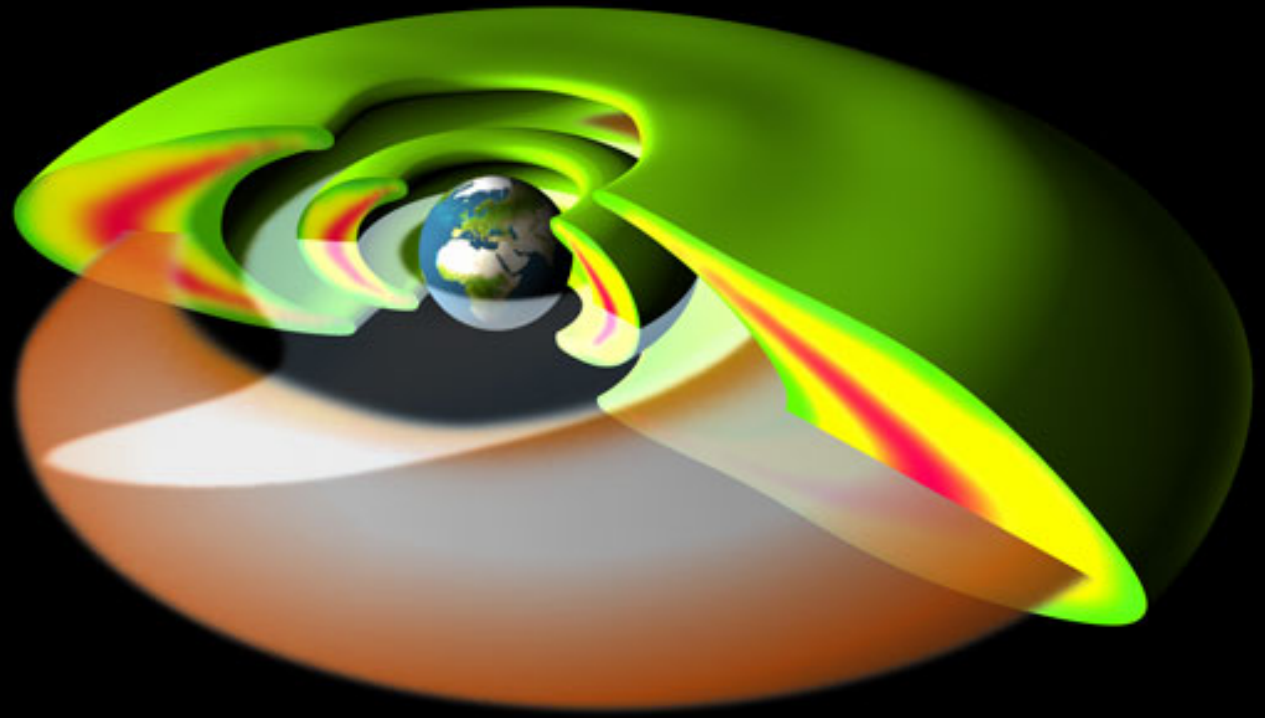
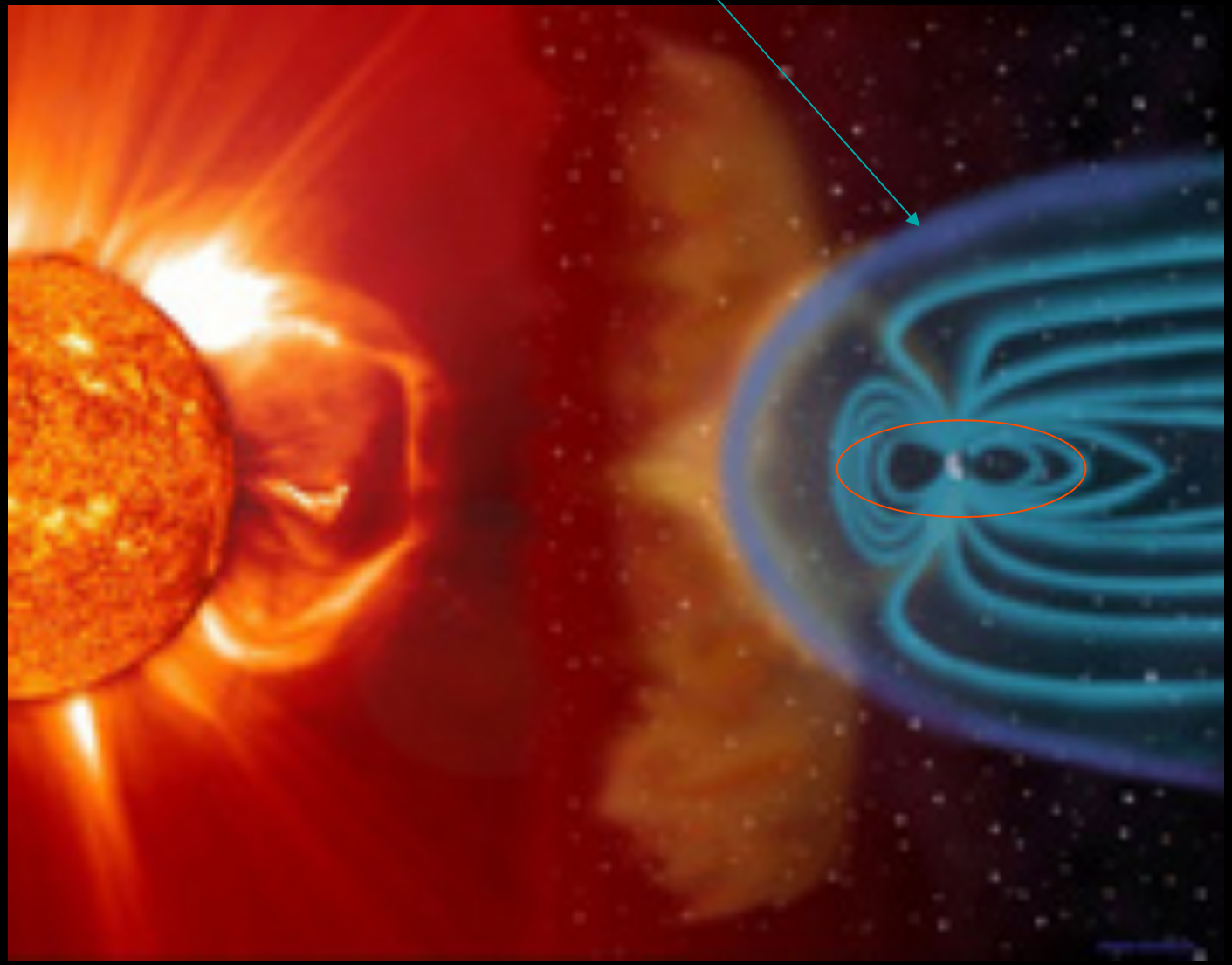
Dynamics of the Earth's Inner Magnetosphere: Current Understanding and Challenges



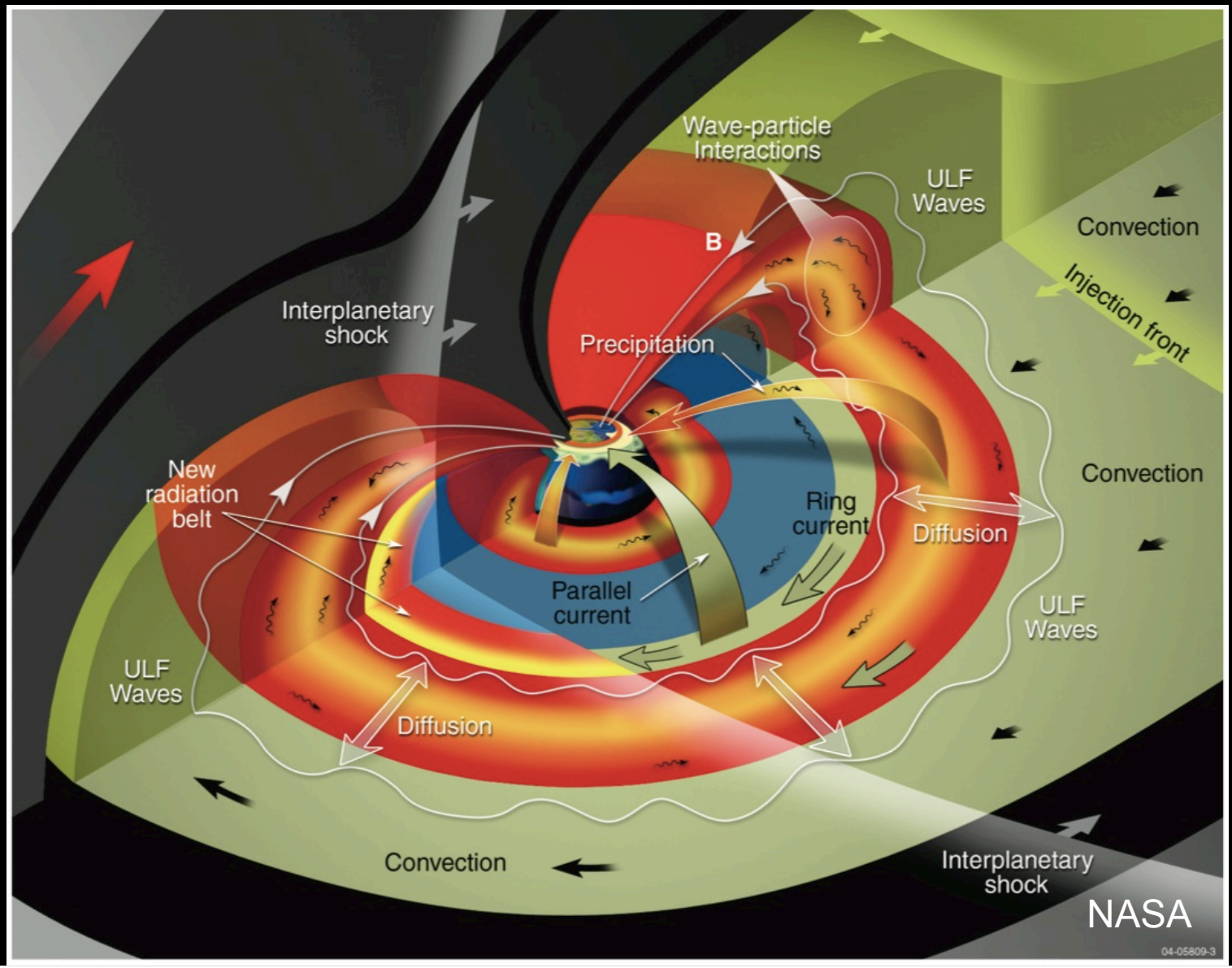
Yihua Zheng
NASA/GSFC

Introduction

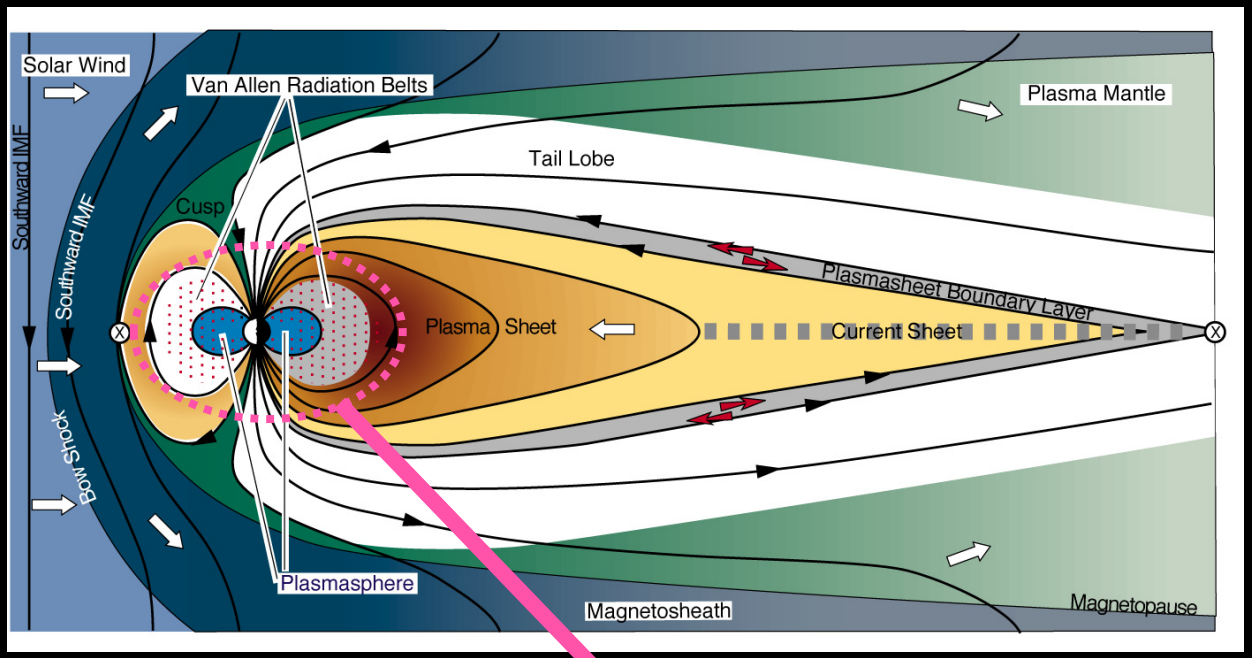
The solar wind pushes and stretches Earth's magnetic field into a vast, comet-shaped region called the magnetosphere. The magnetosphere and Earth's atmosphere protect us from the solar wind and other kinds of solar and cosmic radiation.



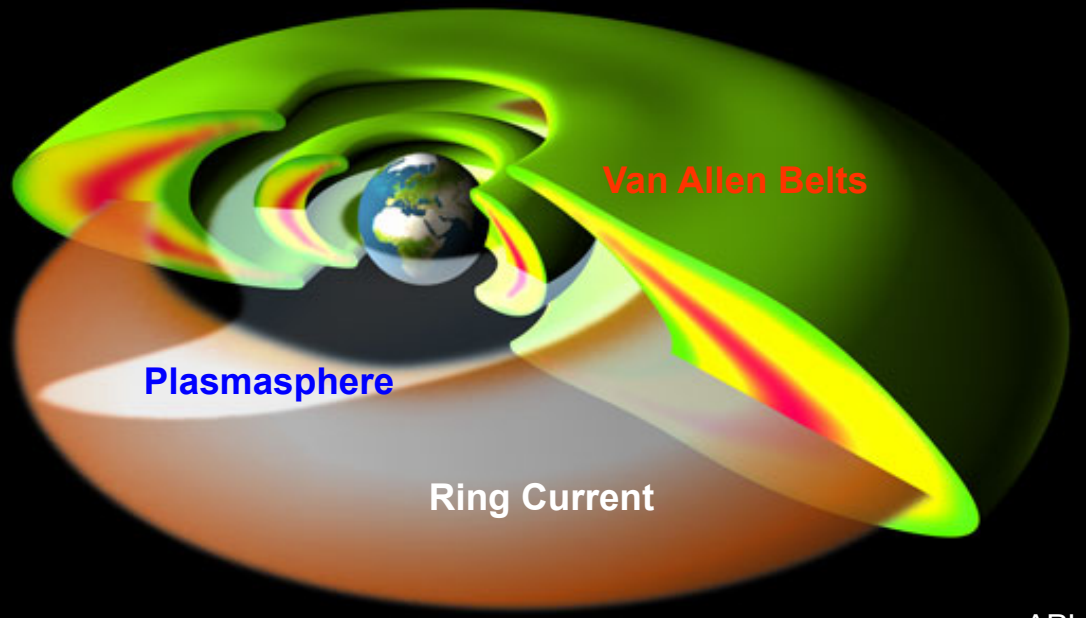
The Earth's Magntosphere -processes



The Earth's Magnetosphere



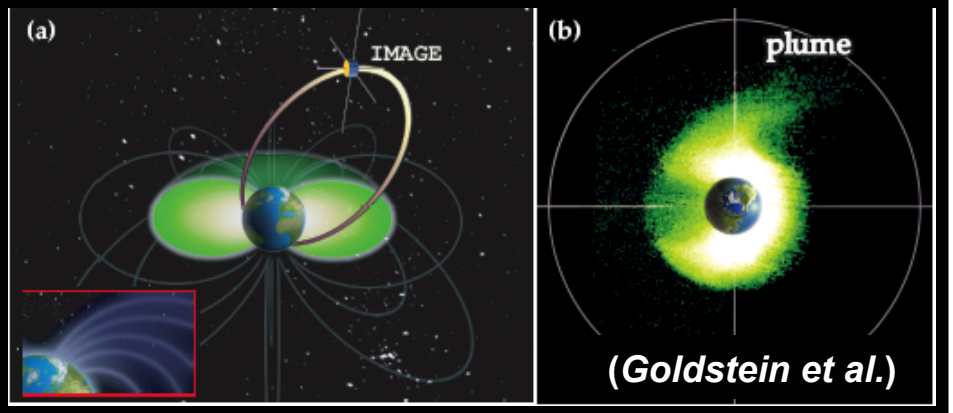
Inner Magnetosphere

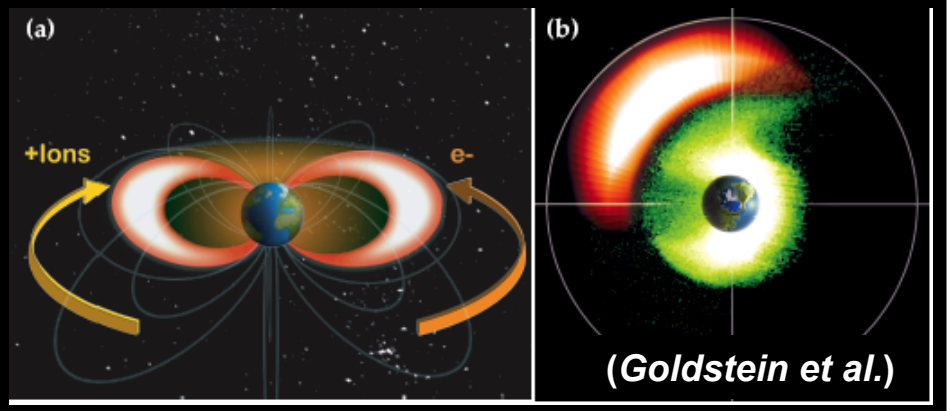


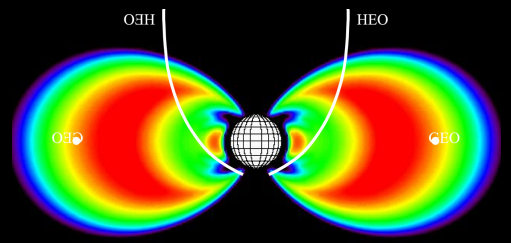
APL

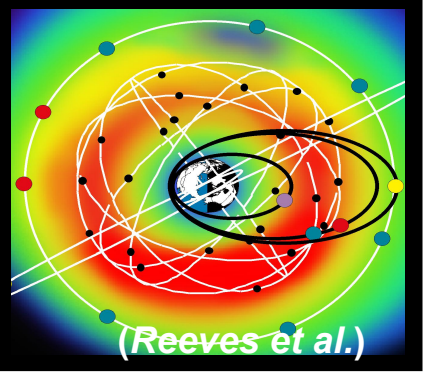
Inner magnetosphere plasmas

- Plasmasphere
  - 1-10 eV ions
  - ionospheric origin
- Ring current
  - 1-400 keV ions
  - both ionospheric and solar wind origin
- Outer radiation belt
  - 0.4-10 MeV electrons
  - magnetospheric origin





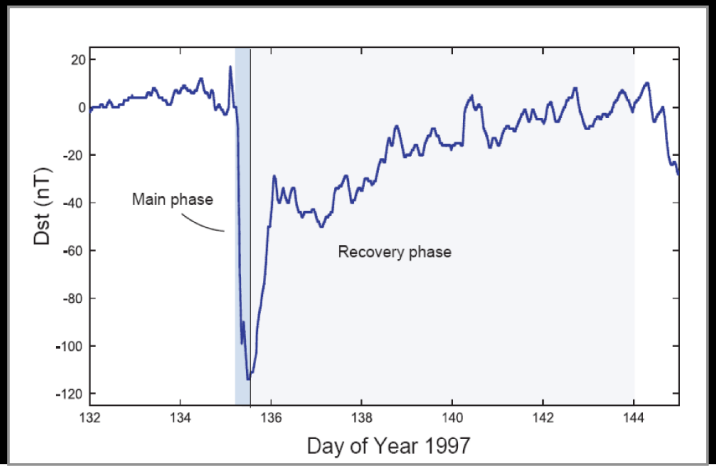




Magnetic Storms

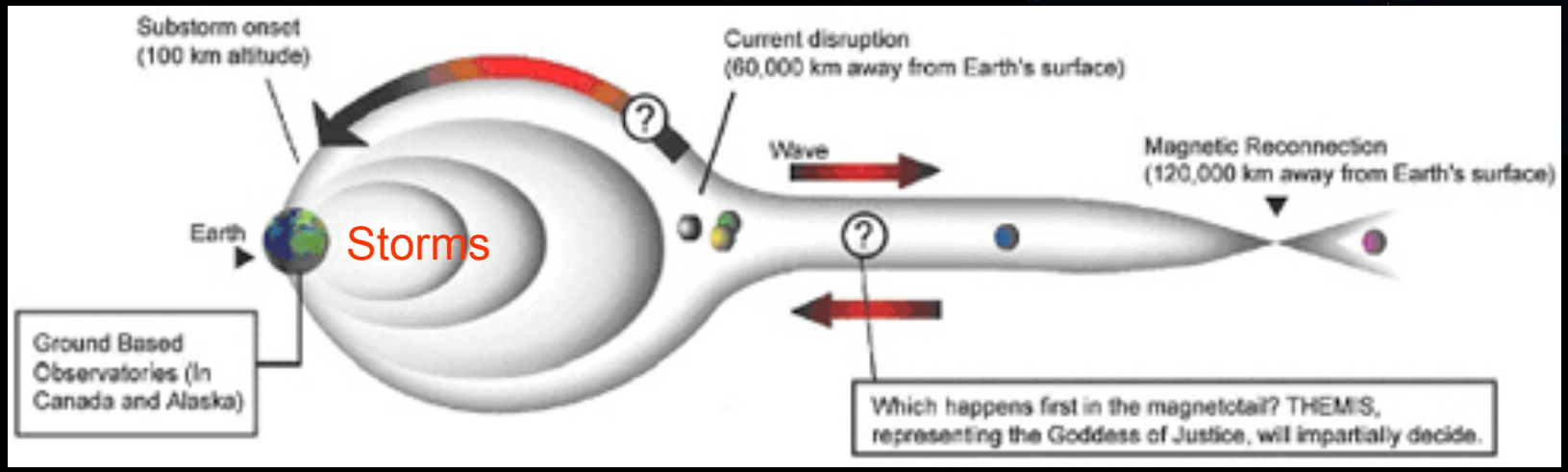
- Most intense solar wind-magnetosphere coupling
- Associated with solar coronal mass ejections (CME), coronal holes
- IMF Bz southward, strong electric field in the tail
- Formation of ring current and other global effects

- Dst measures ring current development
  - Storm sudden commencement (SSC), main phase, and recovery phase
  - Duration: days



Substorms

- Instabilities that abruptly and explosively release solar wind energy stored within the Earth's magnetotail.
- manifested most visually by a characteristic global development of auroras
- Last ~ hours



Space Weather Effects

Interior charging
Solar cell degradation

Astronaut Safety

Pipelines & power grids
Telecommunication &
Navigation

The inner magnetosphere is a major player of space weather

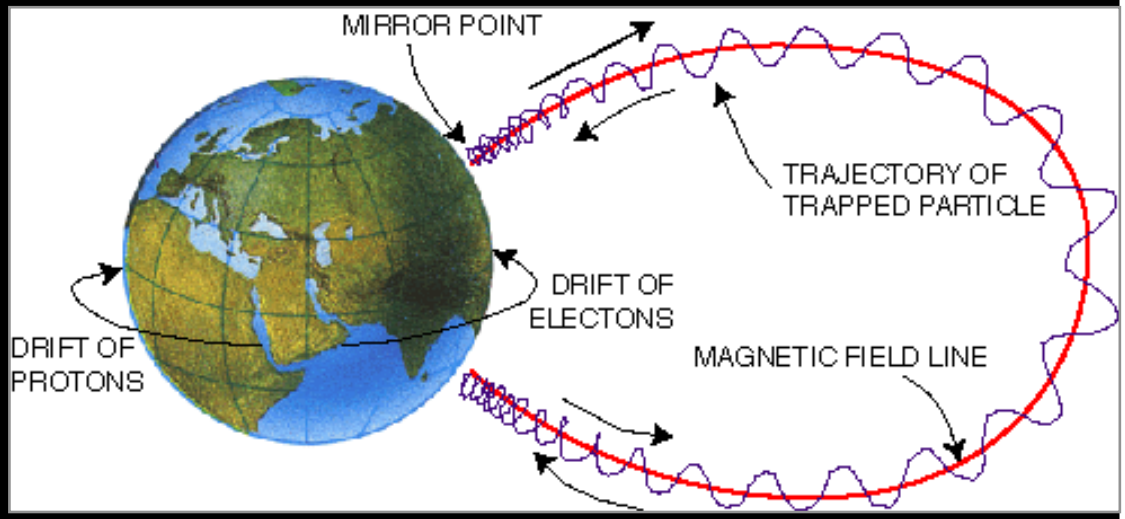
Charged Particle Motion in Magnetosphere (ring current and RB particles)

Adiabatic Invariants

$$\mu = \frac{W_{\perp}}{B}$$

$$J = \int p_{\parallel} ds$$

$$\Phi = \oint B dS$$

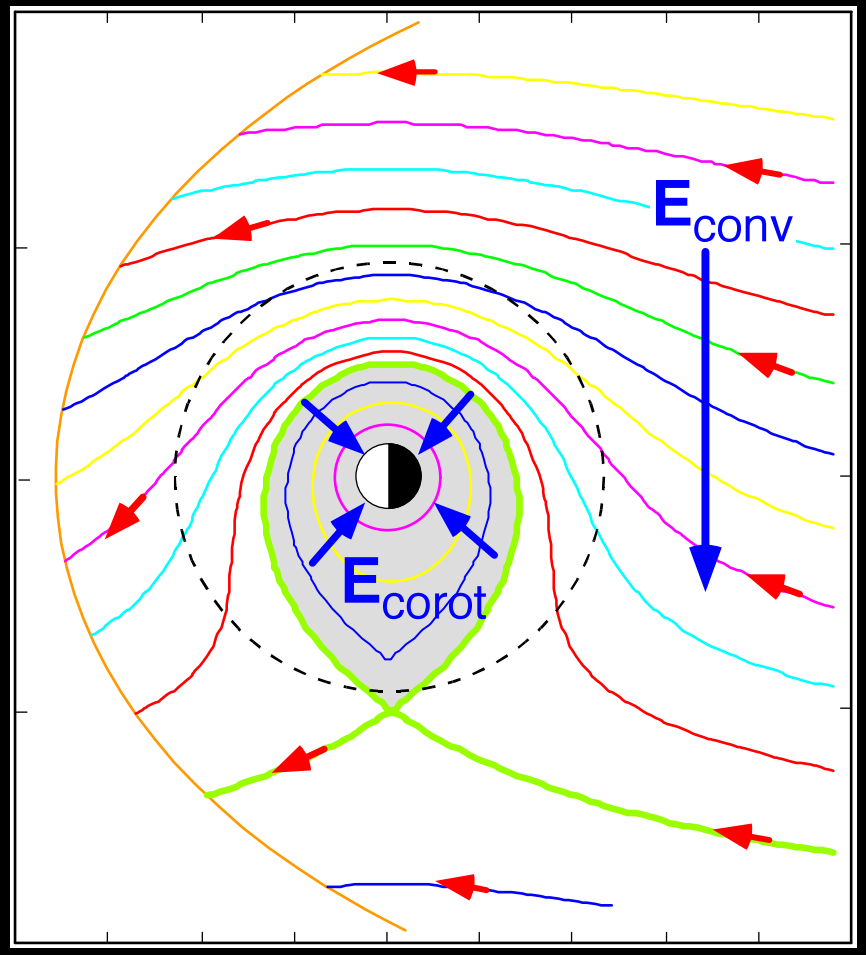


To change particle energy, must violate one or more invariants

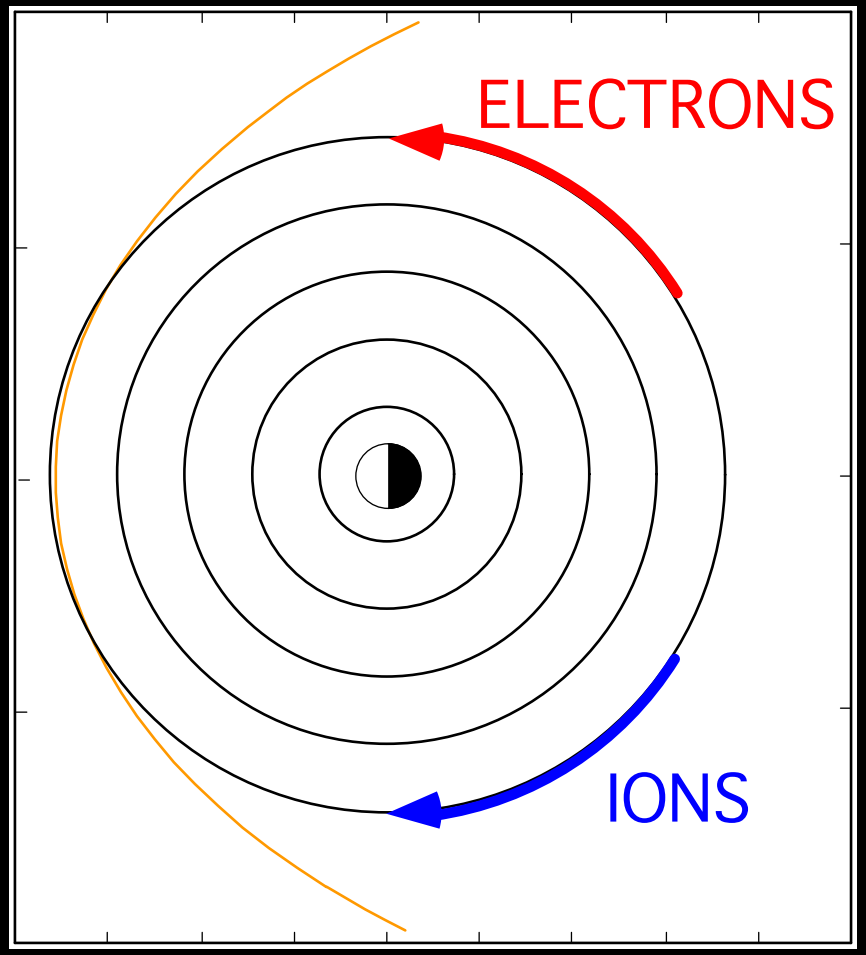
1. Sudden changes of field configurations
2. Small but periodic variation of field configurations

For a 1 MeV electron with an equatorial pitch angle of 60˚at *r*=6 *R*E, the gyration, bounce, and drift peroids are about millisecond, second, 1000 seconds respectively.

Particle drift



Convection



Gradient/Curvature Drift

$$\mathbf{v}_D = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{m}{2q}\left(2v_{\parallel}^2 + v_{\perp}^2\right)\frac{\mathbf{B}\times\nabla\mathbf{B}}{B^3}$$

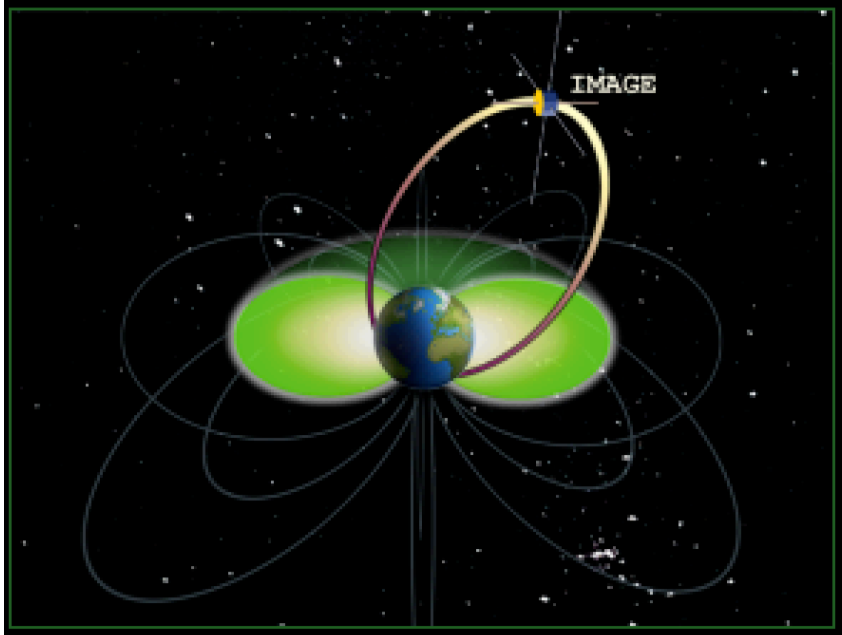
Advances

Plasmasphere

- Cold: Less than 1 eV, maybe up to 10 eV
- Dense: 100s-1000s cm^{-3}, lower out near geos.
- Ionospheric source
- Mostly Protons: often-quoted composition, 77% H^+, 20% He^+, and 3% O^+
- E-field dominated: spatial extent governed by magnetospheric electric field time history, B is also important
- dominates the mass density of the inner magnetosphere

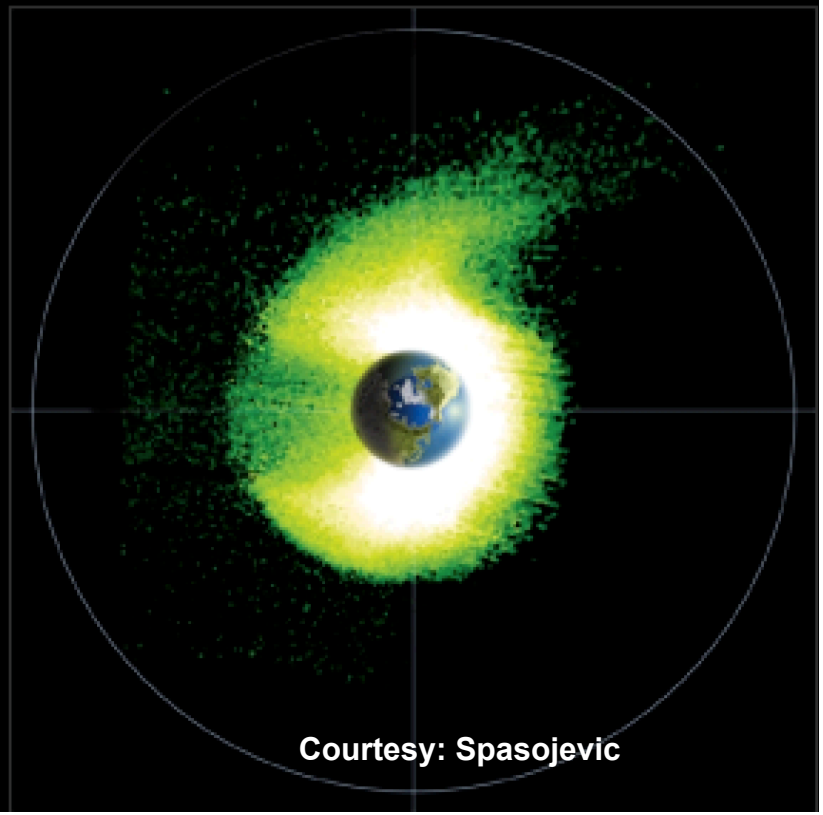
The Plasmasphere

IMAGE EUV



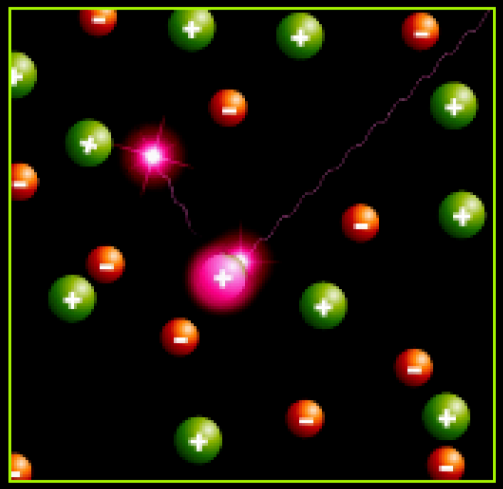
Imager for Magnetopause-to-Aurora Global Exploration

EUV He+ column abundance



Courtesy: Spasojevic

He+ 15%

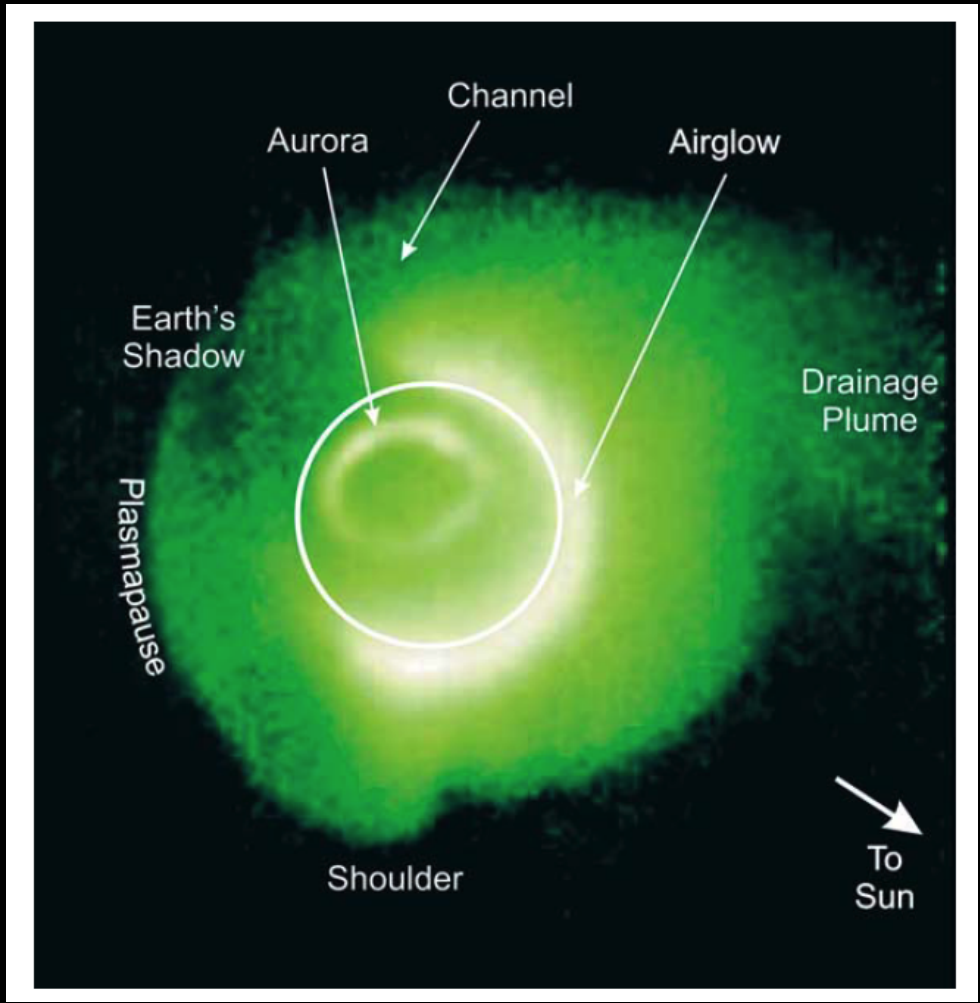


resonant scattering 30.4 nm

Plasmaspheric Dynamics

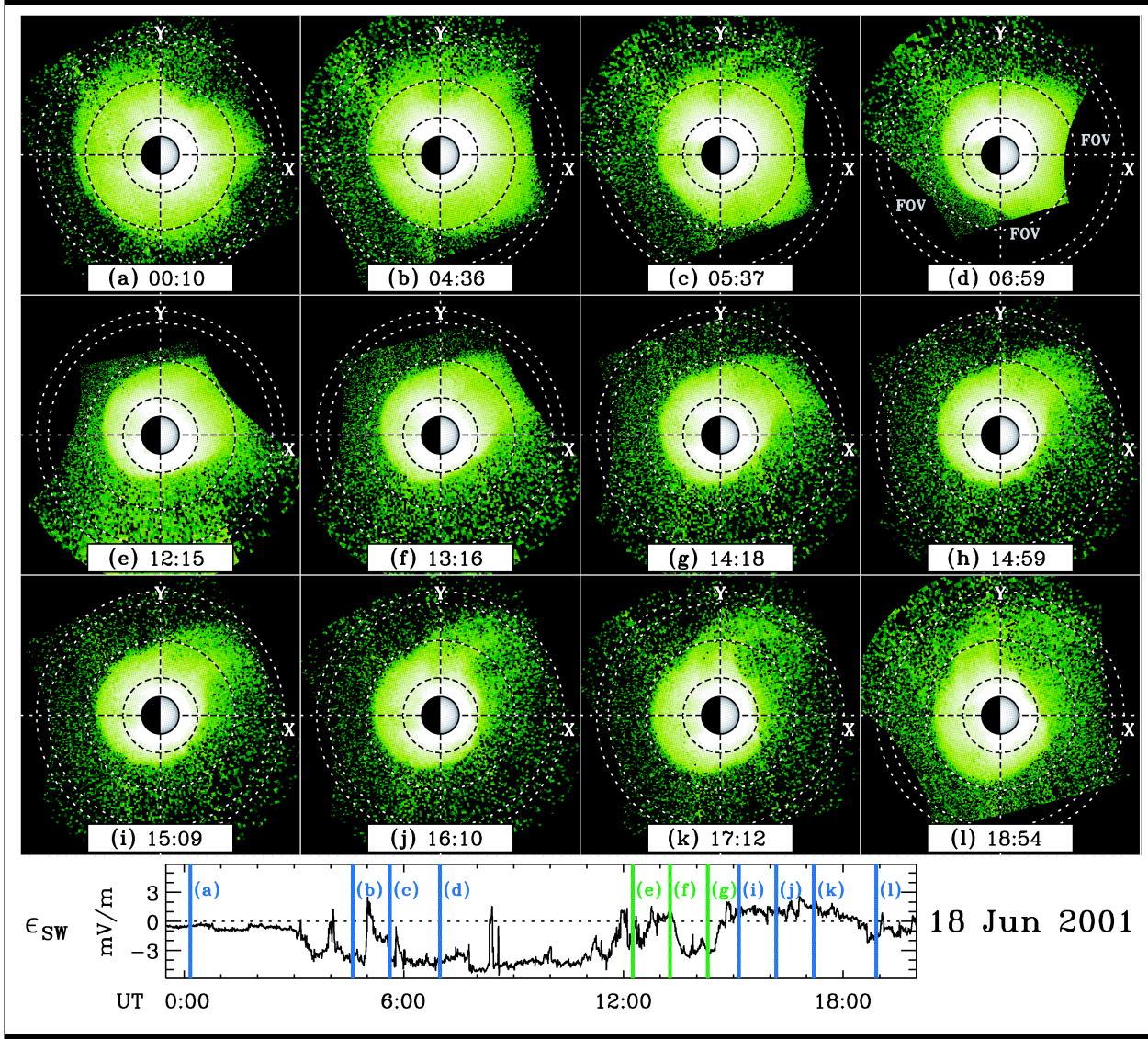
IMAGE EUV
Resonant scattering of He+ at 30.4nm

A lot of structure



Sandel et al., SSR, 2003

Plasmasphere Dynamics



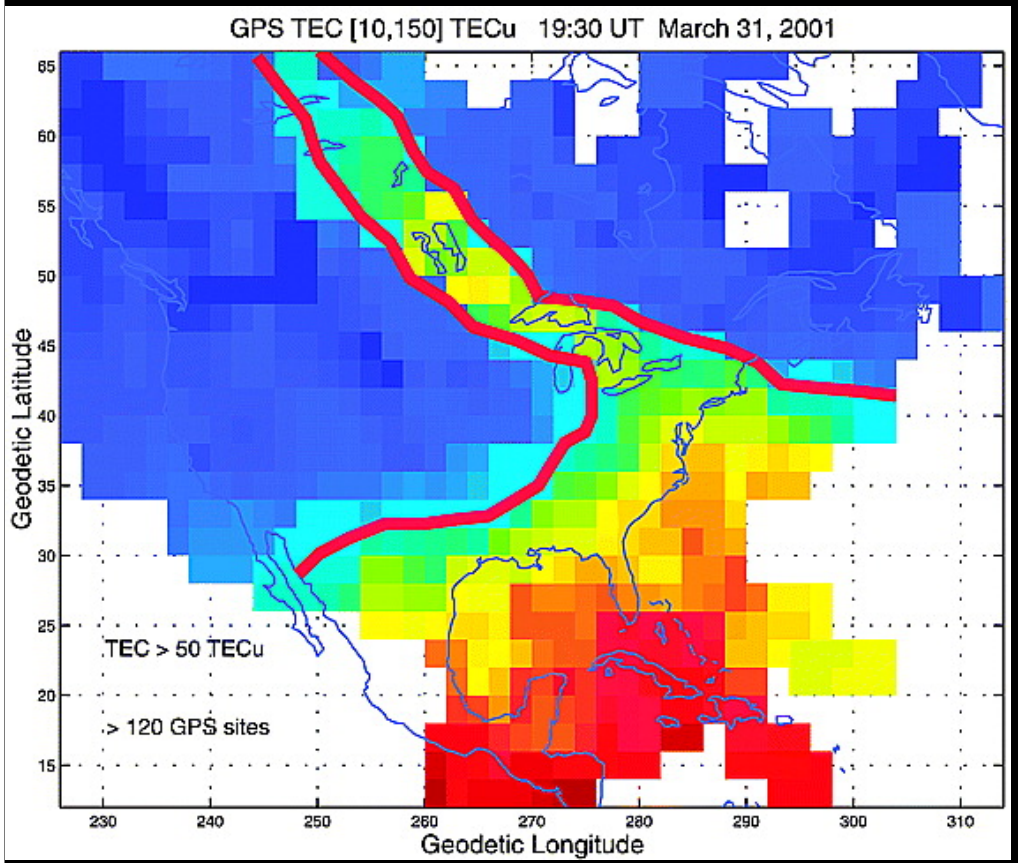
Responds to solar wind driving

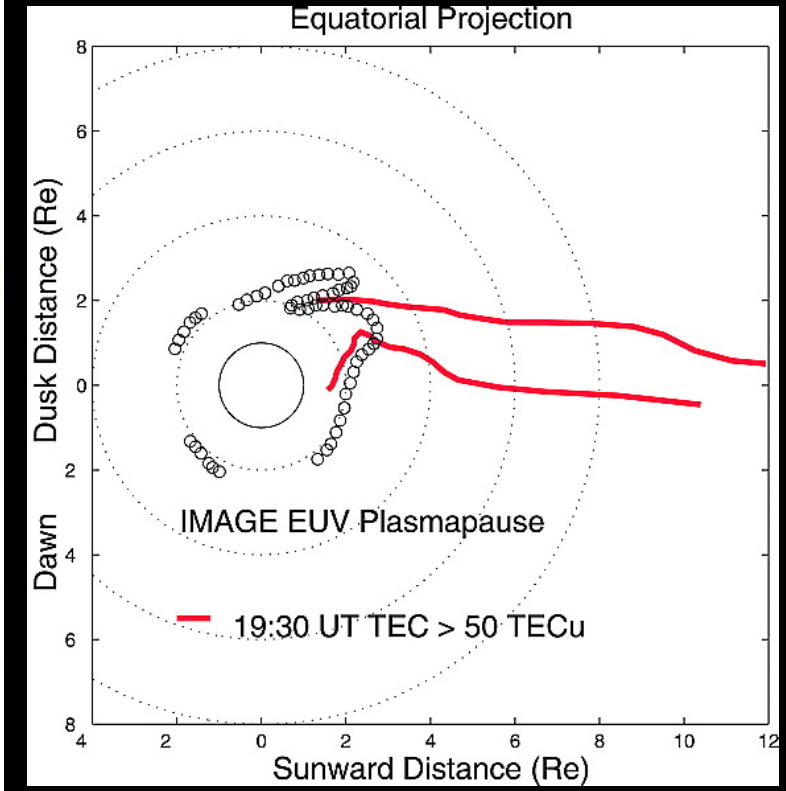
- Erosion of the plasmasphere
- Formation/evolution of a drainage plume

SED and Plume

- The MIT millstone Hill Incoherent scatter radar, located at 55 Λ near the ionospheric projection of the plasmapause and the PBL, regularly observes plumes of storm enhanced density (SED) which stream from the premidnight sub-auroral ionosphere toward the noontime cusp during the early stages of magnetic storms.
- Recent observations using both ground and space-based thermal plasma imaging techniques have revealed such ionospheric SED events to be the low-altitude signature of the plasmasphere drainage plumes recently observed from space by the IMAGE EUV imager.

Using radar and GPS observations of total electron content (TEC) to produce 2-D snapshots, Foster et al 2002 found that the SED/TEC plumes identified at low-altitude map directly to the magnetospheric boundaries of the plasmaspause and plasmaspheric erosion plume determined by IMAGE/ EUV.





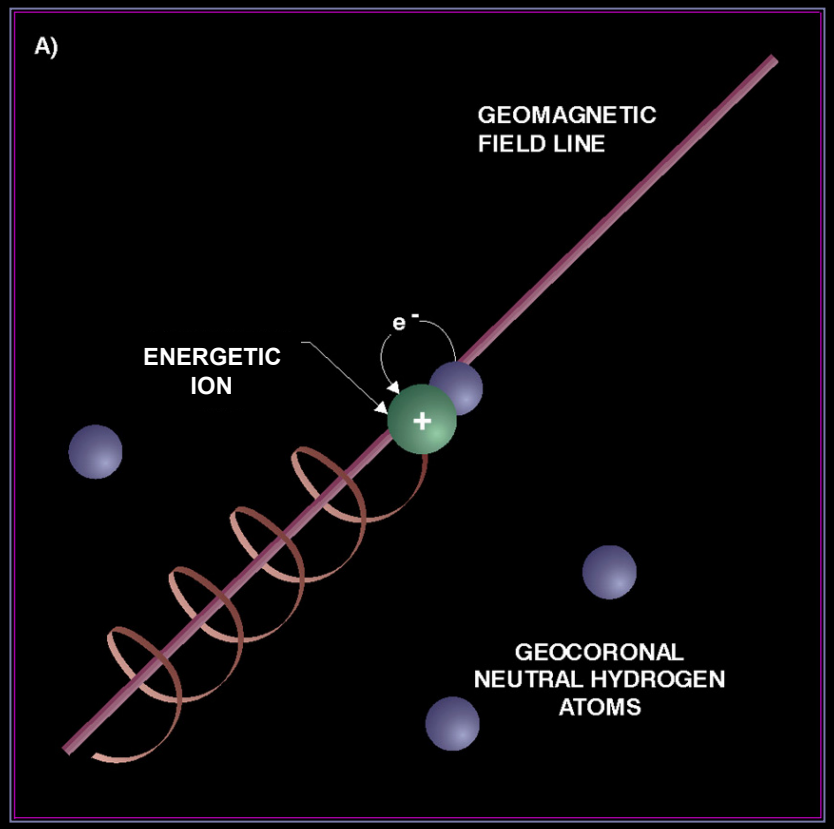
Ring Current

- Hot: 1-400 keV
- Tenuous: quiet, 1 cm^{-3}; active, 10s cm^{-3}
- Plasma sheet: source is near-Earth magnetotail (from solar wind or ionosphere)
- Mostly Protons: During big storms, O^{+} can dominate
- Complicated Drift: E-field, B-field, Gradient-curvature terms
- Important: Dominates the energy density of the inner magnetosphere

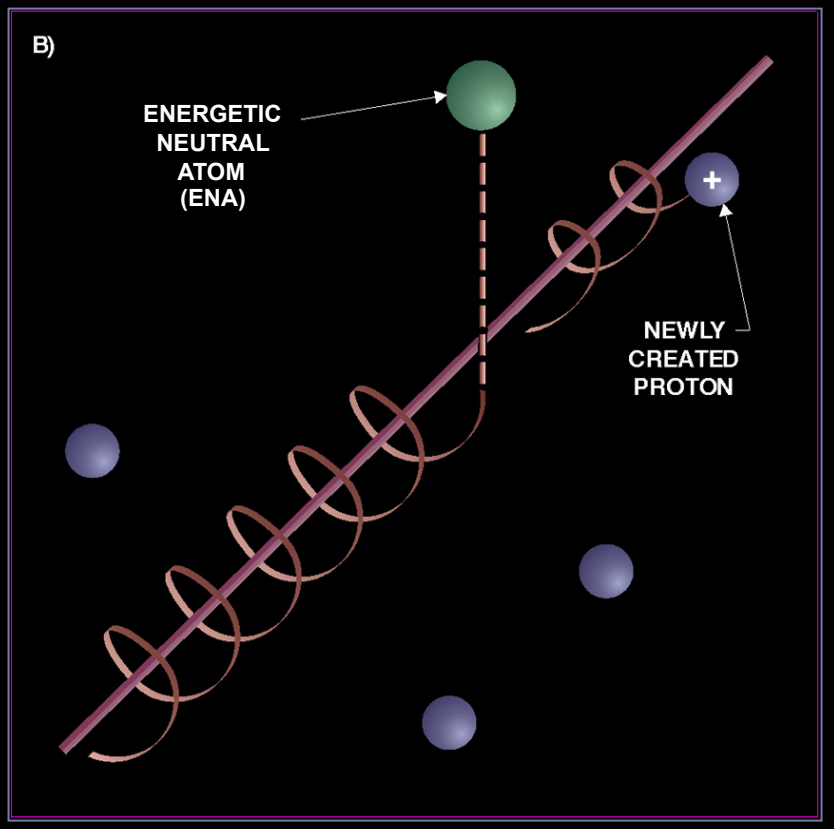
Ring Current Advances

- Storm-Time Ring Current Morphology
  - Partial ring current dominance during storm main phase
- Connection/Feedback with Electric Field
  - The ionosphere matters
- Connection/Feedback with Magnetic Field
  - The B-field can be really altered by currents
- Connection/Feedback with Plasma Sheet
  - Cold dense plasma sheet
- Connection/Feedback with Plasma Waves
  - Collisionless energy transfer

ENA: an important tool of Imaging the ring current



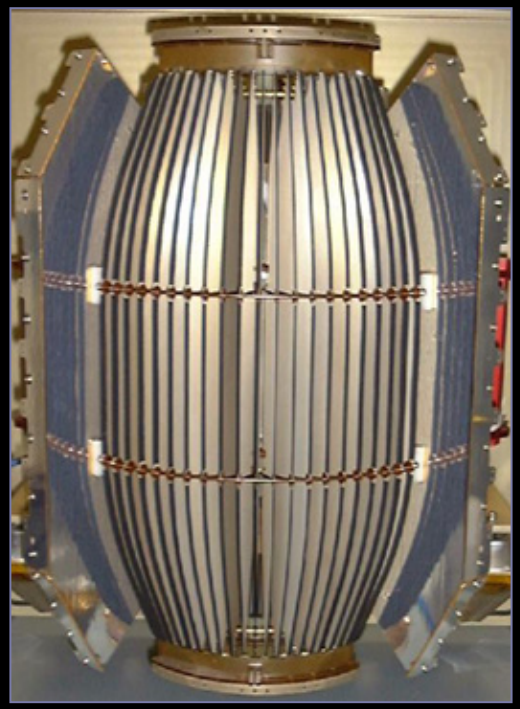
A magnetically trapped ion captures an electron from a neutral hydrogen atom...

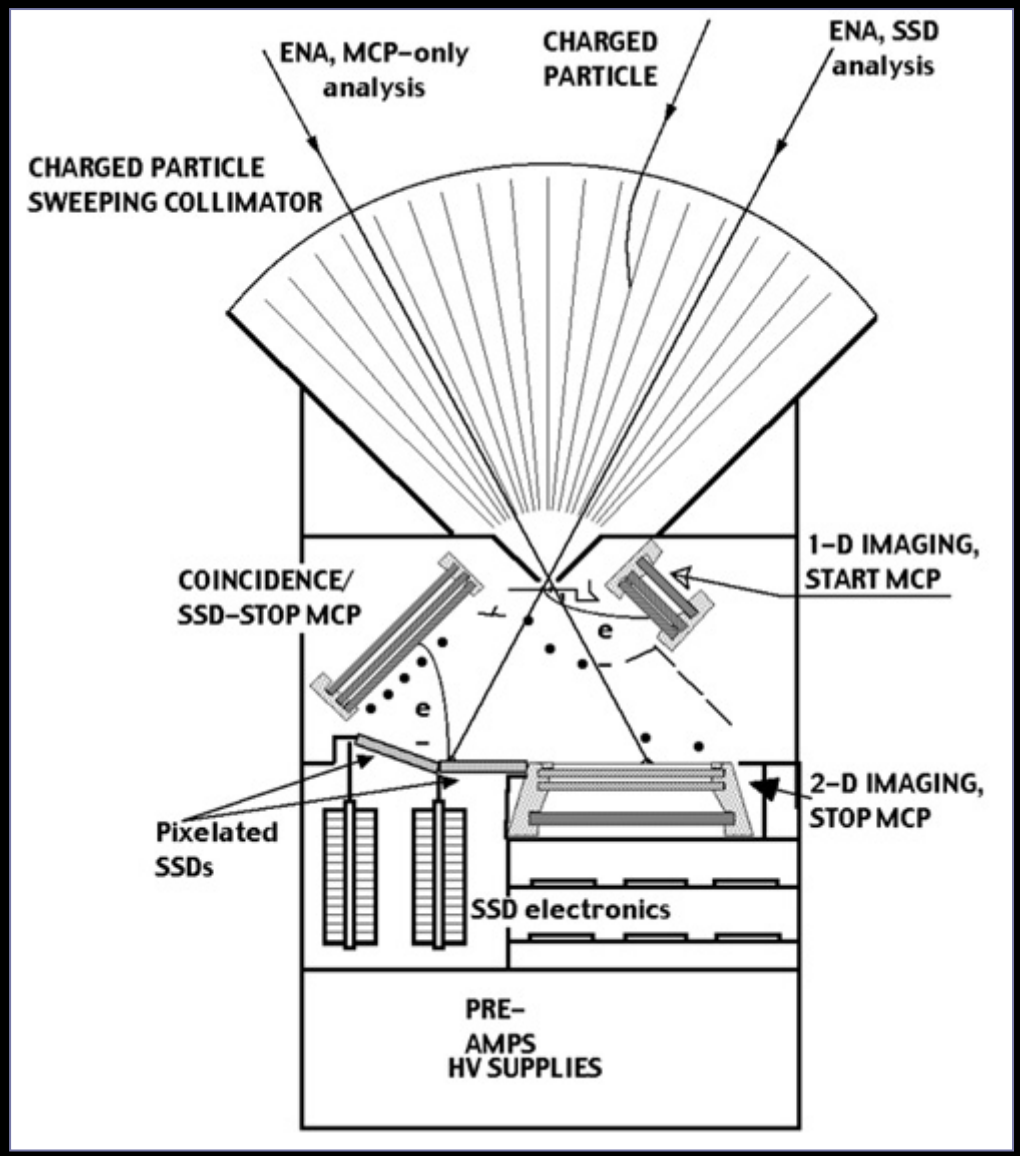


…creating an energetic neutral atom (ENA) that is no longer trapped.

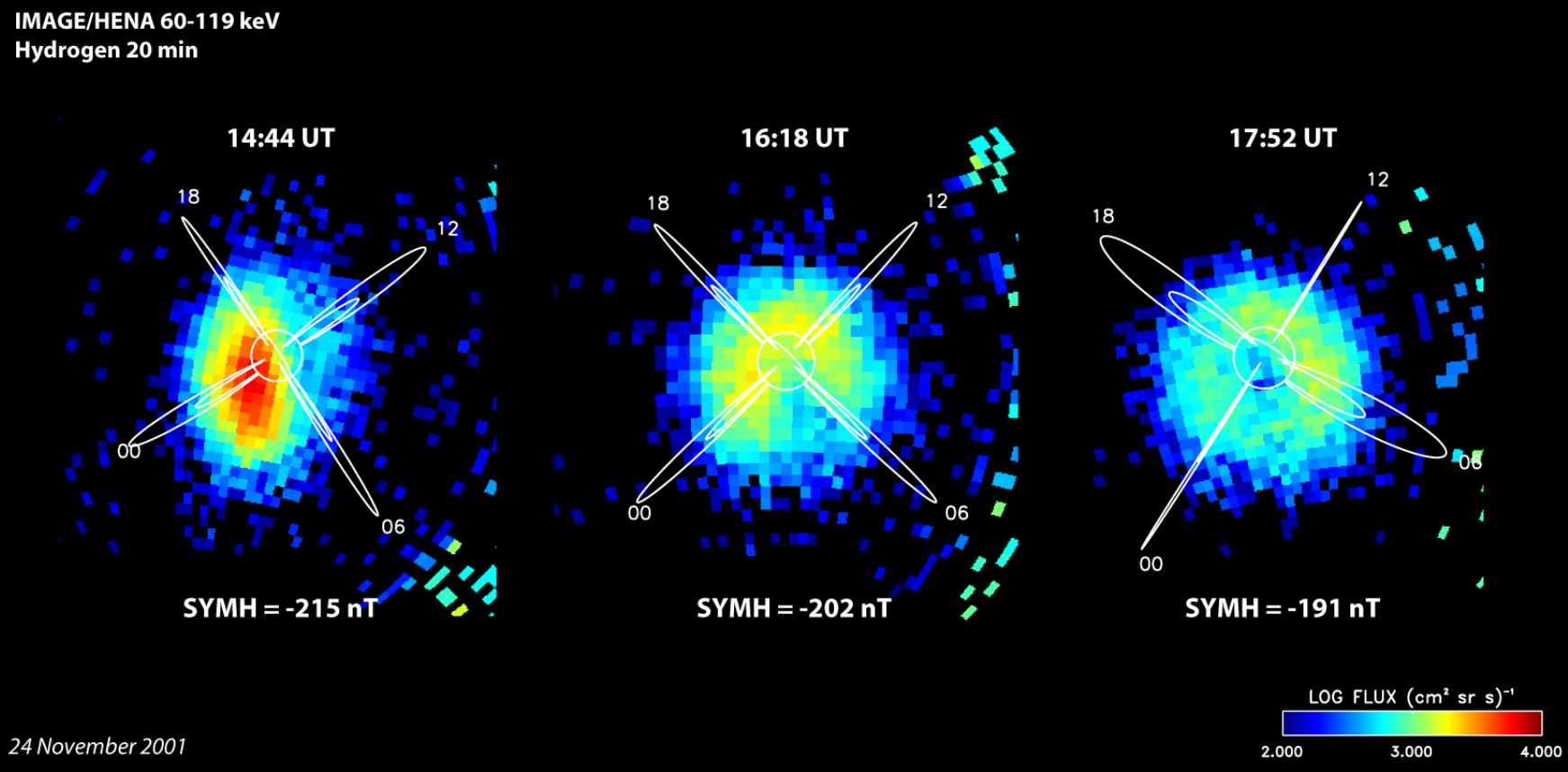
High-Energy Neutral Atom (HENA) Imager

D. Mitchell, JHU/APL



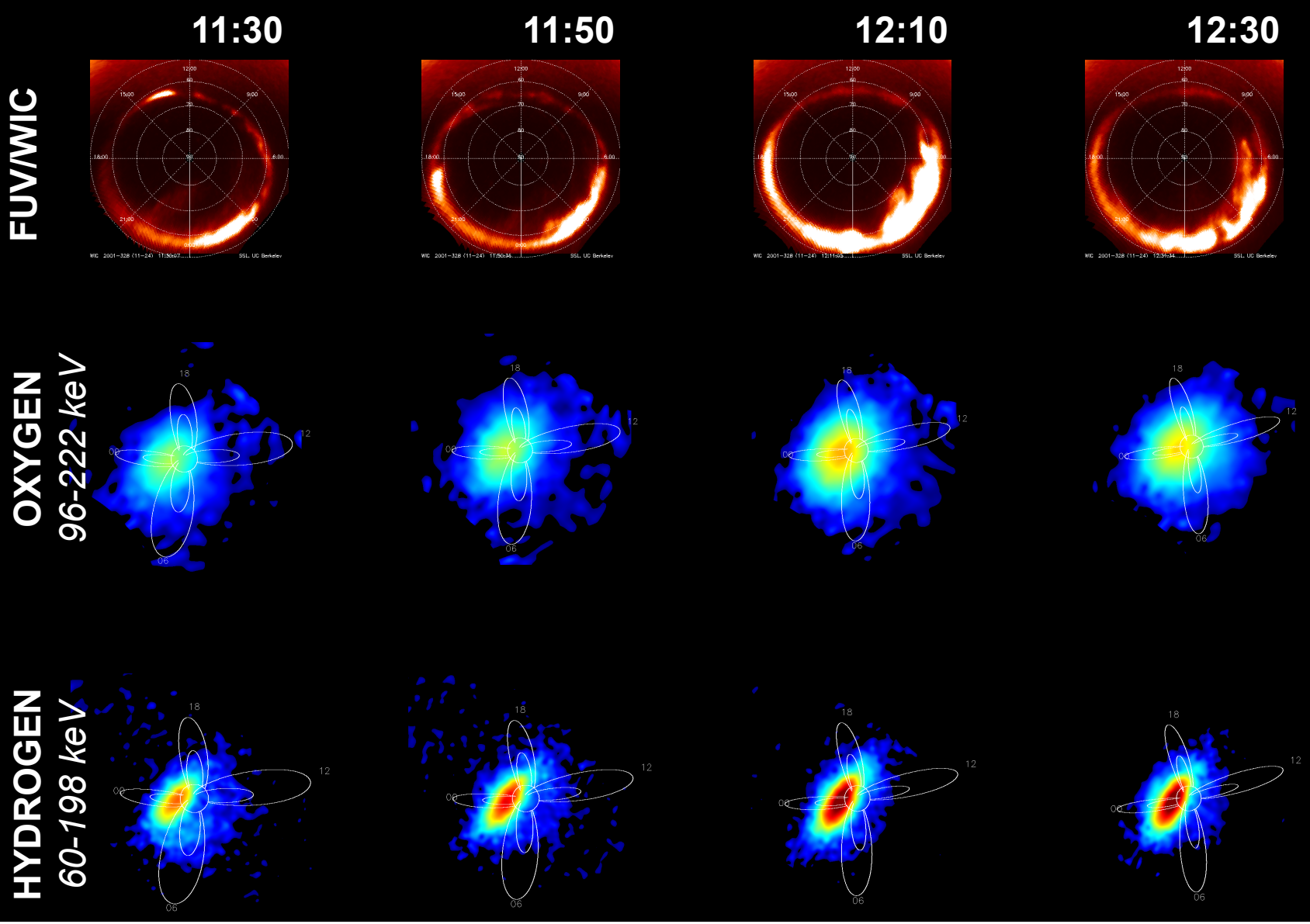


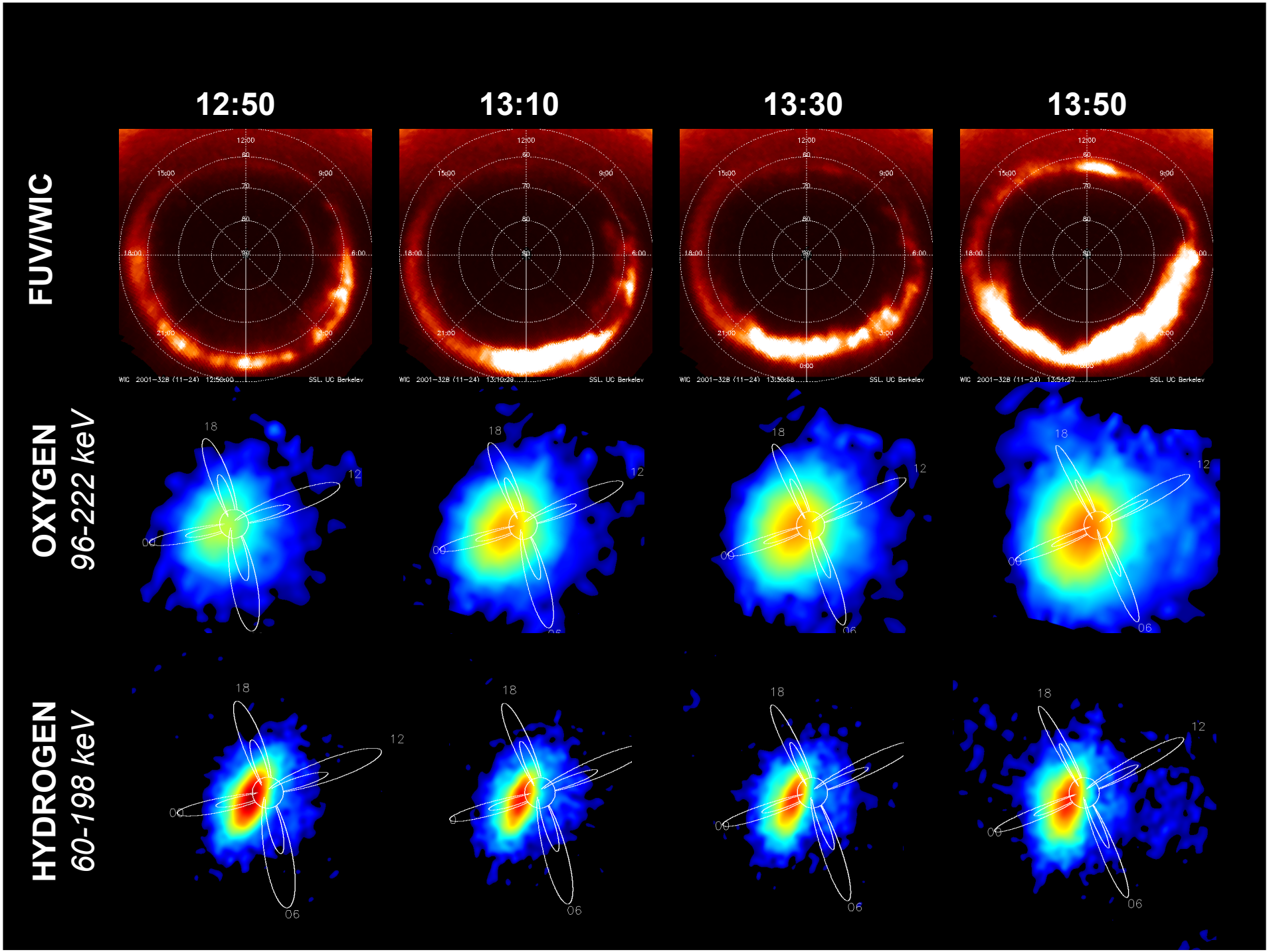
Ring Current Morphology & Dynamics



- **Highly responsive to changes in solar-wind conditions**
- **Change morphology in a couple of hours**

Ring current dynamics: H+ and O+




12:50
13:10
13:30
13:50
FUV/WIC
OXYGEN
96-222 keV
HYDROGEN
60-198 keV
12:00
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6:00
21:00
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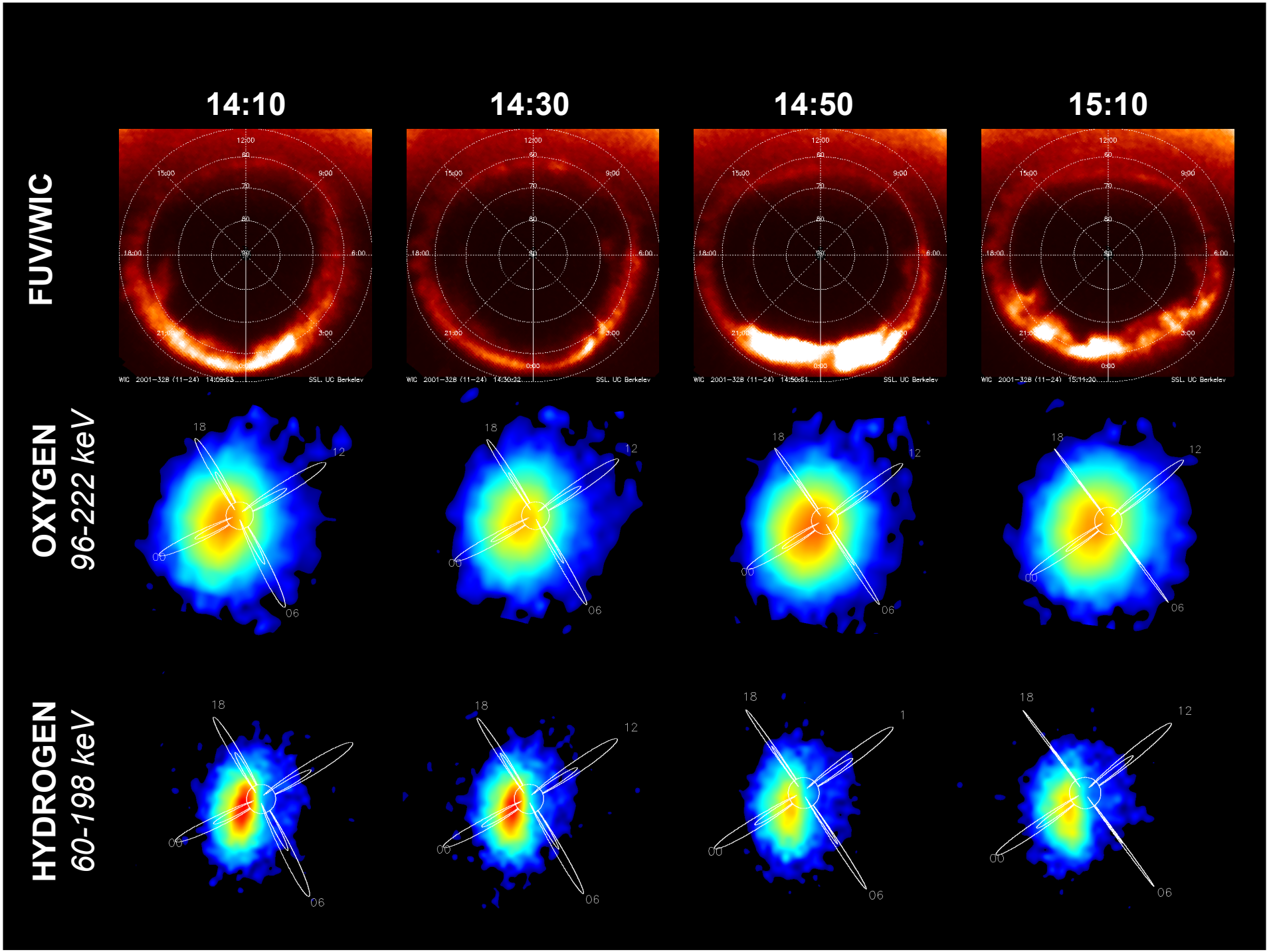
0:00
18
12
06
SSL, UC Berkeley


14:10
14:30
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15:10
FUV/WIC
OXYGEN
96-222 keV
HYDROGEN
60-198 keV
12:00
15:00
9:00
18:00
6:00
21:00
3:00
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SSL, UC Berkeley
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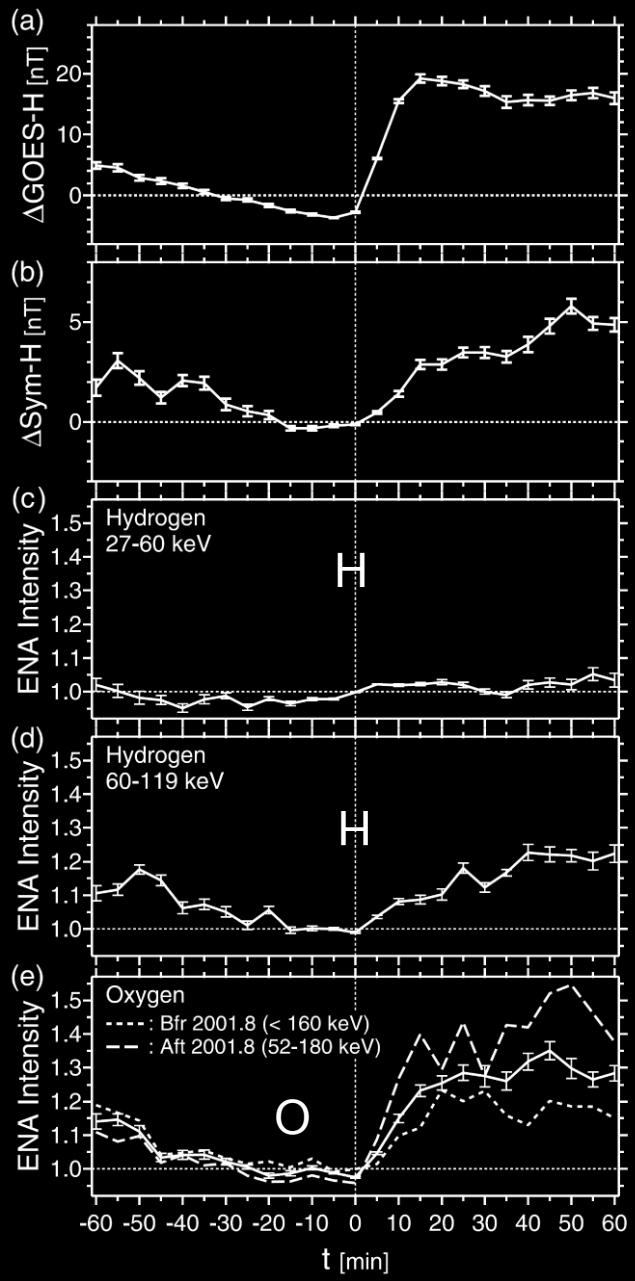
1

Ring current dynamics: H+ and O+

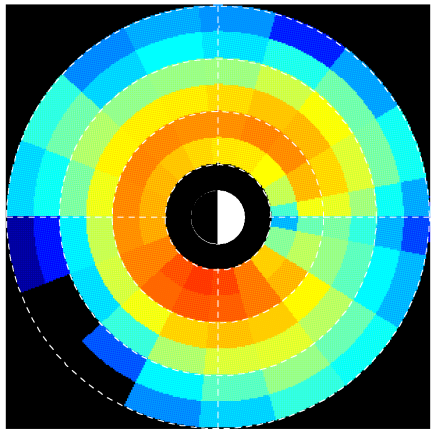
- Superposed epoch analysis by *Ohtani et al. [2005; 2006]:* dipolarization-zero epoch
- Dramatic Oxygen ENA intensification during storm-time substorms
- Hydrogen less dramatic



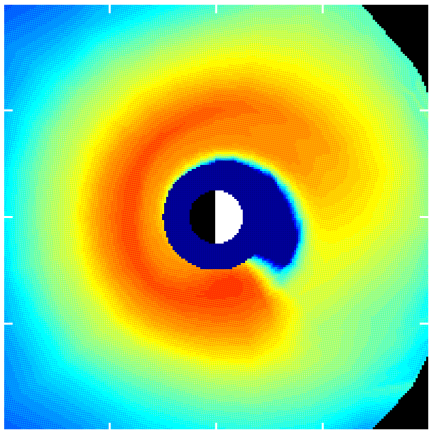
Ohtani et al., JGR, 2005.

Modeling advances: self-consistent E (involves M-I coupling)

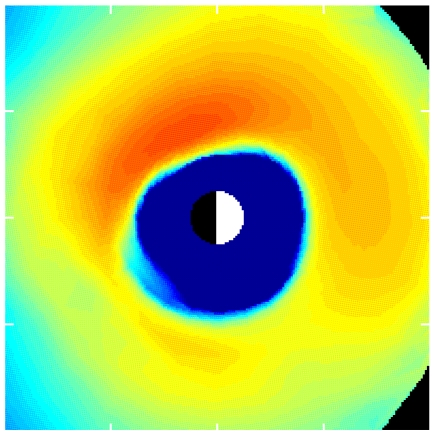
Inverted HENA H+ flux



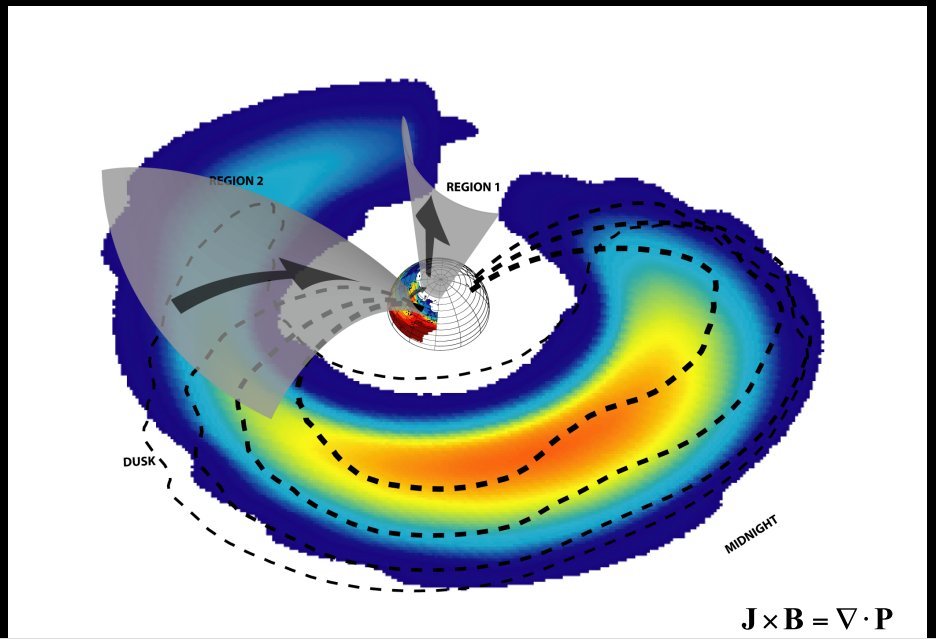
Simulated flux from CRCM



Simulated flux from Weimer



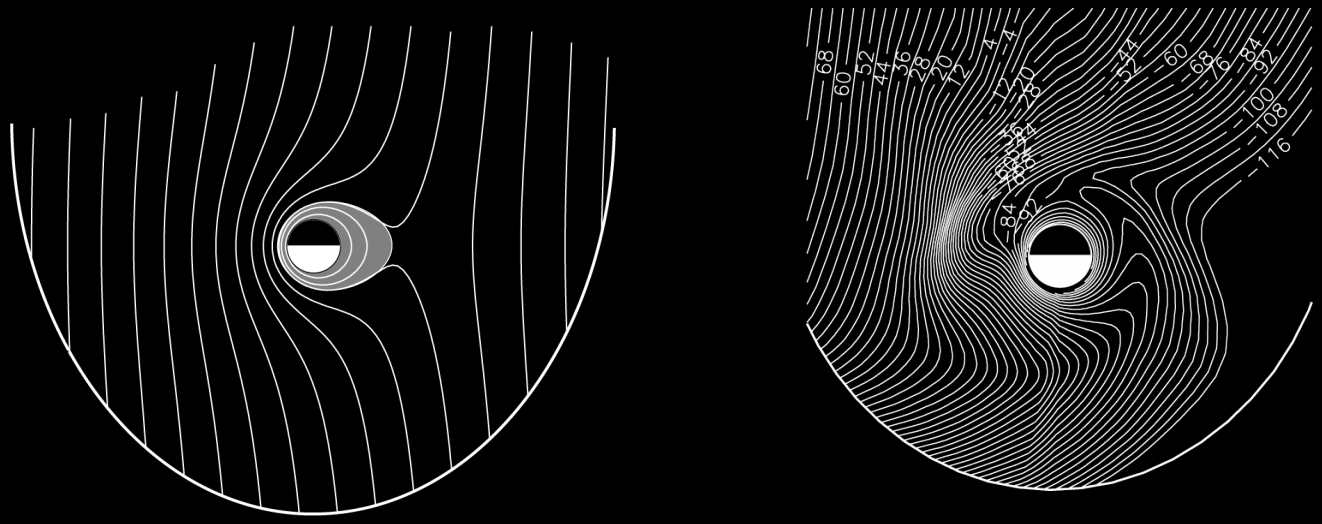
The CRCM with a self-consistent description in E reproduces the post-midnight enhancement of tens keV fluxes, while empirical E models such as Weimer model cannot



Self consistent E

WITHOUT CLOSURE

WITH CLOSURE



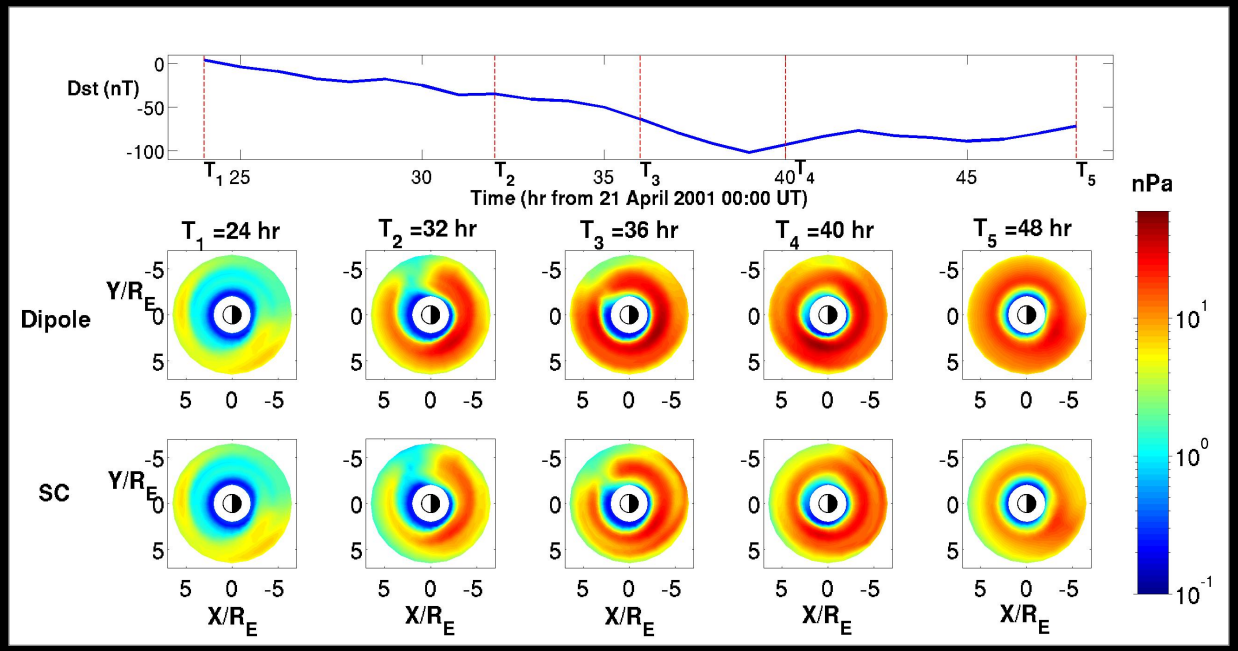
Current closure through conductance gradients formed across terminators, in the auroral region, and in the trough region are responsible for skewing the electric field in the magnetosphere *[Wolf, 1970; Fok et al., 2001]*. The skewing results in a main phase ring current *centered at midnight* and even in the post-midnight sector *[Brandt et al., 2002; Ebihara et al., 2002].*

Ring current advances: self-consistent B

- B-field found from RC pressure, then fed back to RC model

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

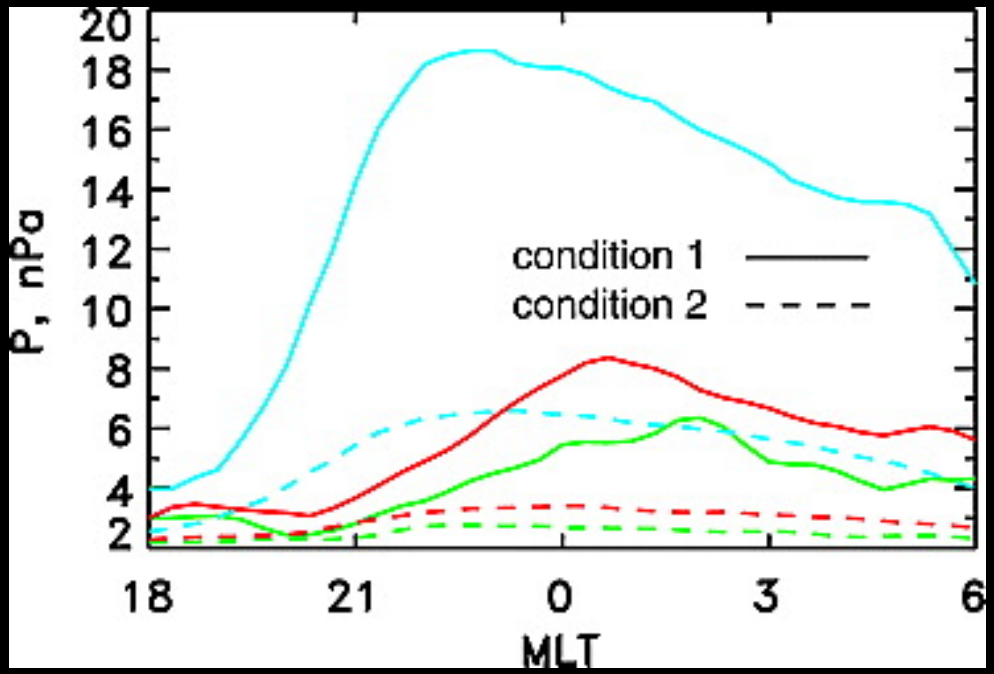
- Pressure ($P_{\perp}$) overall significantly smaller (half) in self-consistent (SC) case vs. dipole field; $P_{||}$ (not shown) not as affected
- Less plasma delivered close to Earth, but more structured



Zaharia et al., JGR, 200

Ring Current Advances: the role of plasma sheet

- Plasma sheet density controls the strength of the ring current
- Plasma sheet temperature also affects ring current intensity (not as density)



Condition 1: cold dense
Condition 2: hot tenuous

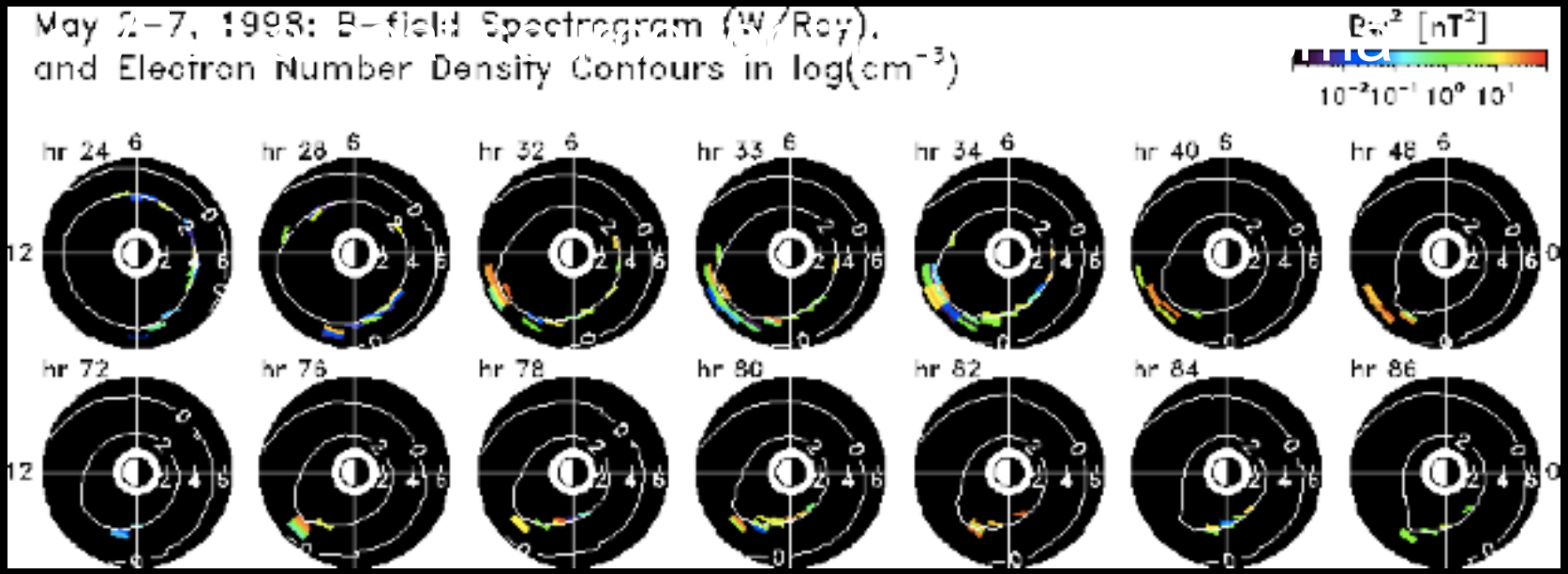
Condition 1 leads to relatively high pressure in the nightside while condition 2's pressure distribution is more uniform

Ring Current Advances: the role of conductance

- Semiannual variation of Dst can be partially explained by conductance effect [Ebihara et al., 2004]
- Large conductance results in a stronger ring current and further equatorward penetration of E [Zheng et al., 2006a]

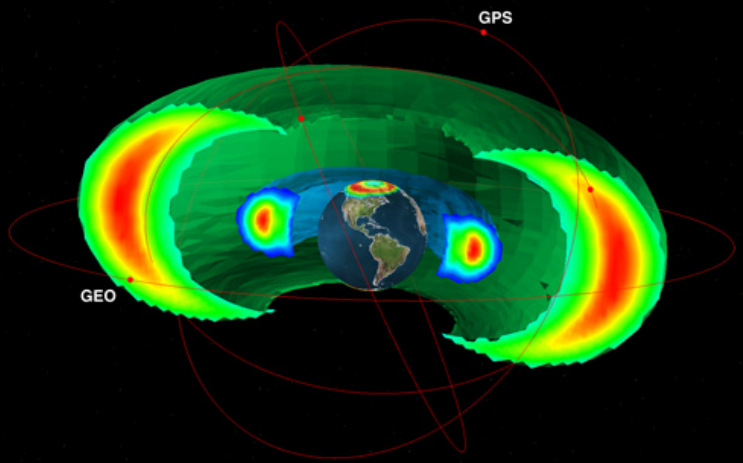
Ring Current advances: Plasma Waves

- Calculating the EMIC wave energy density self-consistently with the hot ions allows for nonlinear feedback between them
  - Scattering of ions depends on B_w and θ
  - Preference for field-aligned θ



Khazanov et al., JGR, 2006

Radiation Belt

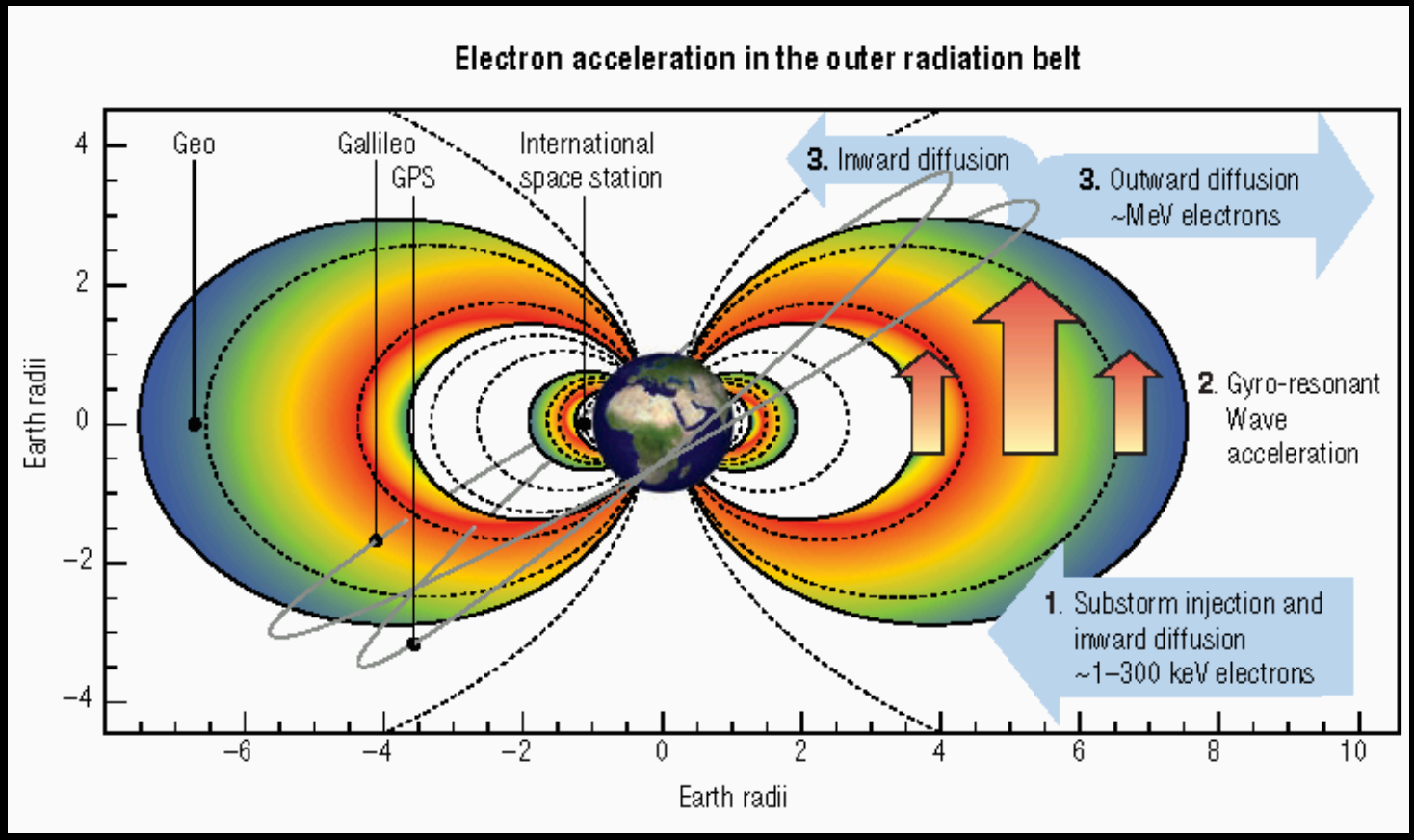


- Typical temperature of ionsphere e-: ~ 1eV
- Typical temperature of the solar wind e-: 10 eV
- RB e-: 400 keV – 15 MeV – How do they get accelerated to such high energies?

RB Dynamics

- Solar wind speed and IMF polarity: controlling parameter
- CME storm - deep penetration
- CIR storm- more effective in geo orbit

RB: Current understanding



Horne et al., 2007, Nature Physics

COUPLING

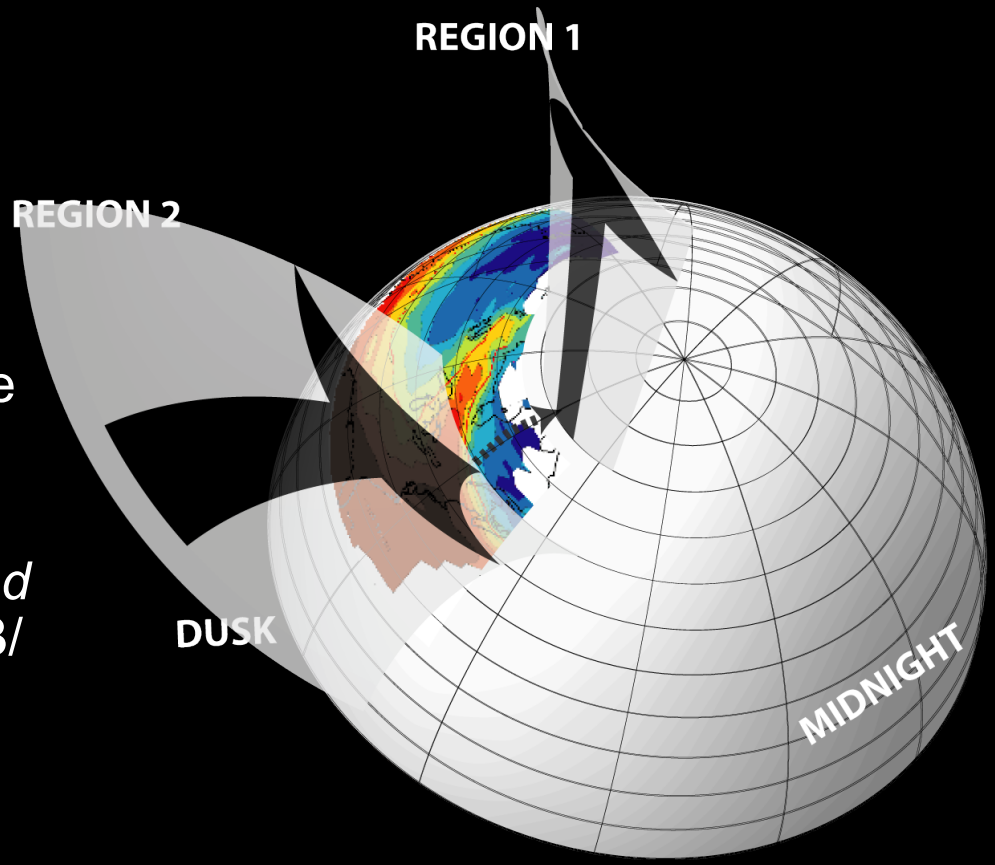
Ring current – Ionospheren – Plasmasphere

An example: SAPS

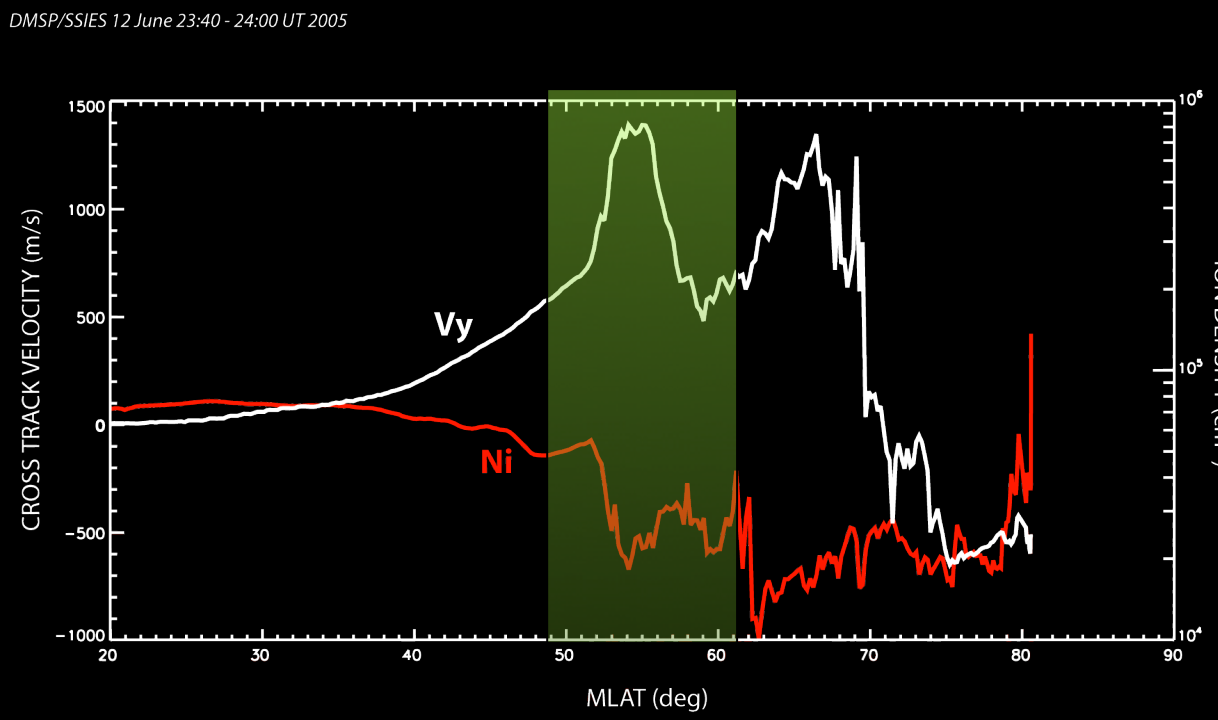
SAPS (Sub Auroral Polarization Streams)
Fast sunward plasma drift

SAPS and the ring current

- Partial ring current sets up region-2 current system
- Closure through sub-auroral ionosphere (low-conductance trough region)
- Poleward E-field is *associated* with westward motion **v=ExB**/ B^2 (or is it JxB force)



Trough cond. and SAPS



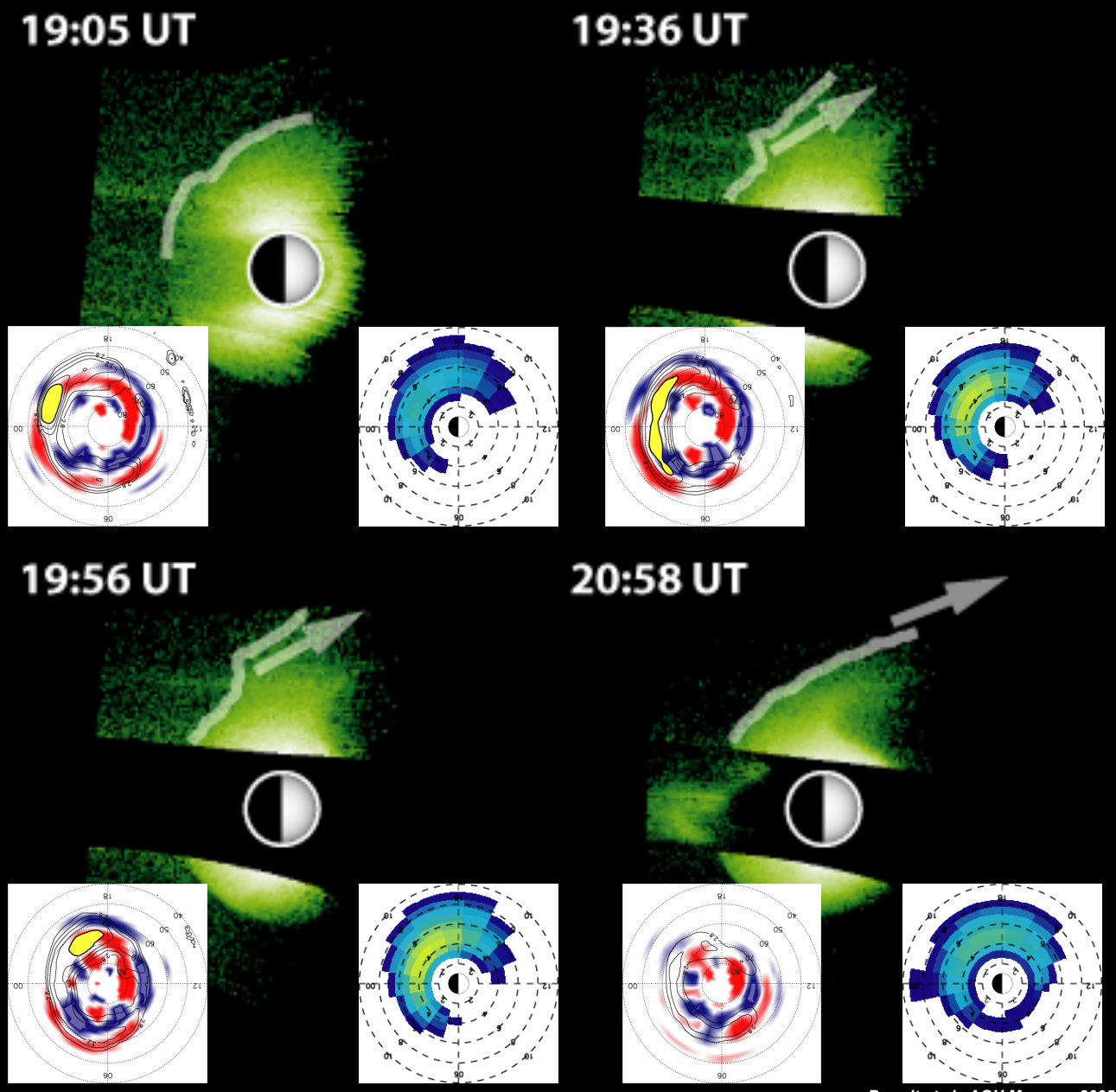
The trough is low-density plasma region exists during quiet times. Evolves and deepens during storms times

Association of the trough with Sub-Auroral Polarization Streams (SAPS) has been recognized from observations.

The association of the ionospheric trough and SAPS is evident in our model results, and resembles what has been observed. Low conductance in the trough is important for the formation of large amplitude flows (SAPS).

Zheng et al., 2008

SAPS and plasmaspheric undulation



Brandt et al., AGU Monogr., 2005

Goldstein et al., JGR, 2005

Consequences of SAPS

Enhanced sunward flow in ionosphere

↓

Increased frictional heating

↓

Enhanced recombination (ionospheric plasma outflow)

↓

Reduced ionospheric conductivity

↓

Stronger SAPS

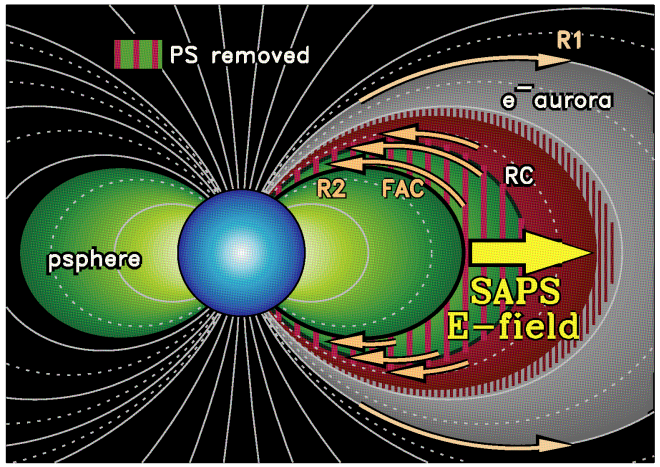
Enhanced sunward flow of the plasmasphere

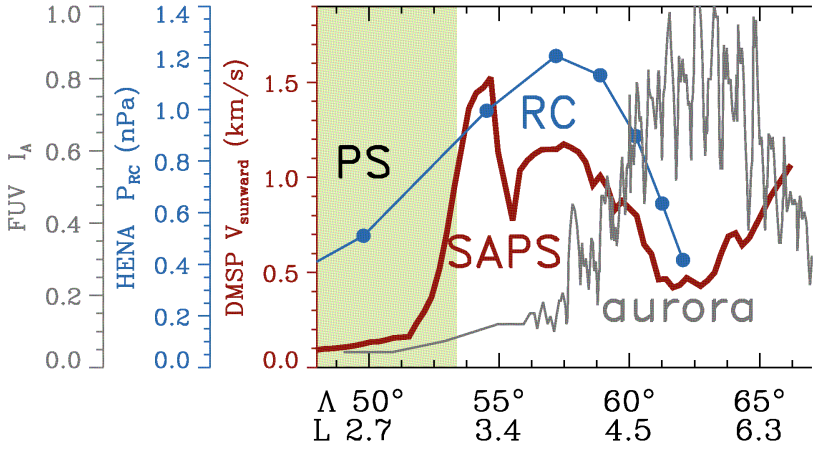
↓

Increased drainage

↓

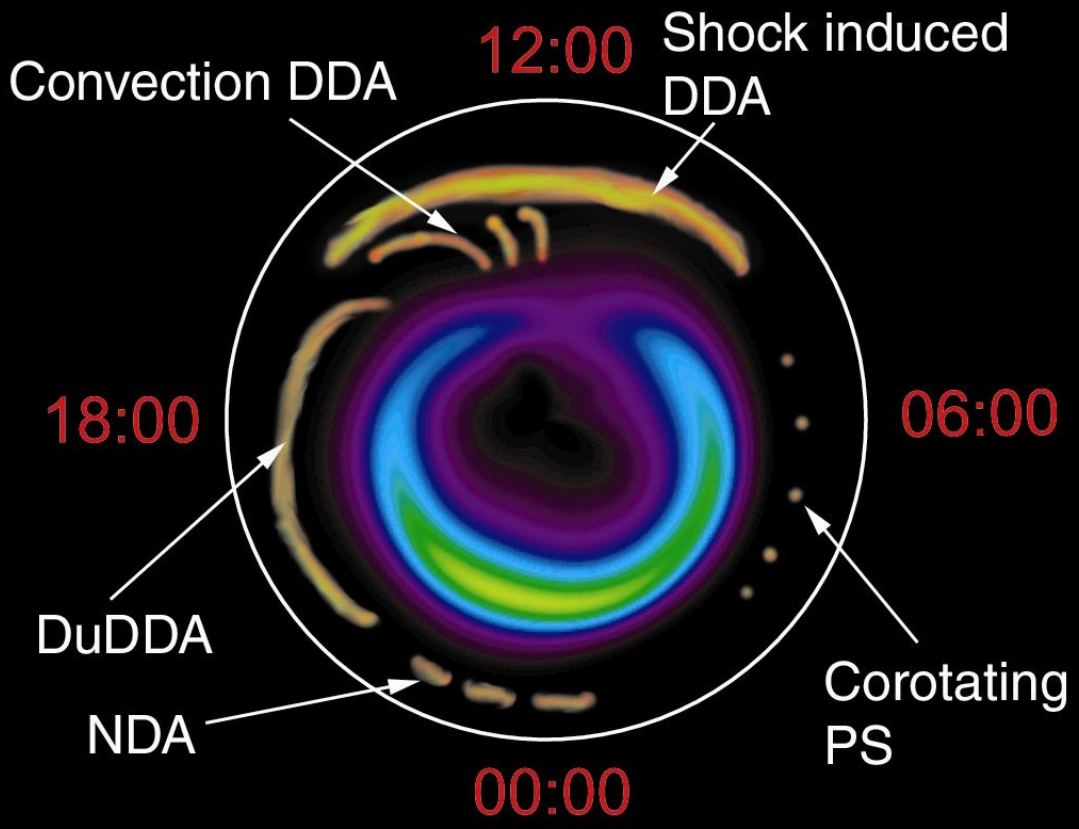
possibly increased structuring of drainage plume



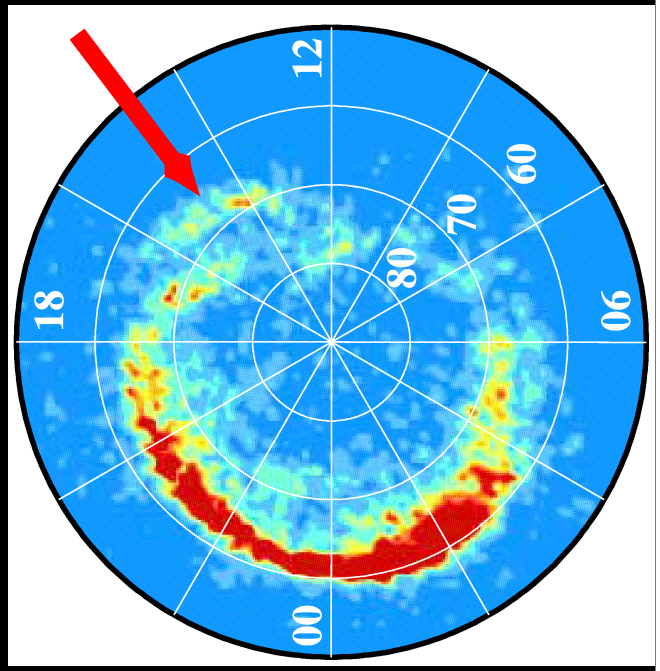


The relationship of the ring current, plasmasphere, SAPS, and aurora. Their interactions reflect the strong couplings of the ring current, plasmasphere and underlying ionosphere. From *Goldstein et al.* [2005a].

Subauroral Proton Arcs/Spots



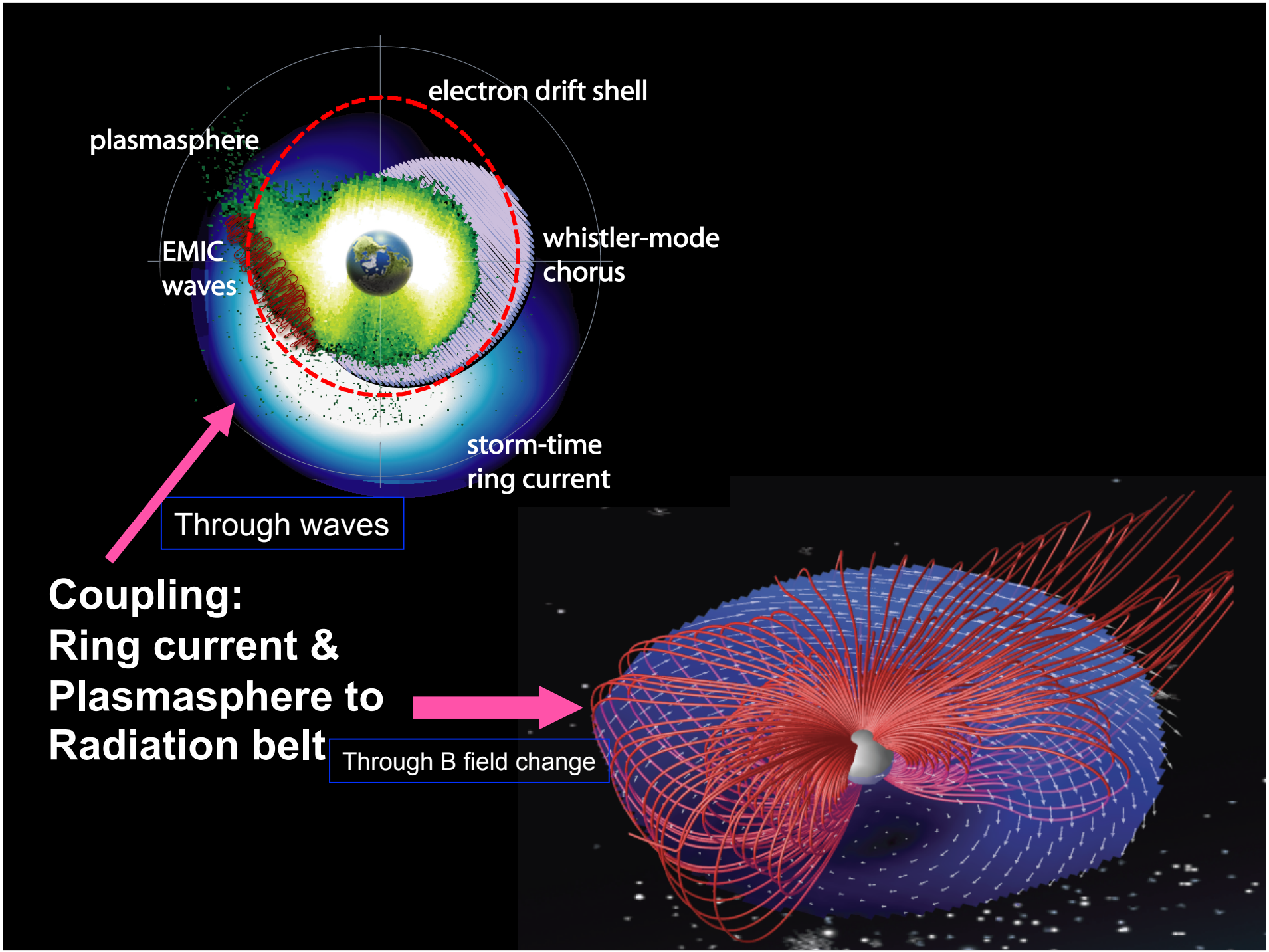
Zhang, GEM 2007



Spasojevic et al., 2004

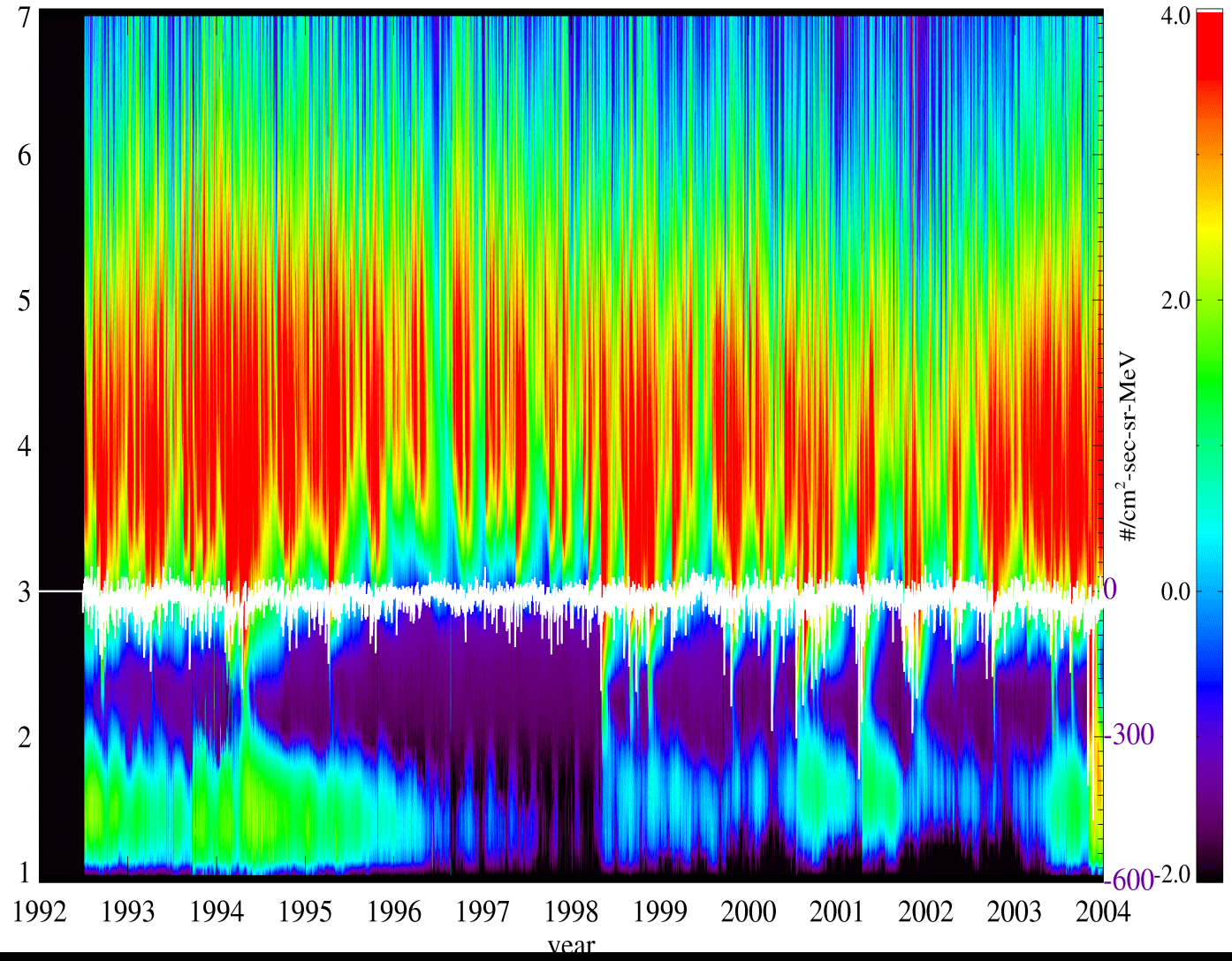
Subauroral proton arcs

- The subauroral proton precipitation is a manifestation of the complex interplay between the dynamics of the ring current, plasmapshere and the involved wave-particle interactions.
- Can be used as means of remote-sensing the magetospheric processes


electron drift shell
plasmasphere
EMIC
waves
whistler-mode
chorus
storm-time
ring current
Through waves
Coupling:
Ring current &
Plasmasphere to
Radiation belt
Through B field change

e- penetration (nearly 12 years of SAMPEX data)

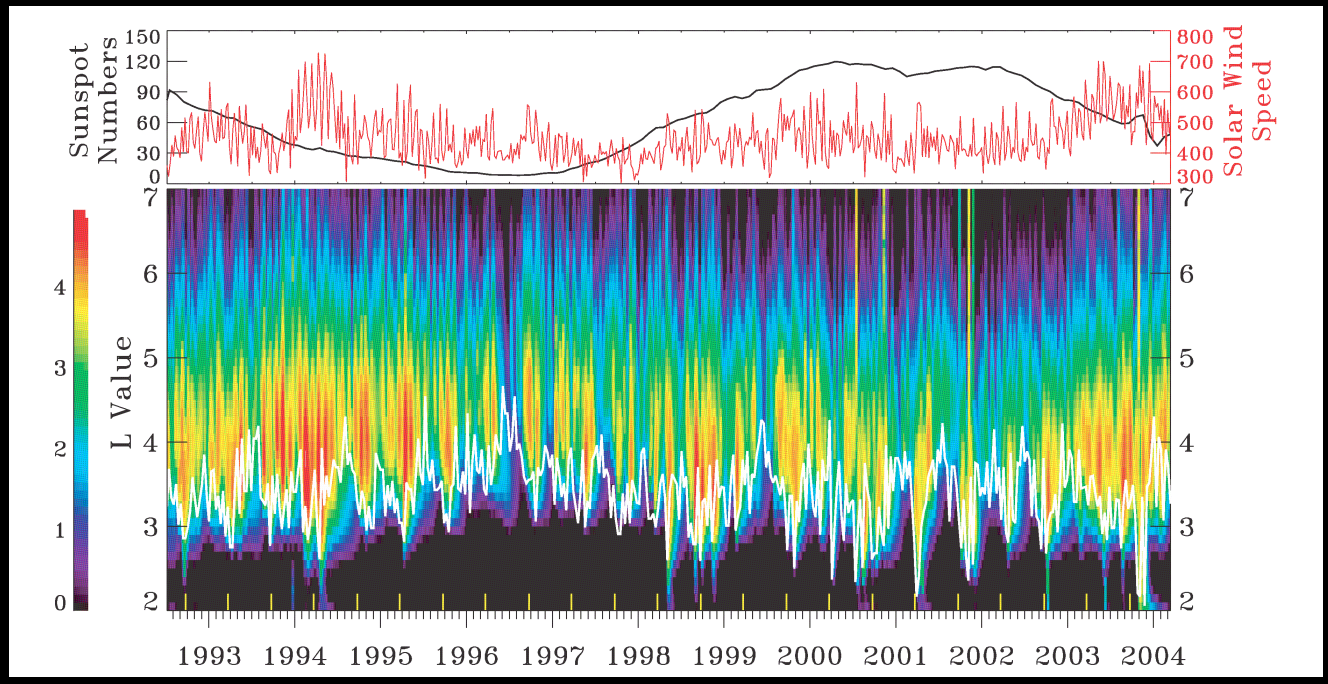
Radiation Belt
- Ring current
Coupling



We can see the association between intense storms (Dstmin<-130 nT) and the electron penetration to the slot region.

Zheng et al., 2006b

Radiation belt - Plasmasphere



A remarkable correlation is evident between the inner edge of the outer radiation belt (Lrb) and the innermost position of the plasmapause (Lpp, the white curve) over a long term period. From *Li et al.* [2006].

A tightly coupled system

Challenges

Challenges: Plasmasphere

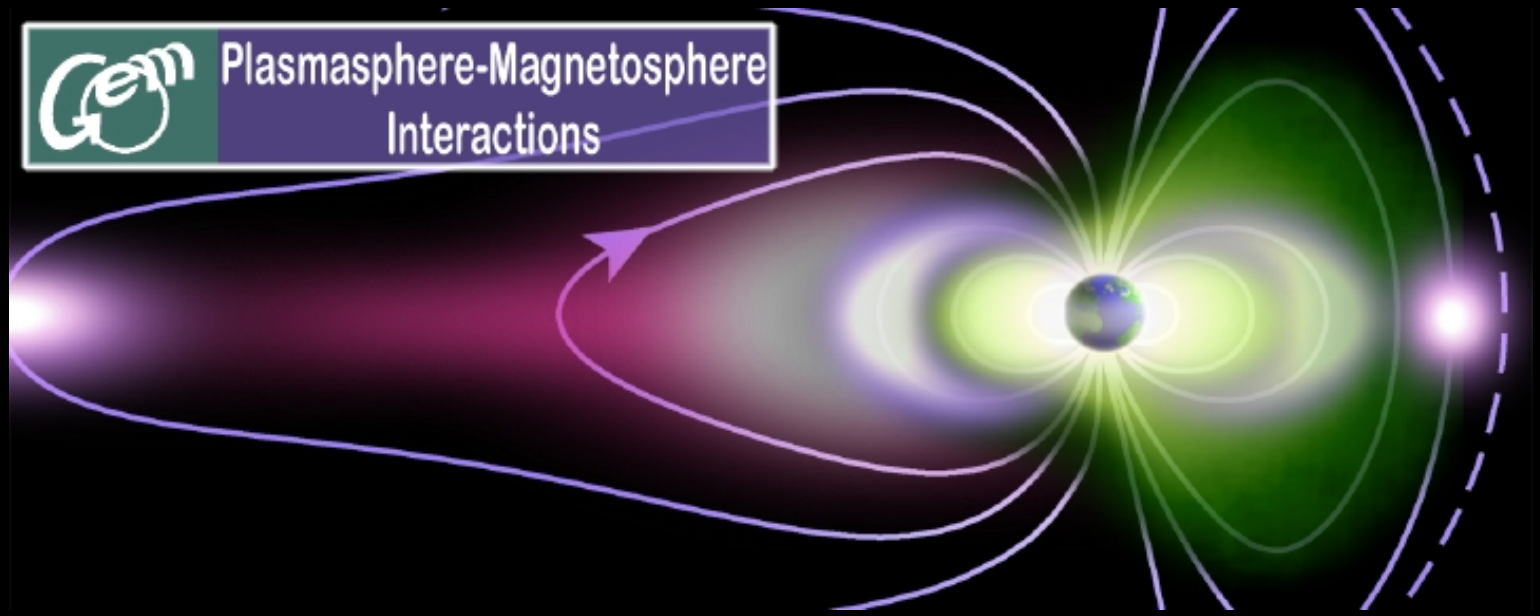
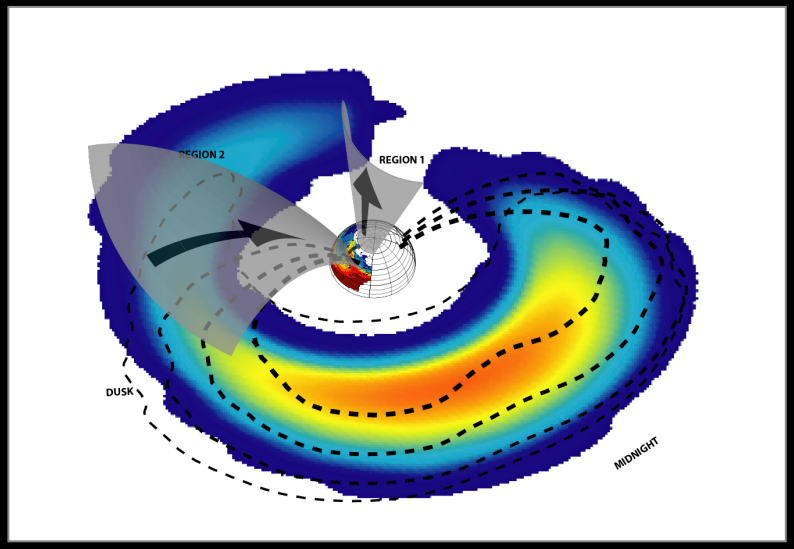


Image courtesy: J. Goldstein

Challenges: Ring Current



1. Role of substorm instabilities
2. O+ physics
3. Fine plasma structures and large-amplitude E & B fields

For modeling:
better conductance model
Plasma sheet source model

Challenges: Radiation Belt

Quantify roles of radial transport and local acceleration

What determines the different flux response of each storm?

Reconcile discrepancy between the theoretical prediction and observations in terms of EMIC wave occurrence location and examine such impact

Nonlinear wave-particle interactions

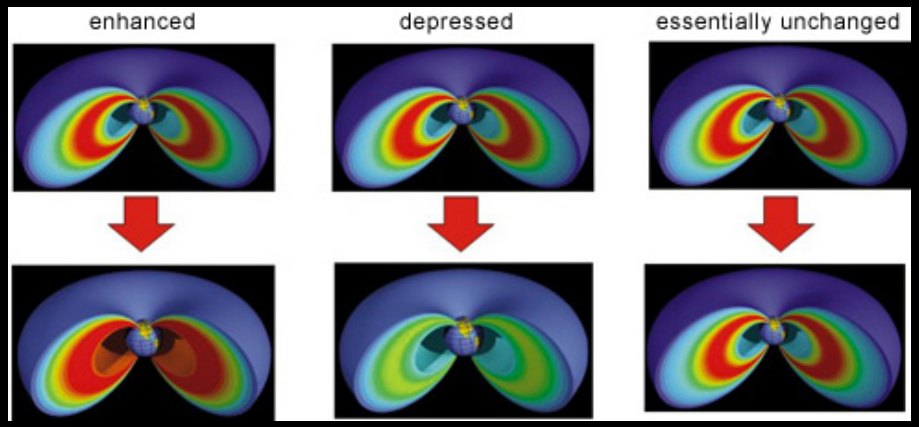
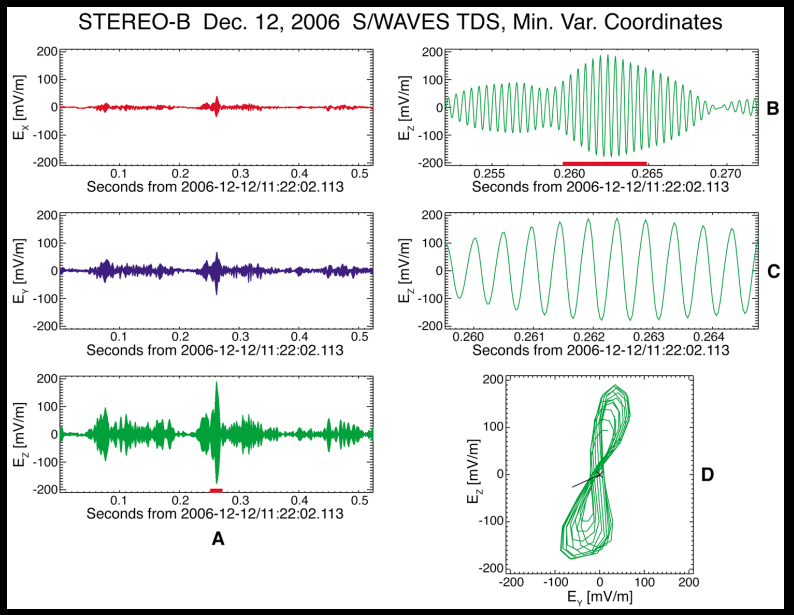


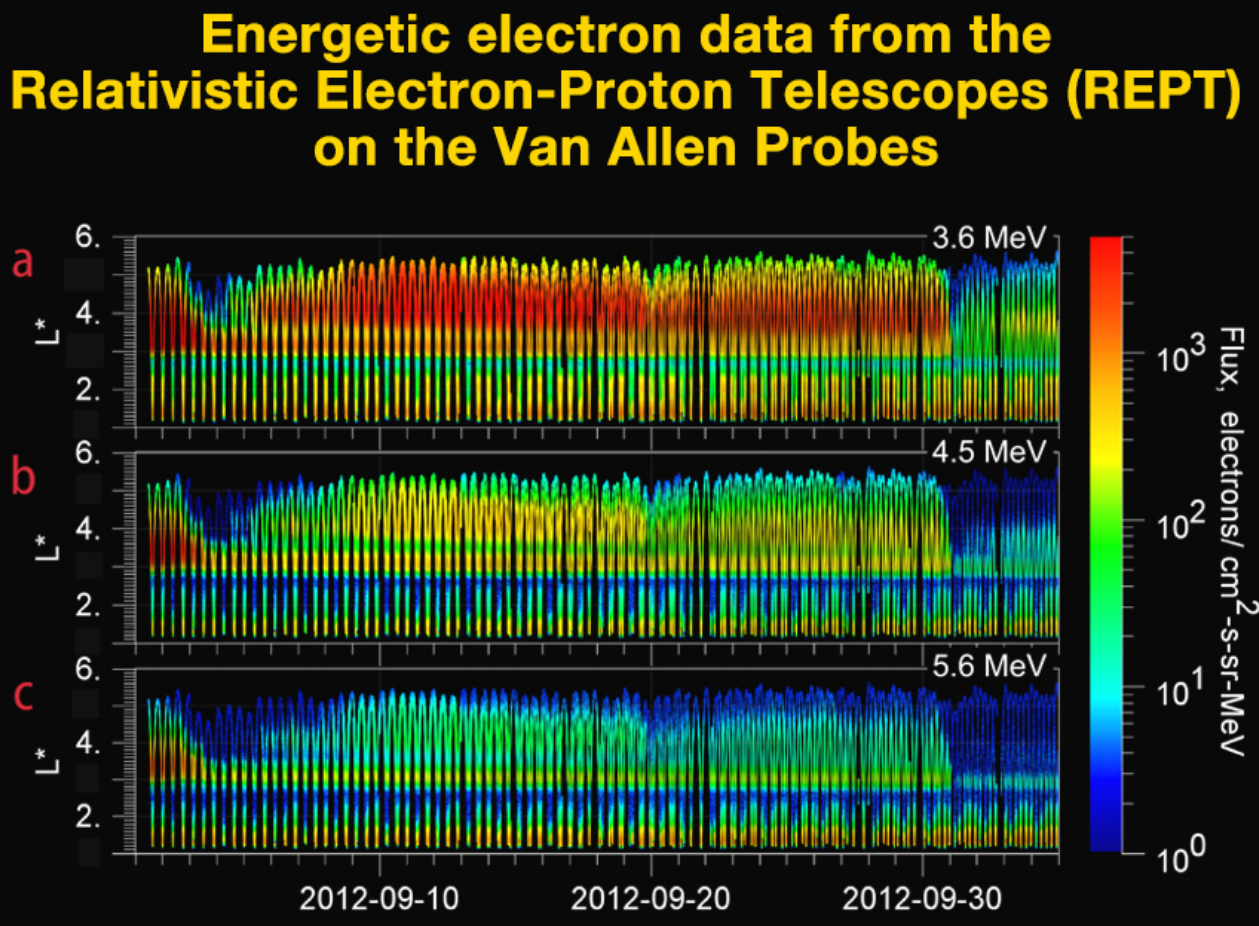
Image courtesy: Reeves

>200 mV/m whistlers, cattell et al., 2008

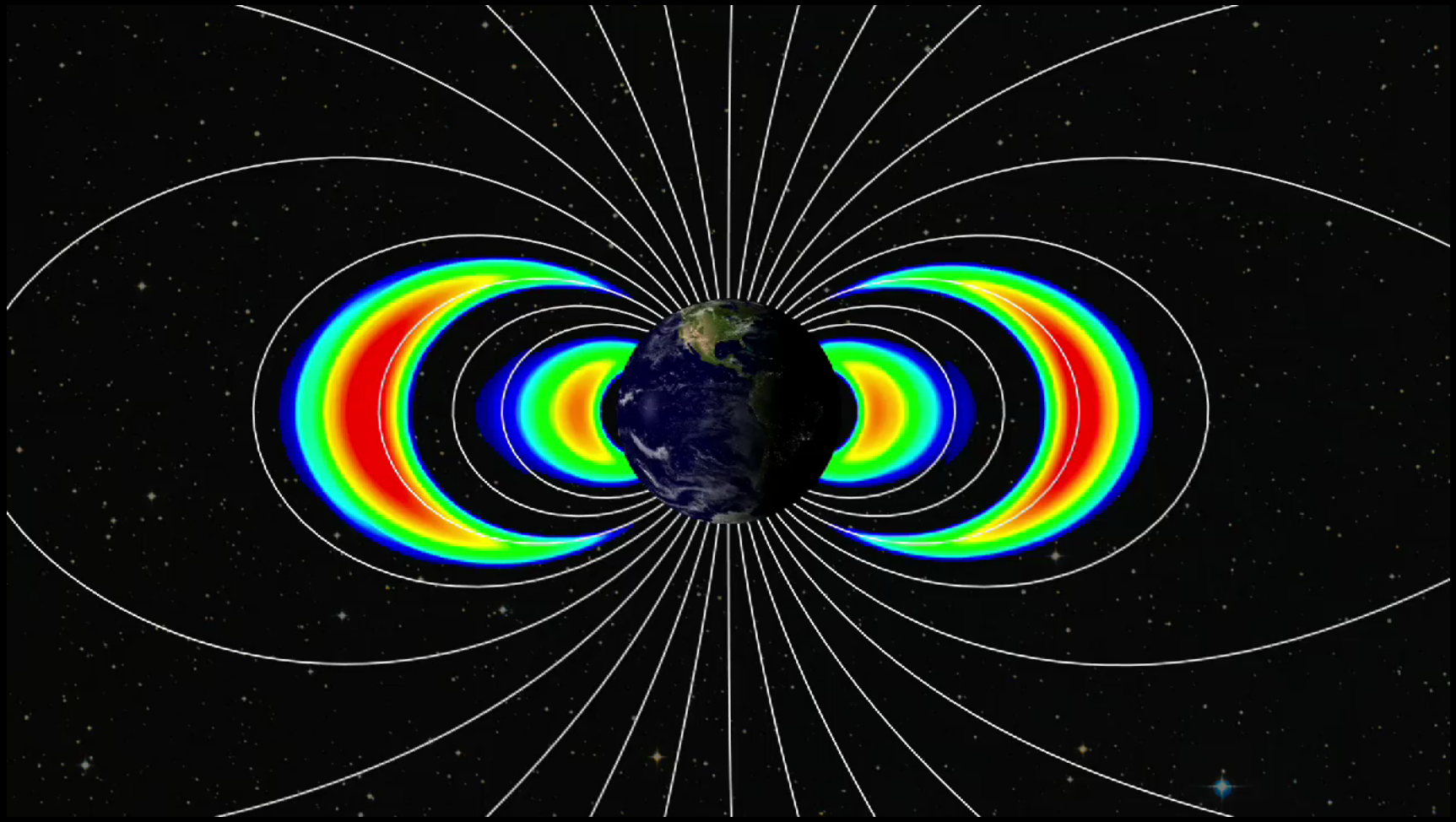


Three-Belt Structure

Quiet-time phenomenon



Van Allen Probes: current mission on radiation belt dynamics



Courtesy: Baker et al.