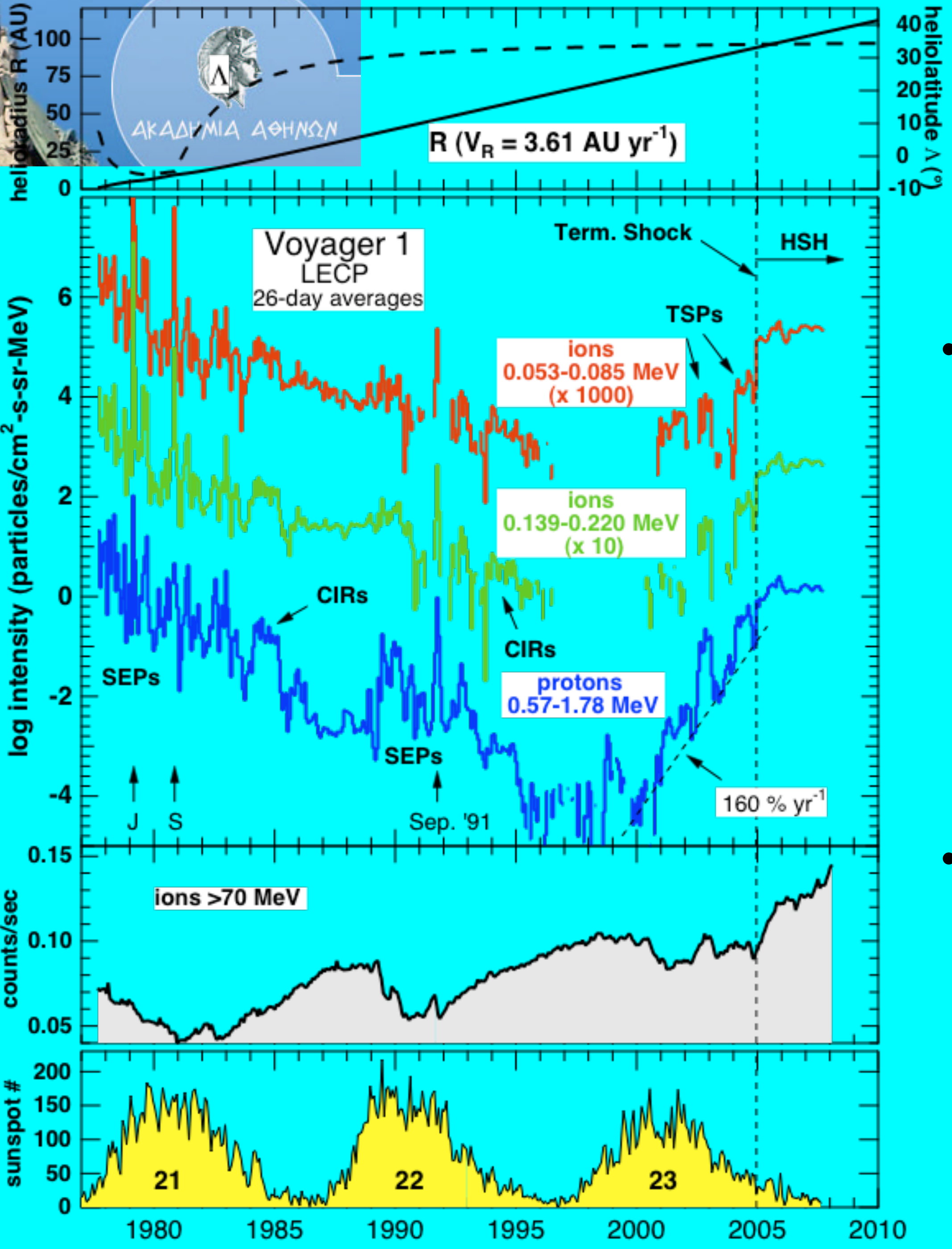
MHD Simulation of Saturn's Magnetosphere (Hansen et al, 2006)



How Does the Solar Wind Affect Magnetospheric Storms? (Brandt et al, 2009)



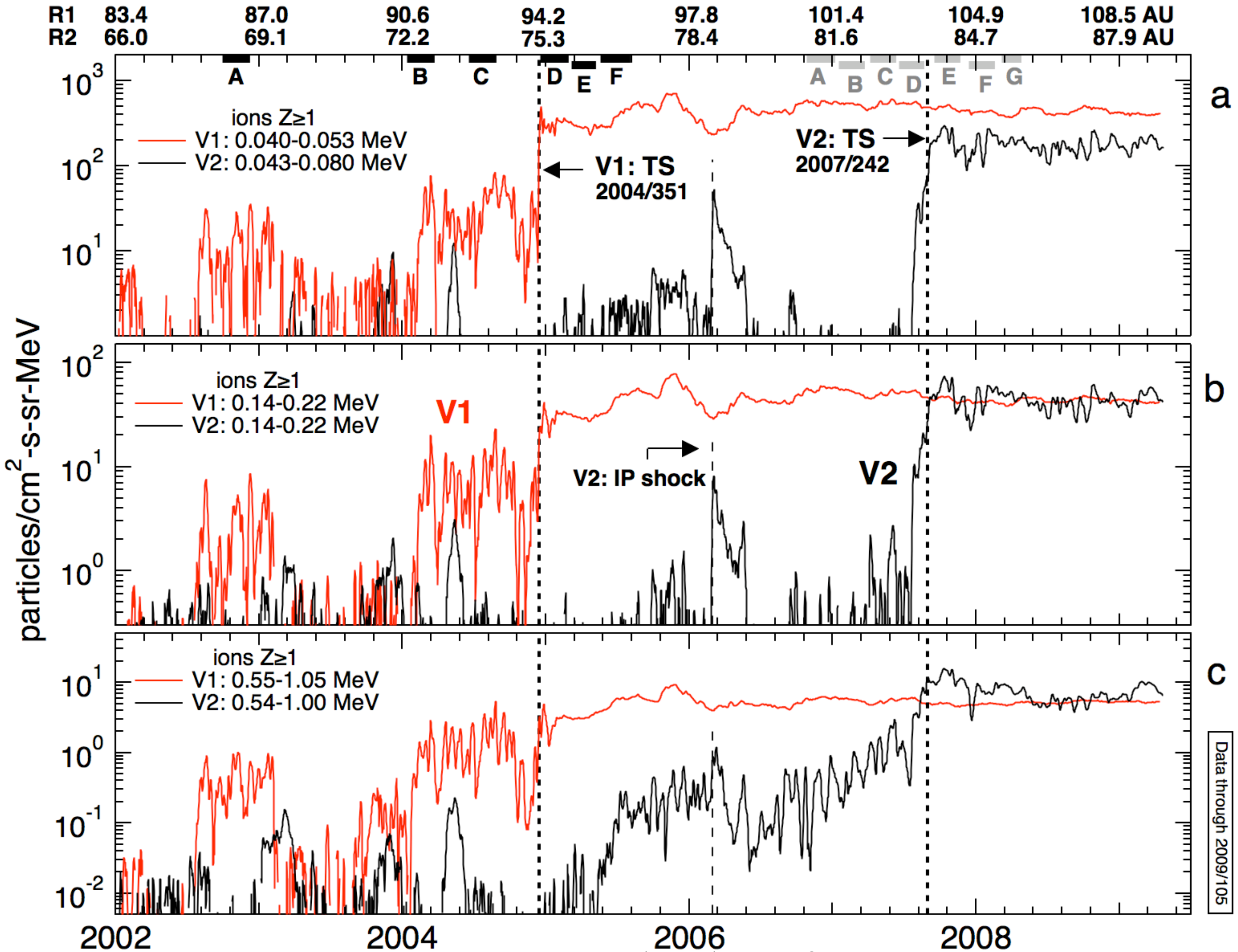




Voyager Mission: 32-year cruise through the heliosphere (Krimigis, 2008)

- *Voyager 1, 1977.7-2008.2*
  - *Trajectory*
  - *Ions 53-85 keV*
  - *Ions 140-220 keV*
  - *Protons 0.6-1.8 MeV*
  - *Protons >70 MeV*
  - *Sunspot number*
- *Relatively slow S/C speed ≈0.01 AU/day gives in-depth look at solar phenomena (ICMEs, SEPs, CIRs, CMIRs, MIRs, GMIRs, TSPs, TS, HSH, ACRs, GCRs ...)*

Ions 0.04-1.0 MeV, V1/V2 comparison: 2002-2009.30 (Decker, Krimigis, Roelof, and Hill, 2009)



Protons ~10s keV

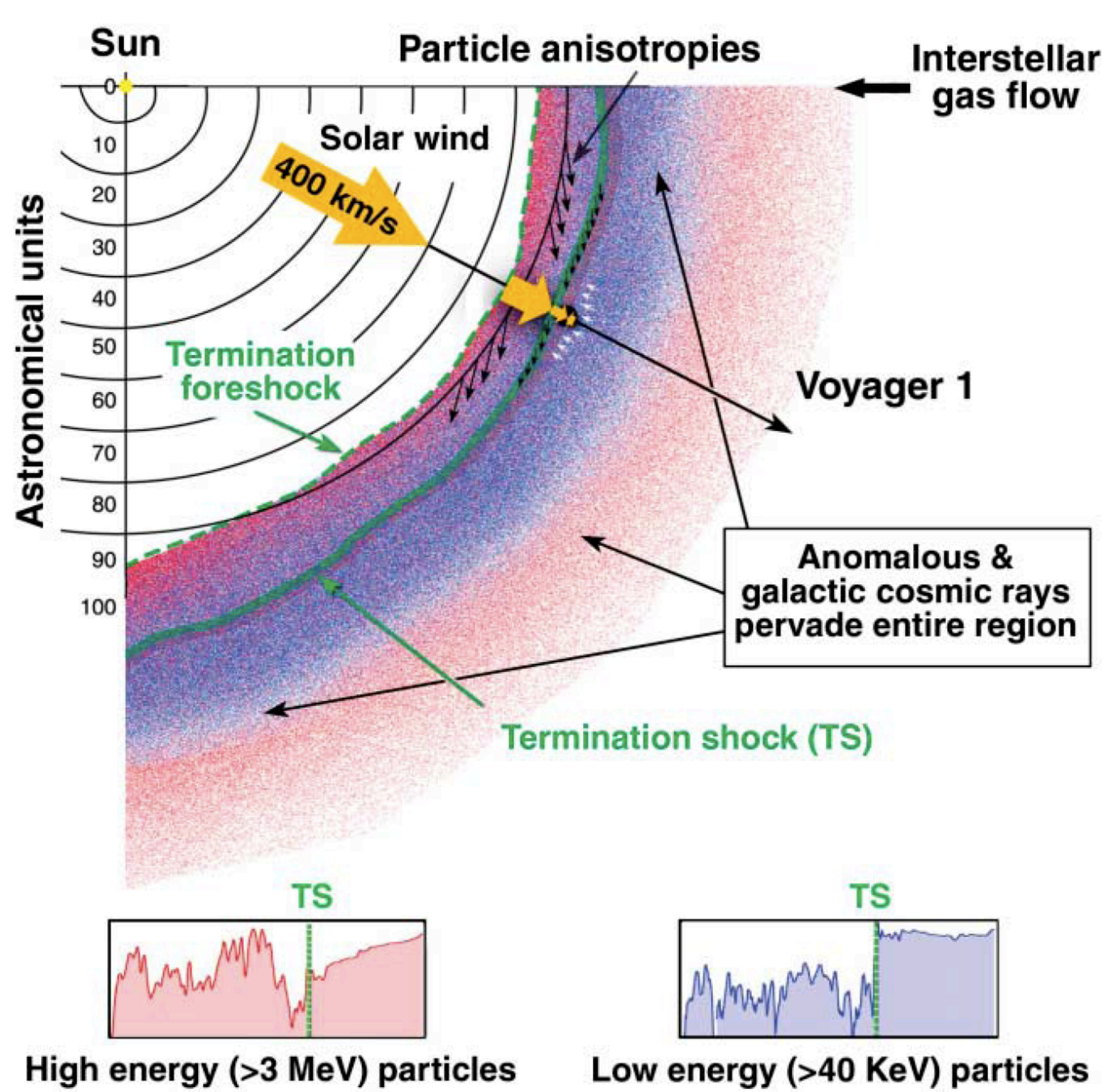
~100s keV

~1 MeV

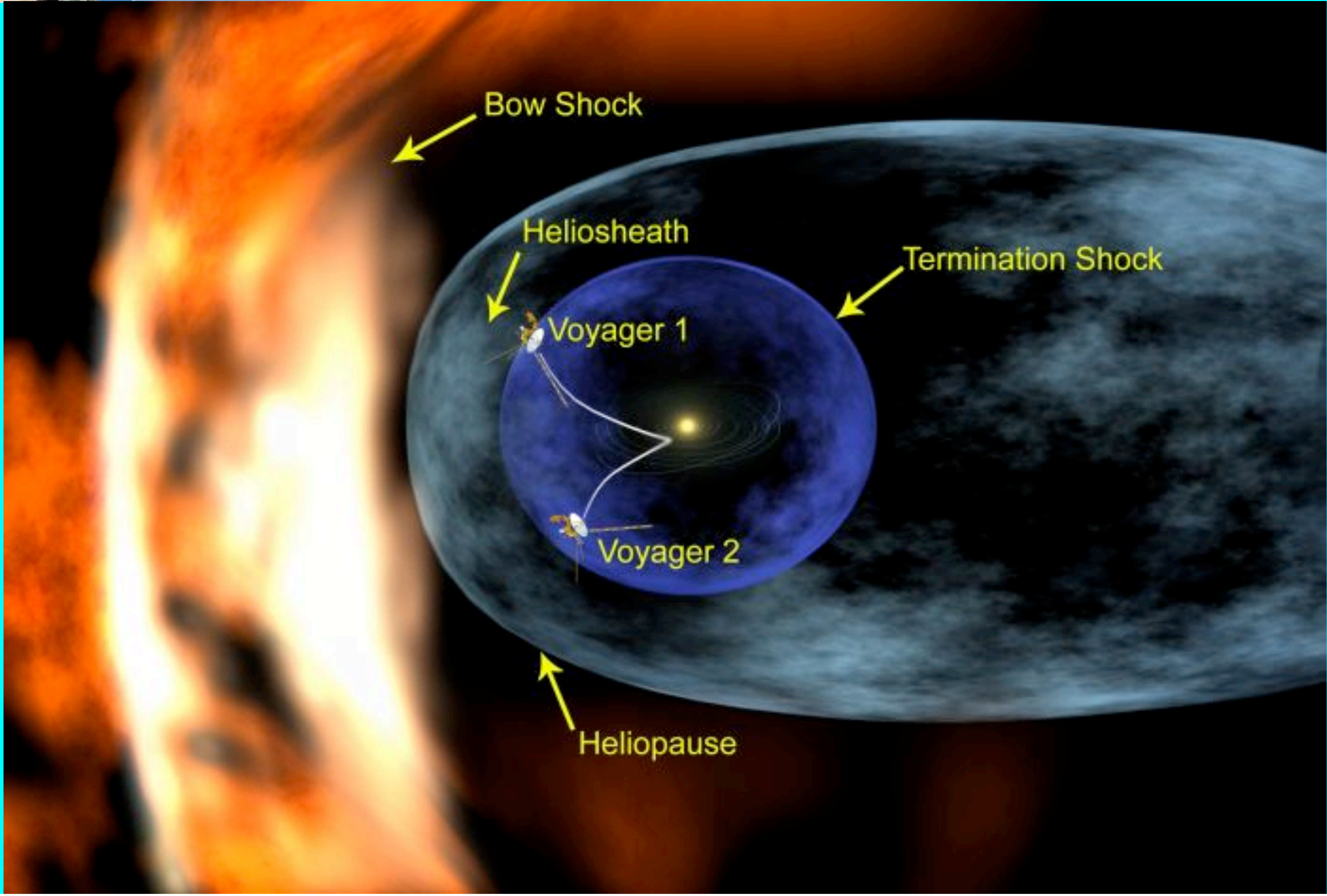
Conceptual overview of Termination Shock-Heliosheath regions from Voyager 1(Decker, Krimigis, Roelof et al, Science, 309,2020, 2005)

HELIOMAGNETOSPHERE

VOYAGER 1



Artist's Concept of Heliosphere and Trajectories of Voyagers 1, 2



Concluding Remarks

- Dynamics of inner planet magnetospheres (Mercury, Earth) are solar wind-driven
- The magnetospheres of outer planets exhibit similar plasma phenomena (e.g. K-H and interchange instabilities, plasma injections, reconnection, AKR generation etc) to those at Earth
- Dynamics, however, are dominated by planetary rotation, and internally generated plasmas consisting mostly of heavy (M ≥ 16) ions that carry most of the mass and pressure
- Periodicities close to, or near, the planetary rotation period manifest themselves in SKR, magnetic field, particle acceleration, and possibly plasmoid formation and release
- Asymmetric ring currents drive field-aligned currents to the ionosphere where slippage slows down plasma corotation at the equatorial plane.
- MHD models suggest plasmoid formation down the magnetotail, but do not account for the origin and behavior of the hot, heavy ion plasma