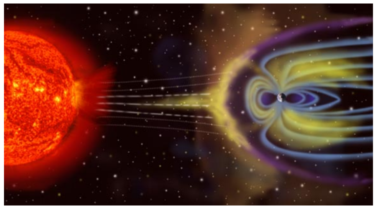
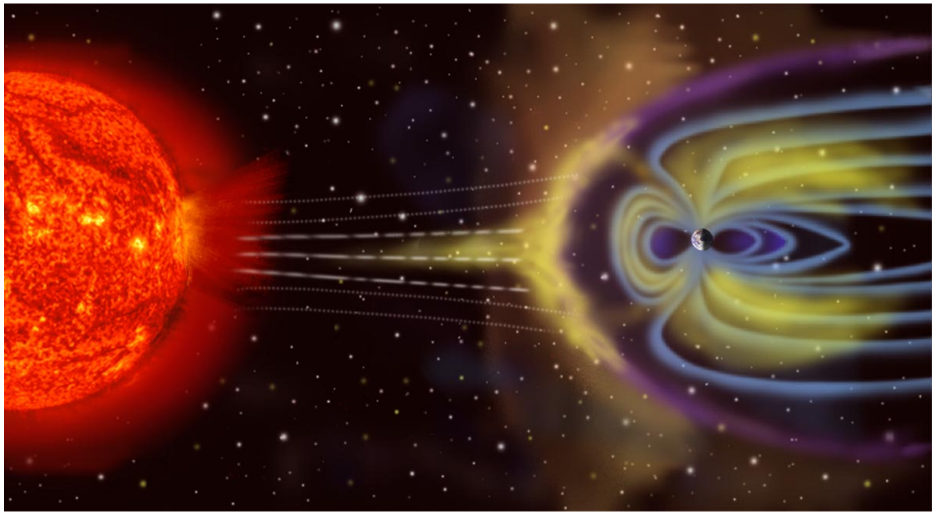
The Magnetosphere as a Sink of Ionospheric Plasma



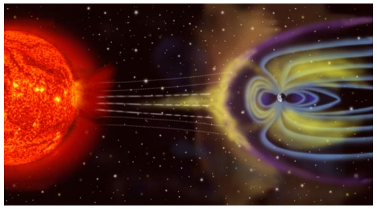
- T. E. Moore, NASA GSFC LEP Code 692, Greenbelt, MD 20771 USA

Outline:

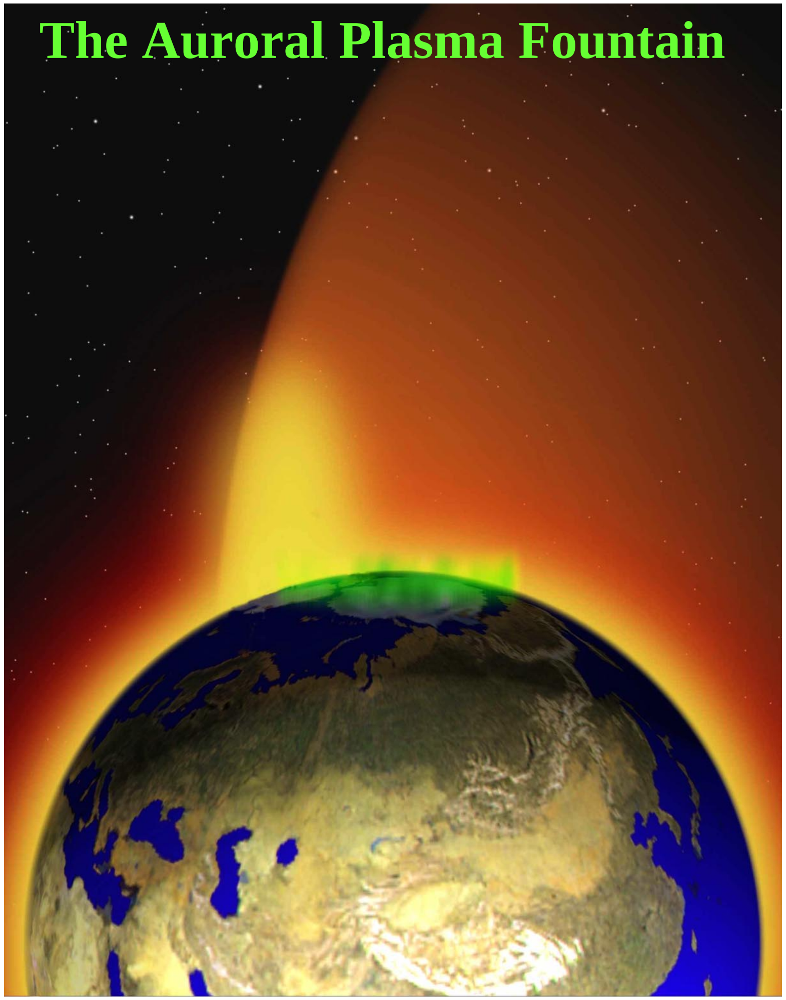
- Ionospheric formation, transport, distribution
- GeoMagnetopause, Geopause
- Auroral zone and polar cap
- Spatial, Temporal anadiabaticity
- Dipolarizations and Ring Currents
- Improving on cartoons
- Expanding horizons
- Conclusions



Outflow Basics

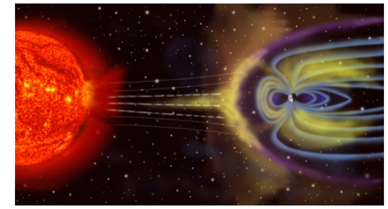


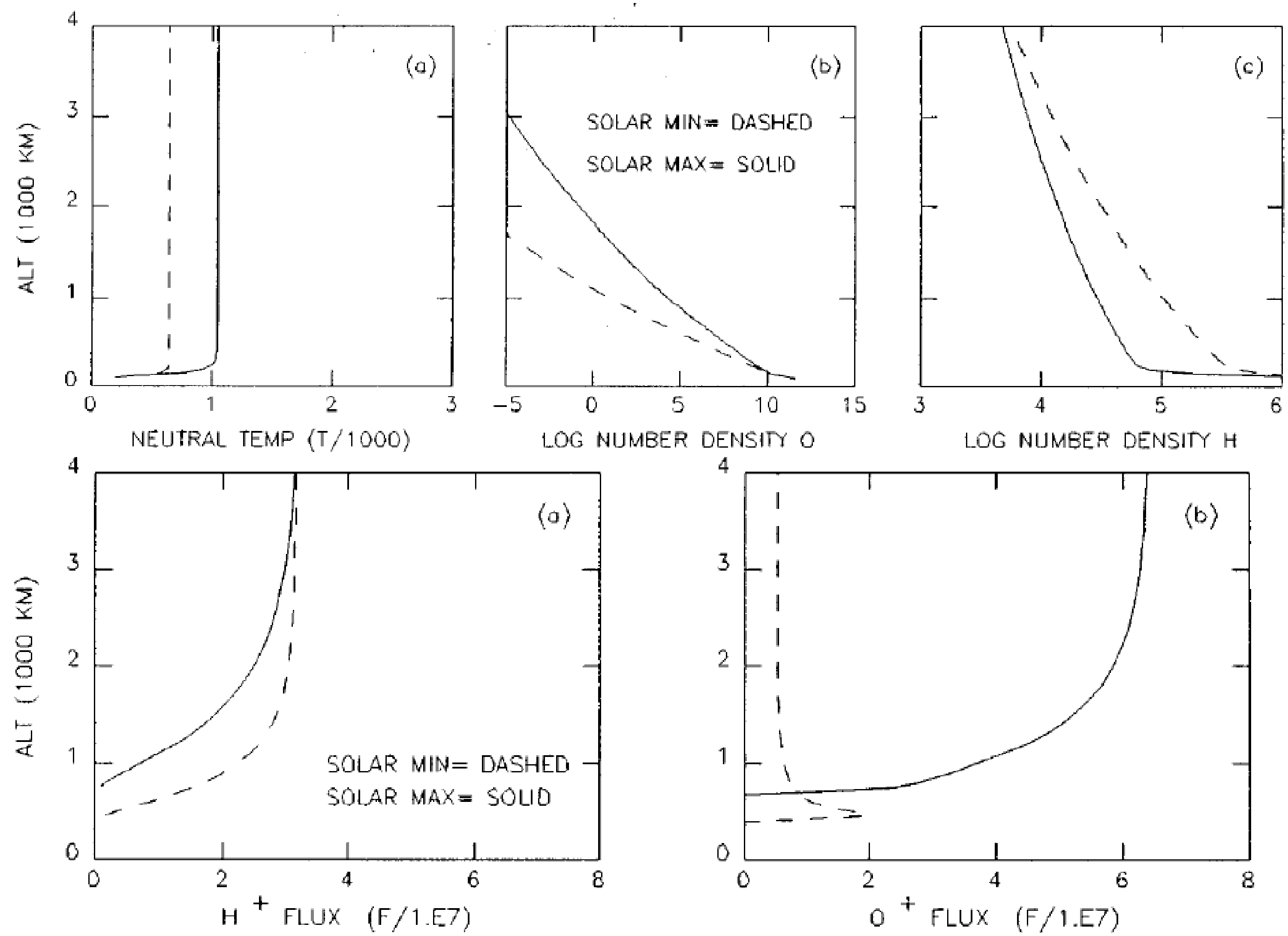
- $(T/T_{esc})_{earth} > (T/T_{esc})_{sun}$!
  - For H^+, not O^+!
- Outflow flux is limited by CE, friction:
  - H^+ on O, O^+; O^+ on O
  - $F_{l,H+} \sim 3x10^8\ H^+\ cm^{-2}s^{-1}$
  - $F_{l,O+} \sim 3x10^{10}\ O^+\ cm^{-2}s^{-1}$
- Ambipolar $E_{//}$
  - Couples e^- with i^+
  - Fast e^- take ions with them
- Type 1, Type 2 Outflows
  - e^- heating, i^+ heating
  - Either suffices



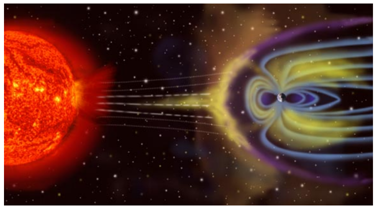
Courtesy of D. L. Gallagher

Ionospheric Structure, Solar Variations





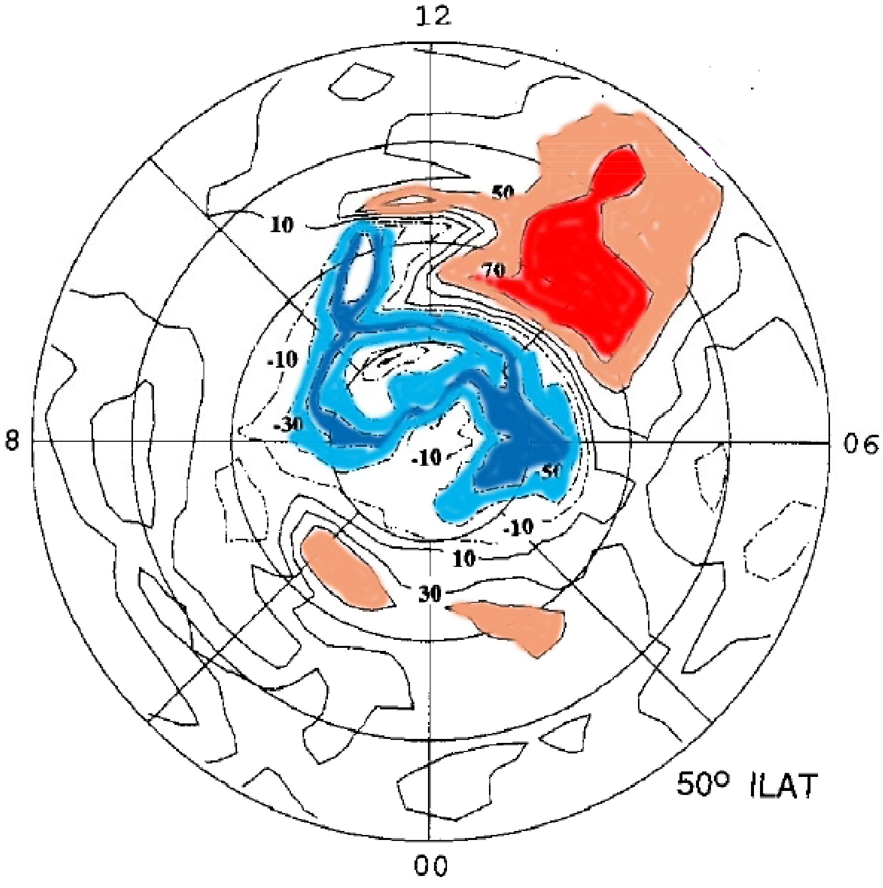
Cannata and Gombosi. '89 GRL



3D Ionospheric Circulation

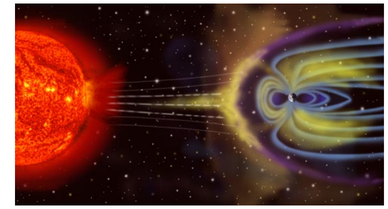
- Ionospheric circulation is 3-dimensional
- FA motions are variable, fluxes far exceed escape:
- Streamlines thread entire high lat magnetosphere
- Plasmasphere defined by convection dichotomy:
- But, also can be defined by slow FA velocities
- MUST think in terms of the response of plasma flux tubes as they circulate

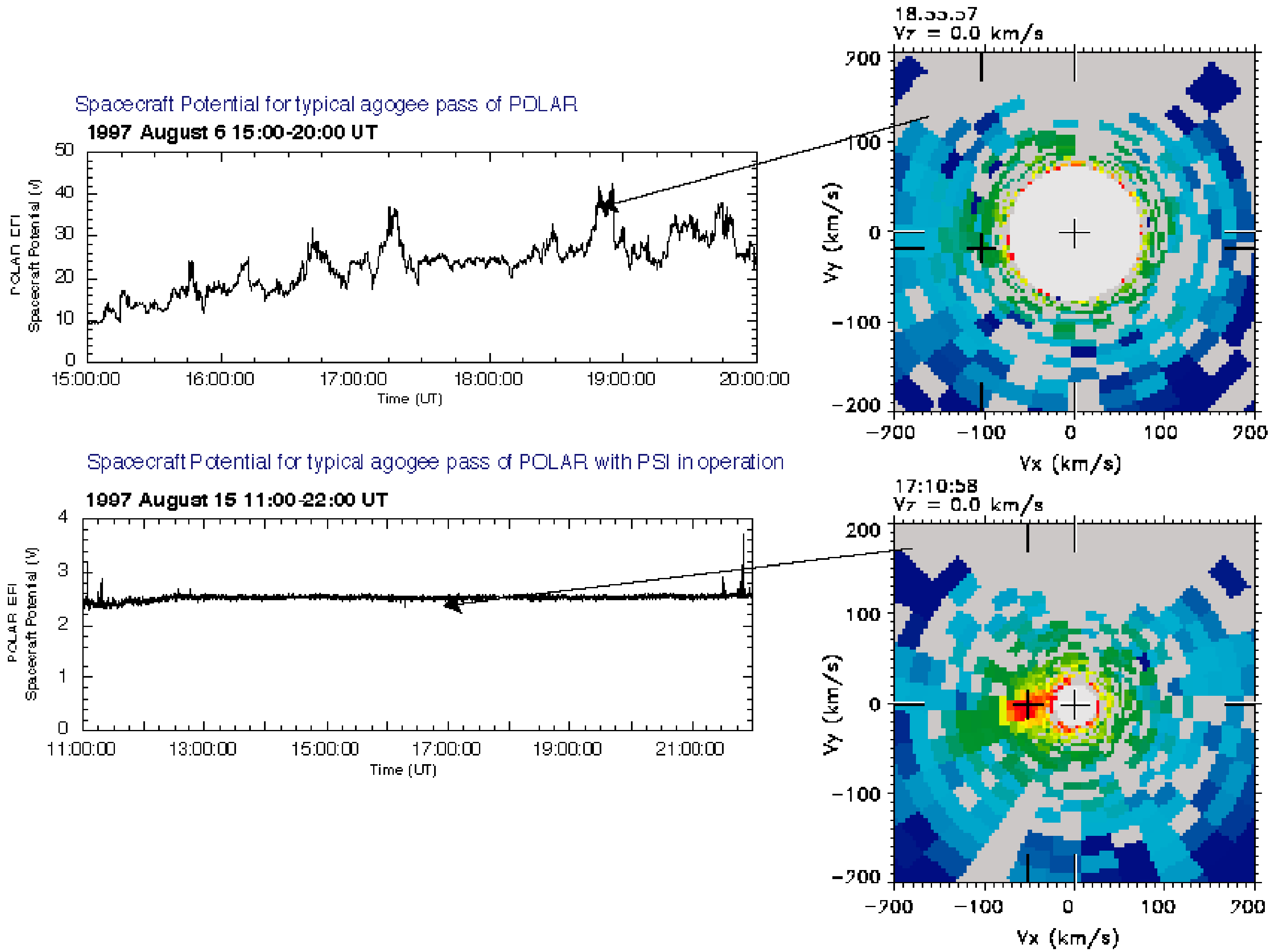
Red/Blue shift rel. to Earthbound observer.

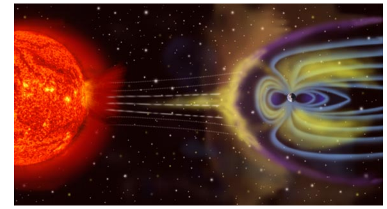


Heelis et al. JGR ‘92

S/C Neutralization Fills Polar Cap “Void”

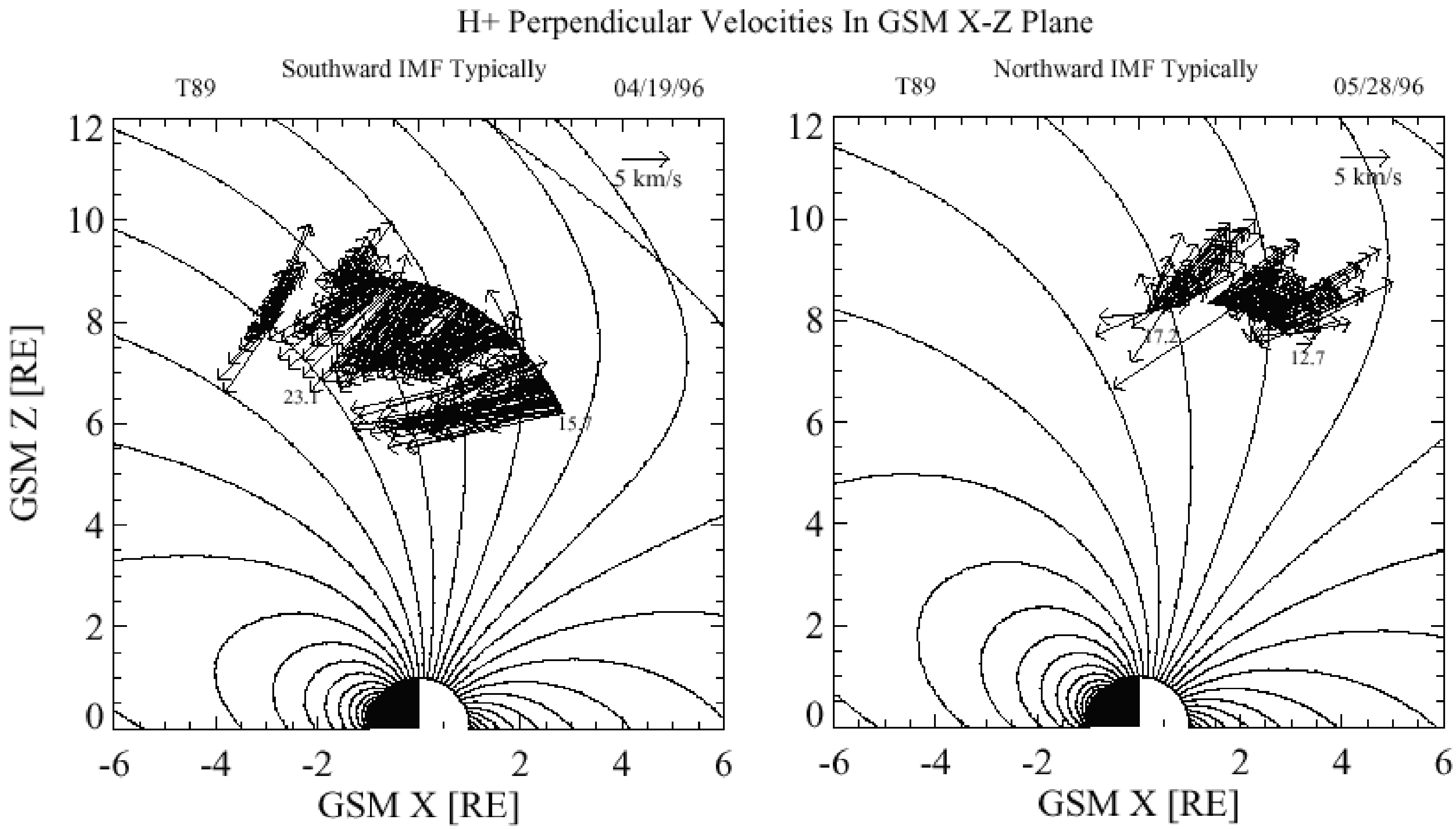


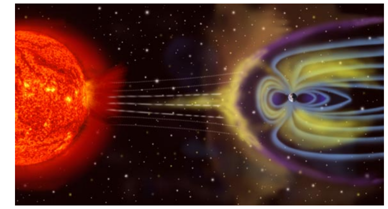




Polar Wind Convection

- High latitude convection observable in the polar cap.
- Polar wind streamlines responsive to IMF Bz

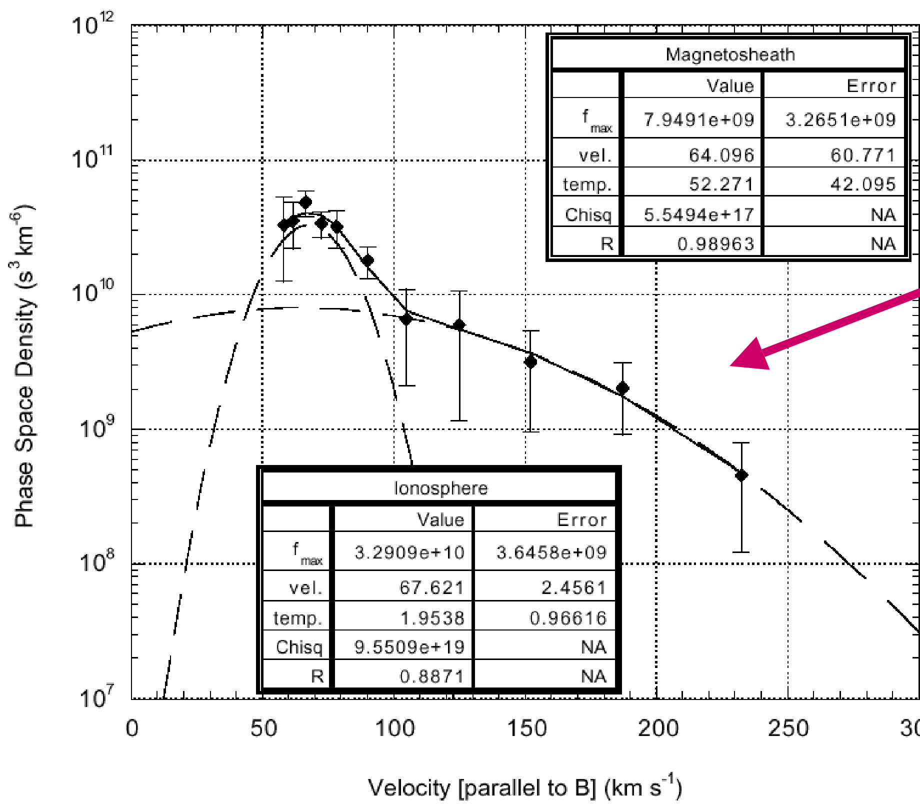




GeoMagnetopause Leaks

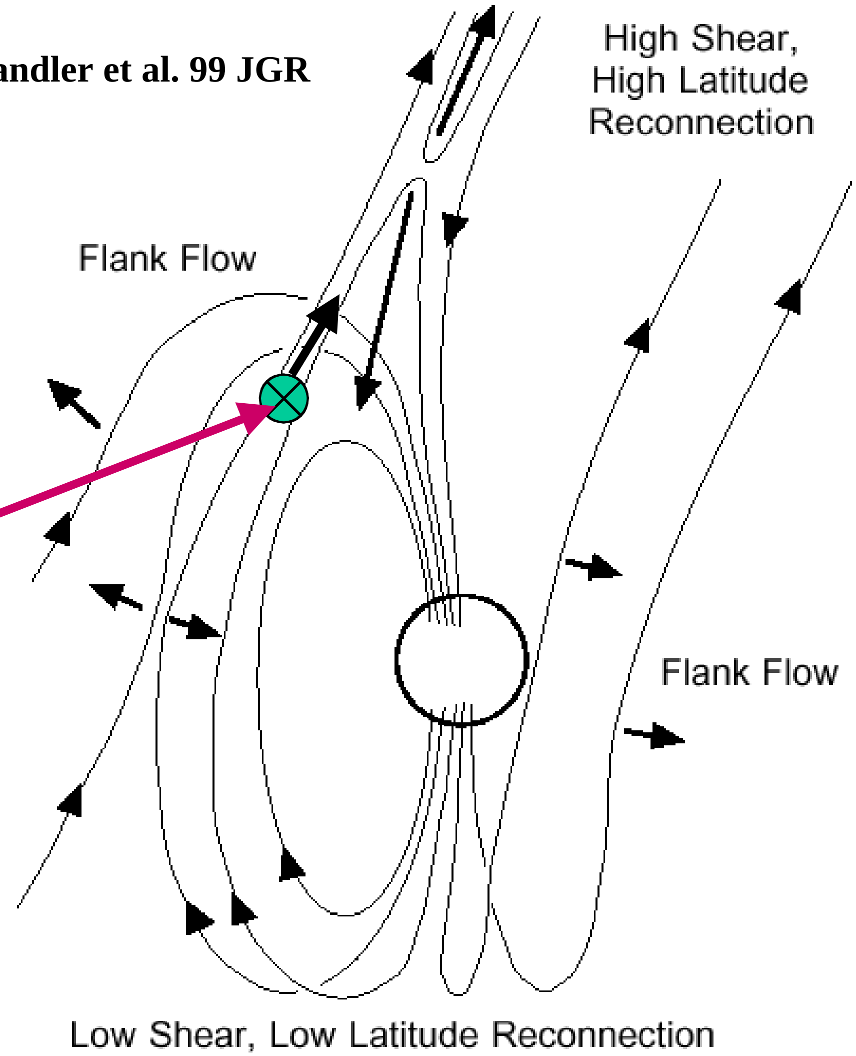
- Reconnection and the boundary layers

Chandler et al. 99 JGR

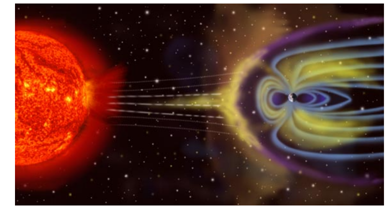


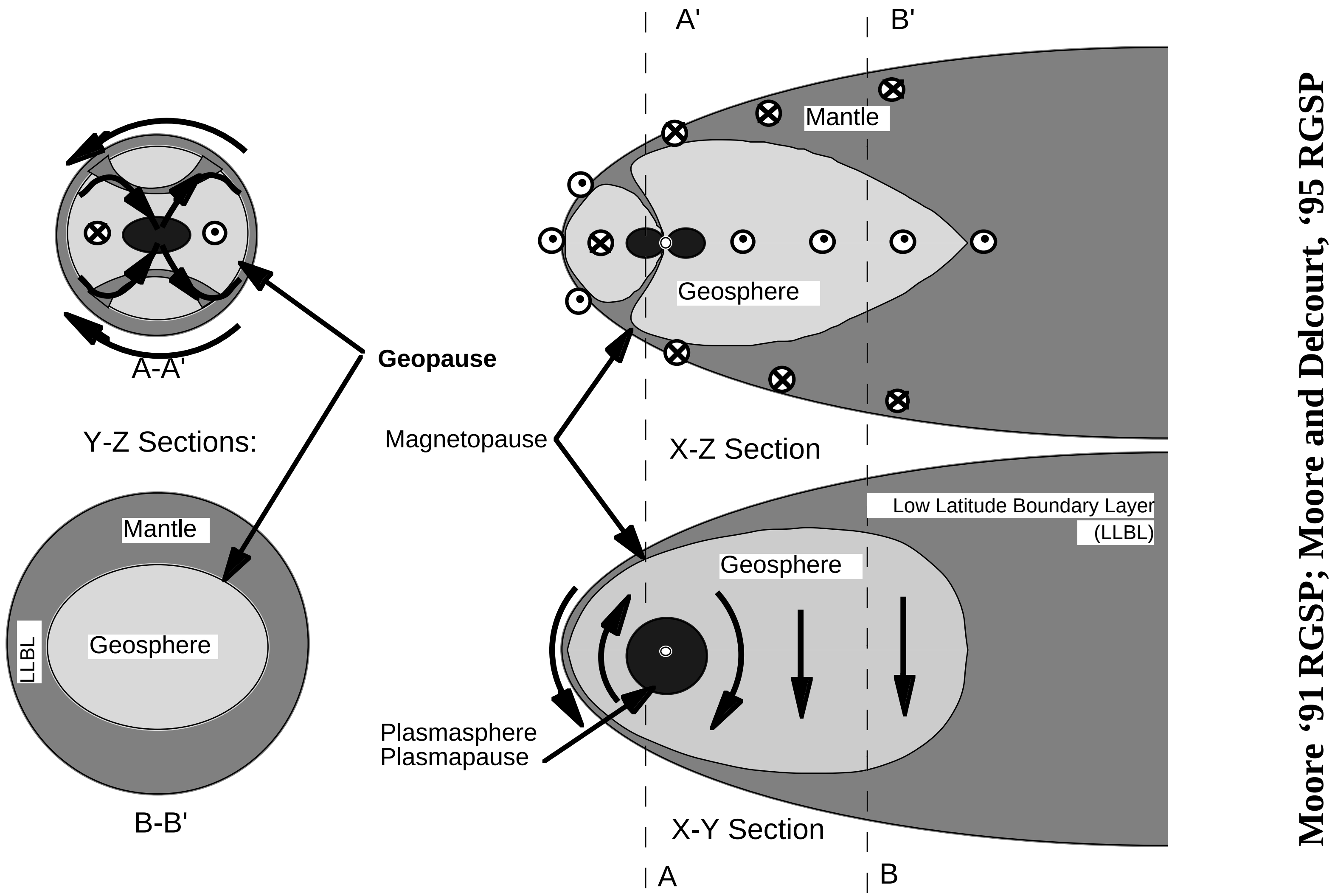
Magnetosheath	Value	Error
f_{max}	7.9491e+09	3.2651e+09
vel.	64.096	60.771
temp.	52.271	42.095
Chisq	5.5494e+17	NA
R	0.98963	NA

Ionosphere	Value	Error
f_{max}	3.2909e+10	3.6458e+09
vel.	67.621	2.4561
temp.	1.9538	0.96616
Chisq	9.5509e+19	NA
R	0.8871	NA



Conceptual Geopause





Arrows indicate position and orientation of major current systems.

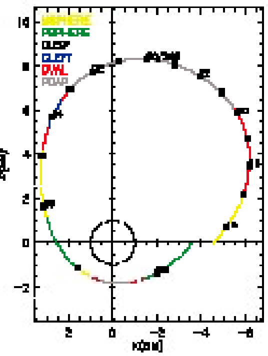
Real Geopause

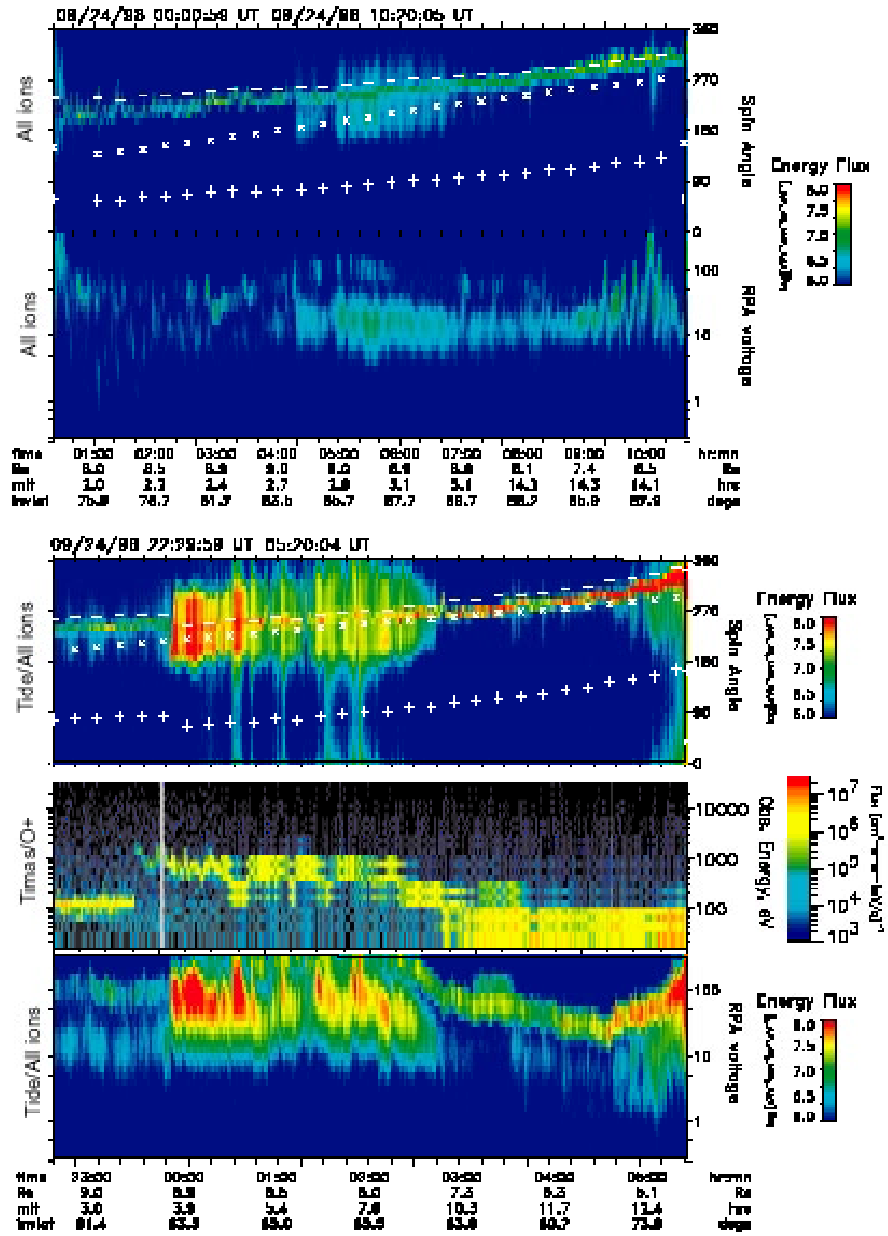
- Solar wind is repelled from magnetosphere by mirror force
- Polar outflows are expelled from the ionosphere by mirror force
- Plasma transition from terrestrial to solar = *geopause*
- Routinely crossed by s/c.

Case Study: September 24-25, 1998 Ionosphere response to CME-generated interplanetary shock and magnetic cloud
TIDE/PSI & TIMAS/ POLAR spacecraft

Apogee pass before event

Apogee pass during event

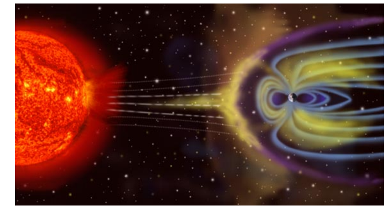




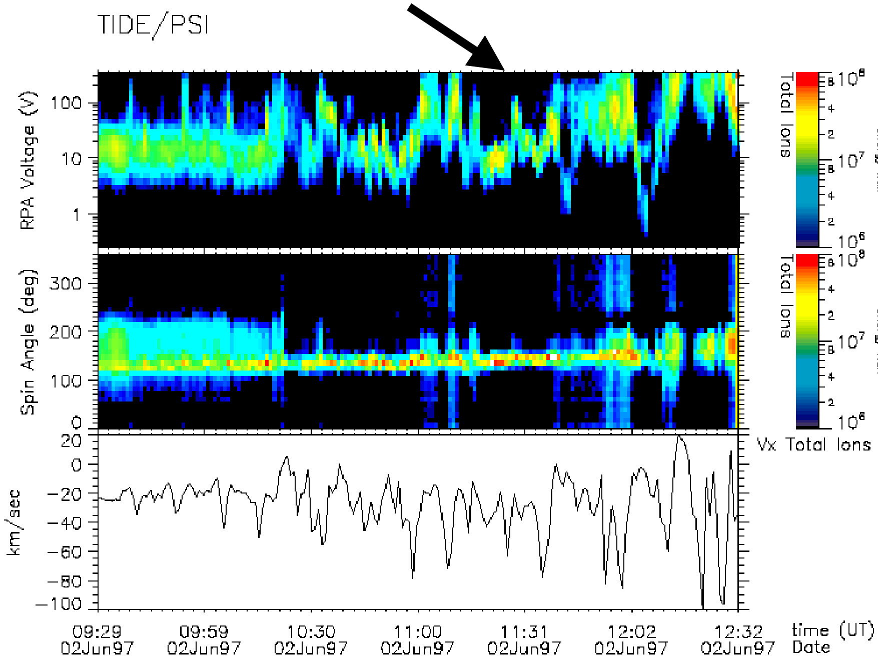
2000|06|27

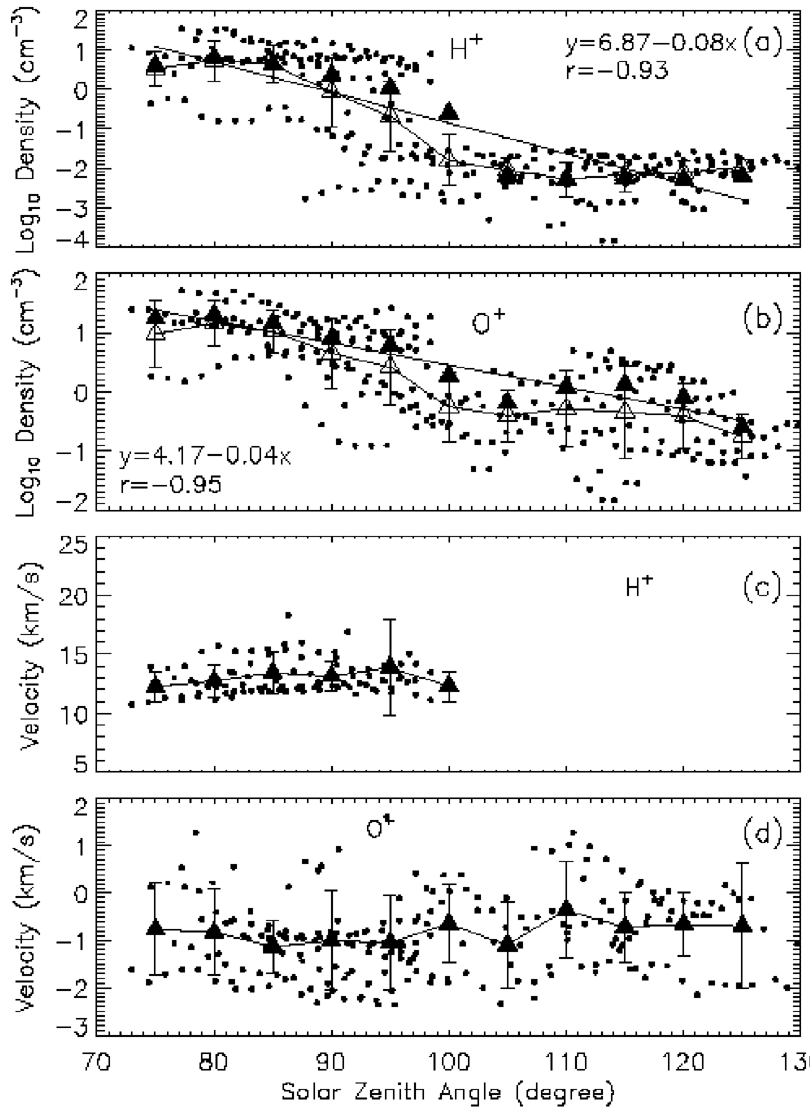
Moore et al. 99 GRL

Polar Cap Structure and Dynamics



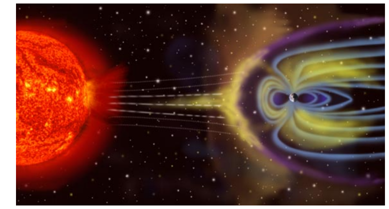
- Fountain effect at ~ 1 RE altitude: decreasing density, downward O+ flow polar cap.
- Polar rain, standing ES shocks, theta-aurora produce strong high altitude surges





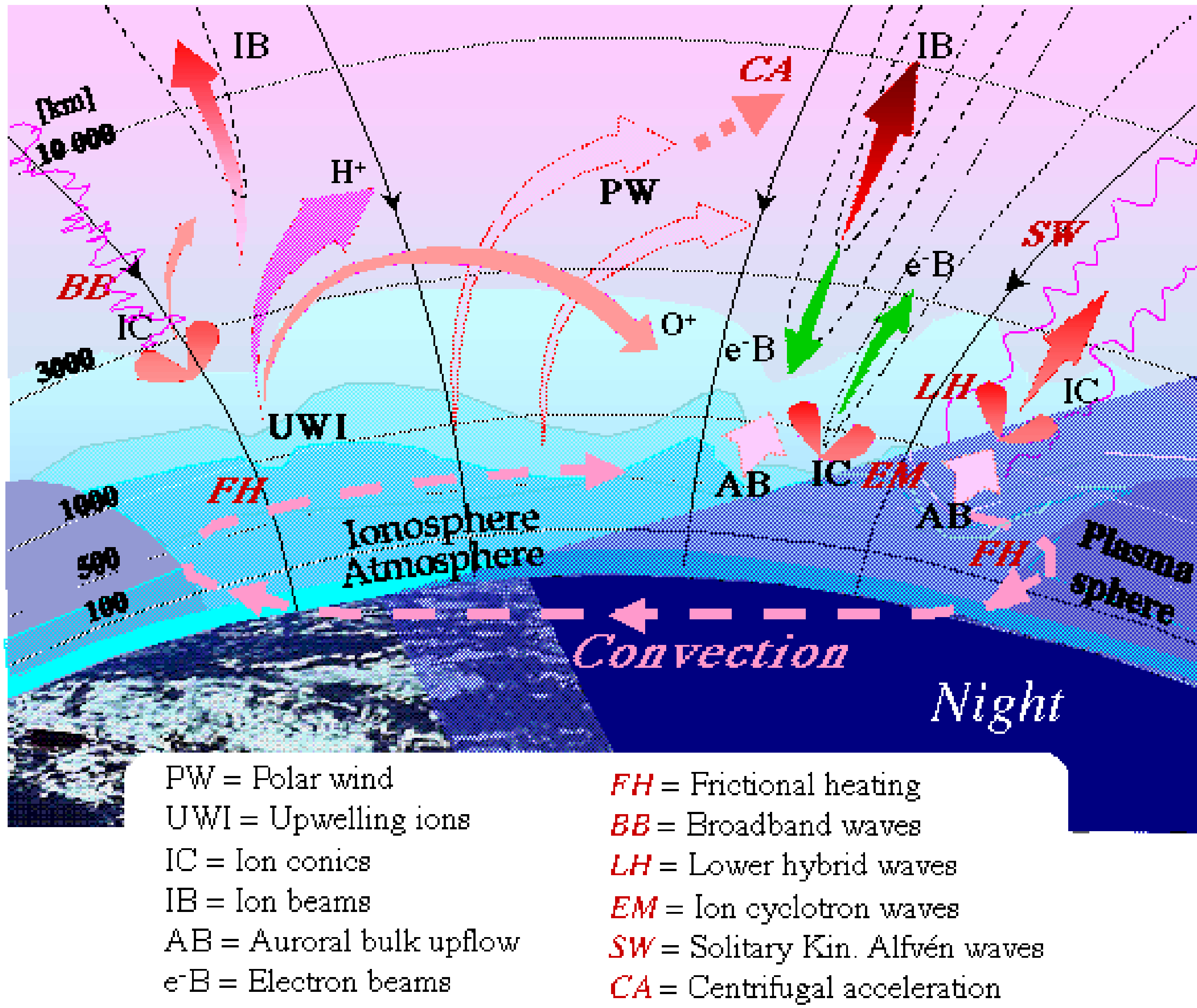
Su et al 98 JGR

Moore 98 GM109

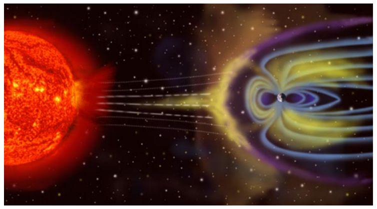


Auroral Source Processes

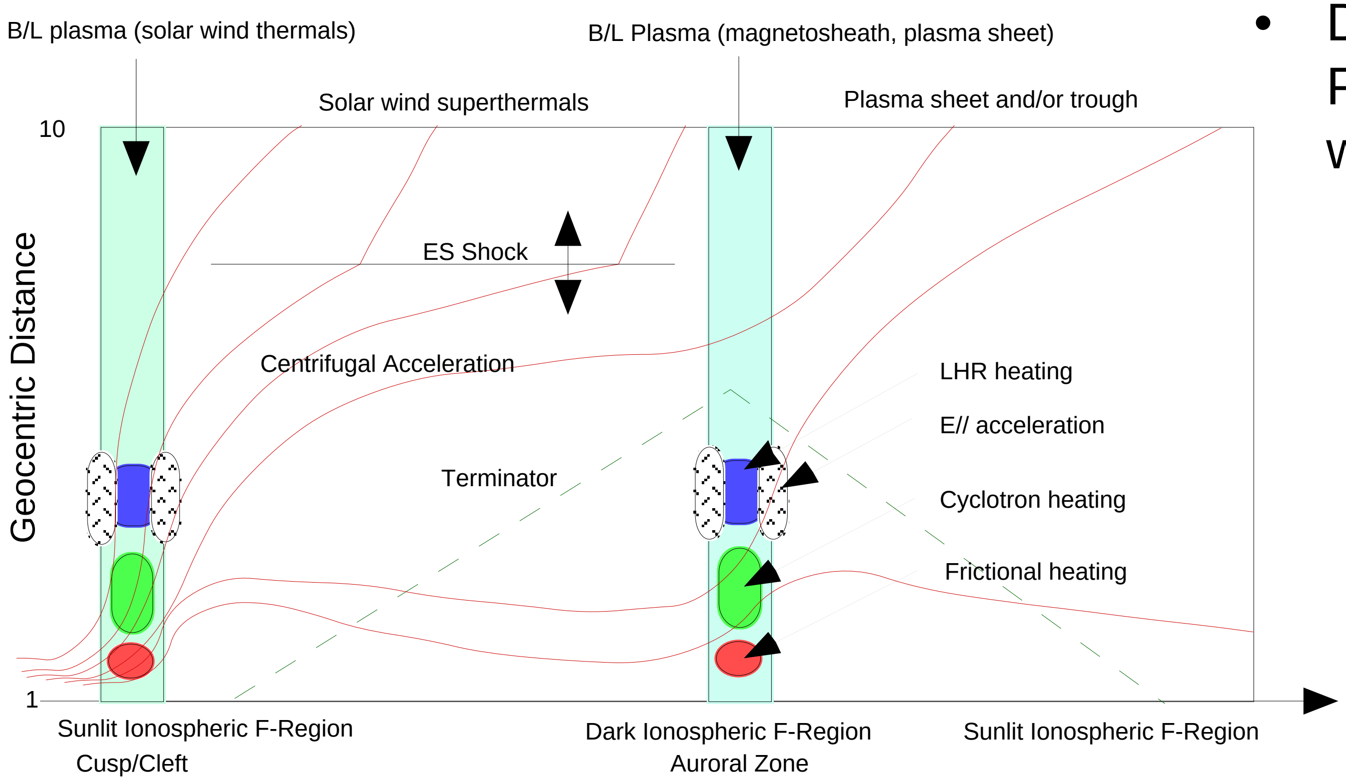
Moore, Lundin et al. 99 SSR



Auroral/Polar Ionosphere

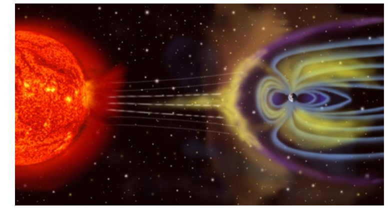


- Circulating Plasma Flux Tubes Are Subject to Many Effects
  - Low: Frictional heating, BBLFWs, Solitary Structures
  - High: LHW, E//, Centrifugal Acceleration, ES Shocks,



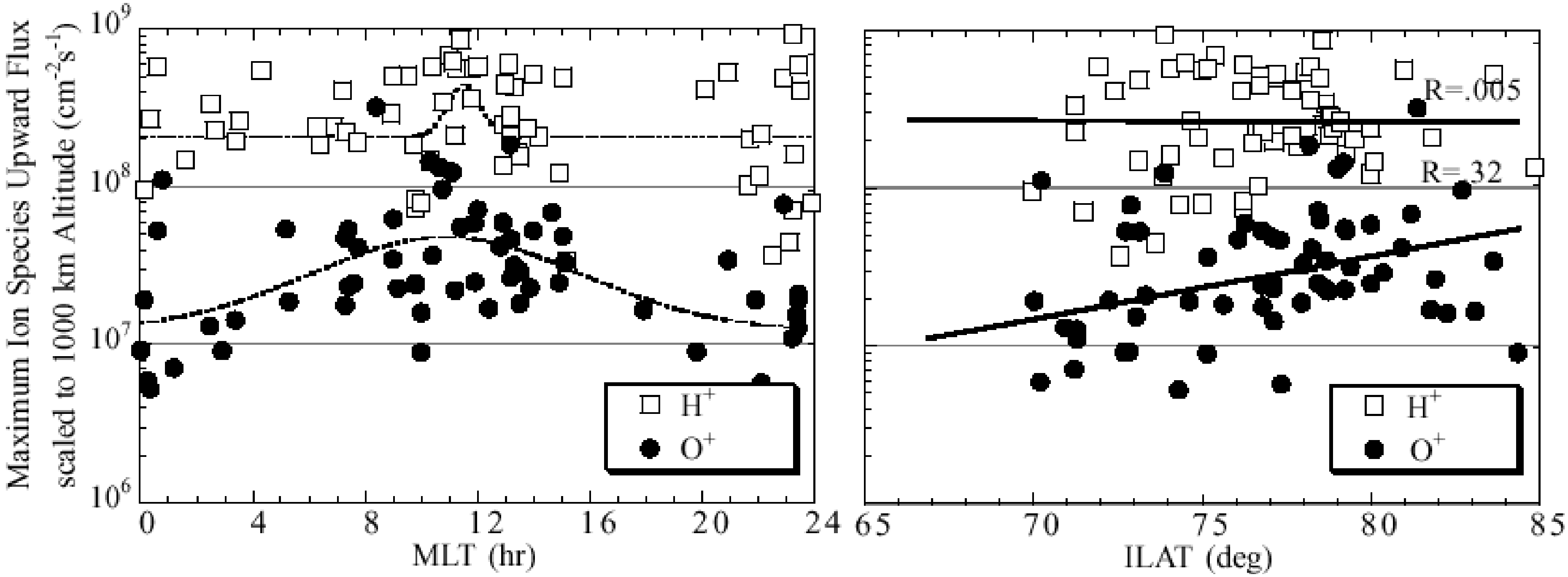
Streamline tube position (periodic boundary conditions)

- Define High/Low: Principle from1D wind theory:
  - Energy input below critical sonic level increases **mass flux.**
  - Energy input above the critical sonic level increases the **vel &or temp**



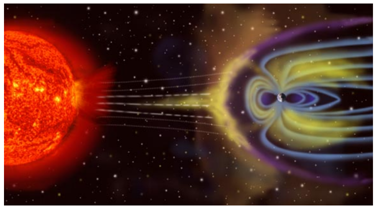
Location of auroral outflows: MLT, ILAT

- Outflows are an order of magnitude stronger near noon MLT
- Outflows extend to low latitudes but peak at cleft dayside latitudes.

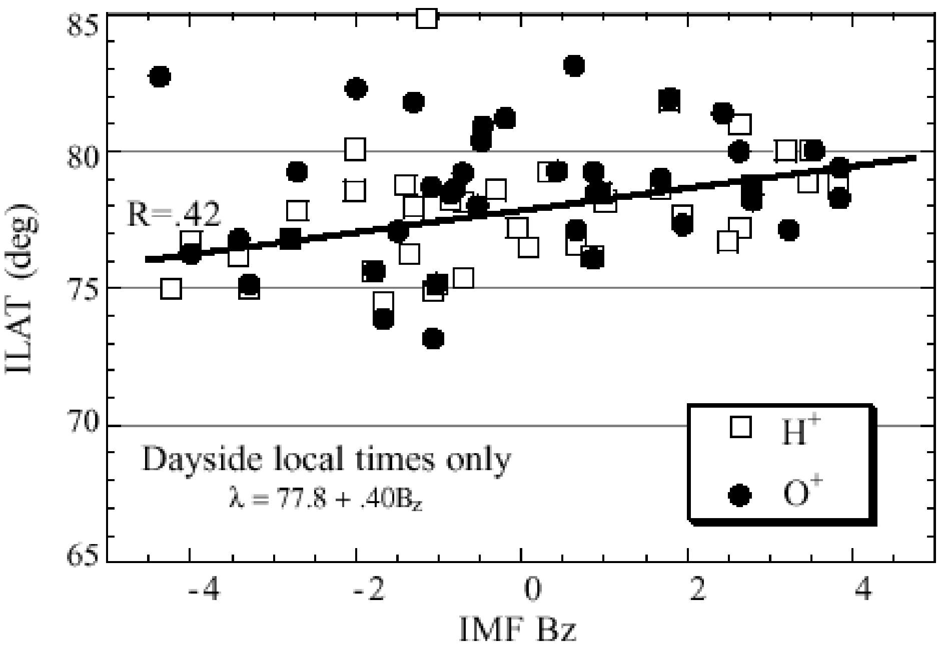


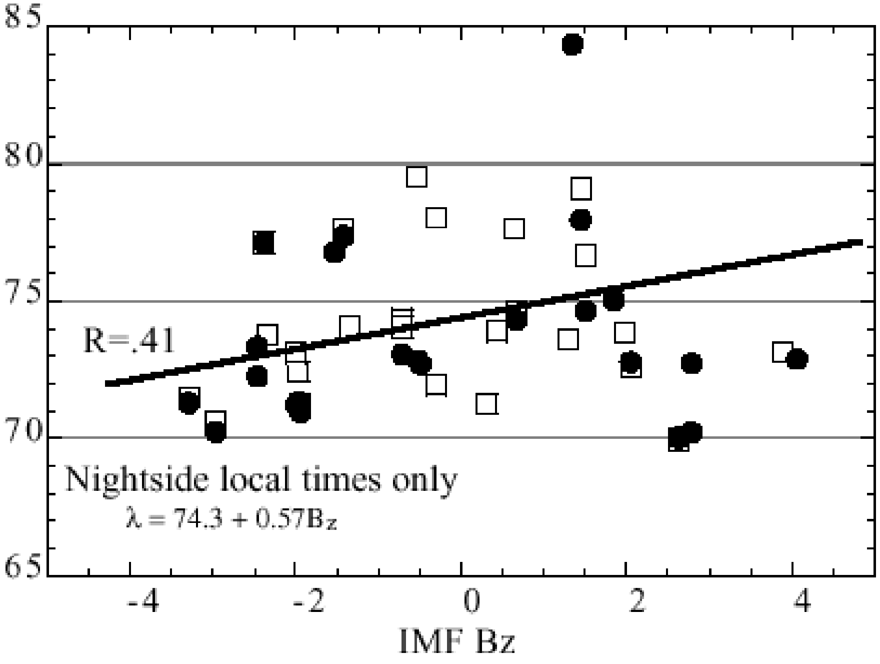
Giles et al. 99 IAGA

Location of Outflows: IMF Bz



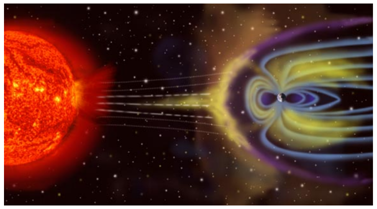
- Outflows follow the well-known variation of auroral zone with IMF Bz, at all local times.



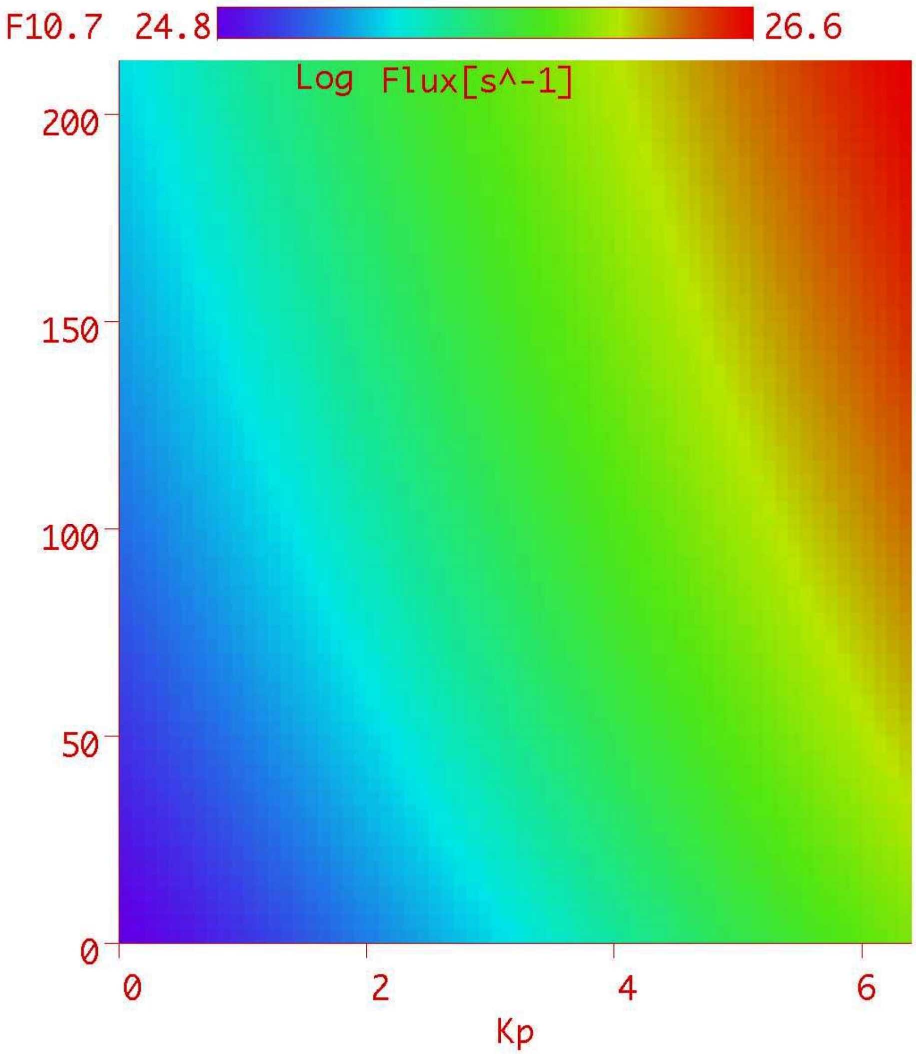


Giles et al. 99 IAGA

Strength of Outflows: Kp, Solar EUV

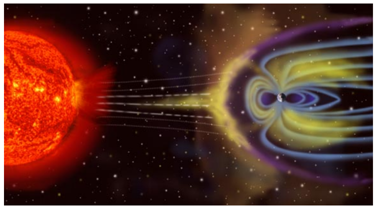


- Total O^+ outflow as fcts. of:
  - Geomagnetic activity Kp
  - F10.7 proxy for solar EUV
- Total H+ outflow nearly independent of these factors
  - F10.7 dependence negligible
  - Kp dependence likely related to energization
- Solar wind influence?

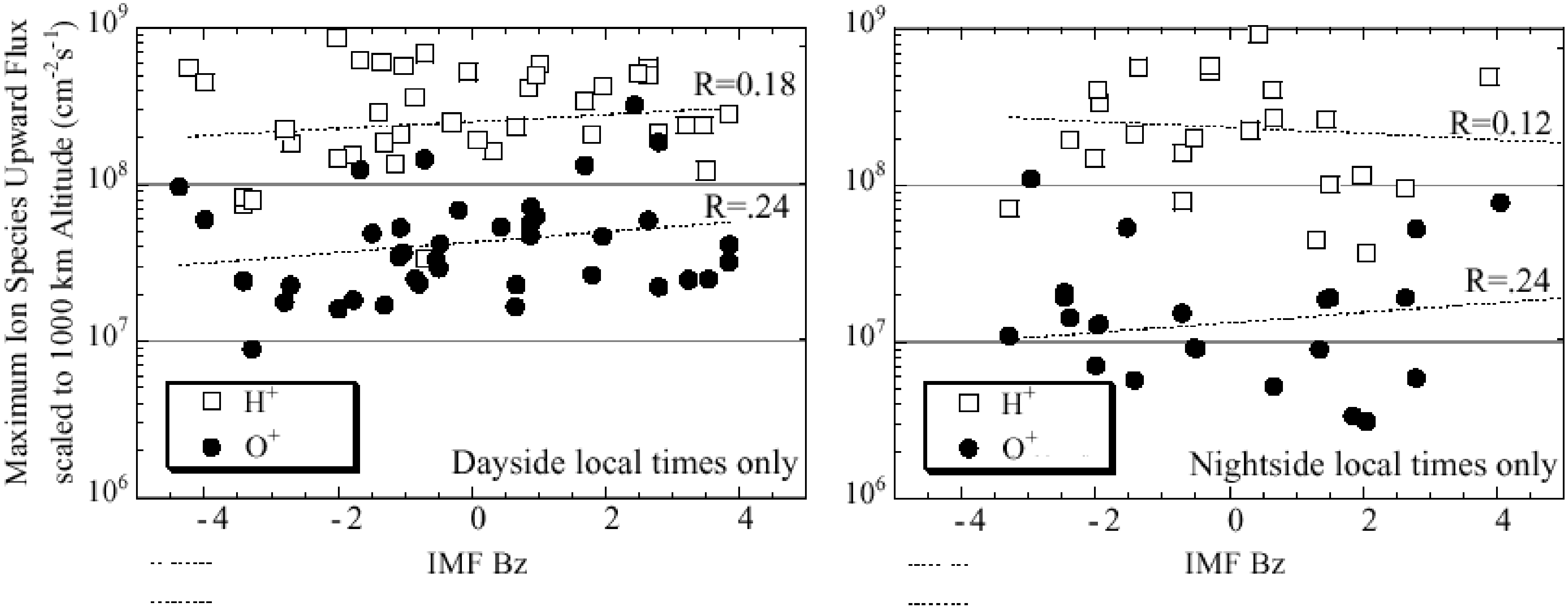


After Yau et al. 1985, 1988

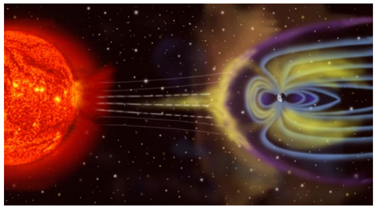
Strength of Auroral Outflows: IMF Bz



- Ionospheric outflow flux does not respond to IMF variations. (Why not?)

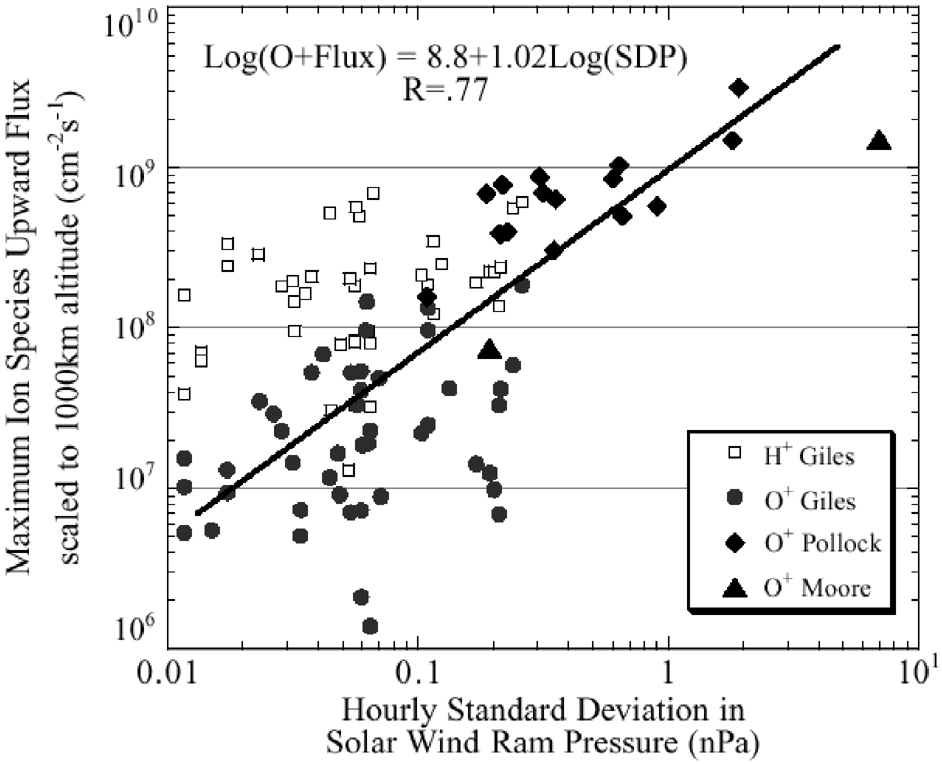


Strength of Auroral Outflows: Pdyn



- Outflow responds strongly to P_{dyn}
- P_{dyn} variability best correl.
- Sudden Impulses from CMEs produce dramatic Ionospheric Mass Ejections (>100 x normal mass)
  - Triangle symbols for 24-25 Sep 98.

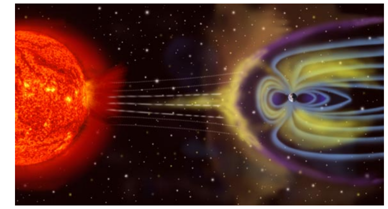
Outflow strength increases with variations in the solar wind ram pressure

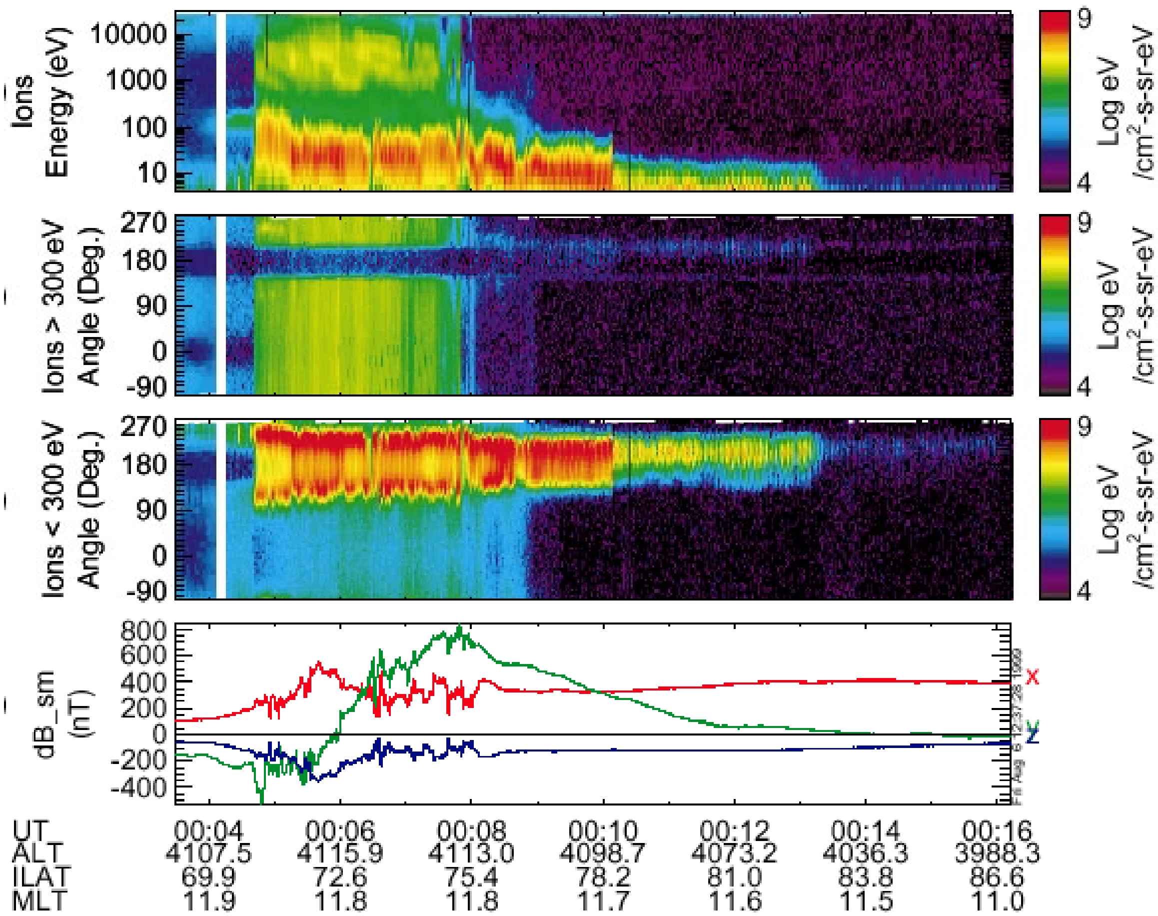


Giles et al. 99 IAGA

Sept 24-25 1998 event was a specific example illustrating the correlation between outflow strength and variations in the solar wind plasma pressure

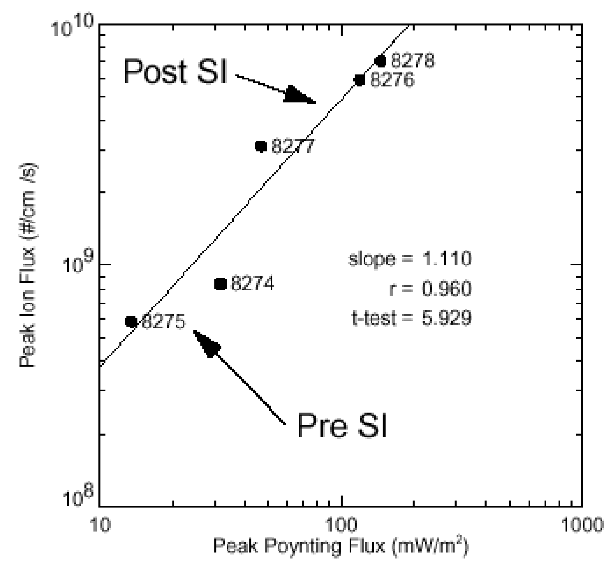
FAST Observations 98|09|25





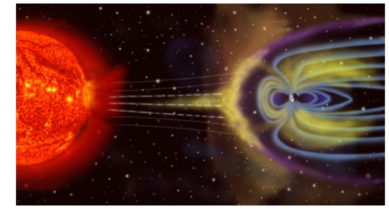
Strangeway et al. 00 JGR

Pre-SI -- Post-SI (Pre-SBz) Comparison



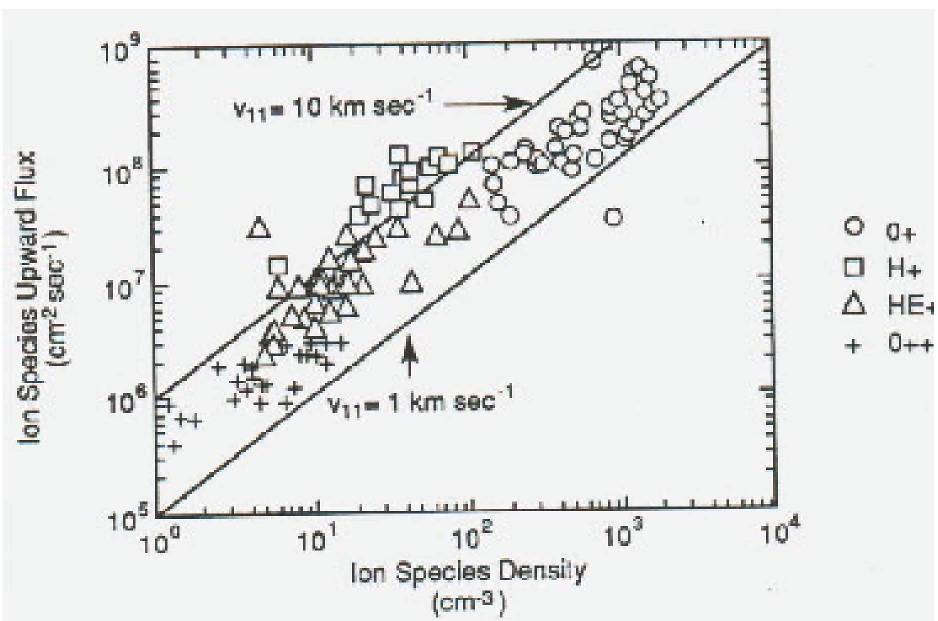
What drives SI-related dayside FAC enhancements?

Strength of auroral outflows: N vs V



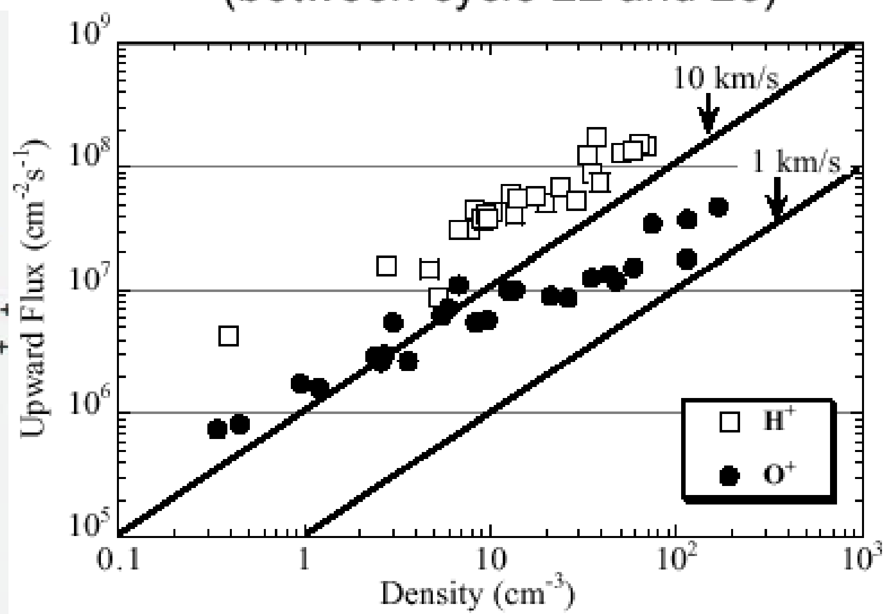
- Outflow flux is strongly density driven
- Velocity variations tend inverse with flux variations
- Flux enhancements are driven by low altitude heating.

Solar maximum conditions
(cycle 21)



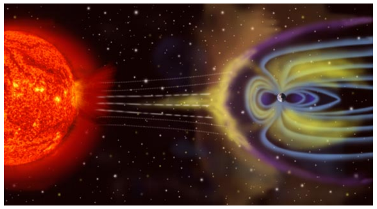
Pollock et al. 90 JGR

Solar minimum conditions
(between cycle 22 and 23)

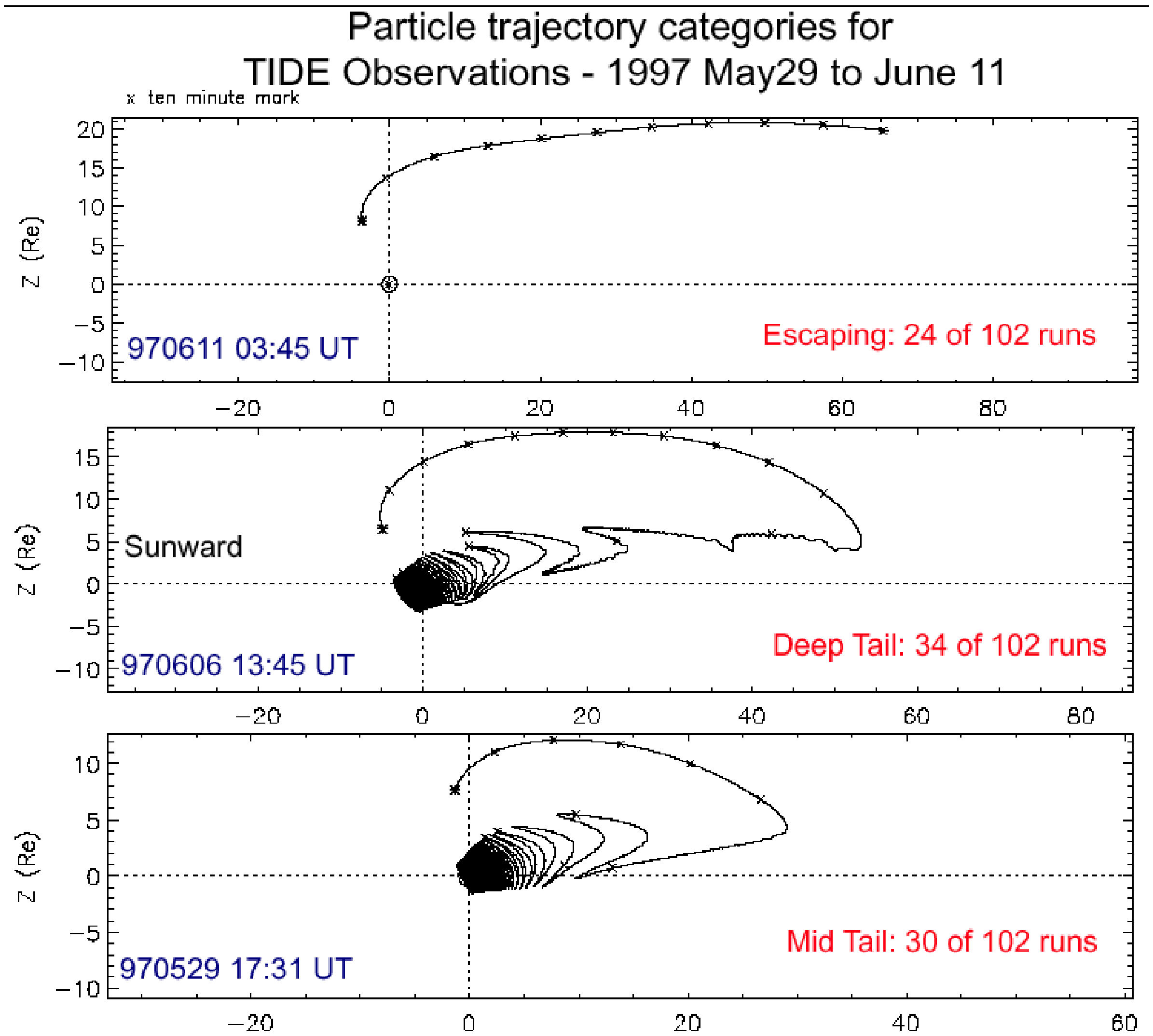


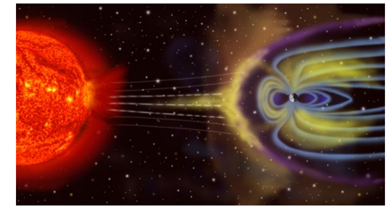
Giles et al. 99 IAGA

Centrifugal Acceleration



- Destiny of polar wind outflows
- Gradual energy increase in polar cap
- Large increase at neutral sheet
- Assumes mapping of mean ionospheric convection to plasma sheet

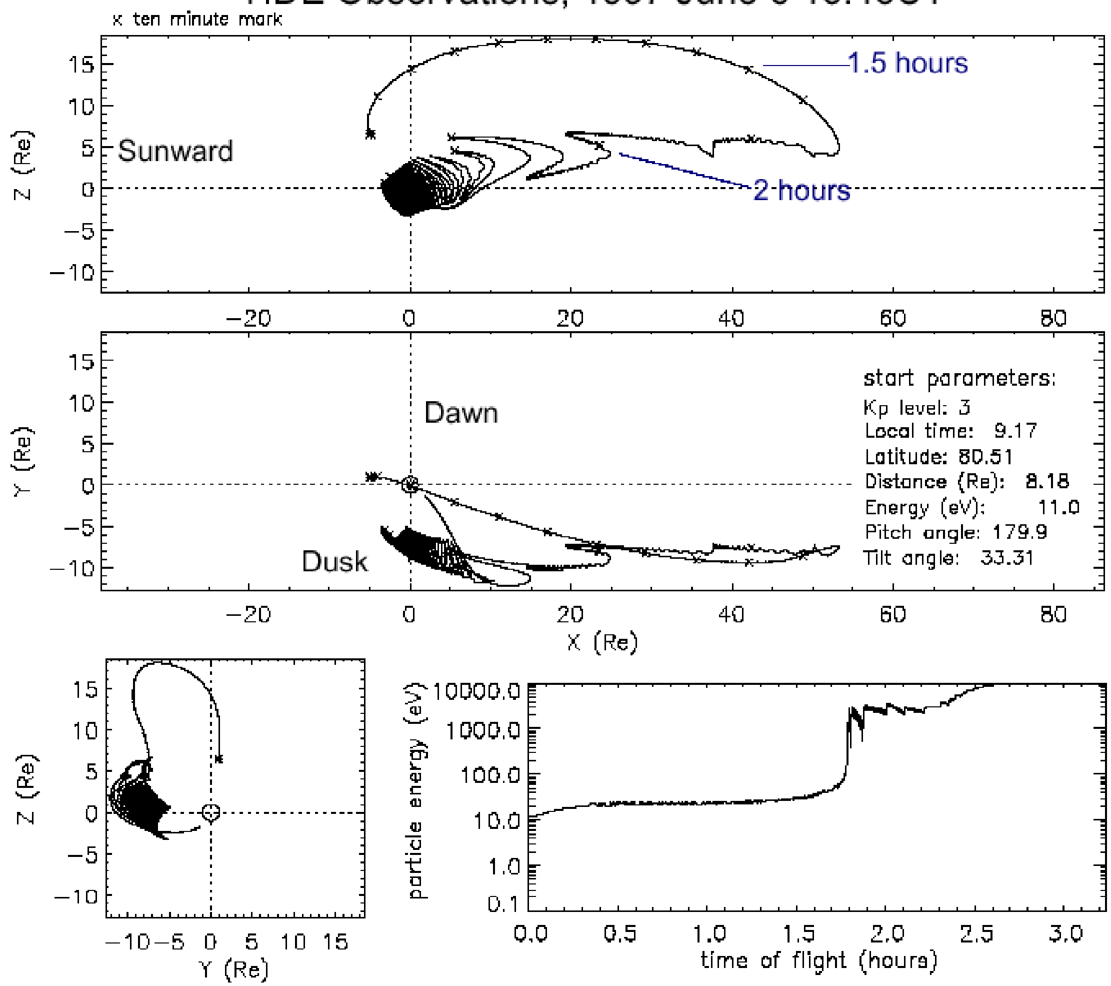




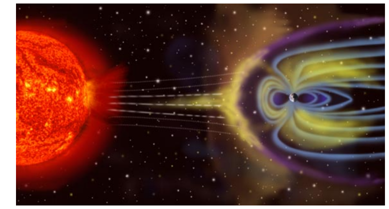
Spatial Anadiabaticity

- Spatial scale ~ r_g
- Mild polar cap dE
- Extreme plasmasheet dE
- Regimes:
  - Adiabatic betatron
  - μ "scattering"
  - μ increase and gyrobunching
- e^- analogous very near NL
- Time-reversible

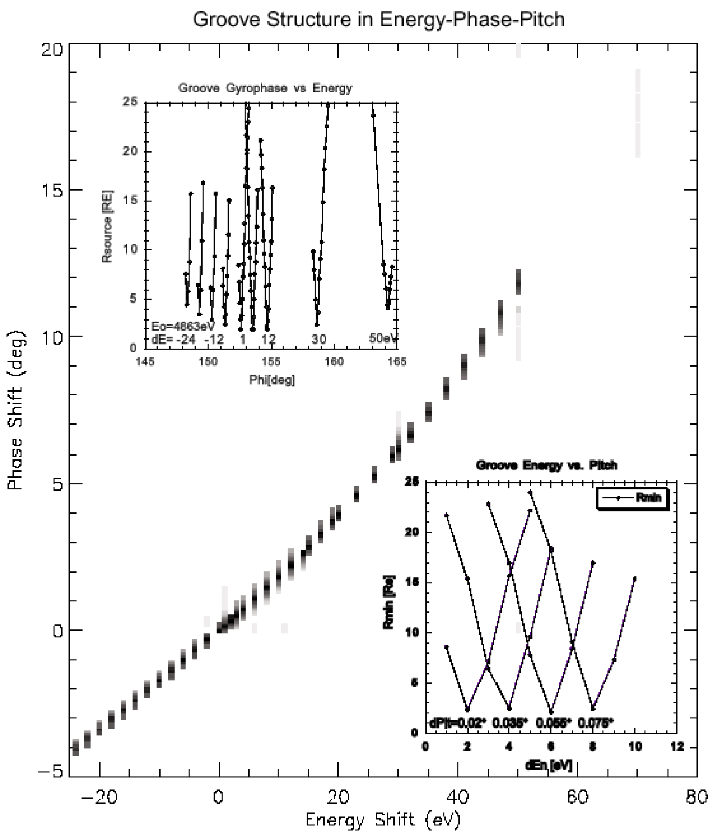
Particle trajectory simulation for
TIDE Observations, 1997 June 6 13:45UT

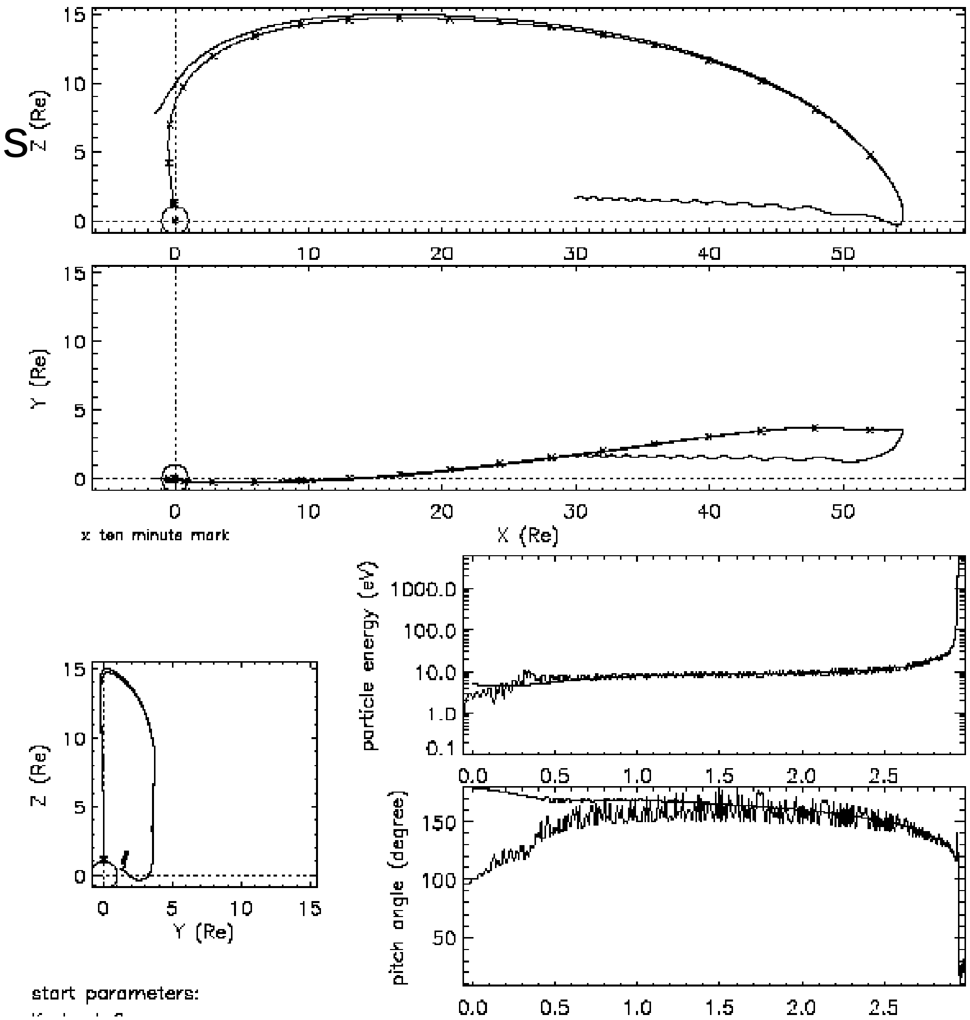


Source Groove

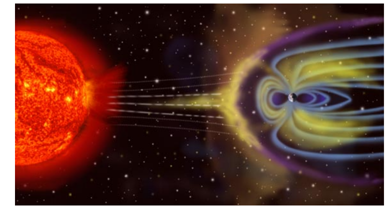


- Chaotic - reversible
- Extreme sensitivity to IC
- Structured velocity distributions
- Backtracking problematic

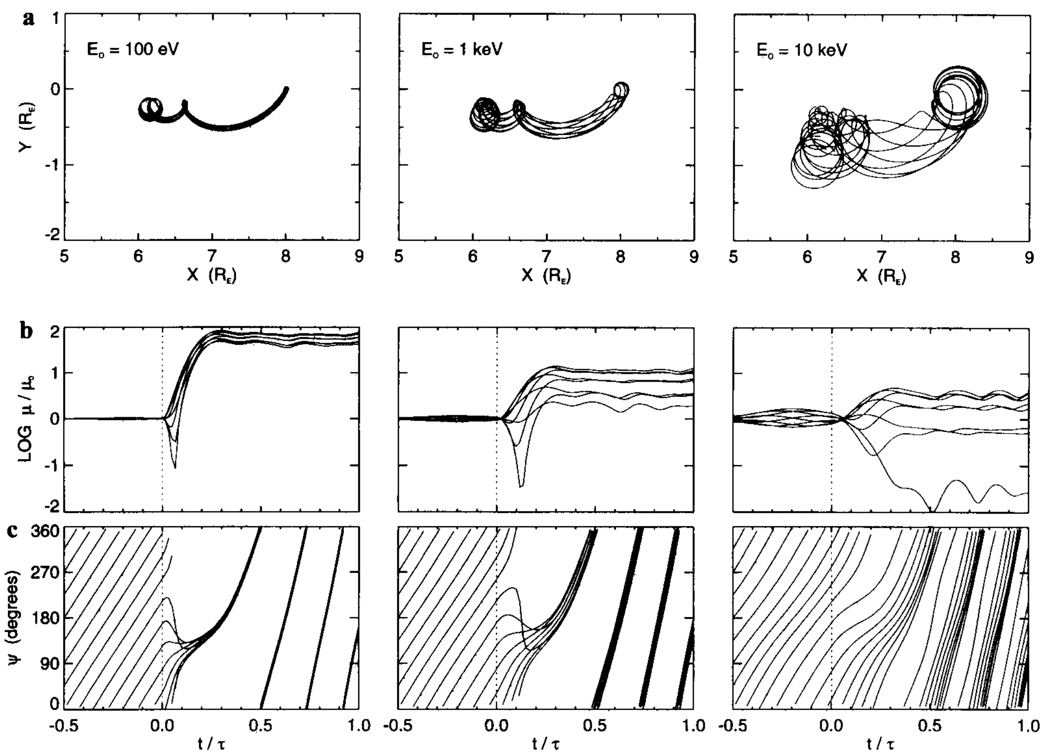




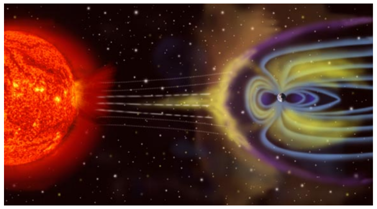
Temporal Anadiabaticity



- Inductive **E**, duration ~ τ_g
- Regimes:
  - Adiabatic betatron
  - μ "scattering"
  - μ increase and gyrobunching
- Time-reversible
- e^- analogous for higher freq
- Energy dependent, tends to bring all to $\mathbf{E}_{ind}\mathrm{x}\mathbf{B}$ velocity

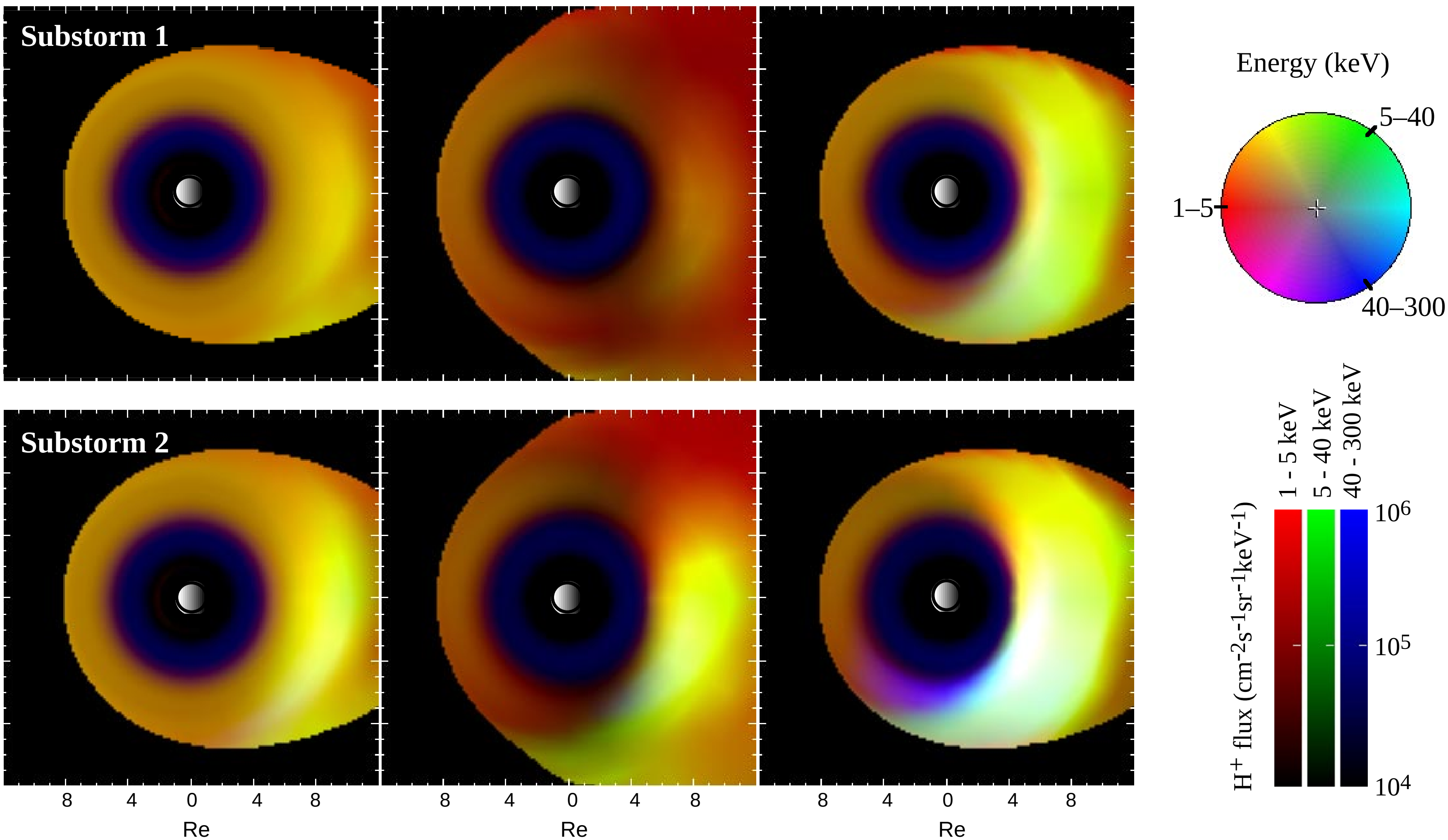


Eo=100 eV	Eo=1 keV	Eo=10 keV
μ increase	μ "scattering"	μ ~ const.
gyrobunching	mild bunching	weak bunching



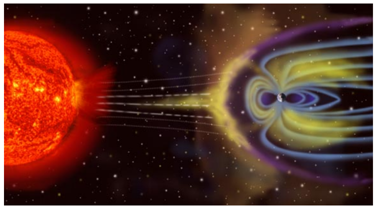
Dipolarization Injections

t1: Pre-substorm **t2: Substorm onset** **t3: Post-dipolarization**

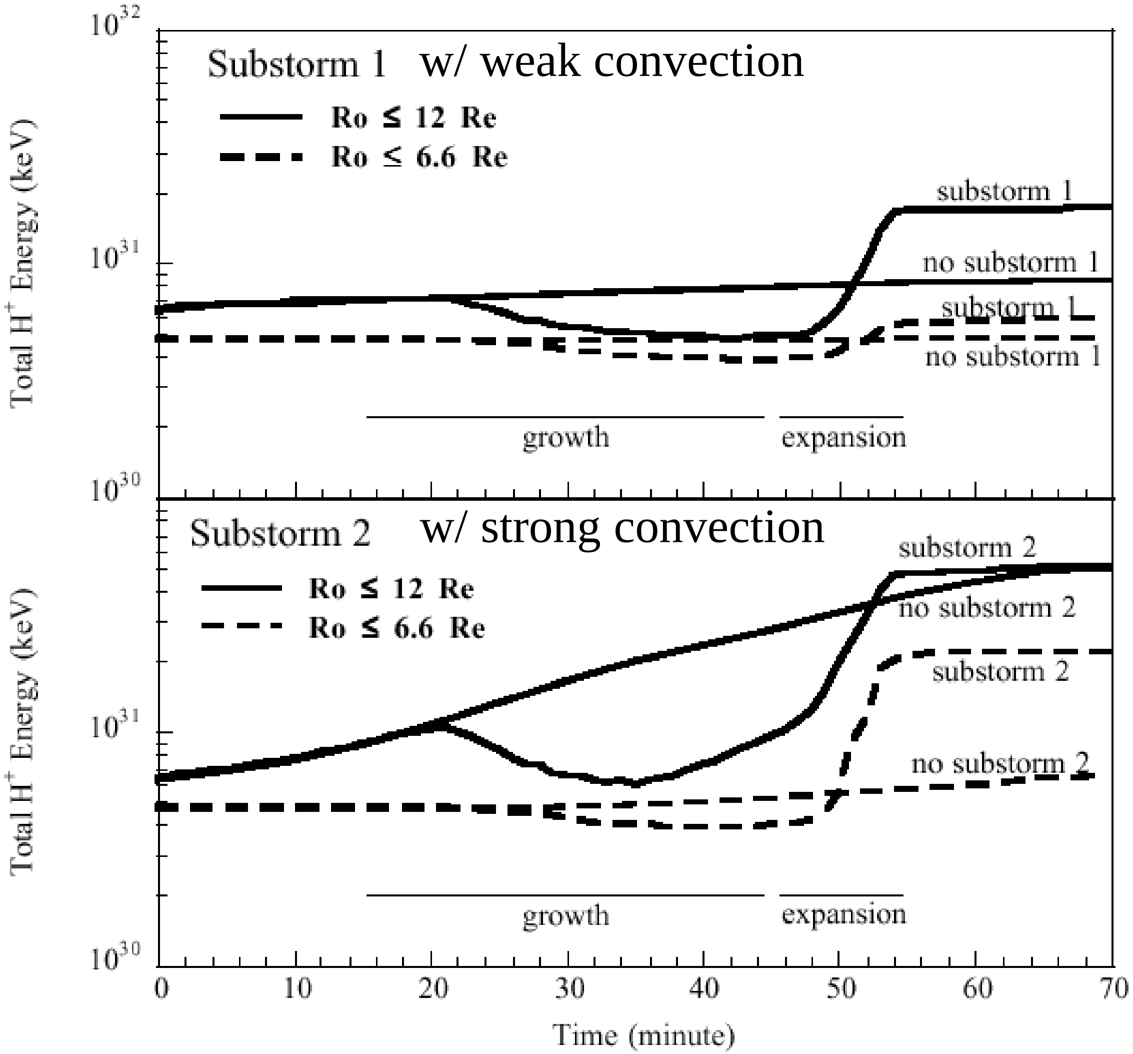


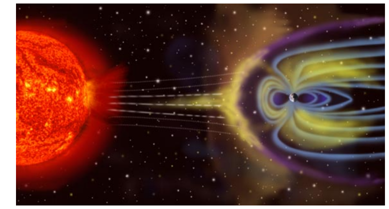
Fok et al. 99 JGR

Ring Current and Substorms



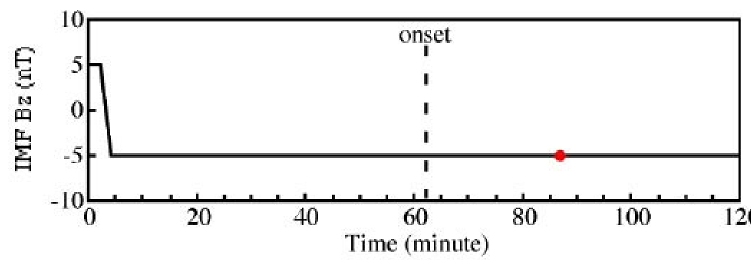
- Decomposition
  - Dipolarization
  - Convection
- Dipolarization
  - L = 6 -12 Re
- Convection
  - L = 6 -12 Re
- Both together
  - L < 6.6
- Neither sufficient alone.

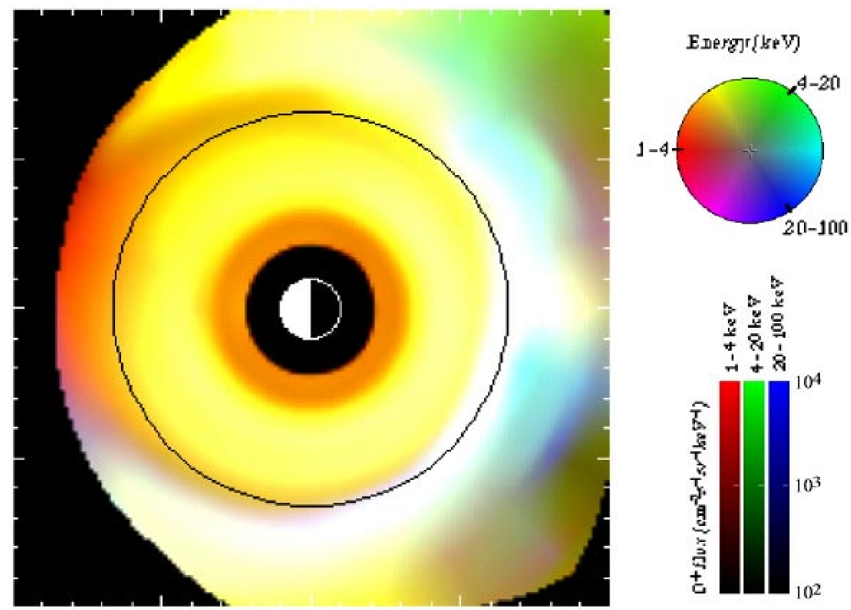




O$^+$ in MHD Substorm Fields

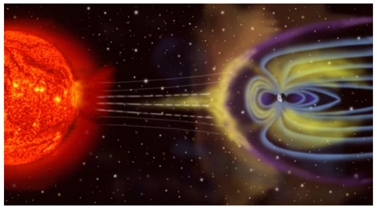
- Fedder-Slinker MHD fields
- Dipolarization in few minutes
- First to go anadiabatic: O$^+$
- Large moment & energy gains
- Gyrobunching
- Bounce bunching
- Initial energies become irrelevant



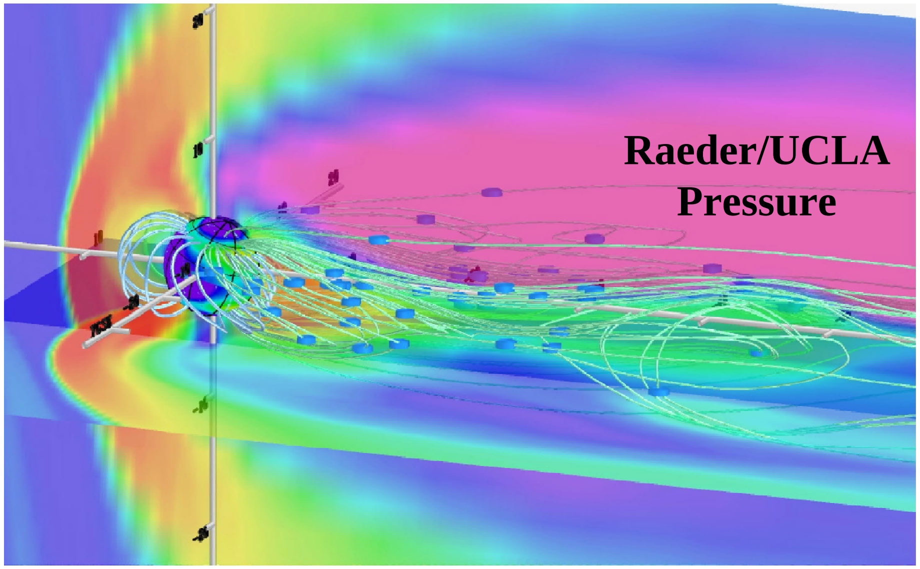


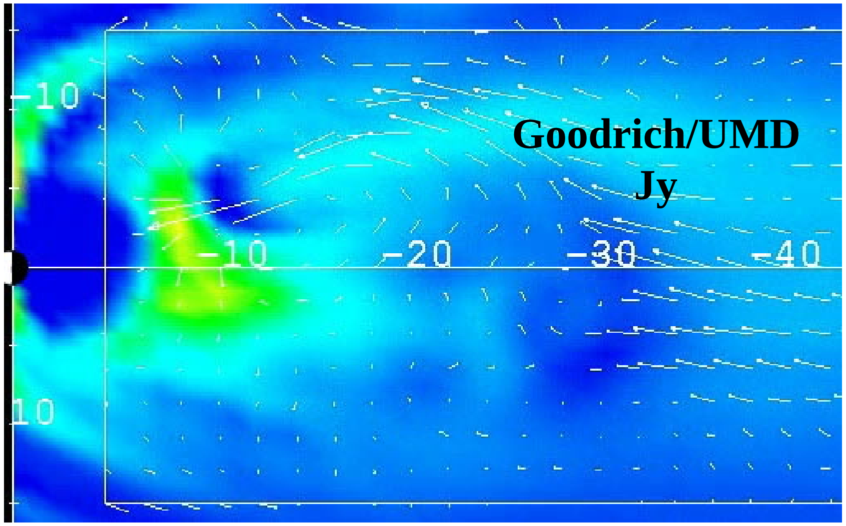
 Fok et al. 99 IAGA

Improving on Cartoons: Simulations

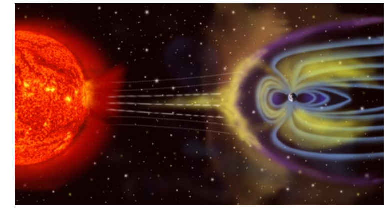


- Self-consistent, physical picture with solar wind driving.
- Frighteningly detailed dynamics
- Is the simulated tail realistic? [see movie]
- How do ionospheric outflows fit into the picture?
- Must run with/without ionospheric source?

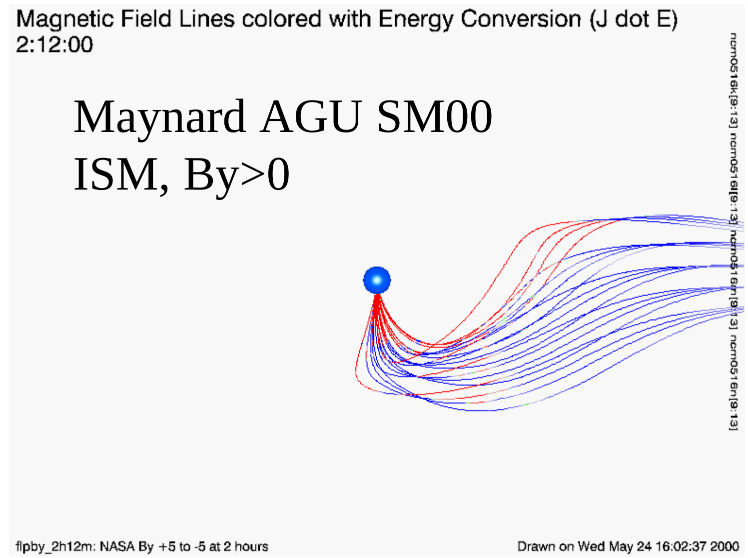


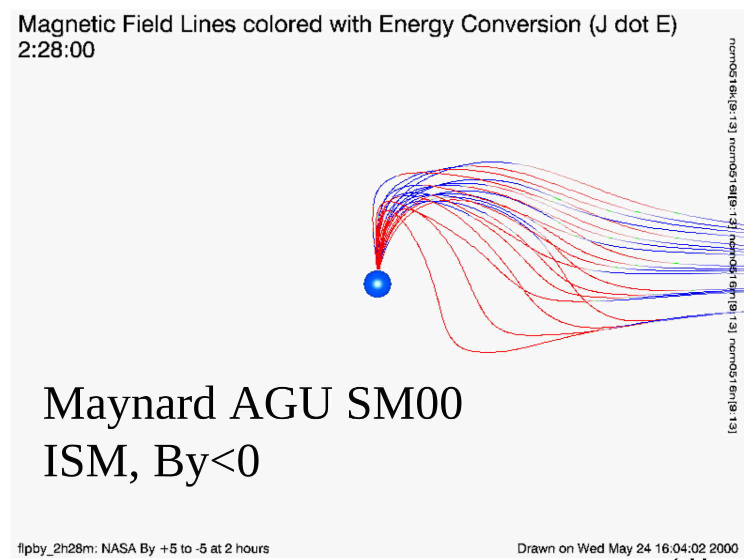


Problem with Global Simulations

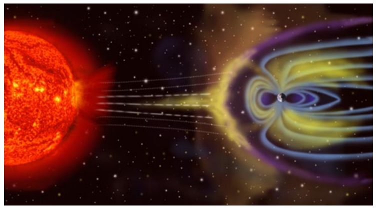


- Big problem with simulations
  - No explicit ionospheric plasma, but
  - Plasma added to reduce JxB acceleration (Alfven speed) explicitly or per Boris [1971] to resolve Alfven waves in an “empty” magnetosphere
- Problem more significant than it seems
  - Ionospheric energy dissipation assumed to be electrodynamic across inner boundary, but see figures =>
  - Evidence of “Boris” plasma presence?
- Simulation results are misleading
  - “Boris” plasma unassessed, could be similar to mean ionospheric outflow.
  - Can MHD simulations work without internal plasma addition?
  - IME’s will alter system wave dynamics
  - Can Mercury be simulated?

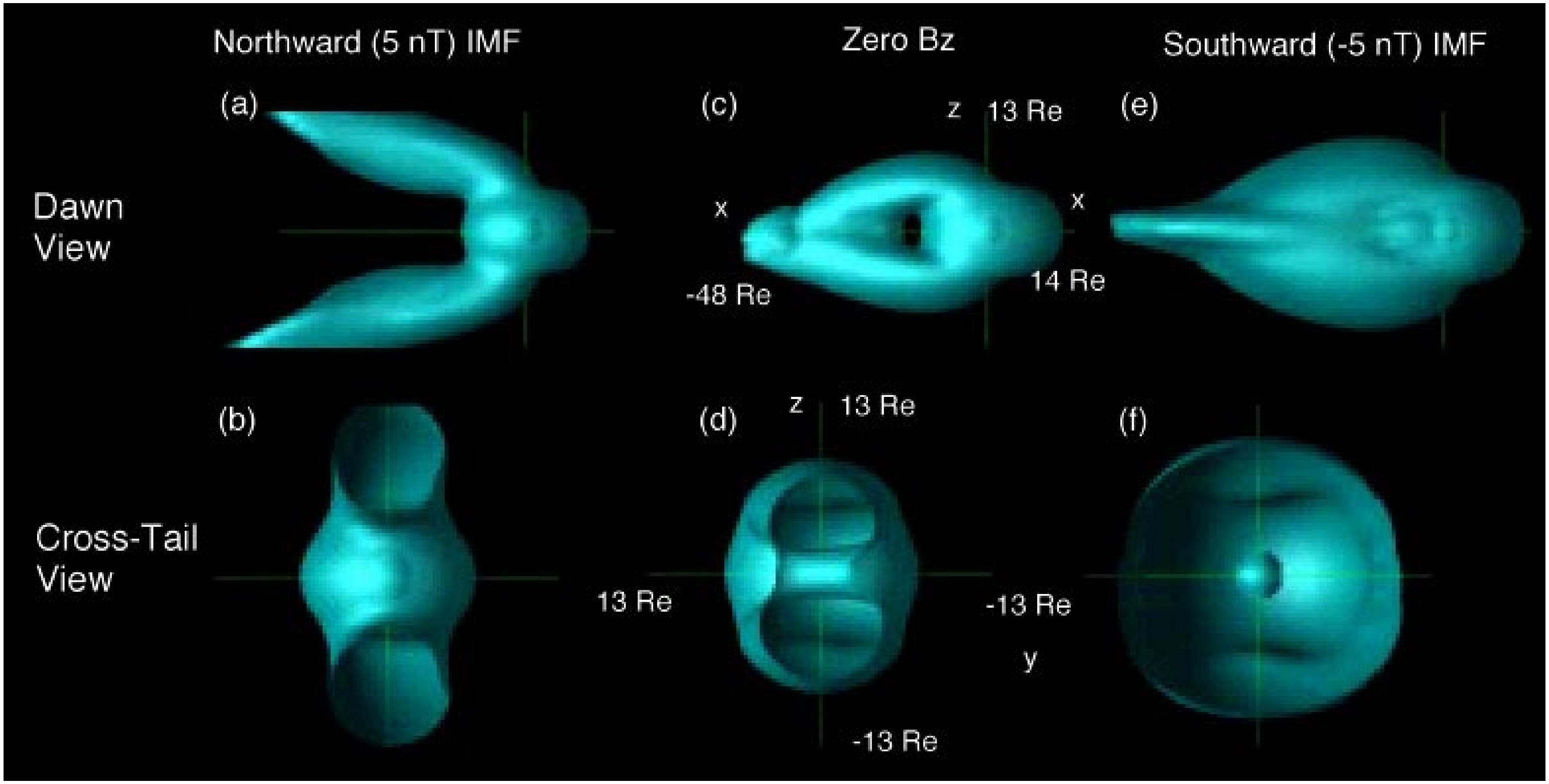




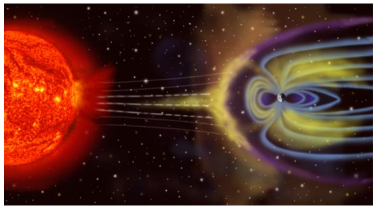
The Computed Geopause



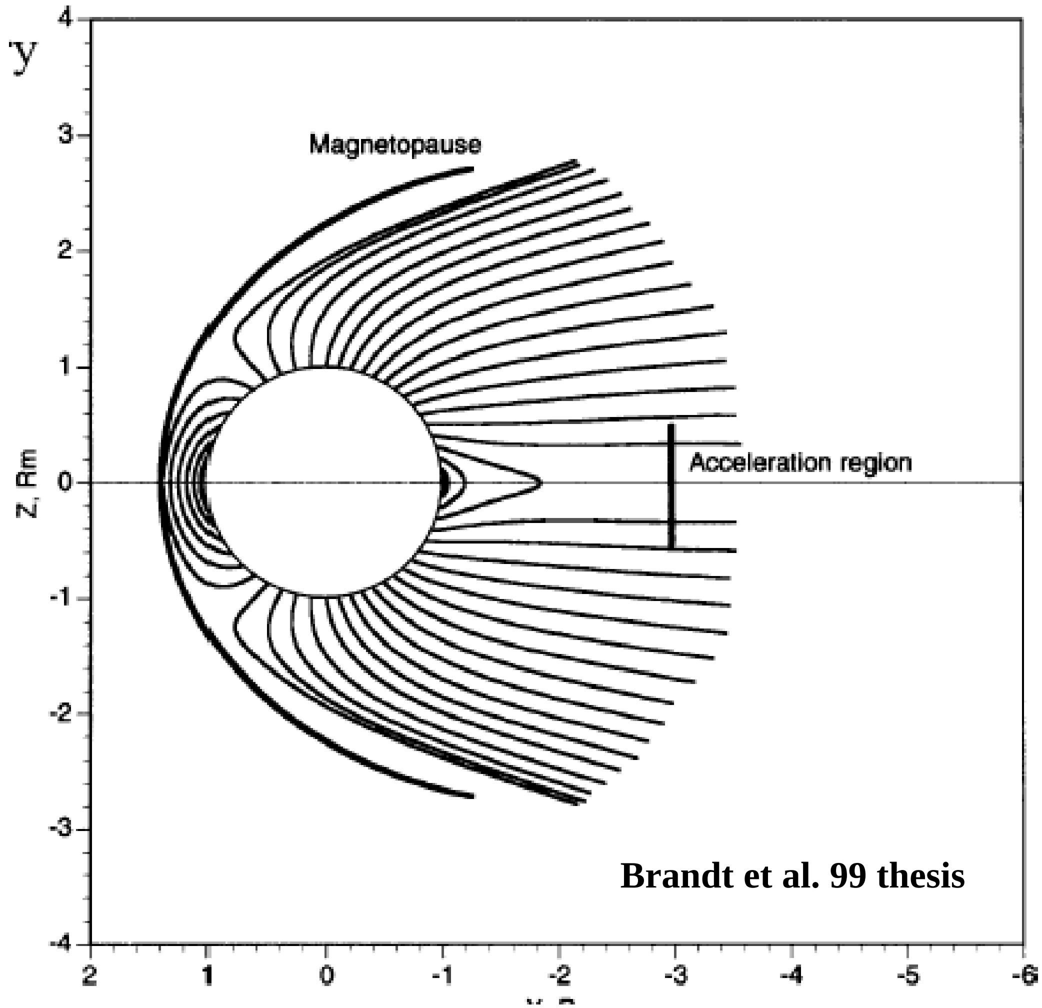
- Compute the geopause [Winglee, GRL 1998,...]
- Explicit ionospheric fluid(s) and parallel transport
- Clarification of IMF effects:



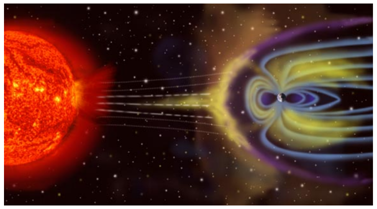
Exploring space (other magnetospheres)



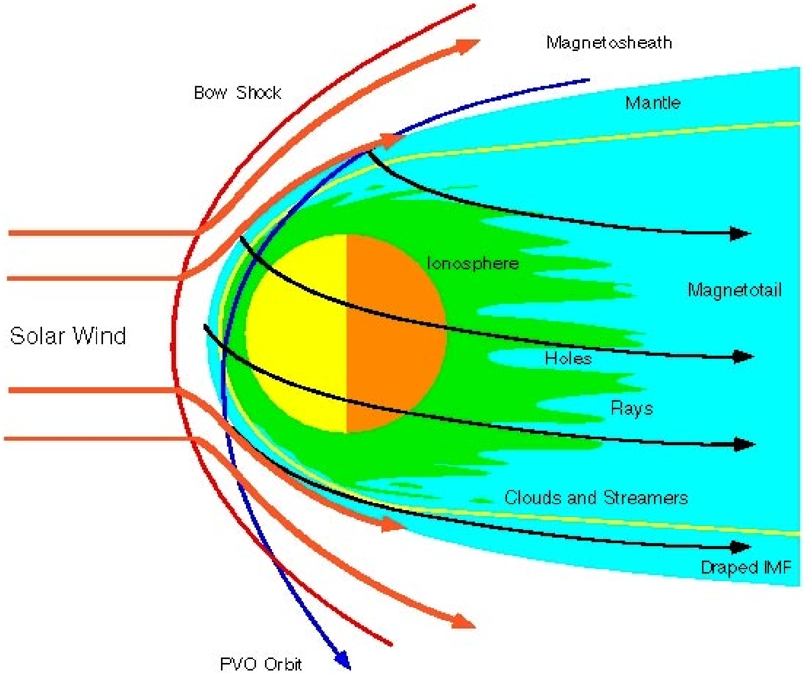
- Mercury:
  - For lack of an ionosphere or other internal source
- Jupiter:
  - For lack of a solar wind interaction (rotation dominated)
- Mars or Venus:
  - For lack of a magnetic field
- Saturn, Uranus
  - Signif' satellite, ionospheric sources



Exploring Time (Solar System Evolution)

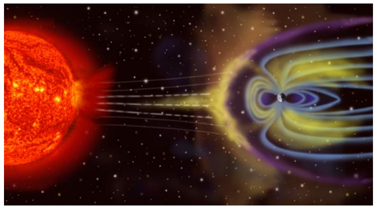


- Geomagnetic Reversals
  - Vastly reduced dipole moment.
  - Reconnection in unmagnetized planets, comets.
  - Diffuse vs. concentrated exposure to solar wind
  - Limits to escape in solar wind capacity
- Solar Wind Variations
  - Early solar wind, T-tauri phase
  - Solar variability and geospace

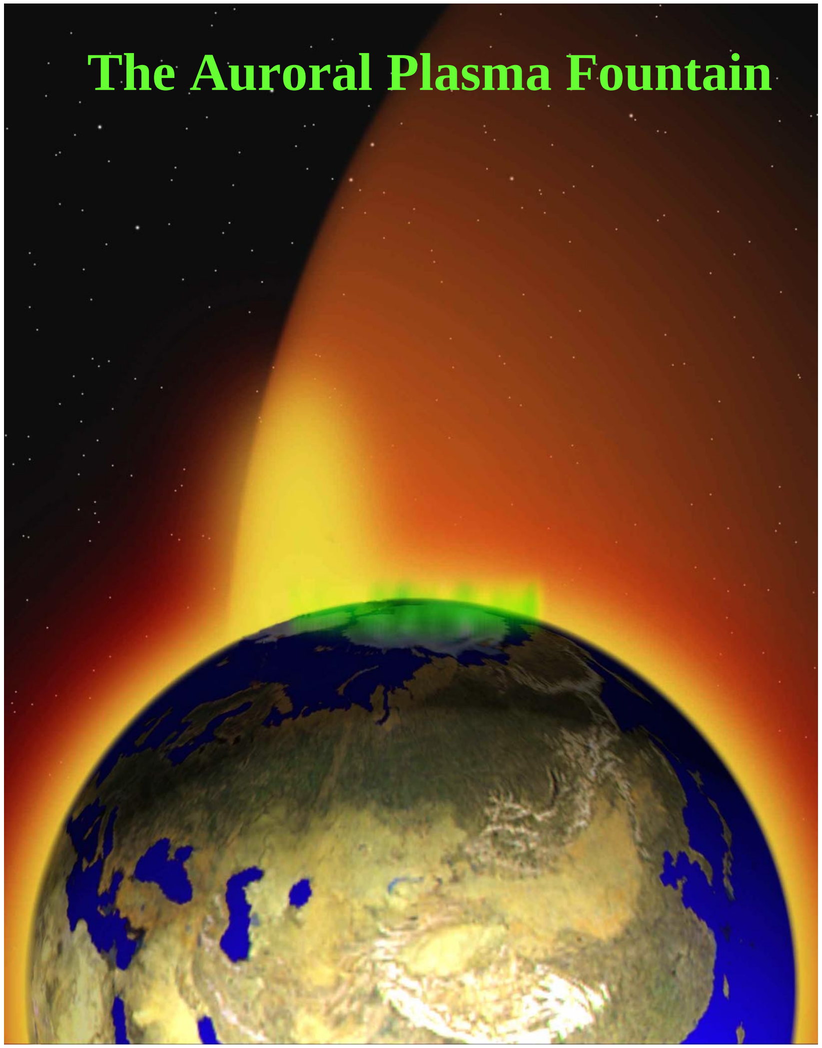


SEC Roadmap, C T Russell

Conclusions



- Observations led
- Must now simulate
- Test against reality
- Reality must include:
  - The 3D ionosphere
  - Causes of outflow
  - Morphology of outflow
  - Variations of outflow
  - Consequences of outflow
  - Outflow on extended time and spatial scales
- Talk this pm on impact on storms, ring current



Moore et al. 96 GRL