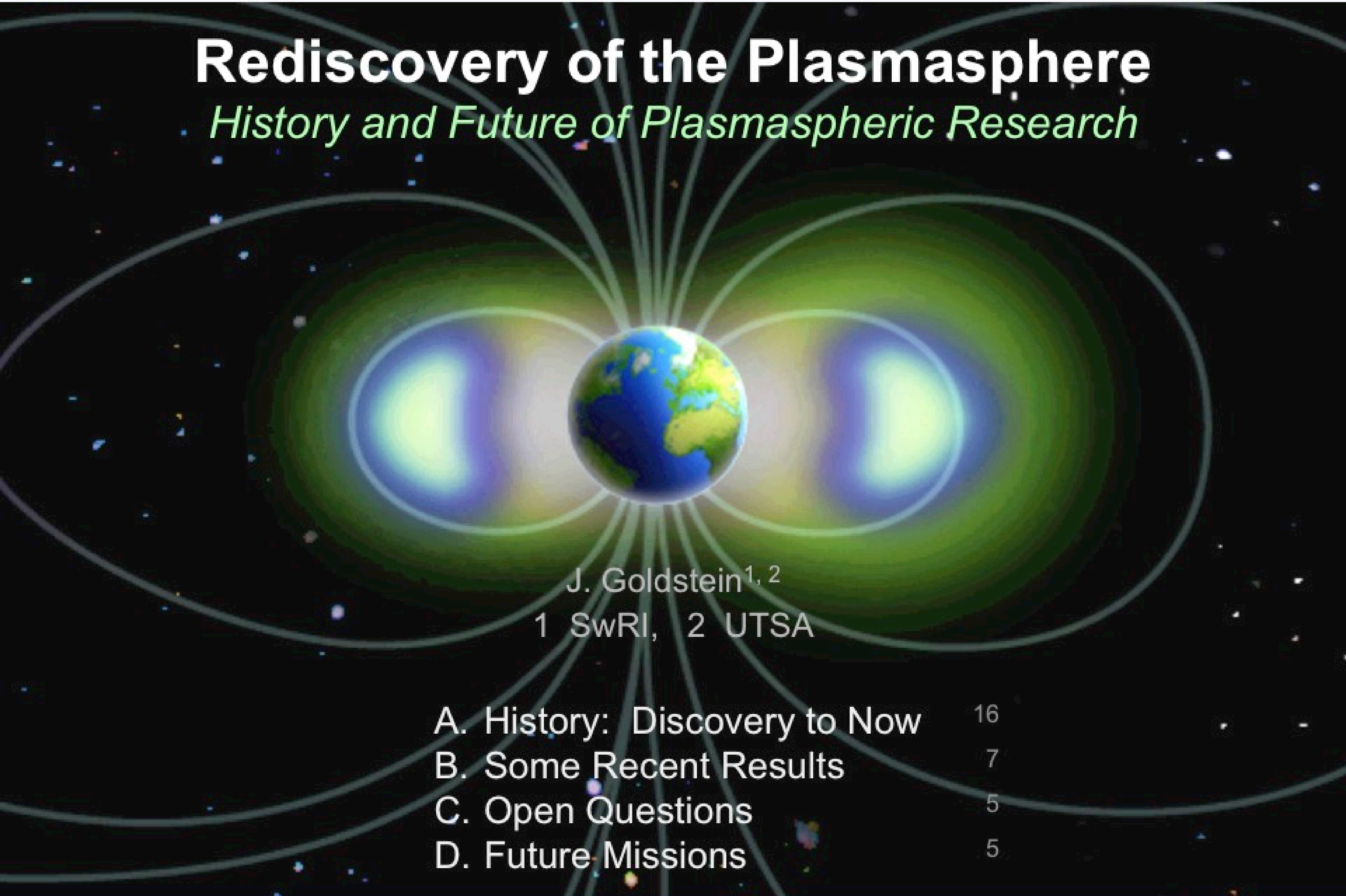
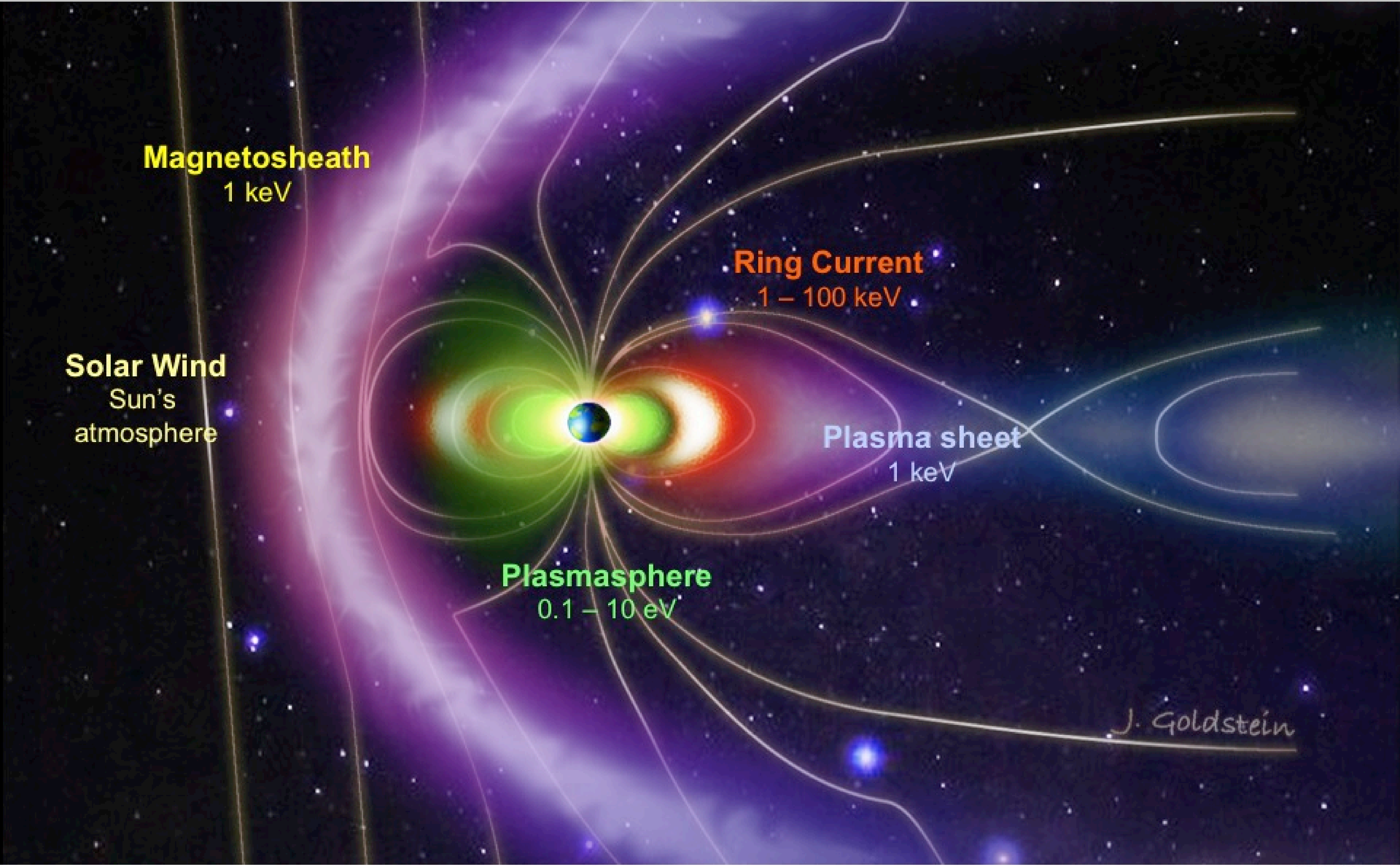
Rediscovery of the Plasmasphere

History and Future of Plasmaspheric Research

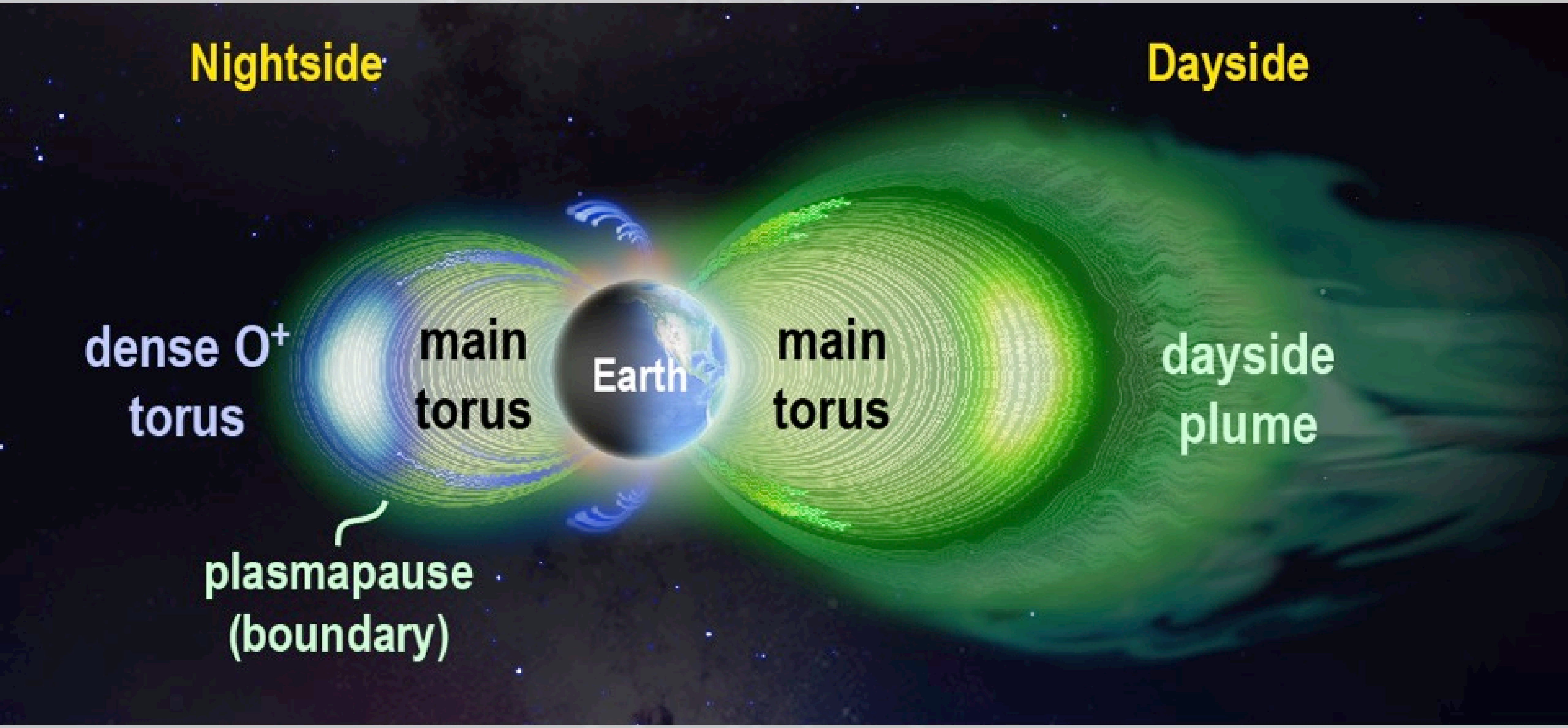


J. Goldstein[1, 2]
1 SwRI, 2 UTSA

Space Plasmas Near Earth



The Plasmasphere

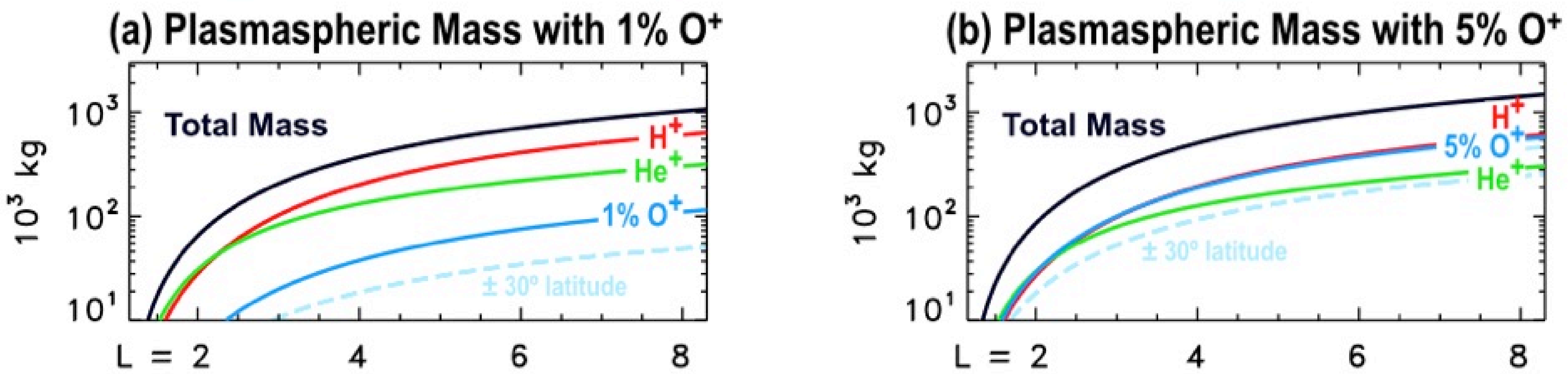


Cold, 1 eV, dense 10-10,000/cc torus of H^+, 80% He^+, 15-20% O^+ few %

outer boundary = plasmapause

Plasmasphere: Why is it Important?

(Answer: Mass / Inertia)



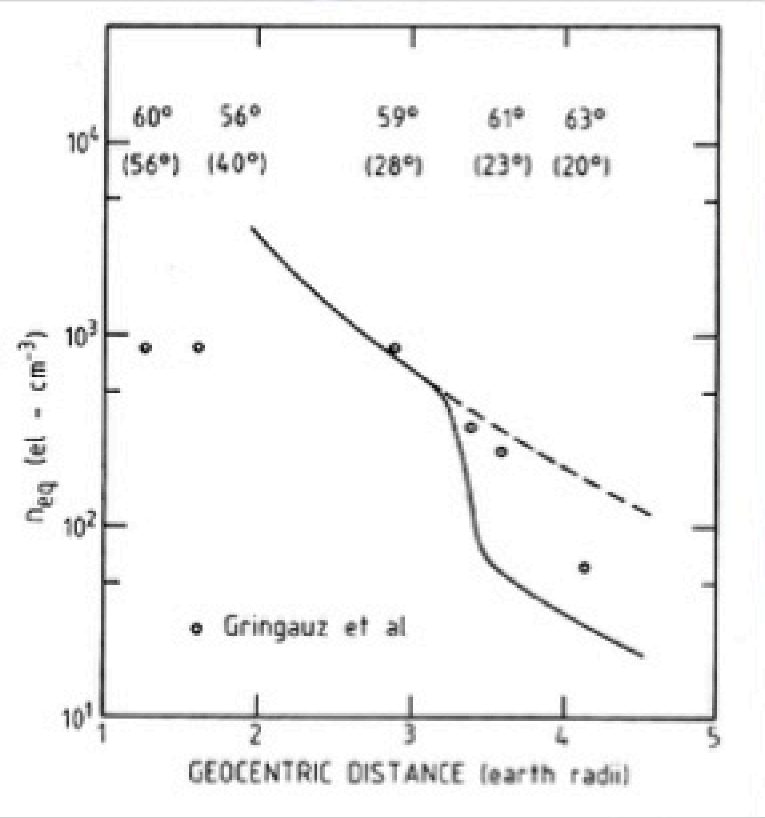
tens to hundreds of metric tons of plasma
[*Goldstein et al* 2019b doi:10.1029/2019JA026822]

⇒ majority of mass/inertia in magnetosphere
⇒ controlling influence on fundamental wave modes

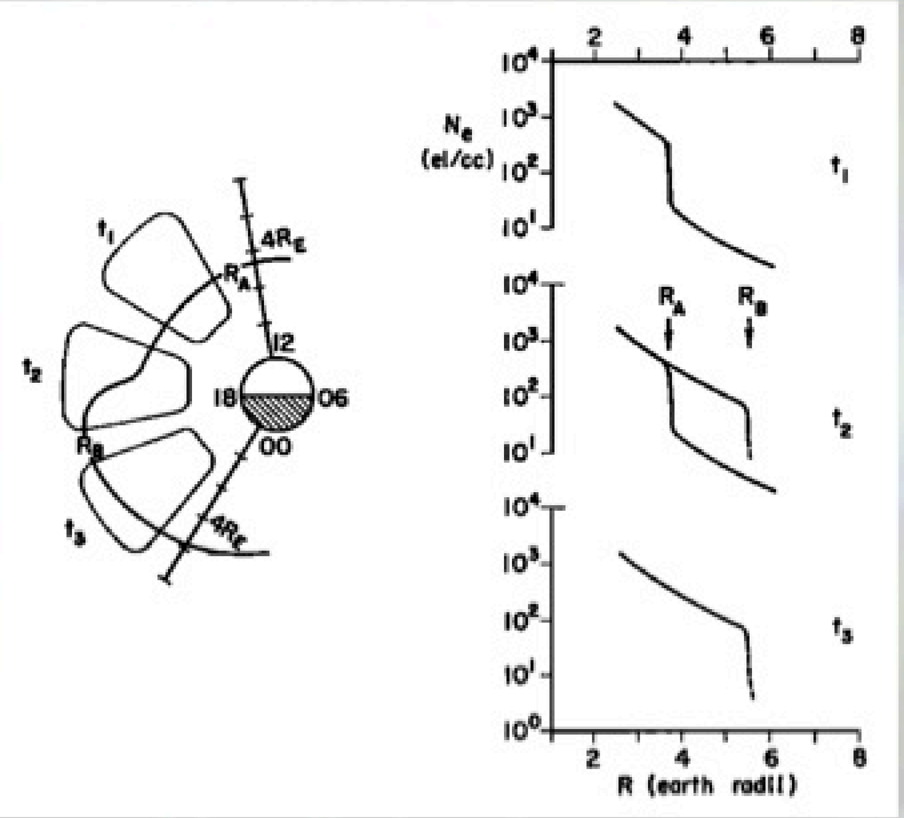
Discovery of the Plasmasphere

1960s and early 1970s via whistlers and OGO-5

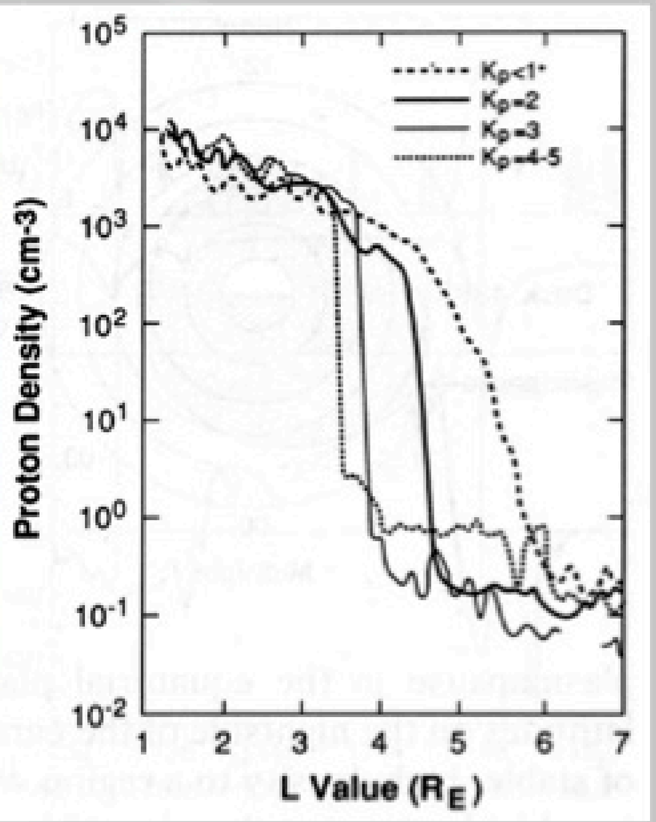
Plasmasphere Existence, Density, Shape, & Dynamic Behavior



plasmapause and cold plasma density [e.g. *Carpenter* 1965; *Chappell+* 1970]



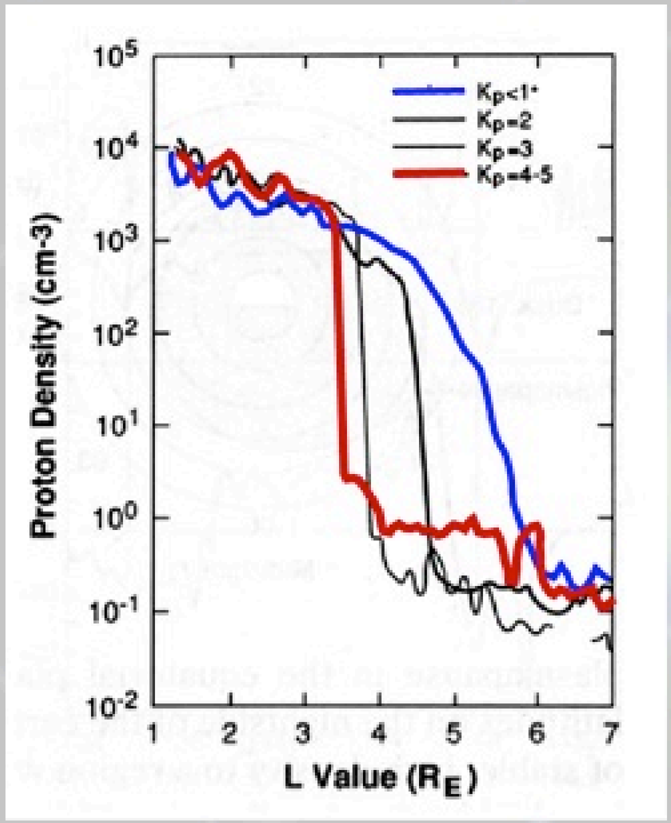
global shape of plasmasphere [e.g. *Carpenter* 1970; *Chappell+*, 1971]



plasmapause versus activity [e.g. *Chappell+* 1970]

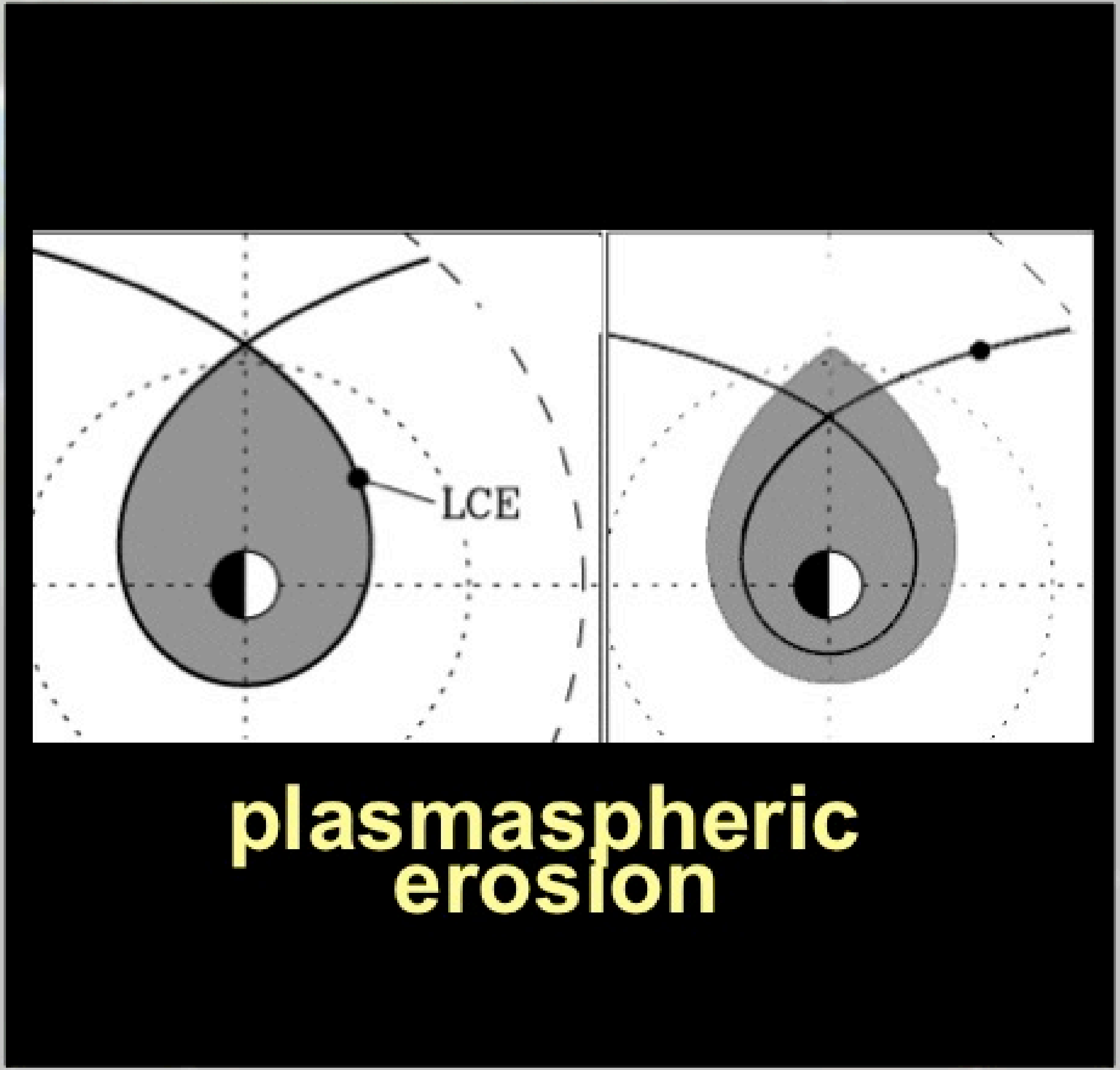
Plasmasphere Erosion: Pseudo-Static View

For many years pseudo-static ("before" ➔ "after") view prevailed



plasmapause versus activity [*Chappell*+ 1970]

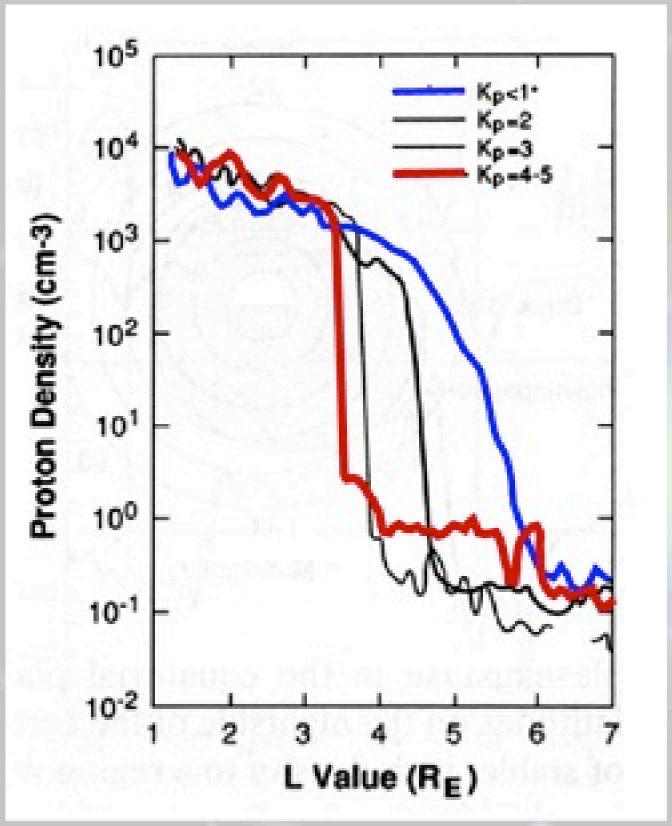
$$\Phi = -E_0 r \sin\varphi - \frac{\omega_E B_0 R_E^3}{r}$$



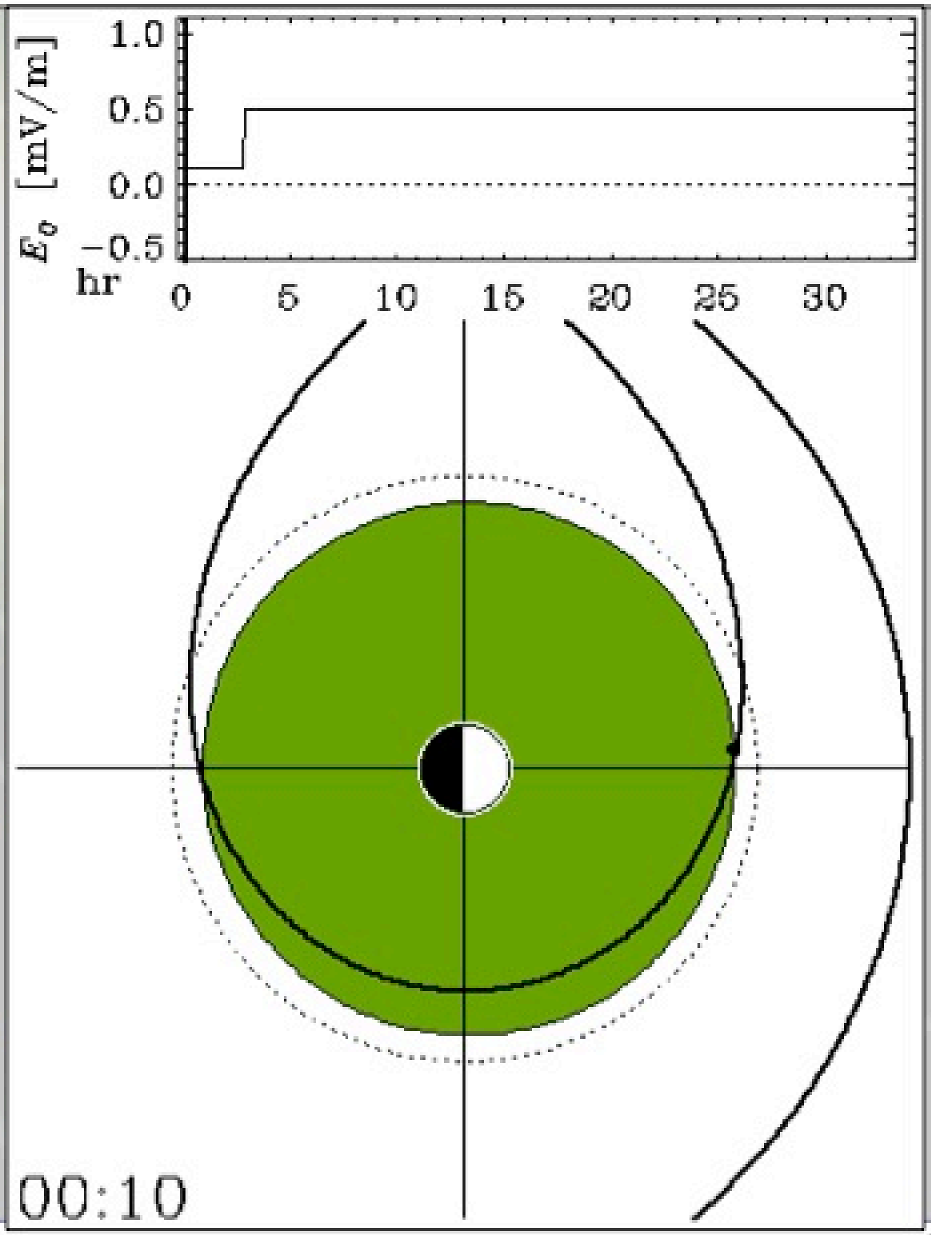
Plasmasphere Erosion: Dynamic View

<u>Reality</u>: New ppause formation takes *many hours* (dep. on MLT)

$$\Phi = -E_0 r \sin\varphi - \frac{\omega_E B_0 R_E^3}{r}$$



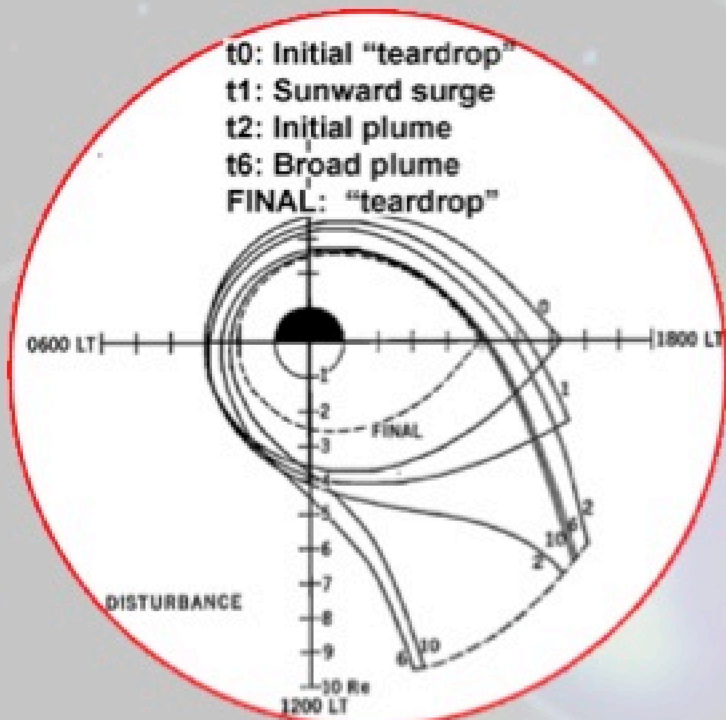
plasmapause versus activity [*Chappell*+ 1970]



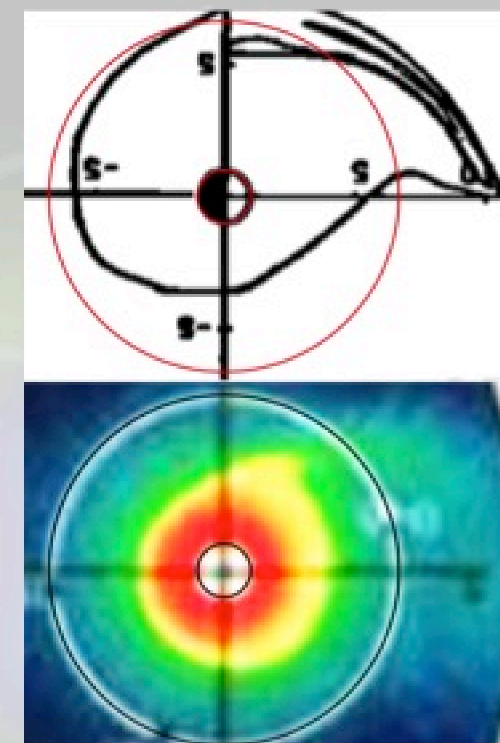
PLUME:
key feature

Plasmasphere Erosion: Dynamic View

Decades of Models: predict dynamic erosion process—with plumes



test particle sims:
sunward surge + plume
[*Grebowsky* 1970; *Chen+* 1975]

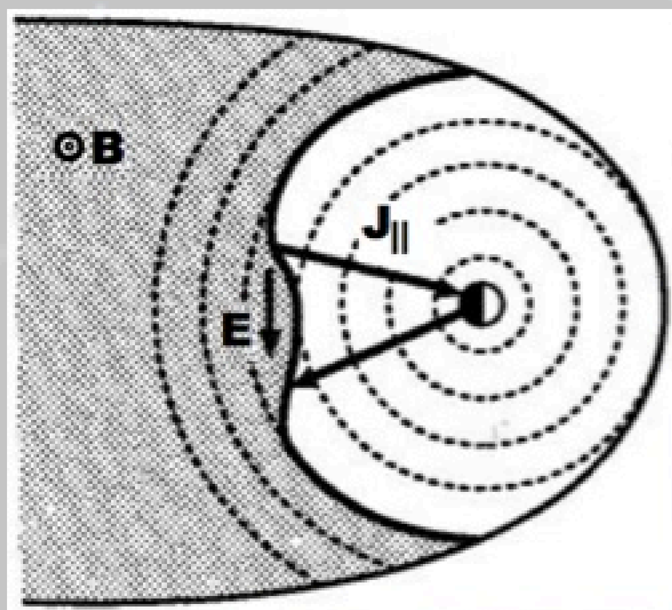


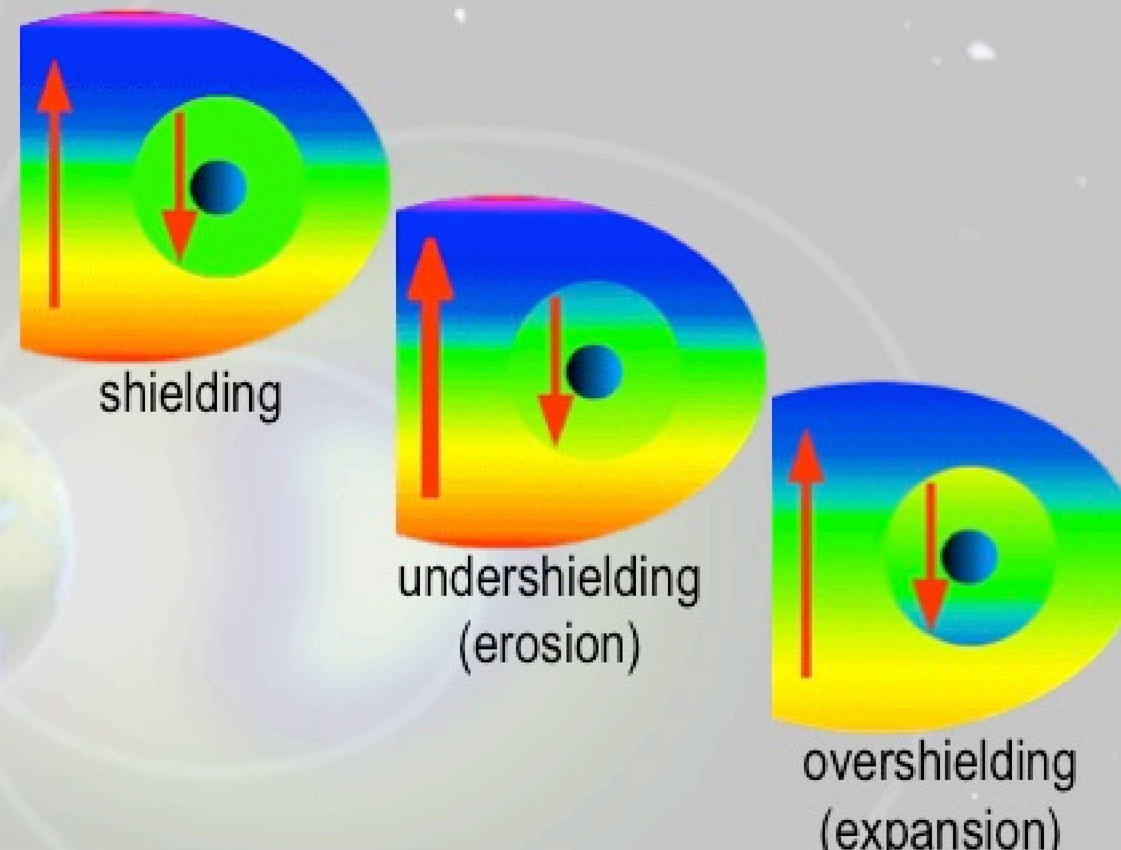
RCM and MSM:
plume evolution during convection
[*Spiro+* 1981; *Weiss+* 1997; *Lambour+* 1997]

...nonetheless, the quasi-static view persisted

Shielding and the "Quiescent Plasmasphere"

Concept of shielding unintentionally fostered a quasi-static picture





Shielding E-field

- inner edge of plasma sheet
- need time to set up R2 currents
  - night side: takes minutes
  - day side: takes hours

  [*Jaggi & Wolf* 1973]

Time Dependent Shielding:

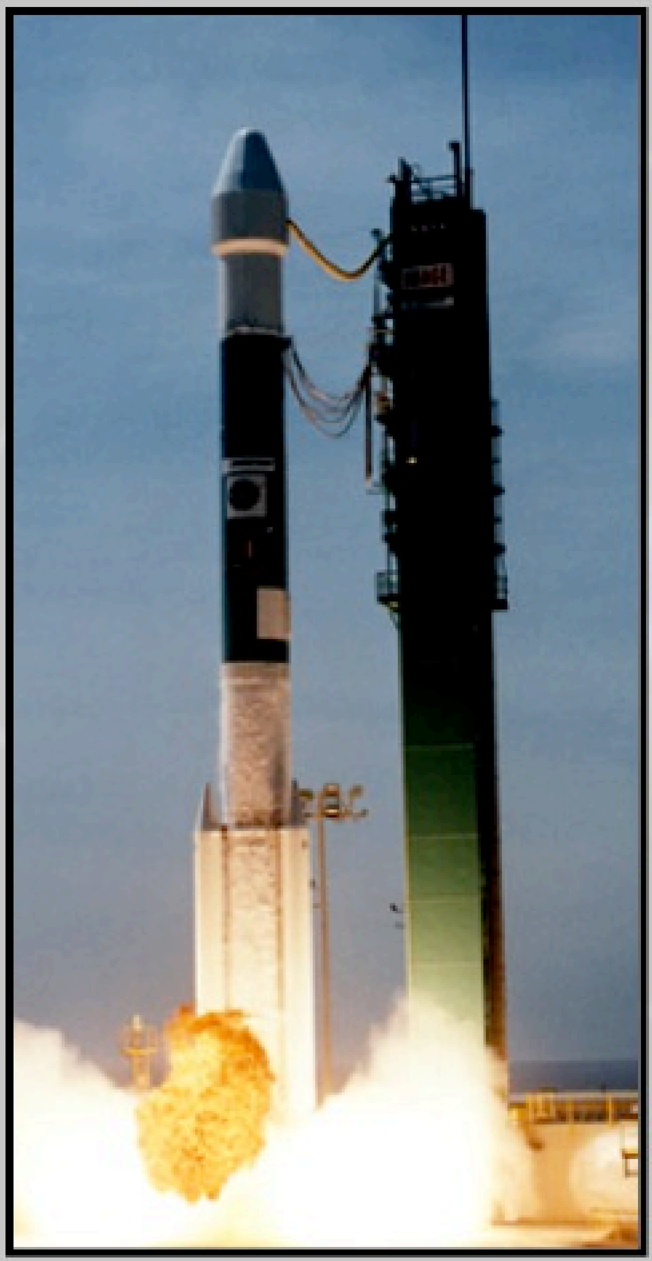
Shielding set-up time ~15–60 min

[*Kelley*+ 1979; *Goldstein*+ 2002; 2003b]

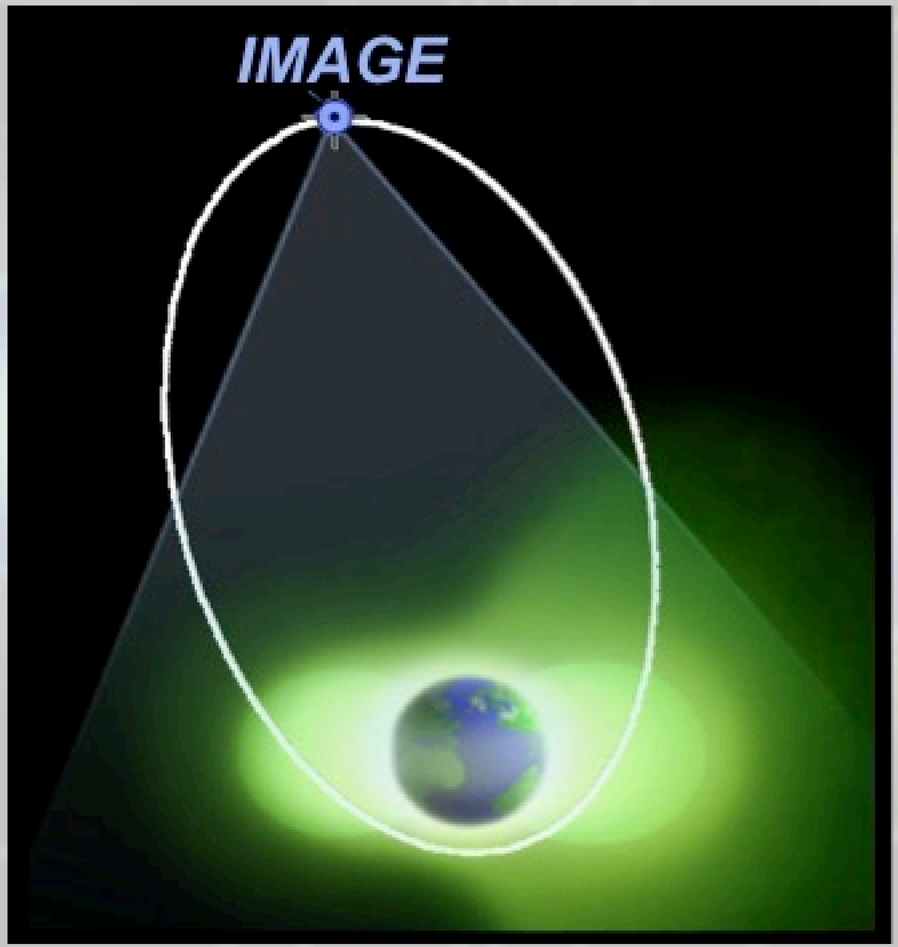
=> Slower than solar wind fluctuations

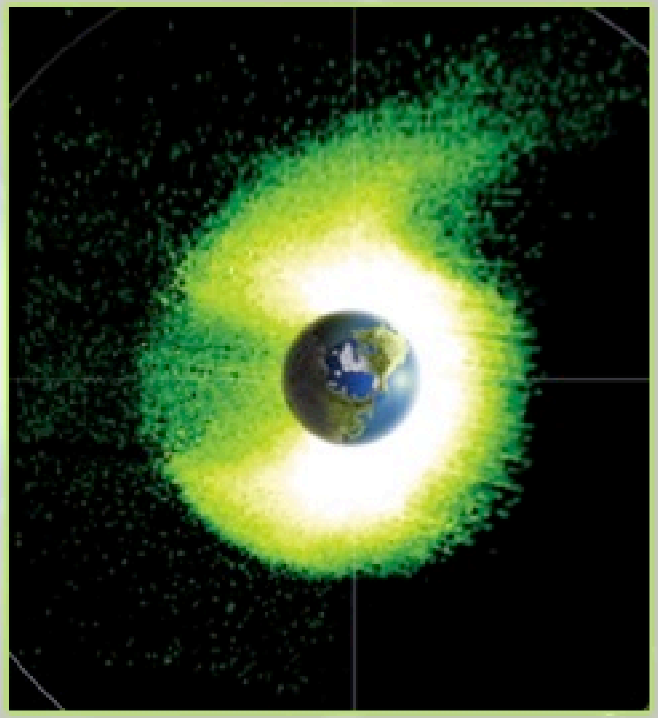
...nonetheless, the "quiescent" picture persisted; plasmasphere was widely believed to be "well shielded".

The IMAGE Mission:
dawn of the era of the dynamic plasmasphere



March 25, 2000
Vandenberg AFB

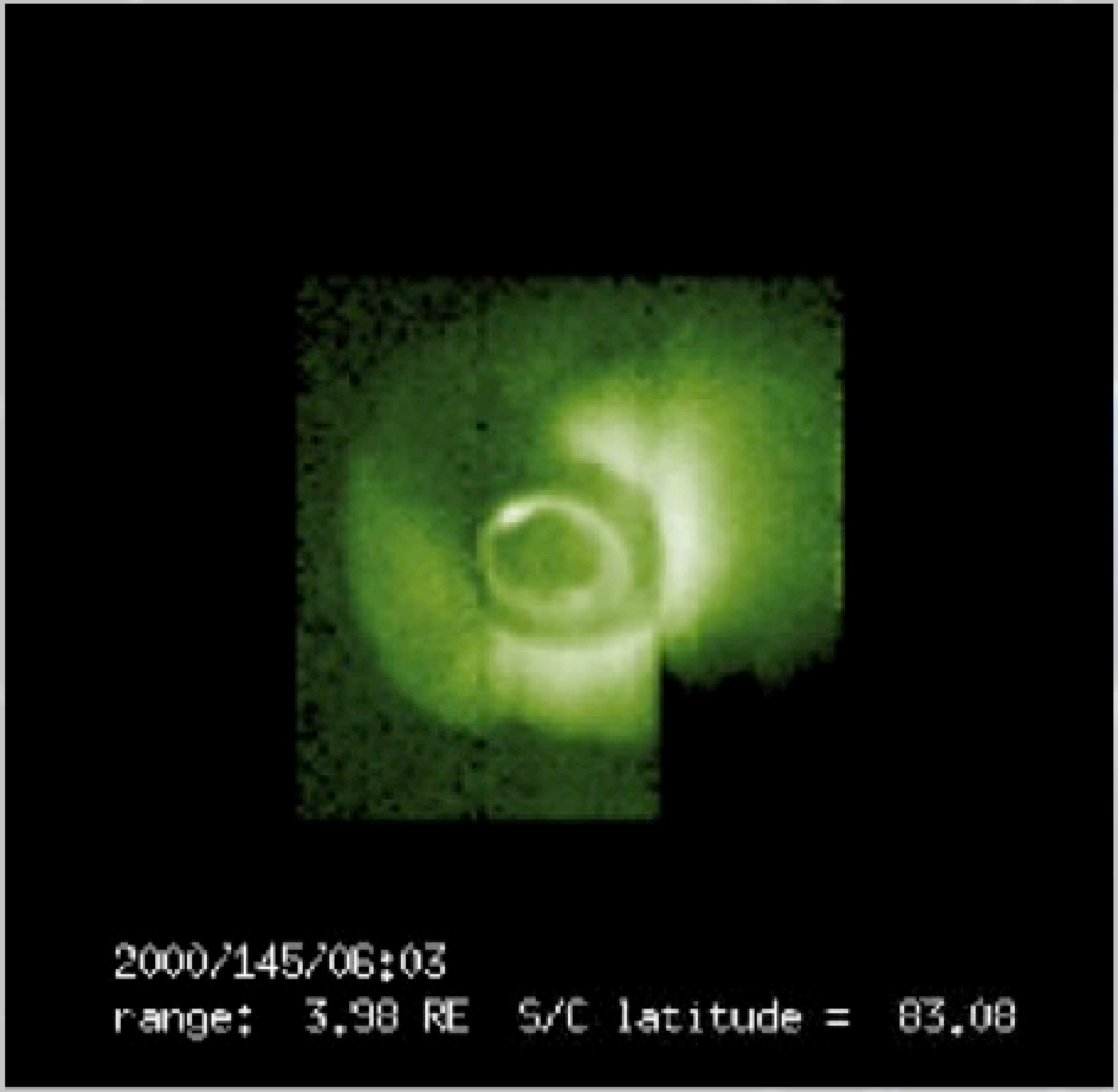


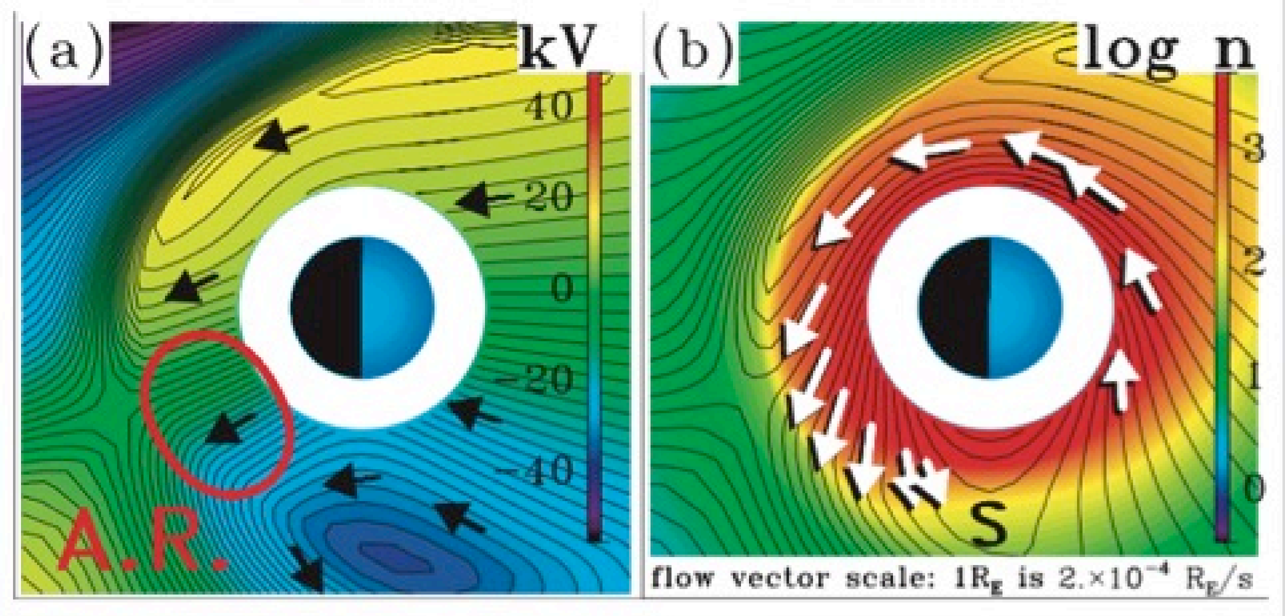


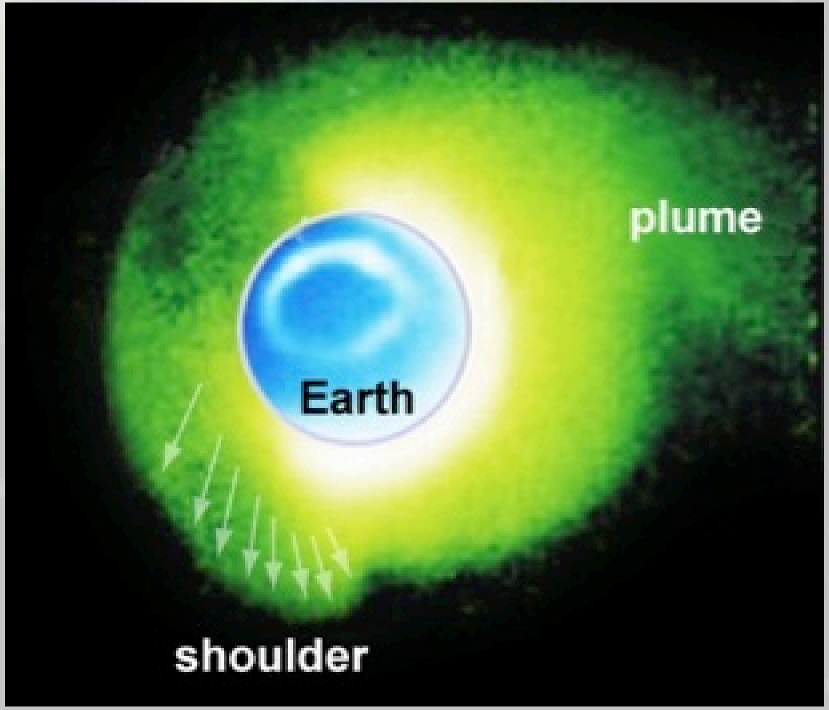
Extreme Ultraviolet (EUV) imager
[*Sandel*+ 2000; 2001; 2003]

Plasmaspheric Shoulder

evidence of time dependent shielding



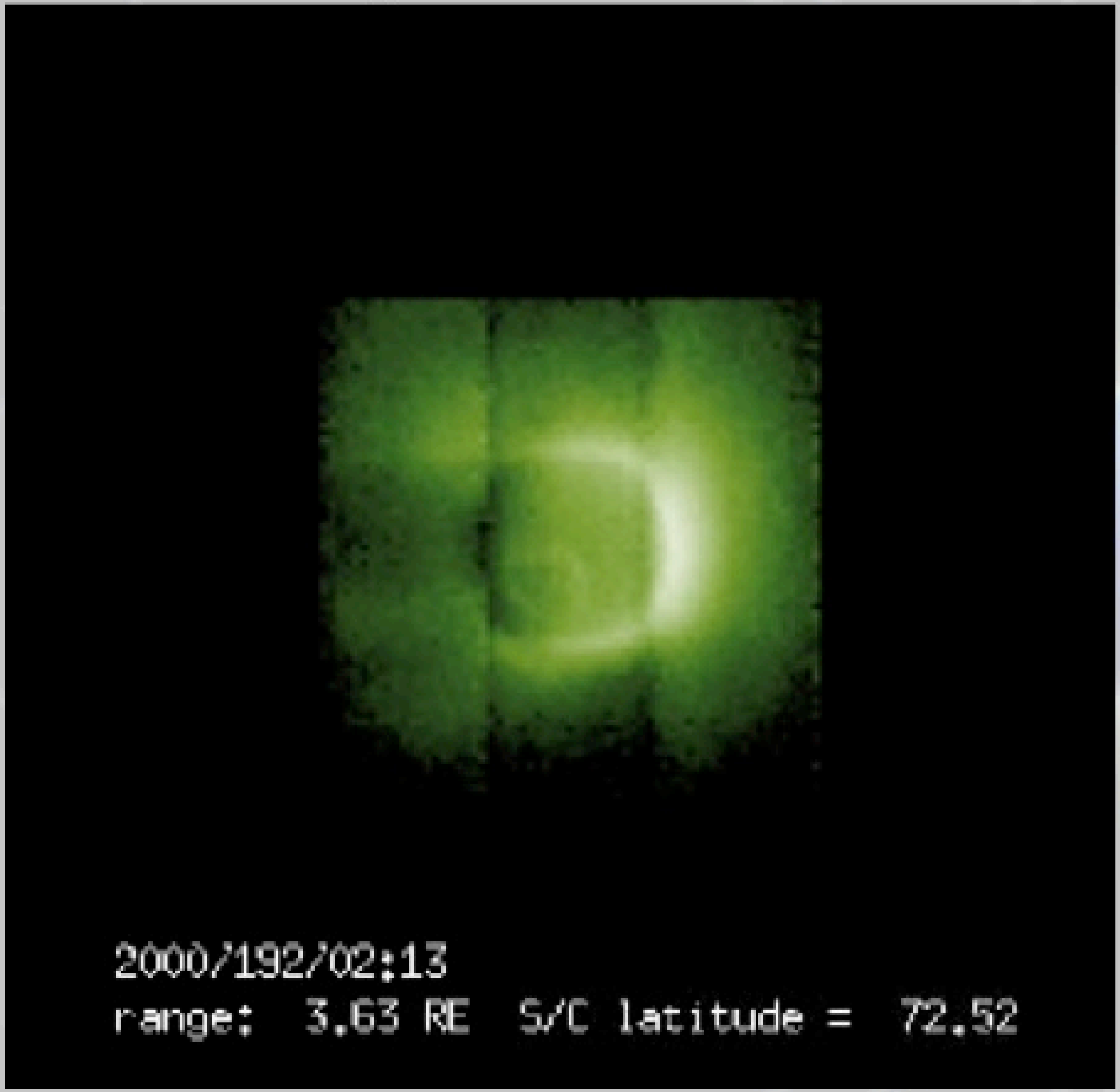


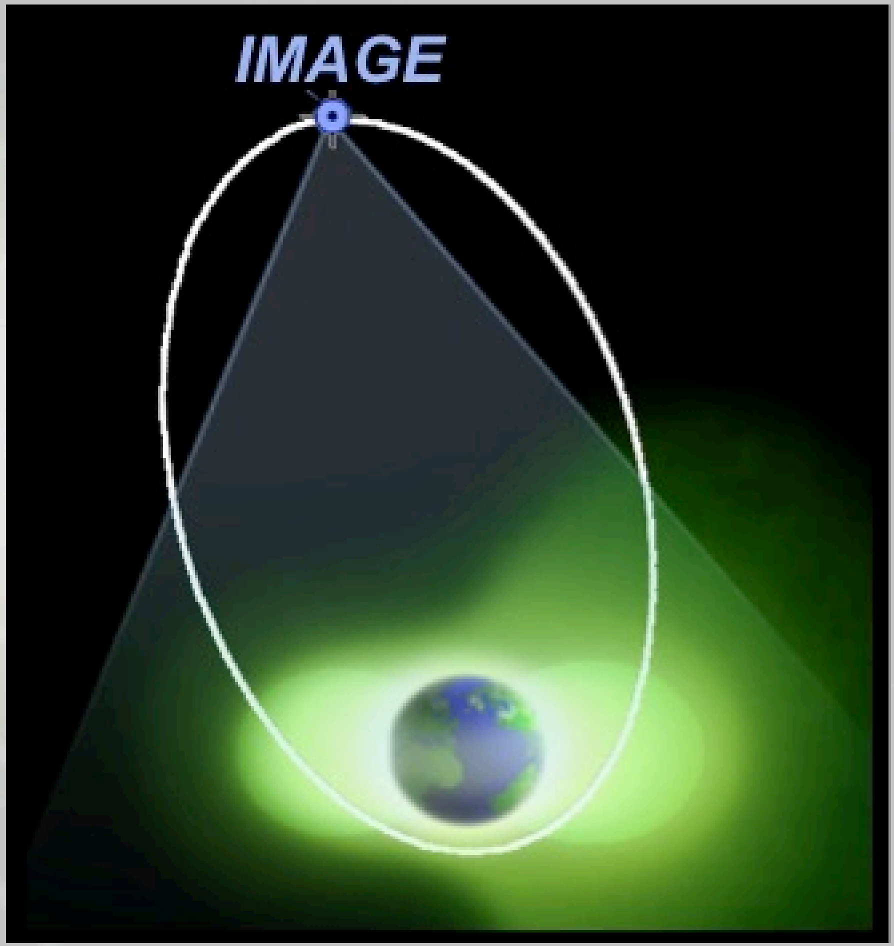


Plasmaspheric Shoulder
overshielding after northward IMF
(i.e., time-dep shielding)
[*Goldstein*+ 2002; 2003b]

Plasmaspheric Erosion

first global observation of the erosion process (undershielding)





10 July 2000

1st erosion event identified by IMAGE

[*Goldstein*+ 2003a]

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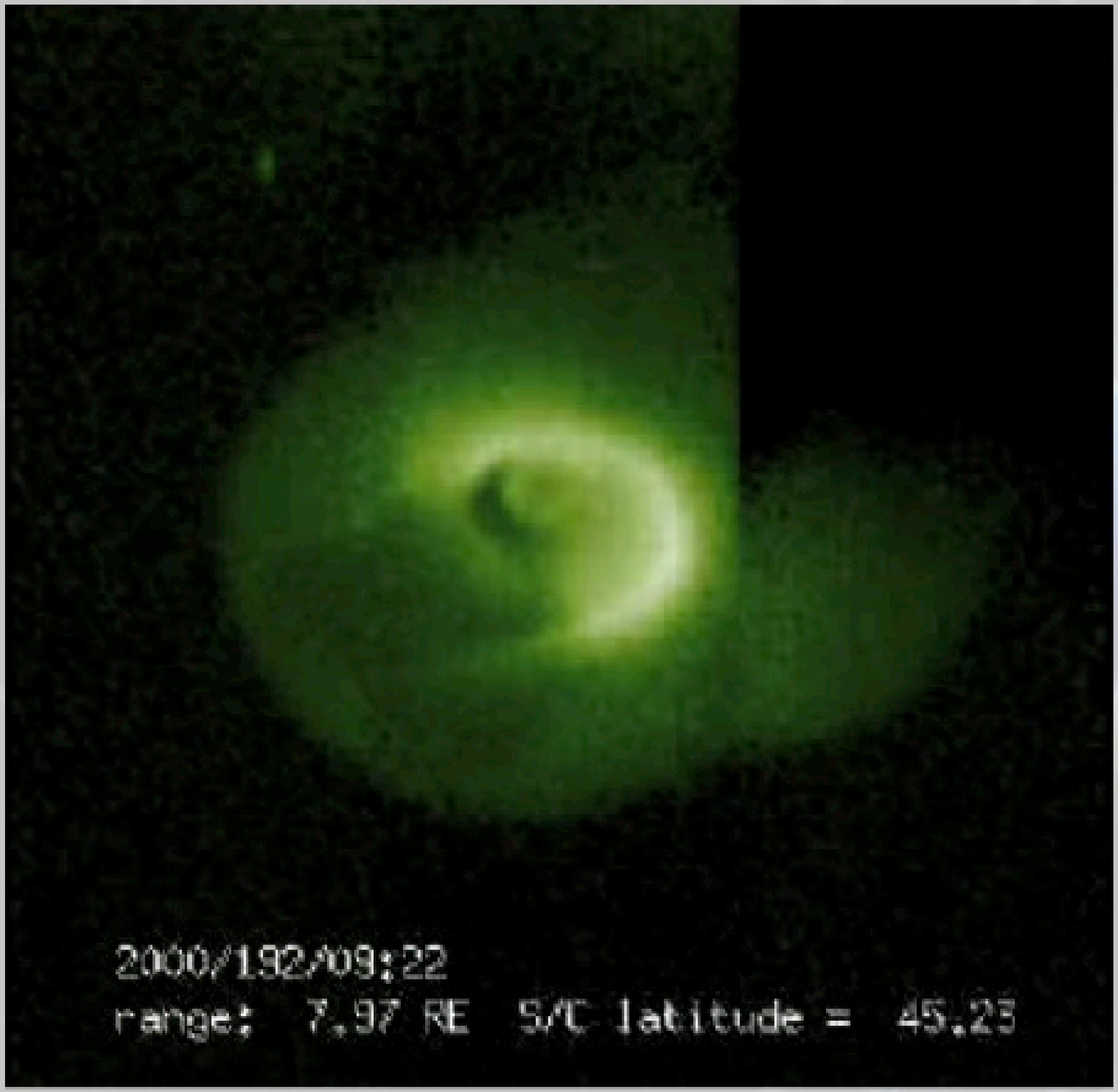

10 July 2000
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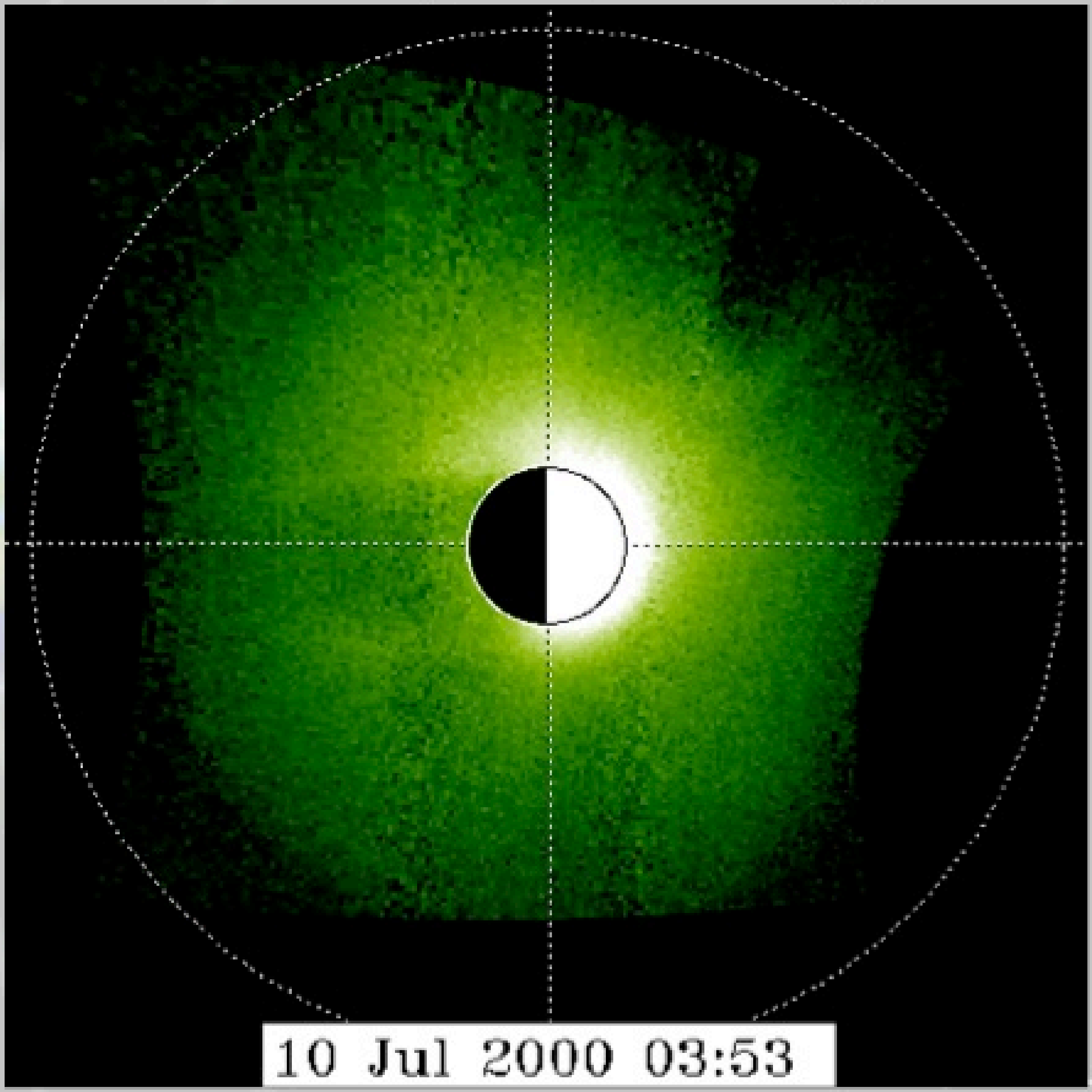
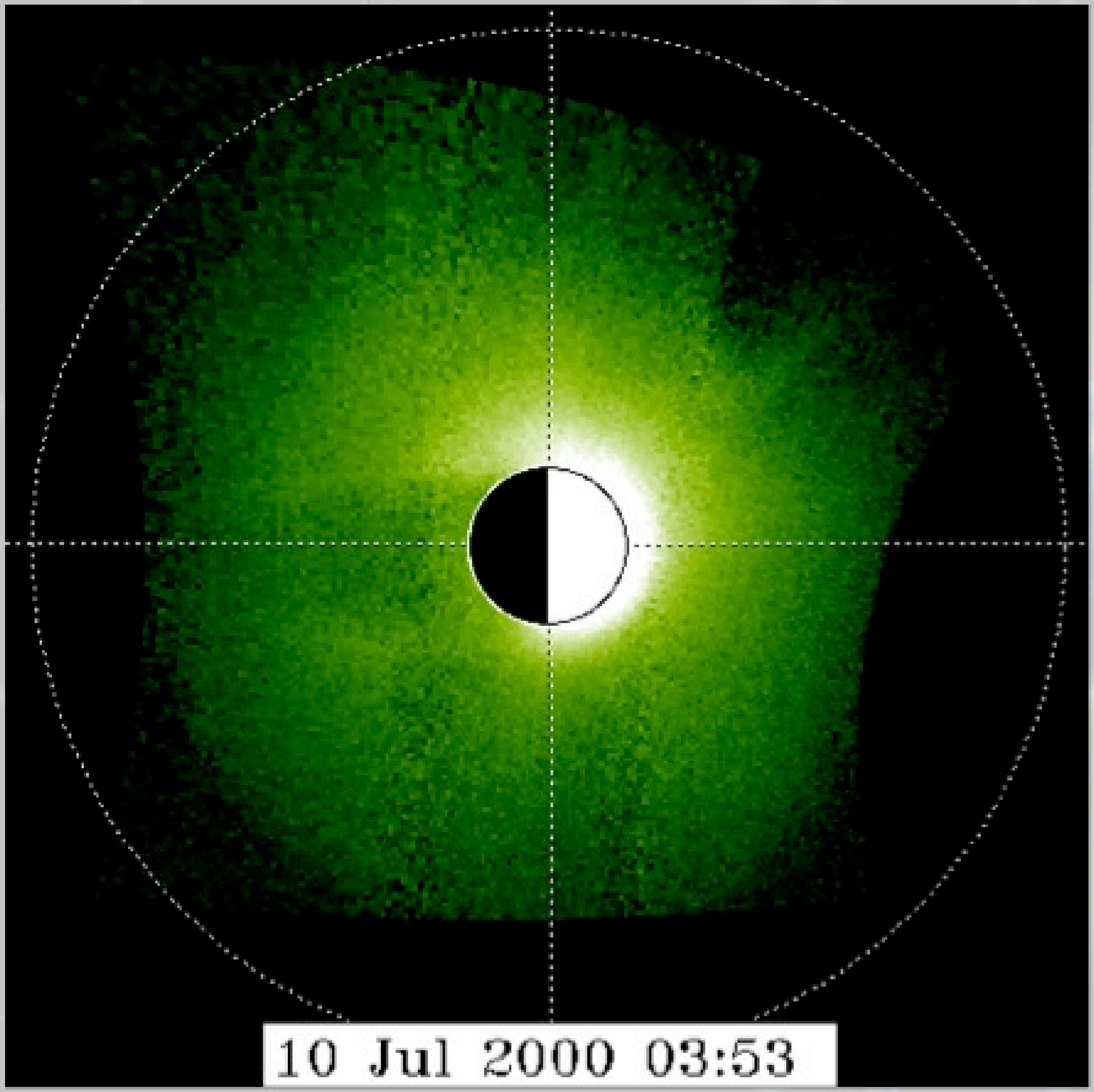


mapping to geomagnetic SM equator
⇒ real erosion
⇒ tens of tons of plasma removed

Plasmaspheric Erosion

first global observation of the erosion process (undershielding)



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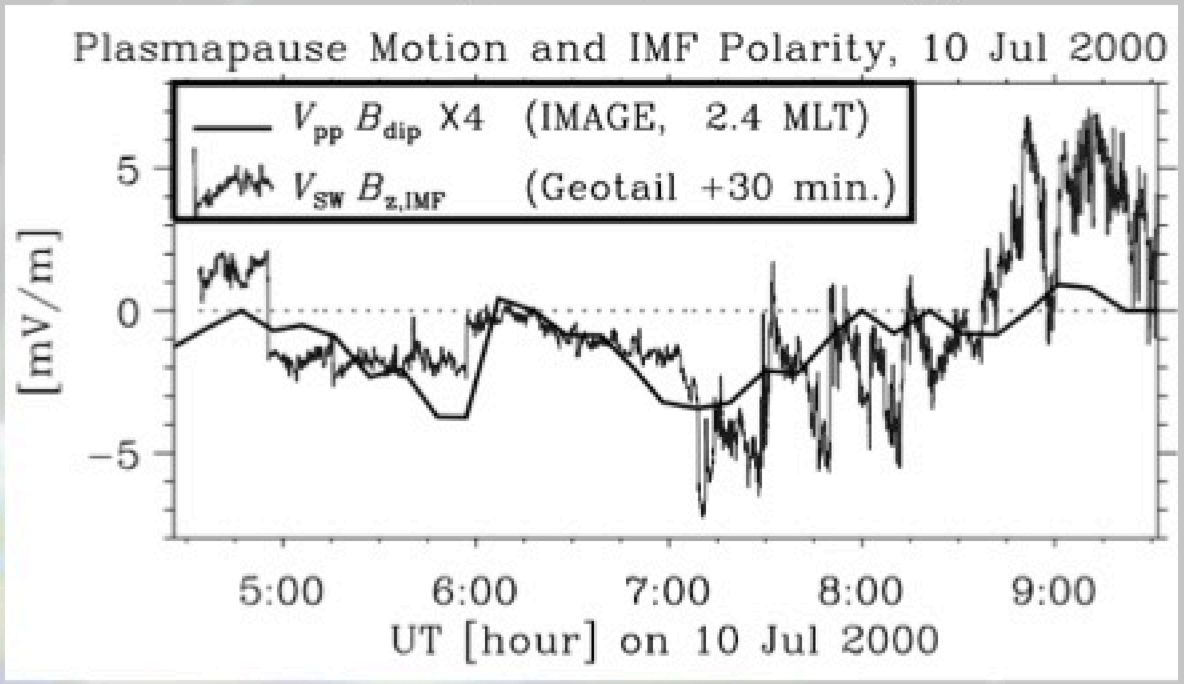
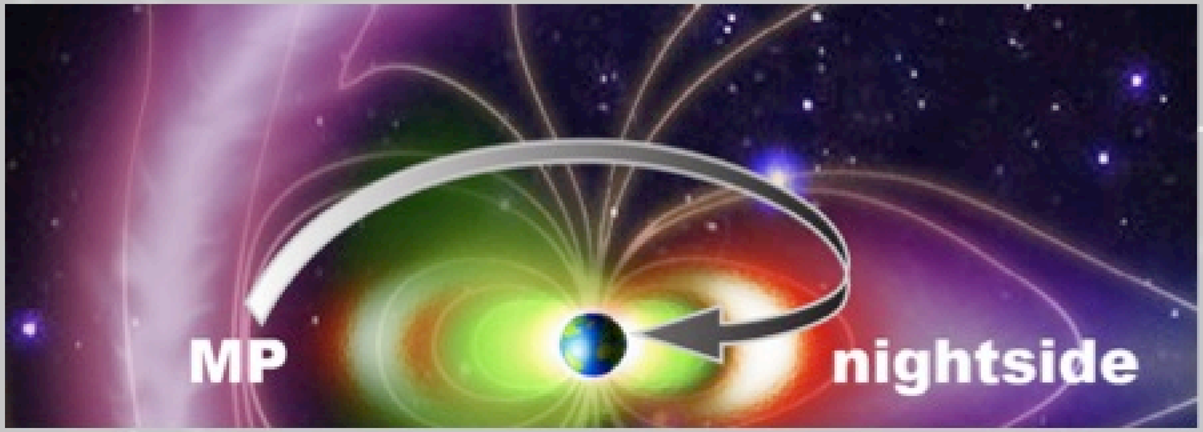


directly driven by IMF polarity changes

⇒ southward IMF: erosion

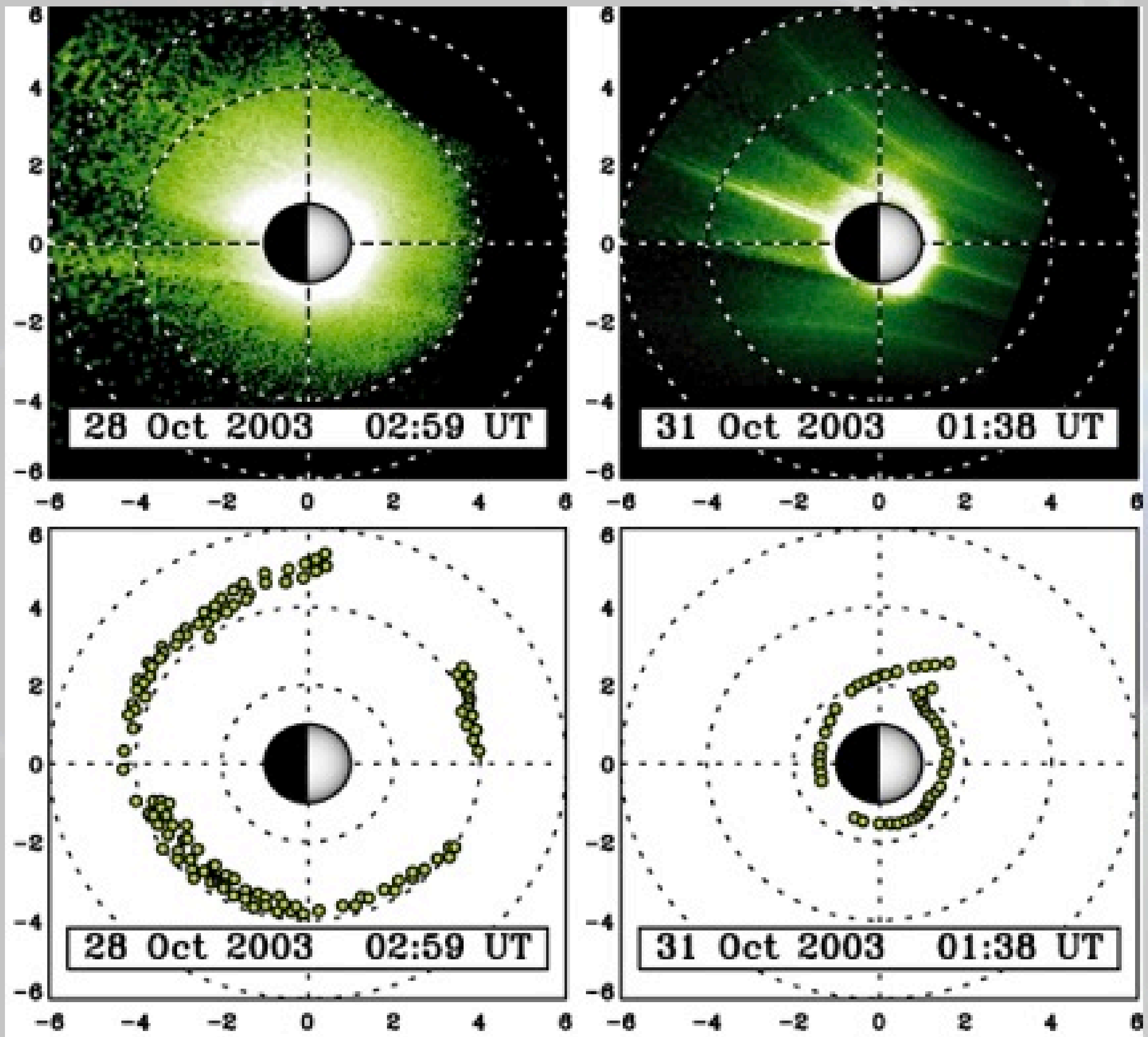
⇒ northward IMF: no erosion

⇒ 30 min MNP delay



Severe Plasmasphere Erosion

the end of the "quiescent" / quasi-static view of the plasmasphere



Quiet Plasmasphere (Pre-Storm) | Eroded Plasmasphere (Post-Storm)

31 Oct 2003 Hallowe'en storm

[*Baker*+ 2004]

plasmasphere was very severely eroded

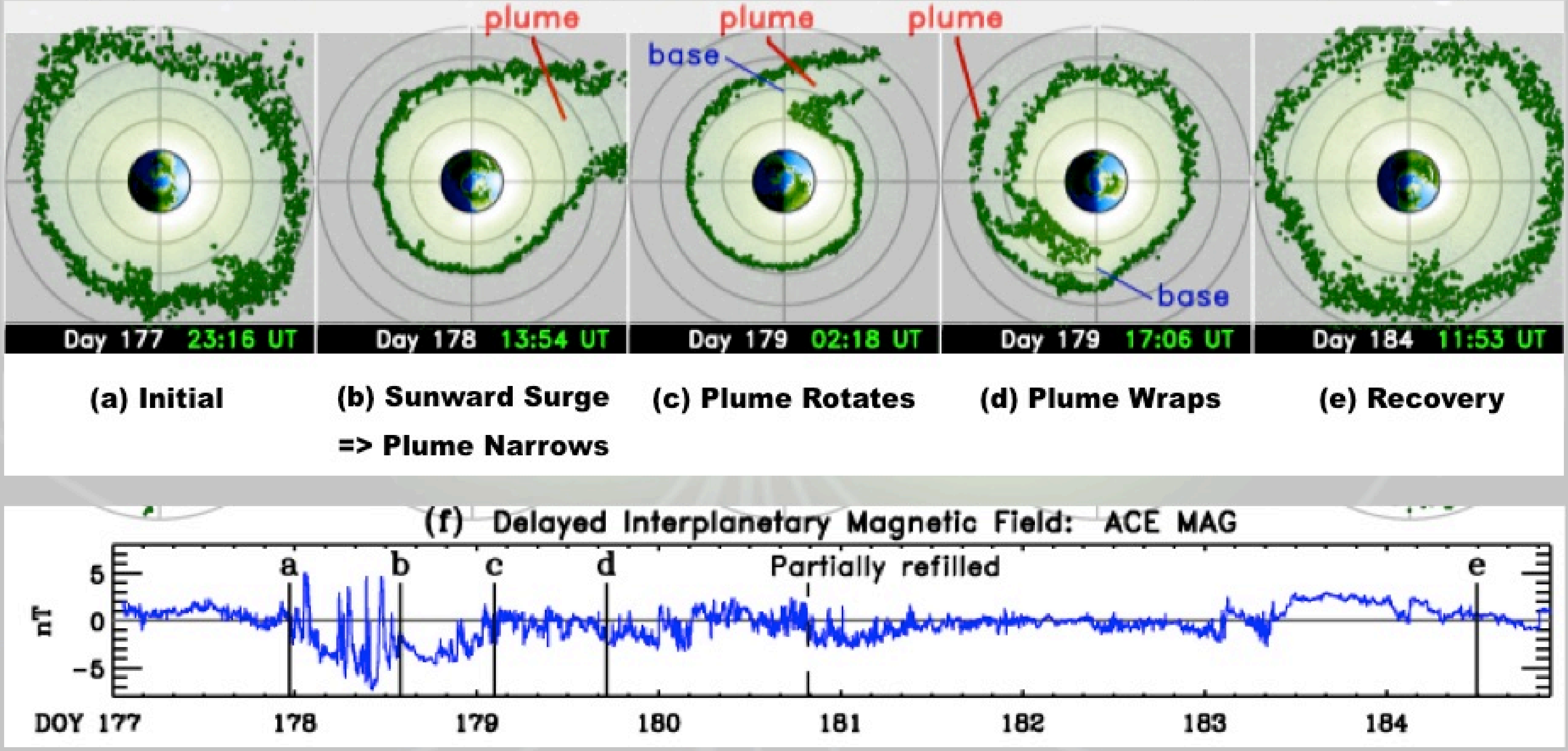
⇒ refuted "well-shielded plasmasphere"

⇒ cold plasma effect on relativistic e^-

Cycle of Erosion and Recovery

repeatable pattern of plasmasphere plume phases

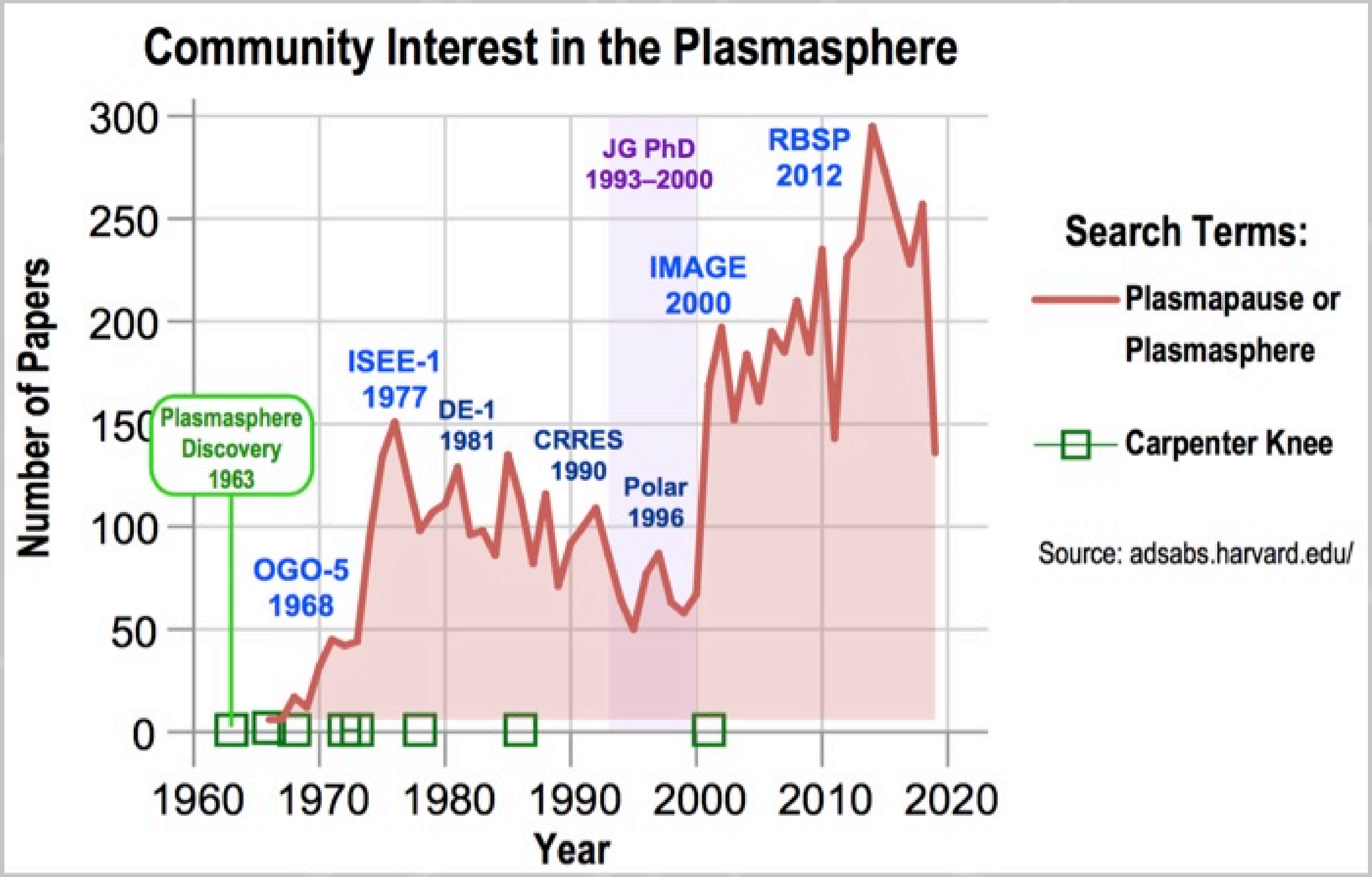
[*Spasojevic+* 2003; *Goldstein & Sandel* 2005; and many, many more]



Decades of modeling studies had predicted these plume phases. IMAGE was able to see them for the first time.

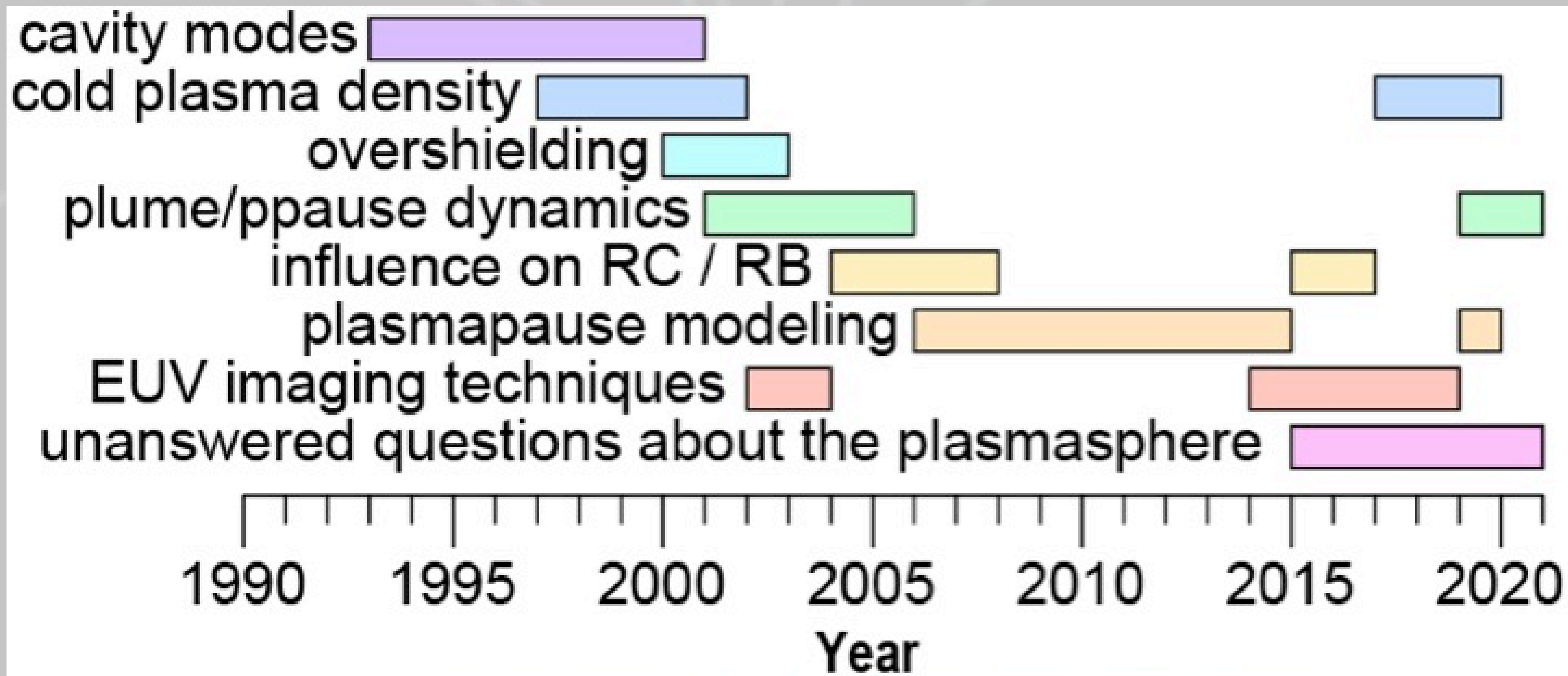
Cycle of Discovery and Rediscovery

interest in the plasmasphere has waxed and waned with time



My Plasmasphere Research

>25 years of work on plasmaspheric science



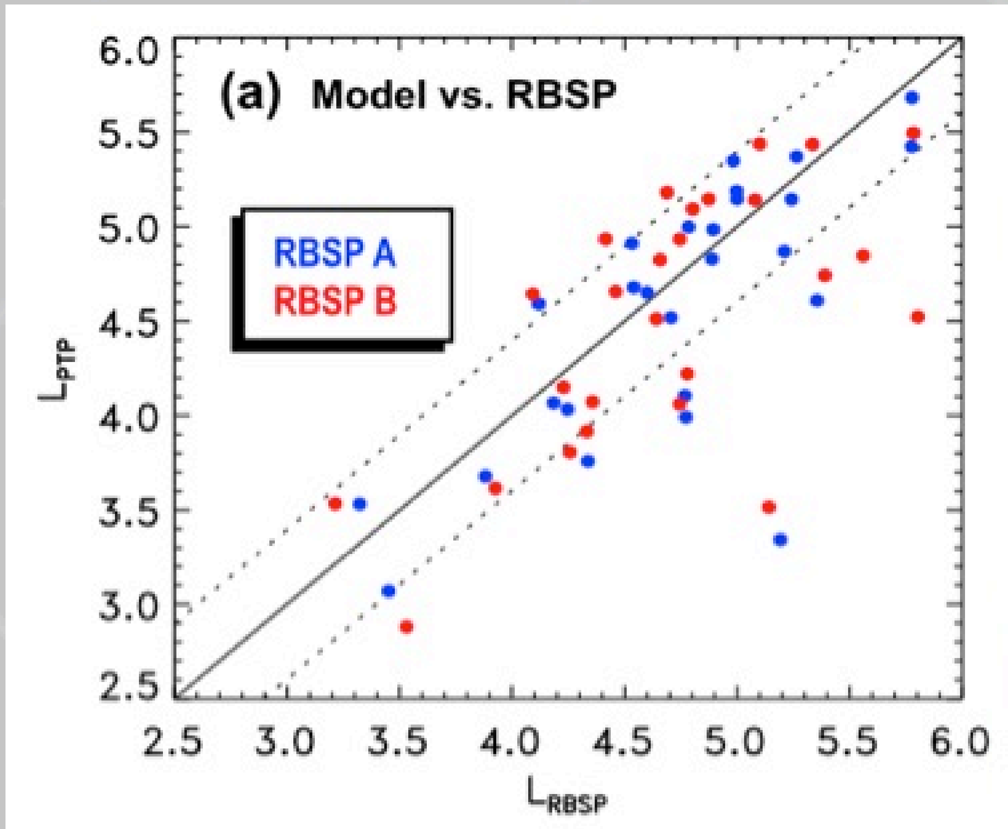
Recent Work

Goldstein+2014a,b	PTP simulations
Goldstein+2016	Influence on RB
Goldstein+2017	EUV backgrnd
Goldstein+2018	O+ EUV imaging
Goldstein+2019	epoch model
Goldstein+2019	DE-1/RBSP
Goldstein+2020	EUV timing

Plasmapause Test Particle (PTP) Simulations

support Van Allen Probes, understand residual structure

Goldstein+2014a,b PTP simulations

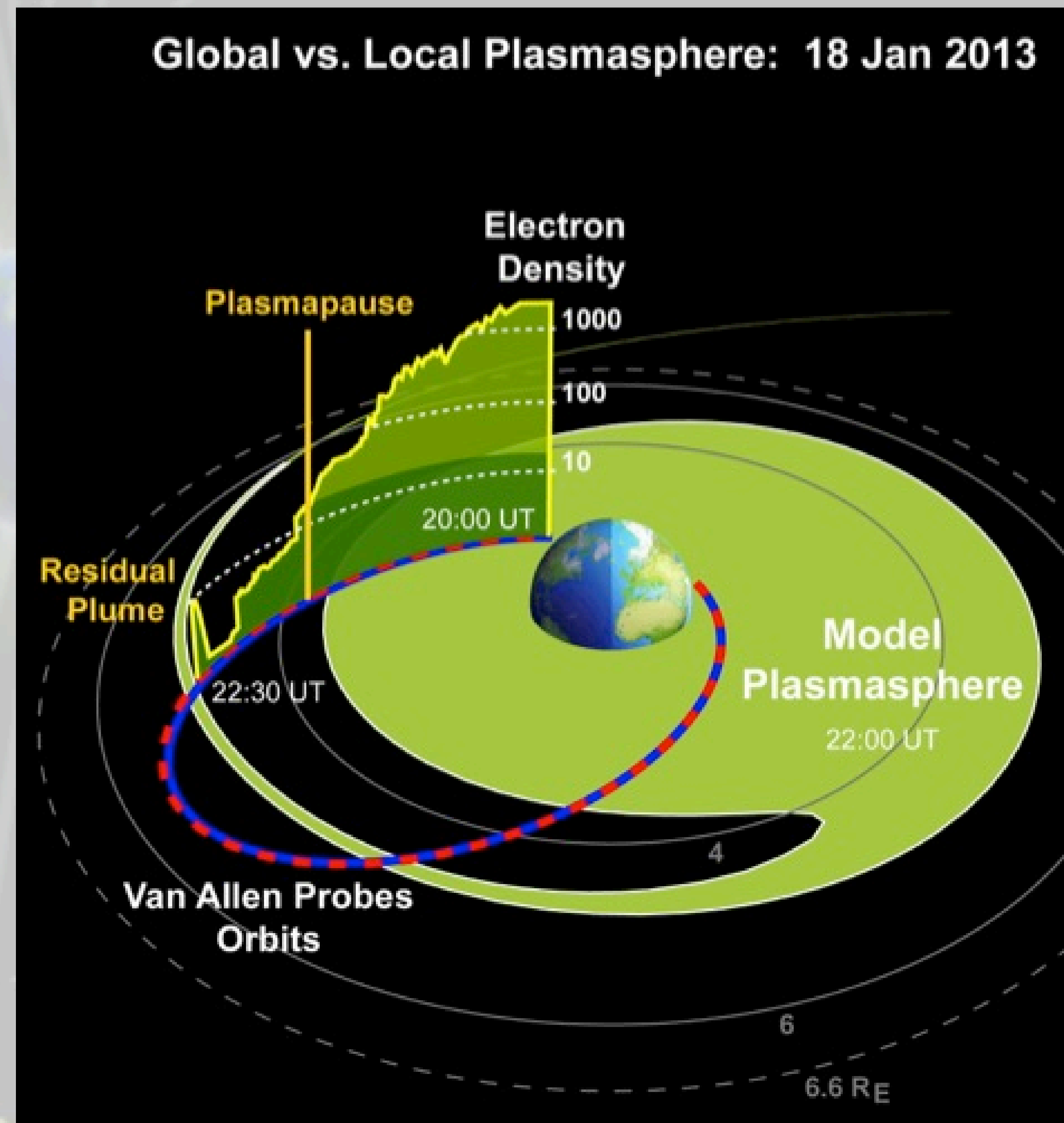


[*Goldstein*+ 2014b]

PTP compared to RBSP plasmapause

⇒ ΔL_P is $\pm 0.4 R_E$

⇒ residual plume ~32 hrs old



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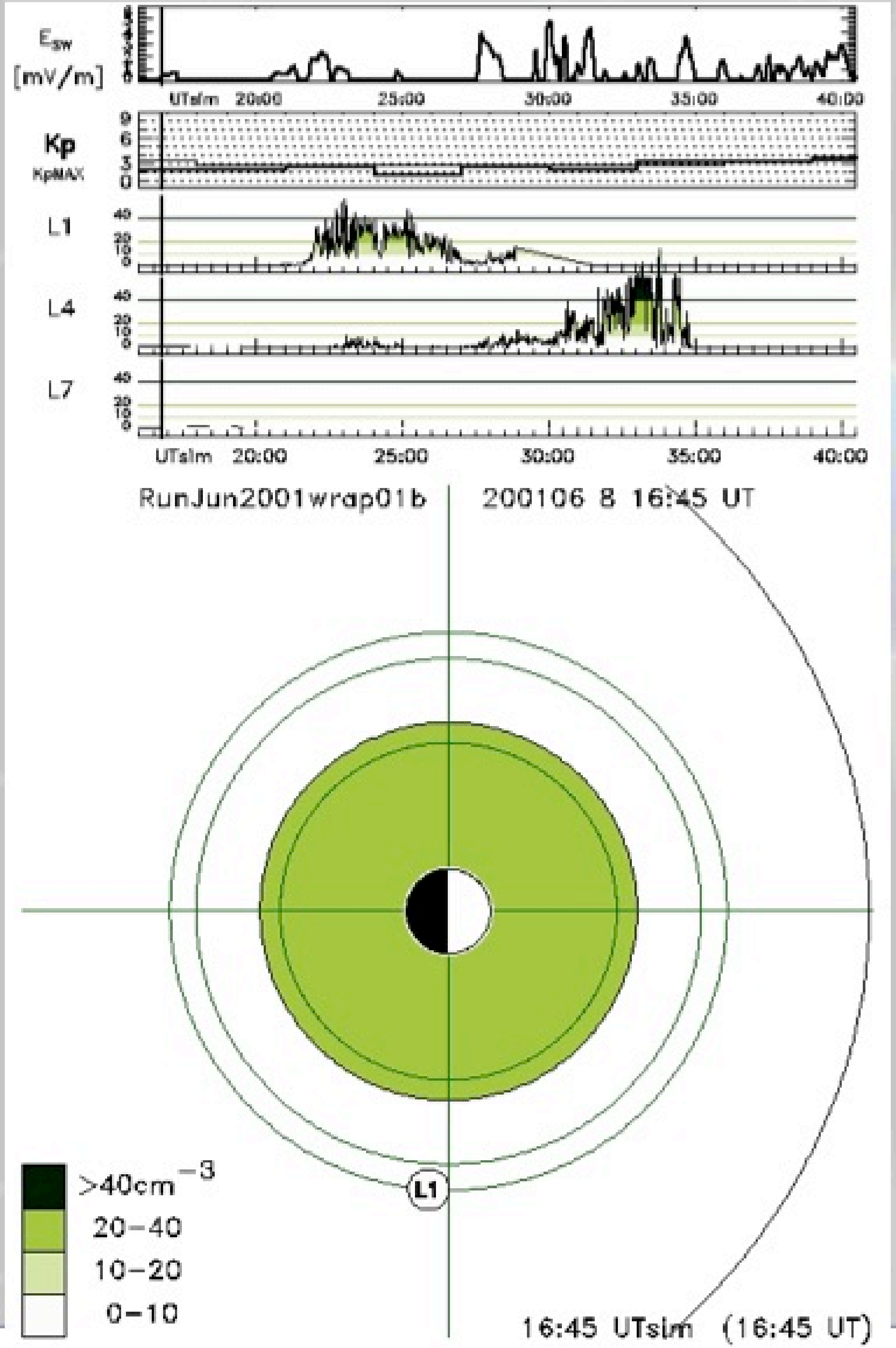
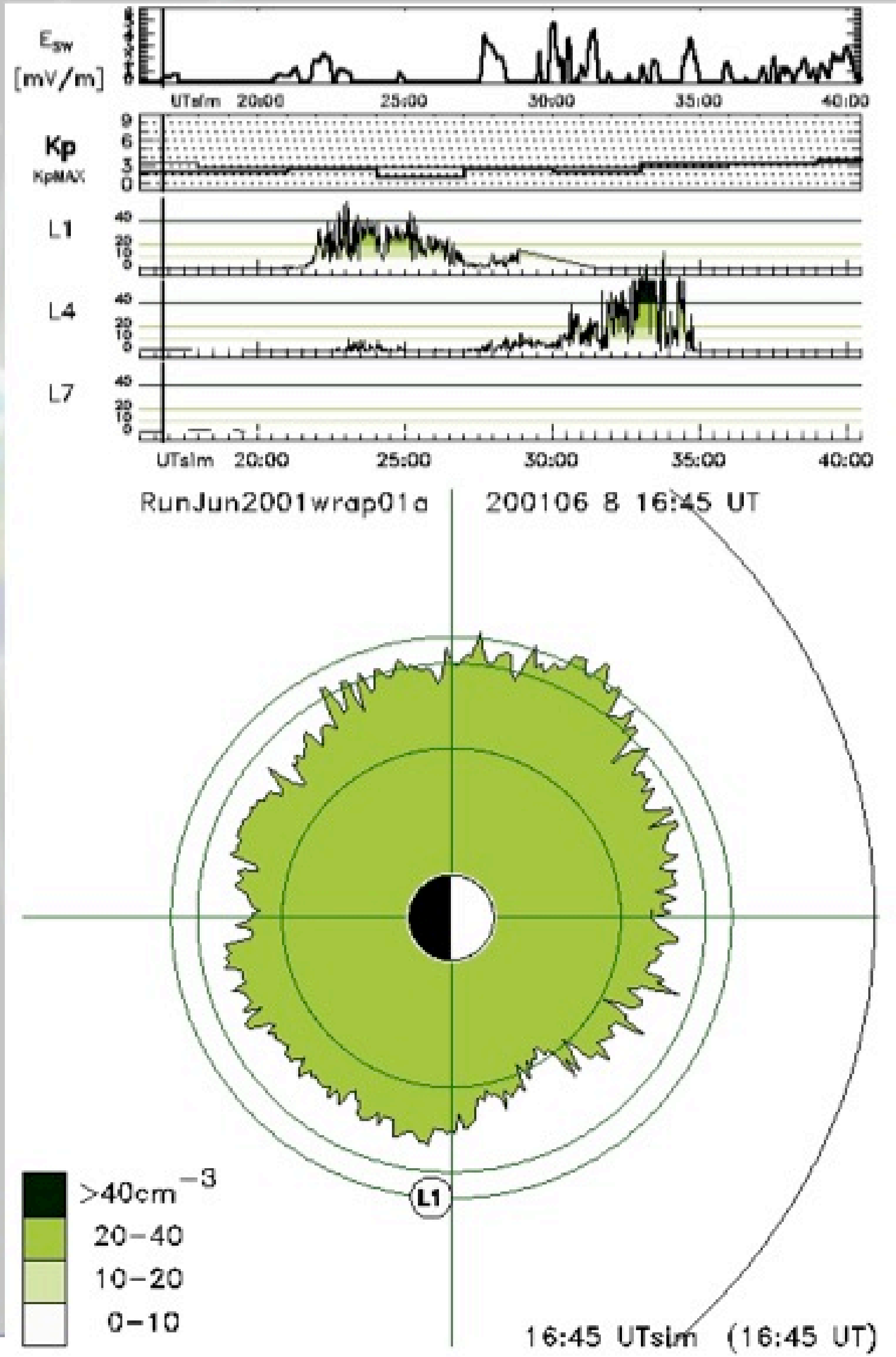
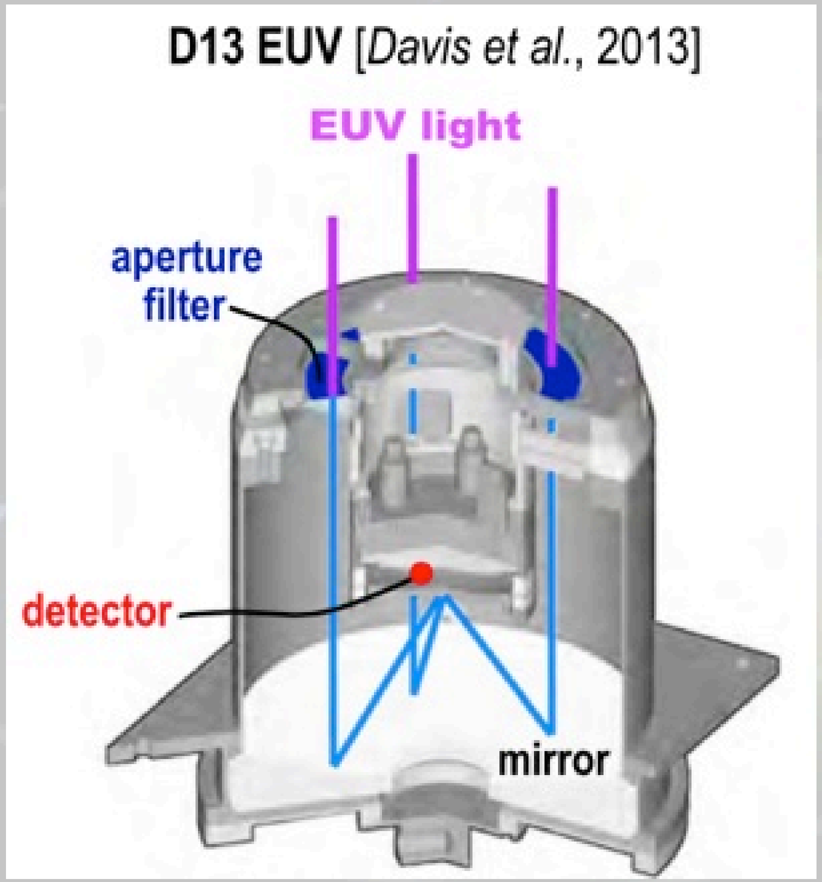




O+ EUV Imaging

design the next generation EUV imager to study the dense O+ torus

Goldstein+2018 O+ EUV imaging



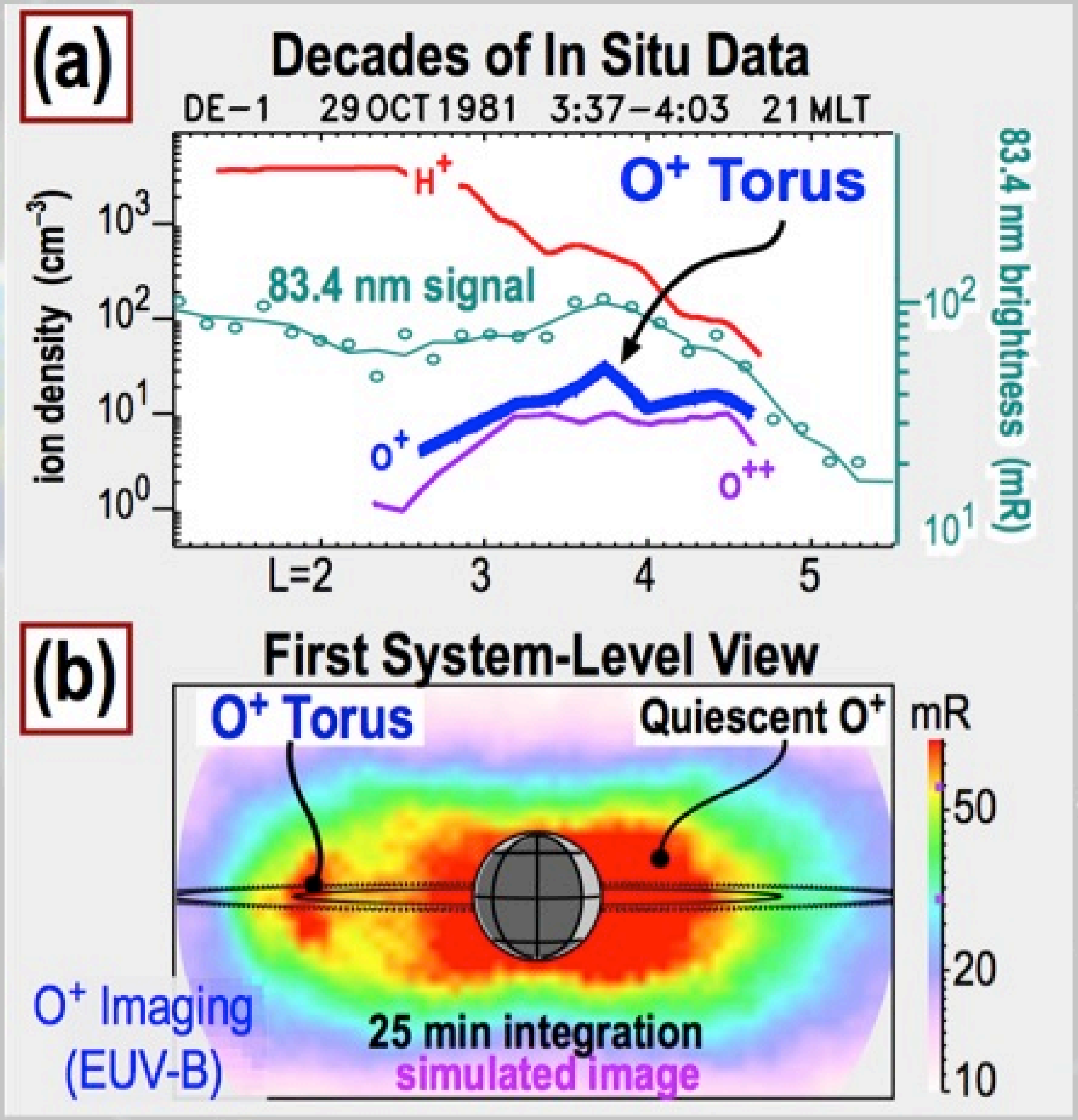
[*Goldstein*+ 2018]

Modify existing EUV camera with new mirror coating, new filter:

⇒ 83.4 nm EUV imaging of O^+ ions

⇒ Dense torus shape, formation

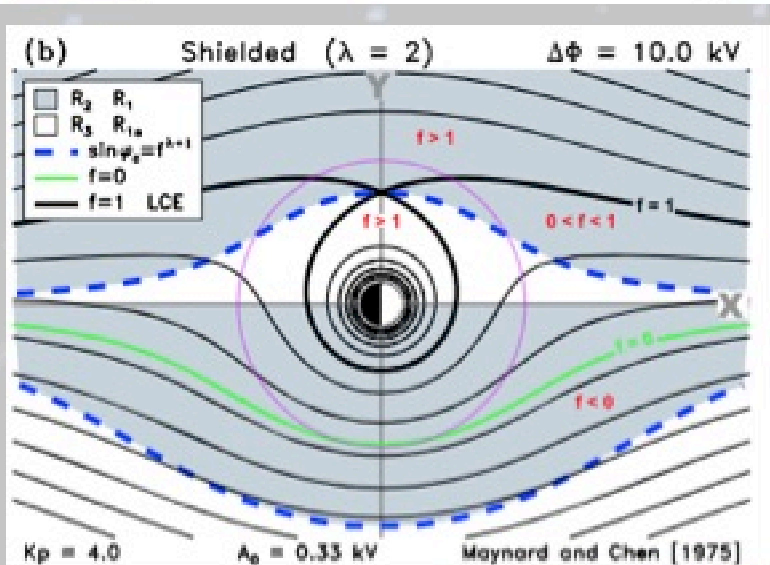
⇒ Possibly capture O^+ outflow

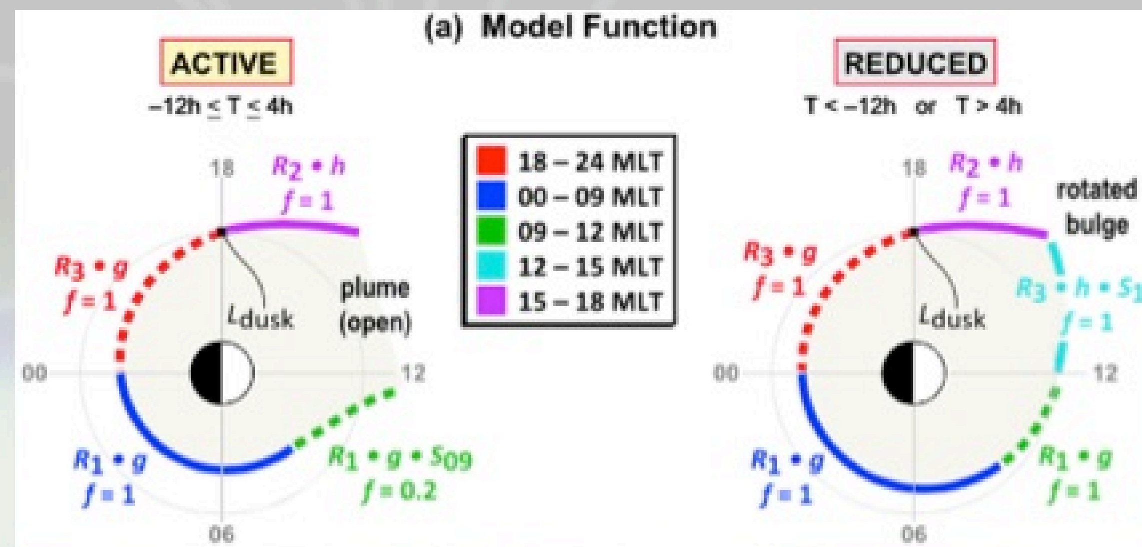


Epoch-Based Model of Plasmapause

analytical functions to predict plasmapause vs epoch time

Goldstein+2019 epoch model





[*Goldstein*+ 2019a]

Analytical plasmapause model

⇒ Volland-Stern equipotentials are basis functions

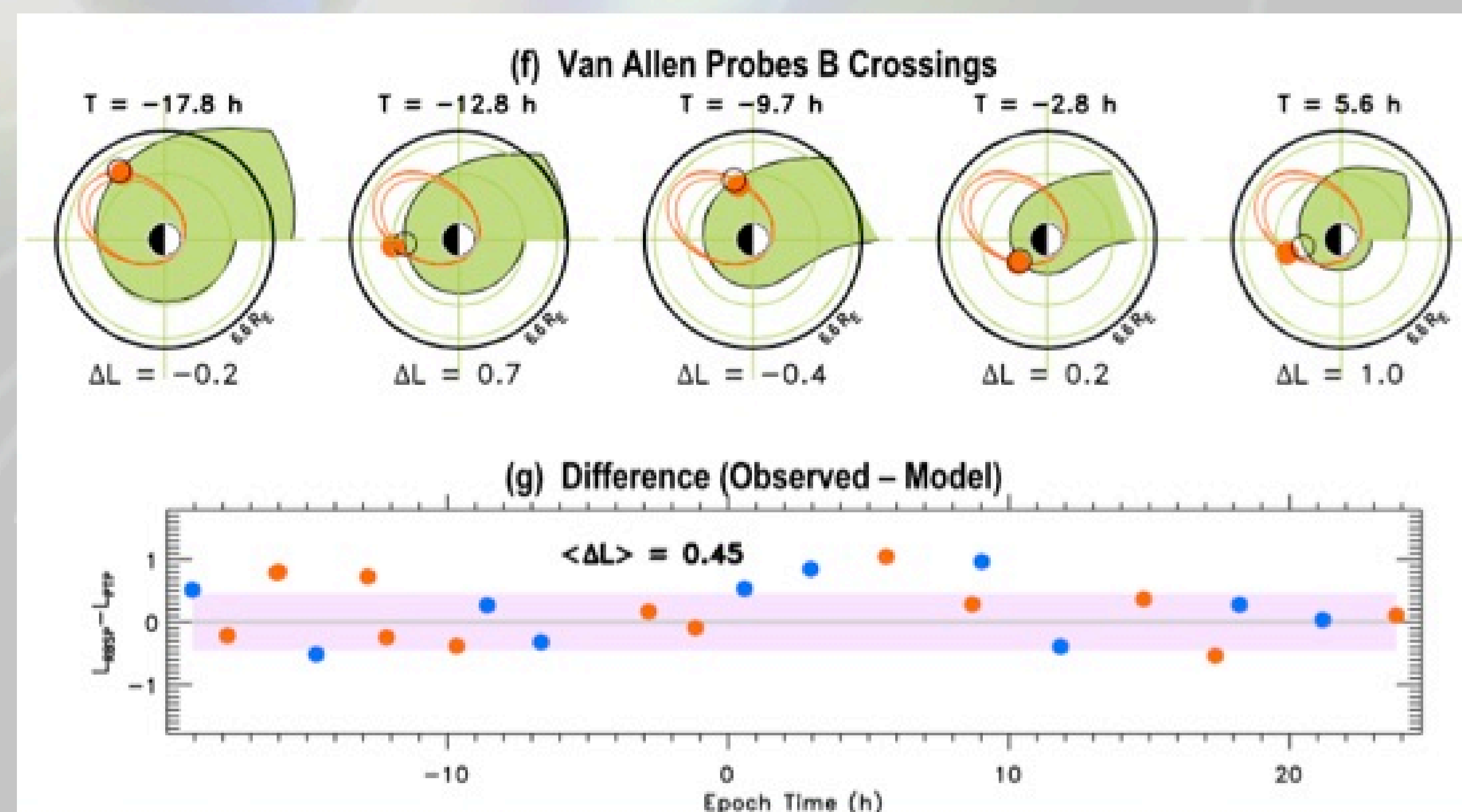
⇒ ***First analytical model with plumes***

⇒ Active vs. Reduced cases

⇒ Moderate vs Strong storms

⇒ RBSP ppause: ΔL~0.45

⇒ LANL plumes: ΔS~0.8R_E.



Temperature Dependence of Cold Ion Composition

understand ion transport, calibrate RBSP HOPE type ion data

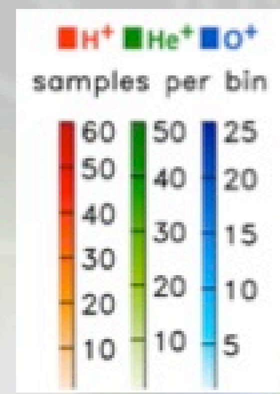
Goldstein+2019 DE-1/RBSP

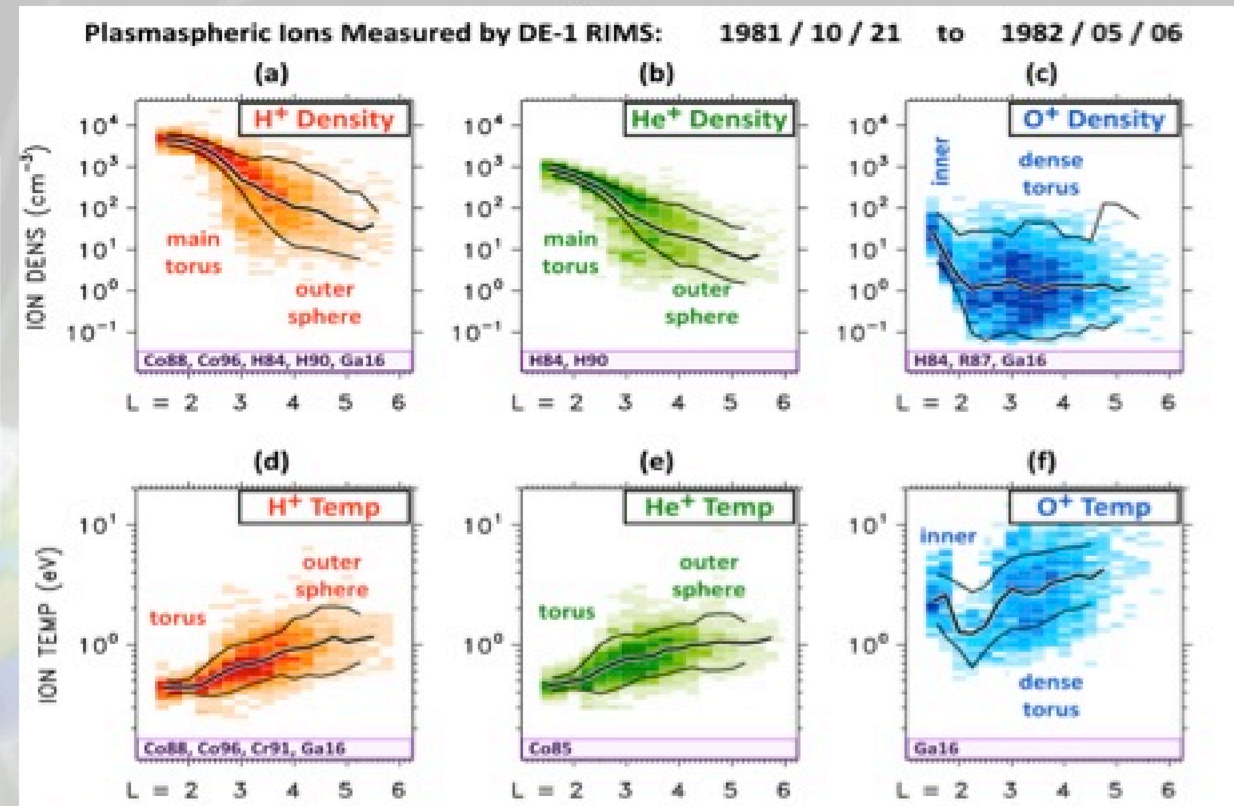
[*Goldstein*+ 2019b]
DE-1 RIMS database (~0.5 yr)

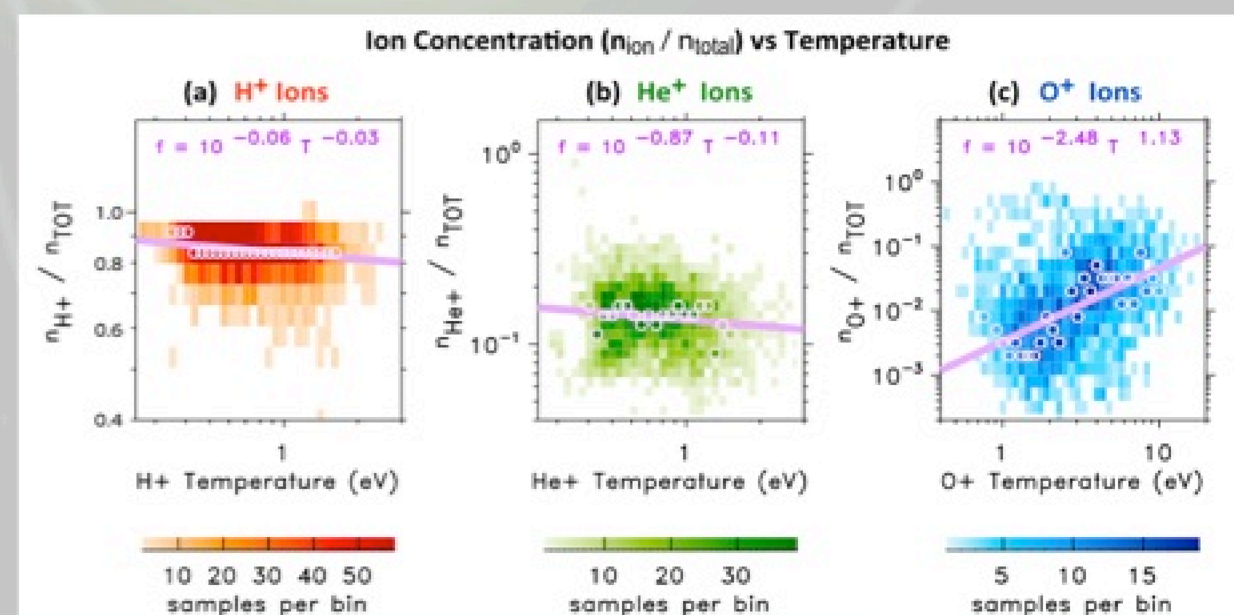
Light Ions (H^+, He^+)
⇒ “classic” density profile
⇒ < 1 eV or so
⇒ ion concentration: very weak dependence vs temperature

Oxygen (O^+)
⇒ dense torus near light ion ppause
⇒ 1 – 10 eV (warmer than light ions)
⇒ ion concentration: increases with temperature

Adjust ion densities from RBSP HOPE
⇒ can compensate for SC potential using this result (+ EMFISIS UHR meas.)







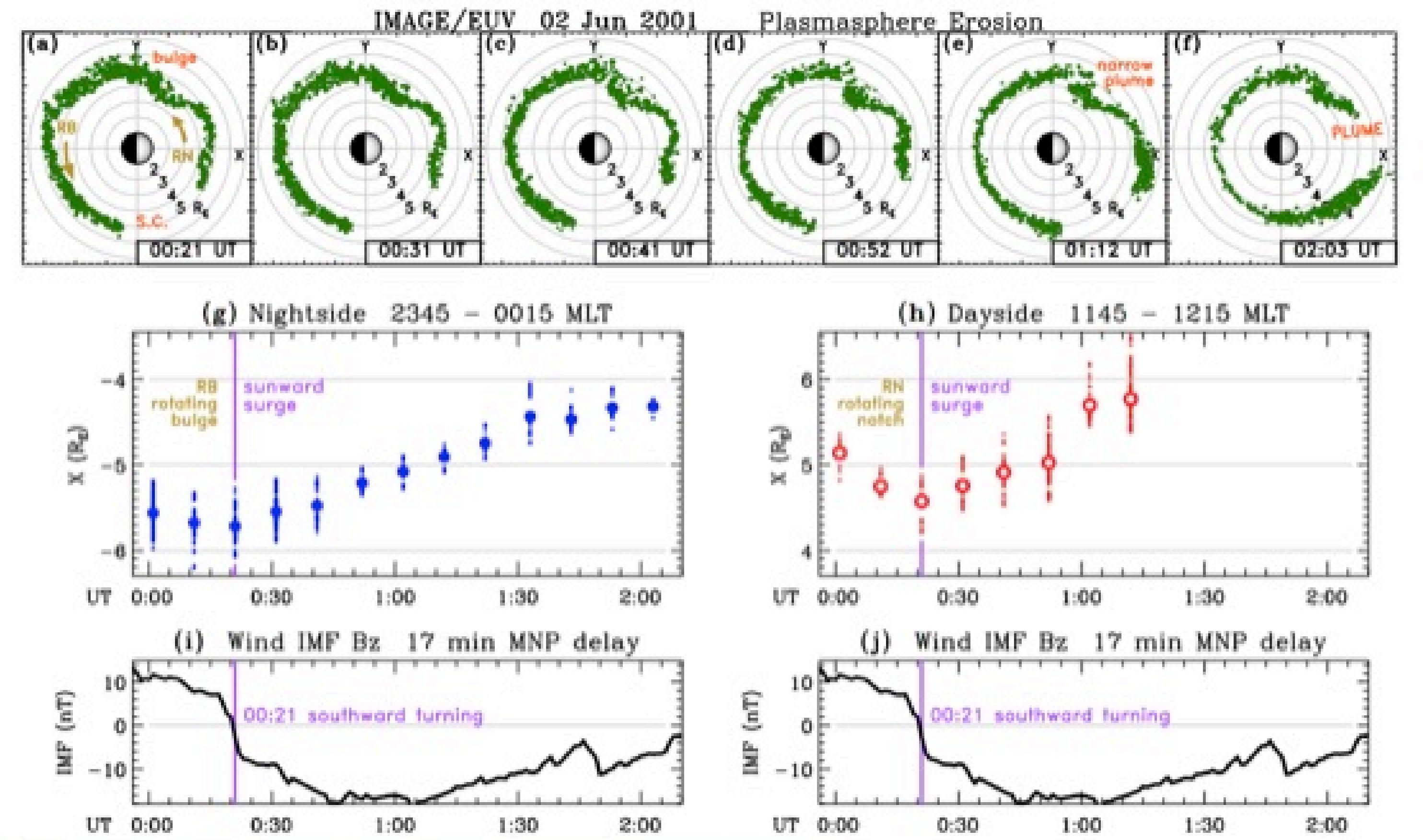
Relative Timing of Dayside/Nightside Erosion Onset

understand how solar wind driving propagates through magnetosphere

Goldstein+2020 EUV timing

[*Goldstein*+ 2020]
IMAGE EUV plasmapause data
Reanalysis to study erosion timing

Delay between dayside and nightside erosion onset ≤10 min



Implications for Erosion Mechanism

Convection: either simultaneous, or dayside first

Interchange: first on nightside requires dayside ionospheric Σ_P~0.02S

What's Left to Learn About the Plasmasphere?

There are still fundamental gaps in our understanding of refilling and erosion

Science Goal	Science Objectives	Science Questions (§D.1.1, §D.1.2)
Understand how the core plasma of the inner magnetosphere erodes and refills	(1) Determine how core plasma fills the inner magnetosphere	*1A* How is the plasmasphere replenished? *1B* How are ions trapped during refilling? *1C* What causes the dense oxygen torus?
	(2) Understand how the plasmasphere is eroded and redistributed during geomagnetic disturbances	*2A* How does convection redistribute core plasma? *2B* What role does interchange play in erosion?

(1) Refilling: *1A* How is the plasmasphere replenished?

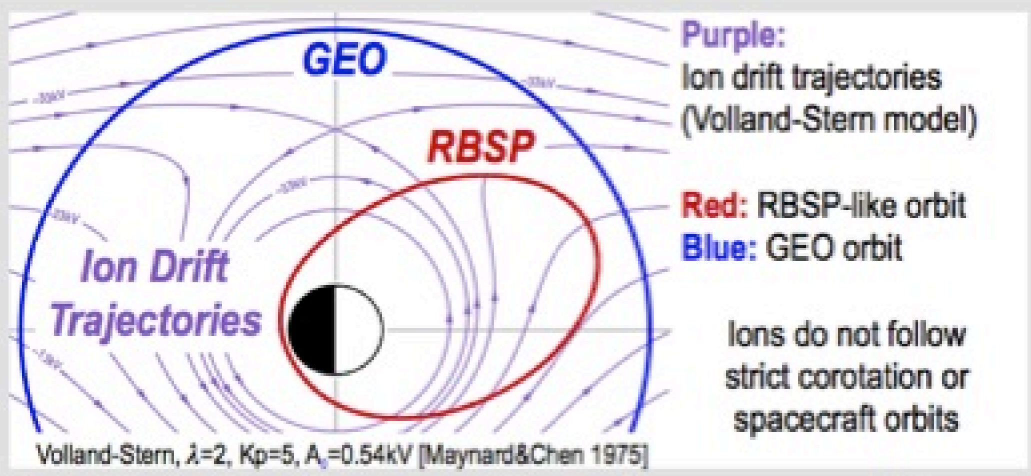
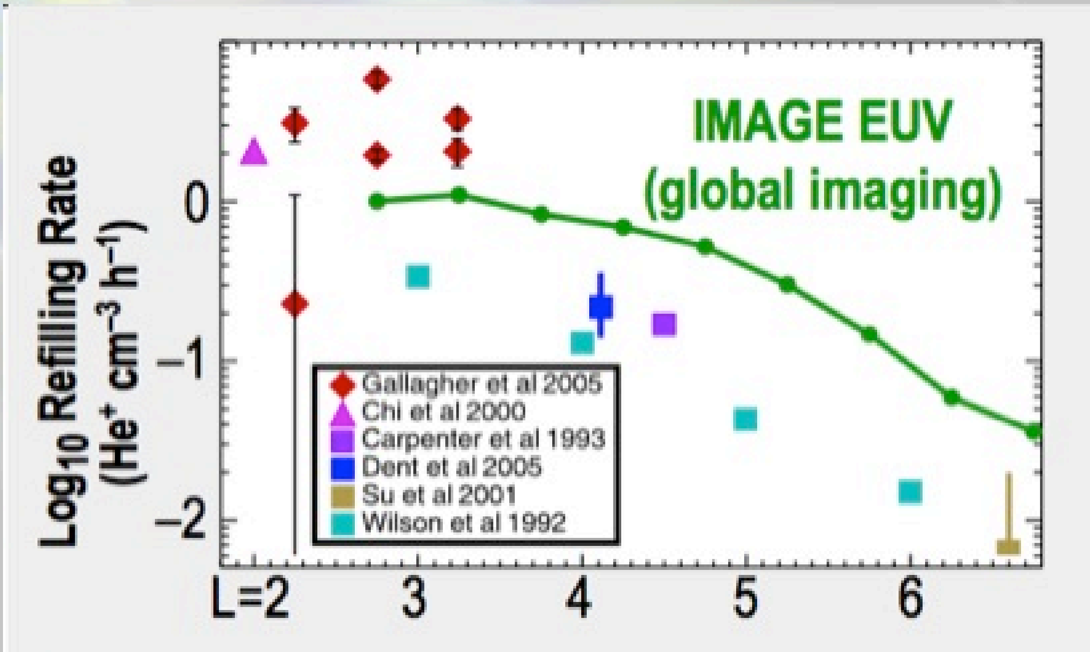


Fig. D.4. In situ sampling along an orbit cannot follow the drift paths of refilling flux tubes



Satellite orbits ≠ Ion drift paths

How do individual flux tubes refill vs location, time, and activity?

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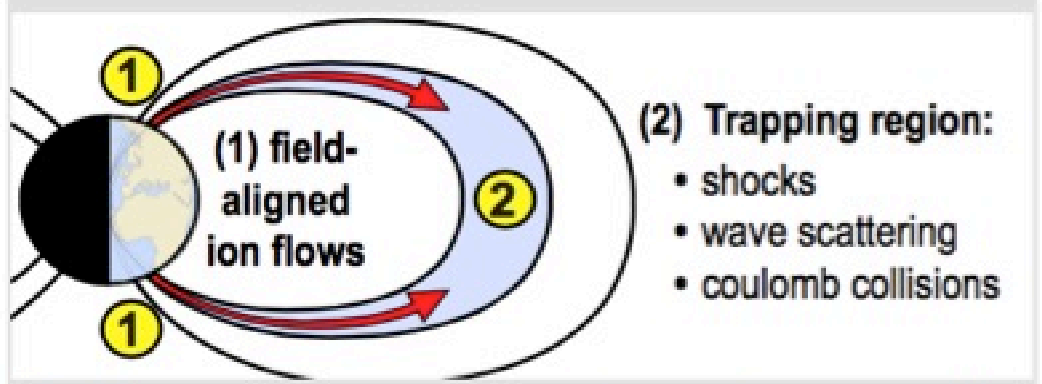
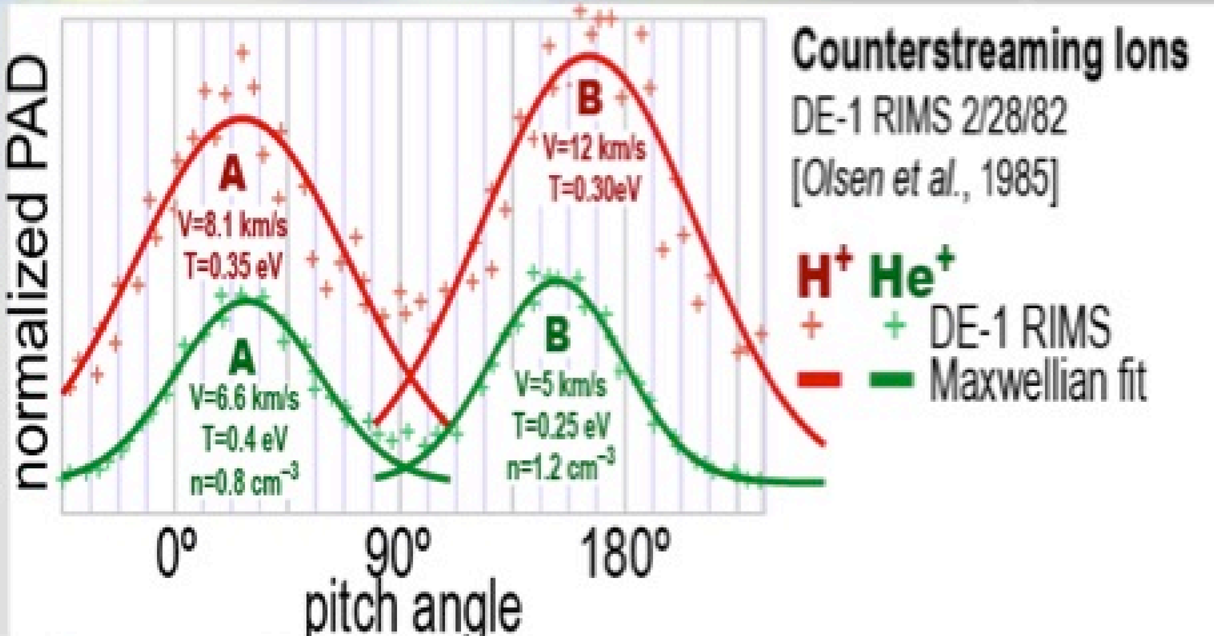


Fig D.5. basic, longstanding question: which mechanisms trap ions: shocks, wave scattering, or Coulomb collisions? [adapted, Singh & Horwitz 1992].



Counterstreaming FA beams => Isotropic or Pancake PAD

How are field-aligned upflowing beams thermalized/isotropized?

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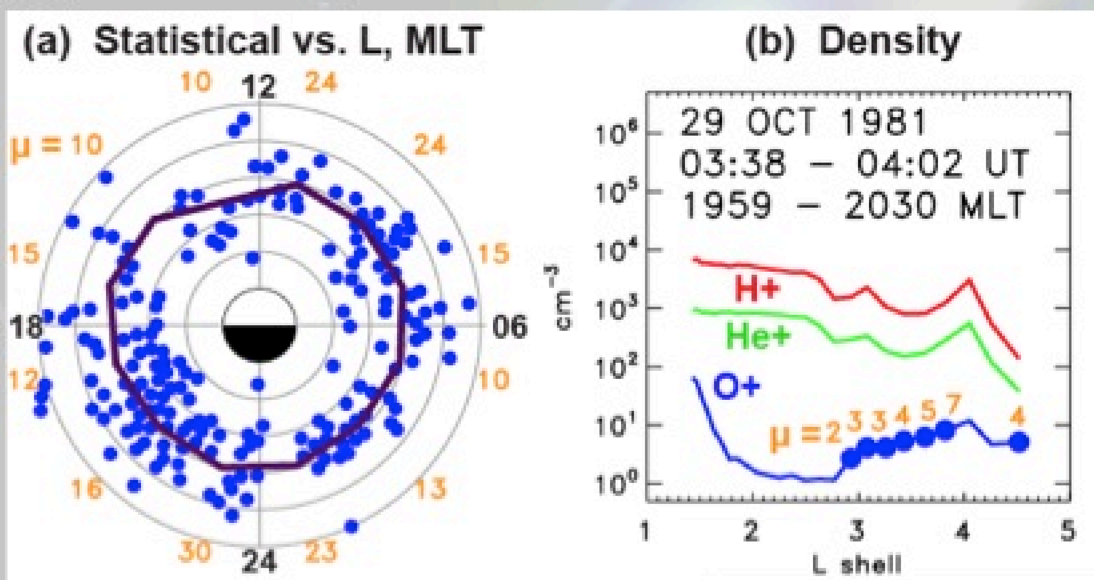
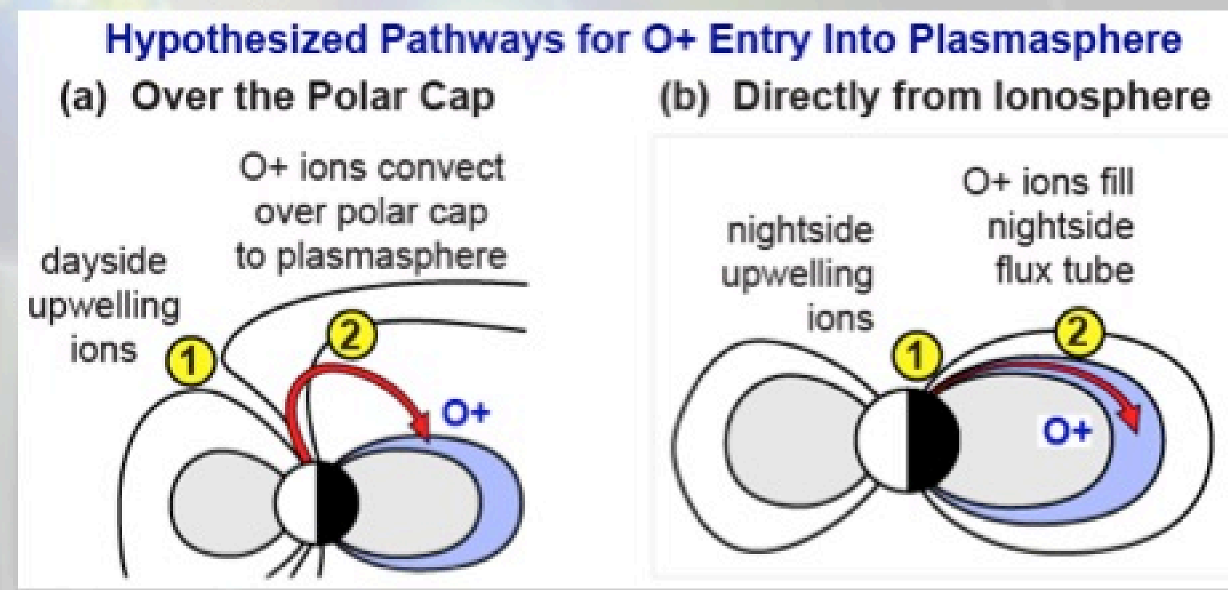
(1) Refilling: *1C* What causes the dense oxygen torus?





Dense O^+ (and O^{++}) torus: shape, timing unknown

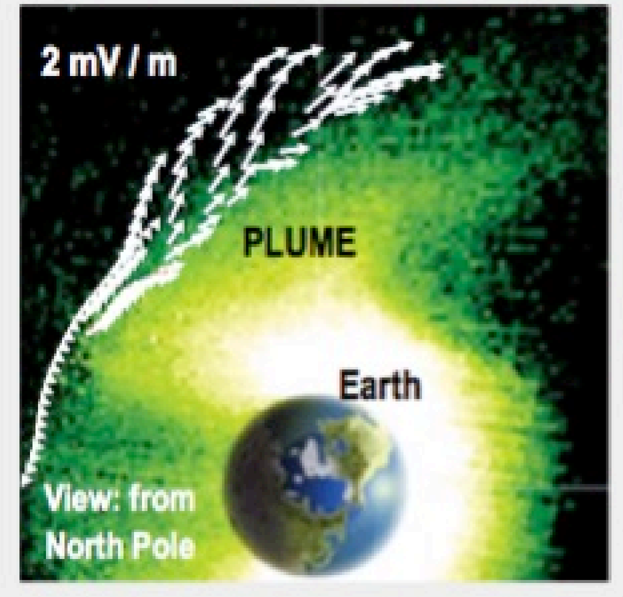
What are the pathways and mechanisms for O^+ to populate the dense torus?

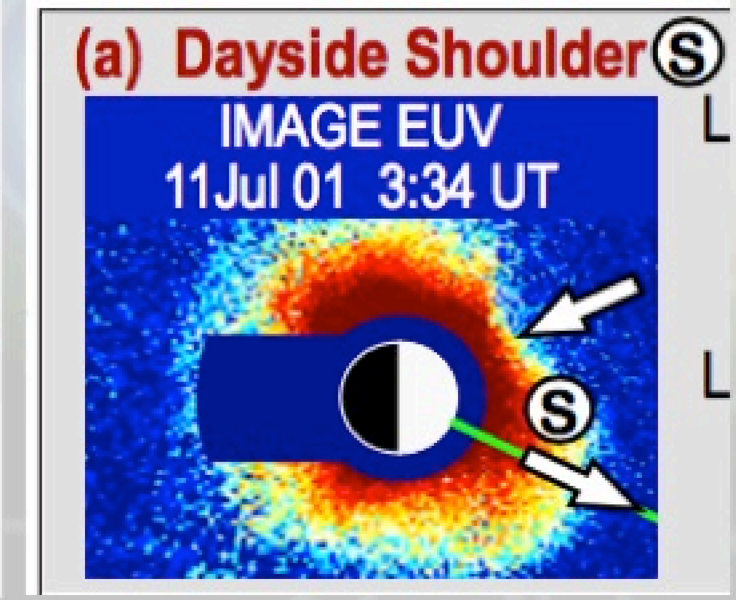
What's Left to Learn About the Plasmasphere?

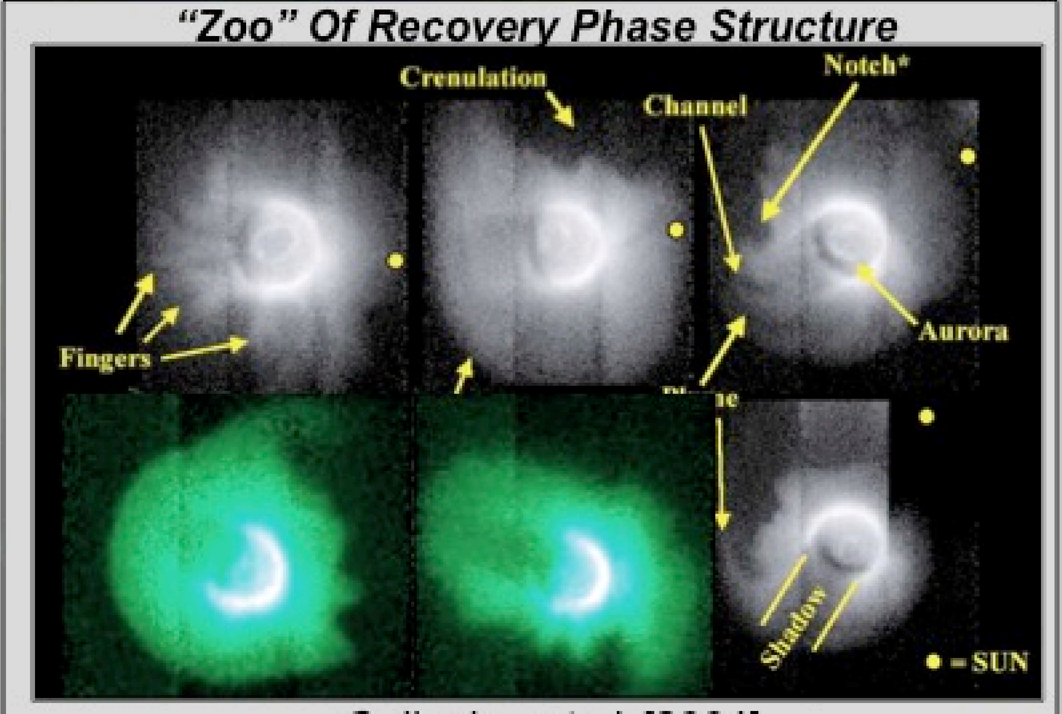
There are still fundamental gaps in our understanding of refilling and erosion

Science Goal	Science Objectives	Science Questions (§D.1.1, §D.1.2)
Understand how the core plasma of the inner magnetosphere erodes and refills	(1) Determine how core plasma fills the inner magnetosphere	*1A* How is the plasmasphere replenished? *1B* How are ions trapped during refilling? *1C* What causes the dense oxygen torus?
	(2) Understand how the plasmasphere is eroded and redistributed during geomagnetic disturbances	*2A* How does convection redistribute core plasma? *2B* What role does interchange play in erosion?

(2) Transport: *2A* How does convection redistribute core plasma?







Gallagher et al. [2004]

Transverse motion (E-field), Transport/Loss, Mesoscale Features

How is plasma transported, redistributed, and/or lost?

What's Left to Learn About the Plasmasphere?

There are still fundamental gaps in our understanding of refilling and erosion

Science Goal	Science Objectives	Science Questions (§D.1.1, §D.1.2)
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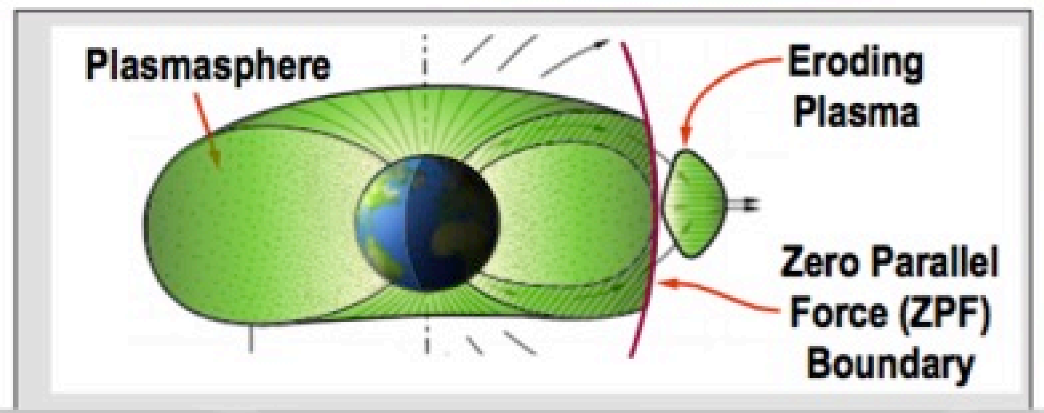
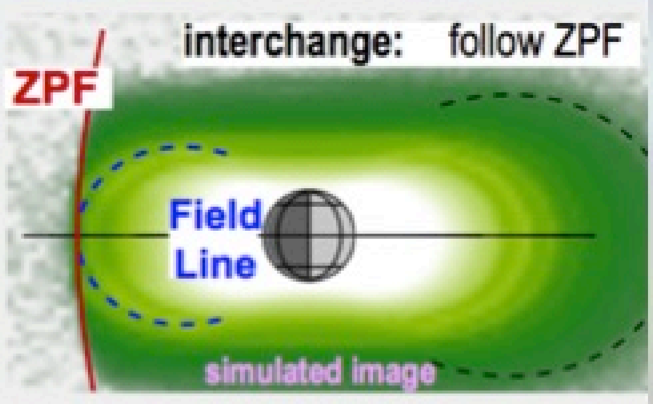
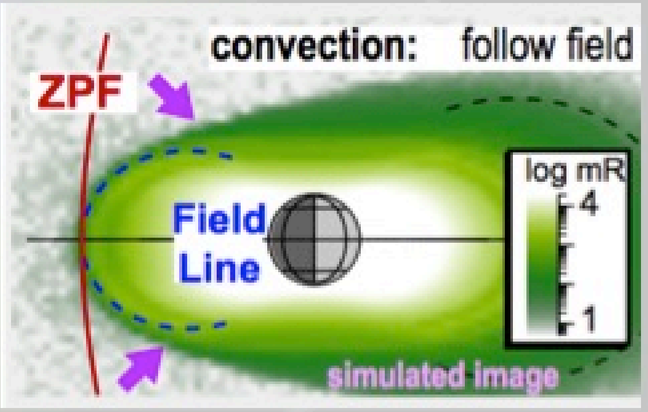




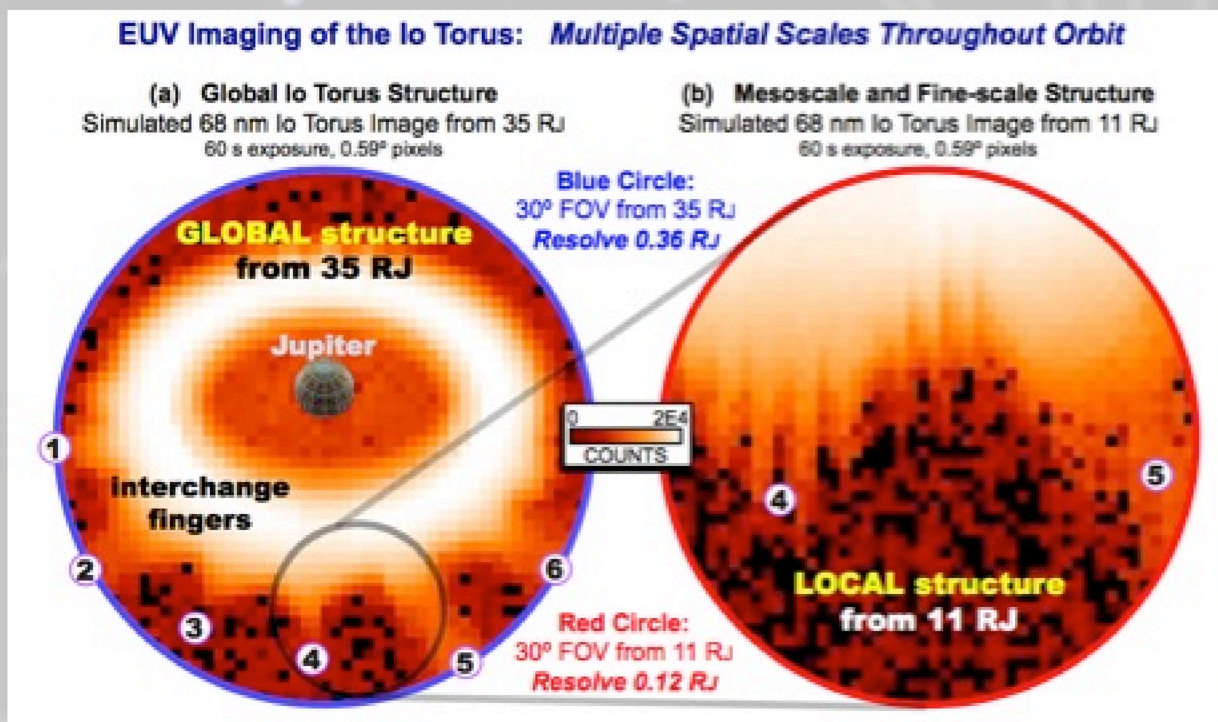


Convection vs Interchange: Different predictions

Global shape and day-night relative timing of eroding plasmapause?

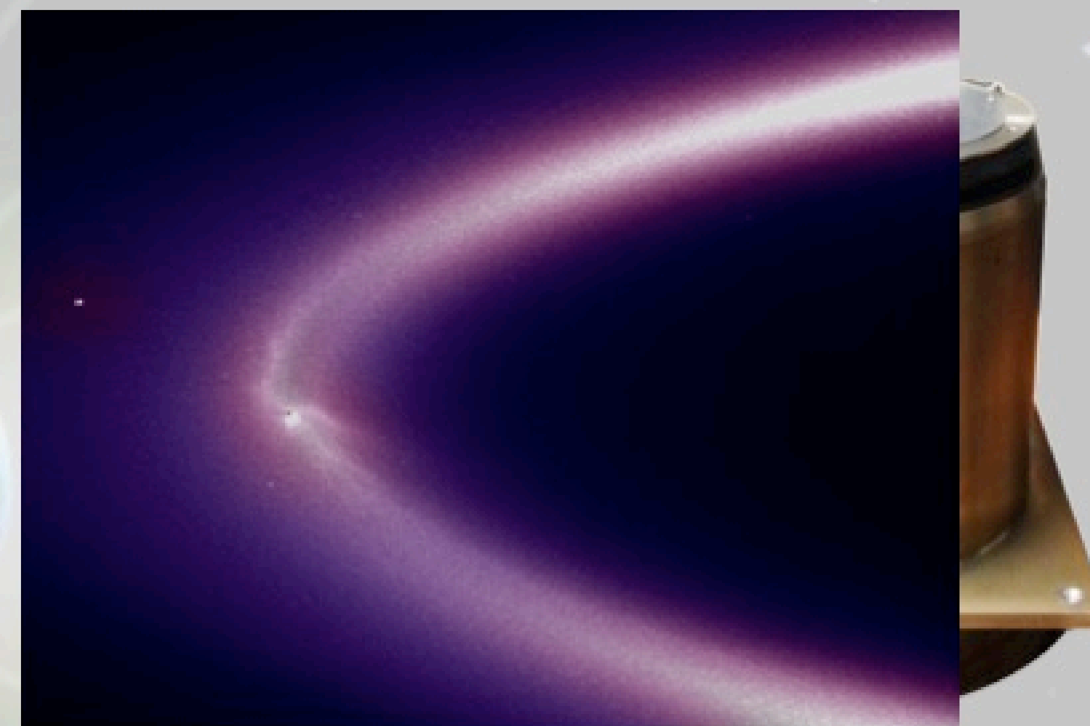
Plasmaspheres of Other Planets

Jupiter and Saturn have plasma tori created by moons



Io Plasma Torus

Volcanoes...



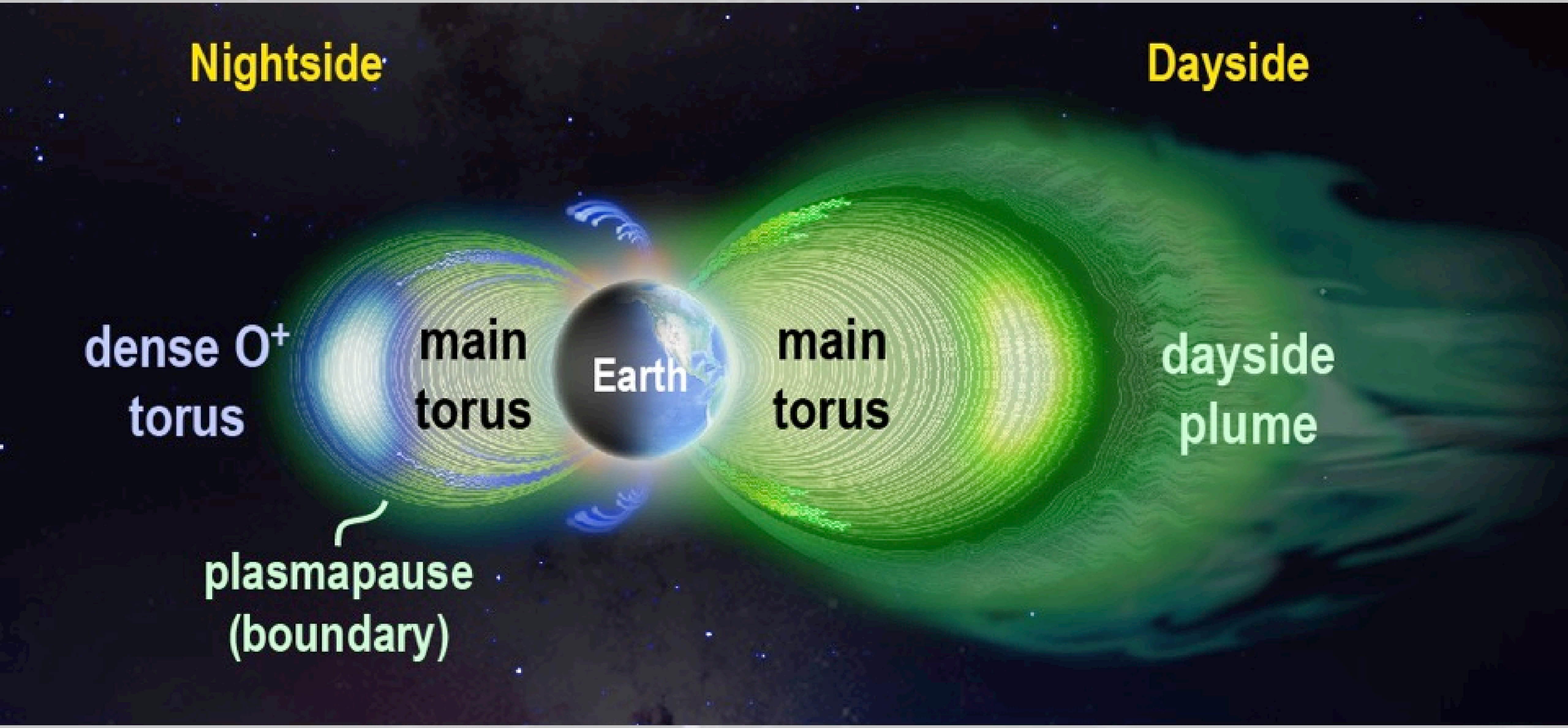
Enceladus Plasma Torus

Geysers...

How does interchange drive convection in the magnetospheres of Jupiter and Saturn?

Rediscovery of the Plasmasphere

The past two decades have witnessed a resurgence in interest and investigation of the plasmasphere

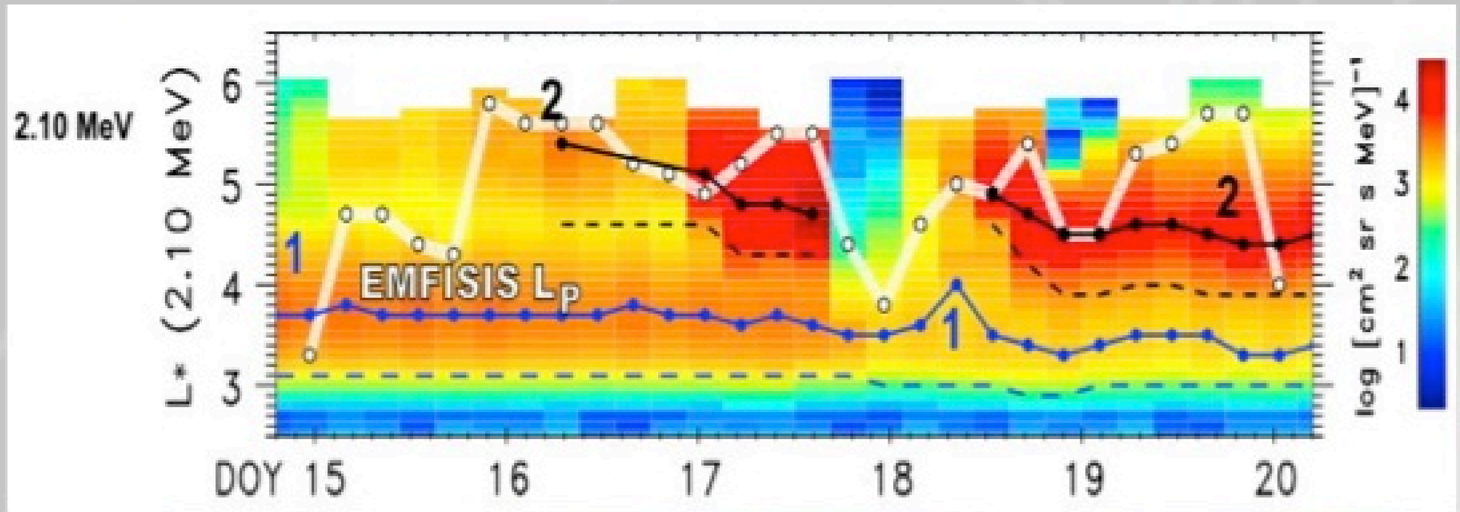


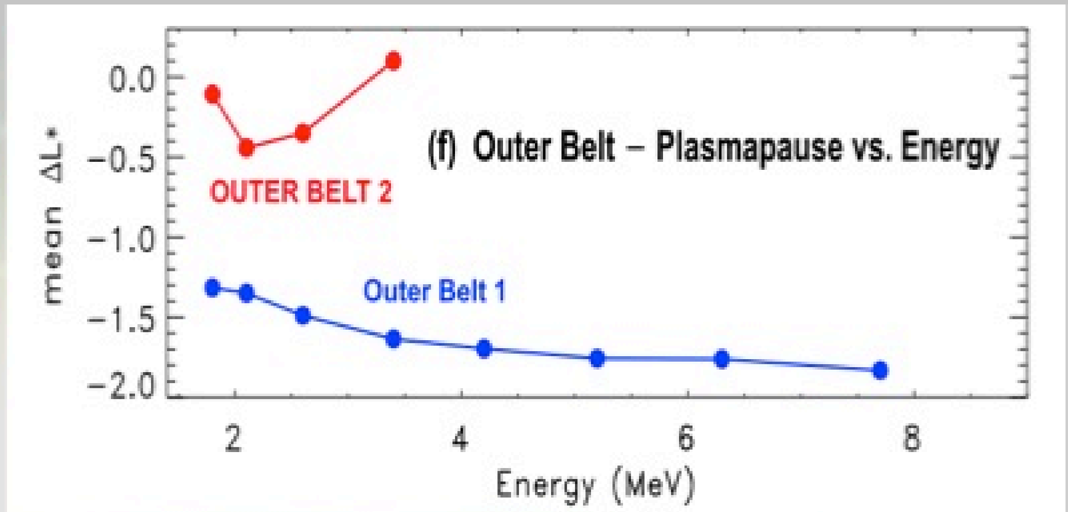
Extra Slides

Influence on Radiation Belts

support Van Allen Probes, understand outer belt structure

Goldstein+2016 Influence on RB





[*Goldstein*+ 2016]
Two outer belts, 15 – 20 Jan 2013

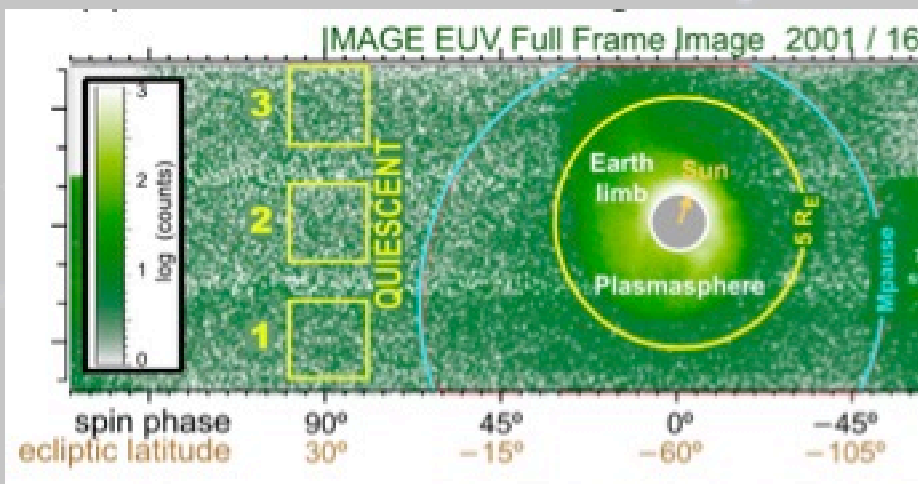
OUTER BELT 1:
⇒ stable
⇒ higher energy (peak 4 MeV)
⇒ decaying on hiss timescales
⇒ deeper inside plasmapause (>1 R_E)
⇒ shielded from main phase dropout

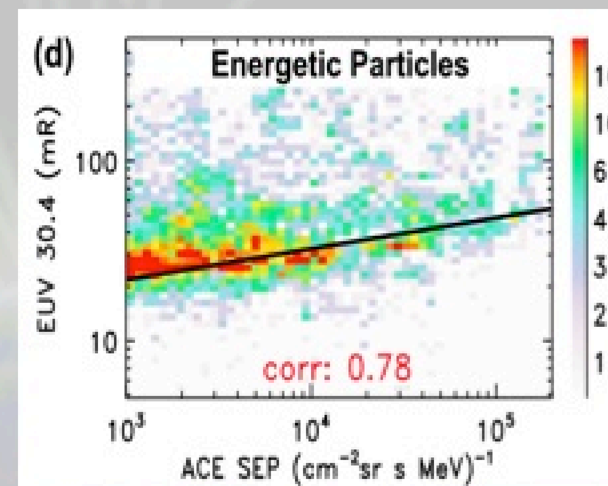
OUTER BELT 2:
⇒ variable
⇒ lower energy (peak < 2 MeV)
⇒ near plasmapause ($\Delta L^* \sim 0.5\ R_E$)
⇒ strong main phase dropout (shadowing)
⇒ full recovery ~1 day later (chorus)

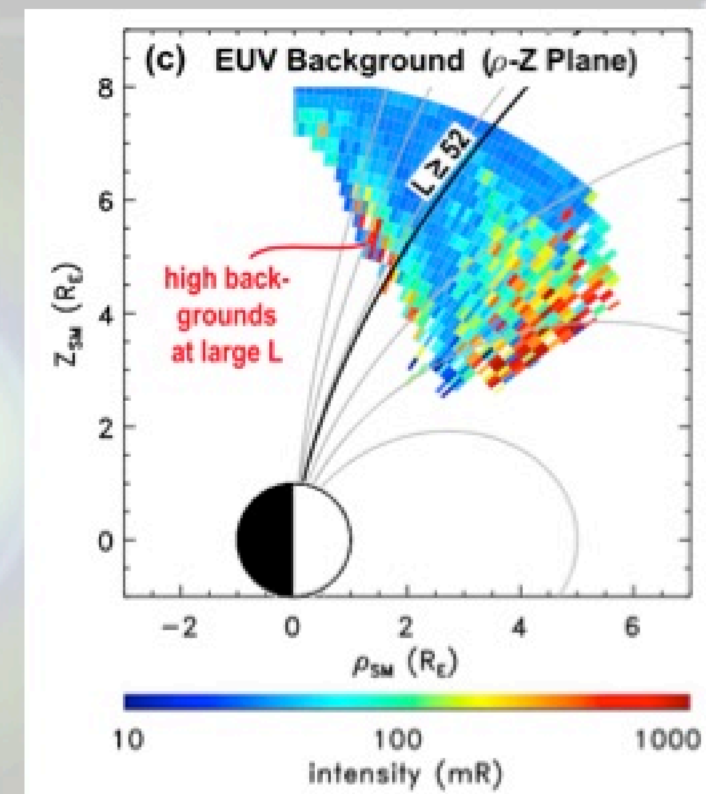
EUV 30.4 nm background

understand sources of background light in IMAGE EUV

Goldstein+2017 EUV backgrnd







[*Goldstein*+ 2017]
IMAGE EUV background signal
from *full-spin images*... 6 months in 2001

Quiescent/Nominal Background
⇒ ~27 mR
⇒ ~50% 30.4nm (nonplasmaspheric He^+)
⇒ ~50% leaked 58.4nm (neutral He)

Elevated Background
⇒ Episodic factor of 3-to-30 increases
⇒ solar wind 50keV – 5MeV particles
⇒ SW density/pressure pulses