2016 GEM SWMI Tutorial

Foreshock and Magnetosheath Transients and Their Geoeffects

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Thanks to: D. Sibeck, H. Hietala, N. Omidi, H. Hasegawa, D. Turner, C. Chu

Outline

Foreshock Transients

- Hot Flow Anomalies (HFAs)
- Spontaneous HFAs
- Foreshock Bubbles
- Foreshock Cavitons
- Foreshock Cavities
- Foreshock Compressional Boundaries
- Density Holes
- SLAMS

Their Geoeffects

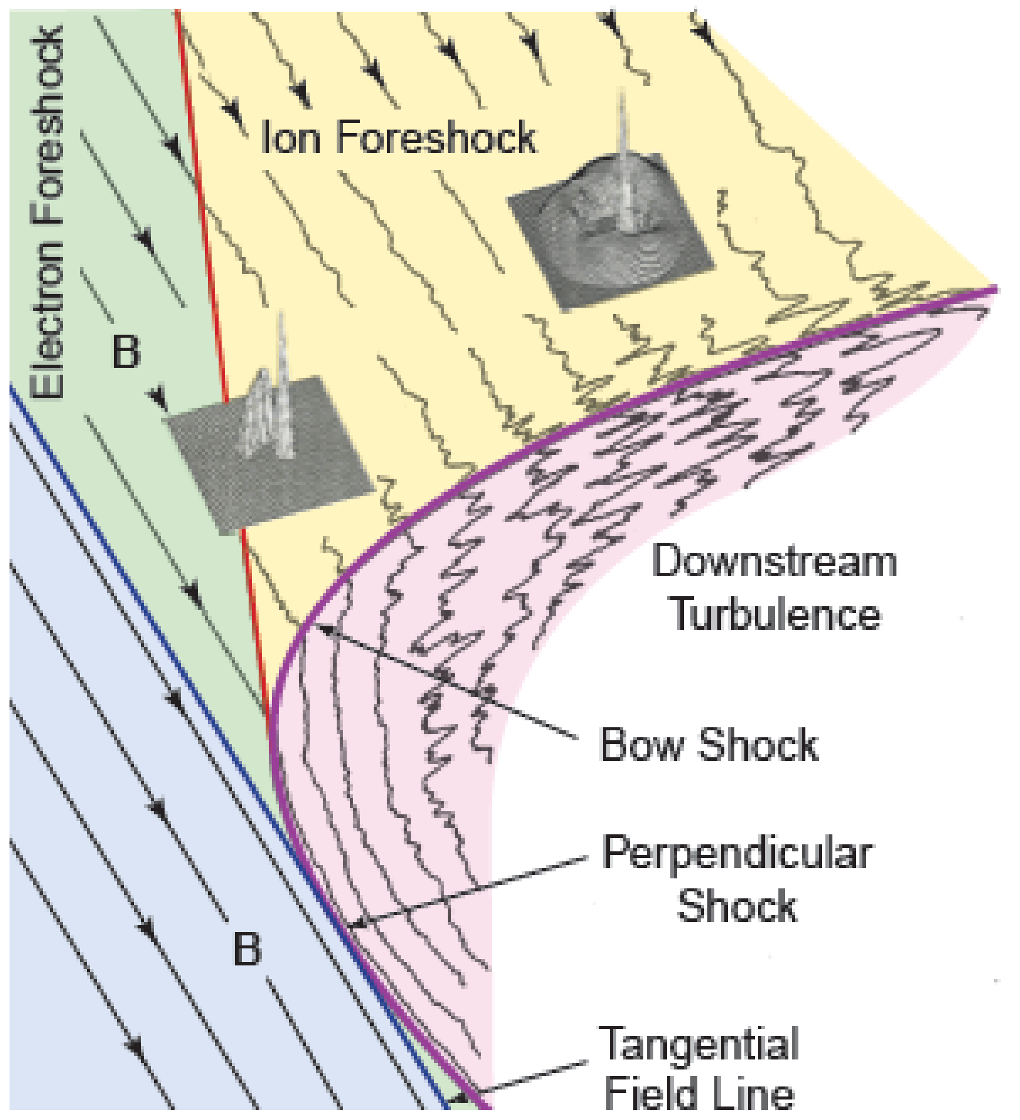
- Trigger magnetic reconnection?
- Drive magnetopause boundary waves
- Generate FACs, TCVs/MIEs
- Excite ULF waves
- Auroral response

Magnetosheath Transients

- Magnetosheath High-Speed Jets
- Magnetosheath Filamentary Structure

Outstanding Questions

Foreshock Transients



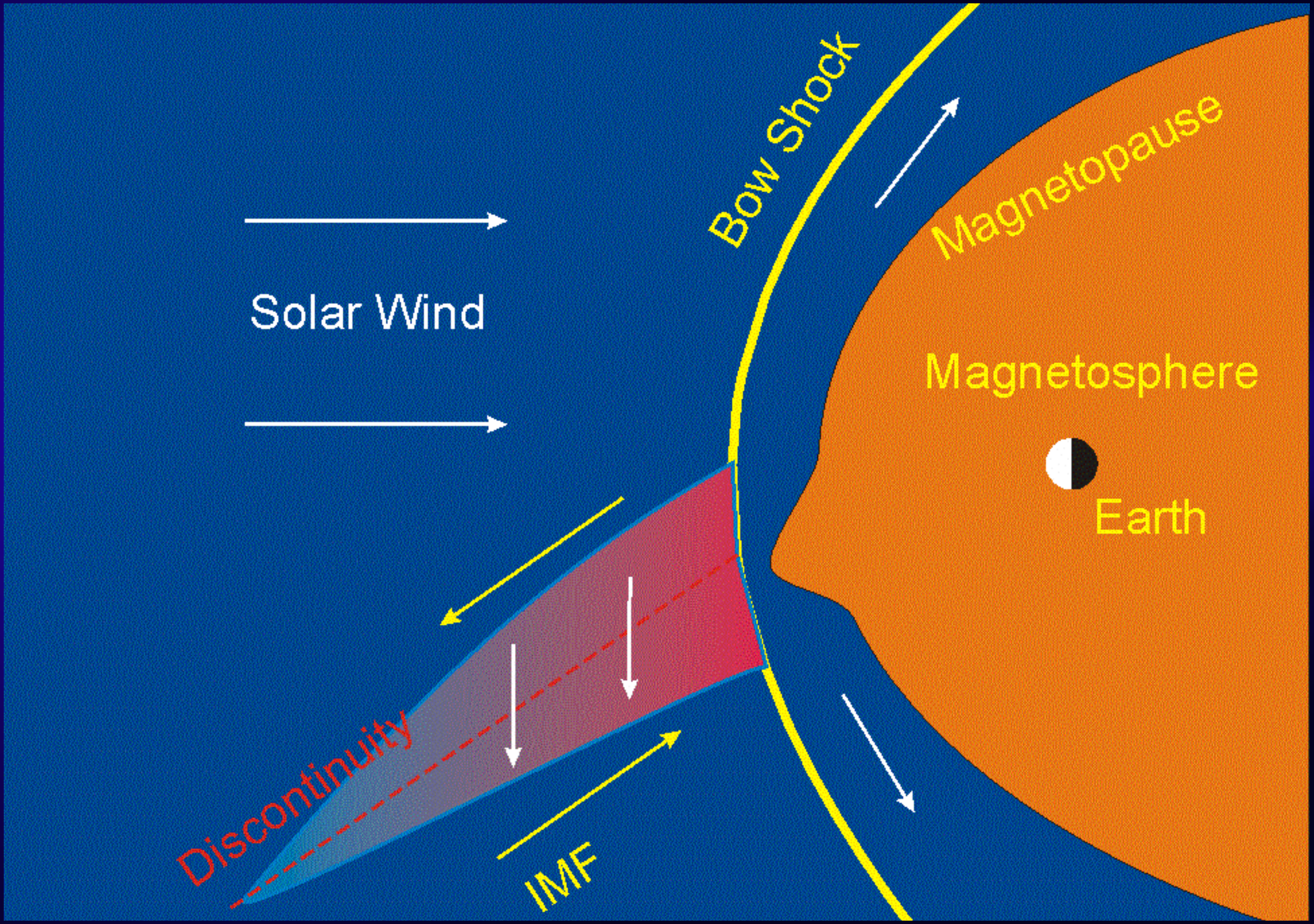
Treumann and Scholer, 2001

- The ion foreshock is quasi-parallel region upstream of bow shock characterized by suprathermal, backstreaming ions and enhanced ULF wave activity.

- We have identified a zoo of events in the foreshock:
  - HFAs
  - Spontaneous HFAs
  - Foreshock Bubbles
  - Foreshock Cavitons
  - Foreshock Cavities
  - Foreshock Compressional Boundaries
  - Density Holes
  - SLAMS

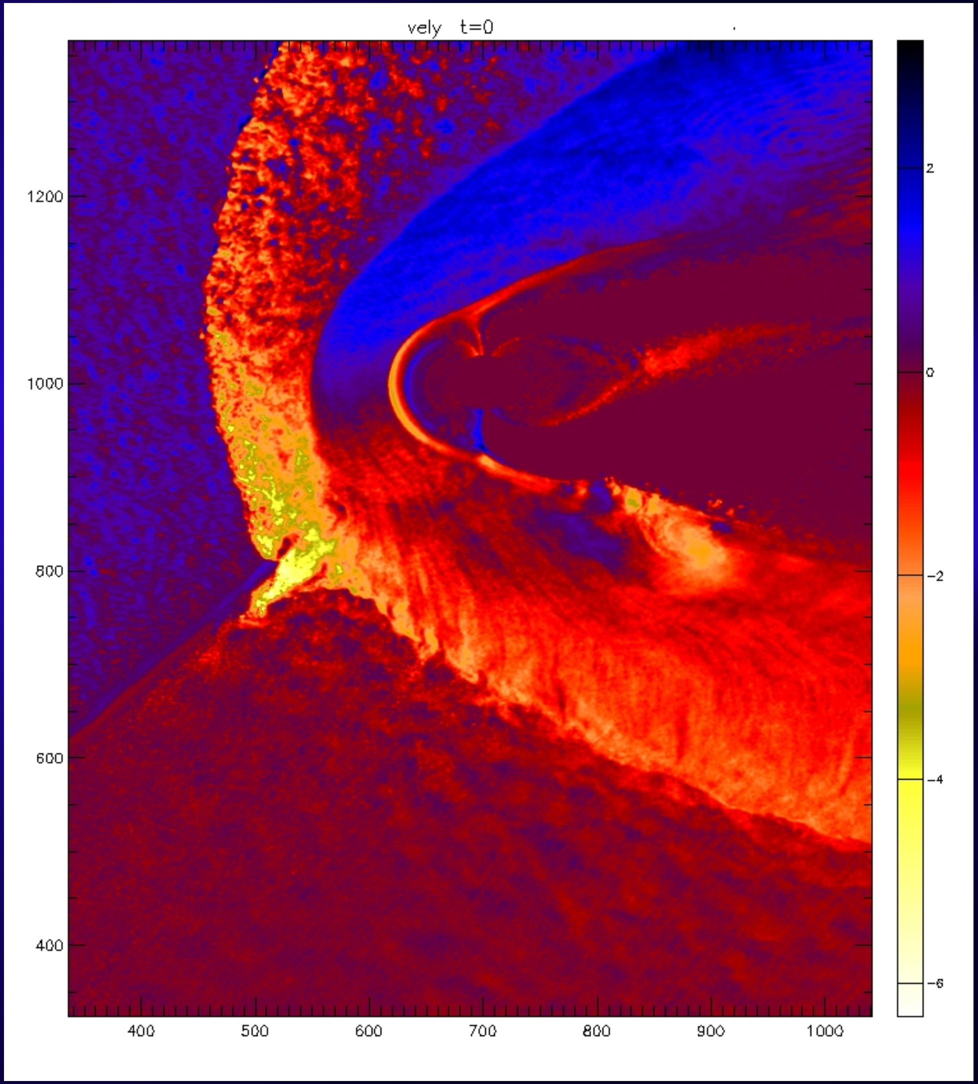
- Kinetic effects

What is an Hot Flow Anomaly



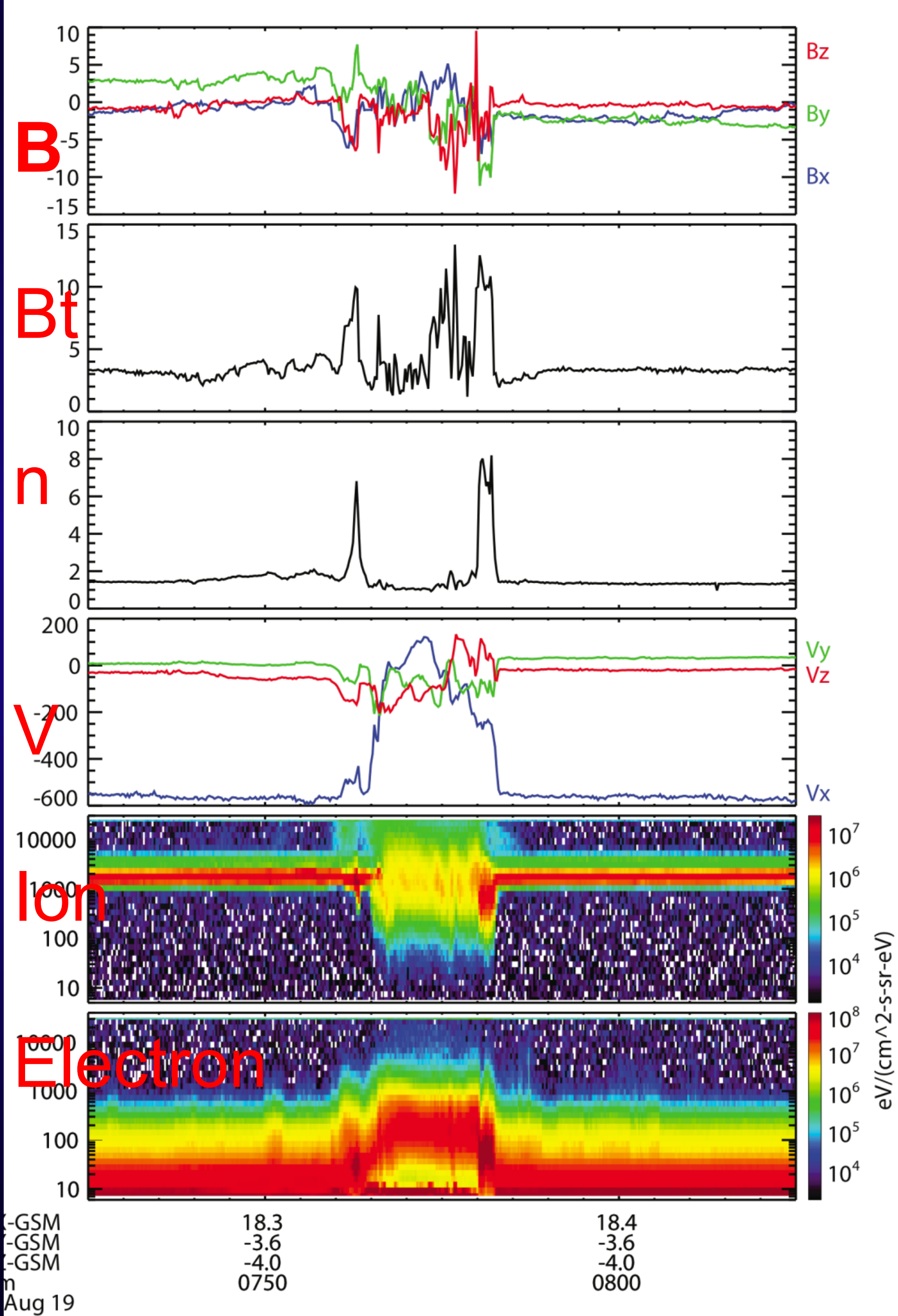
courtesy of H. Zhang

Hybrid Simulation of an HFA



courtesy of N. Omidi

An Example of a Hot Flow Anomaly



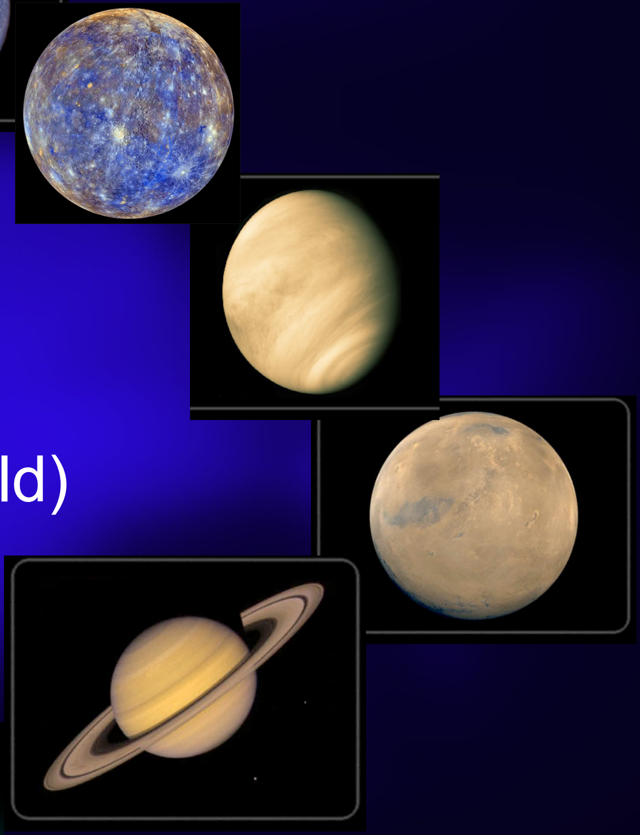
Hot flow anomalies (HFAs) are events observed near the bow shock that are marked by greatly heated solar wind plasmas and substantial flow deflection.

Durations: a few minutes

Scale sizes: a few R_E

Zhang et al., 2010

Hot Flow Anomalies are Universal Phenomena



- Earth (intrinsic magnetic field)
- Mercury (intrinsic magnetic field)

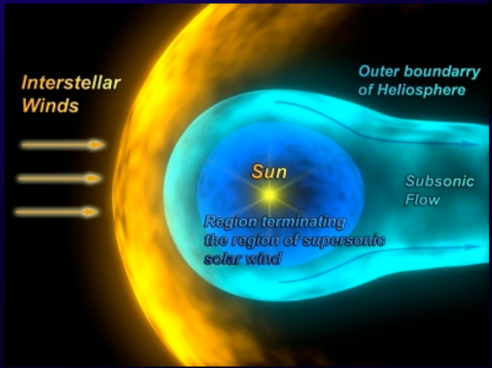
  [*Uritsky et al.*, 2014]
- Venus (no intrinsic magnetic field)

  [*Collinson et al.*, 2012]
- Mars (weak to no intrinsic magnetic field)

  [*Øieroset et al.*, 2001; *Collinson et al.*, 2015]
- Saturn (intrinsic magnetic field)

  [*Masters et al.*, 2009]
- Termination shock

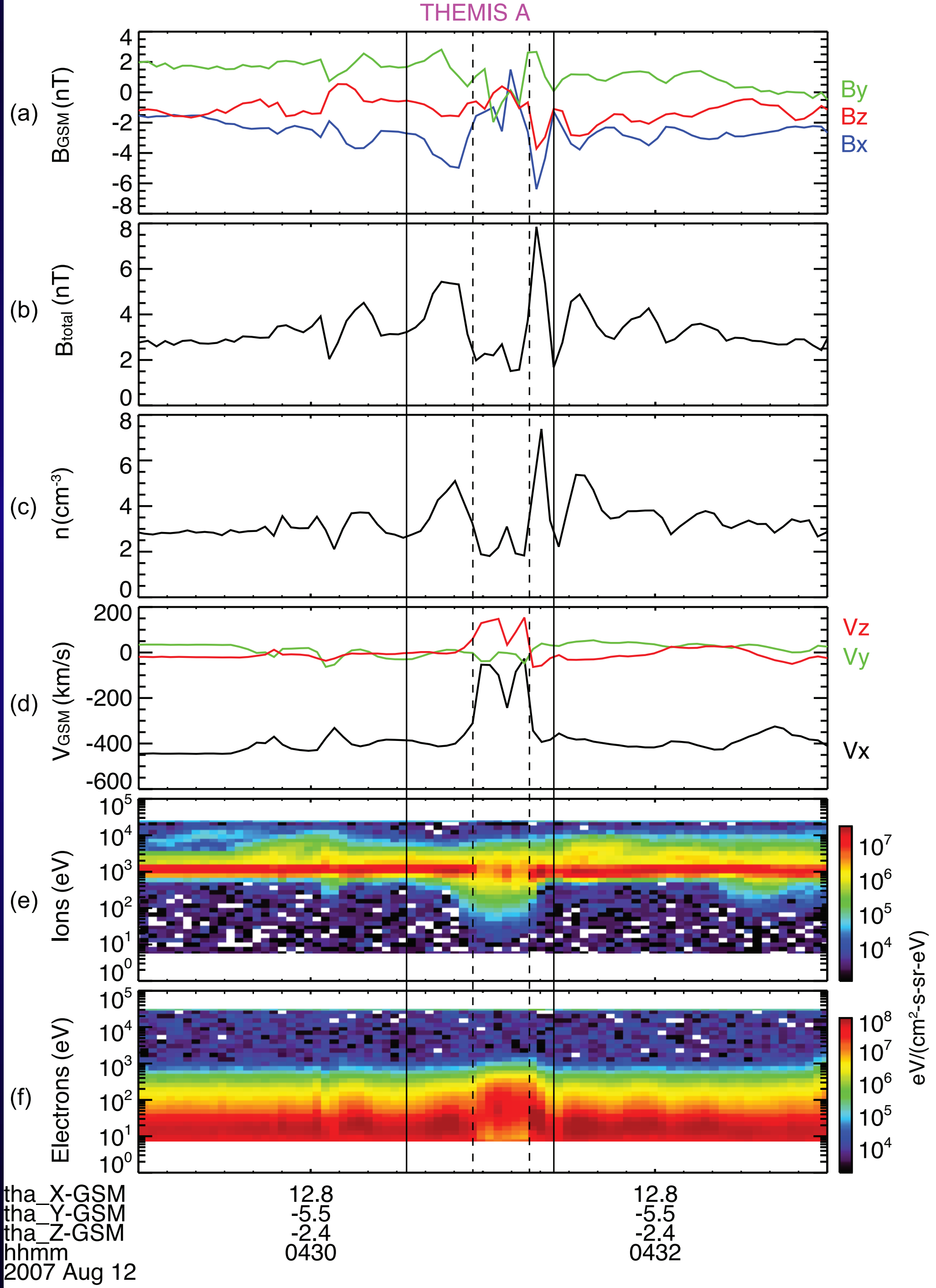
  [*Giacalone and Burgess*, 2010]



HFAs are Frequently Observed

- About 1000 HFAs have been identified from Cluster data from 2001 to 2013 (S. Wang and L. L. Zhao)
- 142 HFAs have been identified from THEMIS C data from June 2007 to December 2009. (C. Chu)

THEMIS A Observation of an SHFA



Not associated with a discontinuity

Depressions in magnetic field magnitude and ion density

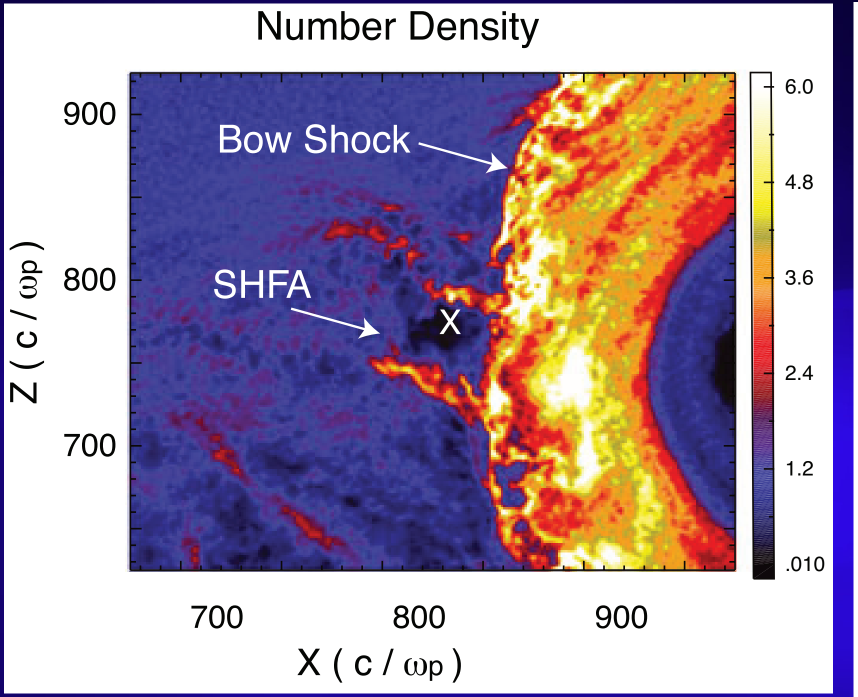
Compression on both edges

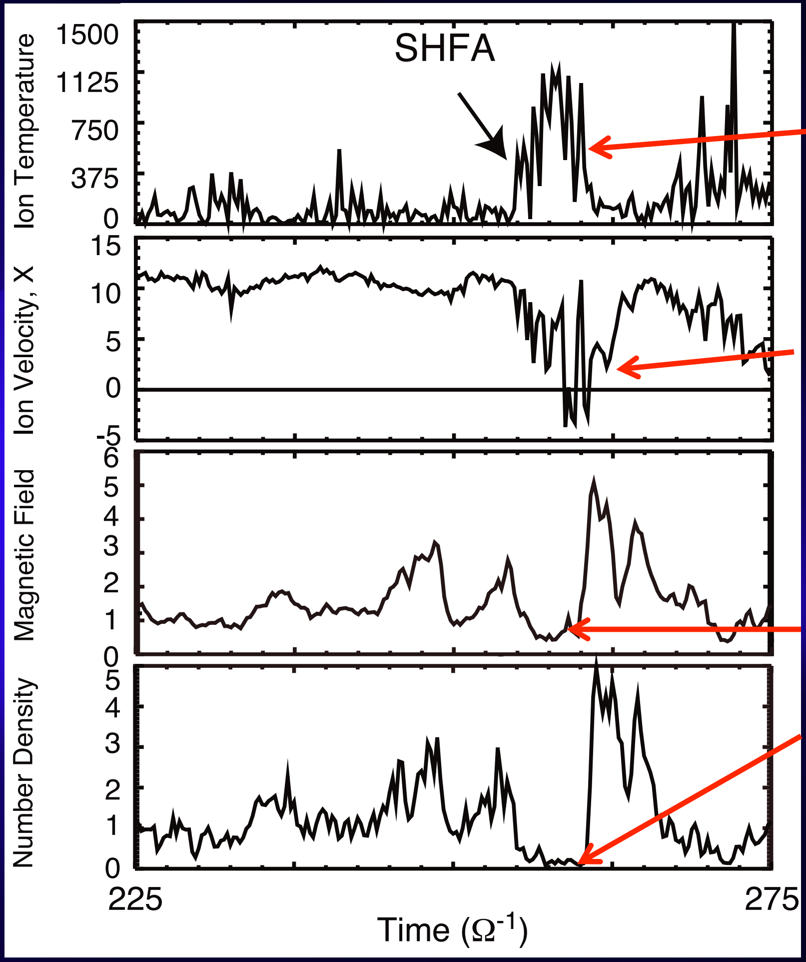
Significant flow deflection

Significant plasma heating

Zhang et al., 2013

Hybrid Simulation of an SHFA





Greatly heated plasmas

Substantial flow deflection

Depletion in density and magnetic strength

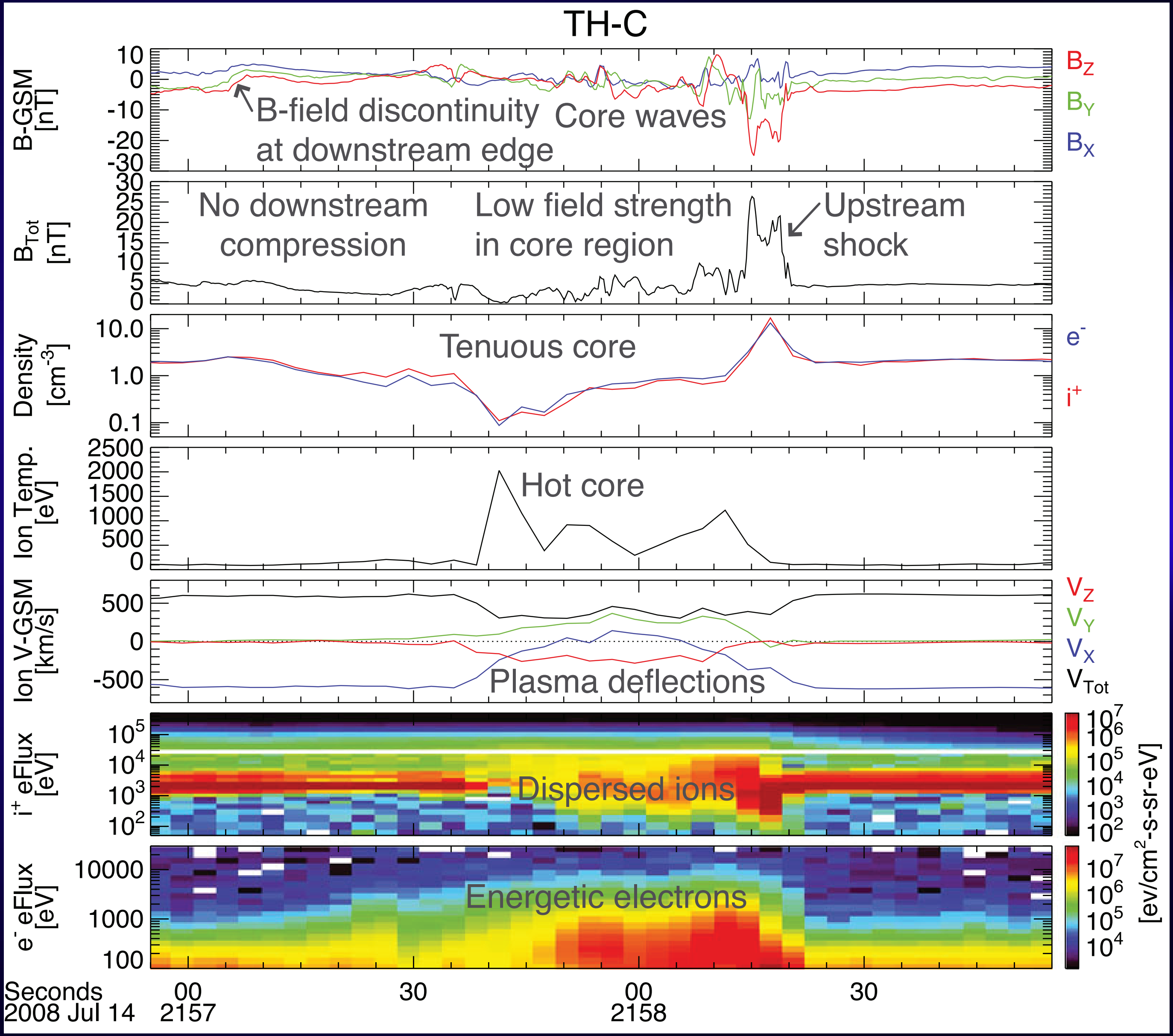
Simulation results from a 2.5-D electromagnetic hybrid code demonstrate the formation of SHFAs upstream of quasi-parallel bow shocks during steady solar wind conditions and in the absence of discontinuities. [*Omidi et al.*, 2013]

Hot tenuous plasma bounded by regions of enhanced |**B**| and **n**

Significance of SHFAs

- Observations of SHFAs are significant because they indicate the need for a significant modification to our current understanding of the solar wind-magnetosphere interaction.
- More specifically, the response of planetary magnetospheres to solar wind input can be very dynamic even for steady solar wind plasma and IMF conditions.

Foreshock Bubble Observations



B-field discontinuity at downstream edge

Core waves

No downstream compression

Low field strength in core region

Upstream shock

Tenuous core

Hot core

Plasma deflections

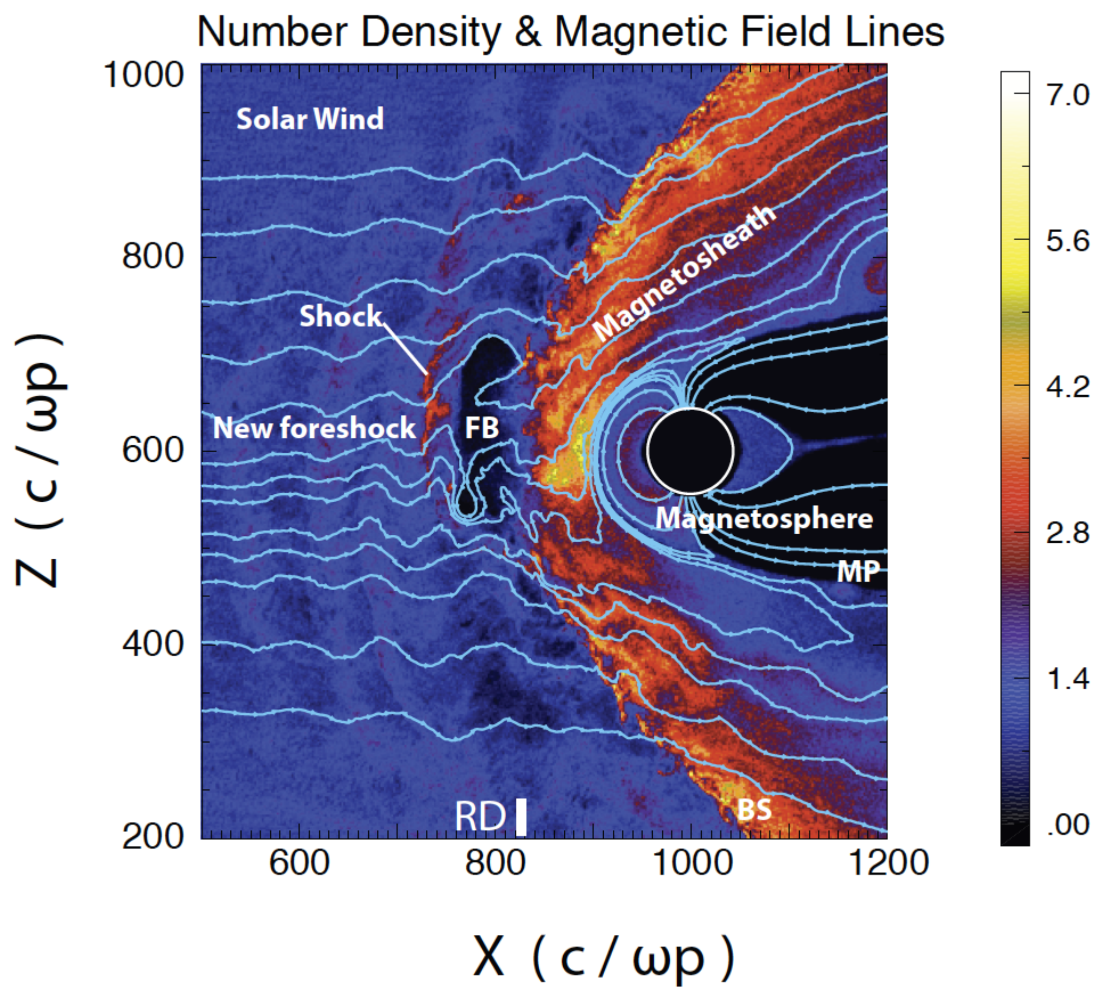
Dispersed ions

Energetic electrons

Turner et al., 2013

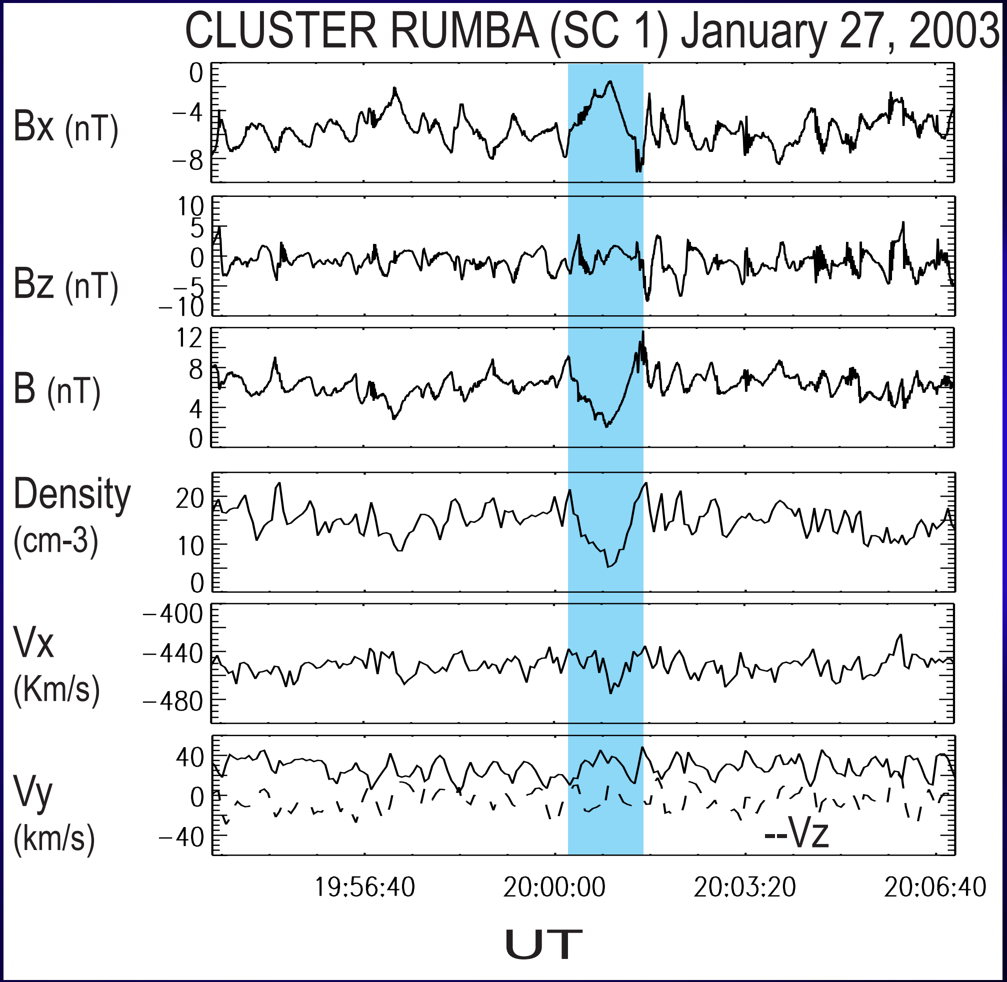
- **Features similar to HFAs:** flow deflection, hot core, decreases in the plasma density and field strength in the core region.
- **Major difference:** HFAs show compressions on both edges. Foreshock bubbles only exhibit compressions on the trailing edge.
- Size: up to 10 R_E

Hybrid Simulation of a Foreshock Bubble



- Foreshock bubbles form due to interaction of rotational discontinuities with the backstreaming ions in the foreshock [*Omidi et al.*, 2010].
- *Liu et al.* [2015] reported observations of tangential discontinuity-driven foreshock bubbles.

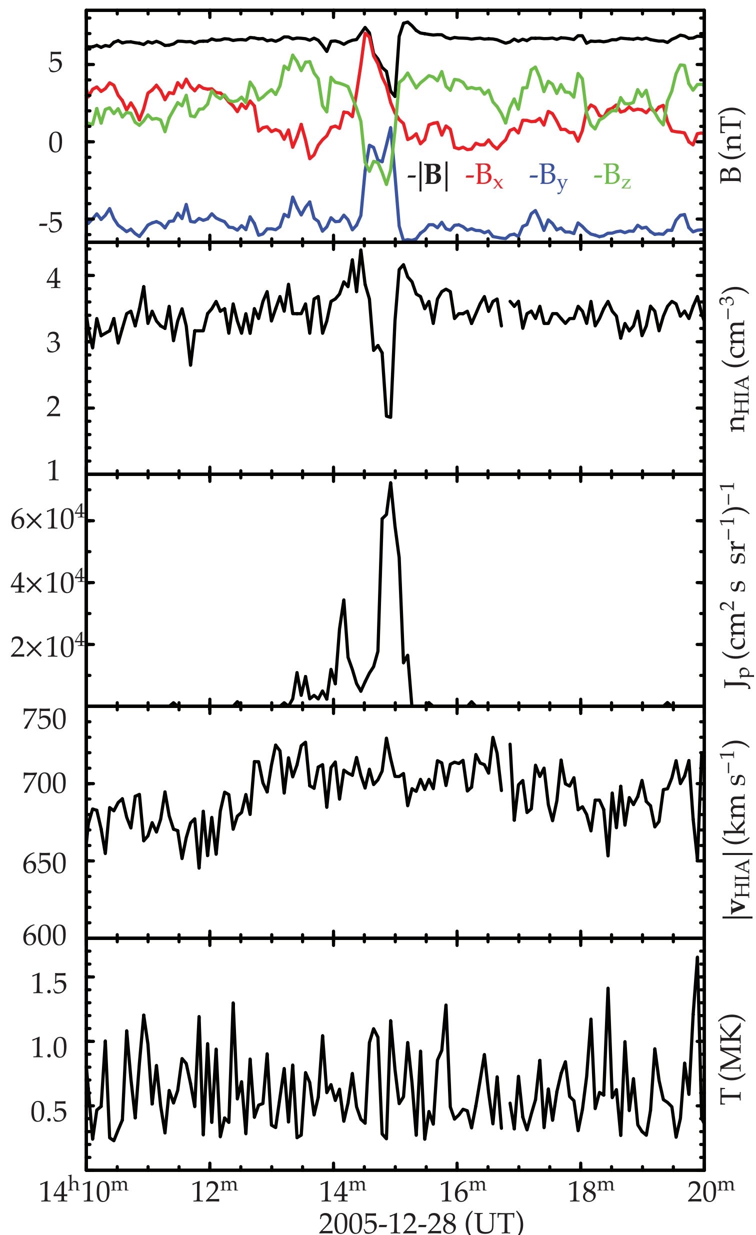
Foreshock Cavitons



Cluster C1 observations of a foreshock caviton. *[Blanco-Cano et al*., 2009]

- Show little evidence of heating or significant flow deflection.
- Not associated with interplanetary discontinuities.
- About an R_E in size.
- Their cores exhibit drops in density and magnetic field, while their outer edges show plasma and magnetic field enhancements.
- Form as a result of the nonlinear evolution of ULF waves [e.g., *Lin*, 2003; *Lin and Wang*, 2005; *Omidi and Sibeck*, 2007; *Blanco-Cano et al.*, 2009, 2011].
- Embedded in ULF waves.

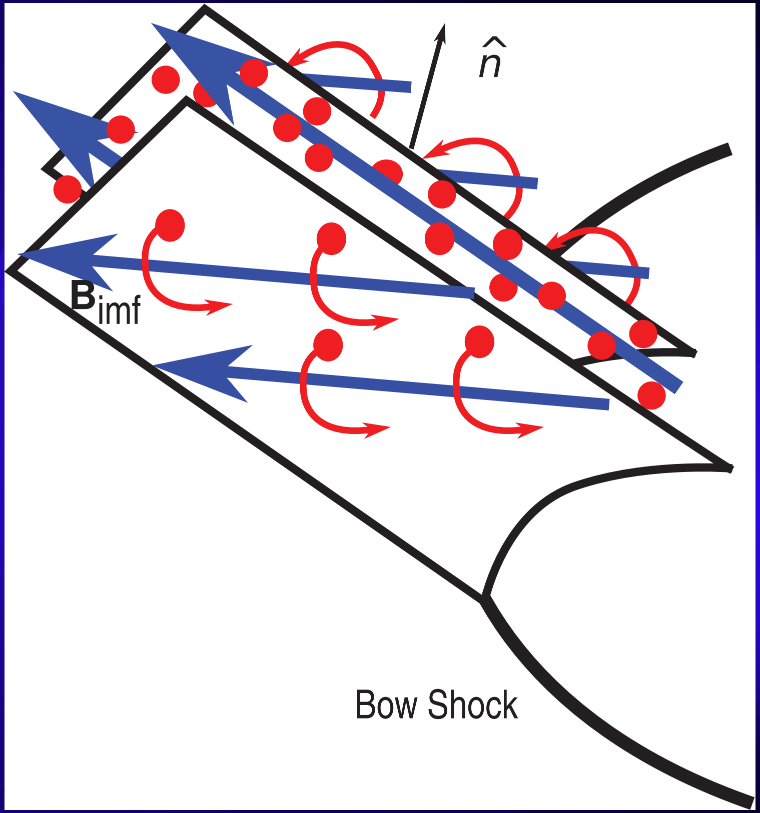
Foreshock Cavities



	Not associated with a discontinuity
|B| Bx By Bz	Depressions in magnetic field magnitude and ion density
Ni	Compression on both edges
Jp (> 27 keV)	Enhanced fluxes of energetic ions
|V|	No significant flow deflection
Ti	No significant plasma heating

Billingham et al., 2008

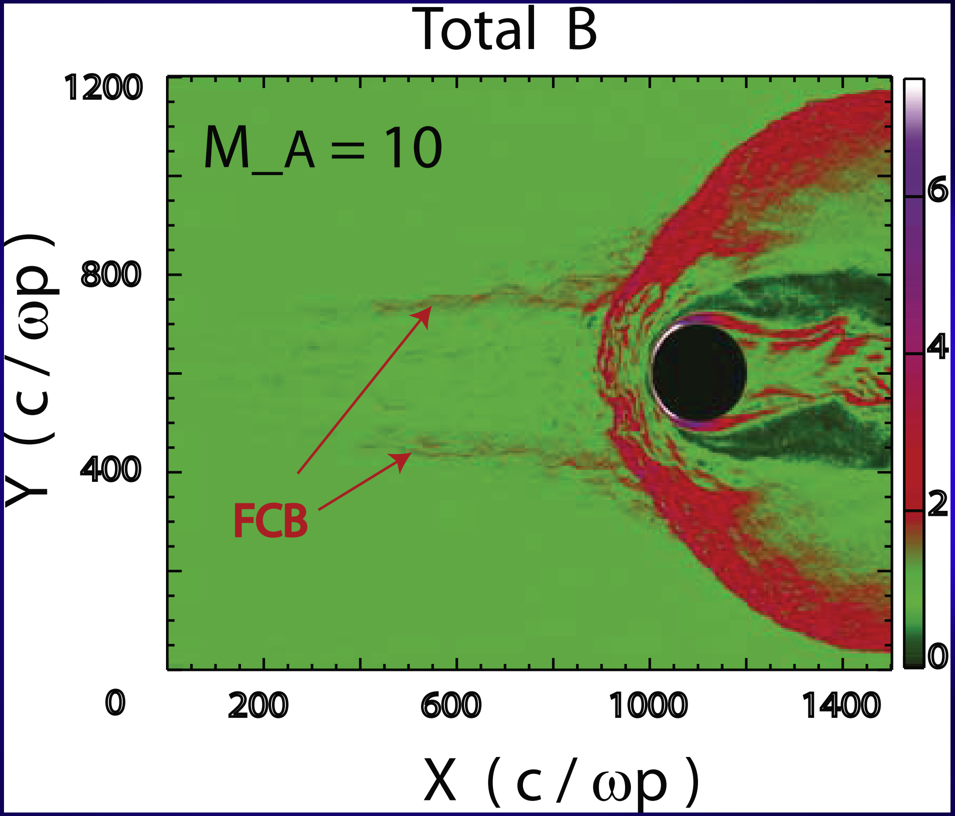
Formation of Foreshock Cavities



Schwartz et al., 2006

- Antisunward-moving slabs of magnetic field lines connected to bow shock embedded within larger regions of magnetic field lines unconnected to the bow shock.
- The slabs fill with reflected and energized particles from the bow shock.

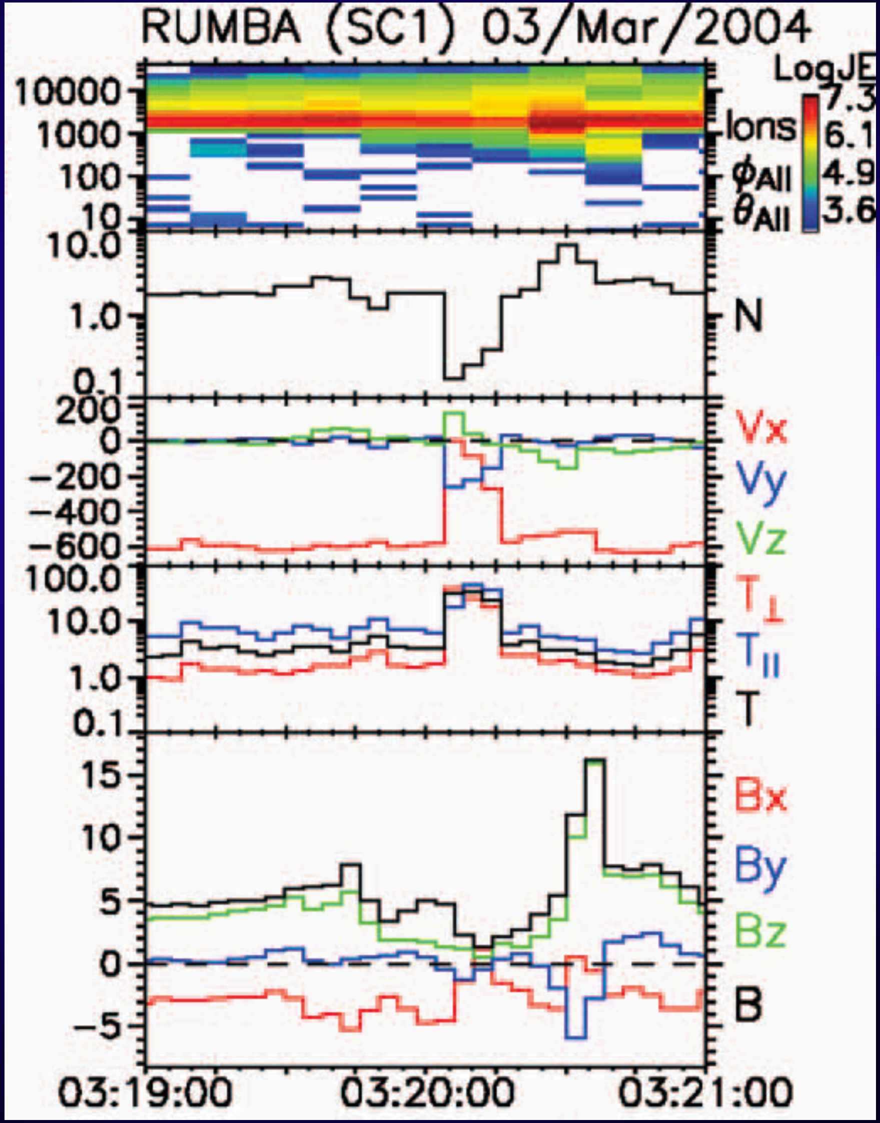
Foreshock Compressional Boundaries



Omidi et al., 2009

- Associated with enhanced densities and magnetic field strengths (these quantities are reduced on the turbulent side of the FCB as compared to the pristine solar wind). [*Sibeck et al.*, 2008; *Omidi et al.*, 2009]
- Backstreaming ions result in increased pressure within the foreshock region leading to its expansion against the pristine solar wind and the generation of FCB.
- FCBs may be a steady state feature, but observed transiently because of slight changes in the IMF orientation.

Density Holes

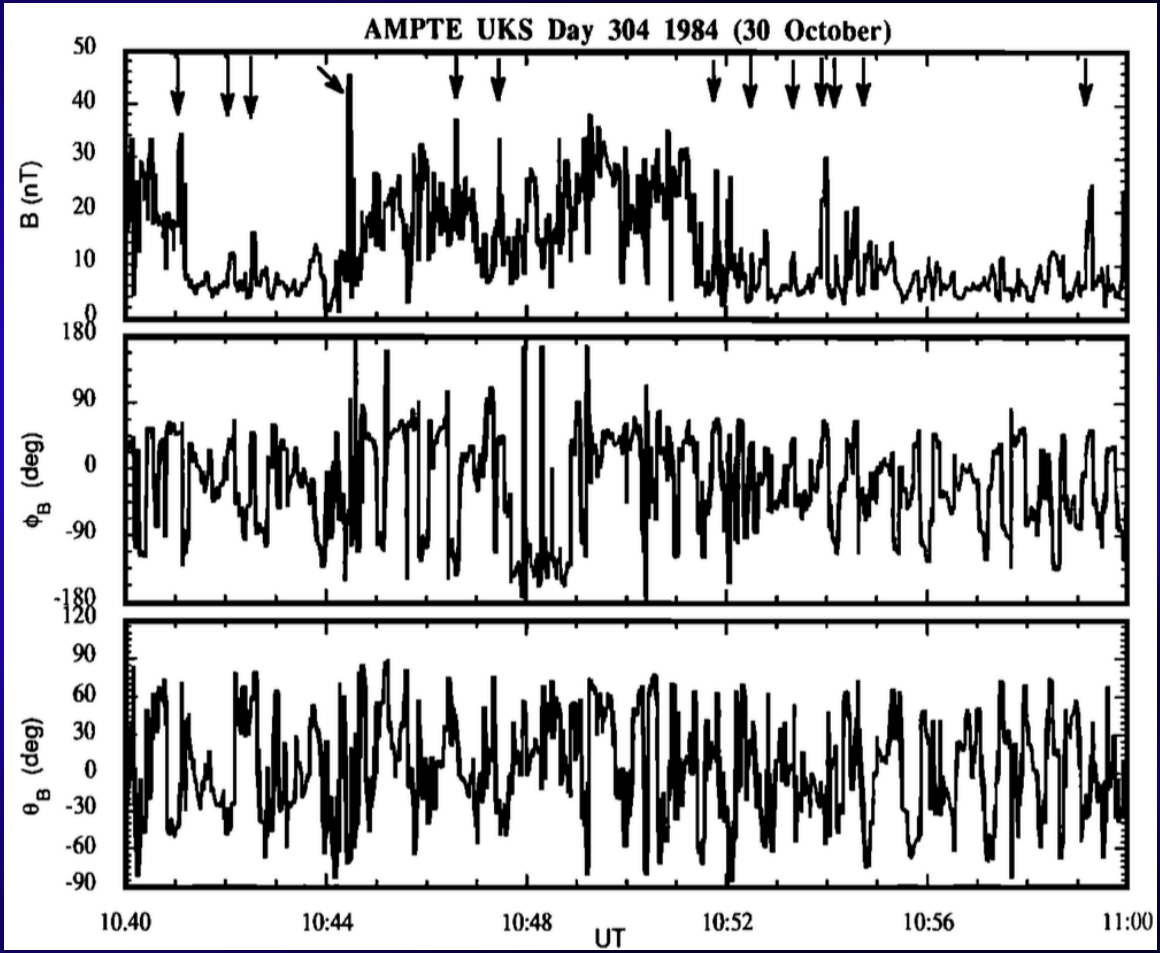


Parks et al., 2006

- Similar to HFAs, density holes display significant bulk flow deflections and are filled with heated plasma.
- Density holes are accompanied by similarly shaped magnetic holes. They have enhanced densities and compressed magnetic field at one or both edges.
- Durations of ~18 seconds (much shorter than that of HFAs)
- Scale sizes of an ion gyroradius
- Possibly formed by backstreaming particles interacting with the original solar wind.

SLAMS

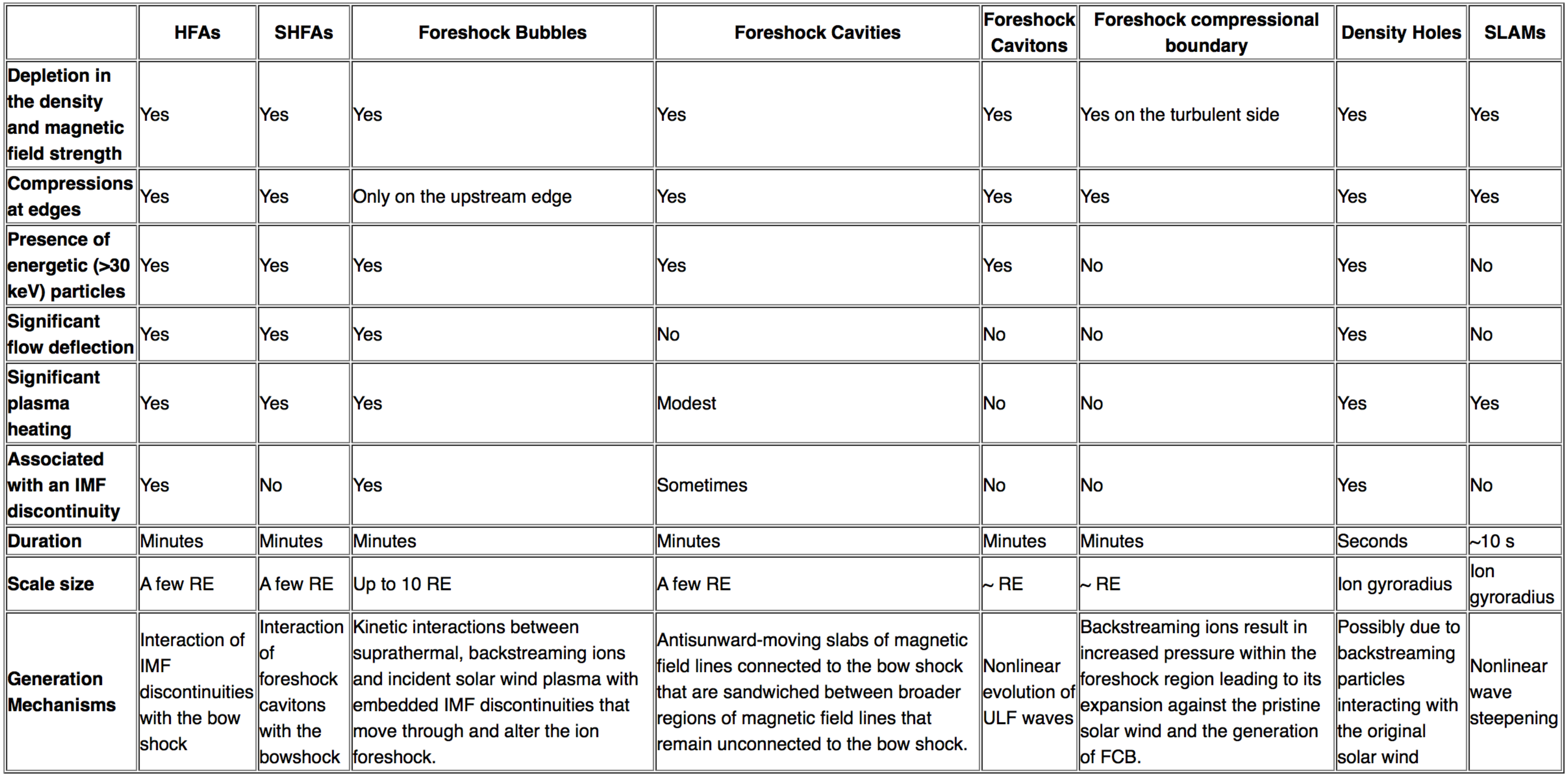
(Short, Large-Amplitude, Magnetic Structures)



Schwartz et al., 1992

- Durations of the order of 10s [*Schwartz,* 1991, 1992; *Lucek et al*., 2002].
- They grow rapidly (~seconds) out of ULF waves in the foreshock region.

Comparison of Foreshock Transients



	HFAs	SHFAs	Foreshock Bubbles	Foreshock Cavities	Foreshock Cavitons	Foreshock compressional boundary	Density Holes	SLAMs
Depletion in the density and magnetic field strength	Yes	Yes	Yes	Yes	Yes	Yes on the turbulent side	Yes	Yes
Compressions at edges	Yes	Yes	Only on the upstream edge	Yes	Yes	Yes	Yes	Yes
Presence of energetic (>30 keV) particles	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Significant flow deflection	Yes	Yes	Yes	No	No	No	Yes	No
Significant plasma heating	Yes	Yes	Yes	Modest	No	No	Yes	Yes
Associated with an IMF discontinuity	Yes	No	Yes	Sometimes	No	No	Yes	No
Duration	Minutes	Minutes	Minutes	Minutes	Minutes	Minutes	Seconds	~10 s
Scale size	A few RE	A few RE	Up to 10 RE	A few RE	~ RE	~ RE	Ion gyroradius	Ion gyroradius
Generation Mechanisms	Interaction of IMF discontinuities with the bow shock	Interaction of foreshock cavitons with the bowshock	Kinetic interactions between suprathermal, backstreaming ions and incident solar wind plasma with embedded IMF discontinuities that move through and alter the ion foreshock.	Antisunward-moving slabs of magnetic field lines connected to the bow shock that are sandwiched between broader regions of magnetic field lines that remain unconnected to the bow shock.	Nonlinear evolution of ULF waves	Backstreaming ions result in increased pressure within the foreshock region leading to its expansion against the pristine solar wind and the generation of FCB.	Possibly due to backstreaming particles interacting with the original solar wind	Nonlinear wave steepening

http://www-ssc.igpp.ucla.edu/gemwiki/index.php/FG:_Transient_Phenomena_at_the_Magnetopause_and_Bow_Shock_and_Their_Ground_Signatures

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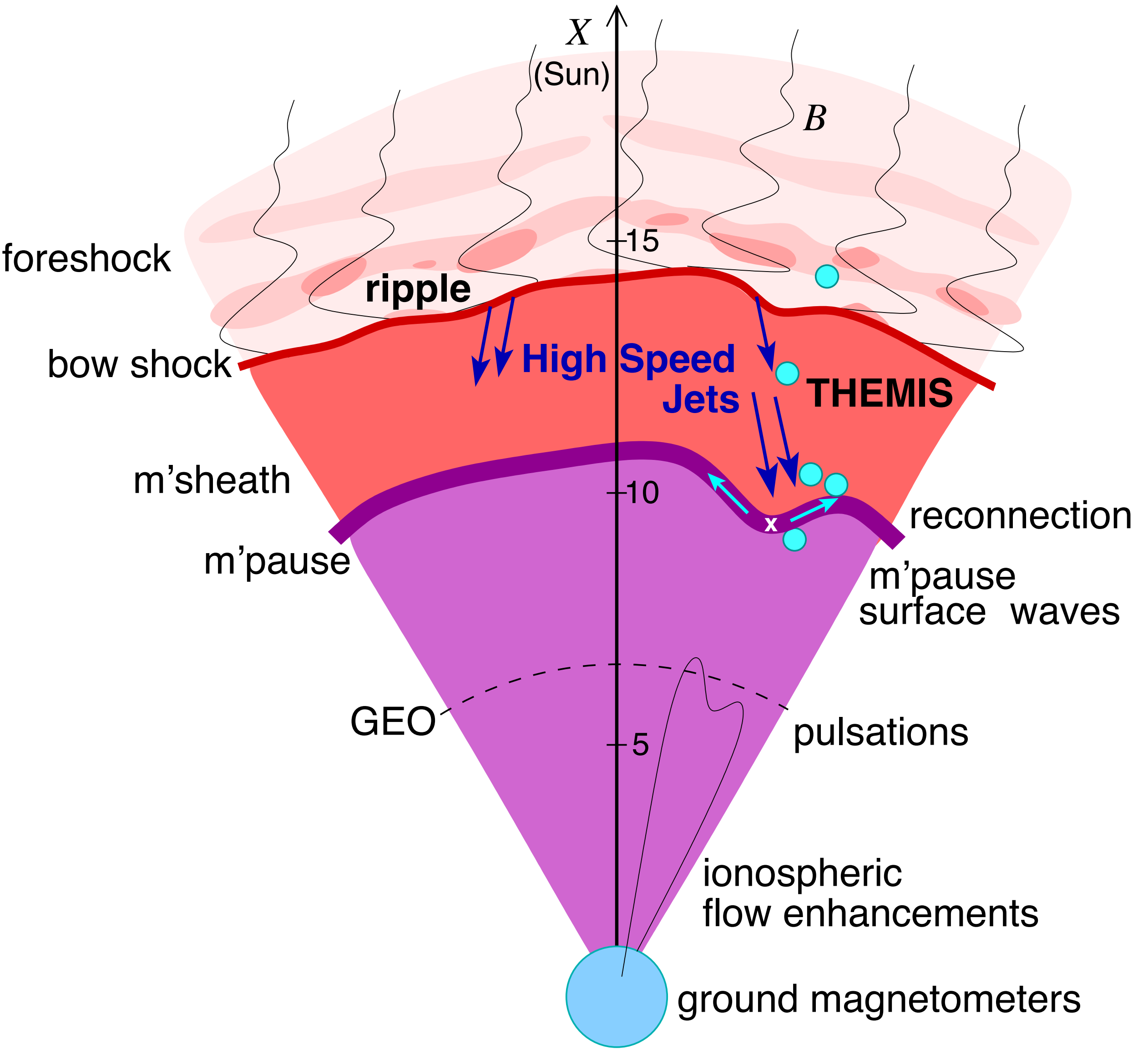
Outstanding Questions

Magnetosheath High-speed Jets



courtesy of H. Hietala

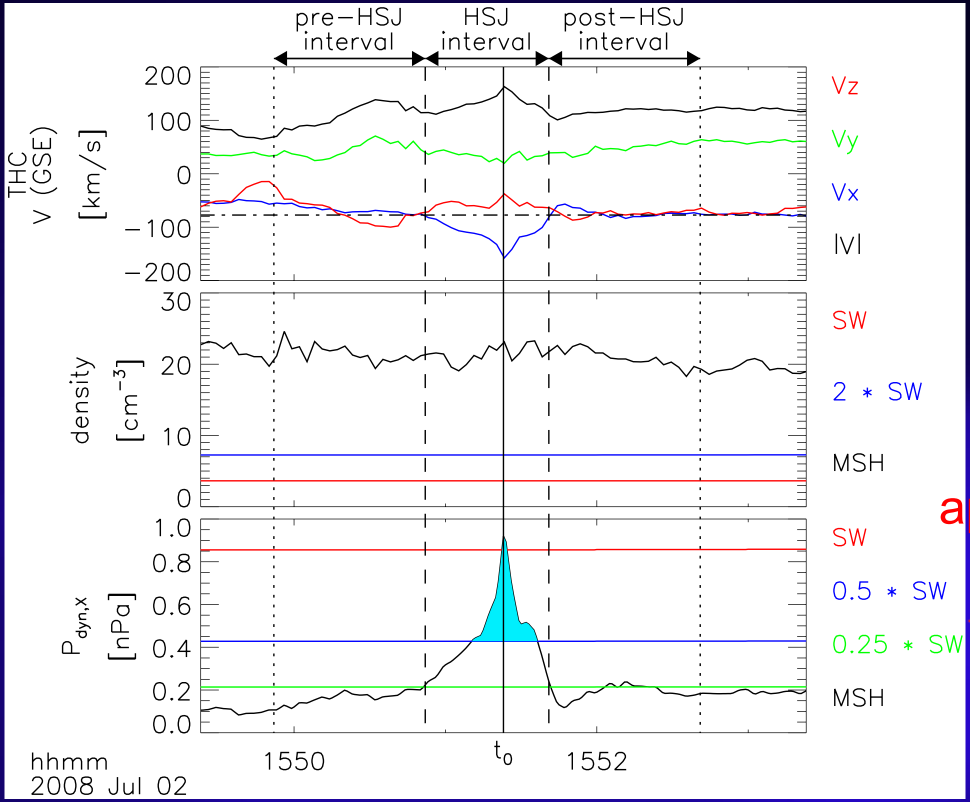
- localized dynamic pressure (ρV_X^2) pulses
- originate from the quasi-parallel shock
- typically 1R_E in scale
- can locally perturb the magnetopause

Impact the dayside magnetopause

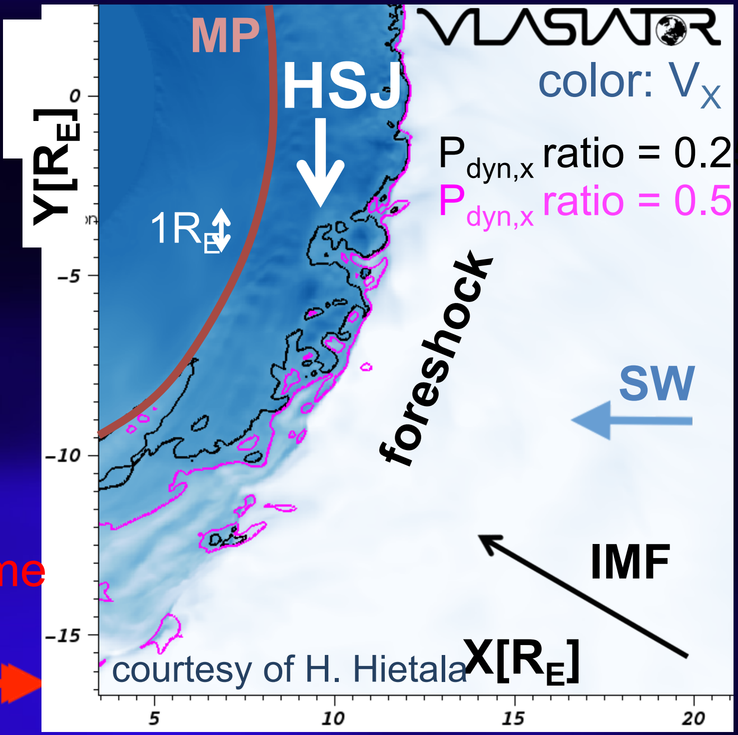
- **every 20 minutes** under general SW conditions
- **every 6.5 minutes** under low IMF cone-angle

Plaschke et al., 2016

Hietala&Plaschke, 2013; Plaschke et al., 2013



apply same criteria



courtesy of H. Hietala

Observations

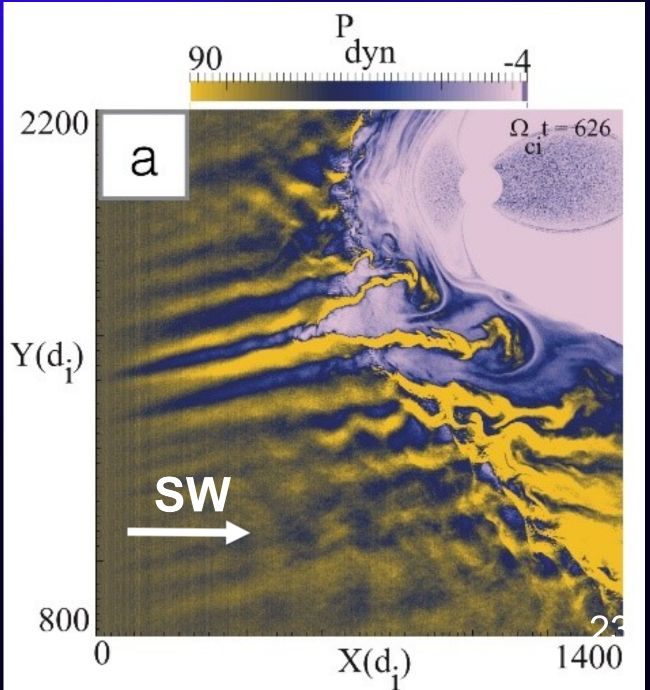
identification based on enhanced dynamic pressure (compared to SW or ambient MSH)

statistics by [Archer&Horbury 2013; Plaschke et al., 2013; Karlsson et al., 2012; 2015]

Simulations

seen behind quasi-parallel shock in kinetic simulations

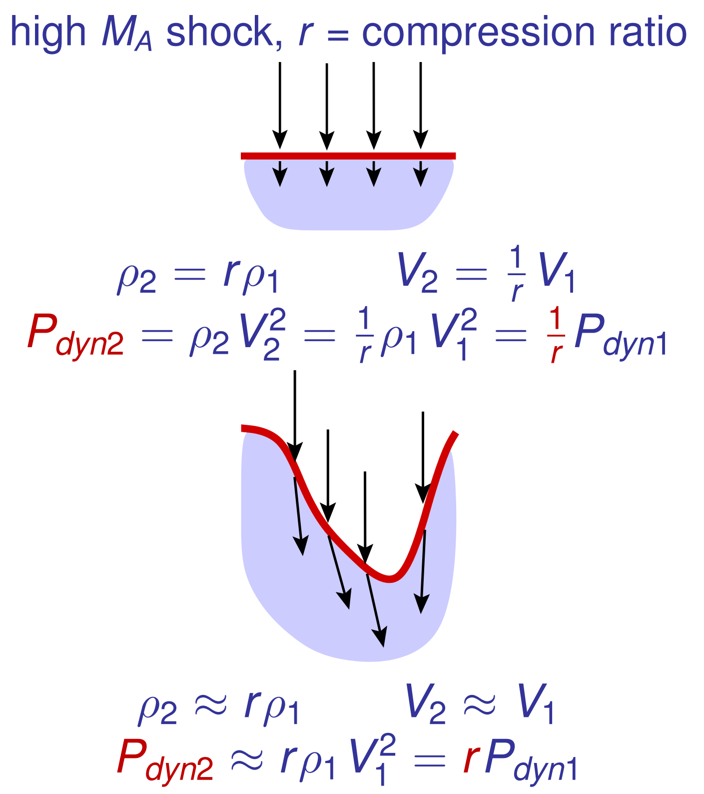
[Karimabadi et al., 2014; Hao et al., 2016; Omidi et al., 2016]



Karimabadi et al., 2014

Origin of Magnetosheath High-speed Jets: Shock Ripples

Approximate calculation



high M_A shock, r = compression ratio

$$\rho_2 = r\rho_1 \qquad V_2 = \frac{1}{r}V_1$$

$$P_{dyn2} = \rho_2 V_2^2 = \frac{1}{r}\rho_1 V_1^2 = \frac{1}{r}P_{dyn1}$$

$$\rho_2 \approx r\rho_1 \qquad V_2 \approx V_1$$

$$P_{dyn2} \approx r\rho_1 V_1^2 = rP_{dyn1}$$

Hietala et al., 2009;2012

More detailed derivation

$$\frac{P_{\mathrm{dyn},2,X}}{P_{\mathrm{dyn},1,X}} = \frac{\left(\cos^2\theta + \frac{M_{\mathrm{An}}^2-1}{M_{\mathrm{An}}^2-r}\,r\sin^2\theta\right)^2}{r}$$

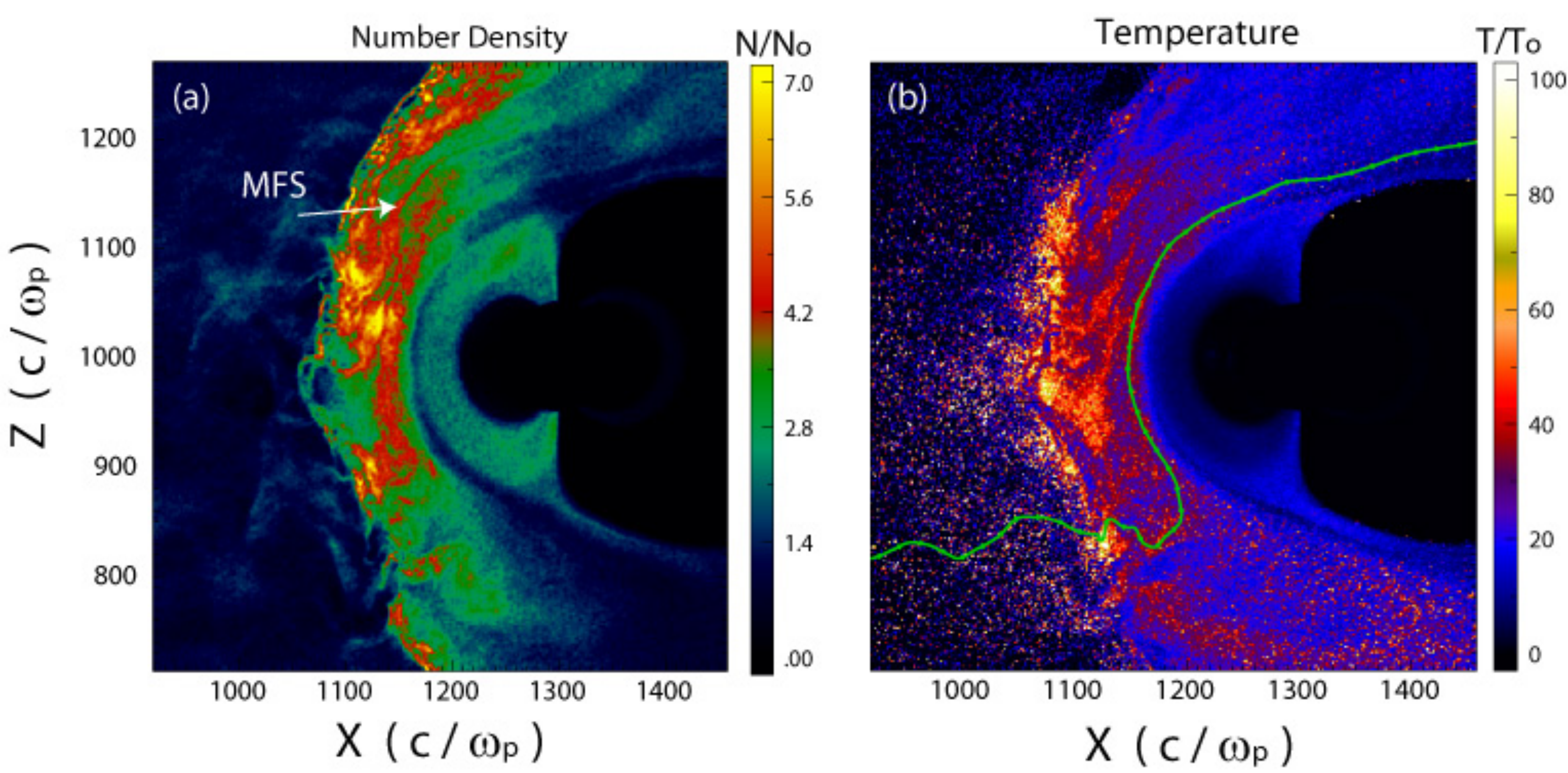
Hietala&Plaschke, 2013

Behind a locally tilted shock the plasma is less decelerated (just like at the flanks of themagnetosheath), and the dynamic pressure can be up to 4 times the solar wind dynamic pressure.

Minority formed by SW discontinuities

Lin et al., 1996a,b; *Archer et al.*, 2012

Magnetosheath Filamentary Structure (MFS)



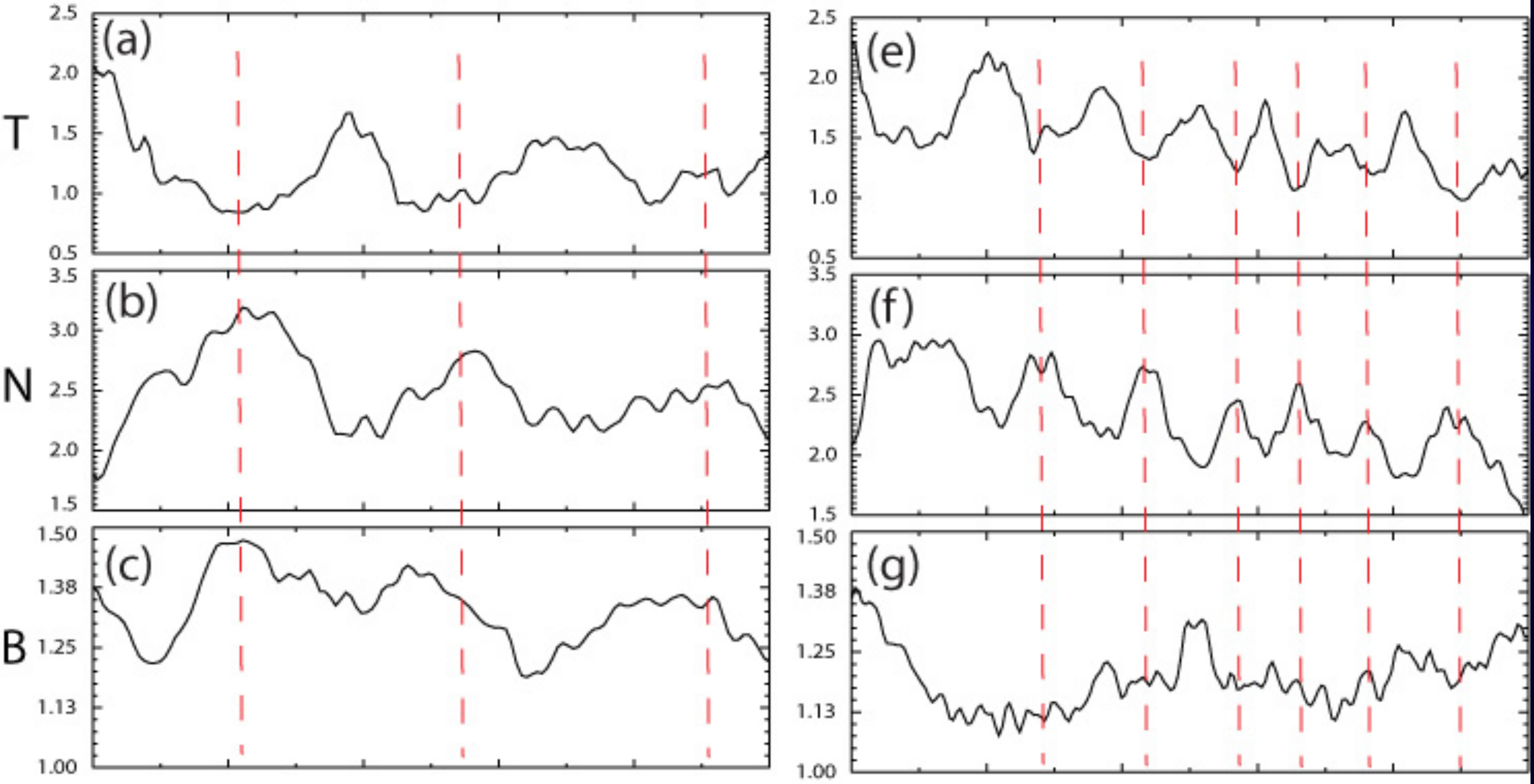
Omidi et al. JGR, 2014

Field aligned structures in density and ion temperature in the magnetosheath formed by the injection of energetic ions associated with SHFAs.

MFS Simulations

Close to Bow Shock

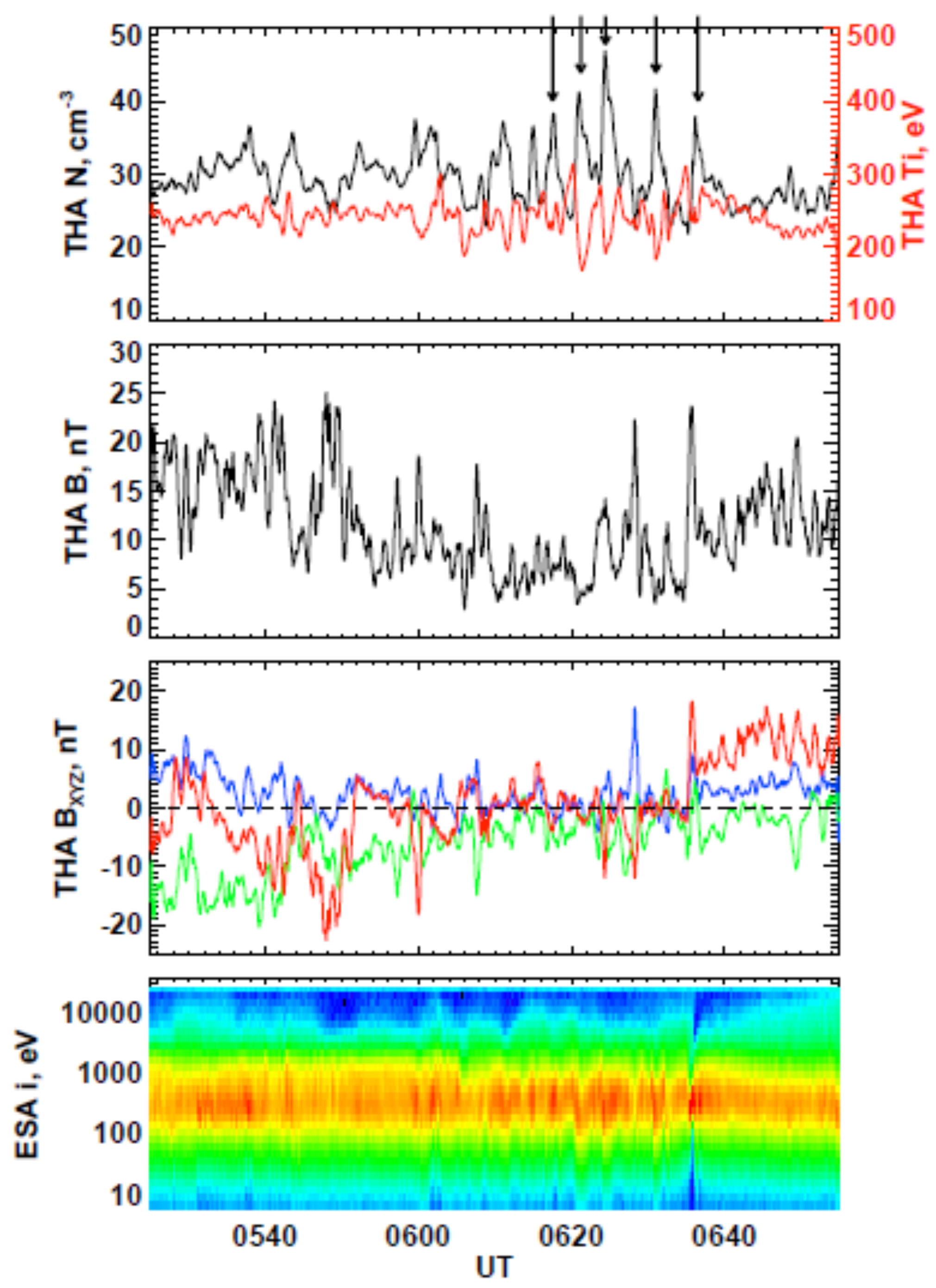
Away from Bow Shock



Omidi et al. JGR, 2014

- Density and temperature are anti-correlated.
- B and N show correlation near the bow shock and no correlations further away from the bow shock.

MFS Observations



Anti-correlated variations in density and temperature

THEMIS observations have confirmed the predictions by hybrid simulations.

Gutynska et al. JGR, 2014

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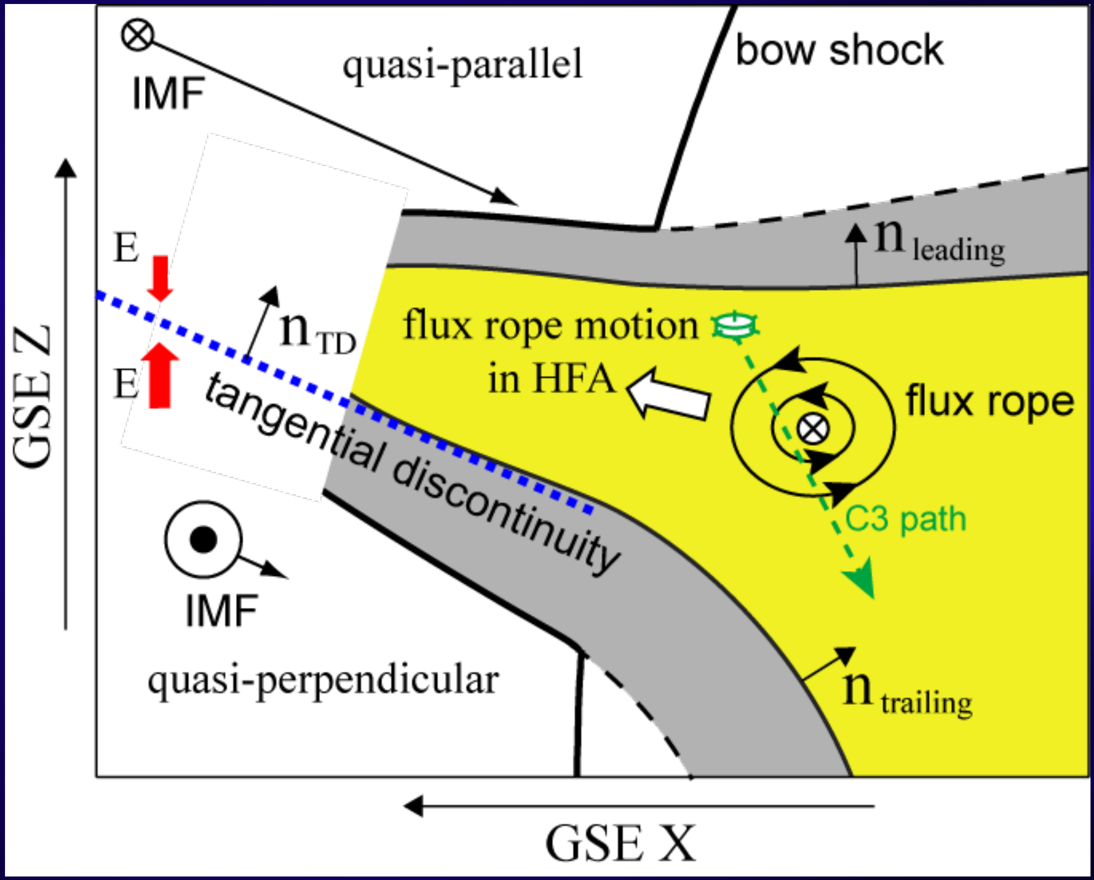
Flux Rope Generation, i.e., Reconnection Initiation, within HFA

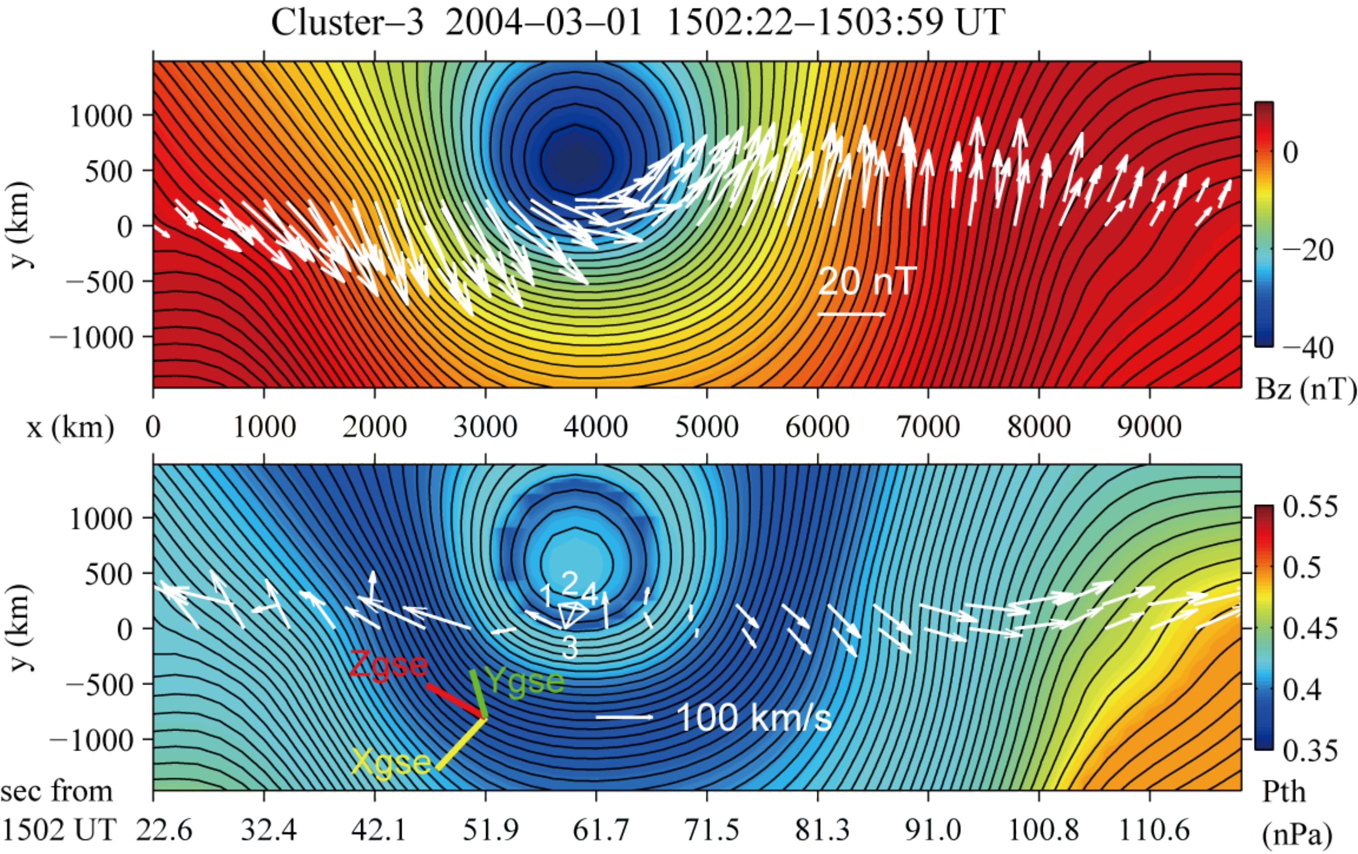


- Low N & high T_i in HFA make ion gyro-radius & inertia length longer, favorable for fast reconnection.
- Moreover, sheath current sheets may be compressed against the magnetopause & become thin (*Phan et al.*, GRL, 2011).

Hasegawa et al., 2012

- Reconnection probably occurred on the side with quasi-|| shock configuration.

Reconstructed Flux Rope in HFA



V_{HT} =(69, 27, 71) km/s

z_{GSR} =(0.39, 0.77, -0.50) in GSE

Flux rope oriented roughly in GSE-*y*.

Hasegawa et al., 2012

- Magnetic flux rope with diameter ~3000 km.
- Leftover velocities directed away from the center, suggesting still ongoing expansion of the flux rope.

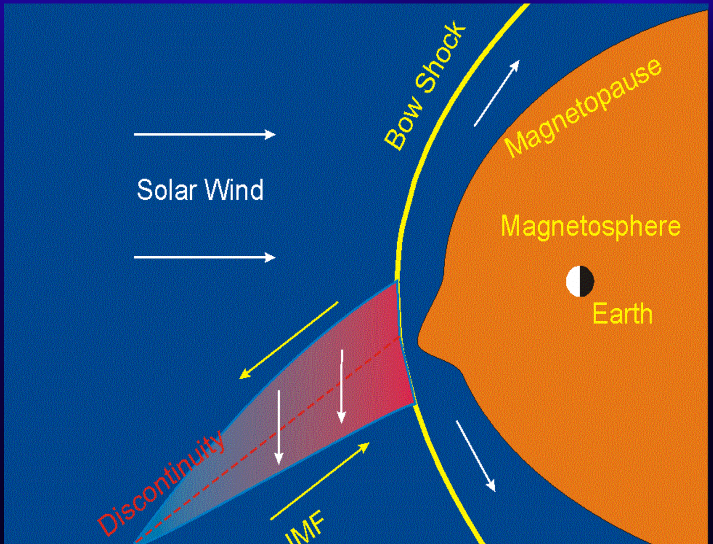
Drive Magnetopause Boundary Waves

Pressure Balance at the Magnetopause

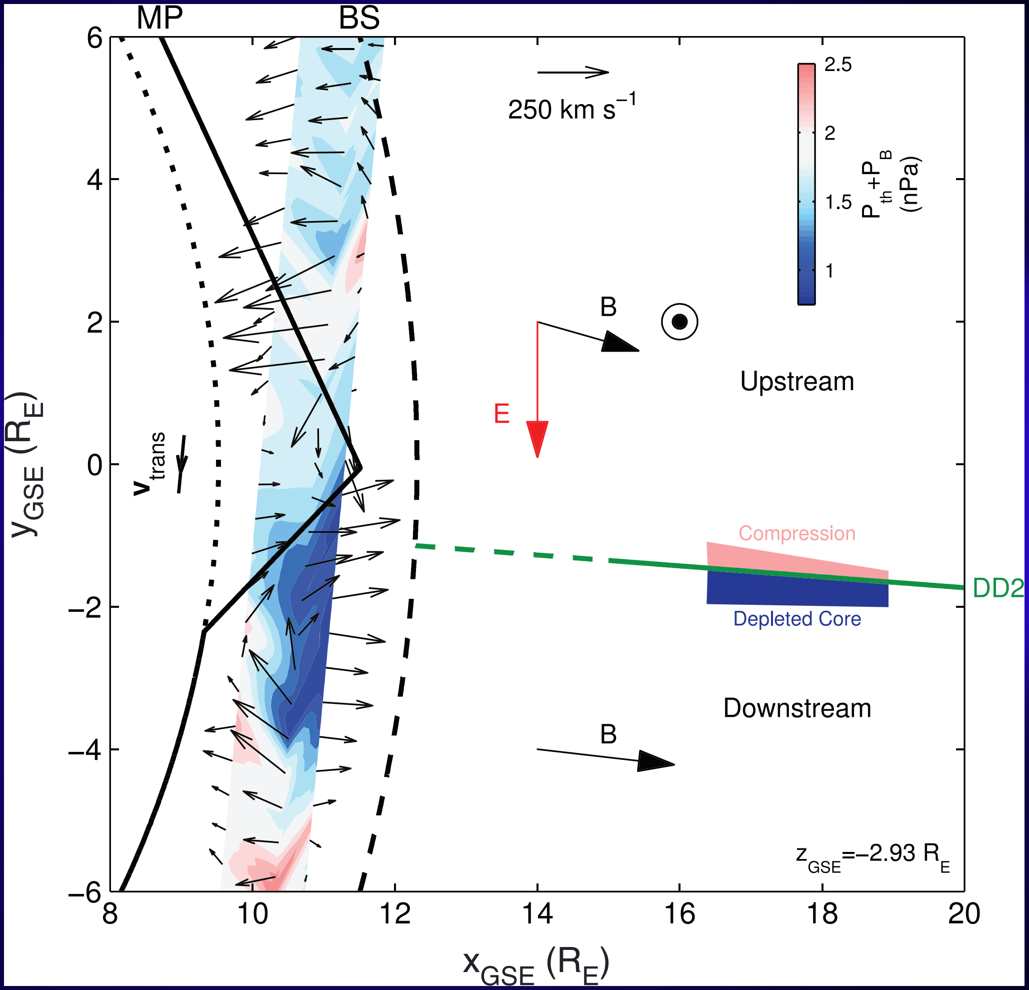
Solar Wind			Magnetosphere	
dynamic pressure	thermal pressure	magnetic pressure	thermal pressure	magnetic pressure

$$n_{sw} m v^2 \cos^2\theta + \cancel{p_{th\_sw}} + \frac{B_{sw}^{\,2}}{2\mu_0} = \cancel{p_{th\_sphere}} + \frac{B_{sphere}^{\,2}}{2\mu_0}$$

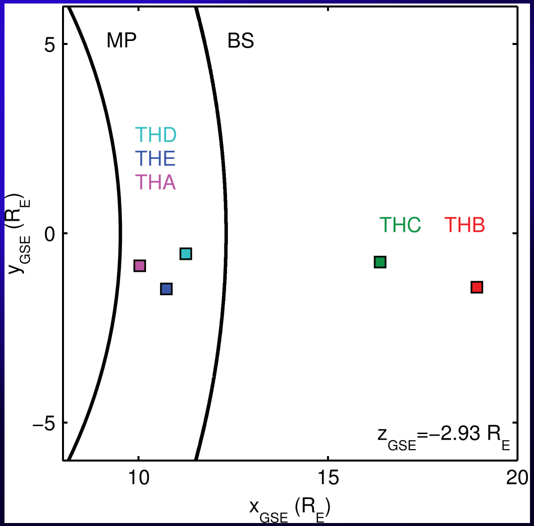
small small



Magnetopause Deformation due to an HFA

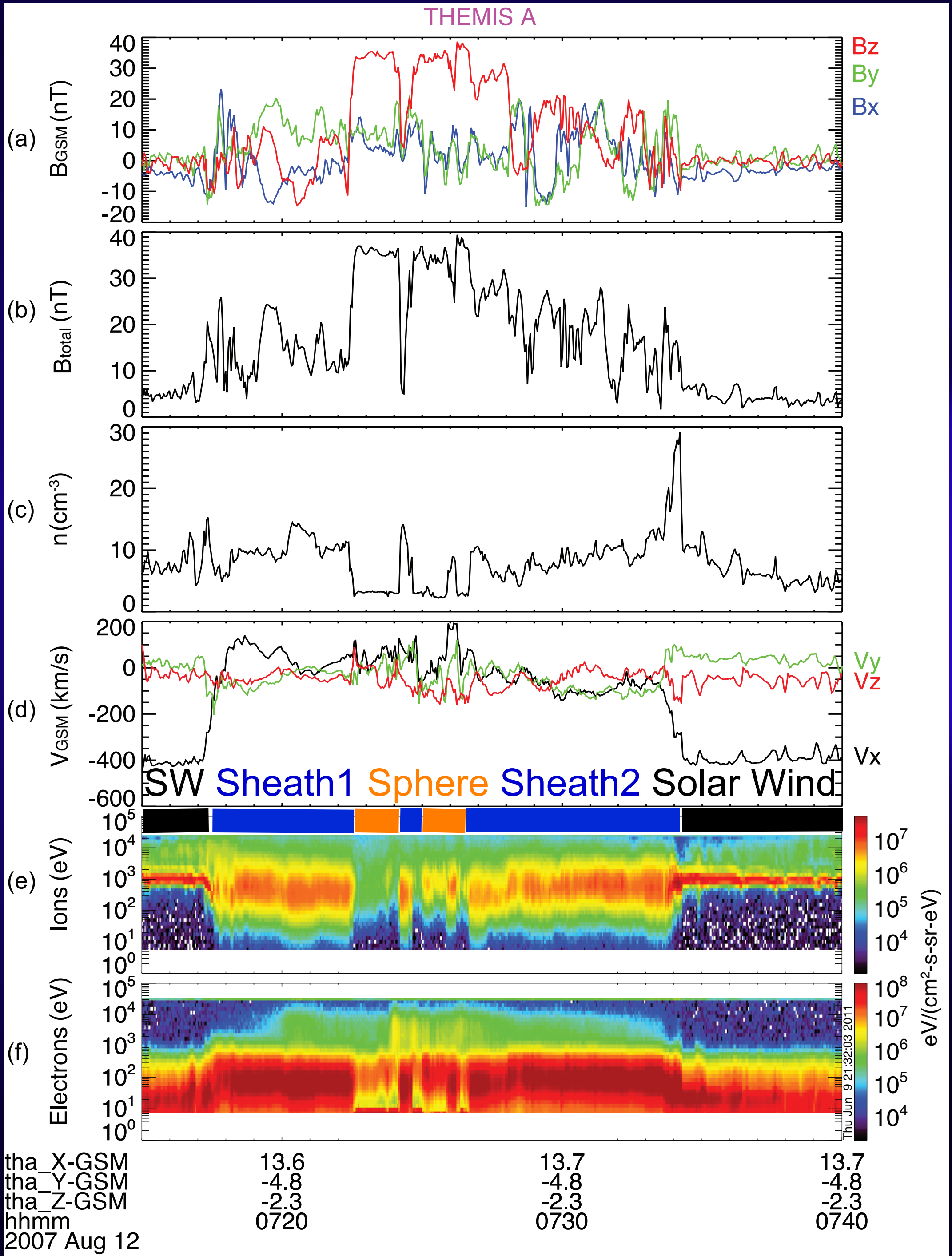


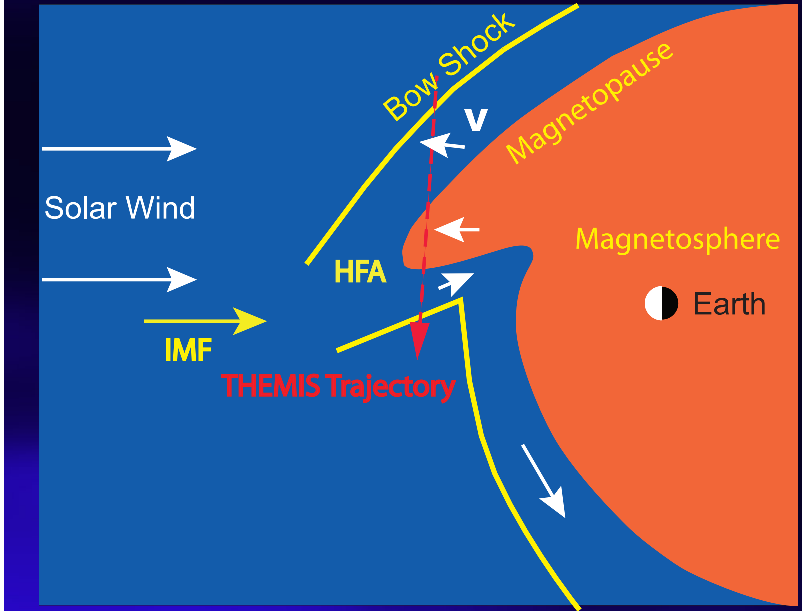
- **Black solid line**: The observed magnetopause deformation
- **Black arrow**: flow pattern
- **Color scale**: the contours of the thermal + magnetic pressure.
- **Sunward magnetosheath flow**



Archer et al., GRL 2014

Jacobsen et al.[2009] reported THEMIS observations of the extreme motion of the magnetopause, with flow speeds 800 km/s. Magnetopause was displaced outward by at least 4.8 R_E in 59 s. A bulge was moving tailward at 355 km/s.

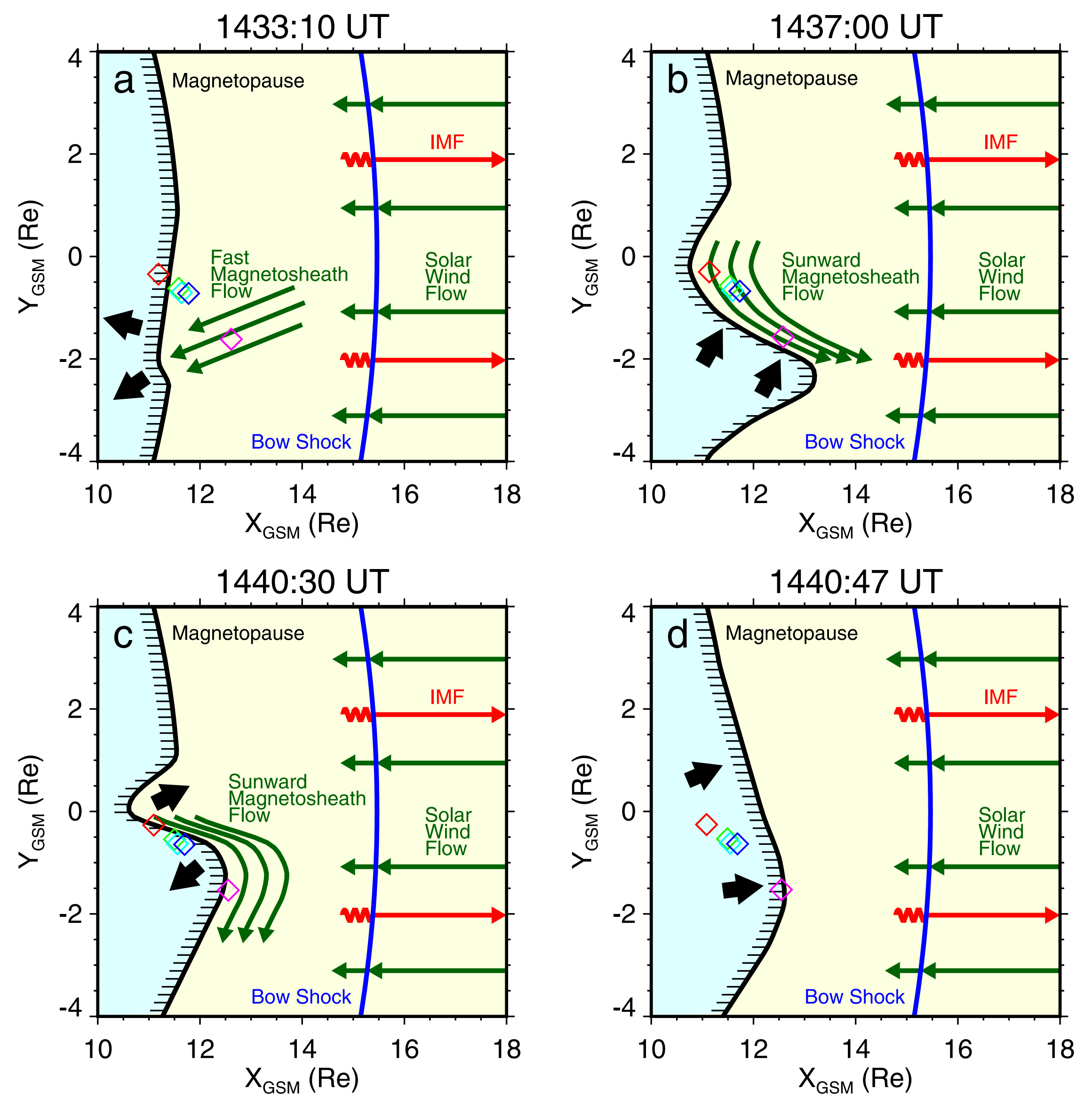




- The magnetopause bulged out by at least 4 R_{E}.
- The event lasted 17 minutes => scale size in y direction > 10 R_E
- The bulge is convecting tailward with the magnetosheath flow at ~100 km/s.

courtesy of H. Zhang

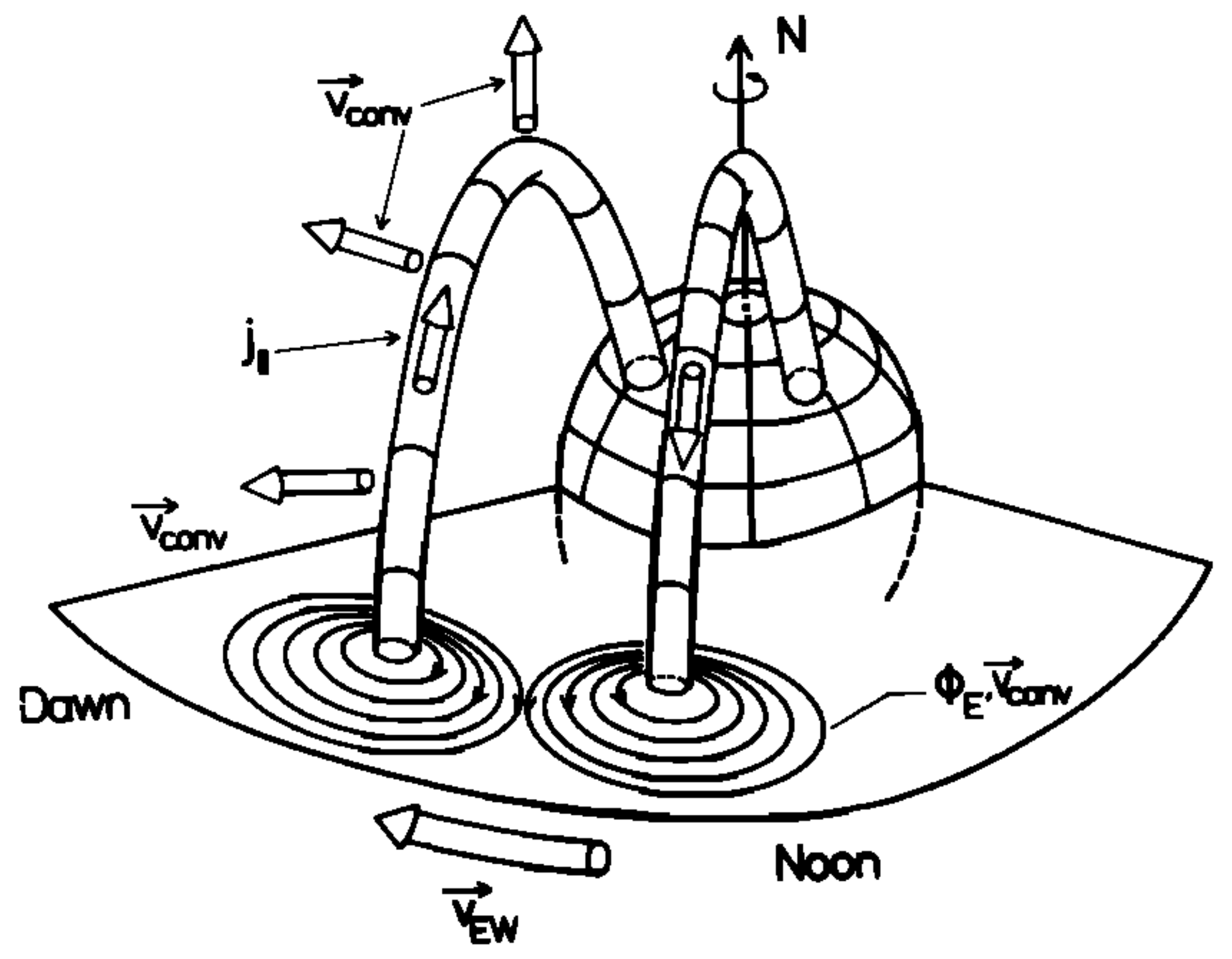
Magnetopause Deformation due to Magnetosheath High-Speed Jets



Shue et al., 2009

THEMIS observations of a magnetopause distortion and recovery

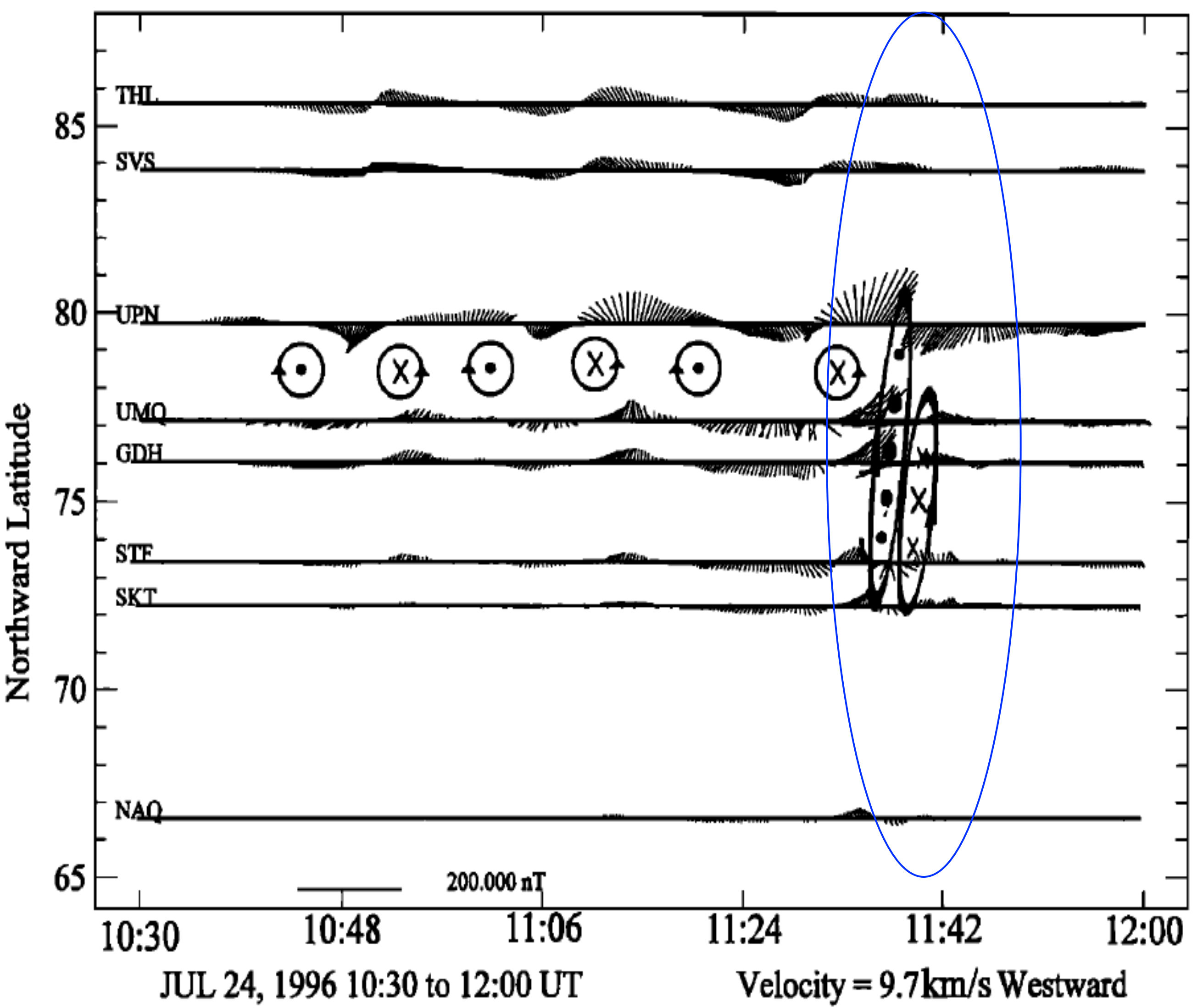
- Deformation of the magnetopause generates field-aligned currents (FACs) into the auroral ionosphere – FAC signatures are measured on the ground as magnetic impulse events (MIEs) or traveling convection vortices (TCVs) [*Glassmeier et al.*, 1989; *Sitar et al.*, 1998]



Glassmeier et al., 1989

Ionospheric TCV Triggered by an HFA

(1) Ground Magnetometer Observations



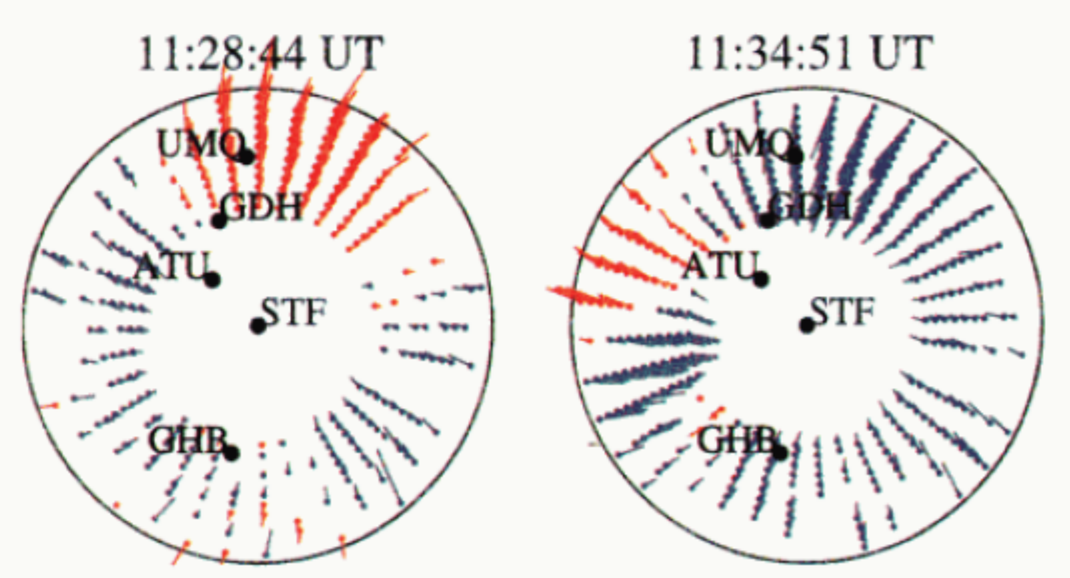
- Ionospheric convection inferred from ground magnetometers located on the west coast of Greenland.
- Traveling Convection Vortices (TCVs) associated with field-aligned currents.
- The velocity of the TCVs, 9.7 km/s westward
- Lifetime ~ 18min

Sitar et al., JGR, 1998

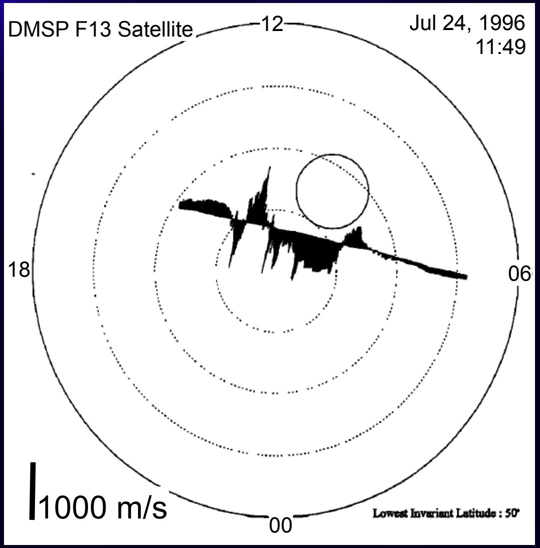
Ionospheric TCV Triggered by an HFA

(2) Radar and DMSP Observations

- F region line-of-sight velocities observed by the Sondrestrom incoherent scatter radar.
- The radar scans show modulation in the flow patterns with the passage of successive TCV field aligned current pairs through the northern field of view.

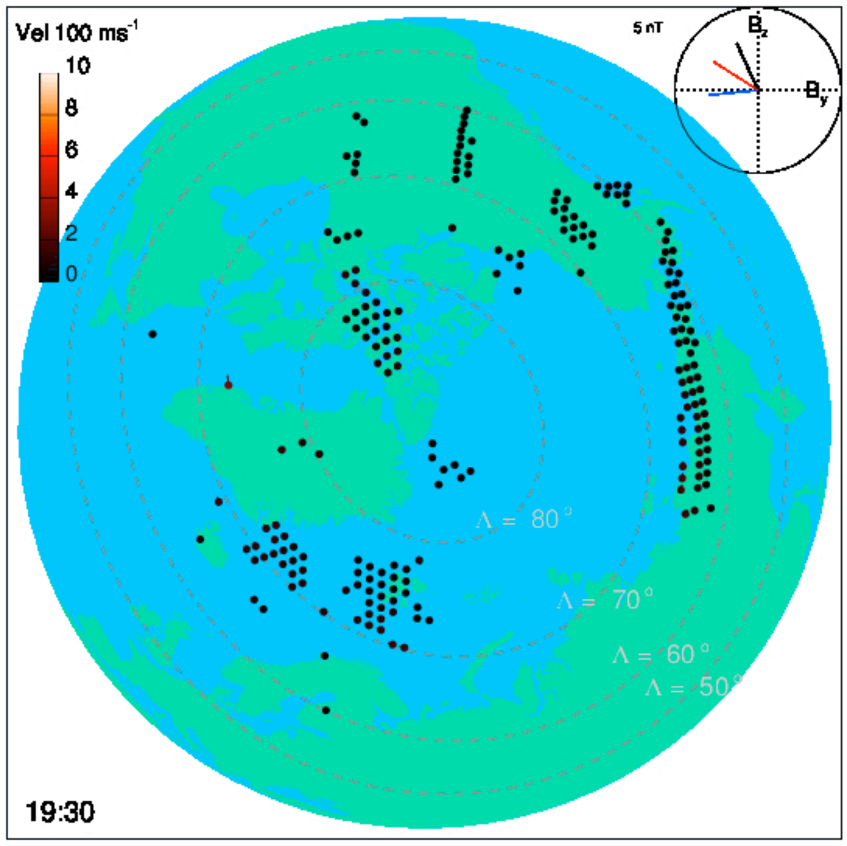


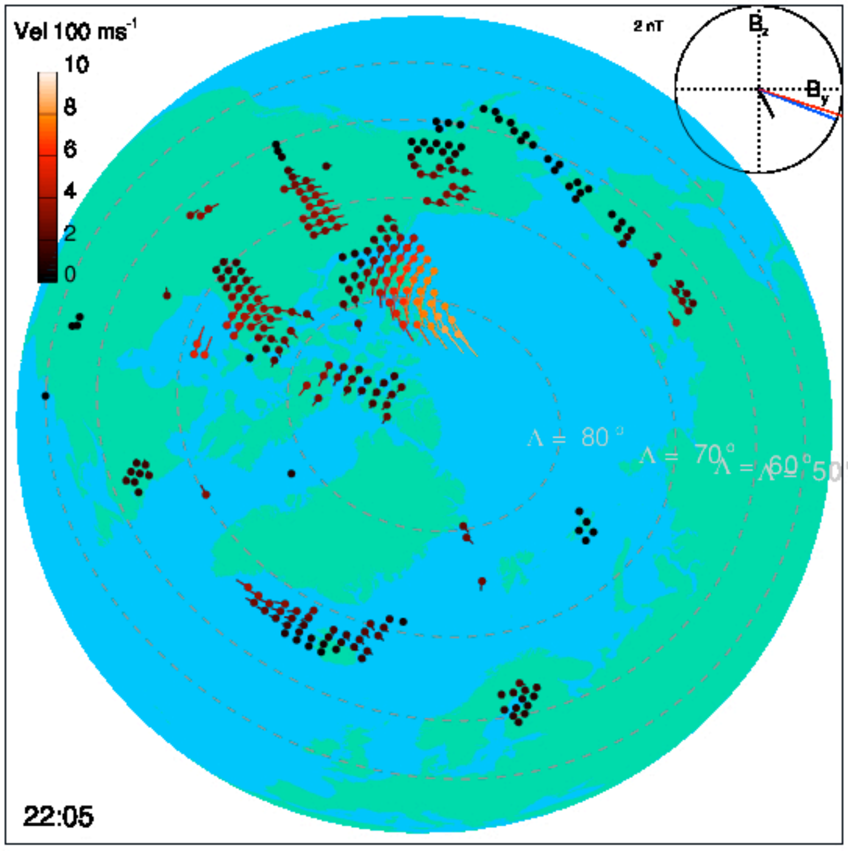
- The horizontal cross-track convection drifts measured by the DMSP F13 satellite.
- The field of view of the Sondrestrom radar is represented by the circle on the plot.
- The strong, organized flows observed by F13 are consistent with the observations of the Sondrestrom radar.



Sitar et al., JGR, 1998

Enhanced Ionospheric Flows Result from a Foreshock Bubble



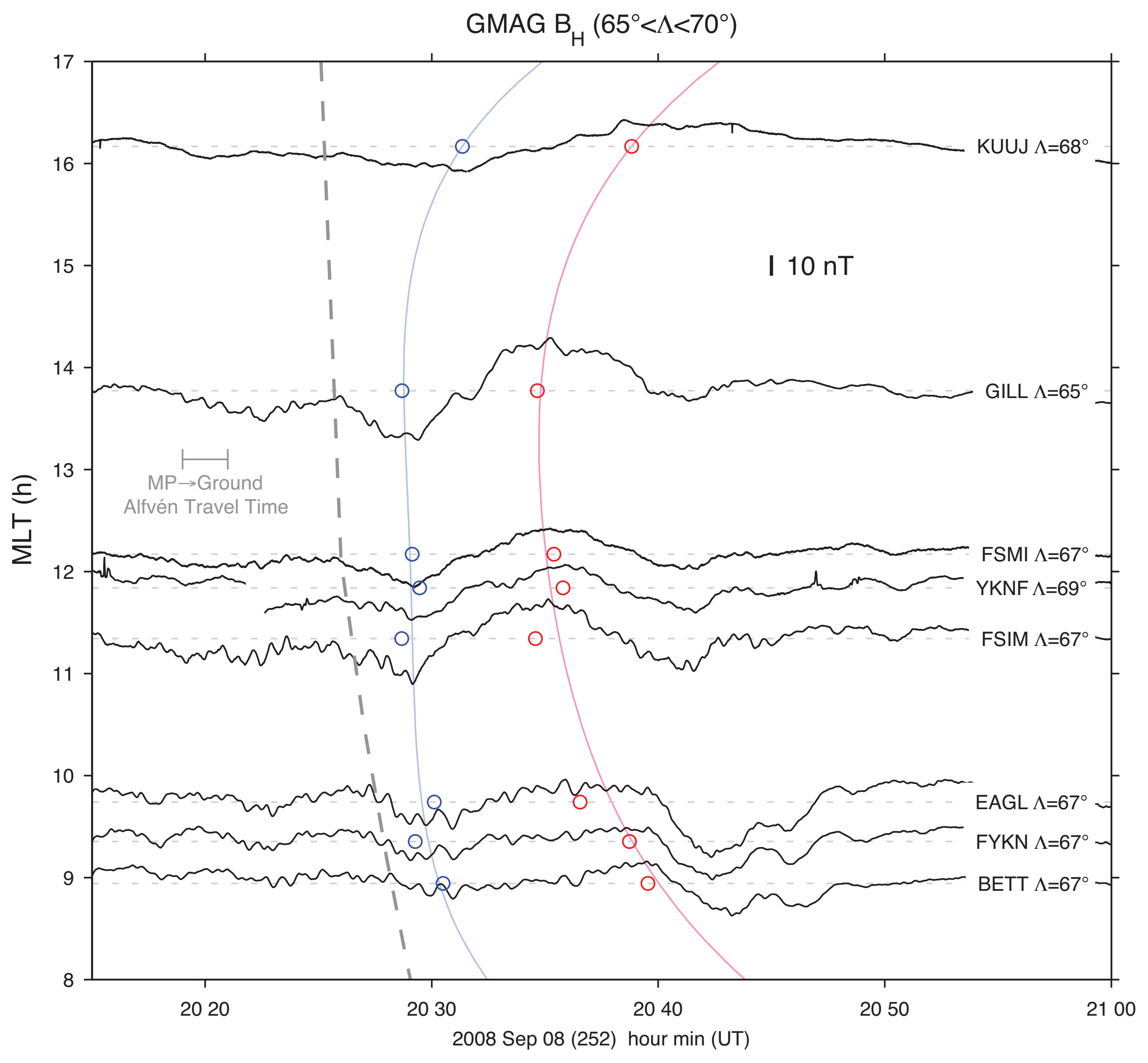


Courtesy of D. Turner

Ionospheri flows during quiet time when there was no transient event upstream.

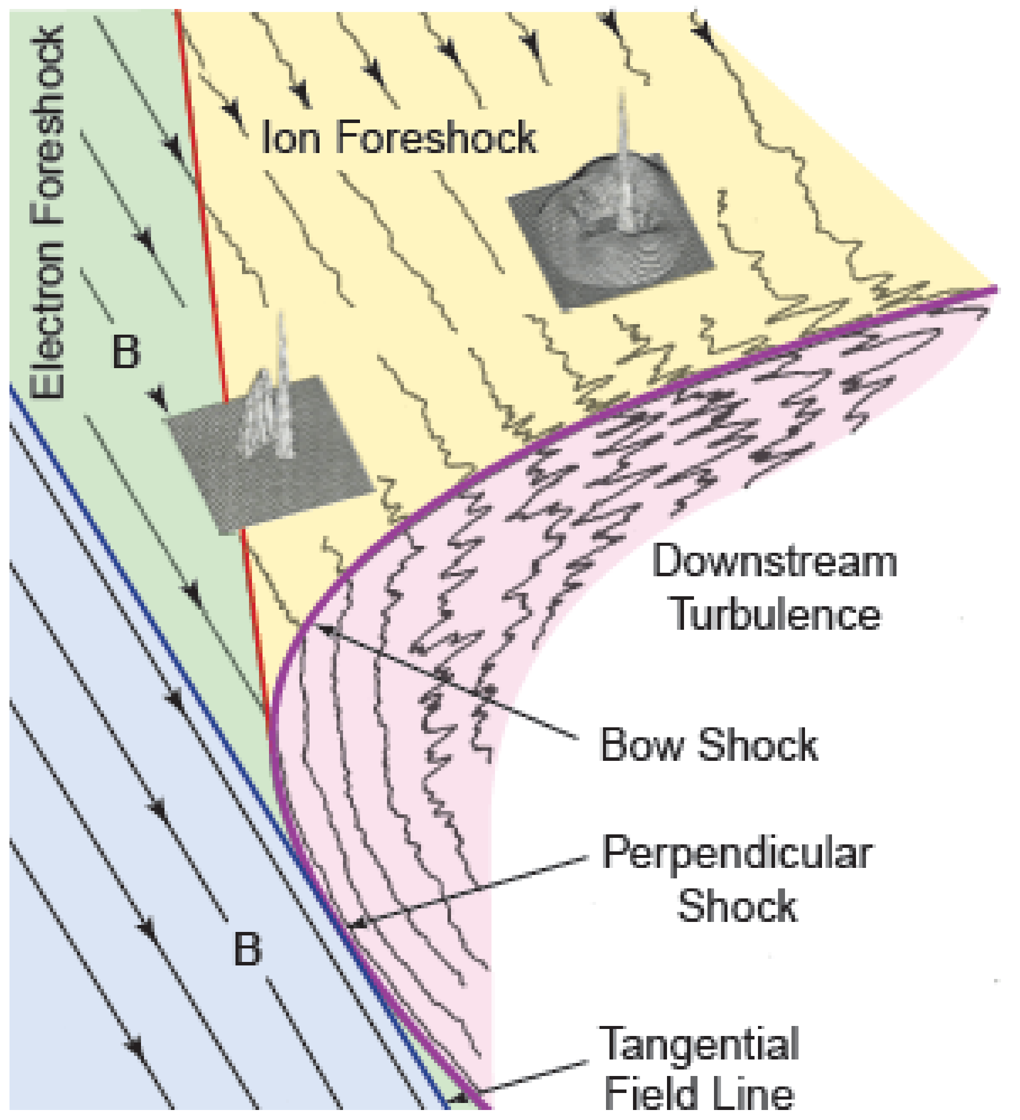
SuperDARN observations of ionospheric flows result from a Foreshock Bubble on 14 July 2008.

MIE Caused by a Foreshock Bubble



Archer et al.,PSS, 2014

ULF Waves from the Ion Foreshock



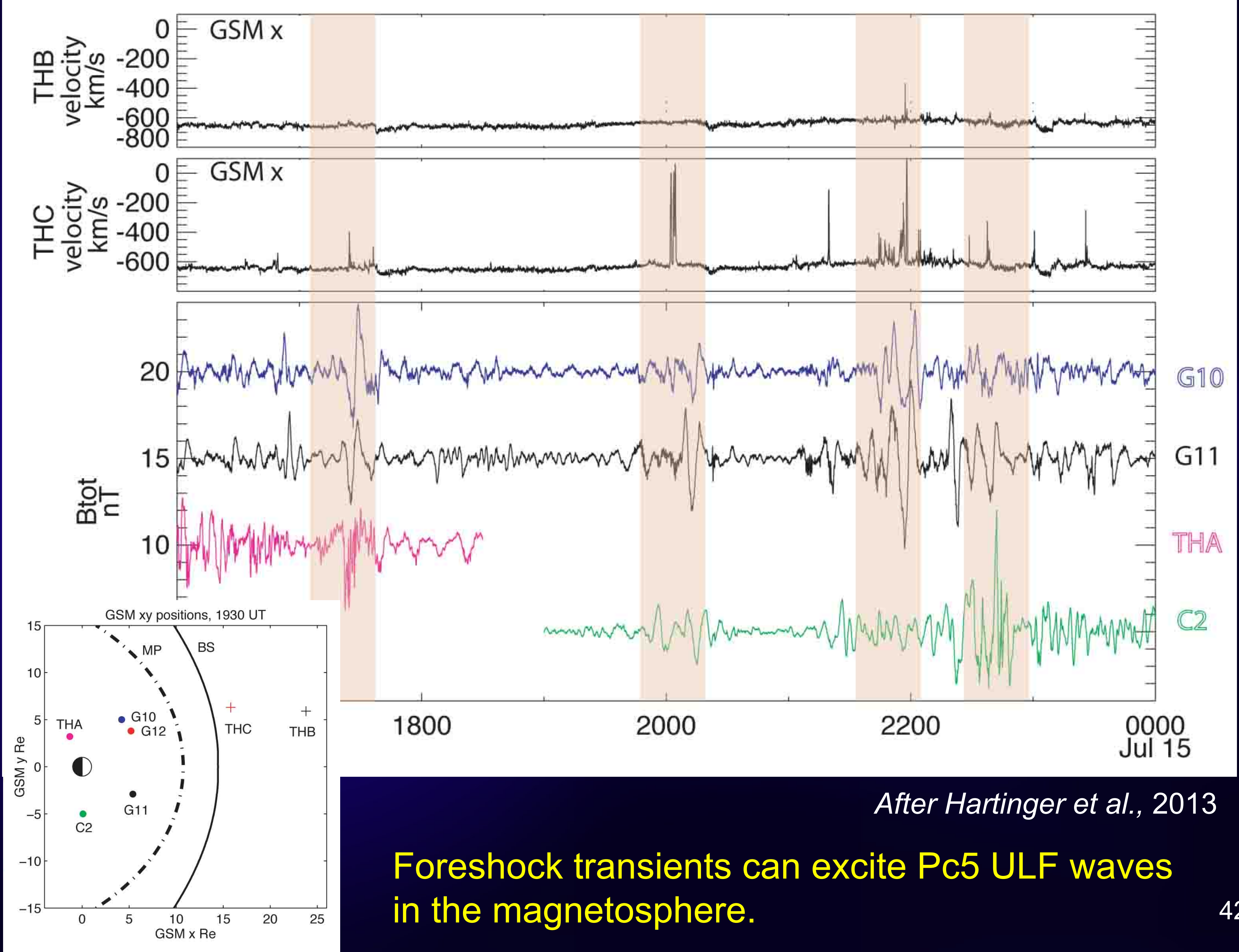
Treumann and Scholer, 2001

Foreshock Transients Generate ULF Waves

- Several studies have demonstrated that transient phenomena near the bow shock (such as HFAs and Foreshock Bubbles) can generate ULF waves in the Earth's magnetosphere. (This is different from the low-latitude Pc3 waves that are driven by upstream waves in the ion foreshock.)

- The ULF waves generated by transient phenomena near the bow shock in both Pc3 [Eastwood et al., 2011] and Pc5 [Fairfield et al., 1990; Hartinger et al., 2013] ranges have been reported.

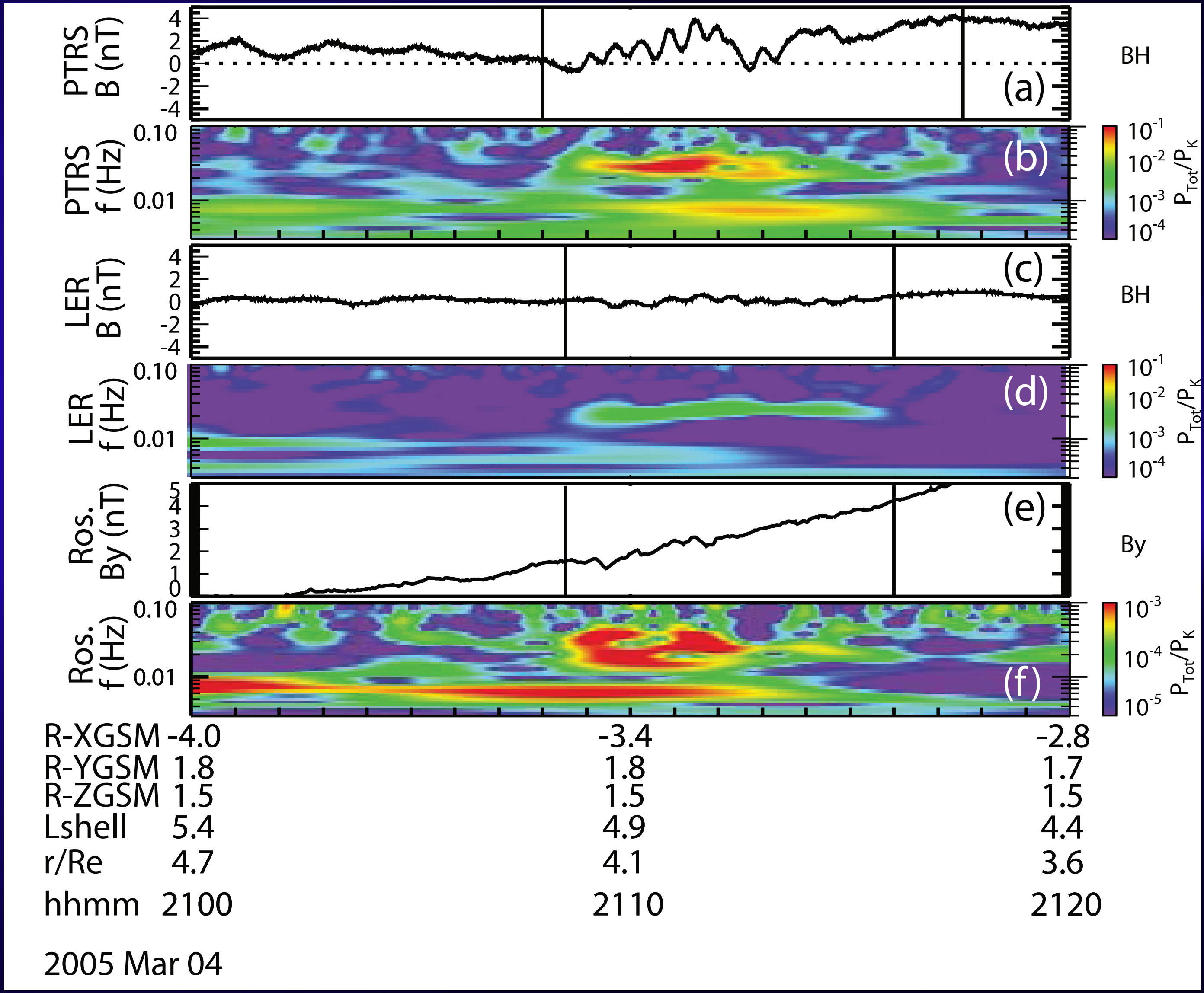
- There may be considerable variation between ULF waves resulting from different transient features (e.g., Hartinger et al. [2013] showed mostly compressional waves whereas Eastwood et al. [2011] showed standing Alfvén waves).



After Hartinger et al., 2013

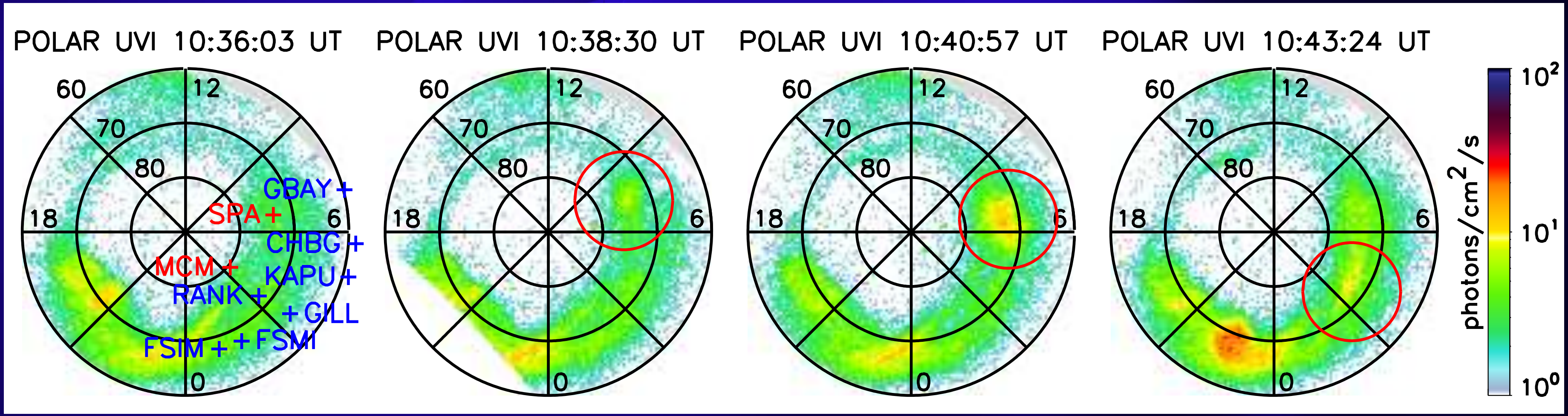
Foreshock transients can excite Pc5 ULF waves in the magnetosphere.

Pc3 ULF Waves Excited by an HFA



Eastwood et al., 2011

Auroral Brightening Triggered by an HFA

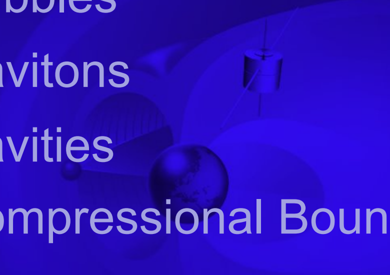


Fillingim et al., 2011

Outline

Foreshock Transients

- Hot Flow Anomalies (HFAs)
- Spontaneous HFAs
- Foreshock Bubbles
- Foreshock Cavitons
- Foreshock Cavities
- Foreshock Compressional Boundaries
- Density Holes
- SLAMS



Their Geoeffects

- Trigger magnetic reconnection?
- Drive magnetopause boundary waves
- Generate FACs, TCVs/MIEs
- Excite ULF waves
- Auroral response

Magnetosheath Transients

- Magnetosheath High-Speed Jets
- Magnetosheath Filamentary Structure

Outstanding Questions

Outstanding Questions

- What are the physical differences and relationships between different foreshock transient phenomena?
- How do they evolve with time and transition through the magnetosheath?
- Do foreshock and magnetosheath transients trigger transient features (magnetic reconnection/FTEs, surface waves etc.) at the magnetopause?
- When, where, and how significantly do foreshock and magnetosheath transient processes modify the solar wind just prior to its interaction with the Earth’s magnetosphere?
- What is the role of foreshock and magnetosheath transient processes in solar wind-magnetosphere-ionosphere coupling?

Ultimate Goal

To obtain a quantitative understanding of these processes so that they could be parameterized for inclusion into space weather prediction models, thereby improving forecast capability.

How to reach this goal?

- Observations and hybrid/particle simulations can help to understand the physical processes and formation conditions of these transient phenomena.

- In addition to coordinated multi-points observations, inclusion of a localized pressure pulse in global MHD simulations can help us to understand the impact of these transients on the magnetosphere and ionosphere.

Summary and Conclusions

- There are many foreshock and magnetosheath transient phenomena. The kinetic processes associated with these phenomena modify the solar wind just prior to its interaction with the Earth's magnetosphere.
- Foreshock and magnetosheath transients have significant geoeffects (drive magnetopause boundary waves, generate FACs, TCVs/MIEs, excite ULF waves, trigger aurora brightening etc.)
- There are still many outstanding questions about foreshock and magnetosheath transients and their roles in the solar wind-magnetosphere-ionosphere coupling. A synergy of both modeling and experimental efforts is crucial to answer these questions.