Don’t Go With the Flow:

An Invitation to Research on the Foreshock and Magnetosheath

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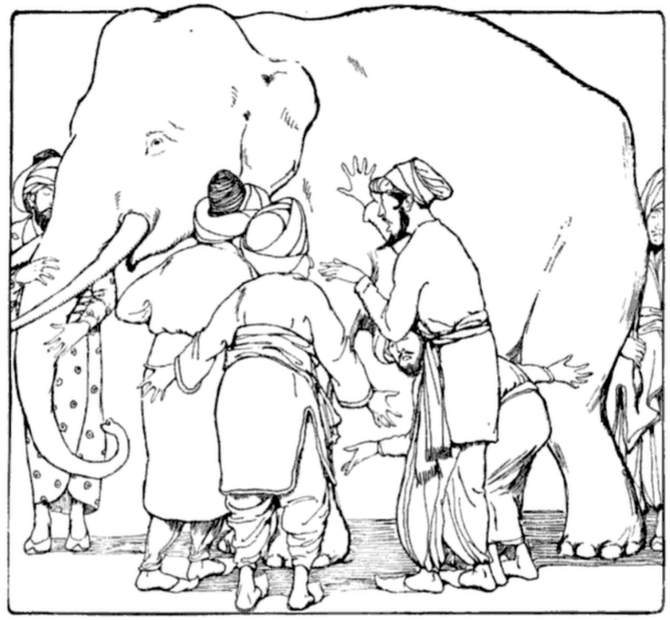
NASA/GSFC



Outline

- 1. Motivation
- 2. Gasdynamics, MHD, and Kinetic Models
- 3. Summary

GEM, Foreshock, and Magnetosheath

Global Geospace General Circulation Models need accurate foreshock/magnetosheath modules:

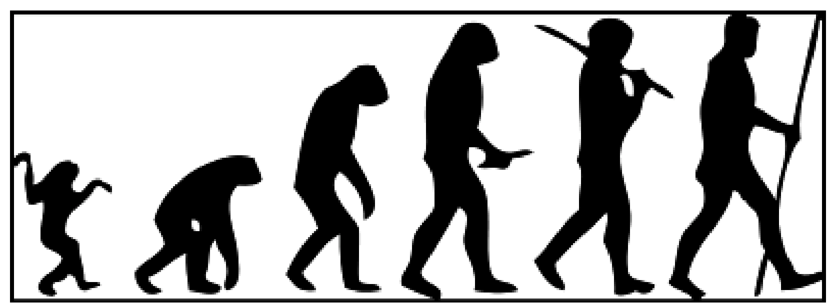
- Magnetosheath (not solar wind) lies in contact with magnetopause.
- Foreshock and magnetosheath processes drastically modify solar wind plasma before it reaches magnetopause.
- The physics underlying these processes is fundamental and deserving of study in its own right: reconnection, particle energization, basic modes of solar wind-magnetosphere interaction.

Global Models and Observations

- Gasdynamic
  - Readily available, easy to use & parameterize
  - Fine if you can neglect magnetic field and kinetic effects

- Magnetohydrodynamic
  - Include magnetic pressures and curvature forces-->
  - Widespread use, runs-on-demand at CCMC

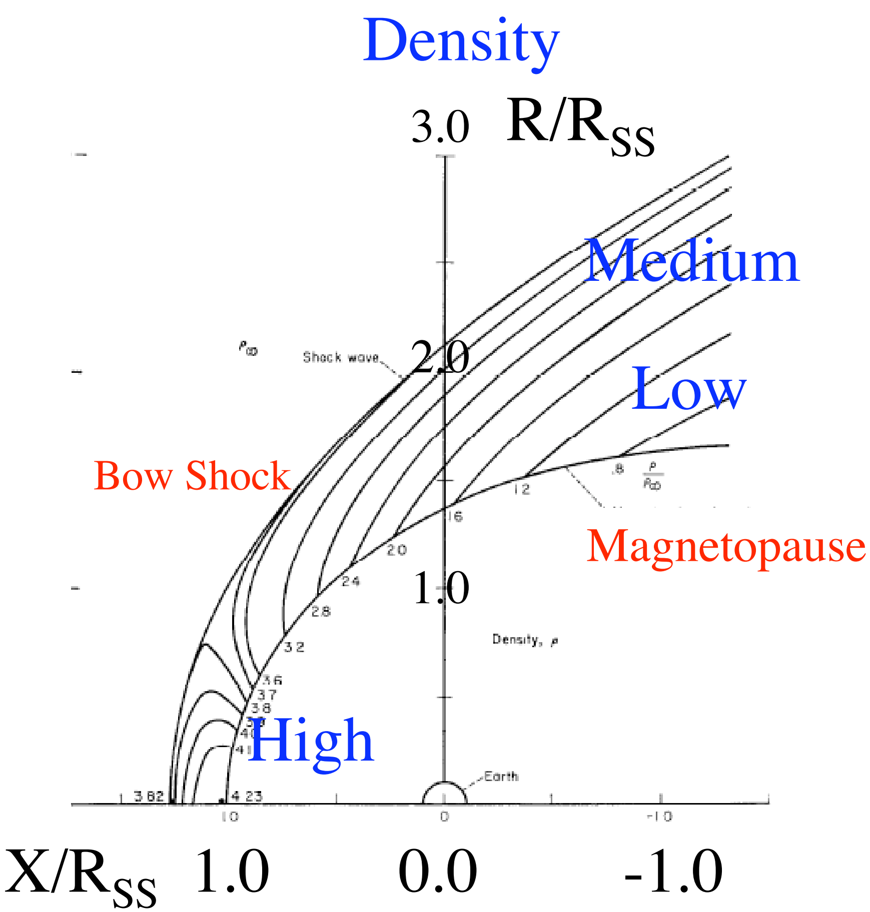
- Hybrid
  - Include kinetic effects
  - Under development

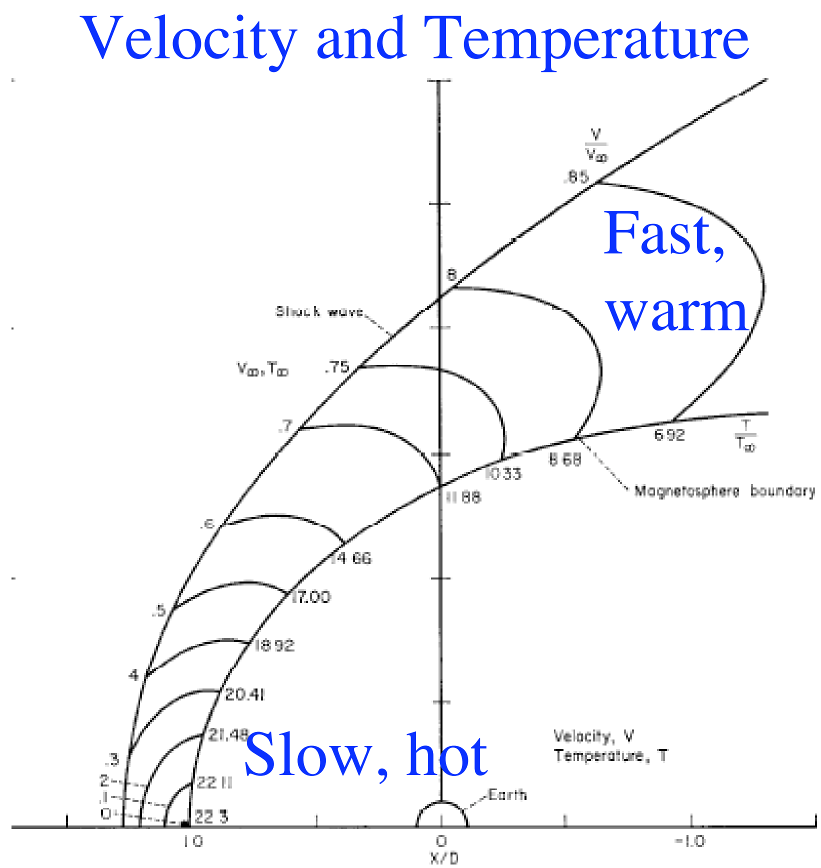


Gasdynamic Models

- Spreiter et al. [1966] presented an axially-symmetric steady-state gasdynamic model for flow around a rigid magnetopause. It predicts:
  - Magnetosheath densities, velocities, temperatures
  - Draped magnetic field strengths and directions (but not self-consistently)
  - Bow shock location
  - Results look good when magnetic pressures and tensions, kinetic effects can be neglected.

Gasdynamics:
Spreiter et al. [1966]



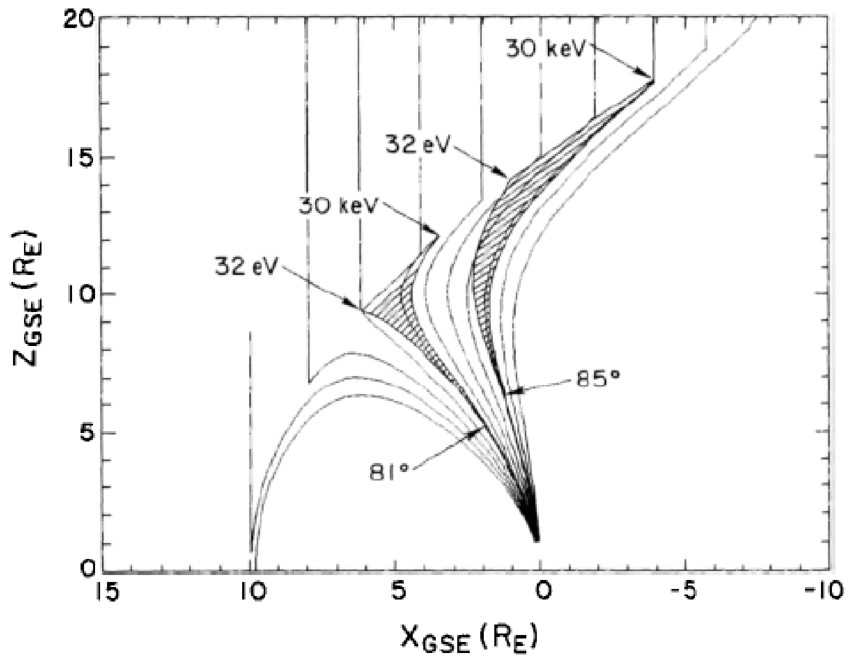


We feel it is right, but there are no empirical models to compare with!

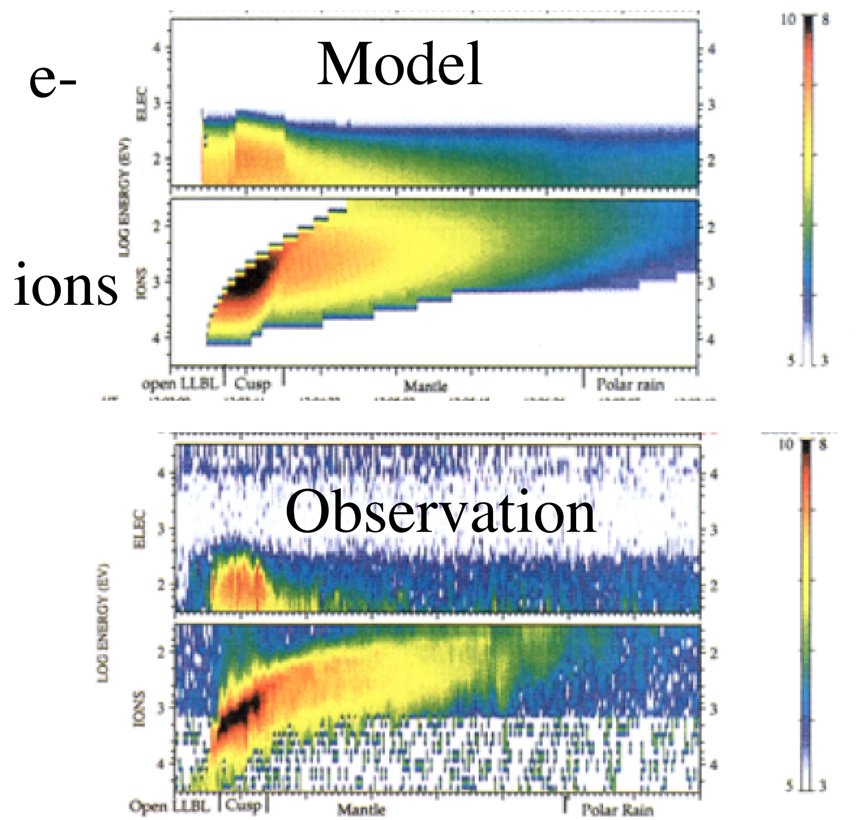
Gasdynamic Model

Provides Good Source Populations for Cusp Precipitation Models

Sources of Precipitating Particles
At 81 and 85°



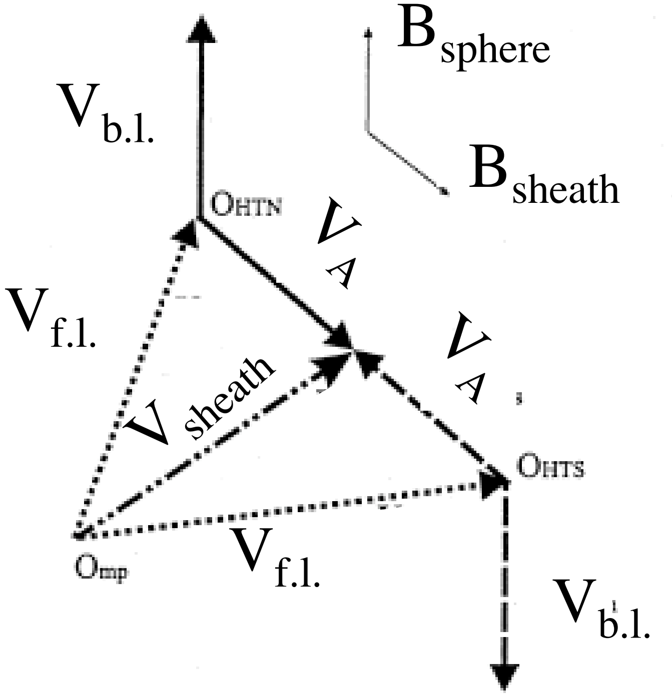
Onsager et al. [1993]



Wing et al. [2001]

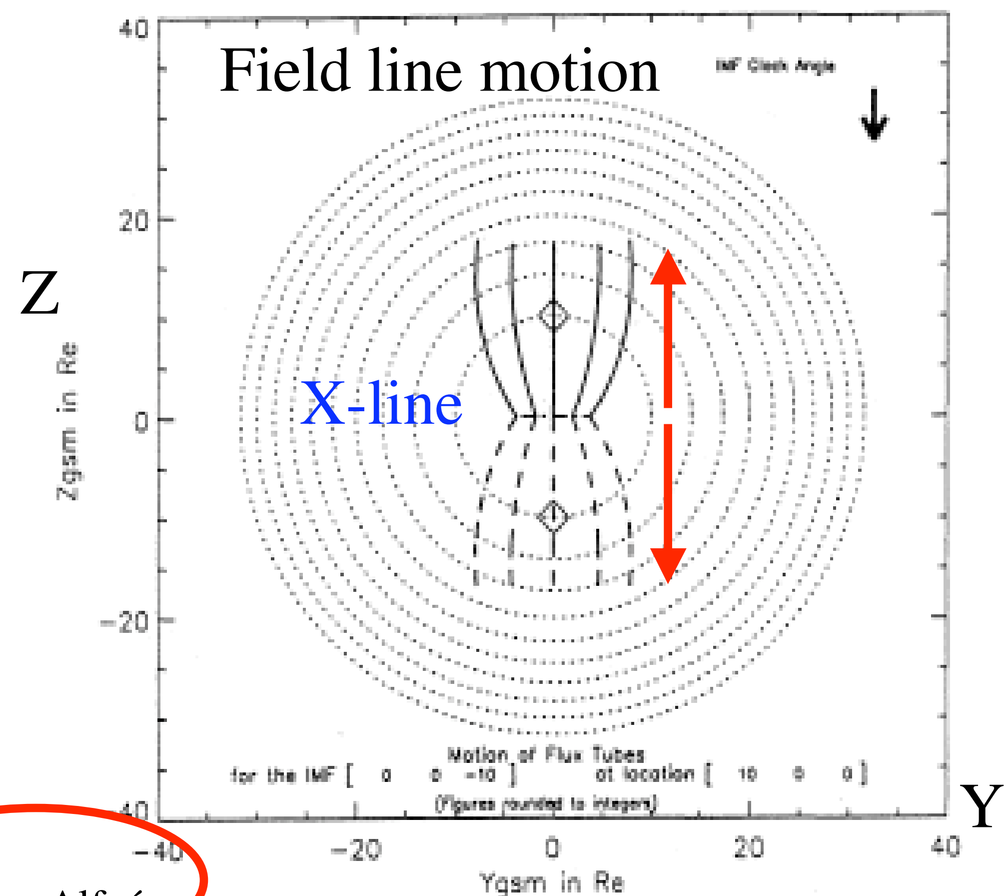
Gasdynamics Model

Provides Densities/Velocities Needed to Predict Motion of Reconnected Magnetic Field lines



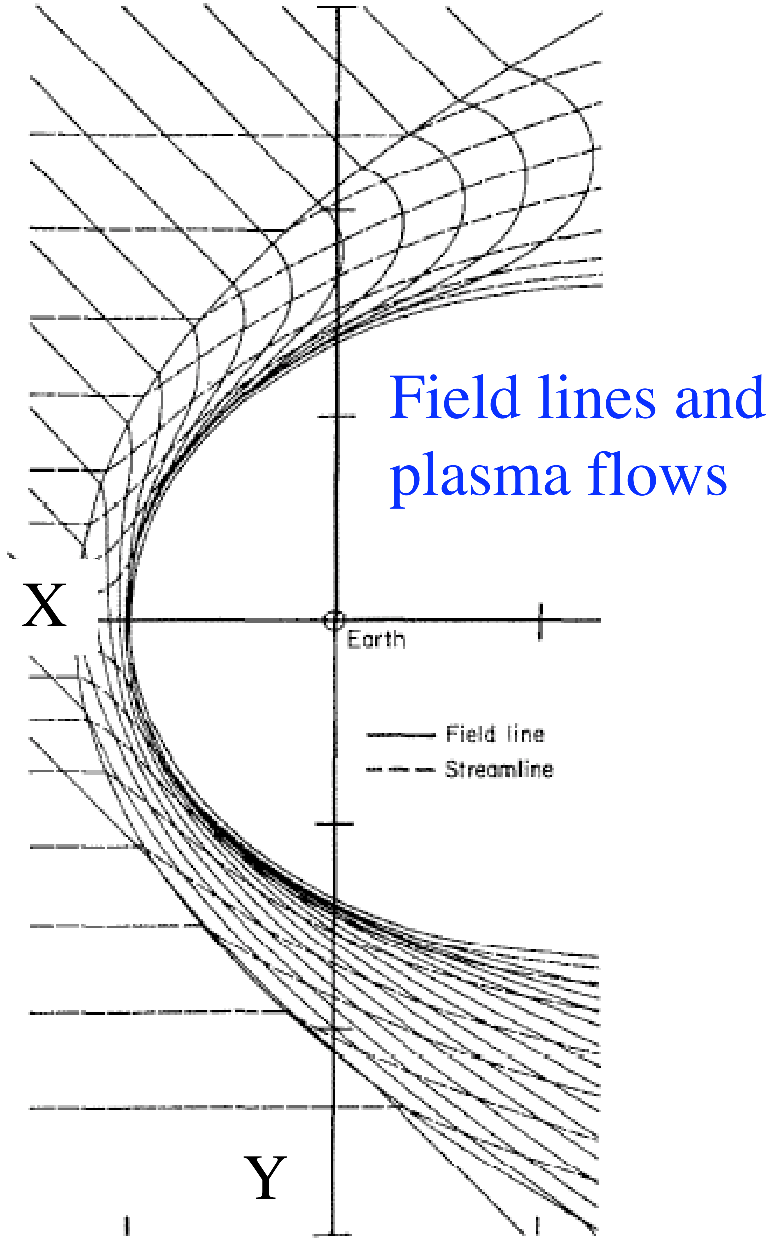
$$V_{\text{field line}} = V_{\text{sh}} \pm V_{\text{sheath Alfvén}}$$

$$V_{\text{boundary layer}} = V_{\text{field line}} \mp V_{\text{sphere Alfvén}}$$

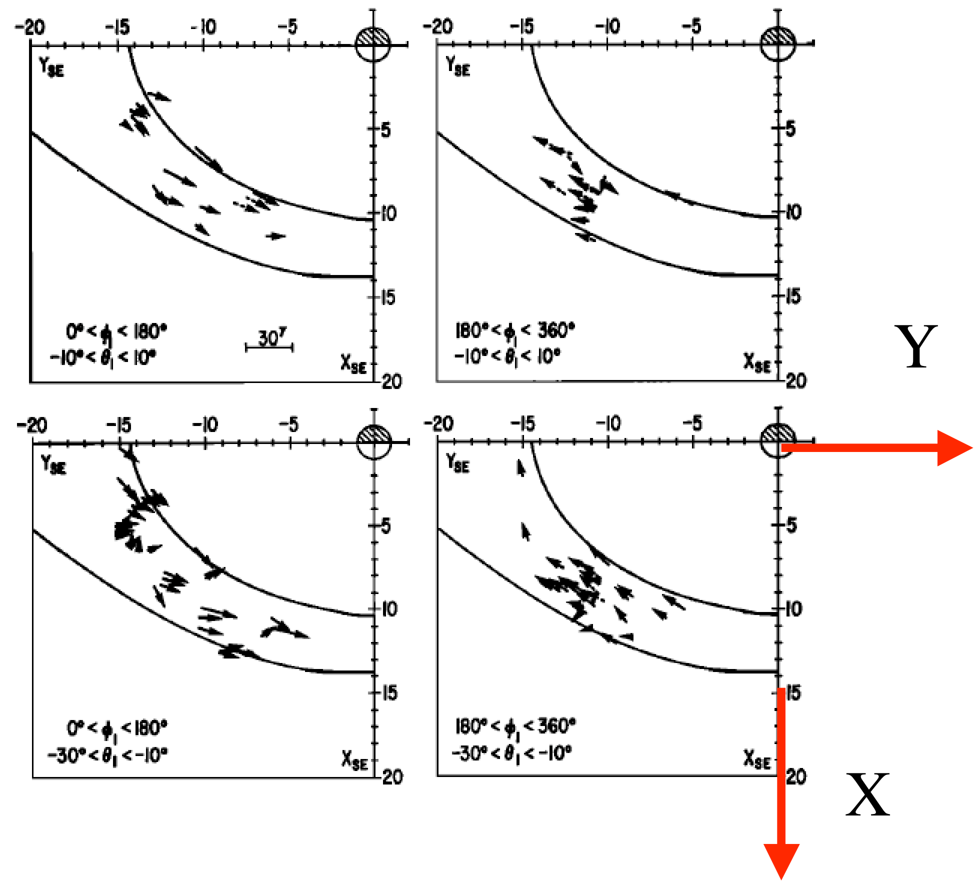


Cooling et al. [2001]

Gasdynamics: Spreiter et al. [1966]



Predicts observed draping pretty well [Fairfield, 1967]…

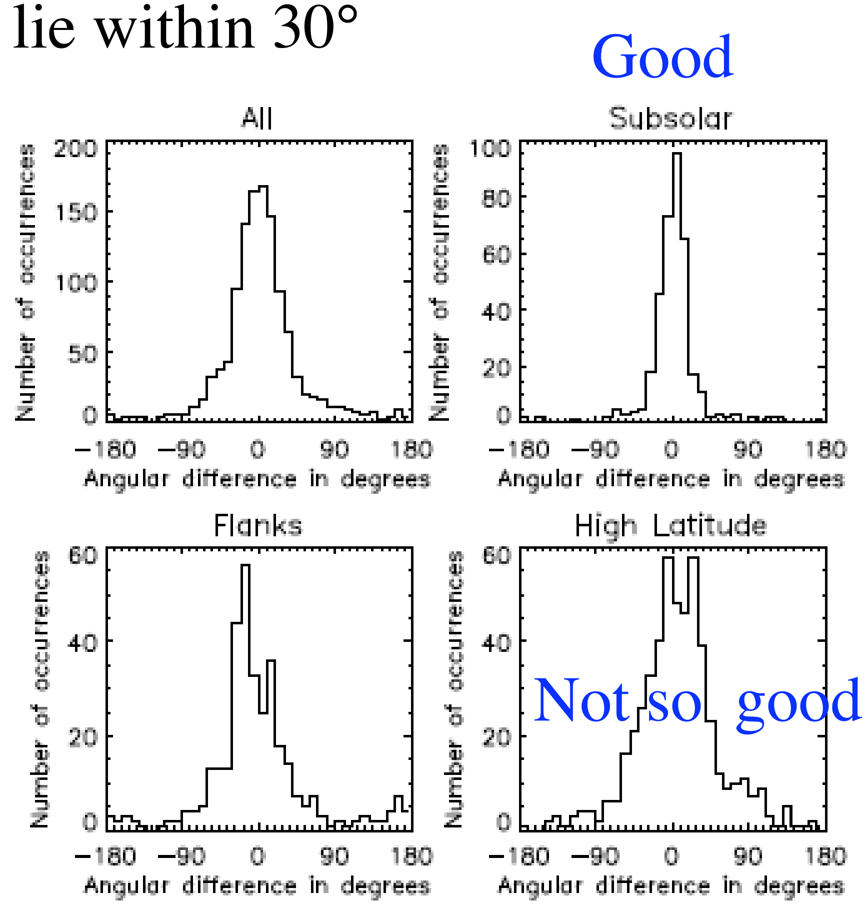


…but not perfect.

Predicting Magnetosheath Magnetic Field Orientations

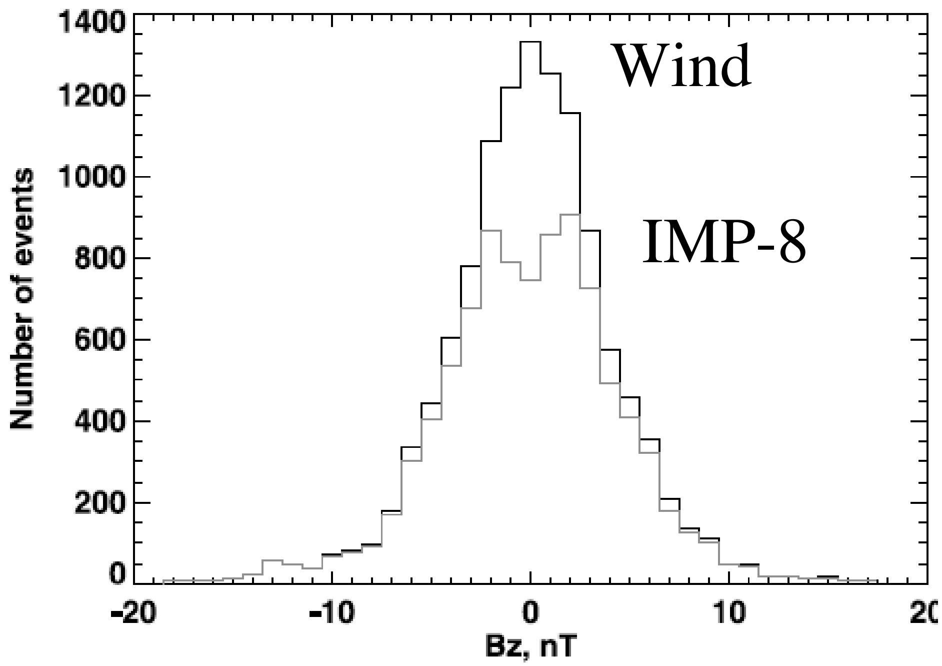
- 30% of magnetosheath magnetic field clock angles lie within 10° of those in the IMF, 70% lie within 30°

- So.. “it is not safe to rely on the orientation of the magnetosheath magnetic field at any given patch within 2 R_E of the magnetopause to be similar to that observed in the upstream IMF or predicted by any simple gasdynamic or analytical model.” [Coleman, 2005]

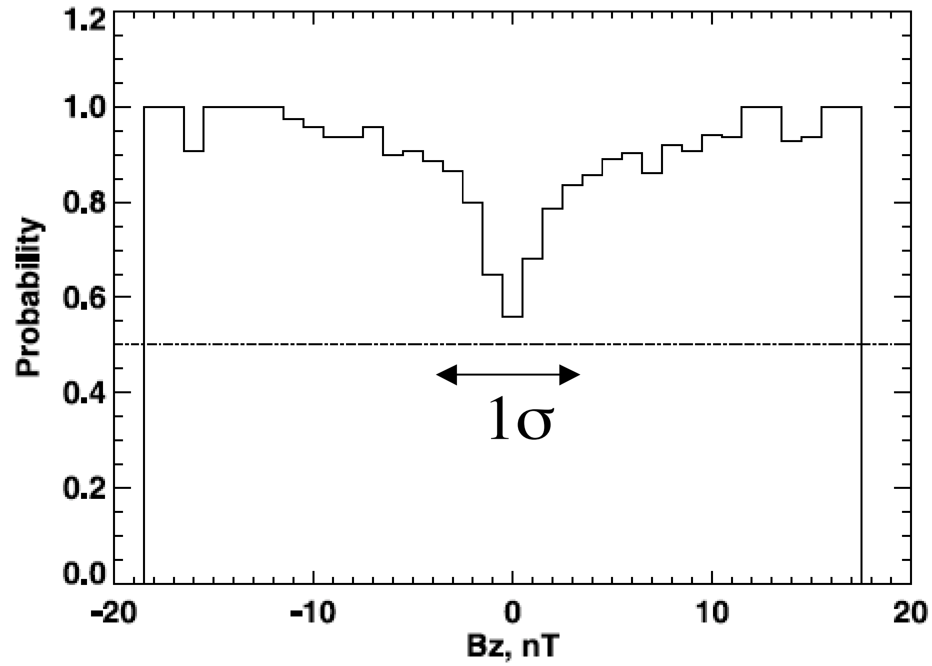


Interplanetary-Magnetosheath Bz Comparisons

Distributions of B_Z



Probability Bz has same sign

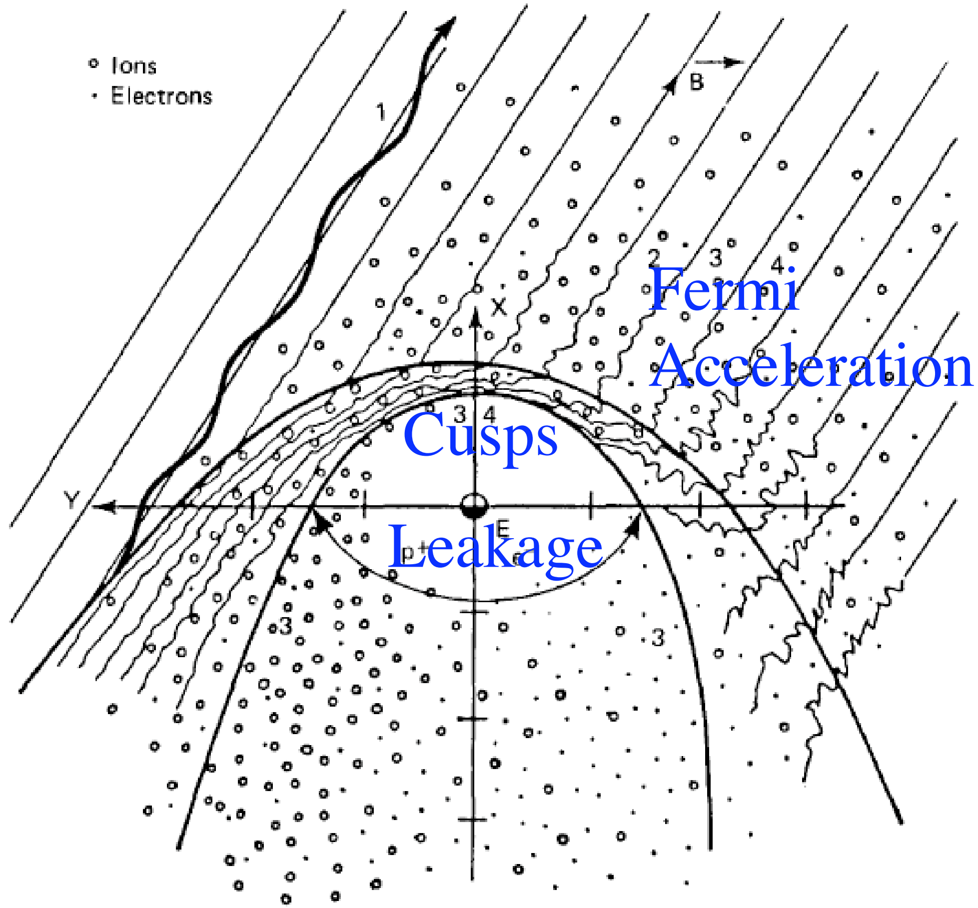


Chance of predicting sign of Bz in sheath increases with increasing IMF |Bz| component. Safrankova et al. [2009]

Analytical Models

Provides Framework to Determine Particle Sources

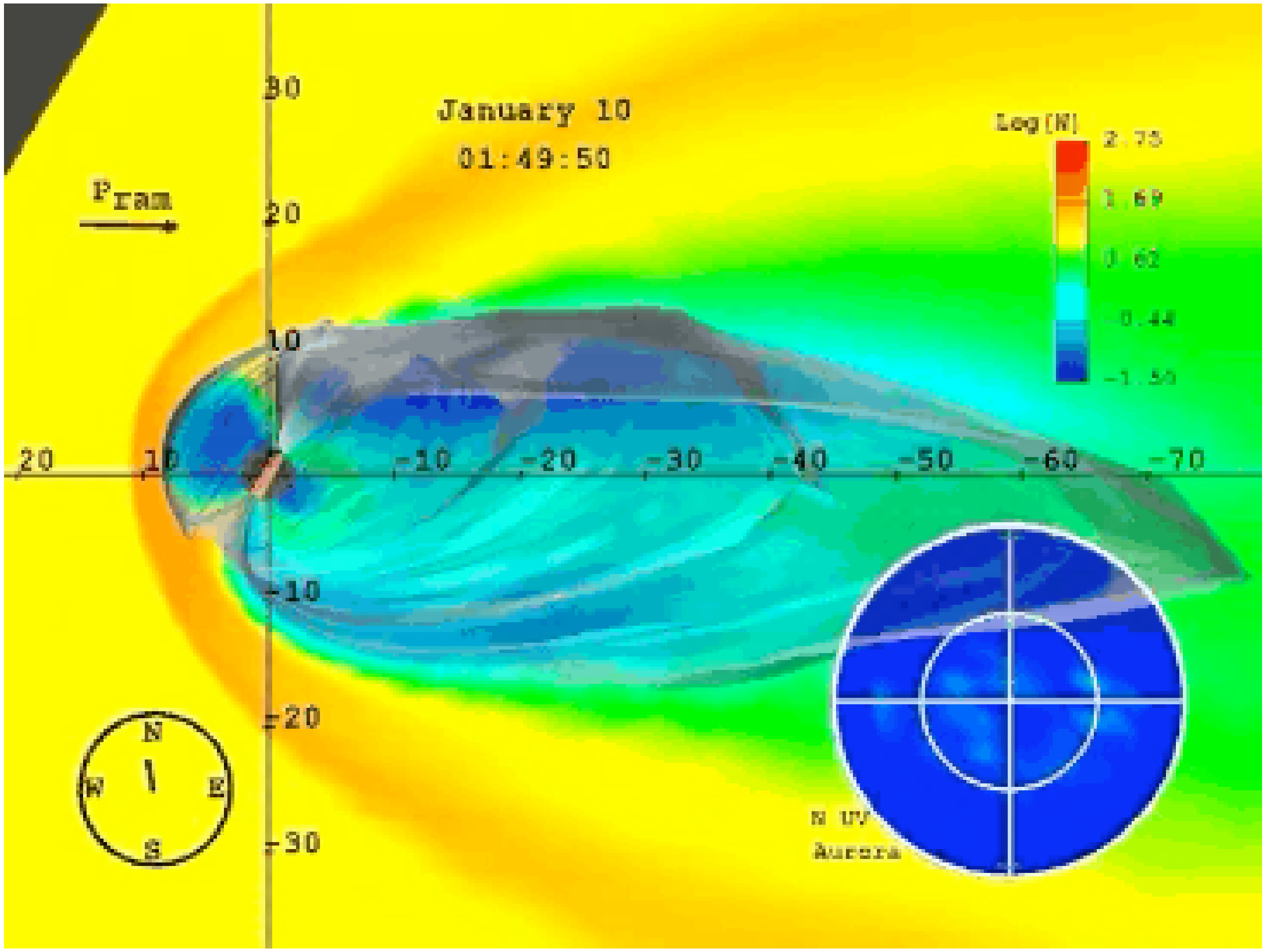
Connectivity determines whether particles can reach a given location
[e.g., Trattner et al., 2003]



MHD Models

- Self-consistent bow shock and magnetopause locations
- Depletion layer and flow acceleration due to magnetic pressure and gradient curvature forces
- Fast, slow, and intermediate mode waves launched when solar wind discontinuities strike the bow shock.
- Reconnection and Kelvin-Helmholtz instabilities on the magnetopause

MHD: Dynamic Interaction



Response to varying solar wind densities and IMF orientations

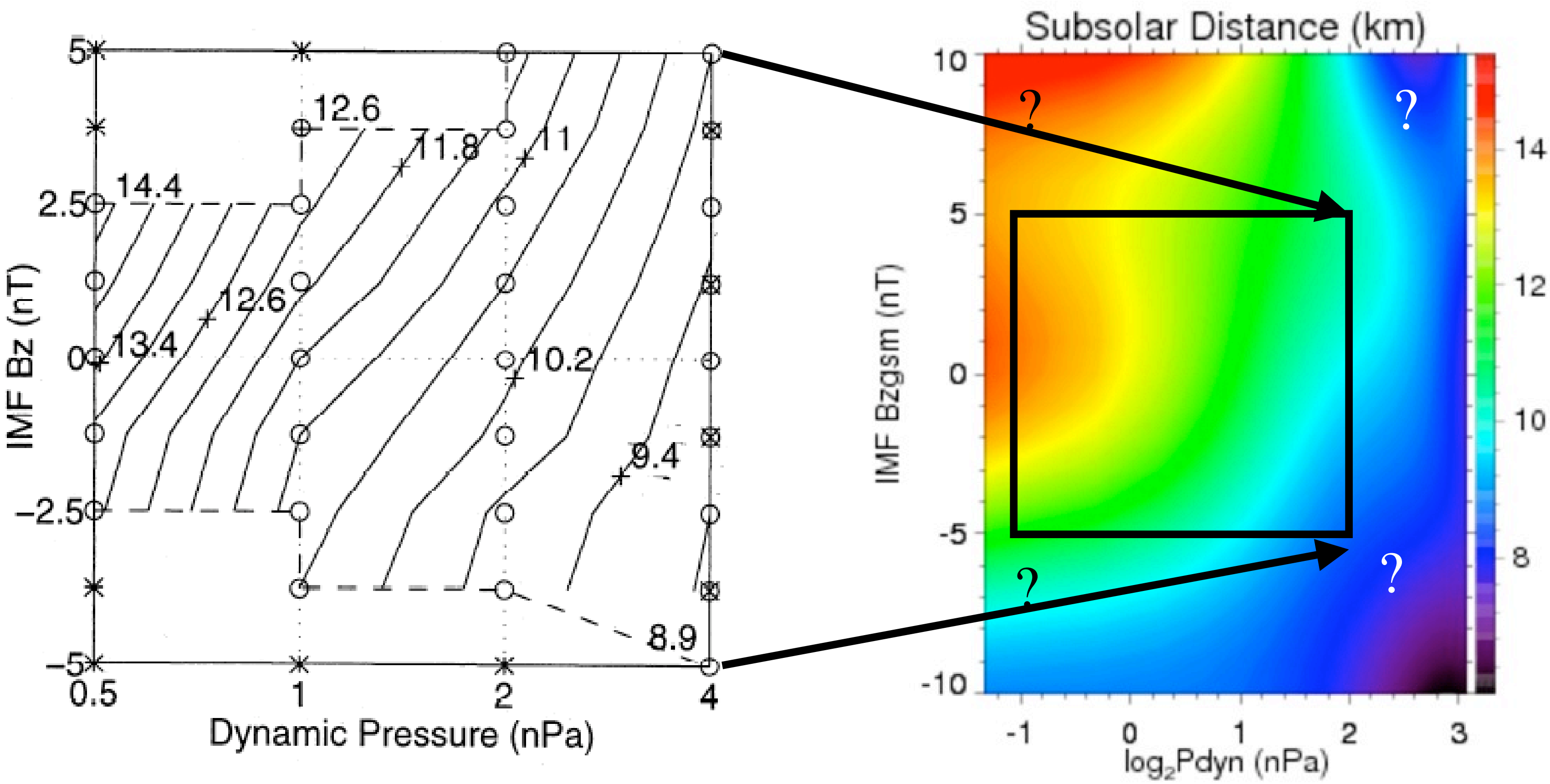
[C. Goodrich, Personal comm.]

Densities and Aurora

MHD Magnetopause Boundary:

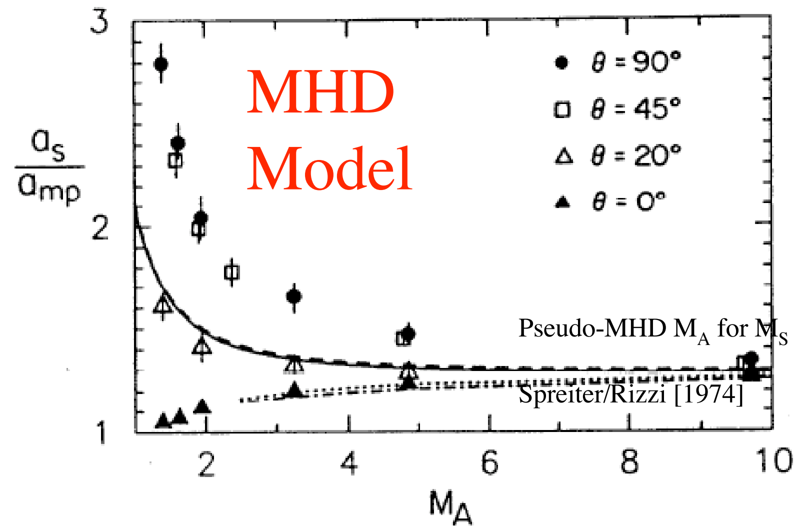
Multivariant Function of Control Parameters

Simulation   Subsolar Magnetopause   Empirical



Elsen and Winglee [1997]   Y. Wang [2010]

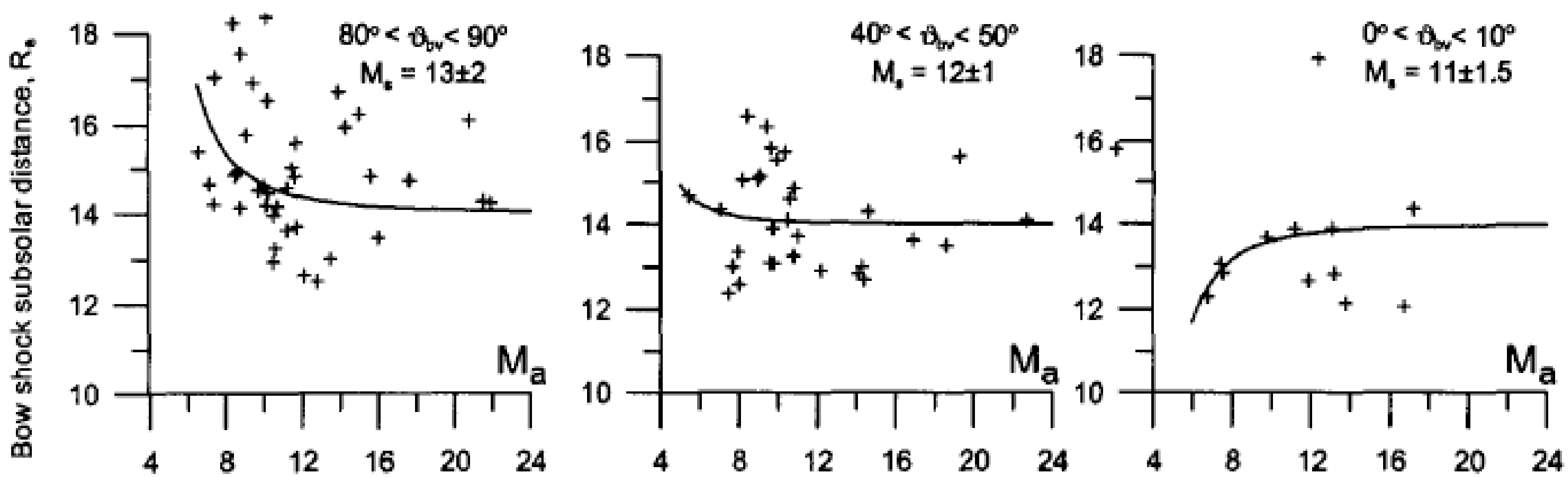
Subsolar Bow Shock location as a function of Θ_{Bn} and M_A



Observations

Cairns & Lyon [1996]

Θ_{Bn} 80-90° 40-50° 0-10°

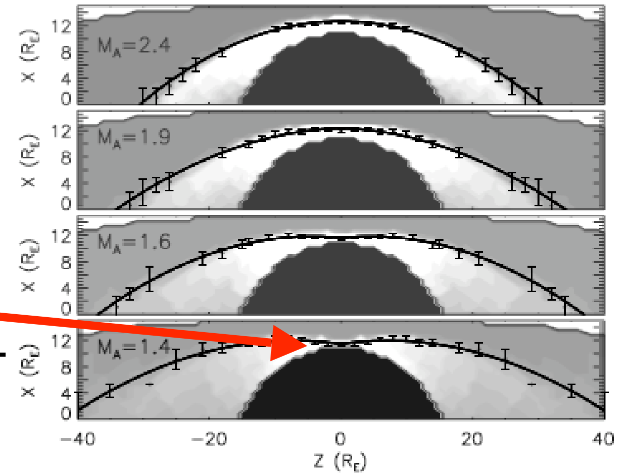


Verigin et al. [2001]

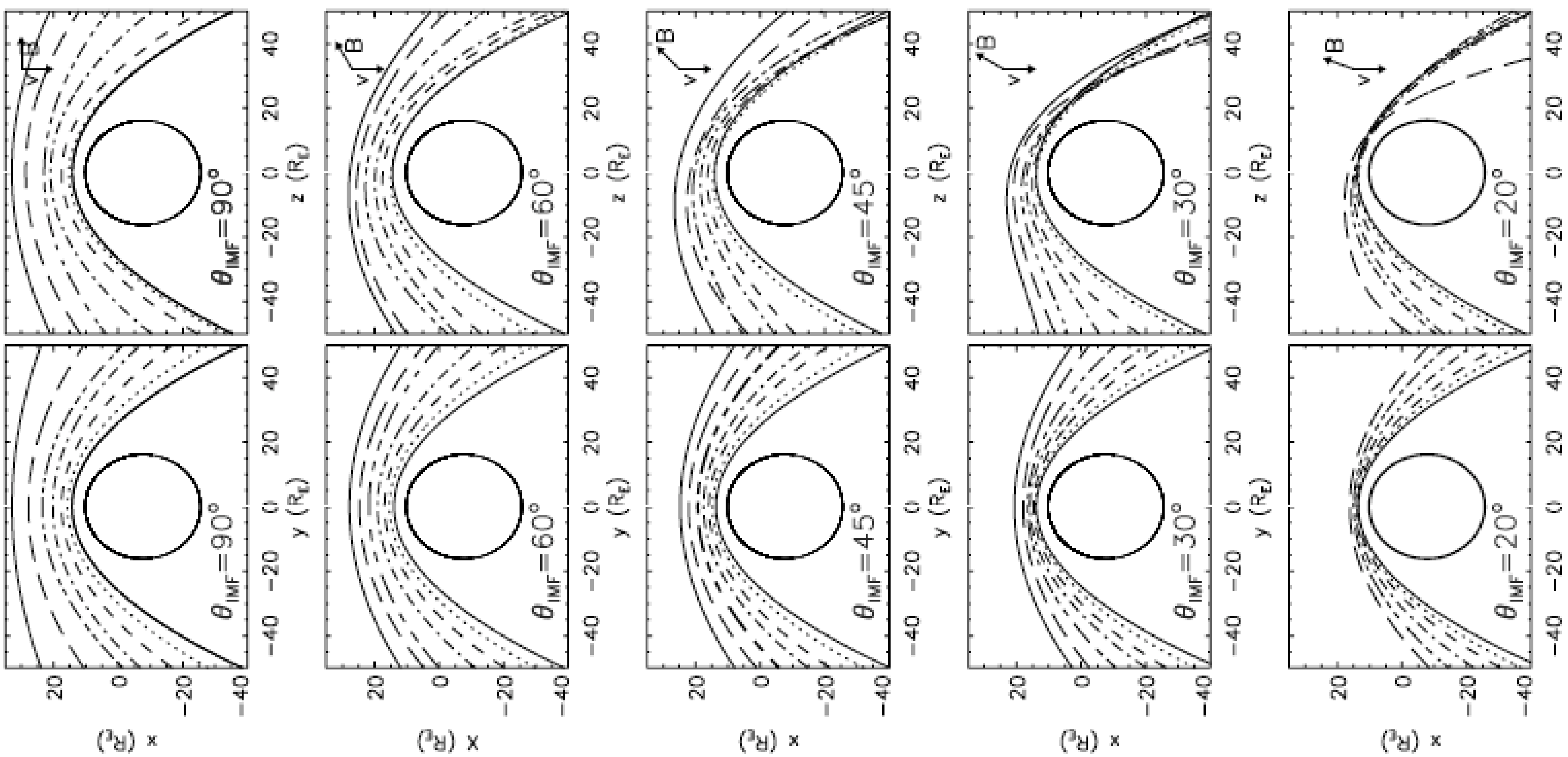
Predicted Sheath Thicknesses

Chapman et al. [2004]

Bow shock dimple for 0° cone angle and M_A = 1.4

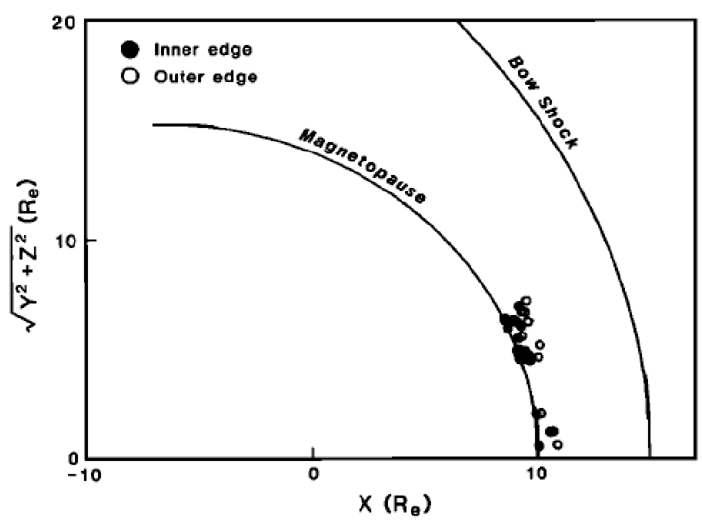


90° 60° 45° 30° 20° Cone Angle

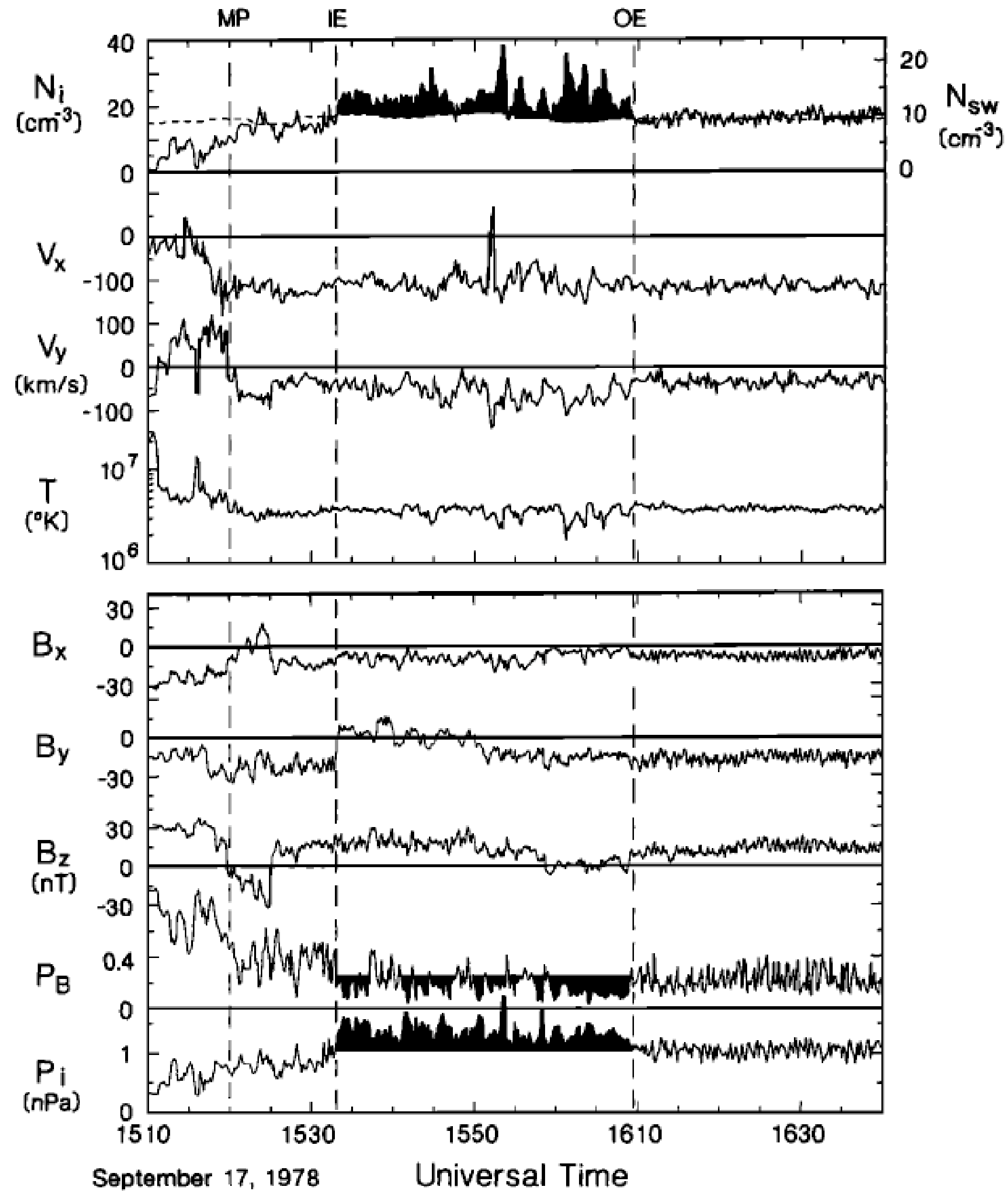


Slow Mode Waves Standing in Inner Magnetosheath:

Density Enhancements (analogous to bow shock)?

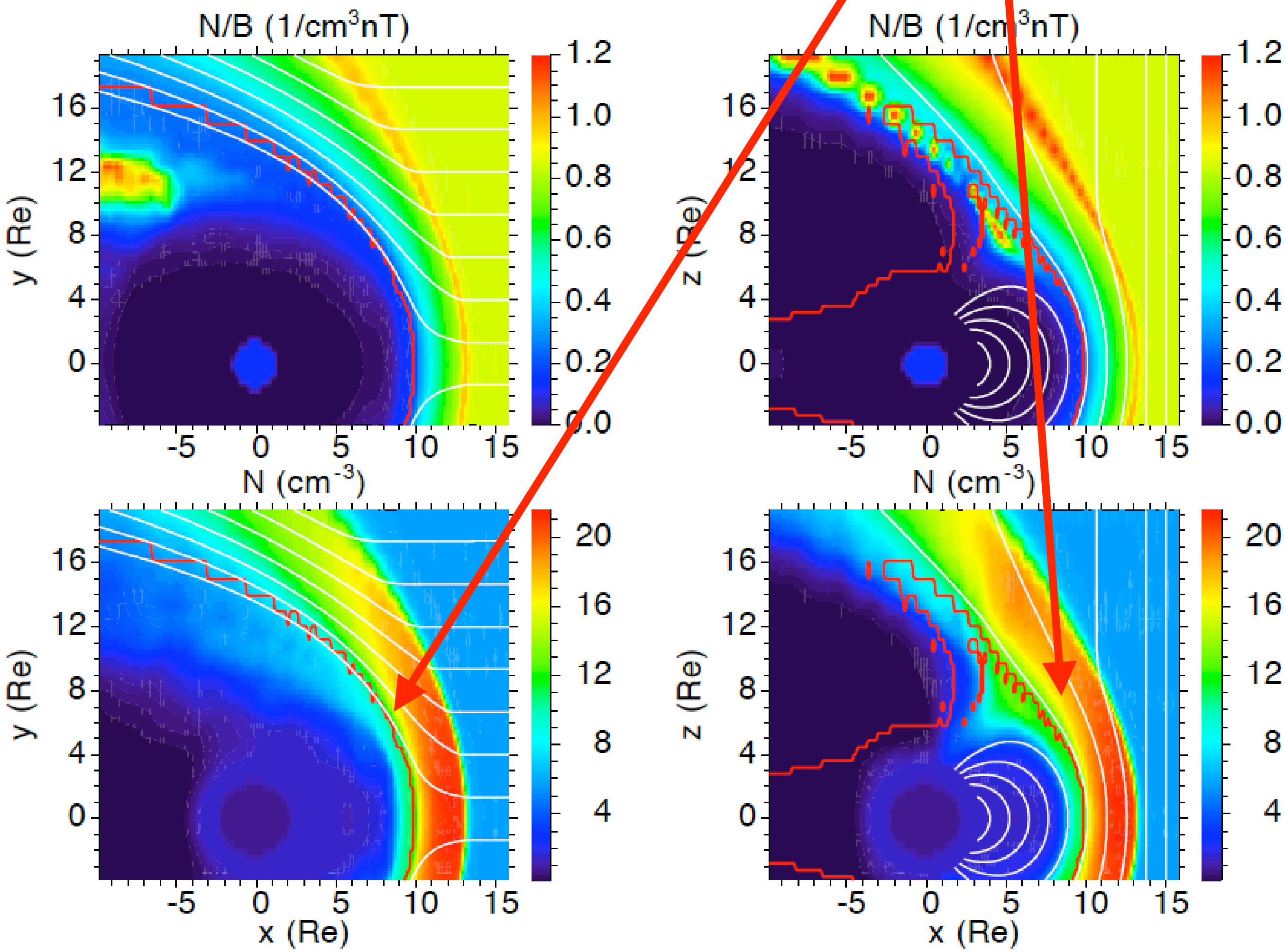


Song et al [1992]



MHD Models Predict

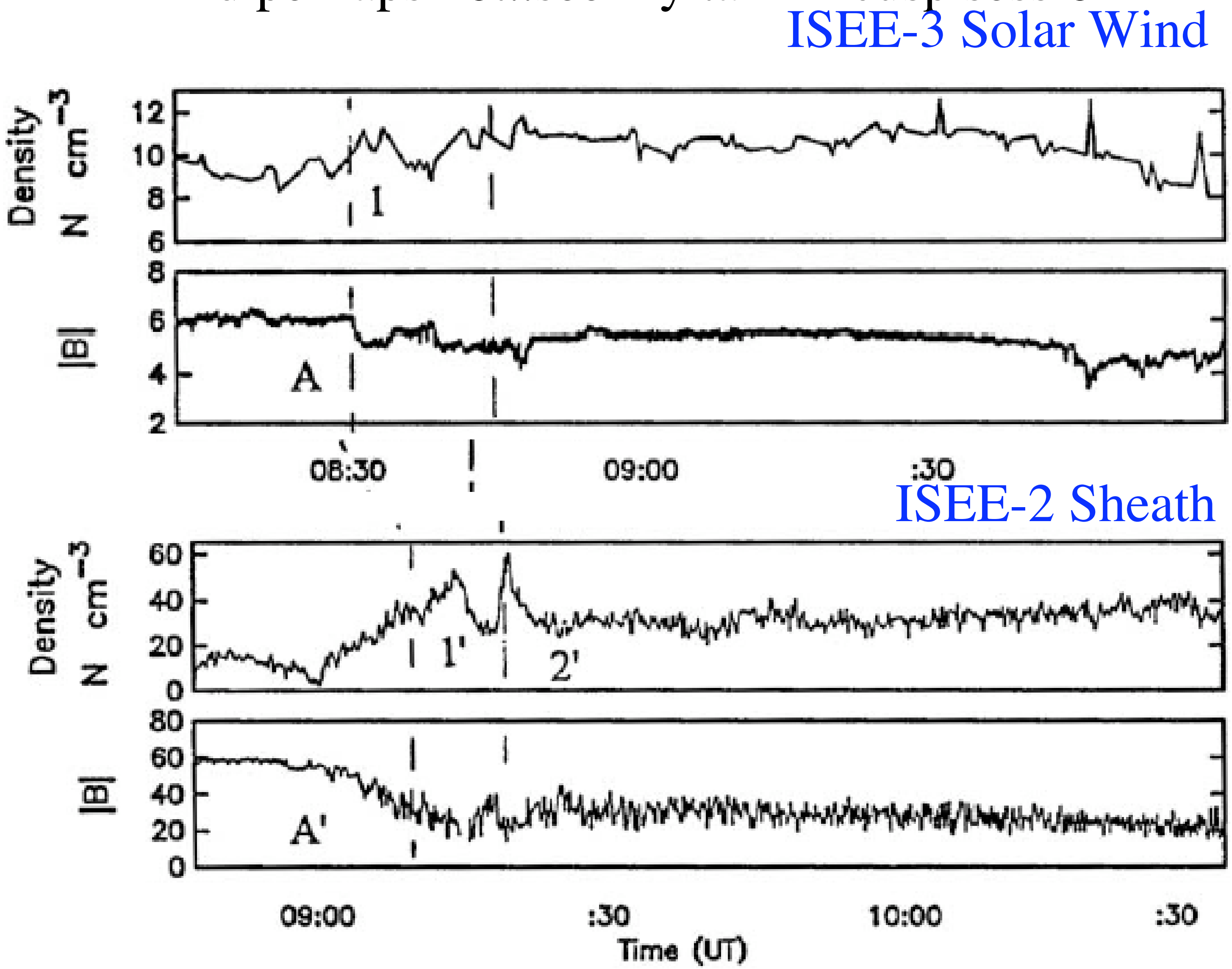
Depletion Layer of Low Densities Outside the Magnetopause but No Density Enhancements



No density enhancements at locations where slow mode waves can stand

Wang et al. [2004]

Perhaps Observed Density Enhancements are Transmitted SW Features [Hubert/Samsonov, 2004]? And perhaps not..see my talk in cusp session

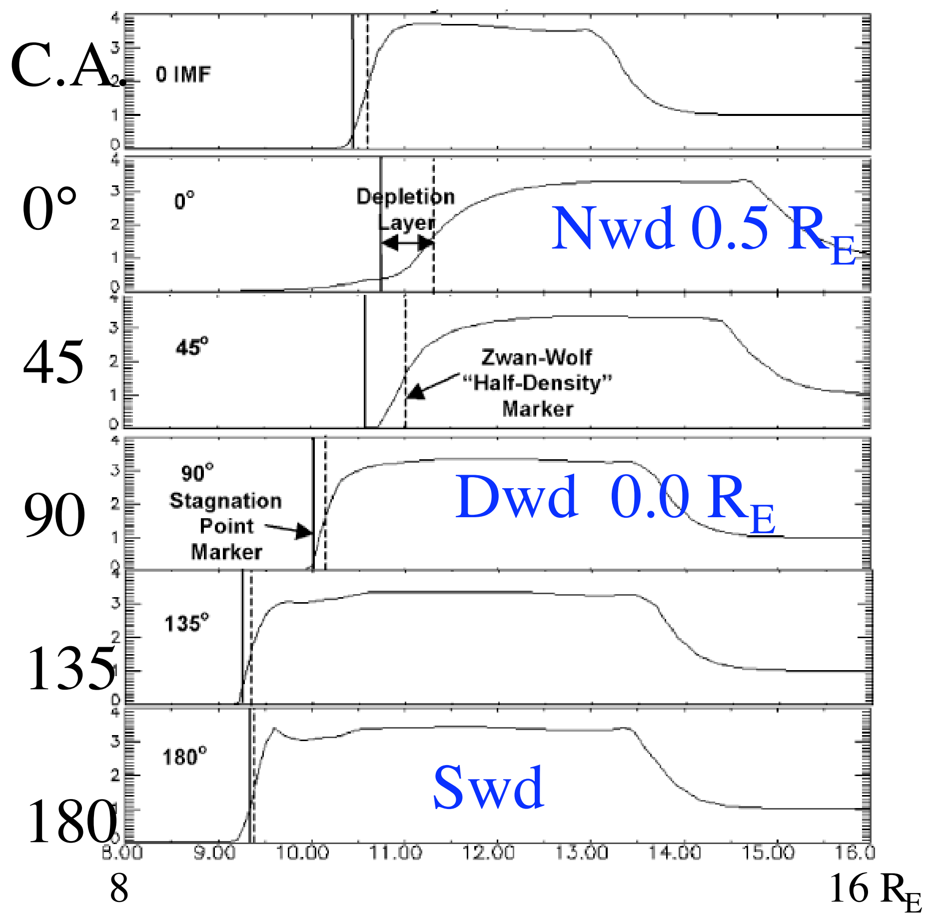


Need more study, THEMIS ideal

MHD: Depletion Layer Density Dependence on IMF

Strong

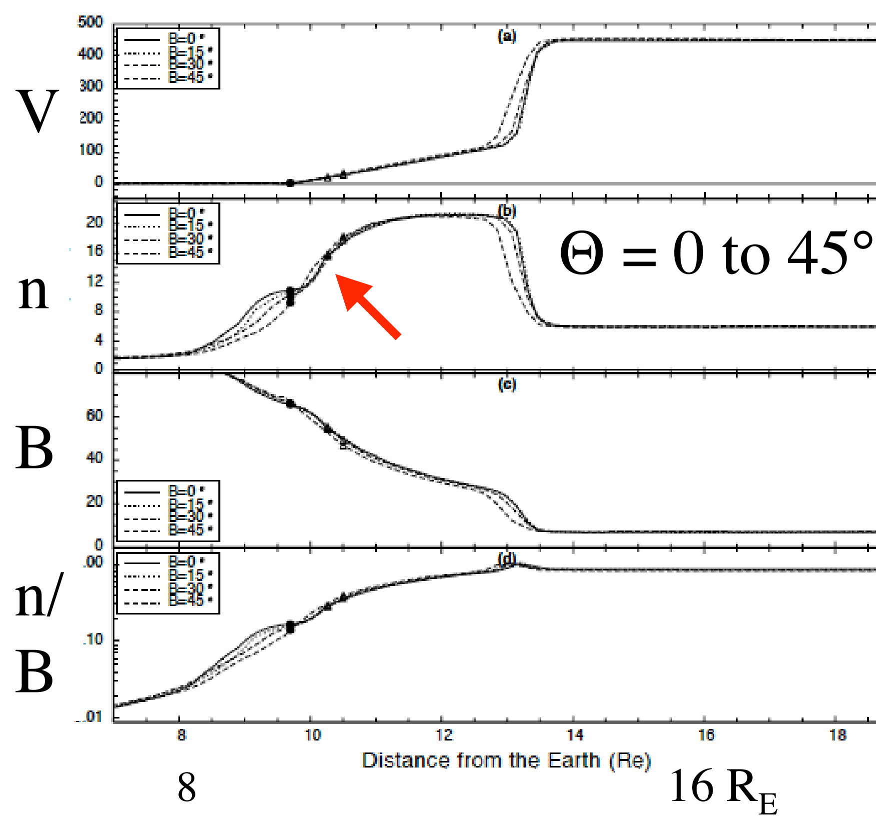
Siscoe et al. [2002]



Strong dependence on IMF latitude

Weak

Wang et al. [2004]

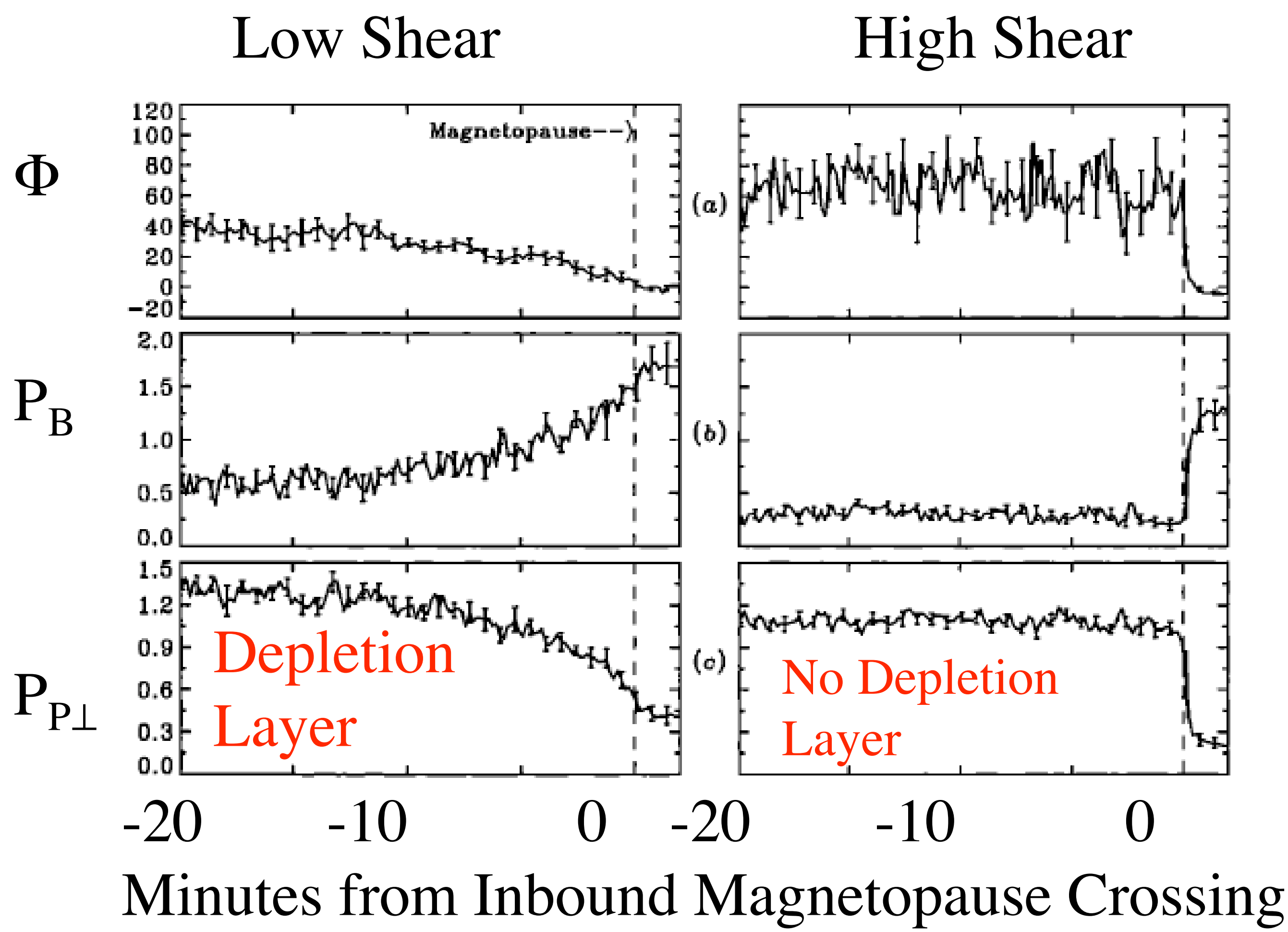


Weak dependence on IMF latitude

Superposed Epoch Analyses of Low and High Shear Dayside Magnetopause Dayside Crossings

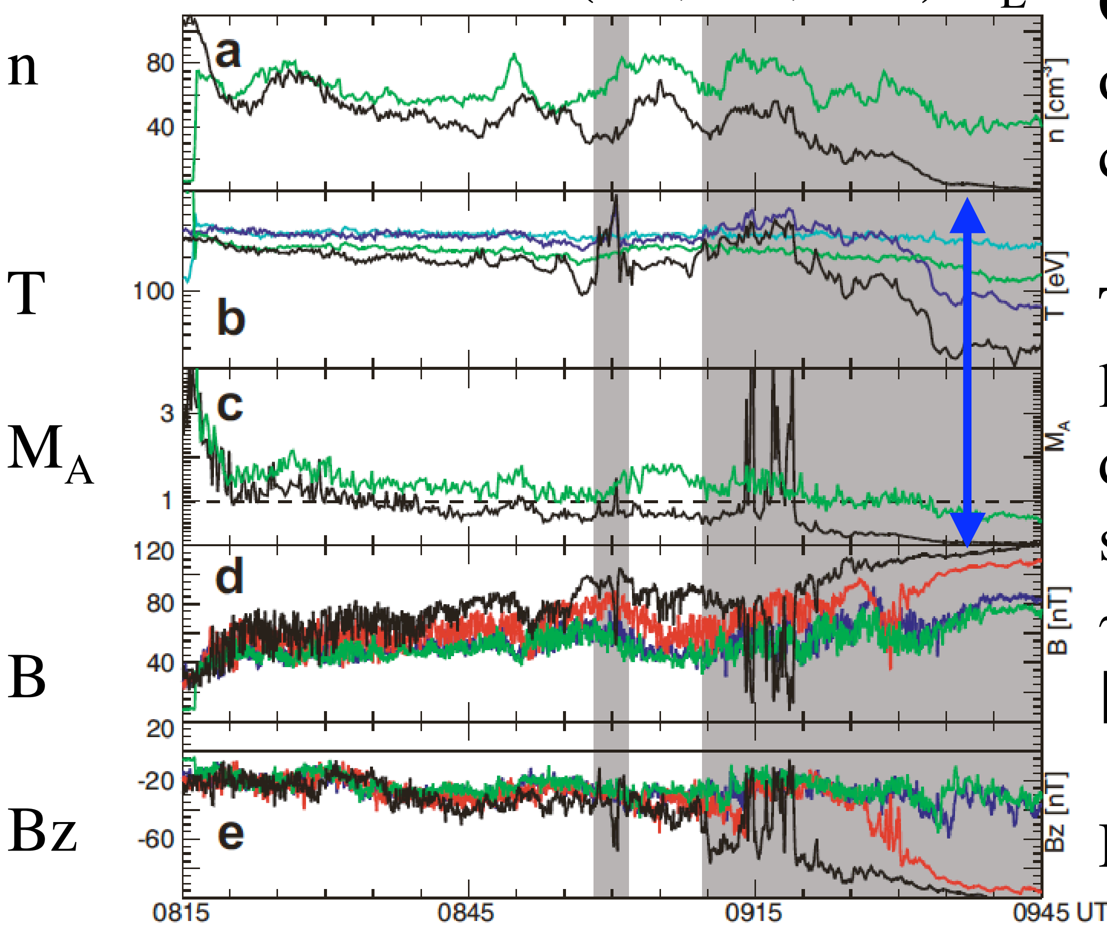
Phan et al. [1994]

More prominent for low shear



Depletion Layer Thicknesses

Cluster GSM (6.3, 0.5, -9.4) R_E



0815 February 2, 2003 0945 UT

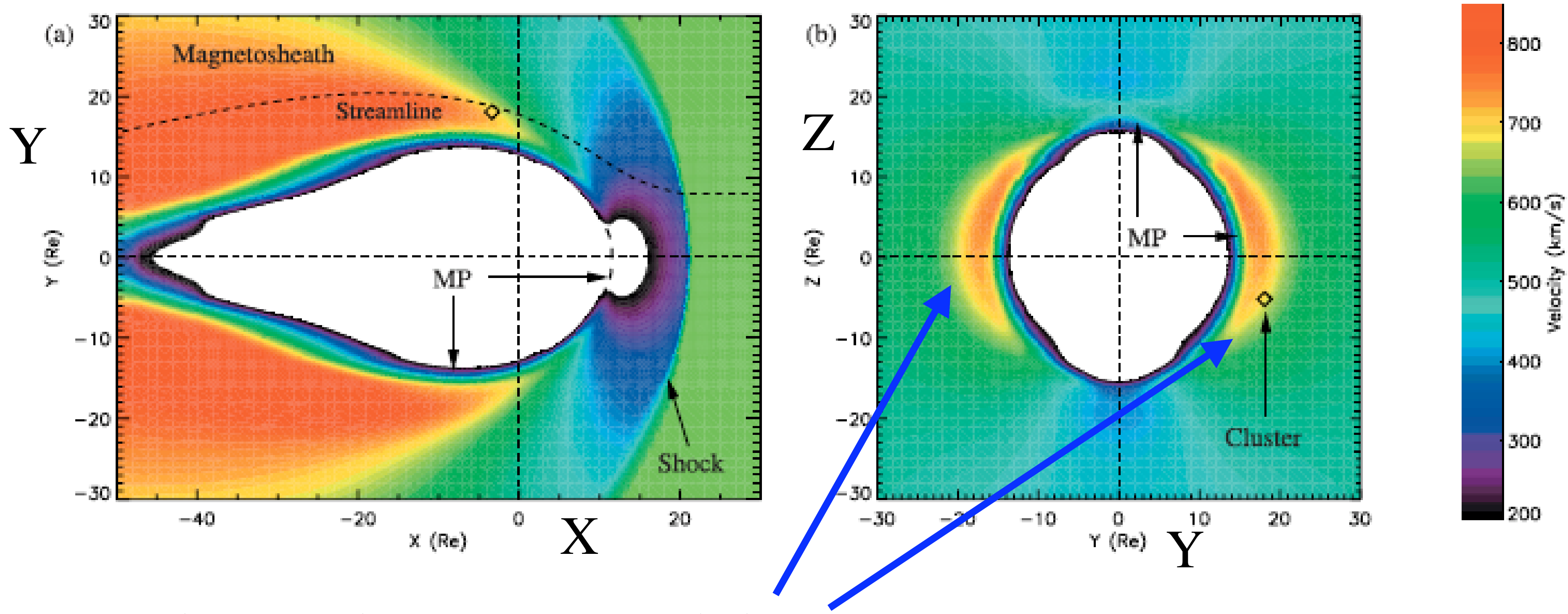
Cluster (and THEMIS) observations are ideal for case studies.

This high-latitude depletion layer exhibited factor of ~2 density and magnetic field strength variations over ~1.8 R_E during IMF Bz < 0! [Moretto et al., 2005].

Depletion layer shaded.

Draped Magnetic Field Lines, Curvature Forces, and Flow Acceleration On Magnetotail Flanks

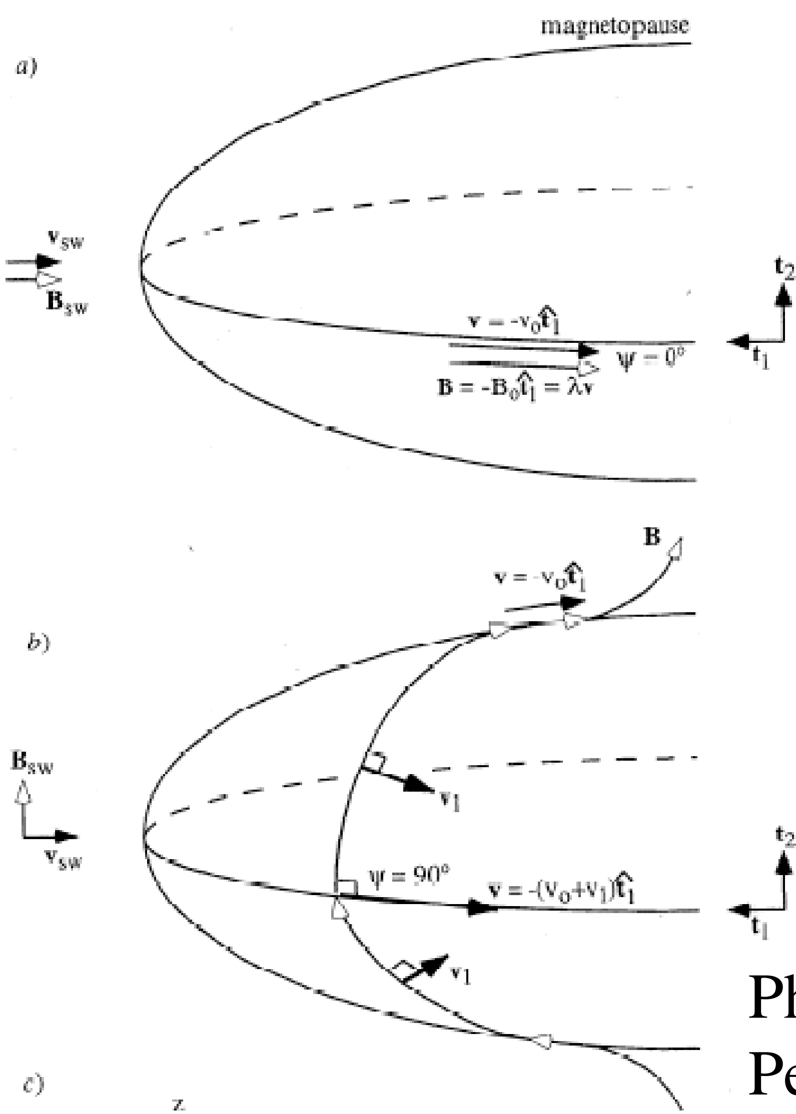
Velocities



Accelerated flows outside tail flanks for IMF Bz >> 0.

Chen et al. [2003]
Lavraud et al. [2007]

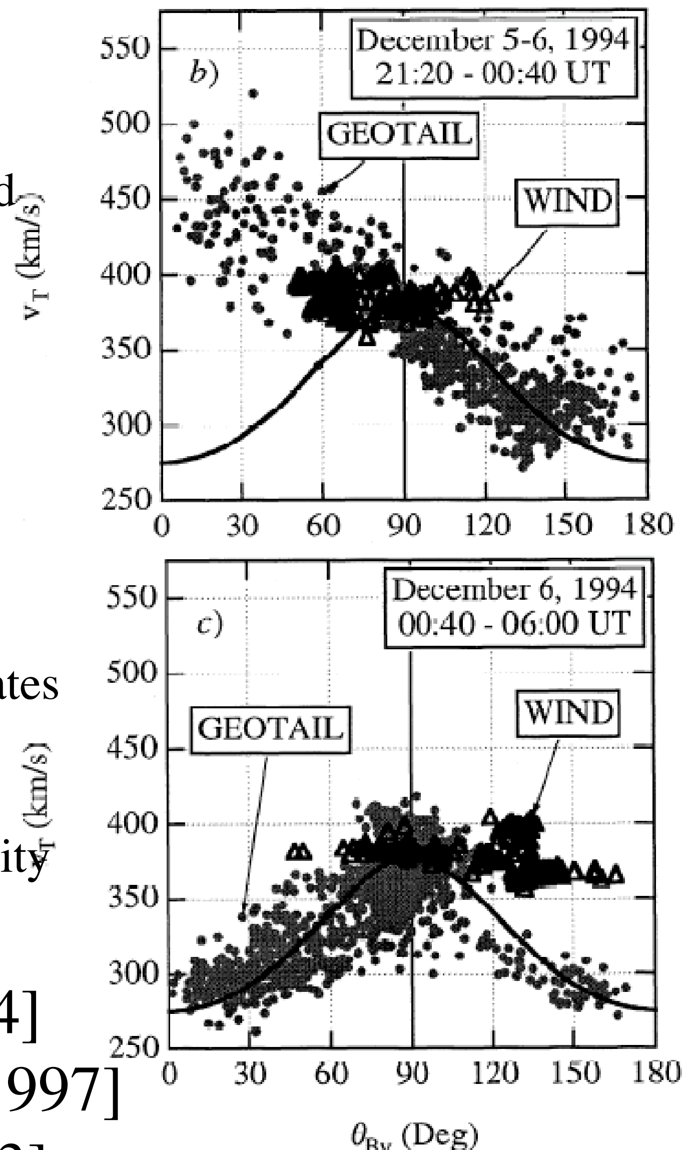
Flow Acceleration



??? accelerates Geotail sheath flow above Wind solar wind velocity!!!!!

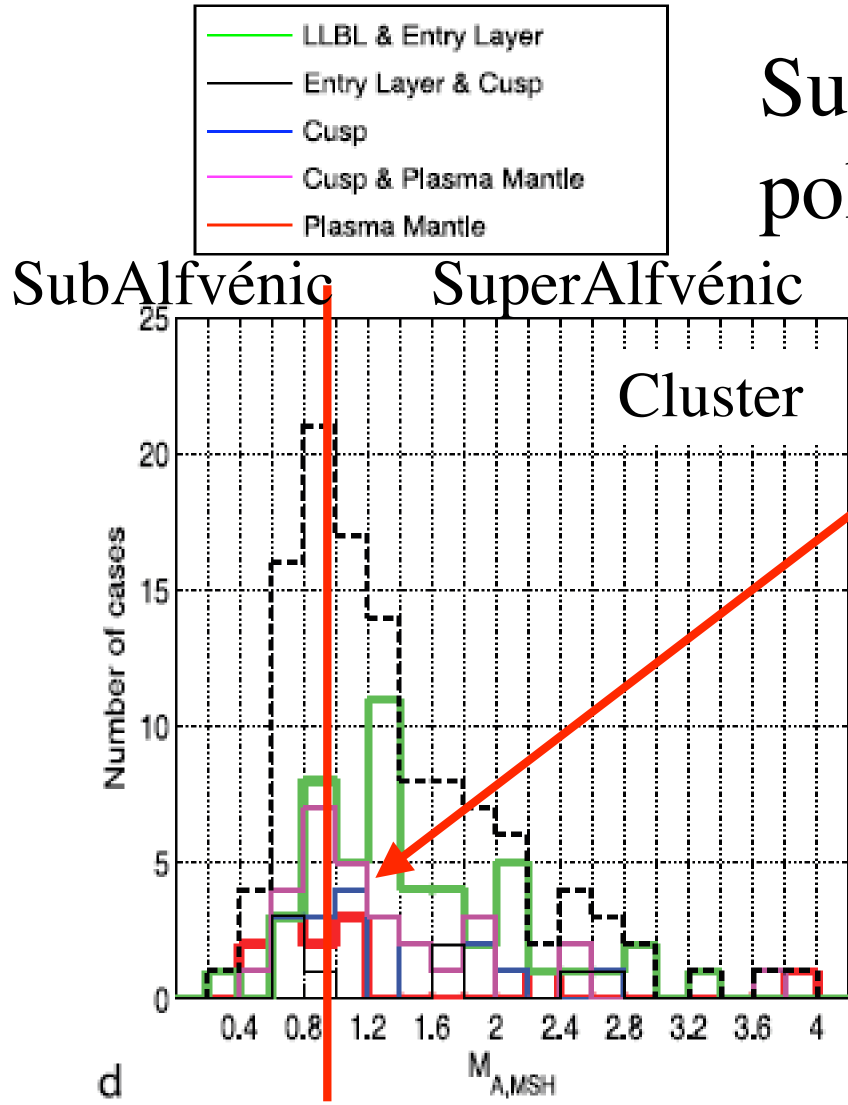
Huh?

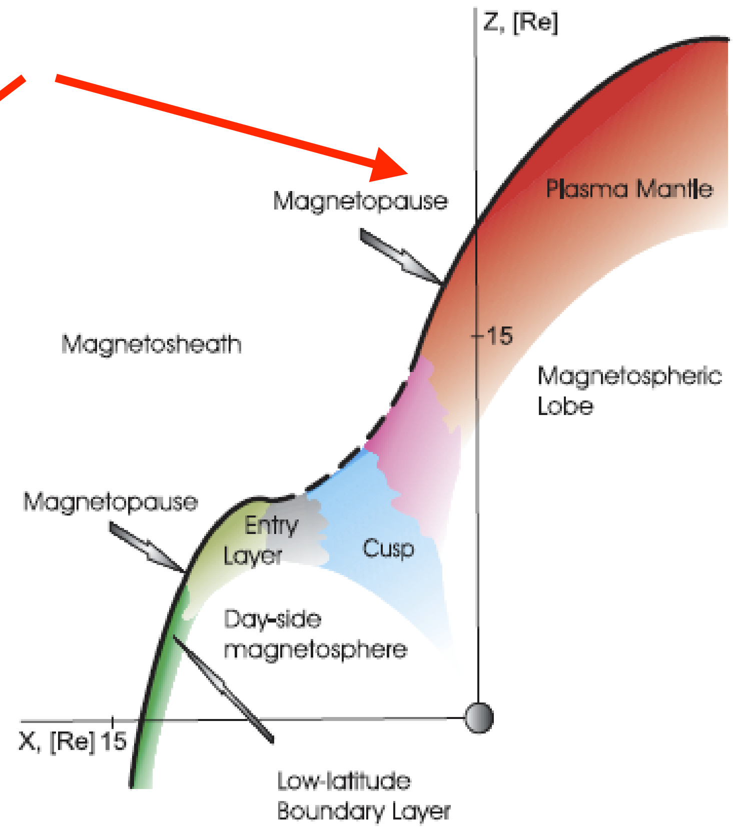
Tension accelerates Geotail sheath flow up to Wind solar wind velocity



Phan et al. [1994]
Petrinec et al. [1997]
Chen et al. [2003]

Subsonic, sub-Alfvénic flows poleward of cusps….



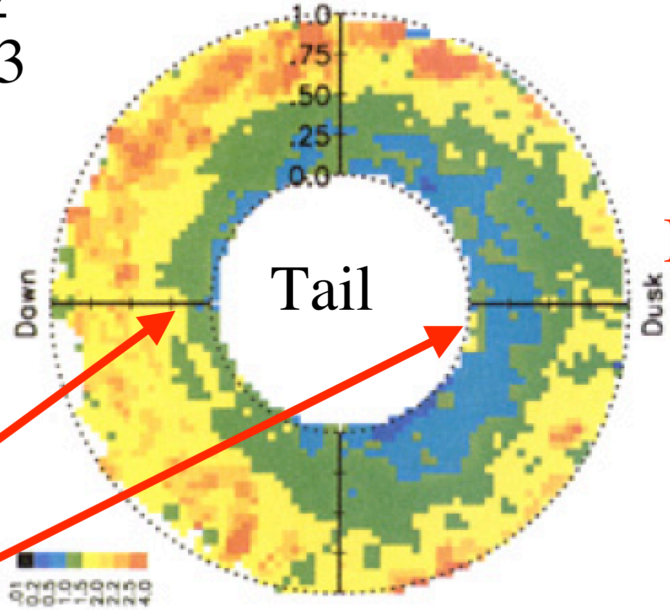


Enable steady reconnection during northward IMF
[Avanov et al., 2001; Panov et al., 2008]

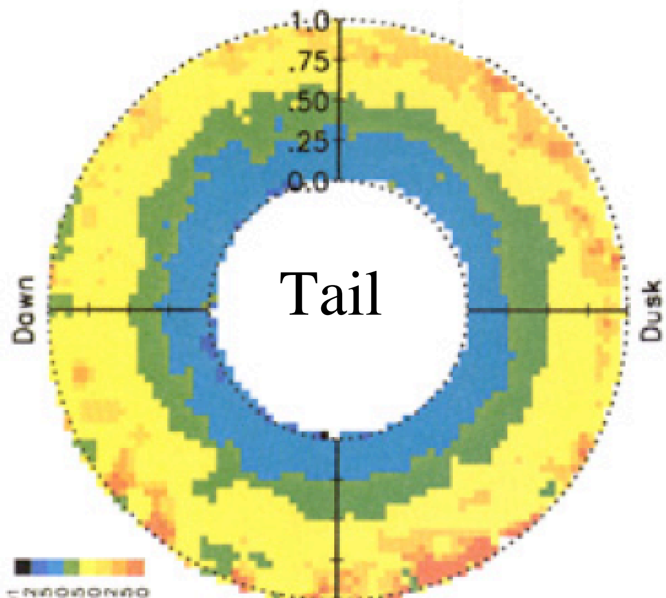
Solar Cycle-Dependent Dawn/Dusk Density Asymmetries???

Paularena et al. [2001]

IMP-8
ISEE-3

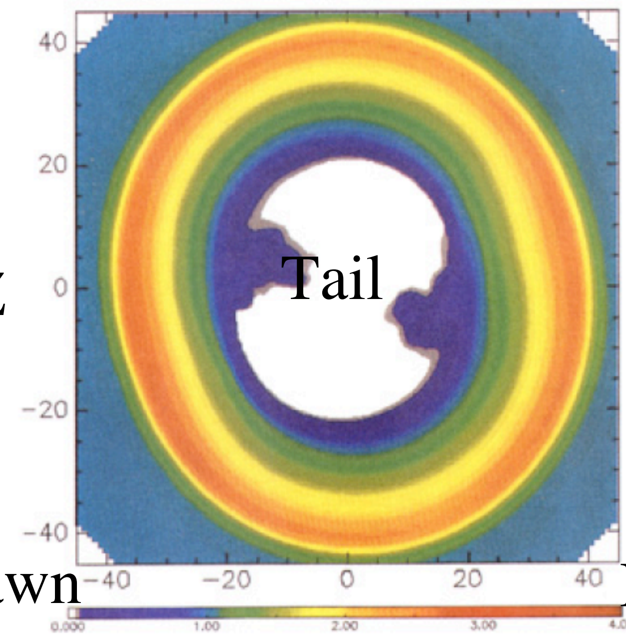


IMP-8
Wind

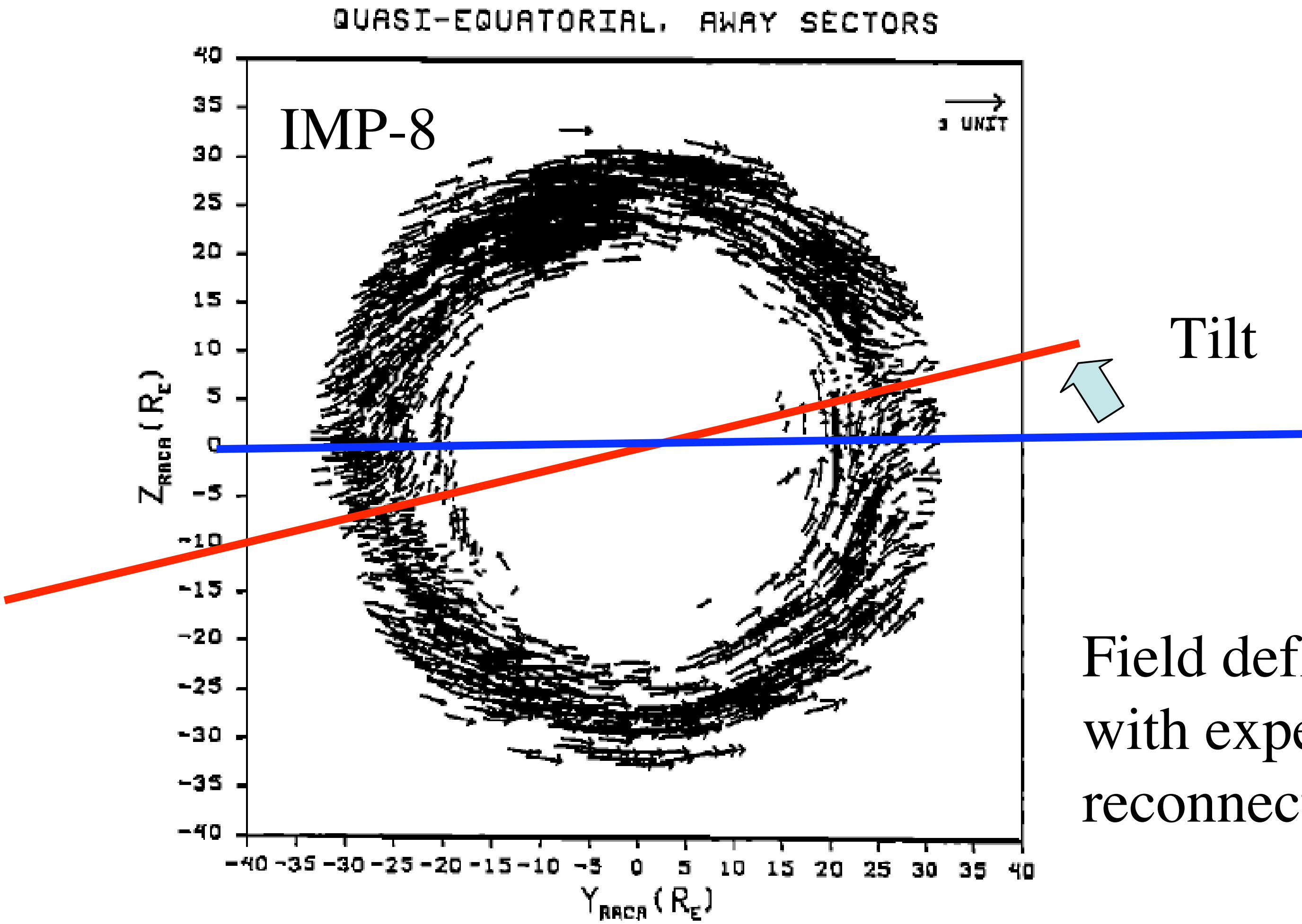


$-2.5 < X/R_{MP} < -1.0$

MHD tail X-section
at $X = -17\ R_E$
Densities 5% greater on dawnside?



Reconnection Affects Field Line Draping Outside Magnetotail

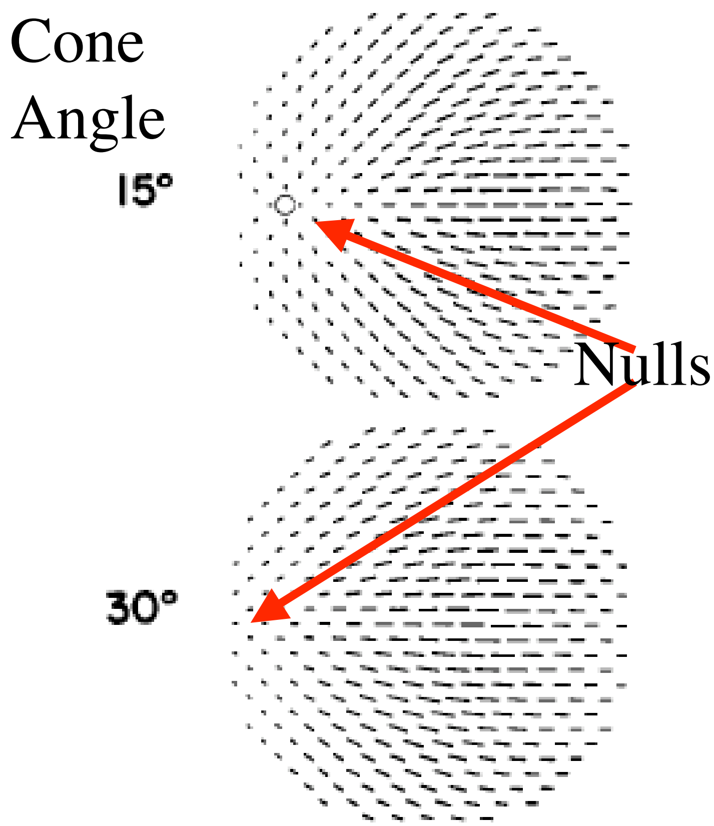


Field deflections consistent with expected tilt of dayside reconnection line

Kaymaz et al. [1992]

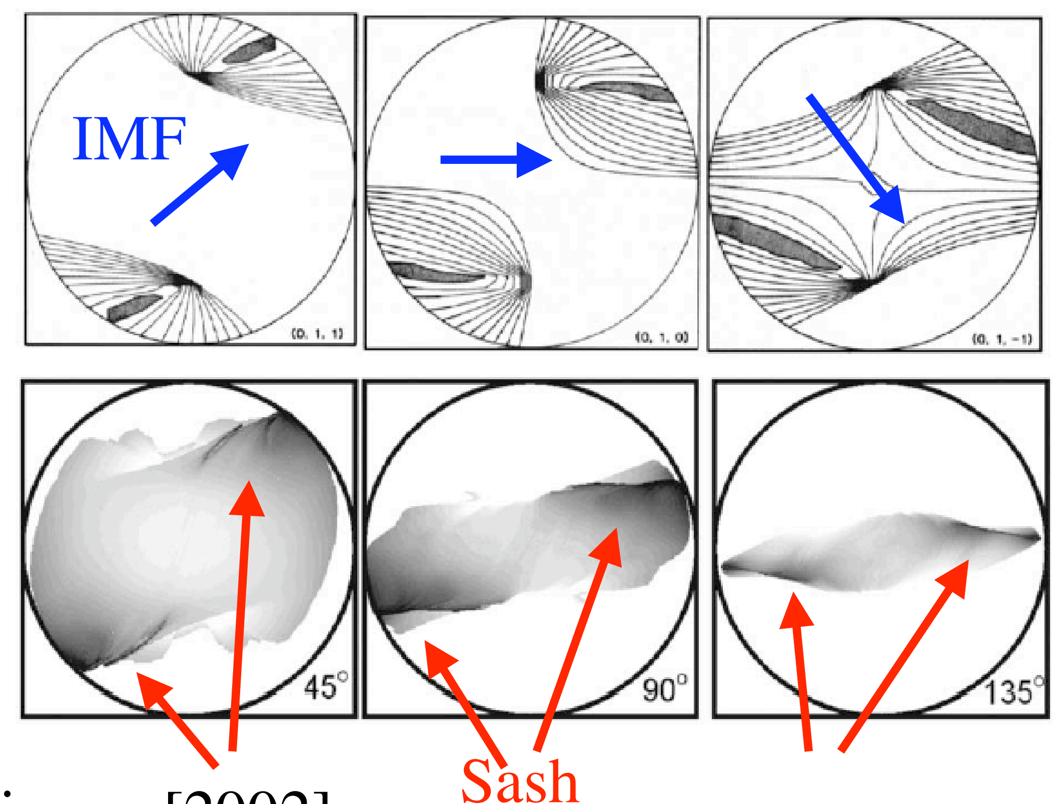
Predicted Weak Magnetosheath Magnetic Fields Await Observational Confirmation

Draping



Crooker et al. [1990]

Sash: Antiparallel Sheath and Sphere Fields

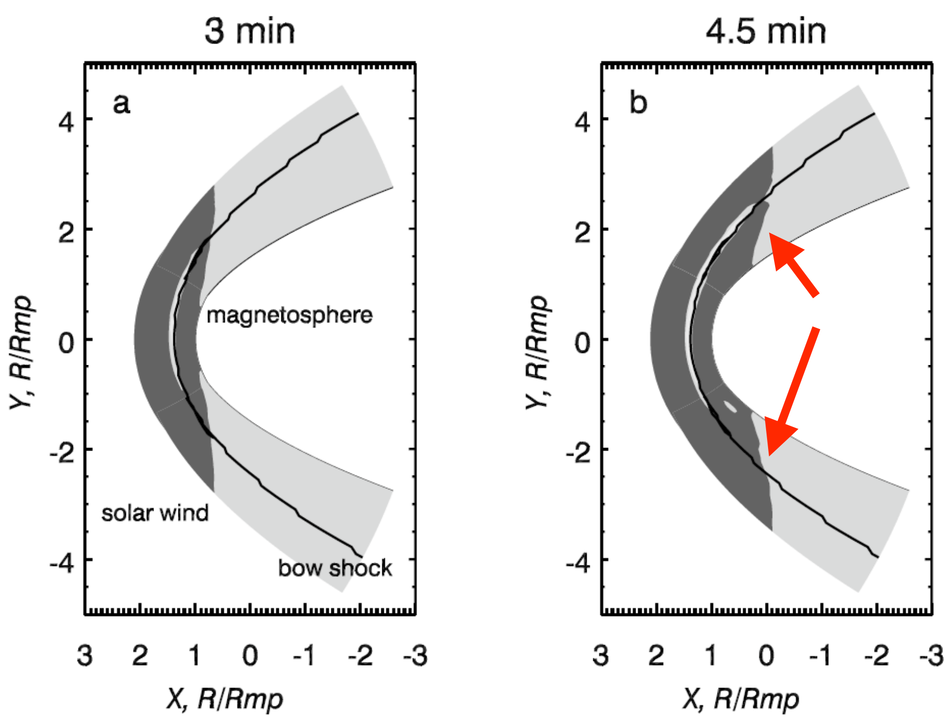


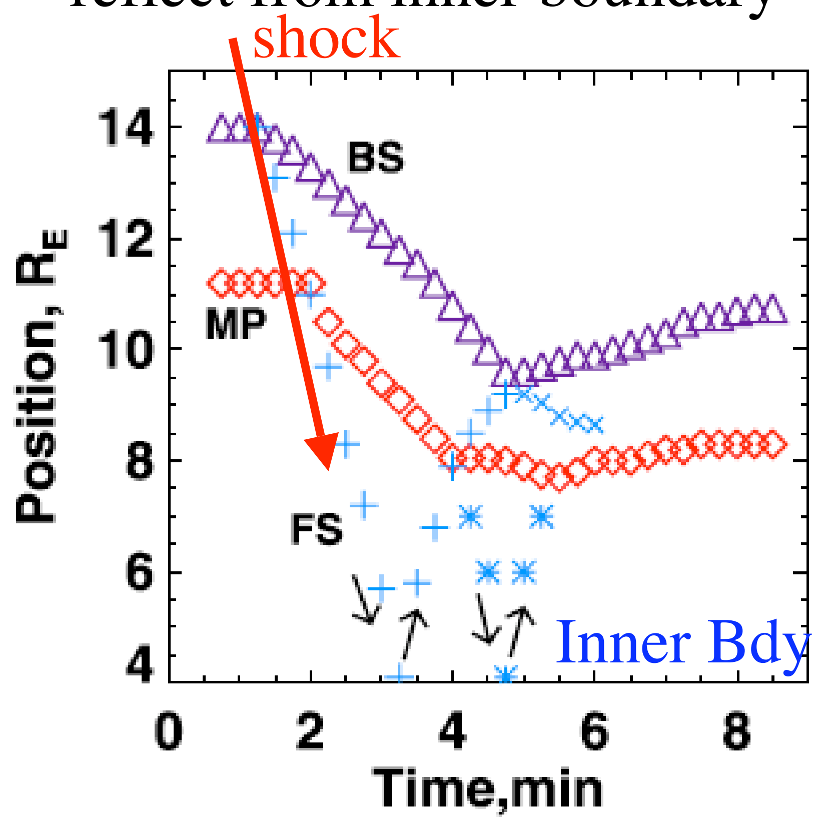
Siscoe [2002]

NEED empirical model…

Interplanetary Shocks and the Bow Shock

Shock fronts become concave…. reflect from inner boundary



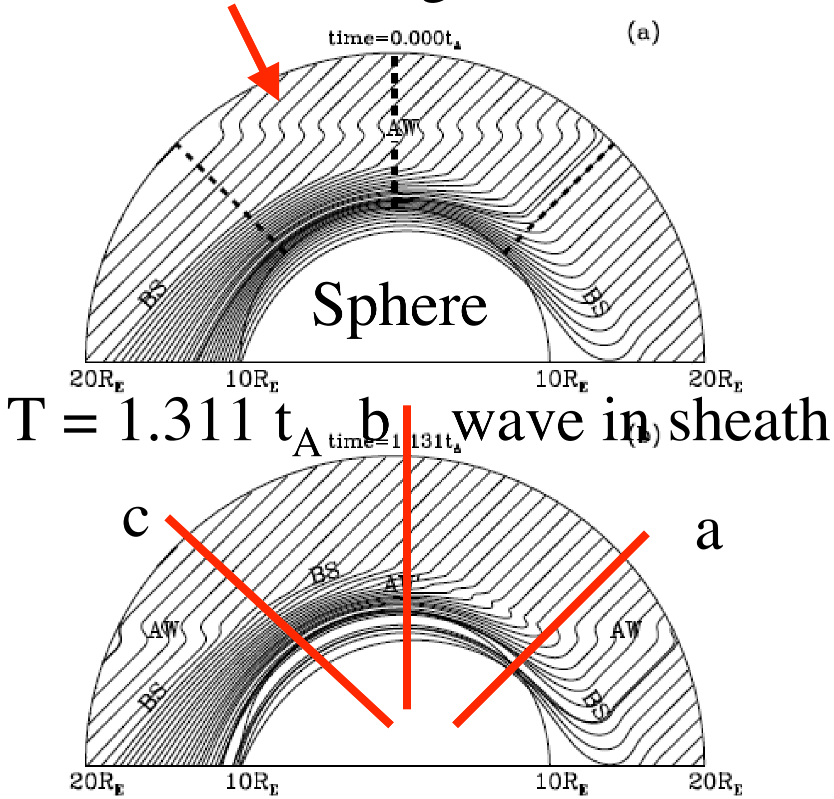


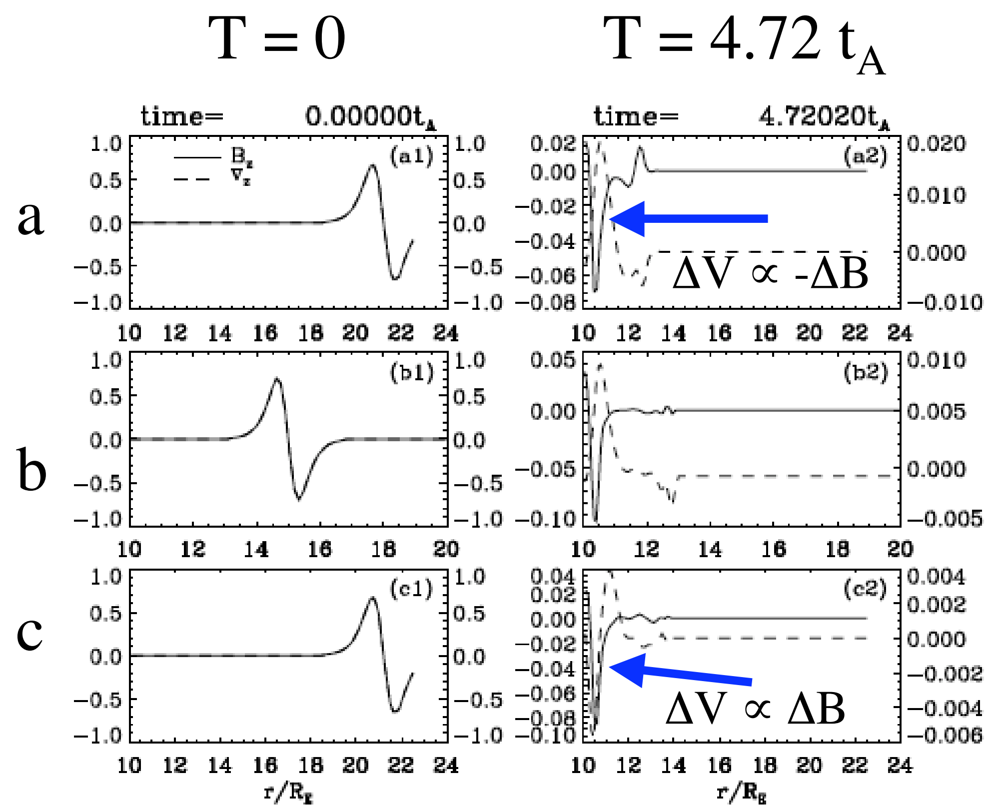
Predicted and Observed
Koval et al. [2005; 2006]

Predicted [Samsonov et al., 2007]
Observed?

Rotational Discontinuities and the Bow Shock

T = 0, incoming wave, $\Delta V \propto \Delta B$





Radial Cuts

Predict

$\Delta V \propto -\Delta B$ pre-noon, but $\Delta V \propto \Delta B$ post-noon [Cable and Lin, 1998]

Fluctuations in Sheath

12/30/1996

- 1. As predicted, ΔV fluctuations reverse across local noon, but….. $\Delta V << \Delta B/(\mu_o \rho)^{1/2}$

Disagreement

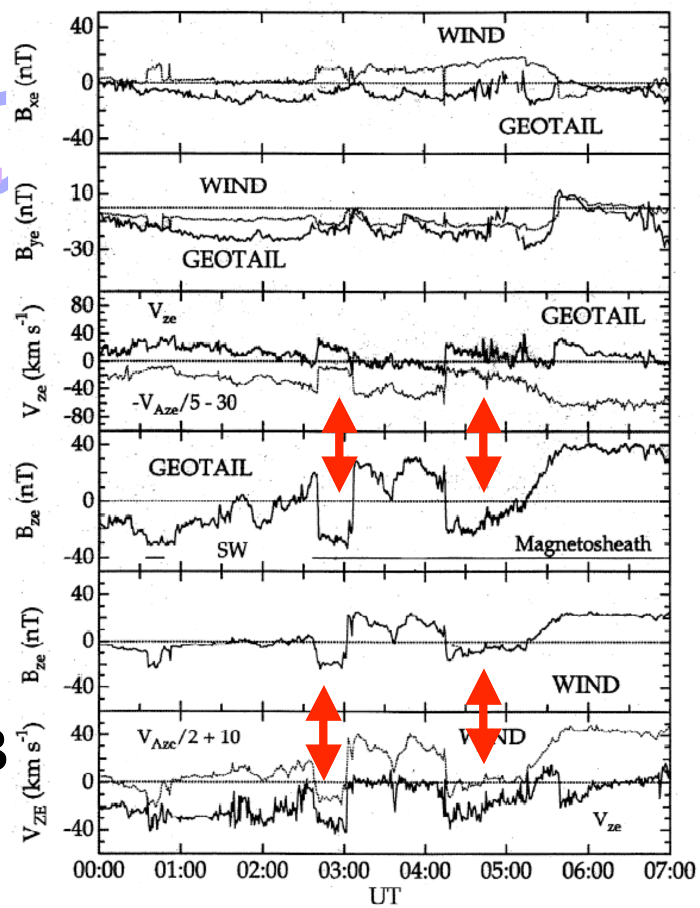
  - Slow mode waves? launched by solar wind Alfvén waves [Sibeck et al., 1997; 2000]

or

  - Alfvén mode waves invariably with $T_\perp < T_{//}$ in sheath (though this is never observed) with a source at subsolar magnetopause, [Matsuoka et al., 2000; 2002]

$\Delta V \propto -\Delta B$ post-noon

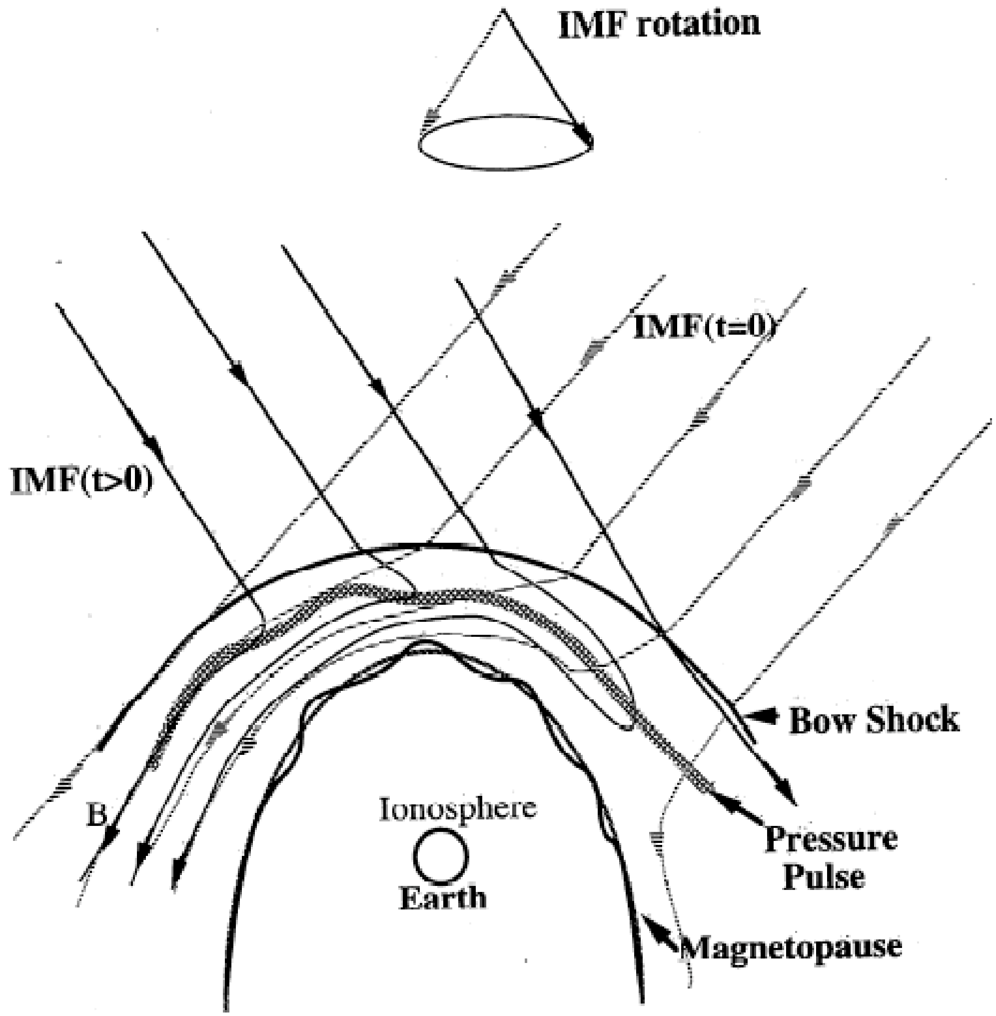
$\Delta V \propto \Delta B$ pre-noon



Rotational Discontinuities and the Bow Shock

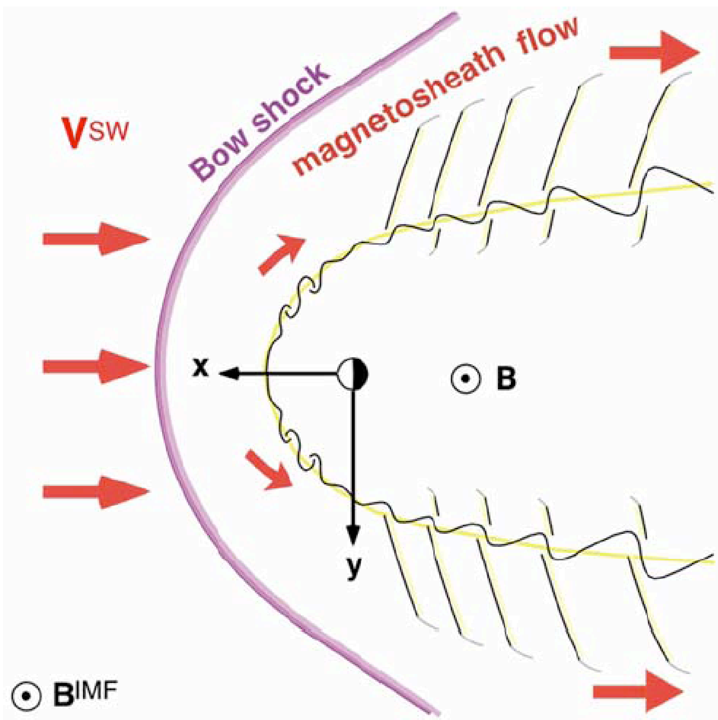
Alfvén waves intensify, drive high speed magnetosheath flows, and magnetopause motion [Lin et al., 1996]

…has not been reported…



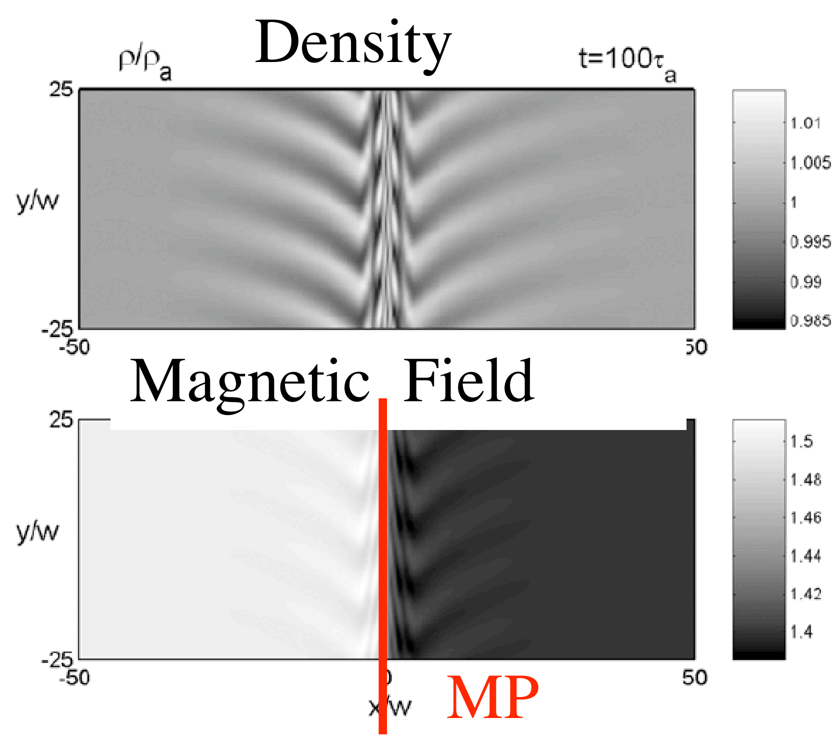
KH Instability and Standing Waves

Standing Fast Mode Waves?



Lai and Lyu [2006]

Upstream Facing Standing Slow Mode Waves?



Lai and Lyu [2008]

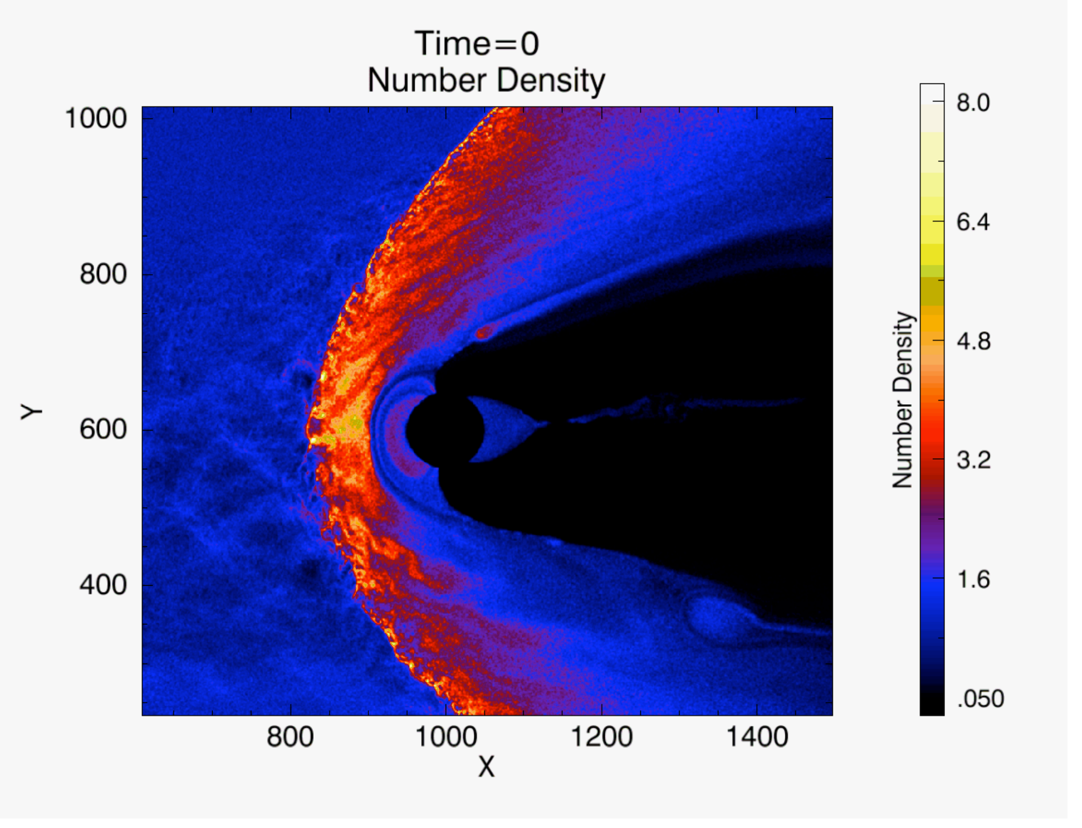
Hybrid Code Models

•Foreshock, compressional boundaries, hot flow anomalies

•Solitary shock --> Unusual flows

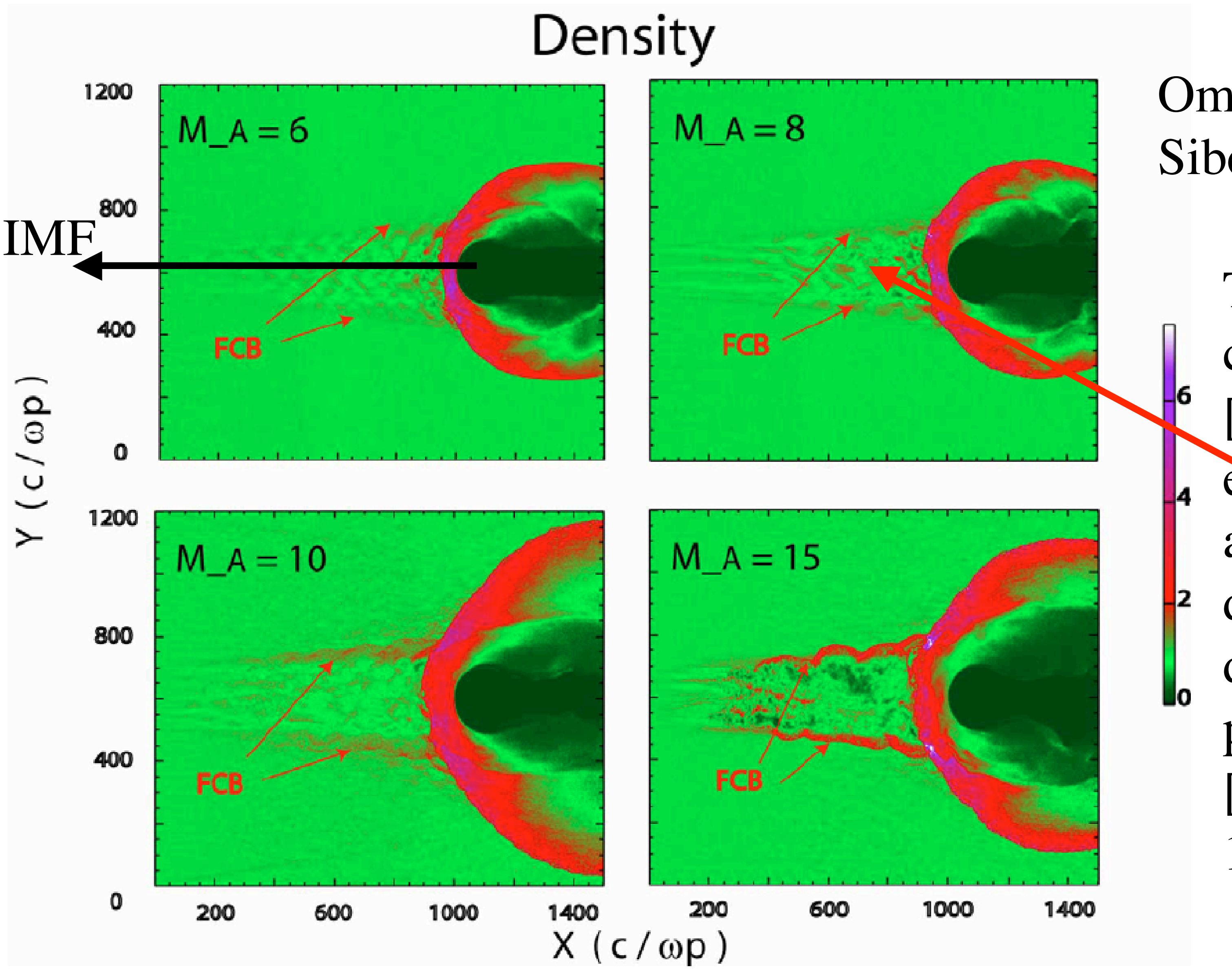
•Triggering reconnection
On transmitted TDs

•Sheath Fluctuations-->
trigger FTEs?



N. Omidi [personal comm., 2009]

Foreshock Compressional Boundaries

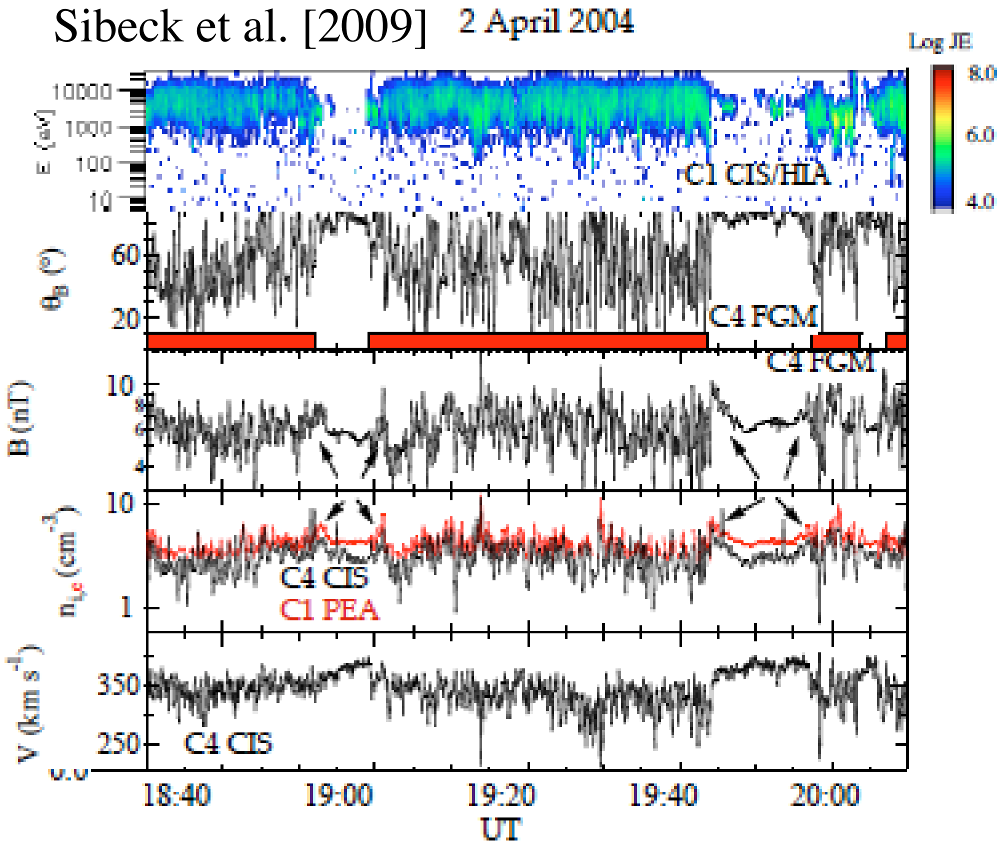


Omidi and Sibeck [2009]

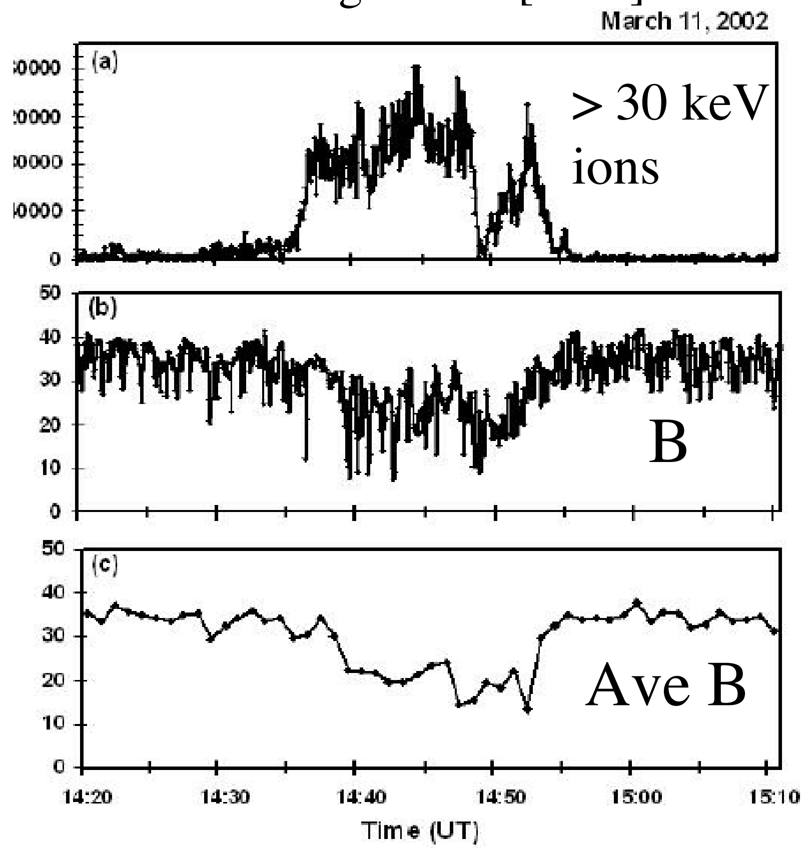
Turbulent cavitons [Blanco-Cano et al., 2009] and depressed dynamic pressures [Fairfield et al., 1990]

Cavities Upstream and in Magnetosheath

Sibeck et al. [2009]



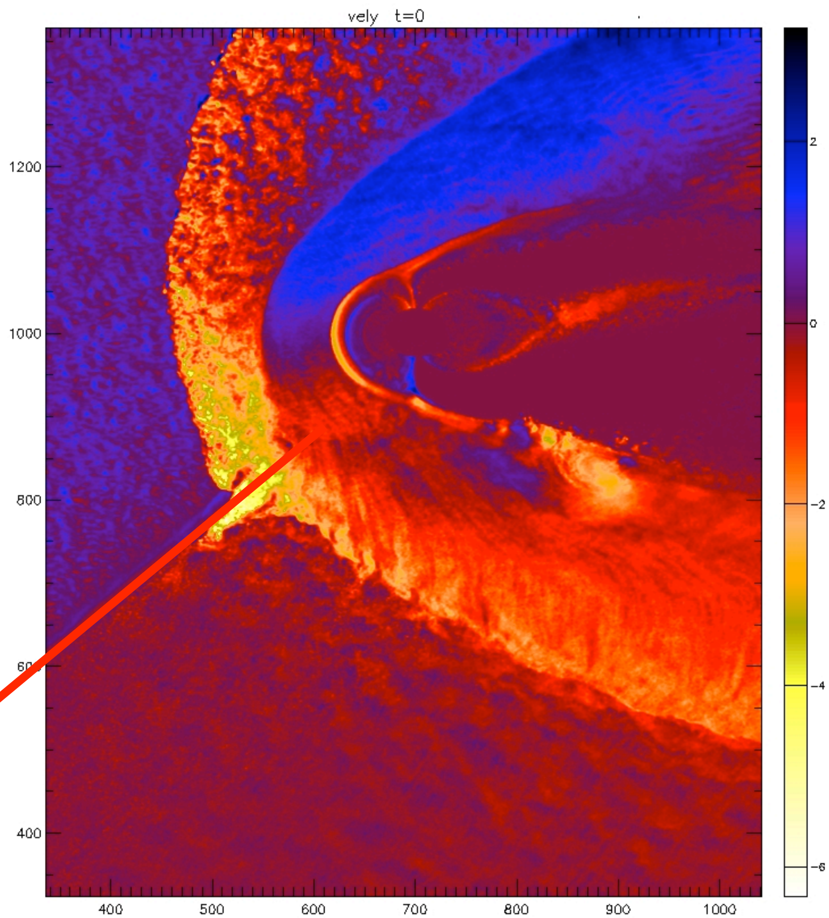
Turk-Katircioglu et al. [2010]



<u>Major source of large-amplitude magnetopause motion and strong magnetospheric compressions</u> [Sibeck et al., 1989; Fairfield et al., 1990]

Hot Flow Anomalies

Vz



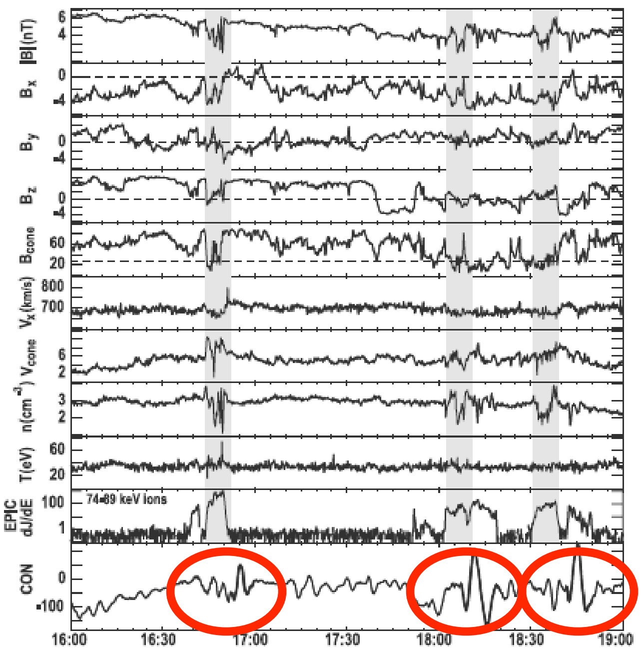
Z

TD

X

Omidi and Sibeck [2008]

HFAs, exhibiting greatly heated plasmas and strong flows transverse to the Sun-Earth line, occur when and where certain TDs intersect bow shock



IMF

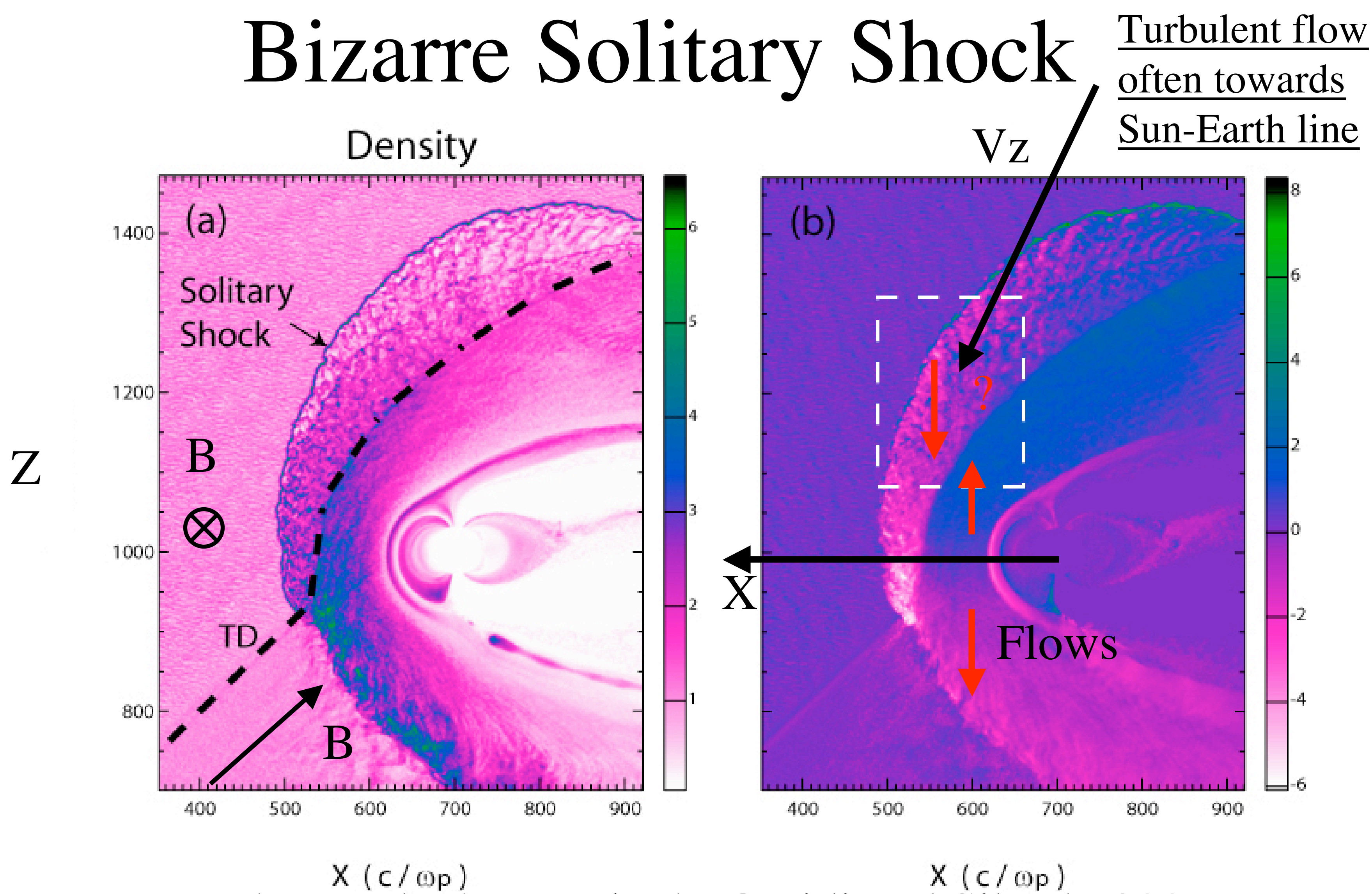
n_{SW}

74 keV ions

Ground

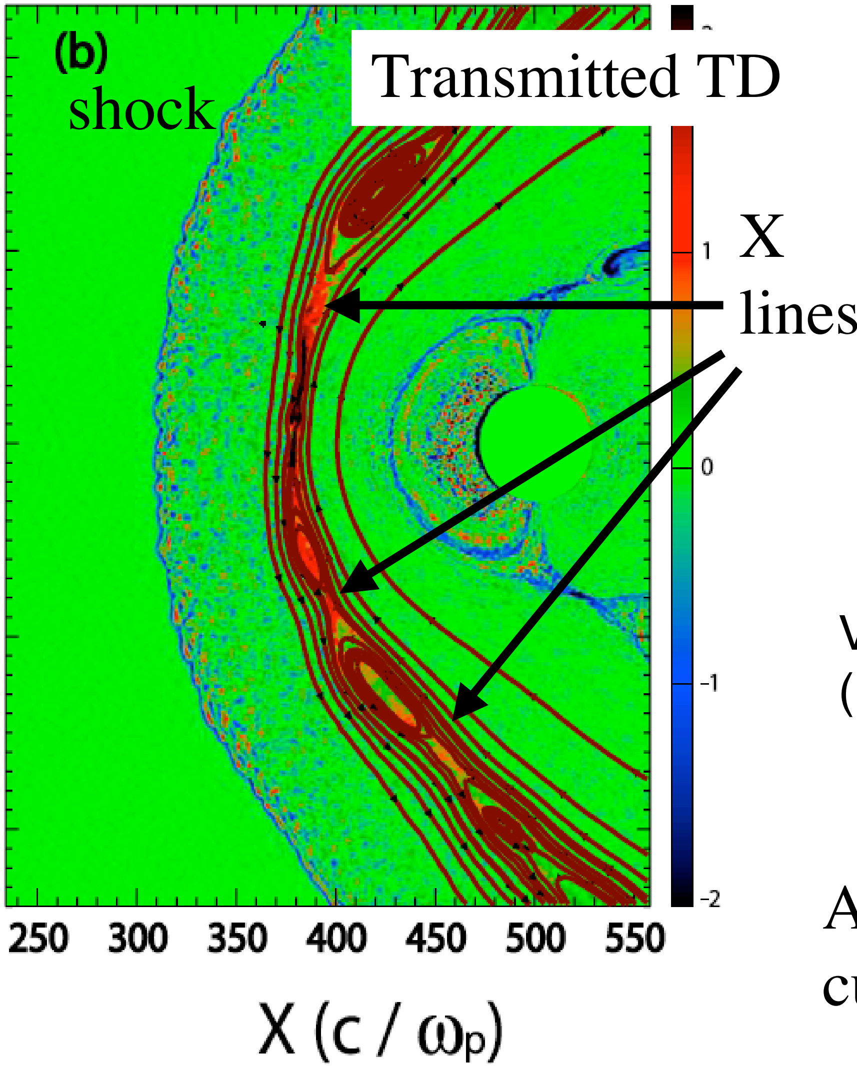
DOMINANT cause of TCVs reported by Murr and Hughes [2003]

Bizarre Solitary Shock

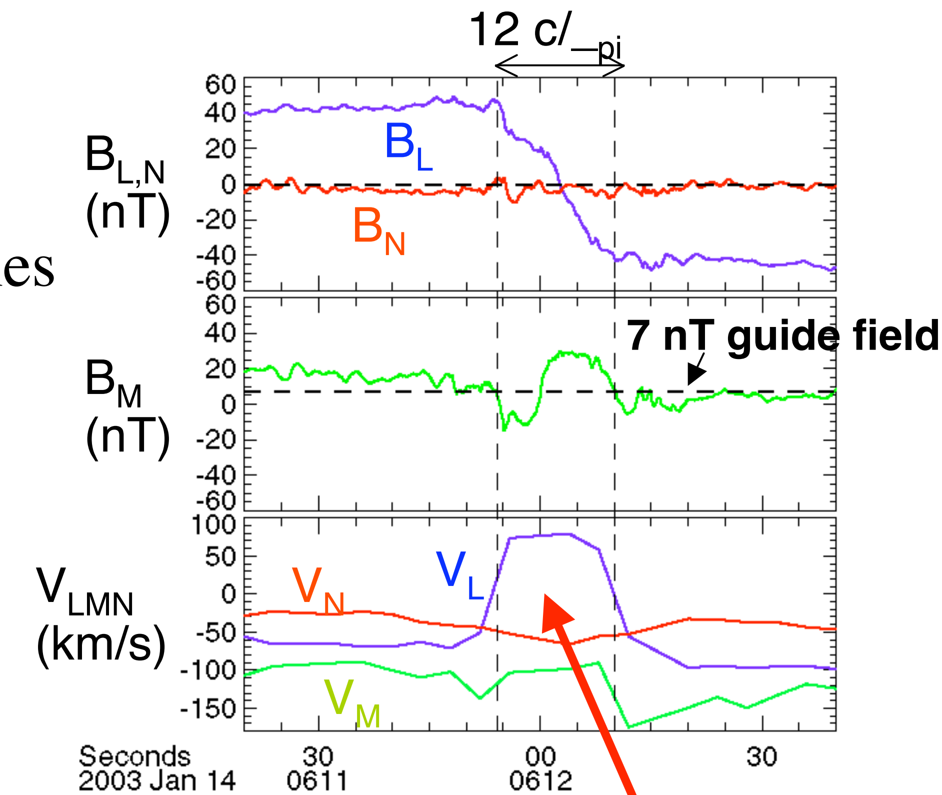


- When and where to look [Omidi and Sibeck, 2007]:
  - –High-lat southern (northern) shock for IMF By > 0 (<0)
  - –Dusk (dawn) shock for IMF Bz > 0 (<0)

Tangential Discontinuities and the Bow Shock: Reconnection



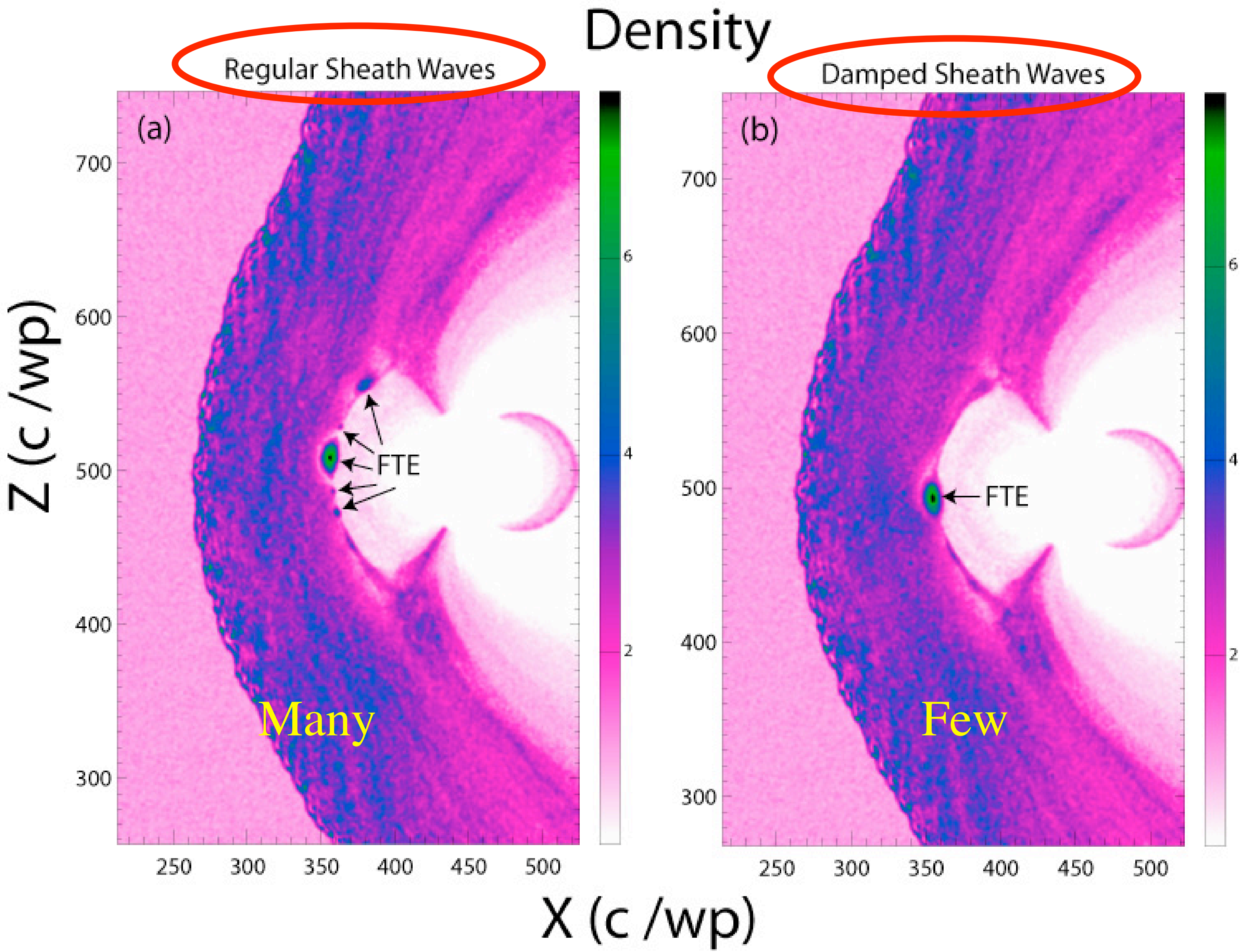
Omidi et al. [2009]



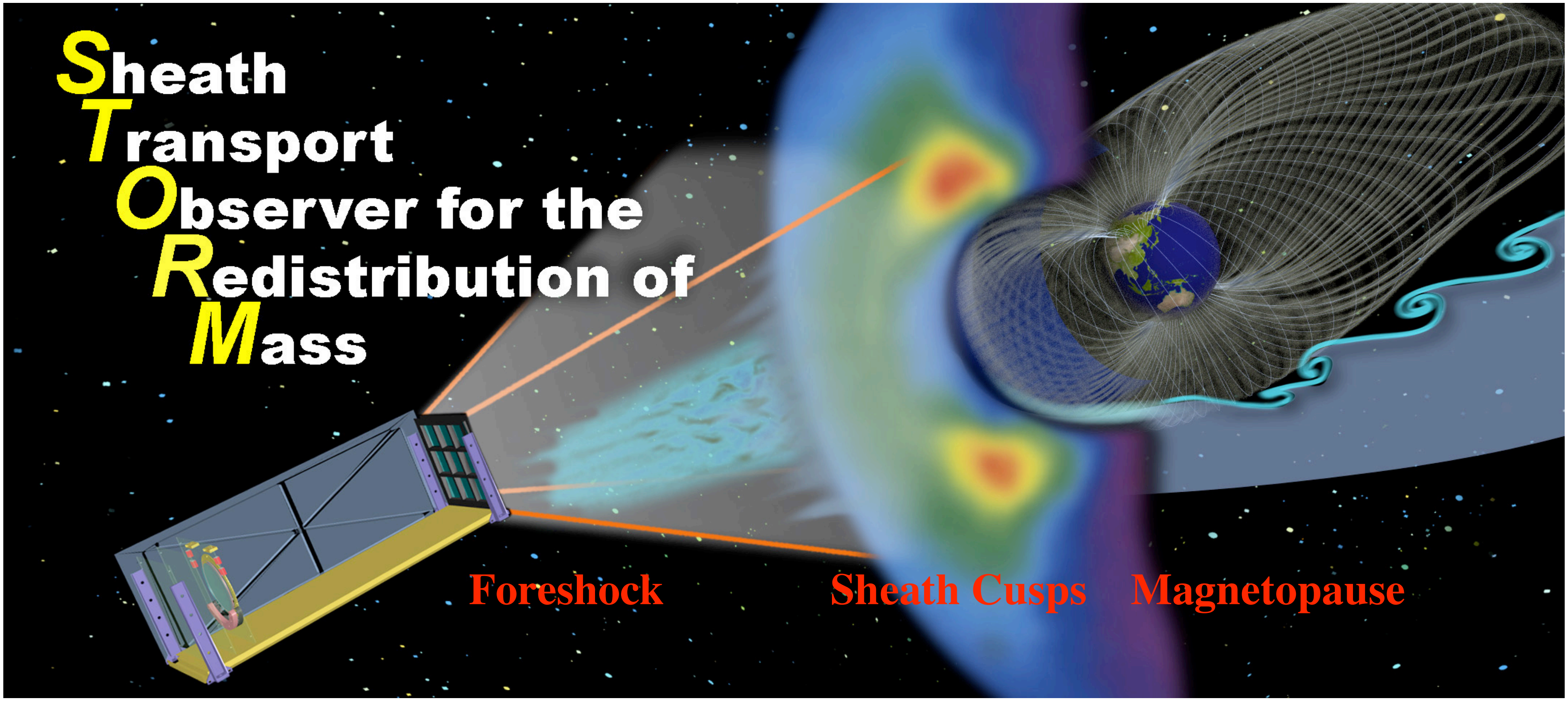
Accelerated outflow in magnetosheath current layer

Phan et al. [2007]

Sheath Fluctuations --> FTEs?



N. Omidi [personal comm. 2009]



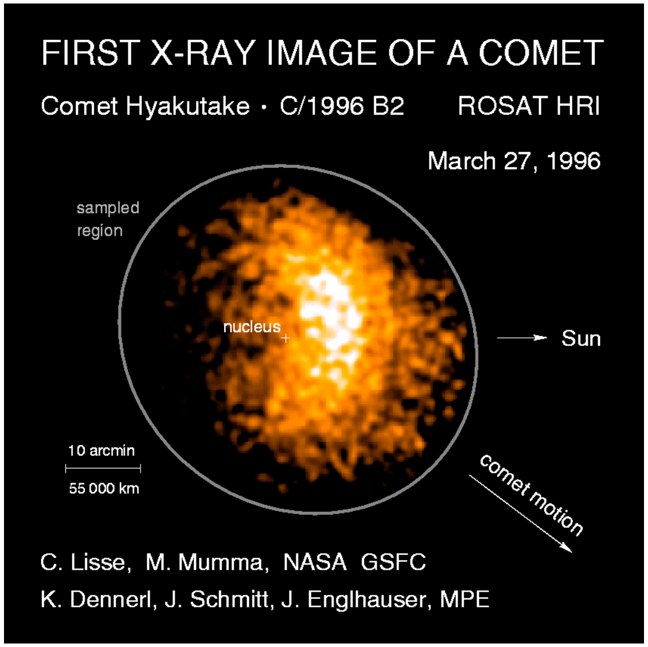
STORM Instrument Concept:

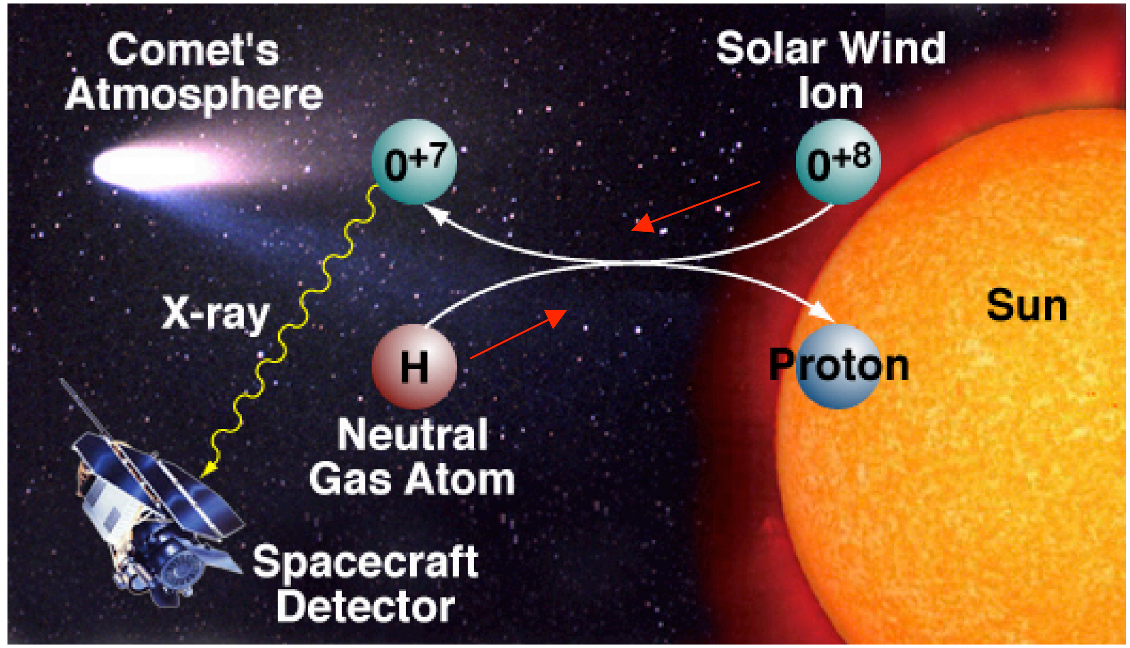
A global soft X-ray imager using an astrophysics technique proven at comets/Mars/Venus/Earth to view the Earth's foreshock, magnetosheath, cusps, and magnetopause boundary layers

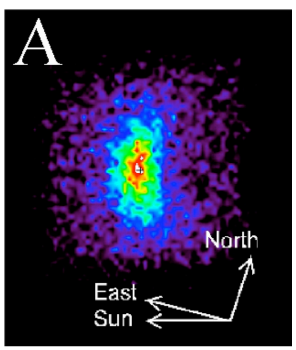
A joint effort of NASA/GSFC, U. Kansas, U. Leicester, and Solana Scientific

See article in latest EOS

Soft X-Ray Imaging: A Proven Technique



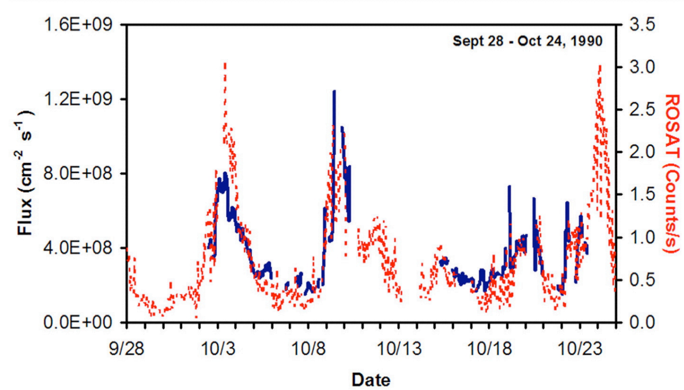


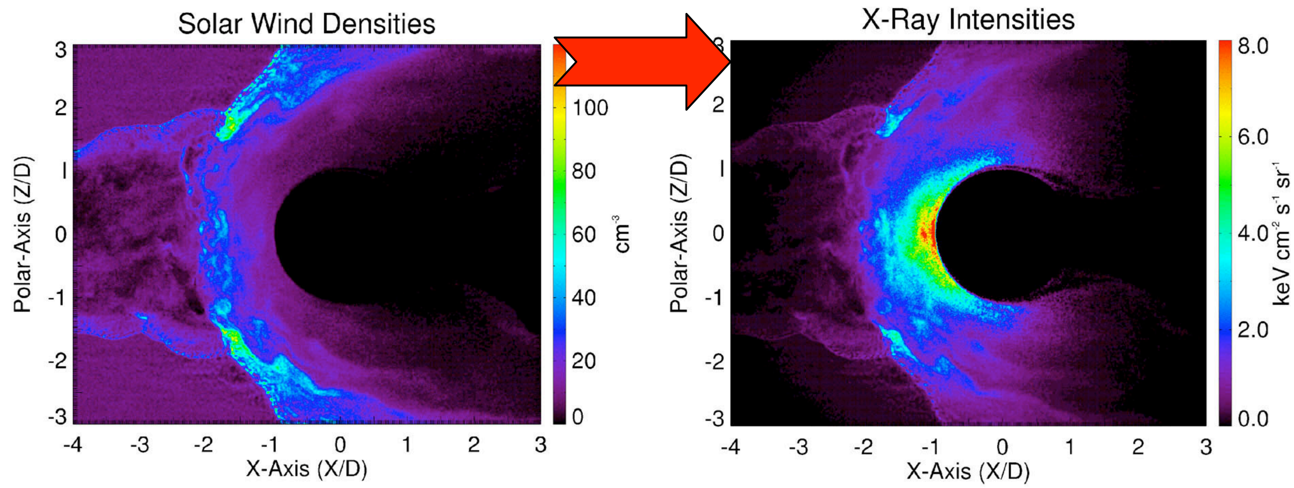


ROSAT, Chandra, and XMM-Newton observations of comets, Venus, Mars, and Earth demonstrate that soft x-rays emitted from solar wind plasma-exospheric neutral atom charge exchange will enable global imaging of Earth's foreshock, bow shock, magnetosheath, and cusps [see Collier et al., EOS, in press].

Chandra X-ray images of Comet Linear

ROSAT soft X-ray fluxes from Earth's magnetosheath track solar wind plasma fluxes





Hybrid Code Model Output (Omidi) Simulated STORM Signatures (Robertson)

Sun

Simulated STORM observations from planned orbit, CCMC MHD model (Robertson)

Summary

- 1. Although the foreshock and magnetosheath are active areas of research, many questions remain unanswered.
- 2. The data sets and simulations needed to address many of these questions are readily available. Global images may be possible soon.
- 3. The results will have a direct bearing on our understanding of the solar wind-magnetosphere interaction and the development of global models.