Ionospheric Plasma in the Earth's Magnetotail

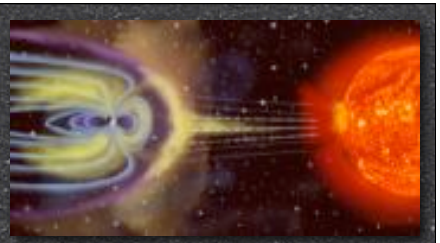
21st Century Outflow Observations:

Andersson '06; Chaston '06;
Chen '04 '06; Cully '03a,b;
Dandouras '04;
Elliott, '01, '02;
Fuselier, '03, '06;
Gardner, '04 '05;
Huddleston '05;
Lennartsson, '04;
Liemohn '05; Lund '00;
Mouikis, '06; Moore, '01, '03, '05a,b;
Peterson '01, '02, '06; Sauvaud '02;
Strangeway '05;Tu, '05;
Tung, '01; Valek, '02;Wilson, '03, '04;
Wu '02; Zeng, '04, Zheng '05;

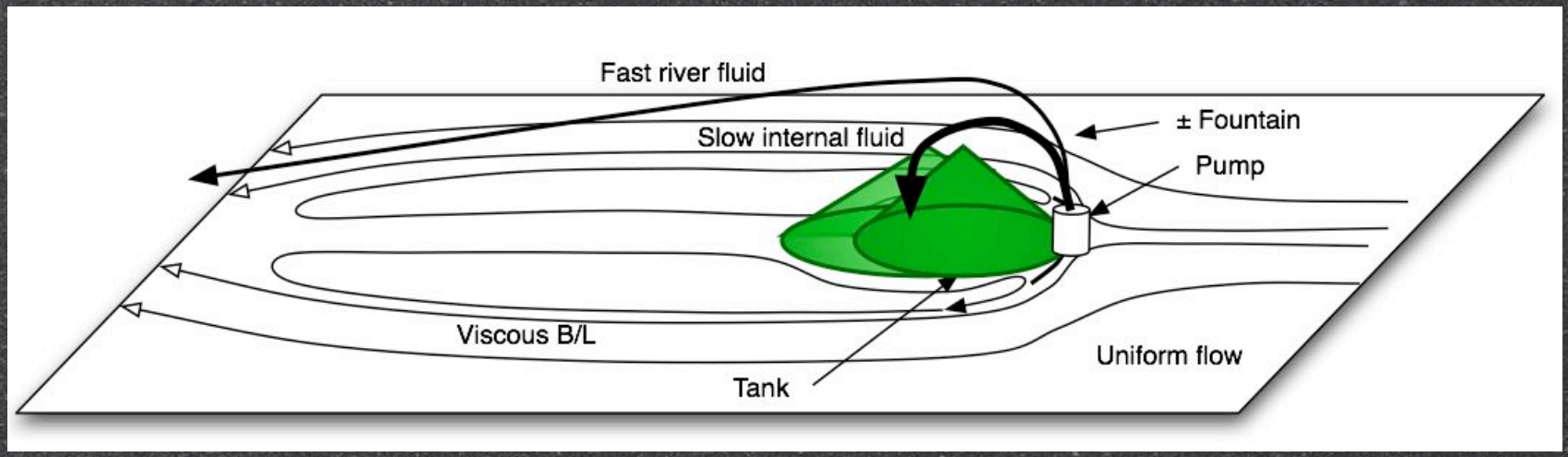
A Tutorial:

Blame: T E Moore, NASA Goddard
Credit: M-C Fok, D C Delcourt,
J A Fedder, S P Slinker

The Central Problem

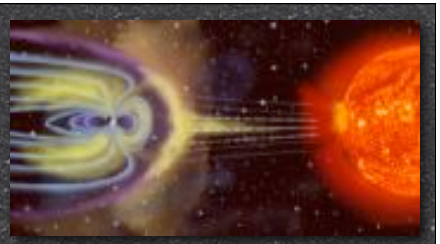


- Consider a conical tank standing in a river, creating a wake flow
- At times, tank gets filled and pressurized to 20x dynamic pressure.
- Q. How can a fluid flow pressurize itself into an embedded tank?



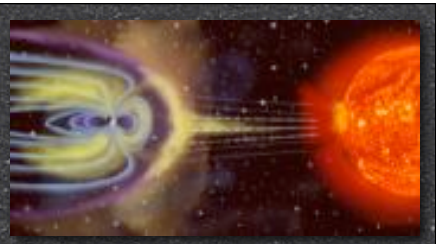
- Perhaps fluid pumped by latent electromagnetic energy?
- Perhaps steady pumping with stretch/relax-compression cycles?
- What role might an abundant cold internal fluid play in this?
- How does this work in real heliophysical situation?

Why a Magnetosphere?

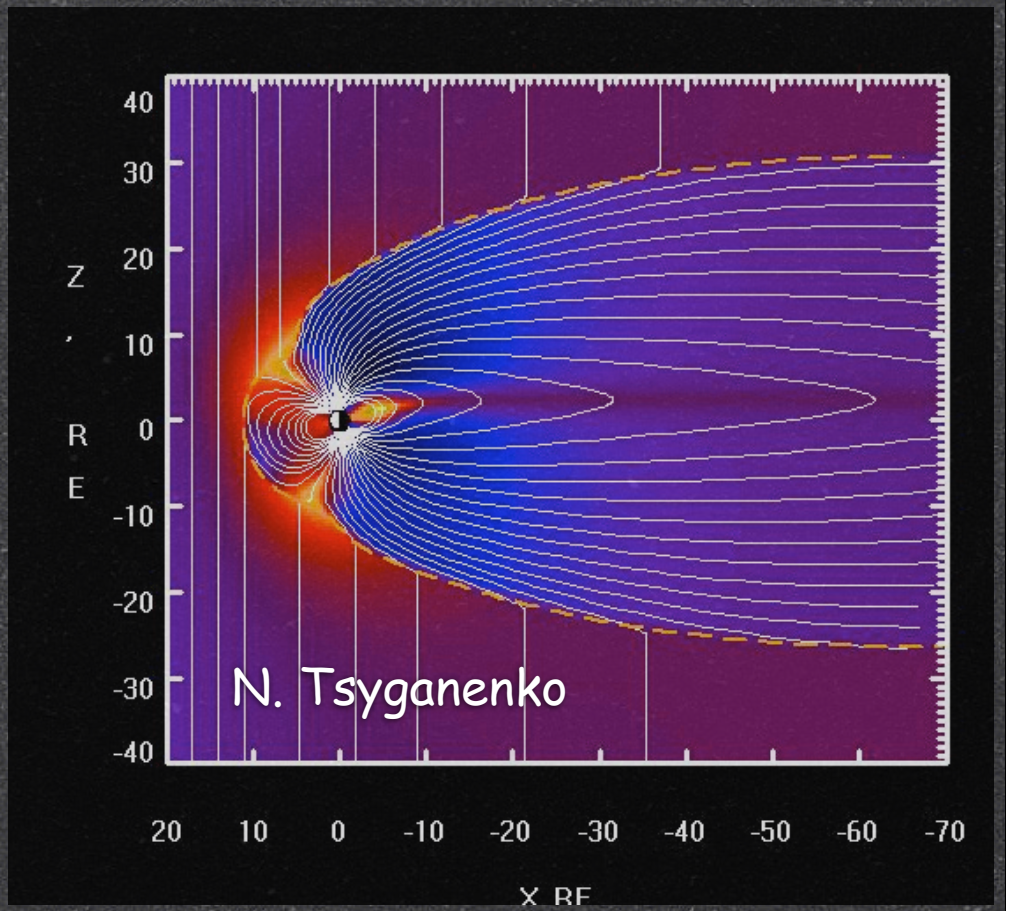


- Stagnant solar breeze ~ 1 nPa
  -> spherical magnetopause, polar cusps
- Magnetized plasma cell constrained by fibrous connective tissue of flux tubes
  - Like surface tension but distributed
- 1. Cell collisions yield linkage of fibres, possibly merging cells
- 2. High relative speed parcels within a cell distend and may split the cell
- 1a. Small cells embedded in larger cells tend to be eroded and-or assimilated

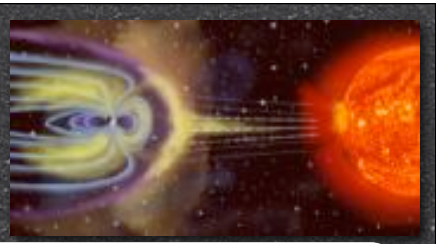
Why a Magnetotail?



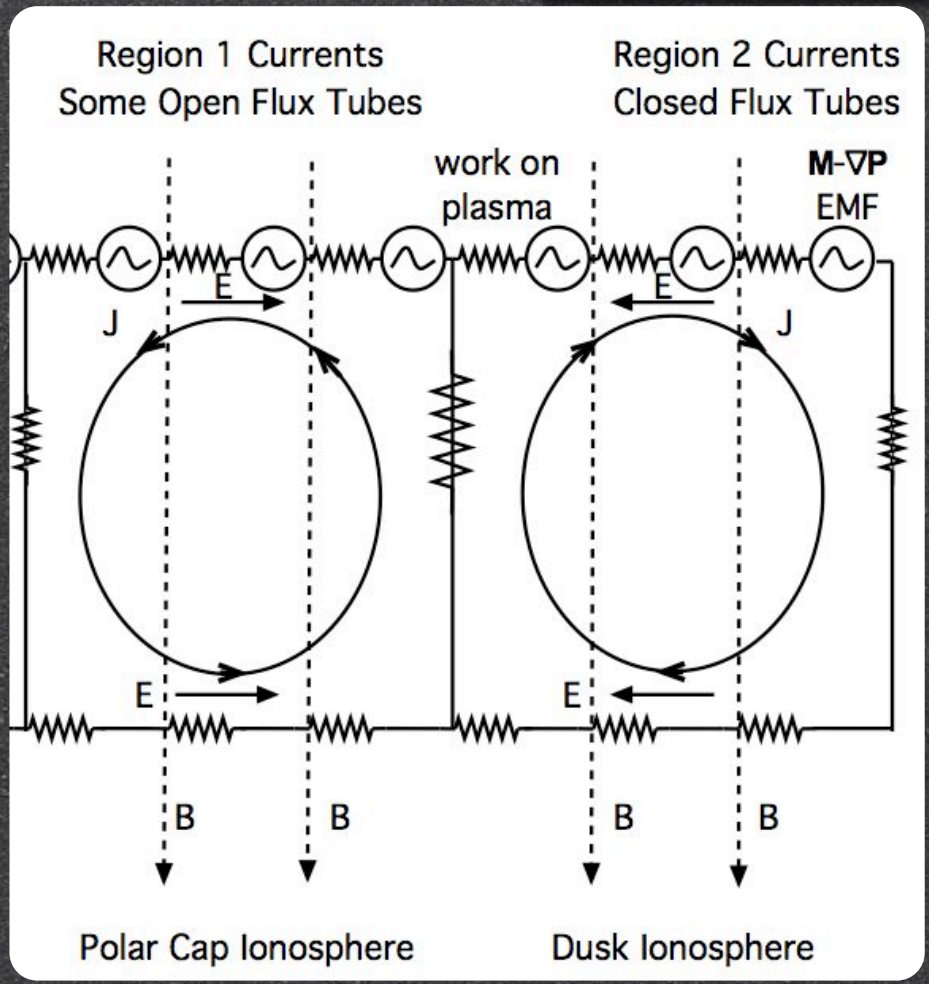
- Solar wind -> pressure asymmetry -> tail and viscous BL
- Embedded in larger cell
- Reconnection for NBz:
  - LLBLs circulate into lobes, PS fattens; yields Cold dense plasma sheet
  - LLBL as upstream source
- Reconnection for SBz:
  - Lobes circulate into Hot PS, NENLs, plasmoids
  - Polar cap as upstream source
- To balance plasma pressure with Maxwell stresses



Why Plasma Flow?

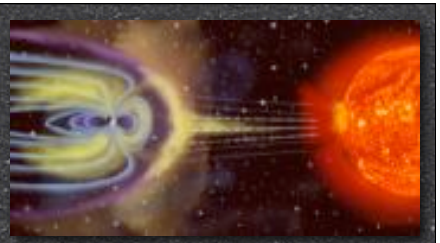


- On the question: does **E** cause **V** or does **V** cause **E**?
- My take:
  - Moving plasmas are electrodynamically coupled, so...
  - No **V** without **E**, BUT
  - **M** - ∇**P** => **V** & **E**

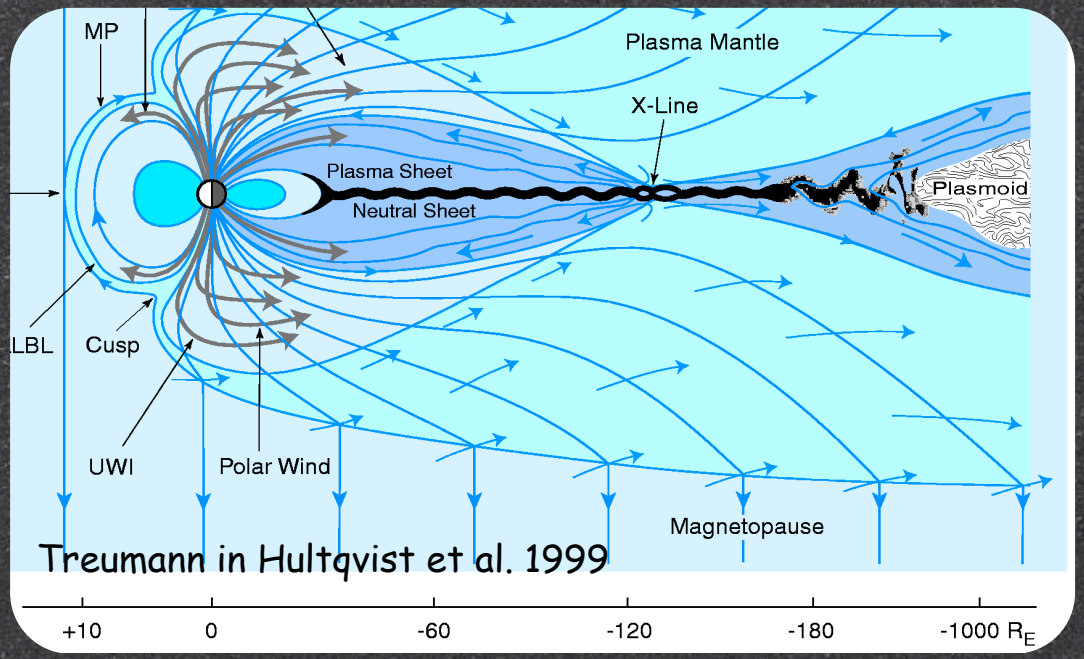


- Pressure gradients unbalanced by Maxwell stresses move plasmas, generate **V**, **E**, EMF of generator

Why a Distant X Line?

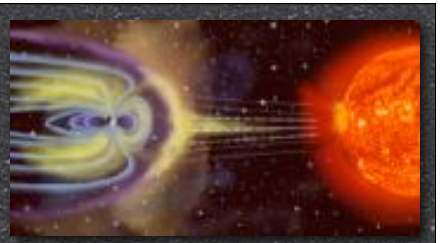


- 1. Disconnection of IMF hung up on magnetopause
  - As for comet tails
- 2. Disconnection of solar wind plasma trapped on closed flux tubes
  - Nearer/farther from Earth for stronger/weaker solar wind

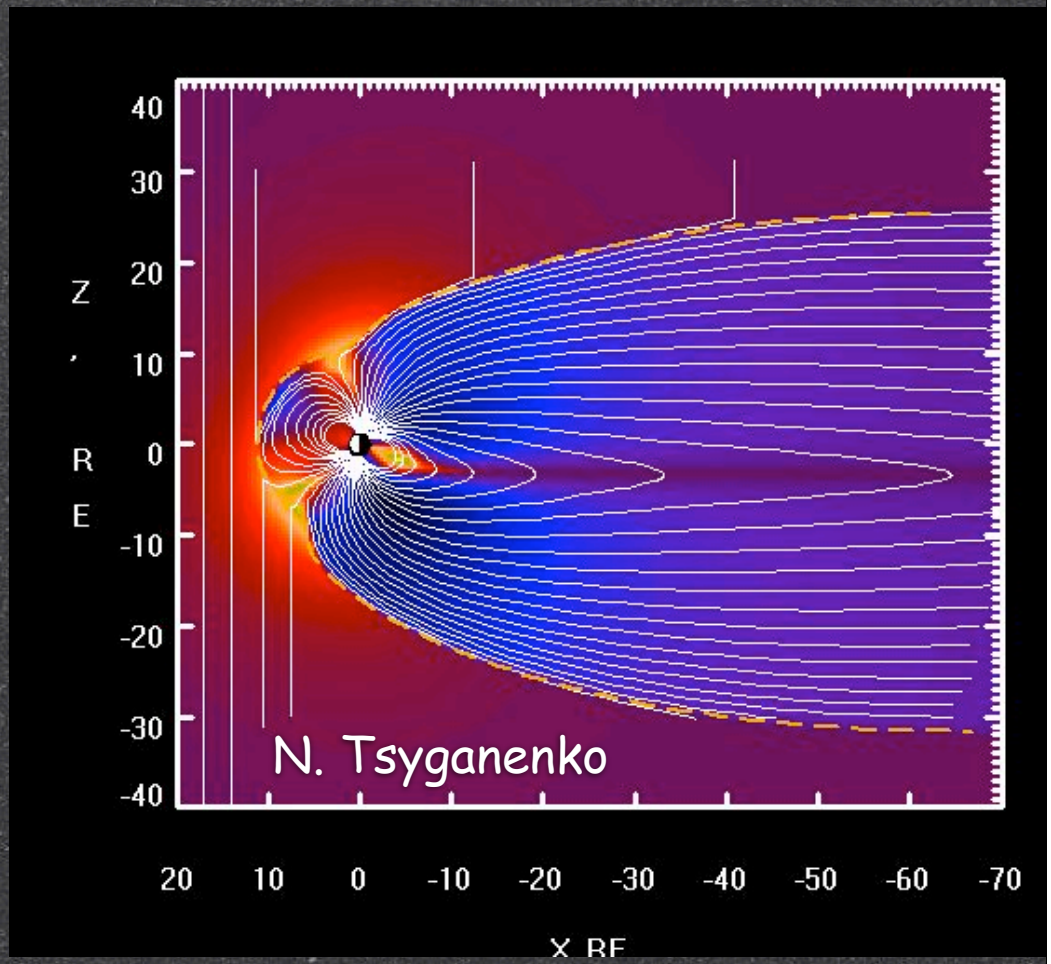


  - Beyond some distance, wind too strong, field too weak, to be confined/closed

Why a Near Earth X line?



- Same as distant X line except much deeper
- Greater pressure req.
- When plasma pressure cannot be contained, in a region of stronger field than for distant X line...

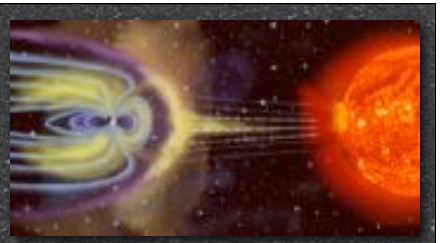


- Excess plasma trapped on closed flux tubes

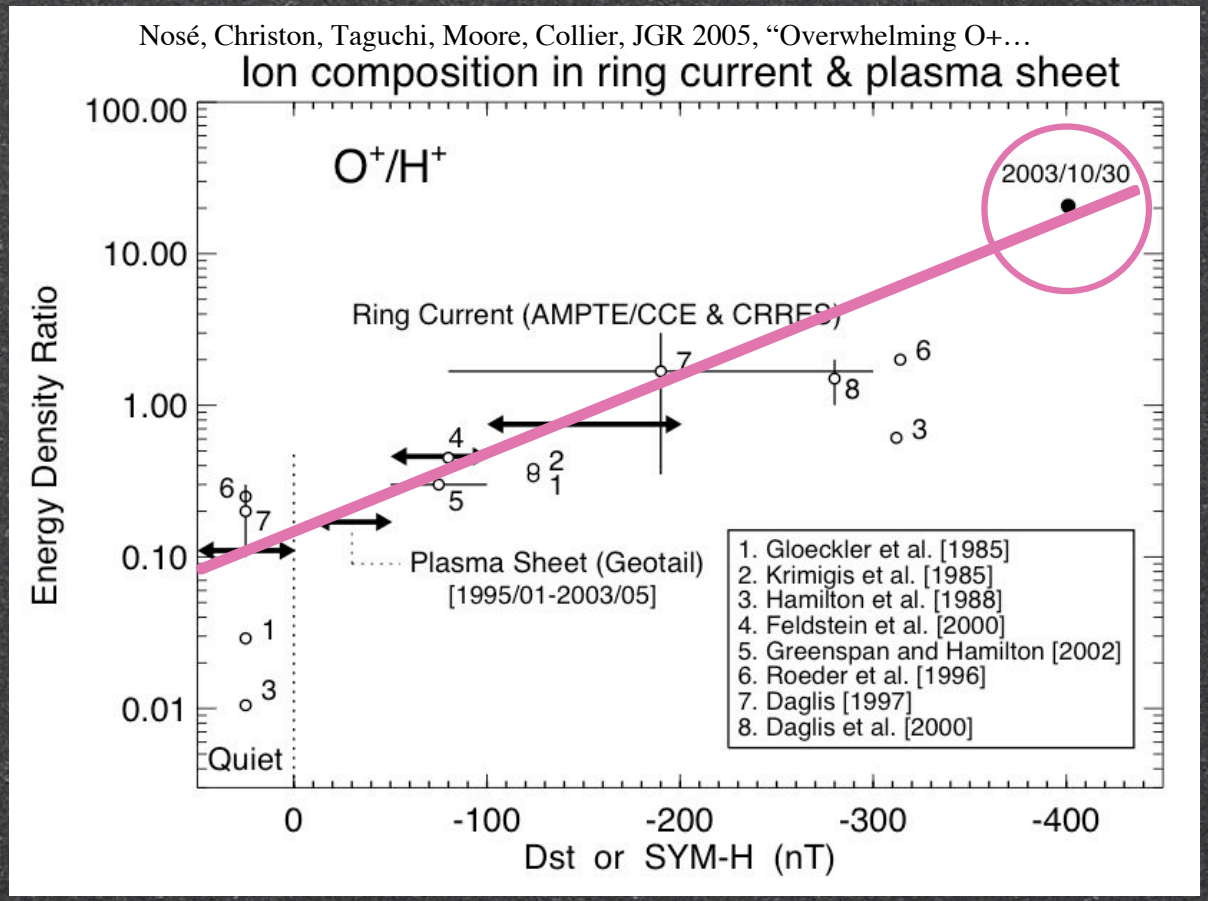
Why a Ring Current?

- Typ' solar wind Pd ~ 1 nPa ~ 6 keV/cc held off at 10Re by ~100 nT field
- Q. What pressure to penetrate to 3-4 Re?
- A. ~20 nPa ~ 130 keV/cc
- [DPS: 2.5e29 keV = -1 nT Dst ring current]
- How can a fluid flow pressurize itself x20?
- Consider pumps/compressors:
  - Some use cyclical motion; some store-release cycle:
  - Venturi pump uses one fluid to pump another:
  - Magnetospheric bicycle tire gets topped up with pressure just by riding real fast!
- Something in the magnetosphere wants out...
  - External or internal plasma, how pressurized?

Why Geopause vs Plasmapause?



The question: How much does the ionosphere contribute to hot plasma?
Answer: Depends on **where** and **when**; magnetosphere is inhomgeneous

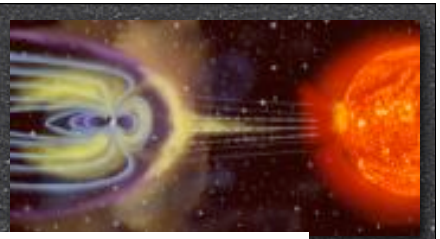


Inner region clearly geogenic = geosphere, expands with activity

Geopause region is hot O+ dominated, unlike plasmasphere

Ring Current growth involves an exponential O^+ increase

Why Test Particles in LFM?



- S
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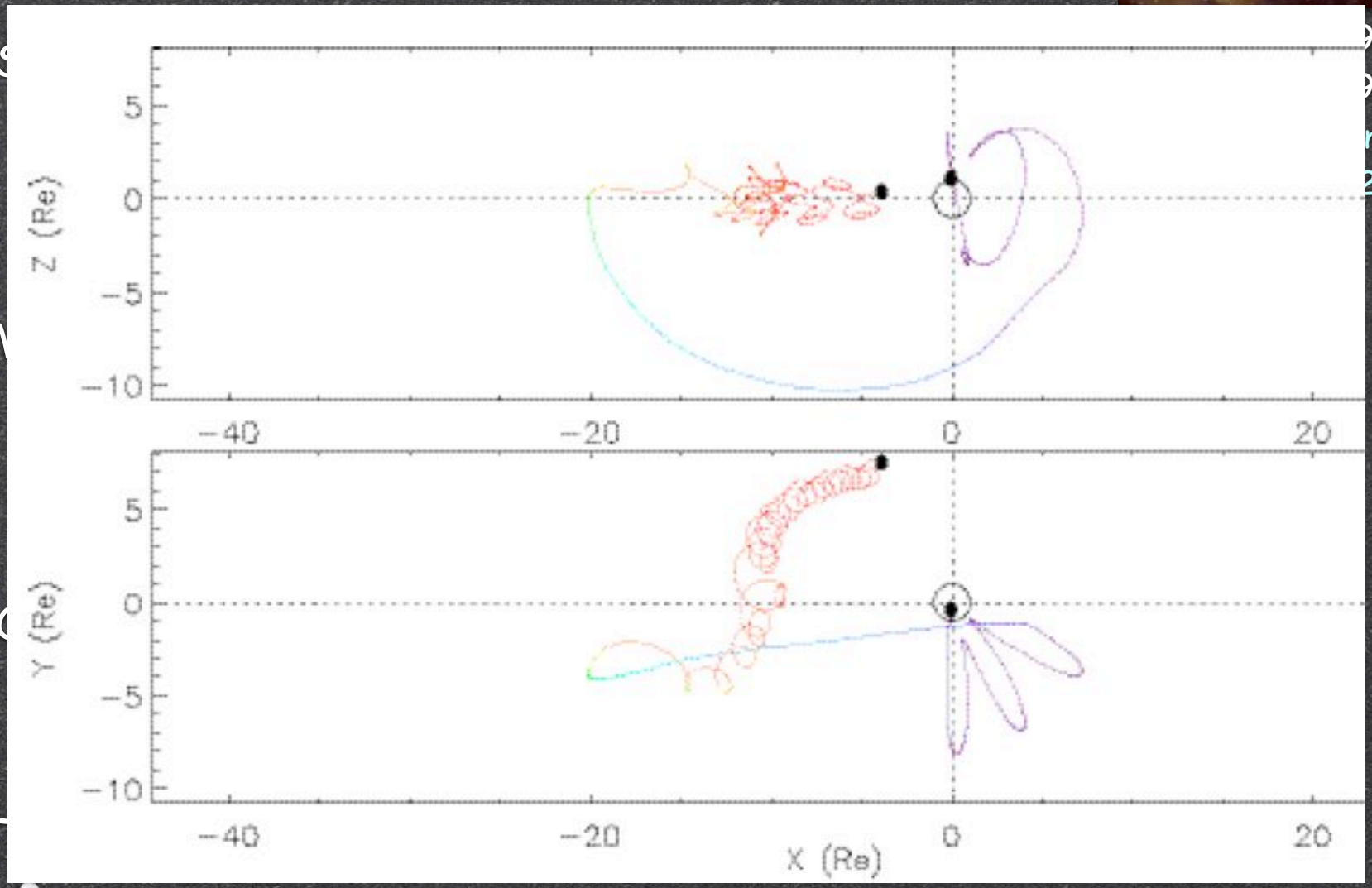

9 JGR
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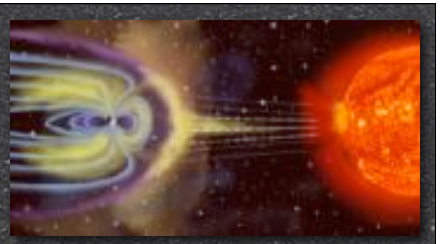
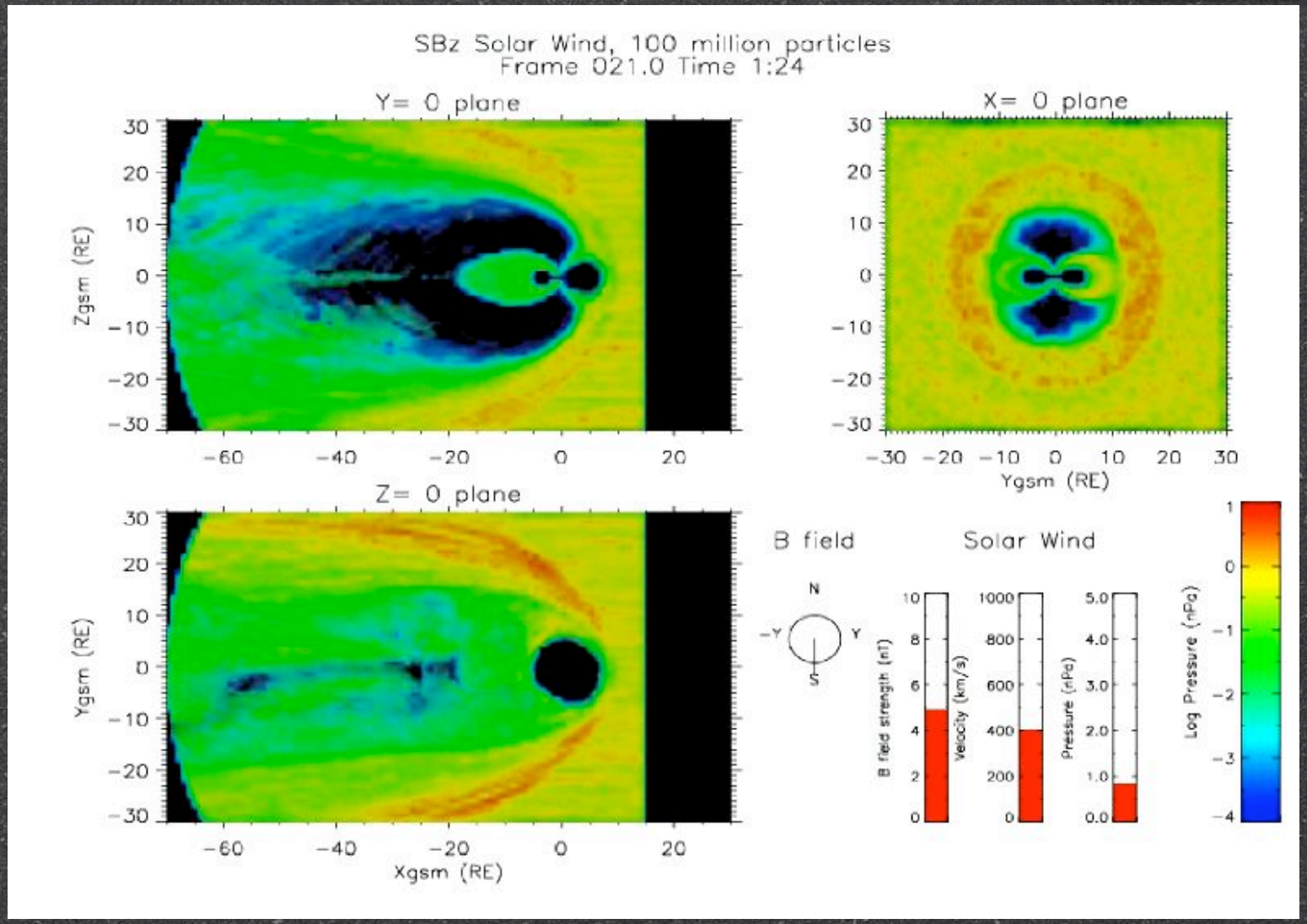
nglee,
2, '03;

- Improved understanding and predictions

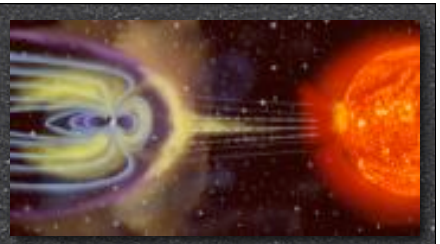
Role of IMF ∂Bz: Solar Wind

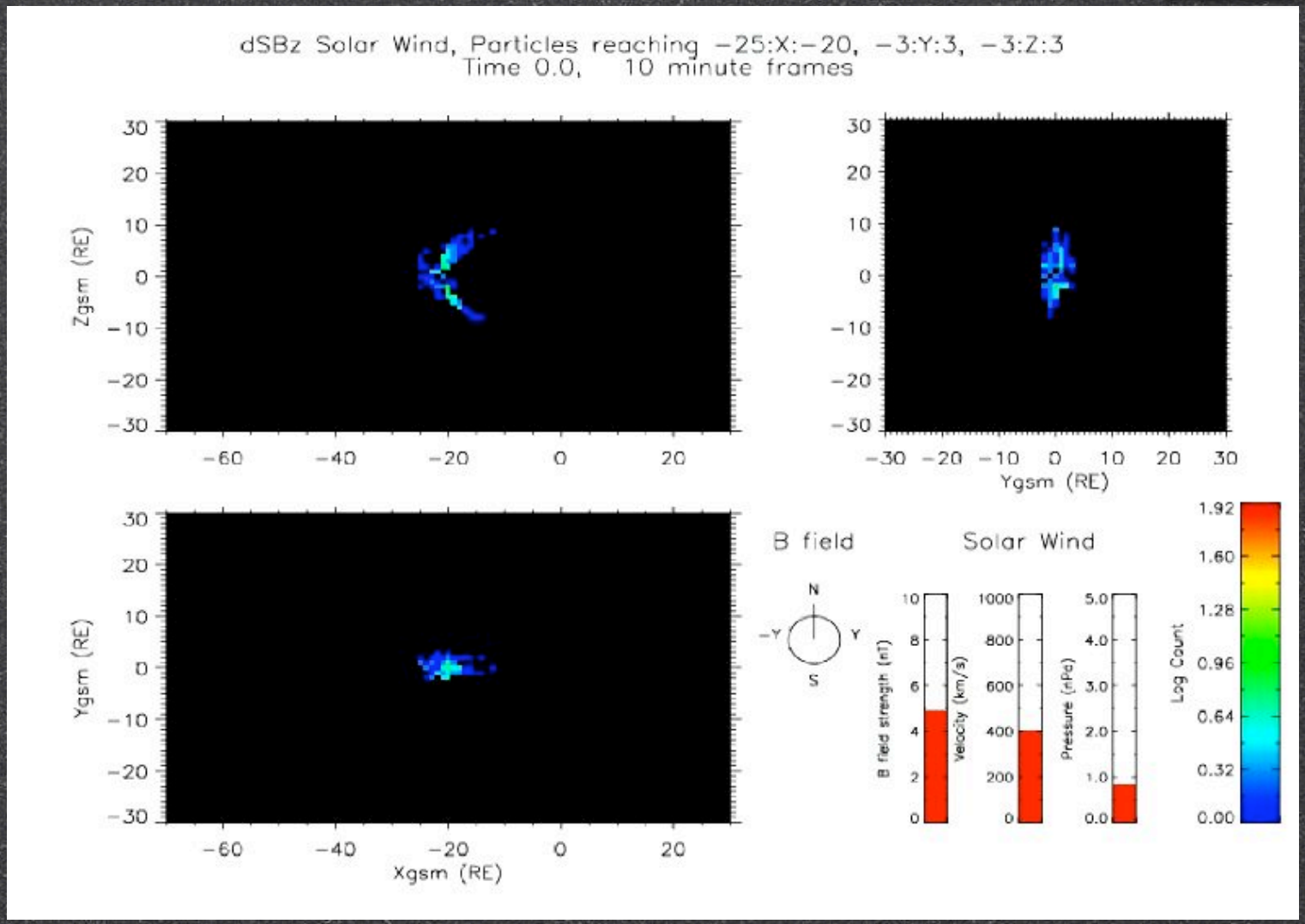




Solar wind behavior is familiar response to SBz

Solar Wind Pathways to PS





Solar wind paths arrive in CPS mainly for NBz, from LLBL

Interactive Ionosphere Outflows

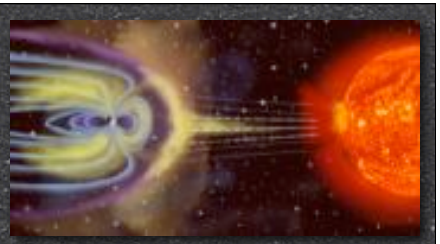


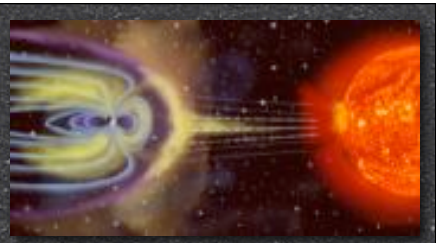
Table 1. Local empirical scalings used to initialize ionospheric particles

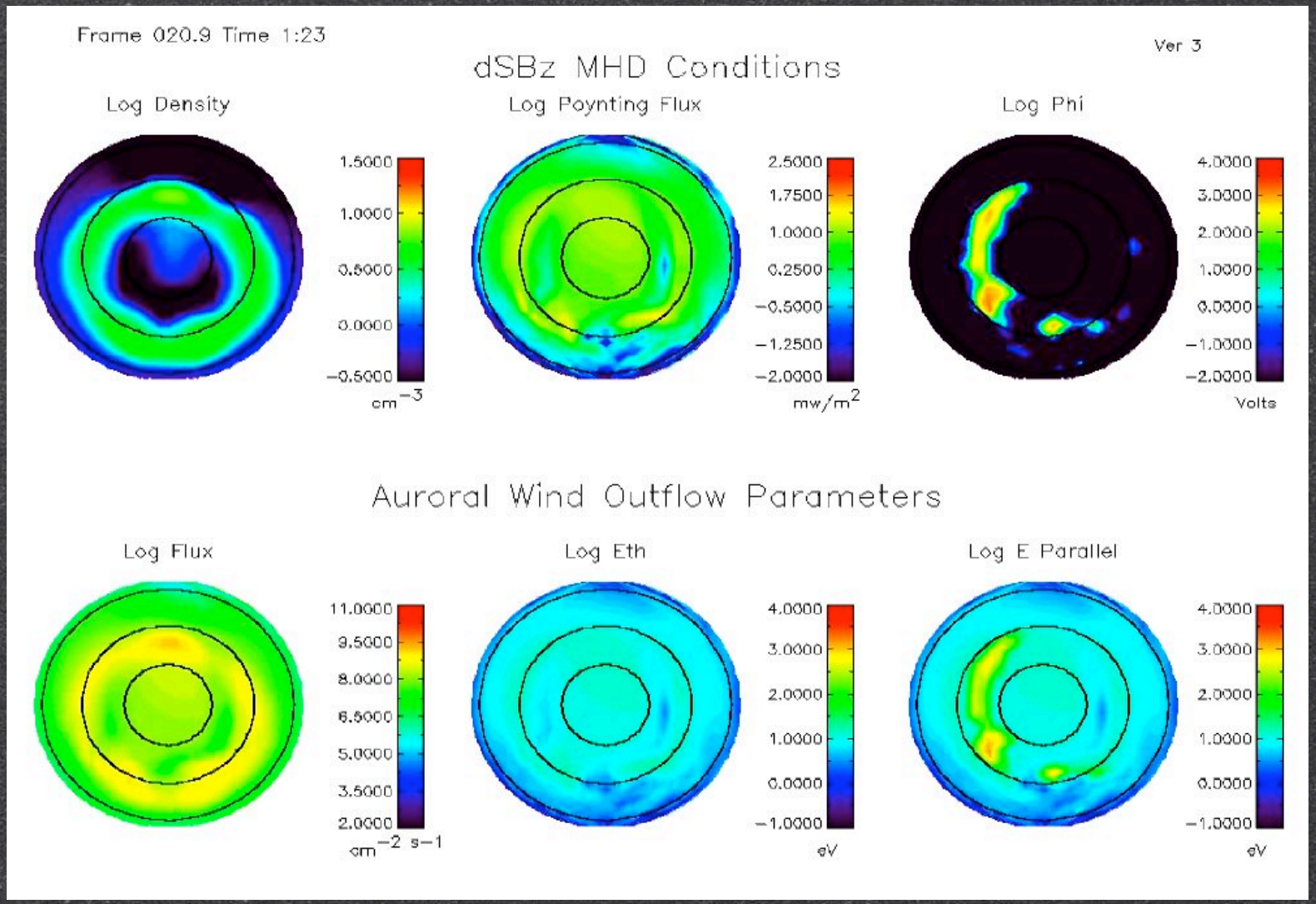
* Indicates parameters that remain poorly determined from empirical studies

Parameter	Scaling	Notes
Auroral wind O+ flux	NVprecip = 2.8e9*(N/10)$^{2.2}$ [cm^{-2}s^{-1}] NVpoynt = 5.6e7*(0.245*S_{120})$^{1.26}$ [cm^{-2}s^{-1}] NV = NVprecip + NV poynt Strangeway et al. [2005 JGR] Zheng [2005 JGR]	N is LFM density in cm^{-3}; * N/10 is assumed fraction of density above instrumental Emin S_{120} is LFM Poynting flux in mW/m^2 at 120 km altitude; 0.245 maps from 120 to 4000 km alt. Fluxes mapped to 1000 km
Auroral wind O+ temperature	0.1 + 9.2*(0.24*S_{120})^0.35 [eV]	Strangeway [private communication]
Parallel energy	$E_{//}$ [eV] = E_{th} + ePhi[V] where Phi[V] =1500[V/μAm^{-2}] *($J_{//}$ - 0.33)^2 [μA m^{-2}]	Moore et al., 1999 SSR Lyons [1981 Geo.Mono. 25] * Threshold current 0.33 μA/m^2 Also applied to polar wind, below
Polar Wind H+ flux	0 < SZA < 90: F_{1000} = 2x10^8 cm^{-2}s^{-1} 90 < SZA < 110: NV_{1000} = 2 x 10^(8-(SZA-90)/20*2.5) 110< SZA < 180: F_{1000} = 2 x 10$^{5.5}$	Su et al., [1998 JGR] solar zenith angle (SZA) dependence All fluxes at 1000 km altitude

Detailed specifications for local response to MHD b.c.

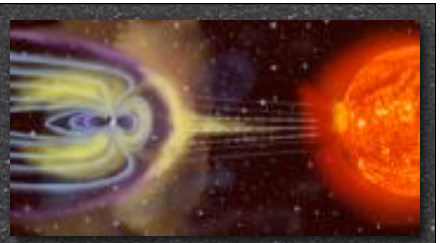
IMF ∂Bz: Auroral B.C.

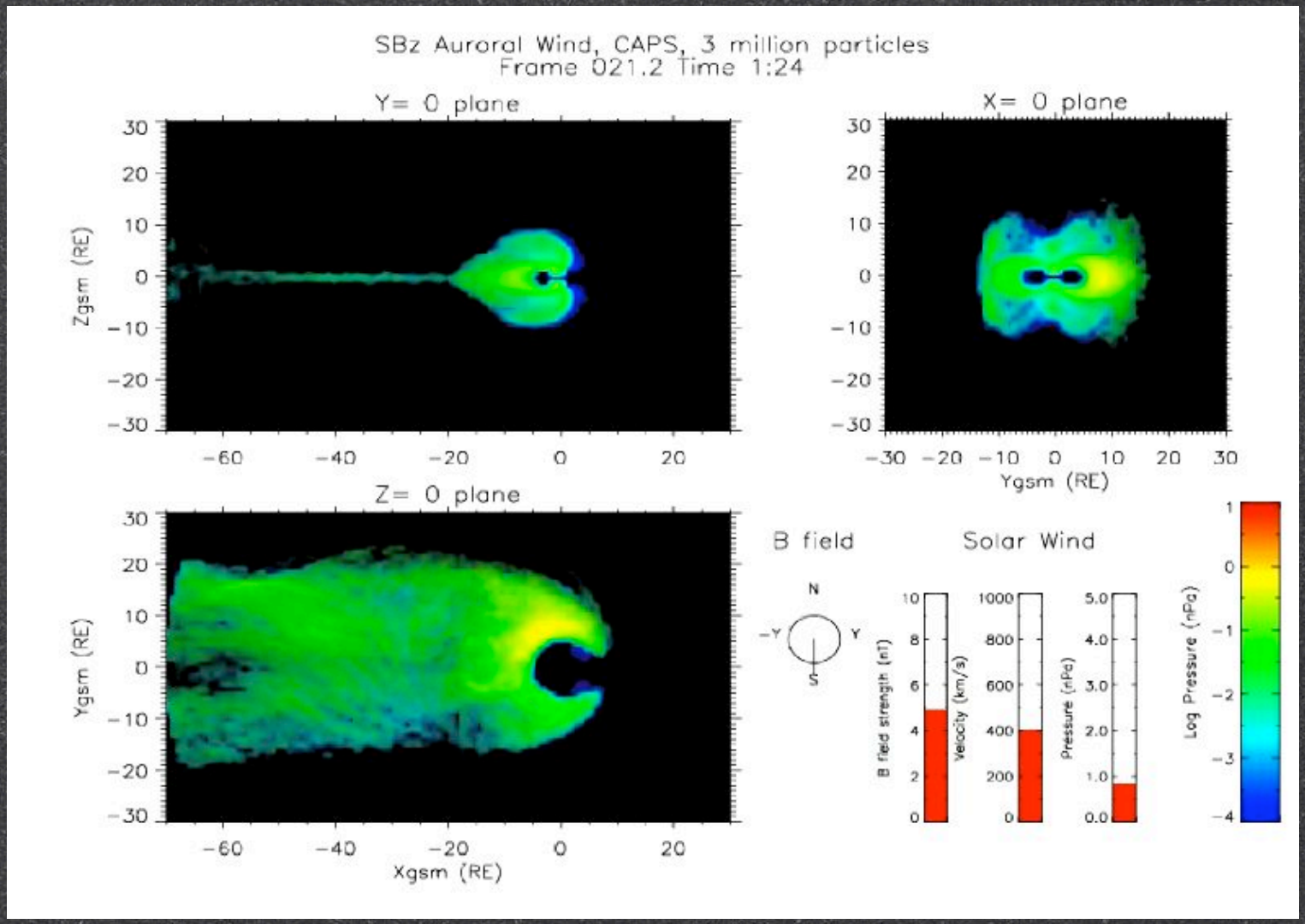




Poynting Flux, soft electrons, and $J_{//}$ drive outflows

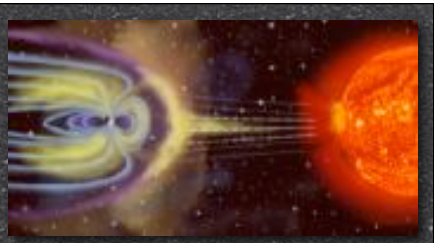
Role of IMF ∂Bz: Auroral Wind

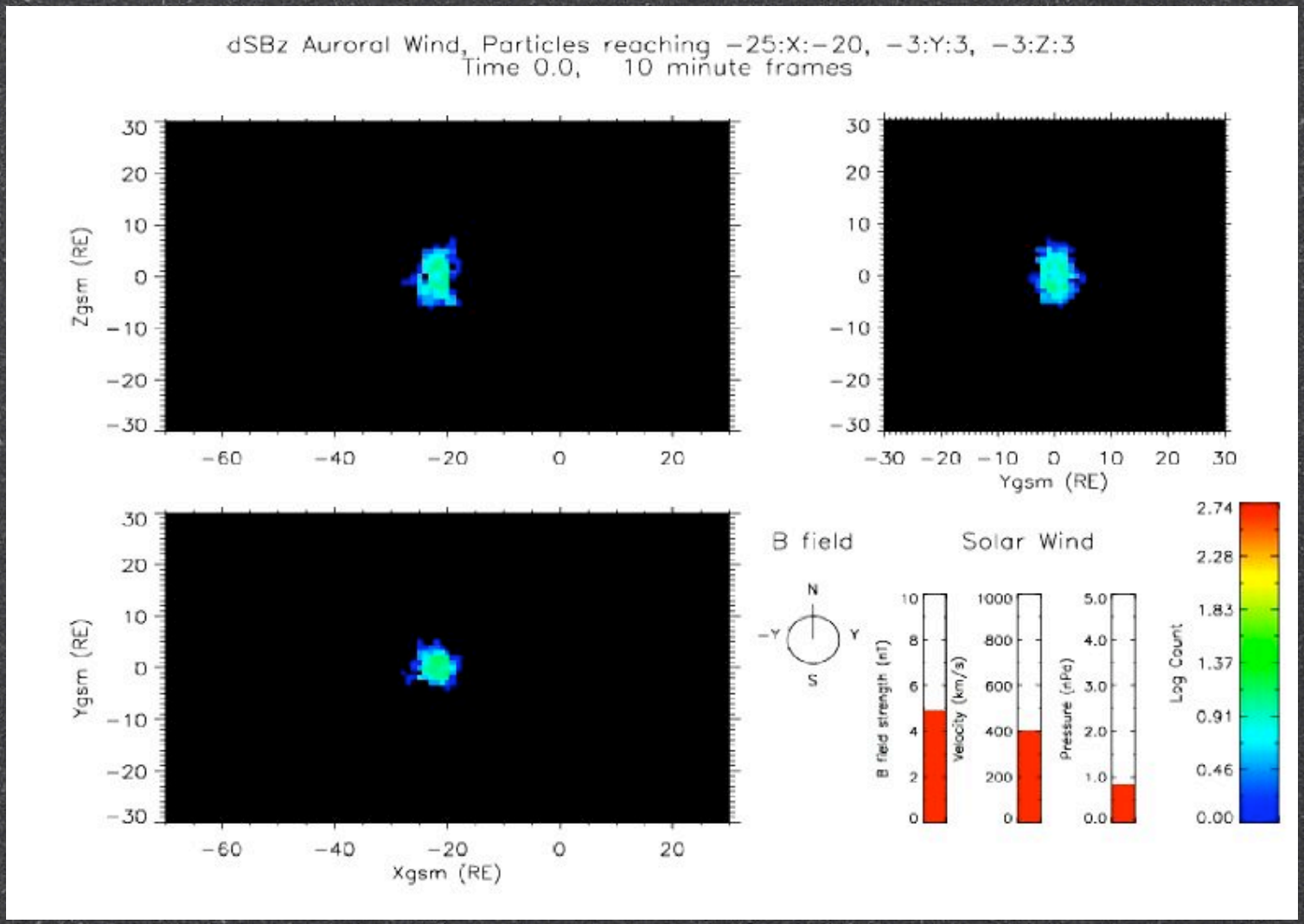




Initial void is filled with O+ outflows as SBz takes effect

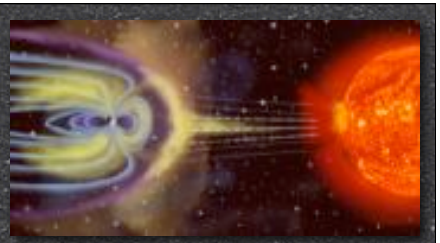
Auroral Wind Pathways To PS





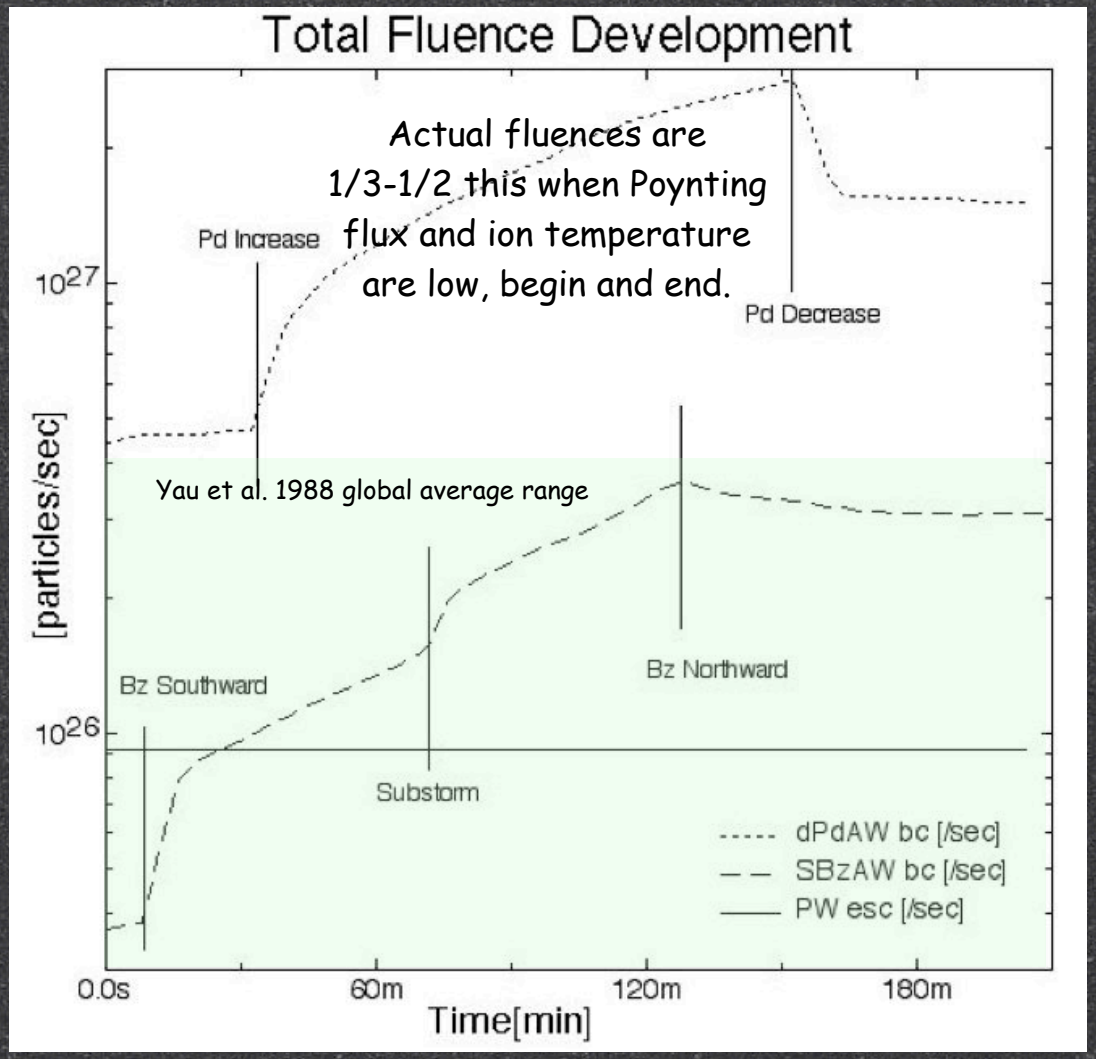
Auroral wind paths arrive at CPS from caps through the lobes

Global Ionospheric Outflow



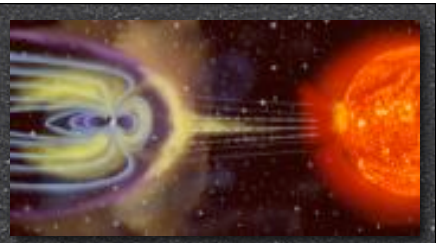
- Upper trace:
  Pd increase 2 hrs
  0.45 to 4.5 nPa
  from:
  Bz = 0, By = 5nT

- Lower trace:
  SBz for 2 hrs
  from: NBz 5 nT
  Pd = 0.8 nPa

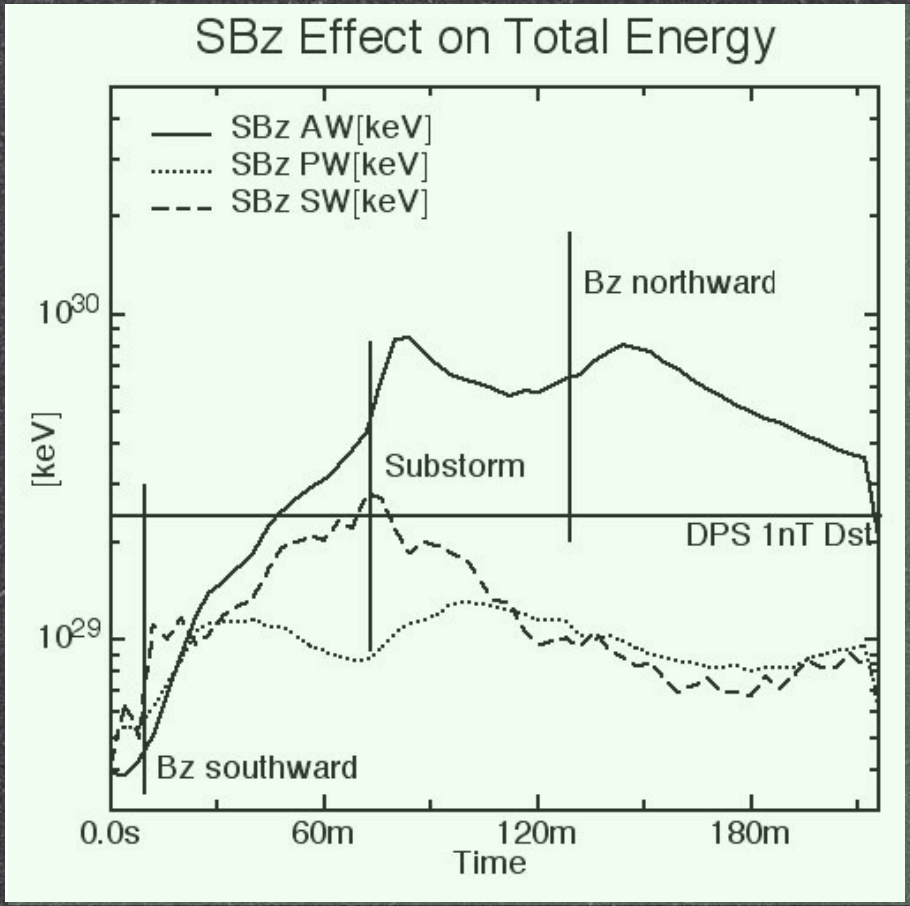


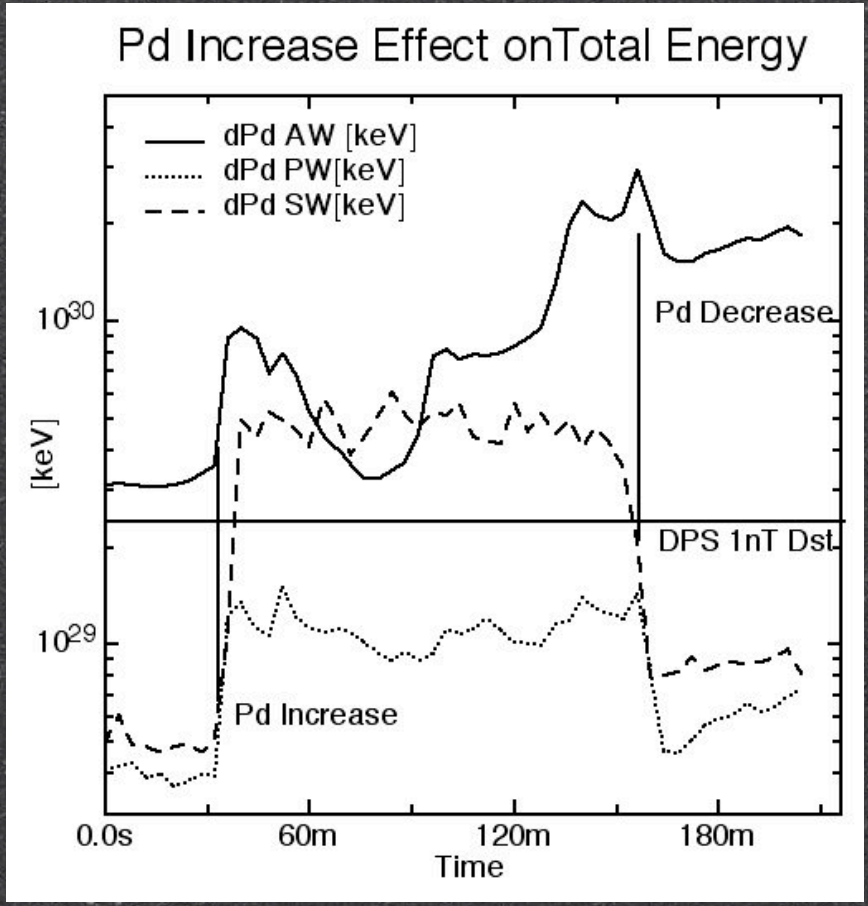
SBz and Pd both enhance outflow, only NBz suppresses

Energy of Ring Current



- Total Energy developed inside 15 Re or Magnetopause

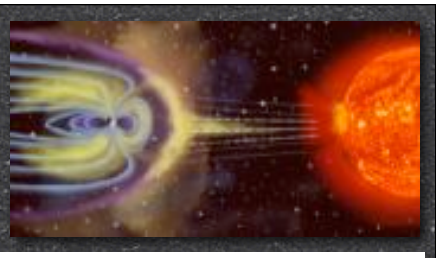




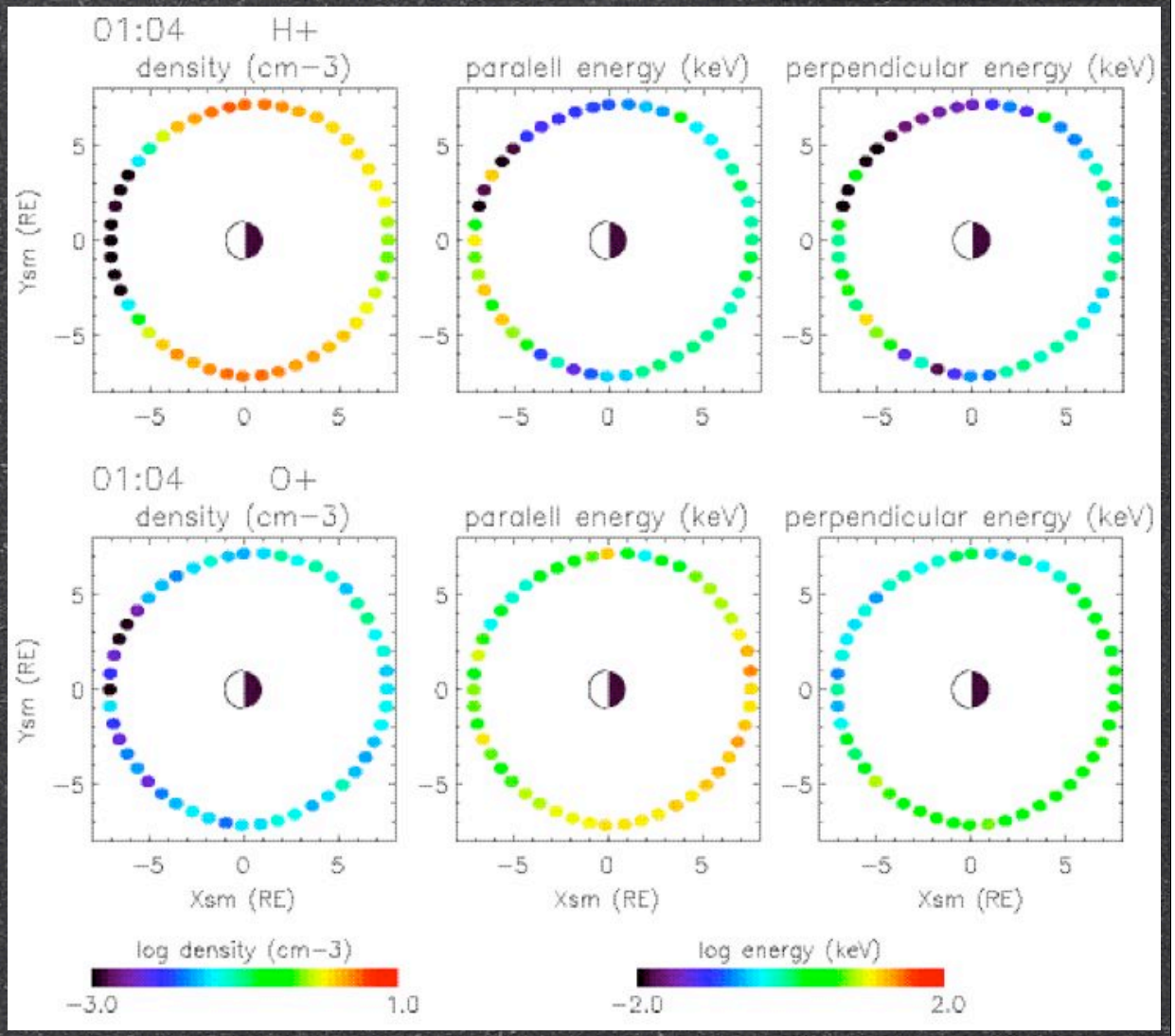
As we know, MHD alone does not produce much ring current

Modeling Inner Magnetosphere

Fok, Wolf et al. Comprehensive Ring Current Model

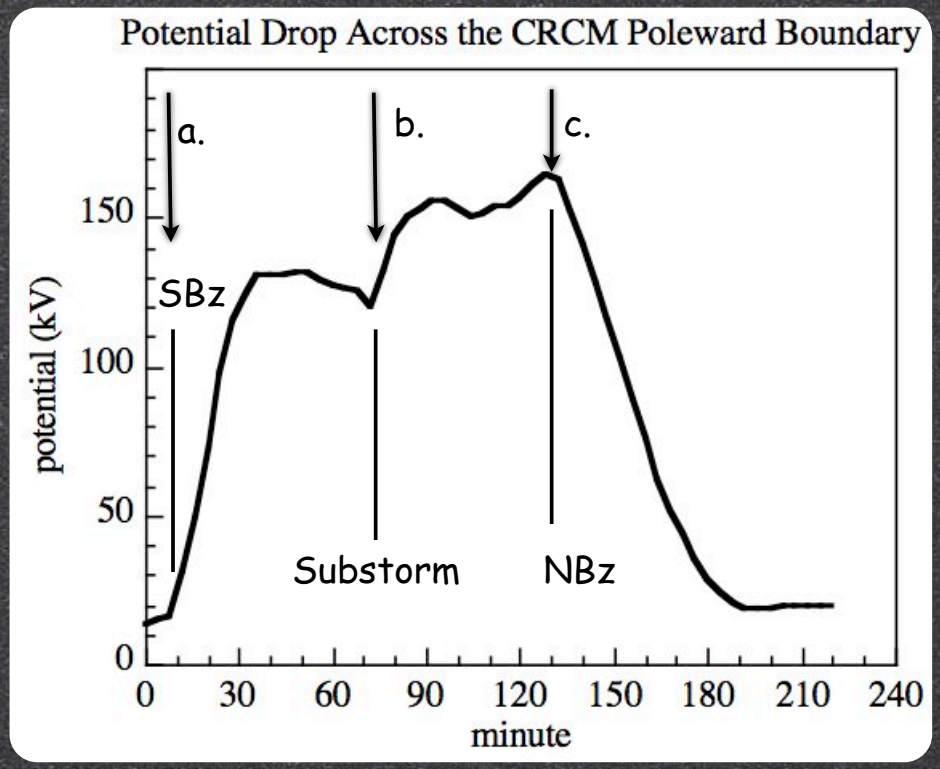


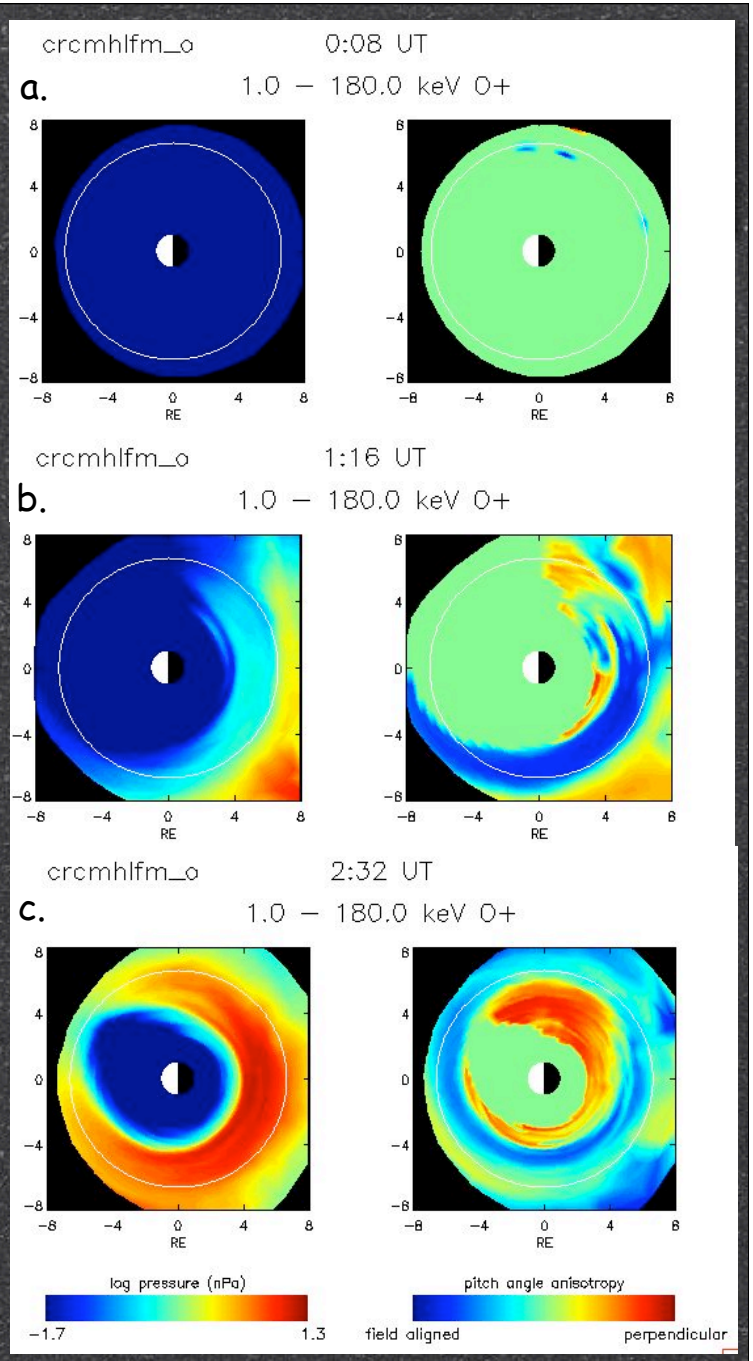
- Driven by V_{TP} MHD imposed
- Supplied by b.c. @ 8 R_E from test particles
- Flow/E loaded by coupled ionosph. conductivity
- Losses accounted
- Self consistent **V**, **E** in inner mag'



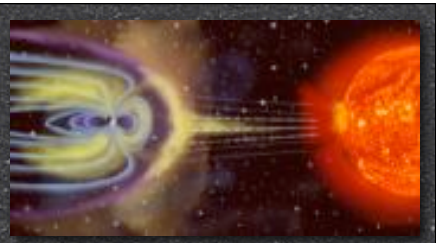
LFM-CRCM Combined Global Pressure Response

- Right: O+ pressure and anisotropy distributions
- Below: driver potential

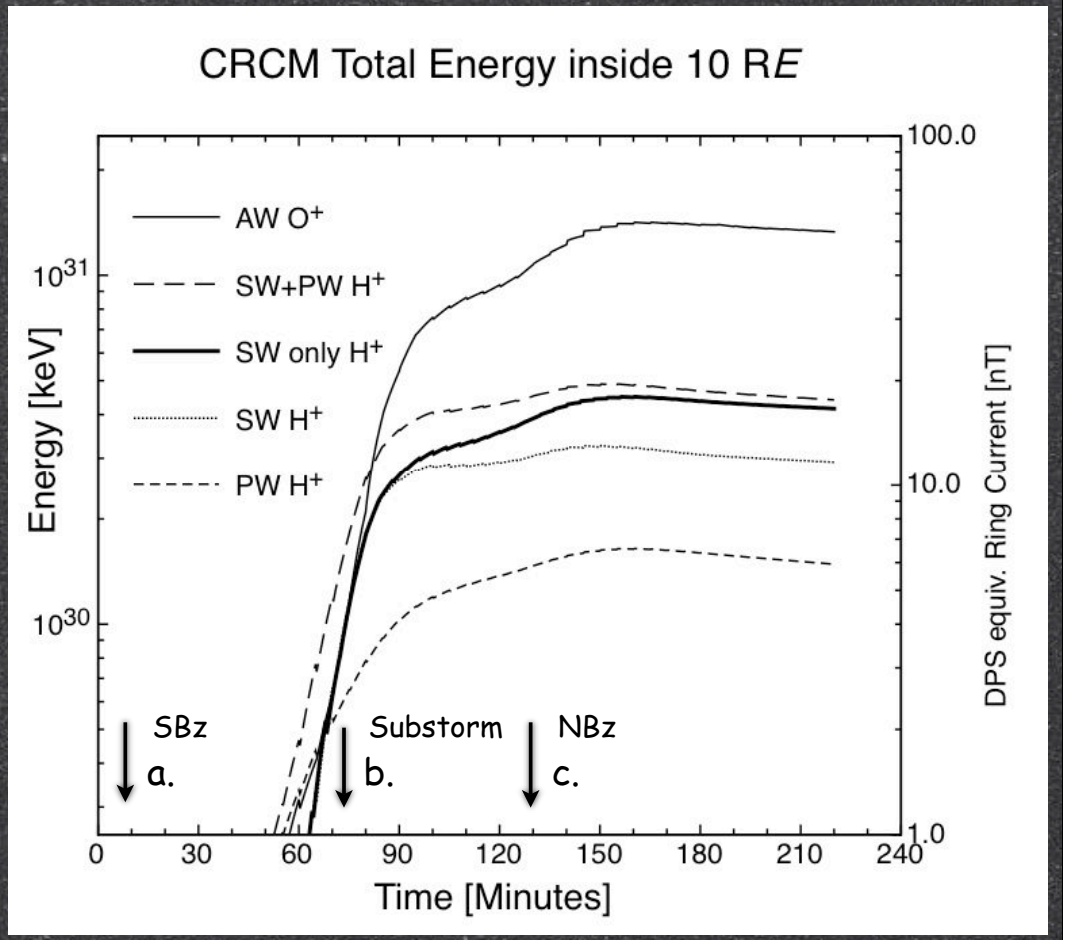




LFM-CRCM Integrated Ring Current



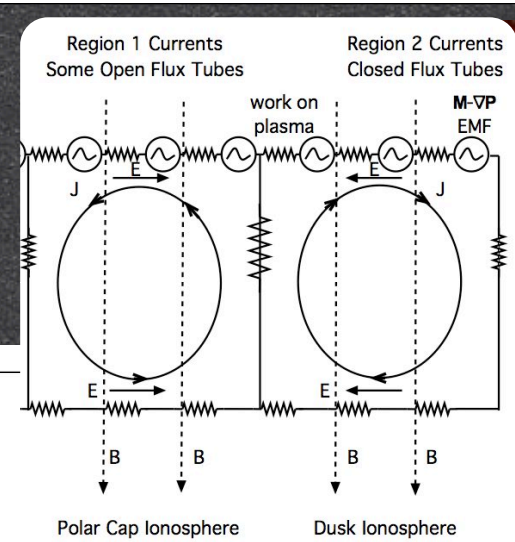
- With outer b.c. for SW, PW, AW from test particle results above
- ~60 nT from O^+
  ~20 nT from H^+ (SW+PW)
- SW H^+: ~18 nT
- What features of CRCM are responsible for this?
  - Anisotropic drift physics, plasma sources, conductance, composition?

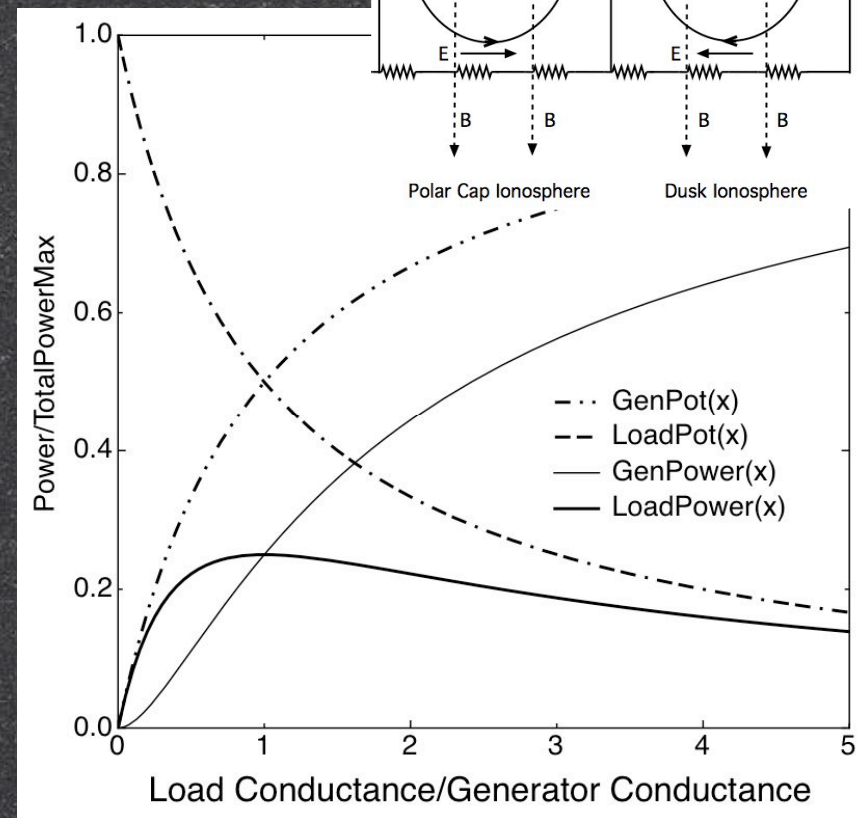


- Ionospheric O^+ dominates when supplied per this prescription

What about Conductance?

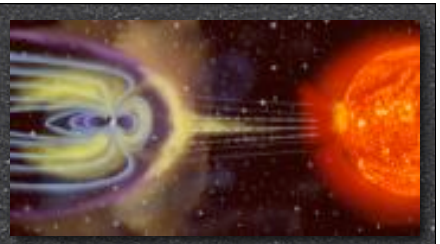
- Ebihara, 2005 JGR stressed importance
- Simple generator-load result:
- If draw excess power, drive gen. into current source mode, reduce load pot. & power:
- Max energy transfer for matched conductances
- "Brownout" makes generator take over as the load





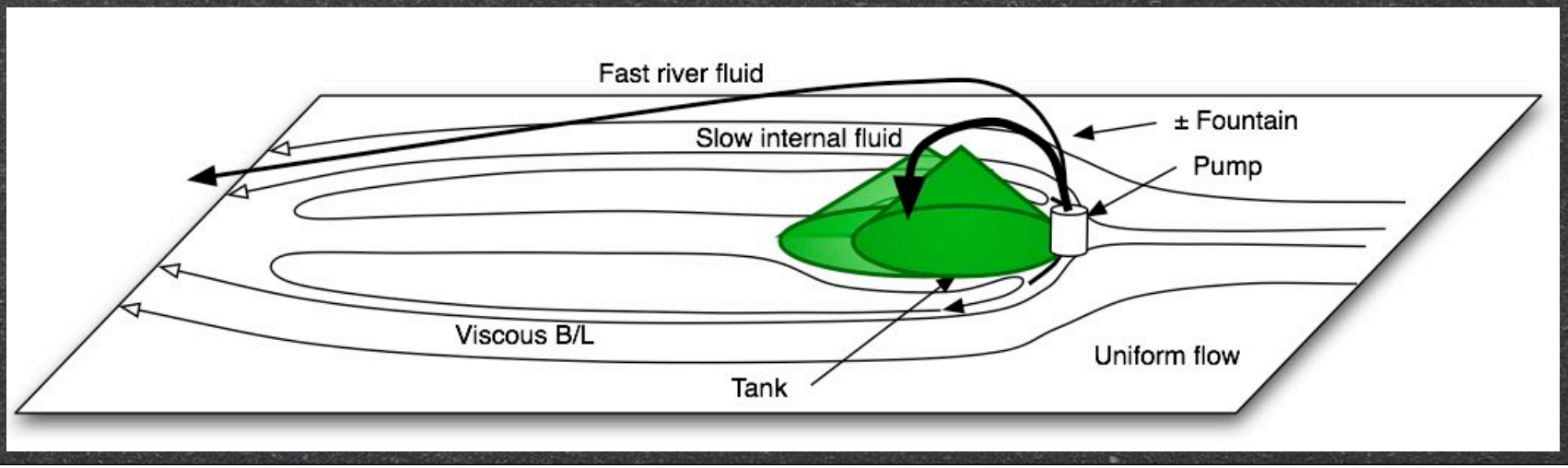
- More conductance makes more ring current: O^+ becomes the generator-load for inner magnetosphere

Why is Ionosphere So Important?

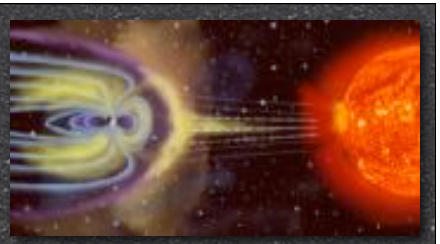


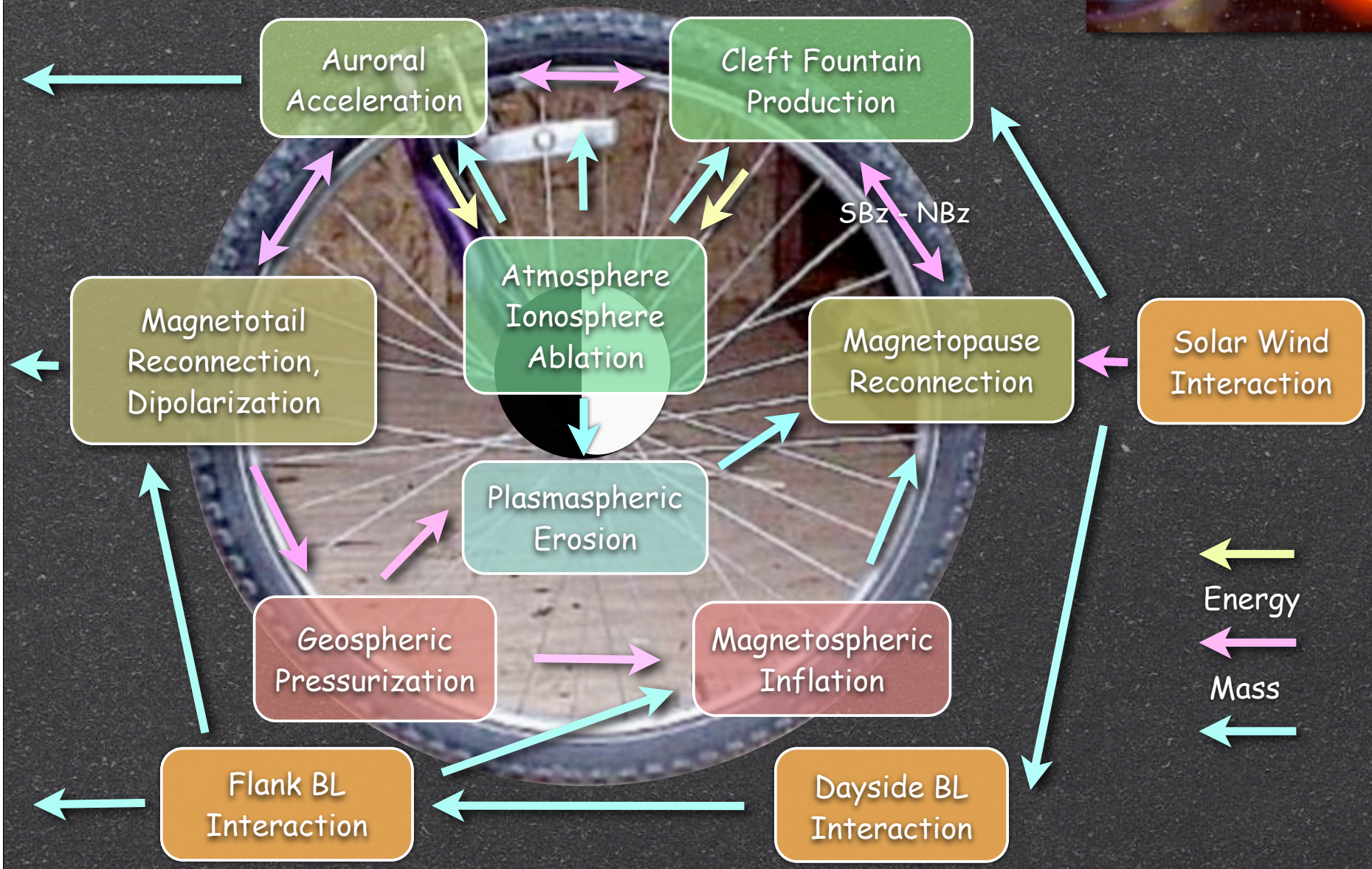
- Ionosphere starts out "inside the tank"
- Heavy and slow enough to remain "in the tank" for multiple passes through "the pump"
- Lower energy particles respond more radially to given size ∇**P**-driven **E** field
- Ionospheric plasmas become load on the generator for the inner magnetosphere in brownout (current supply) mode

"Ionospheric plasma is heated, pumped, and compressed by the solar wind, causing it to expand into and inflate the magnetosphere, until it escapes into the solar wind."



The Self-Pumping Bicycle Tire





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