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THE MAGNETOSHEATH

Ferdinand Plaschke

Space Research Institute
Austrian Academy of Sciences
Graz, AUSTRIA

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and the Space Plasma Physics Team at the Space Research Institute!**

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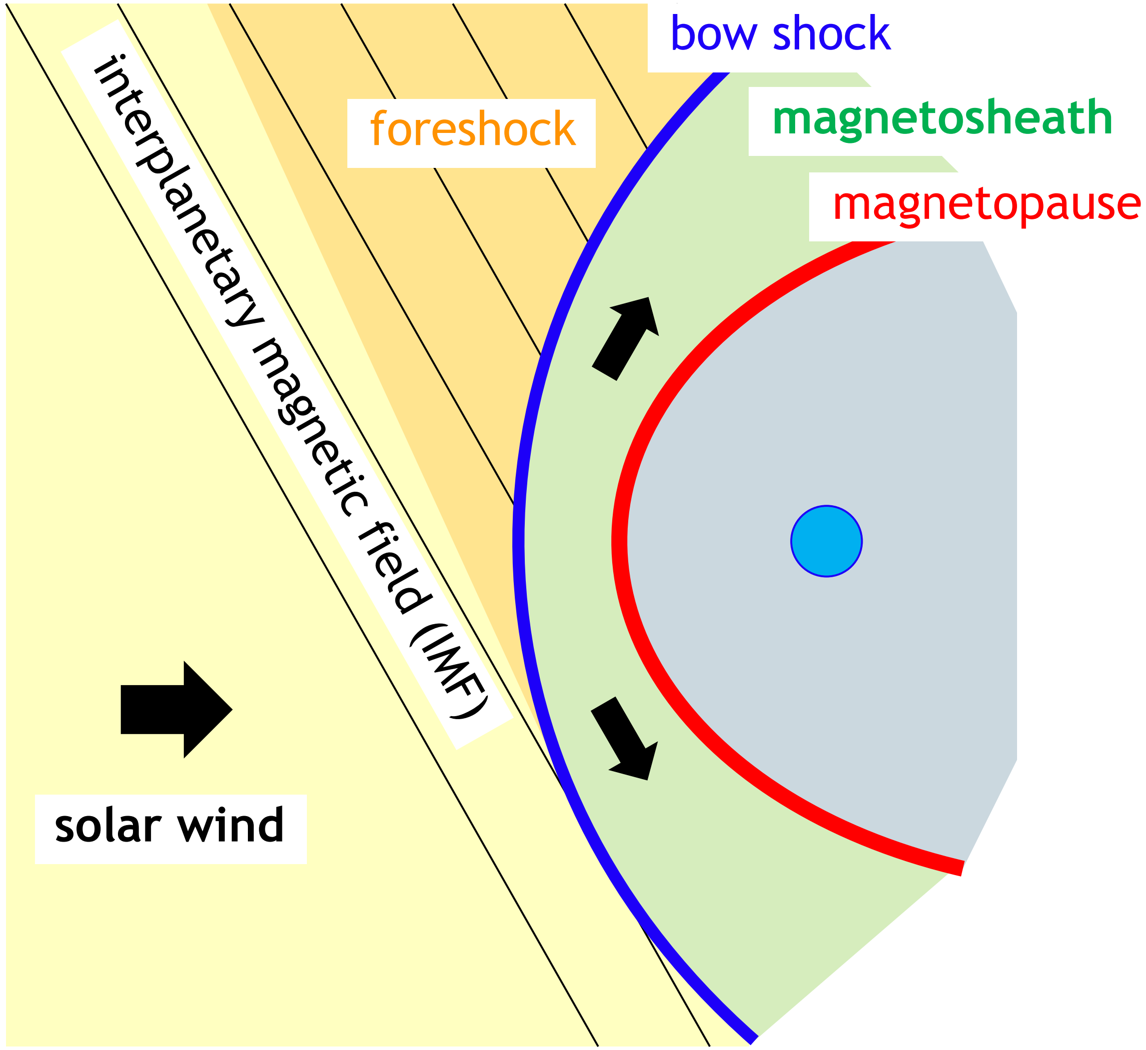
WHAT IS THE MAGNETOSHEATH?



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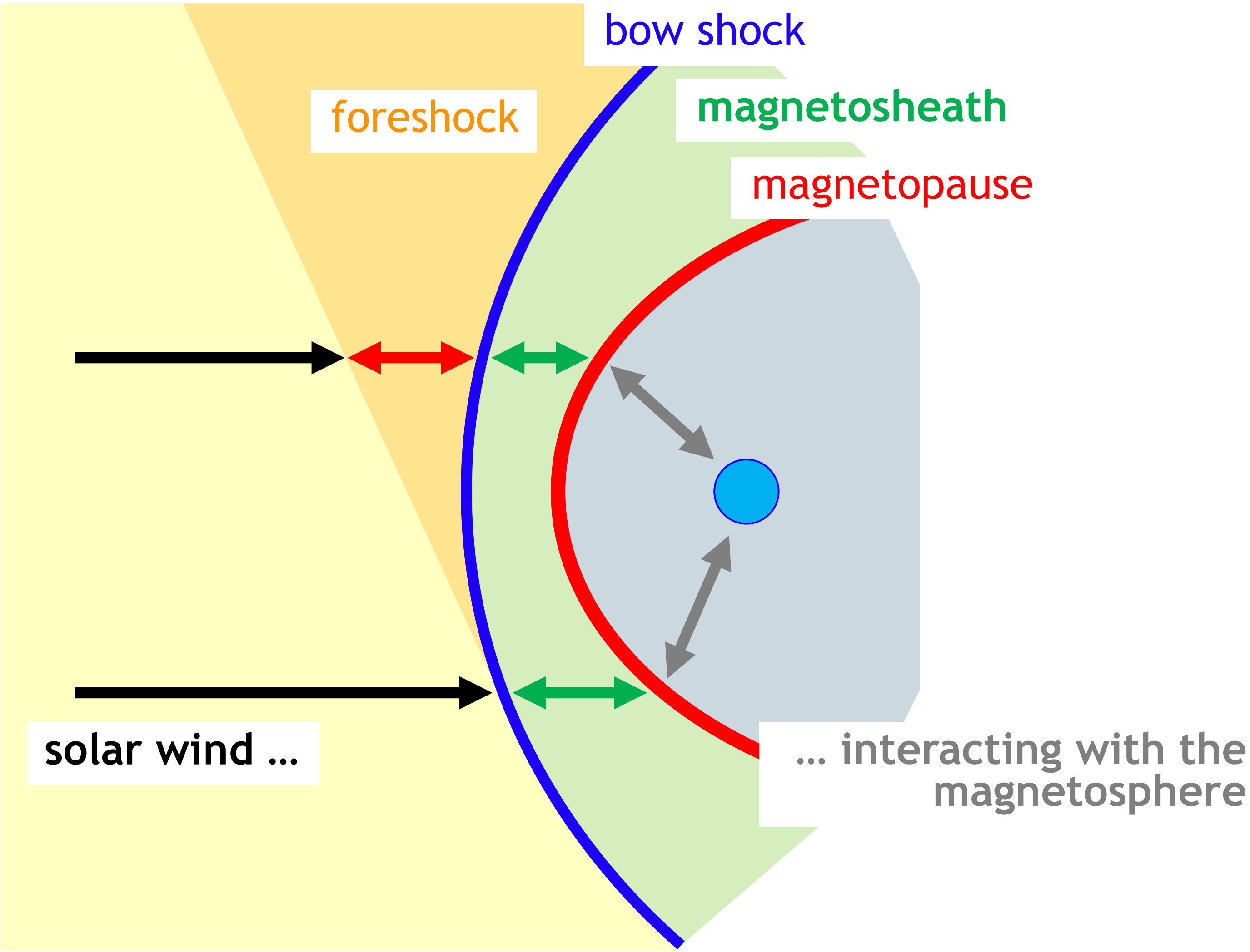
WHY IS IT IMPORTANT?



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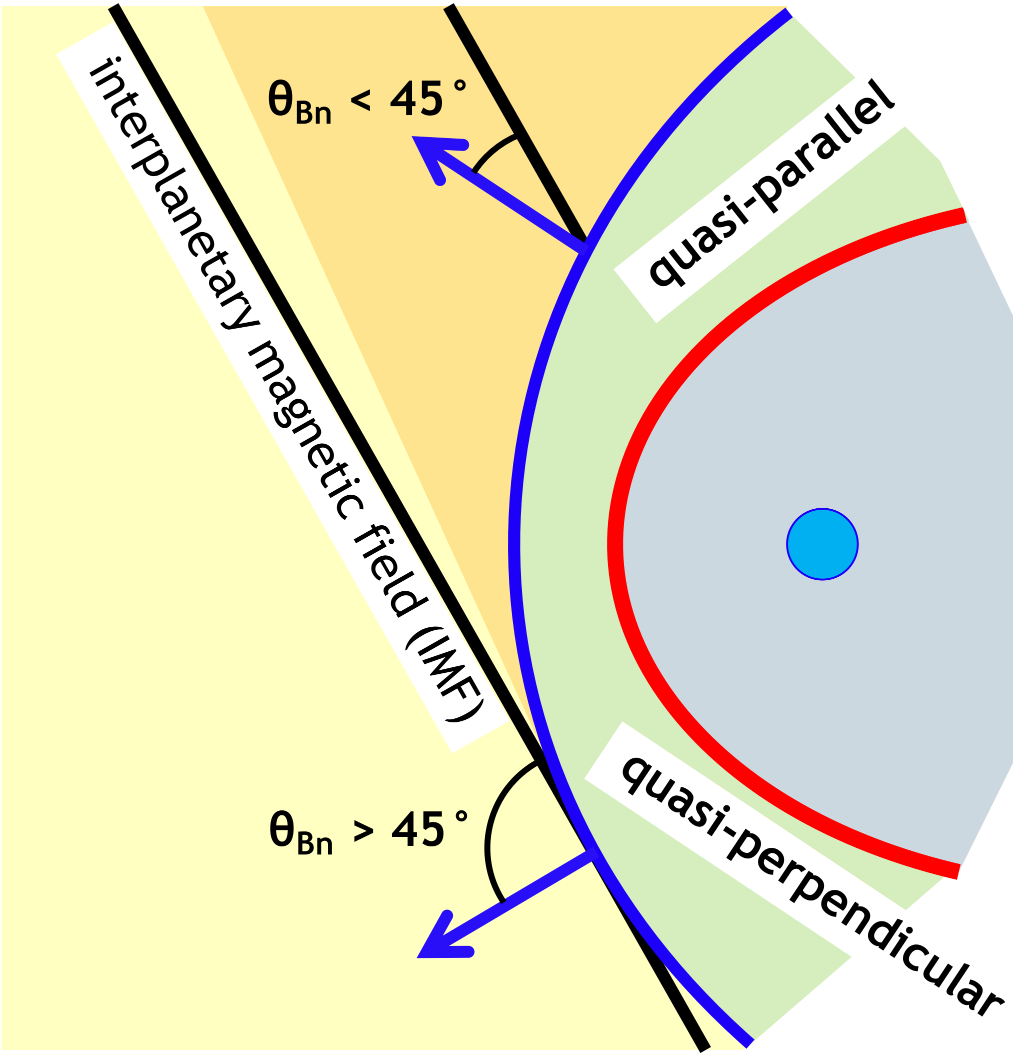
QUASI-PARALLEL AND QUASI-PERPENDICULAR



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OUTLINE

1. global structures
2. local processes
3. external transients

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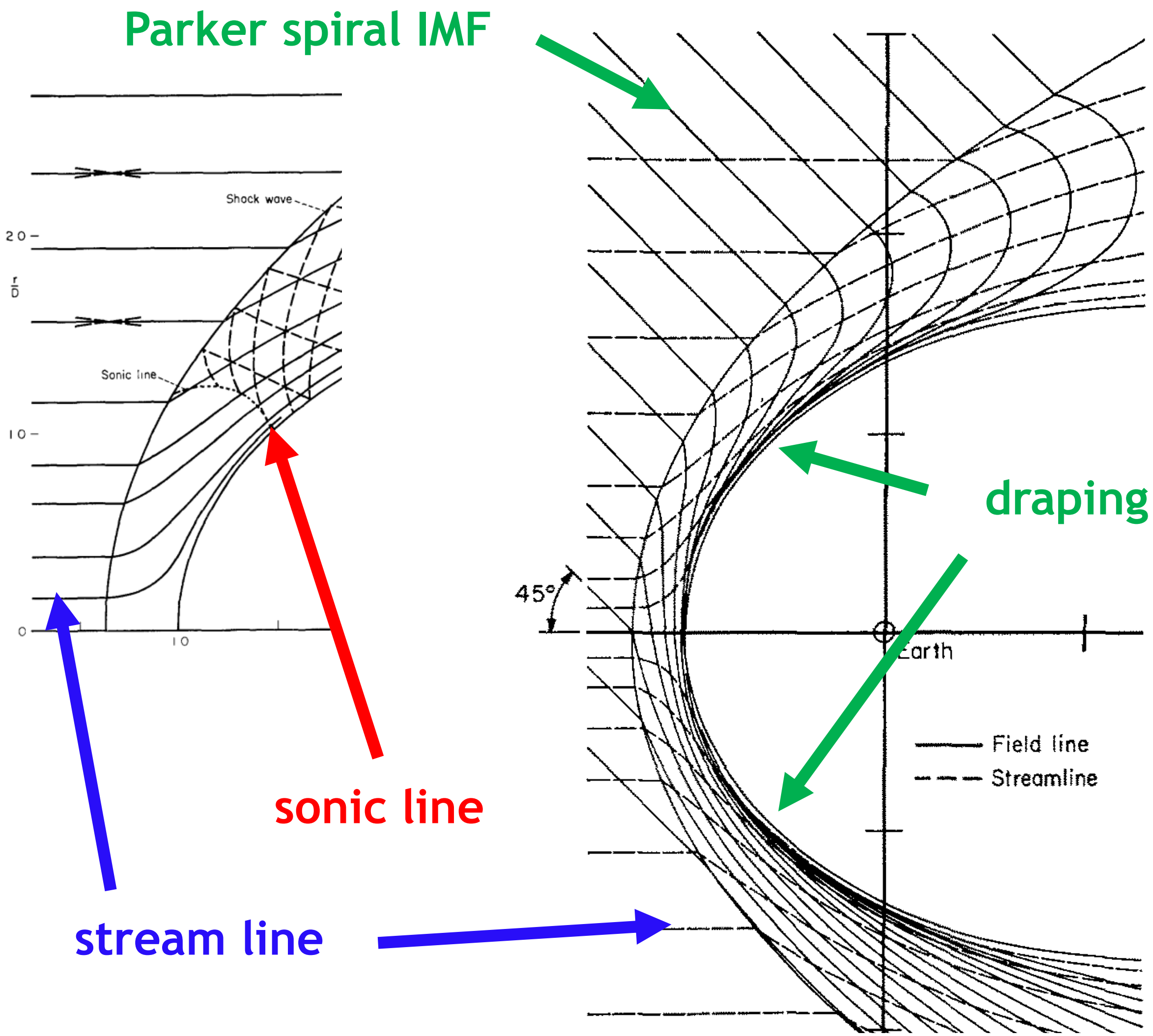
EARLY MODELLING

Spreiter et al. (1966)

- modelling of flow and shock wave:
  - gas dynamic theory (hydrodynamic)
- magnetopause:
  - tangential discontinuity
  - pressure balance
  - axisymmetric
  - field inside:
    twice the geomagnetic dipole field
- magnetic field:
  - frozen-in, added afterwards



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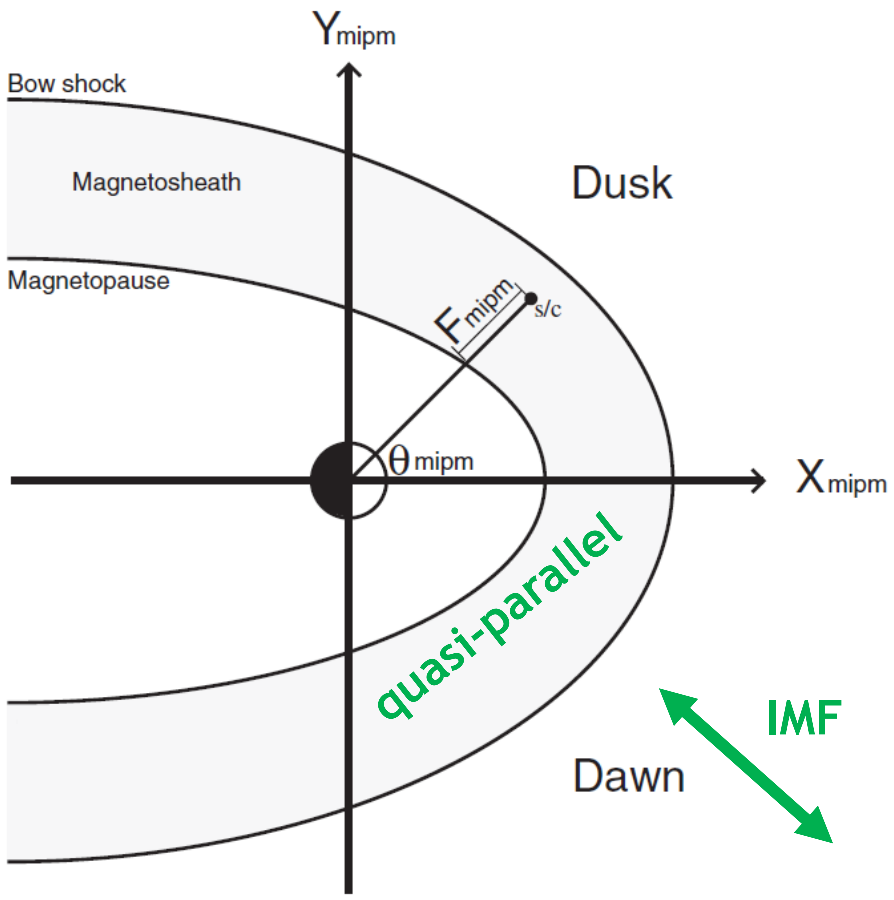
MAGNETOSHEATH INTERPLANETARY MEDIUM (MIPM) REFERENCE FRAME

- X:
  - against solar wind flow
  - aberrated Earth-Sun-line
- Y:
  - IMF in X-Y-plane
  - quasi-parallel on –Y side
- bow shock and magnetopause models
  - Verigin et al. (2001)
  - Shue et al. (1998)
- F:
  - radial fractional distance between boundaries



Dimmock and Nykyri (2013)

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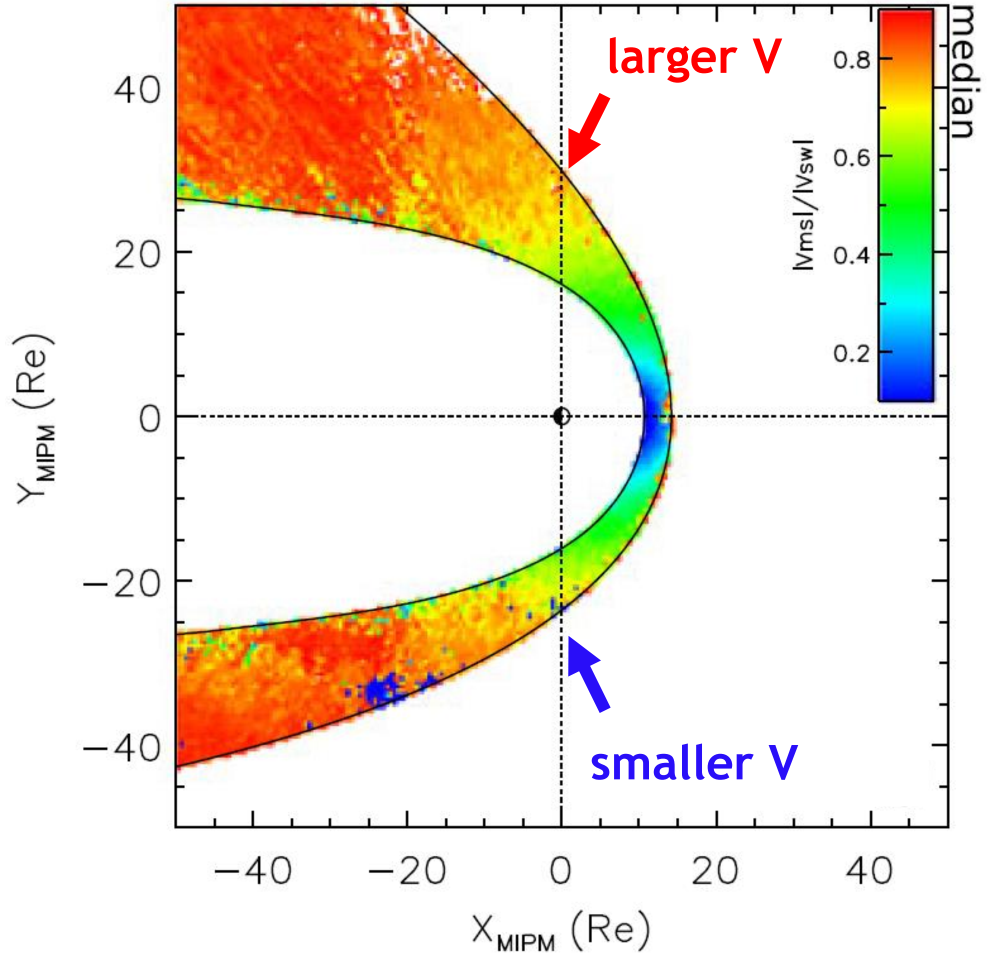
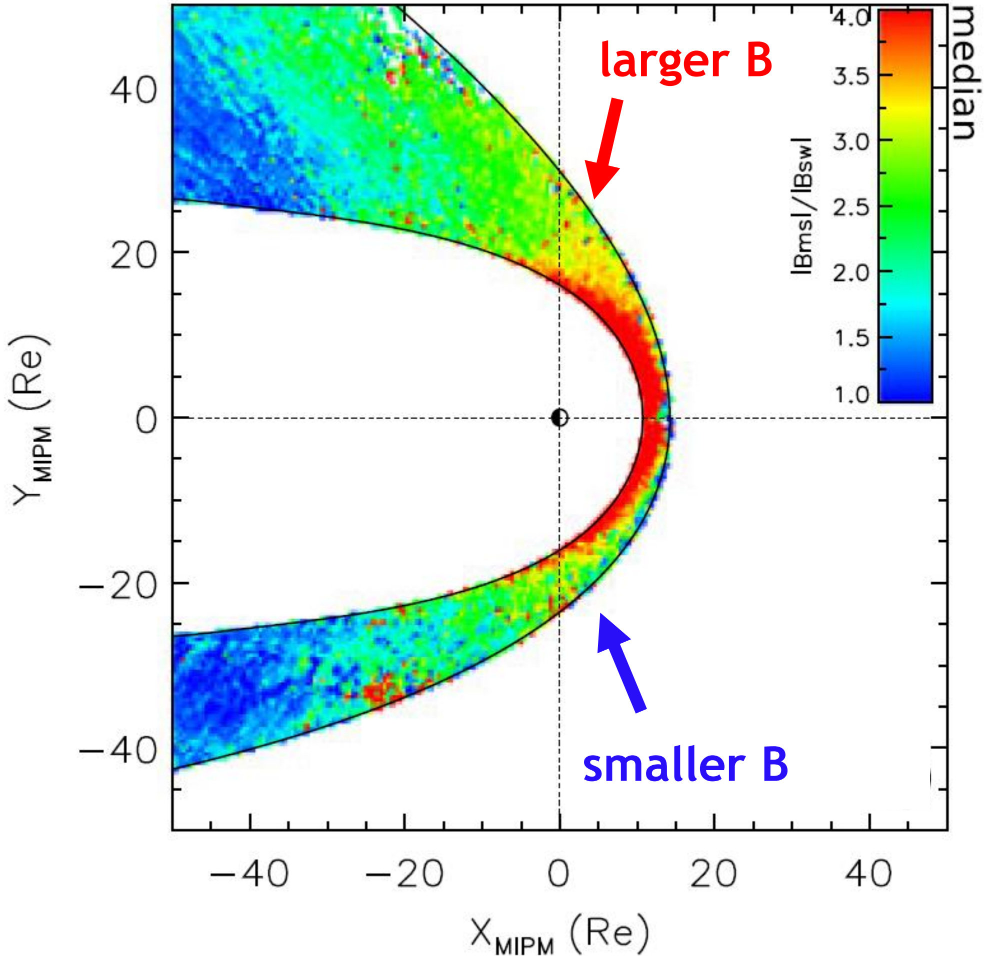
VELOCITY AND MAGNETIC FIELD





Dimmock and Nykyri (2013)

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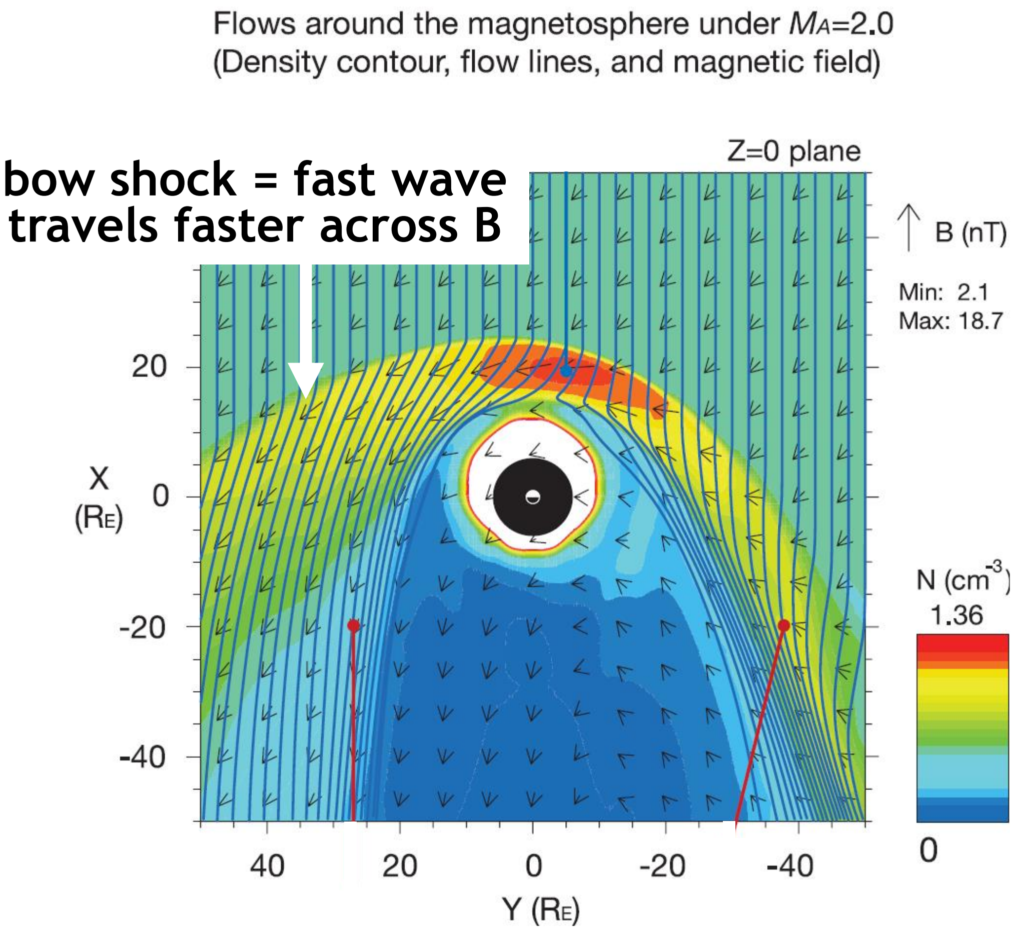
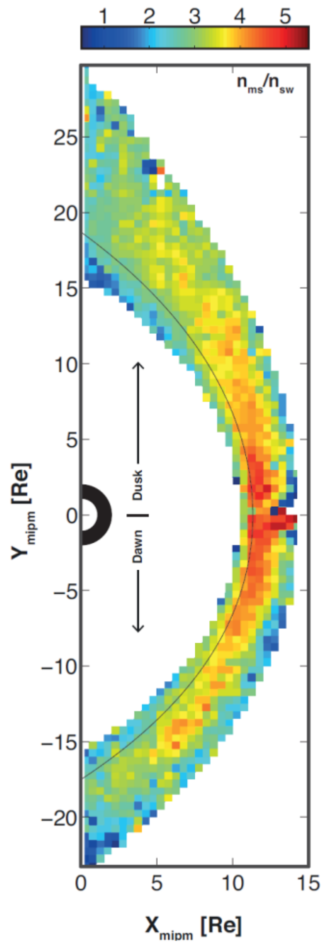
DENSITY, FLOW, AND THICKNESS ASYMMETRIES

- conditions
  - low Alfvén Mach number (M_A)
  - Parker spiral IMF conditions
- anomalous flow
  - duskward on dawn side
- density
  - maximum shifted towards dawn
- reason
  - Rankine-Hugoniot
  - kink of magnetic field at the BS, strong magnetic field effect at low M_A



Nishino et al. (2008)



Dimmock et al. (2016)

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FURTHER ASYMMETRIES

Dimmock et al. (multiple), Walsh et al. (2012), and **Walsh et al. (2014):**

Process/property	Asymmetry preference	Source	Reference
Ion density	dawn, 19 % higher	Theory	Walters (1964)
	dawn, 33 % higher	IMP-8 (1978–1980)	Paularena et al. (2001)
	dawn, 1 % higher	IMP-8 (1994–1997)	Paularena et al. (2001)
	dawn, 21 % higher	THEMIS (2008–2010)	Walsh et al. (2012)
	dawn higher	Cluster (2001–2004)	Longmore et al. (2005)
$\mid B \mid$	dusk, 23 % higher	THEMIS (2008–2010)	Walsh et al. (2012)
T_i (ion temperature)	dawn, 33 % higher	Theory	Walters (1964)
	dawn, 12 % higher	THEMIS (2008–2010)	Walsh et al. (2012)
δB (magnetic field jump)	dawn higher	IMP-4 (1967)	Fairfield and Ness (1970)
	higher at $Q_\parallel$ side	ISEE-2 (1977–1979)	Luhmann et al. (1986)
	higher at $Q_\parallel$ side	INTERBALL+Cluster (1996–2003)	Shevyrev et al. (2007)
Magnetic field turbulence	higher at $Q_\parallel$ side	Geotail (1996–2005)	Petrinec (2013)
Mirror mode occurrence	more frequent at $Q_\perp$	Cluster (2001–2005)	Génot et al. (2009)
Kinetic wave occurrence	91 % at $Q_\perp$, 40 % at $Q_\parallel$	AMPTE CCE (1984)	Anderson and Fuselier (1993)

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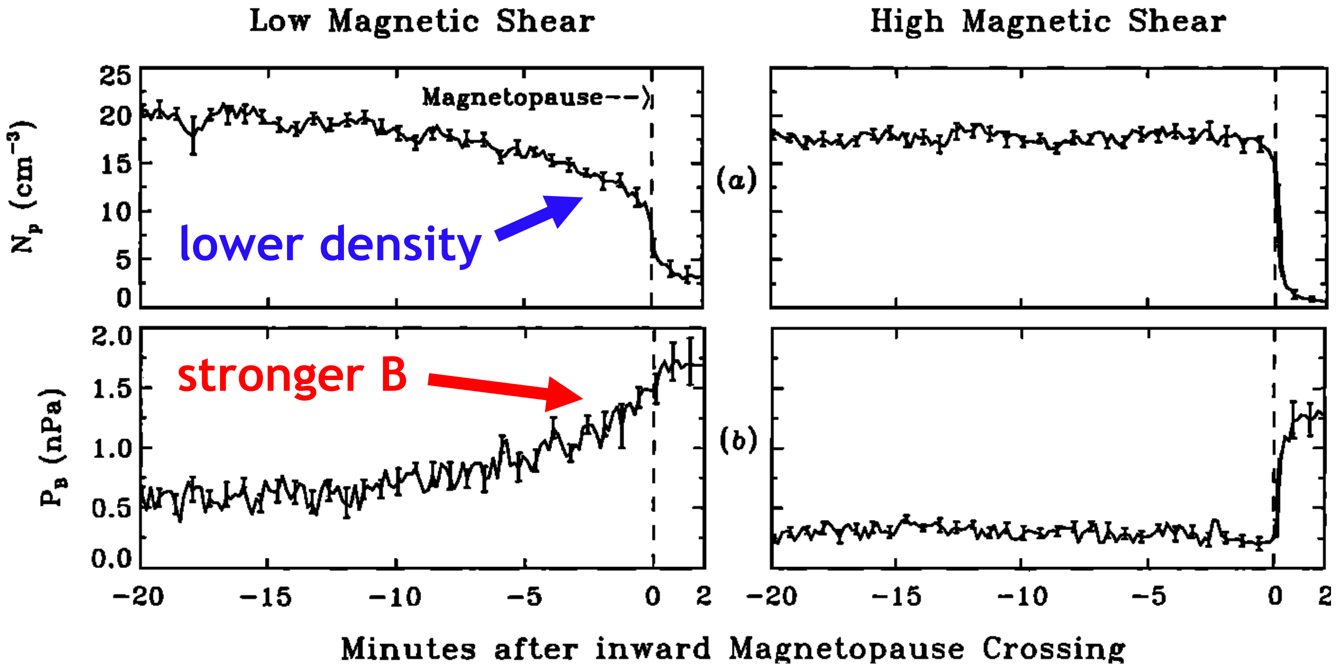
PLASMA DEPLETION LAYER (PDL)

- conditions
  - strongly northward IMF
  - effect enhanced during low M_A

- observations
  - plasma-depleted flux tubes piled-up against magnetopause
  - strong acceleration on the flanks due to magnetic pressure gradient and magnetic tension forces



Phan et al. (1994)

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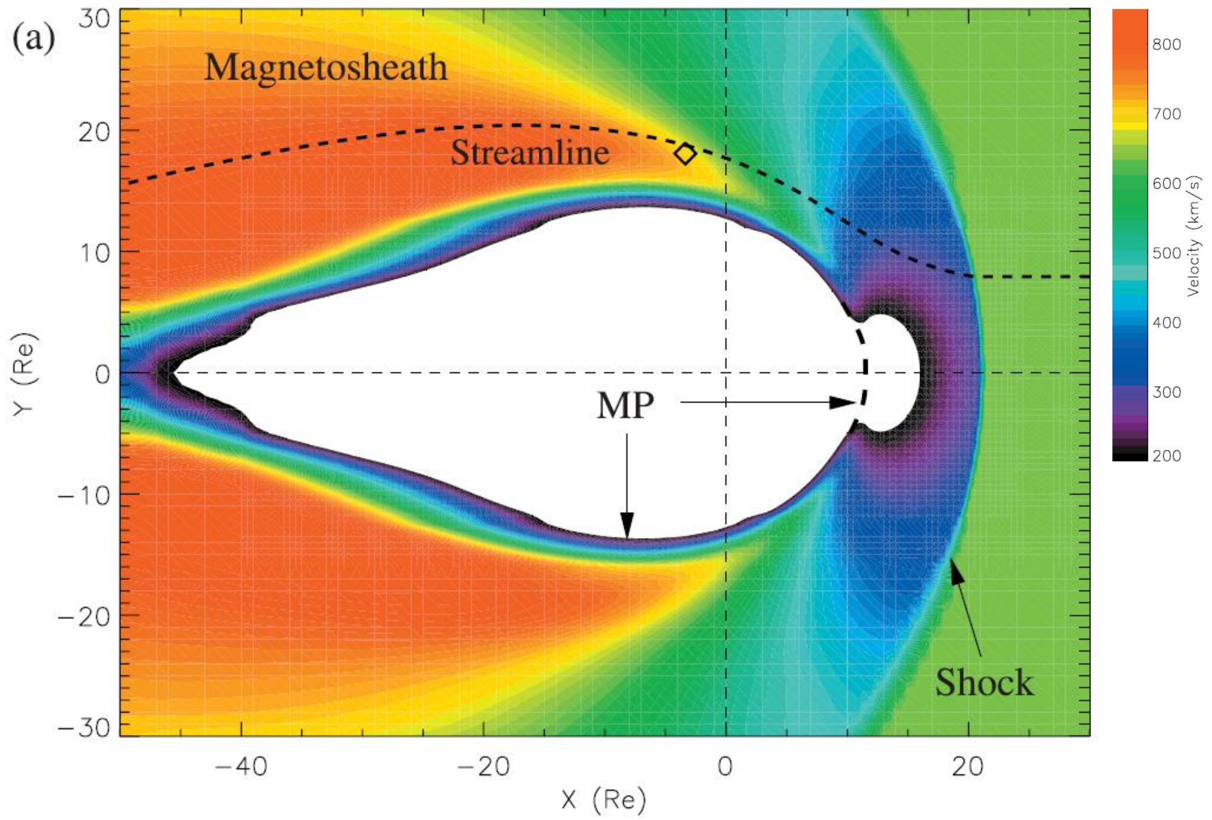
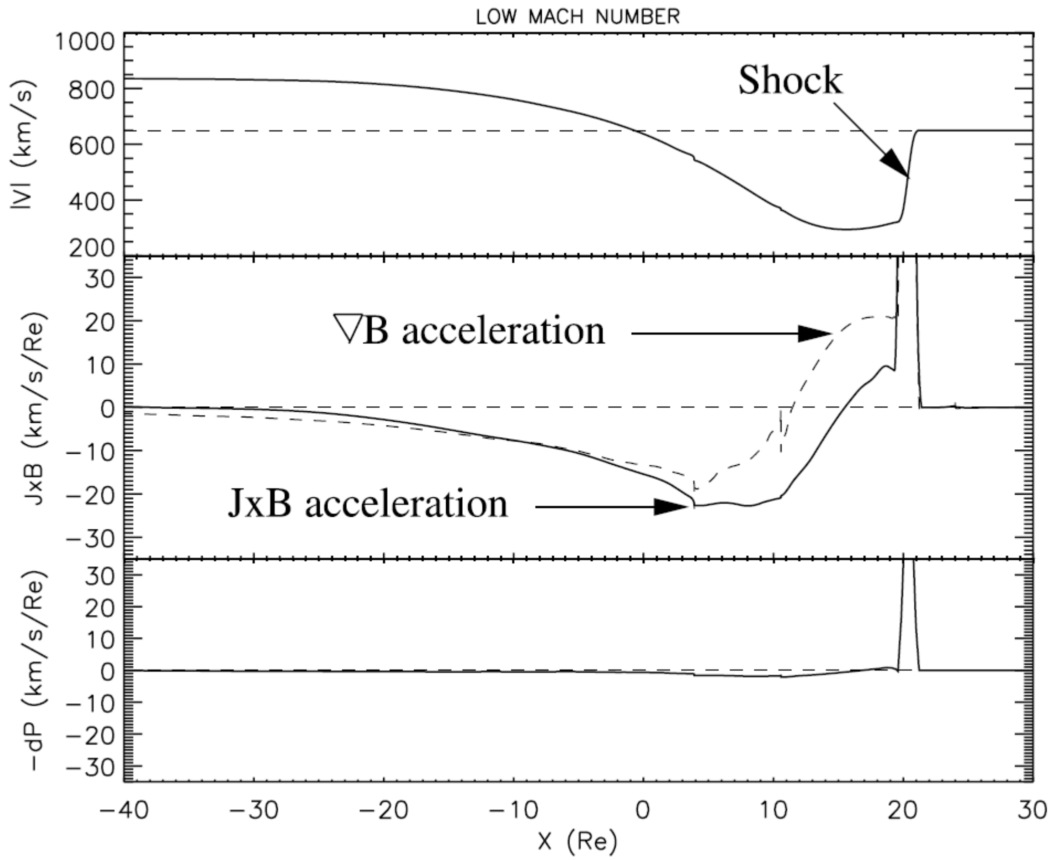
ACCELERATION ALONG FLANKS





Lavraud et al. (2007)

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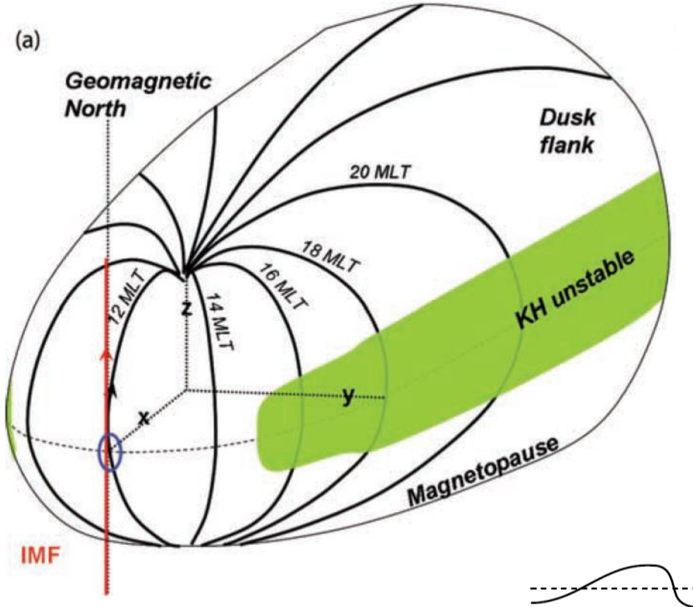
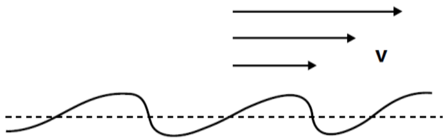
IMPLICATIONS FOR MAGNETOPAUSE WAVES

enhanced Kelvin-Helmholtz instability (KHI)

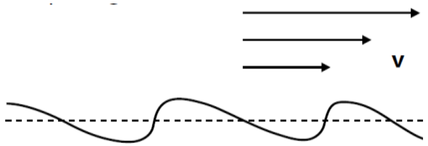
$$[\mathbf{k}.(\mathbf{V}_1 - \mathbf{V}_2)]^2 > \frac{n_1 + n_2}{\mu_0 m_p n_1 n_2}\left[(\mathbf{k}.\mathbf{B}_1)^2 + (\mathbf{k}.\mathbf{B}_2)^2\right]$$

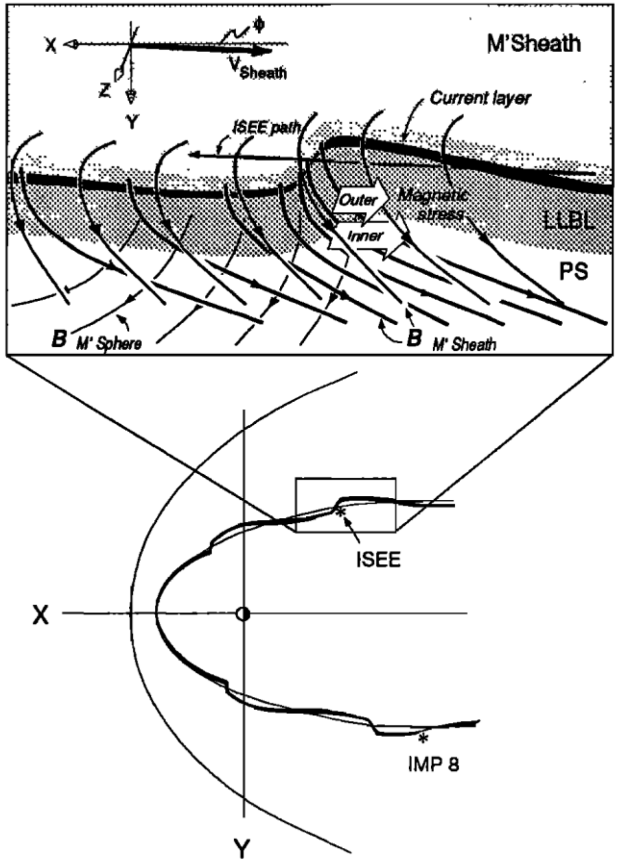




Foullon et al. (2008)

also related to inverse wave steepening





Chen and Kivelson (1993)

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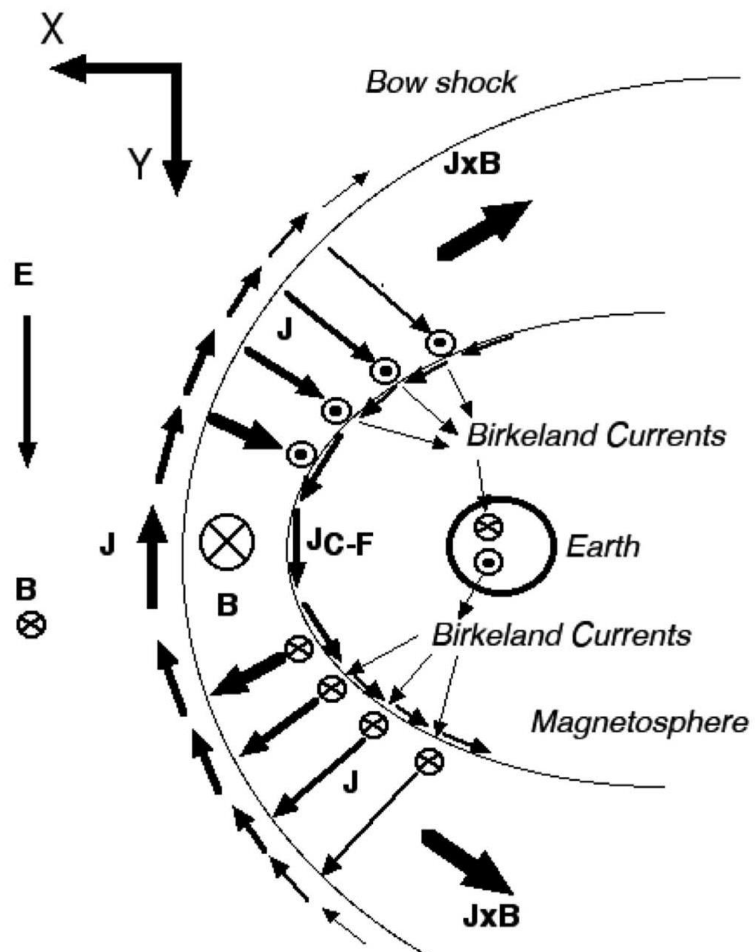
CURRENT CLOSURE THROUGH THE MAGNETOSHEATH

Lopez et al. (2010), Hamrin et al. (2018)

- increasing southward IMF
  - ionospheric potential generated by reconnection increases
- above certain IMF magnitude:
  - saturation reached
  - increased JxB flow deflection becomes dominant over grad(P)
  - decrease in SW geoeffective length
    - limit to global reconnection rate



Lopez et al. (2010)

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   - PDL
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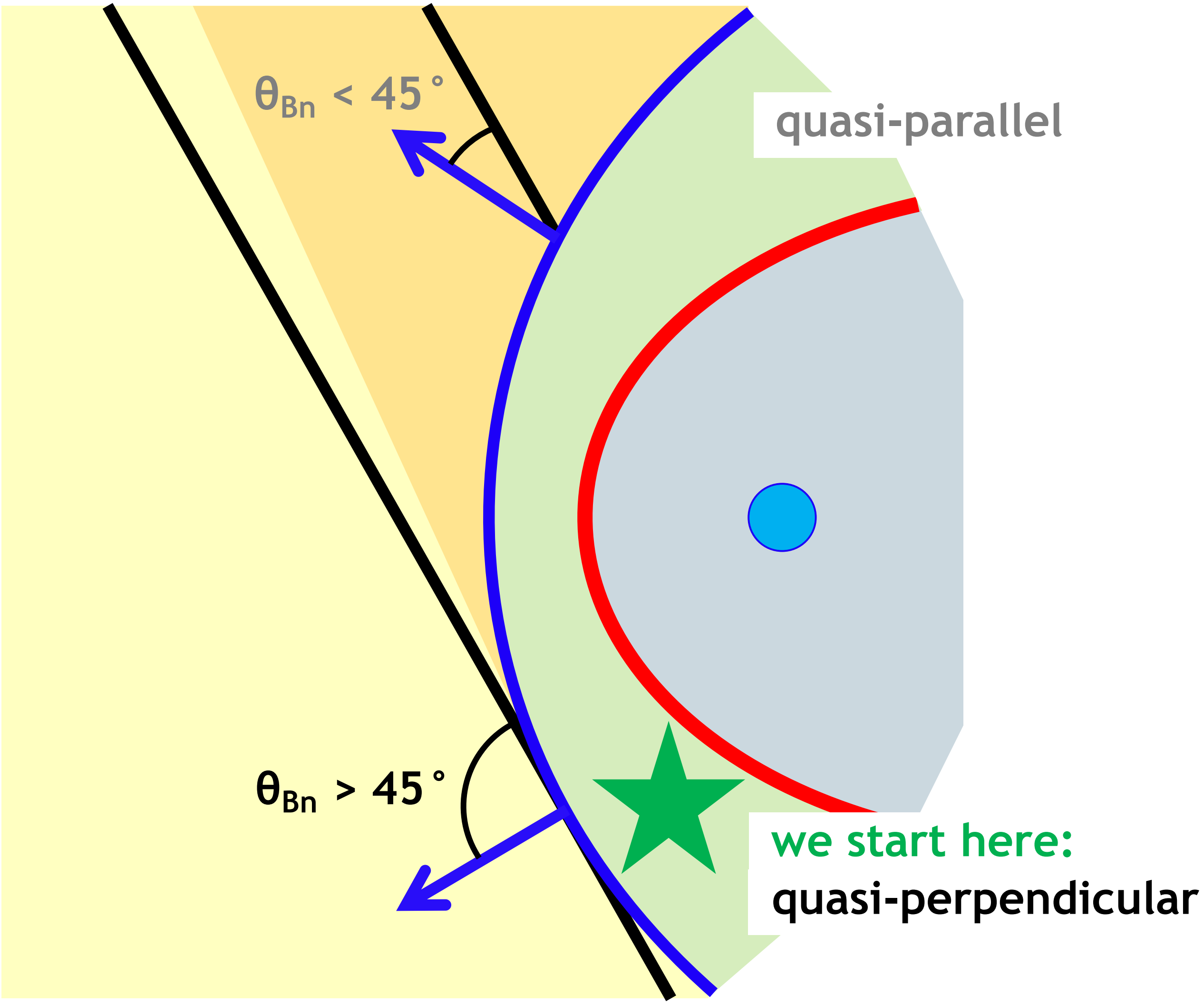
ION TEMPERATURE ANISOTROPY

- ion T anisotropy: $T_{perp} > T_{para}$



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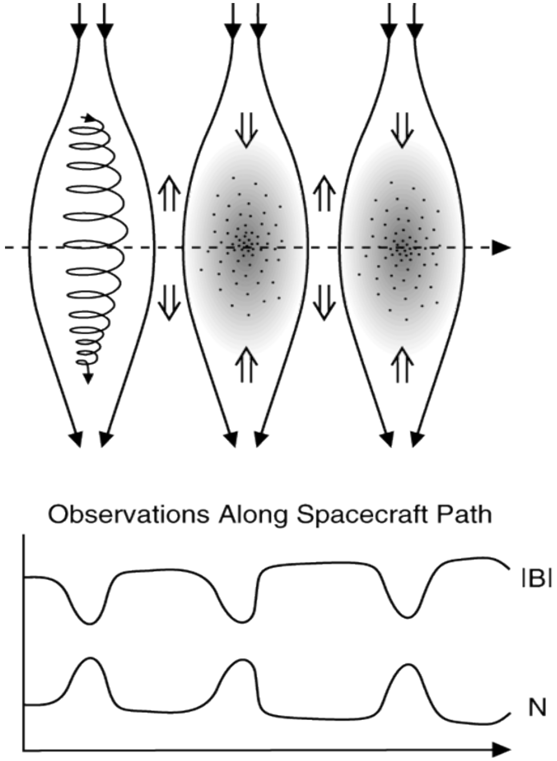
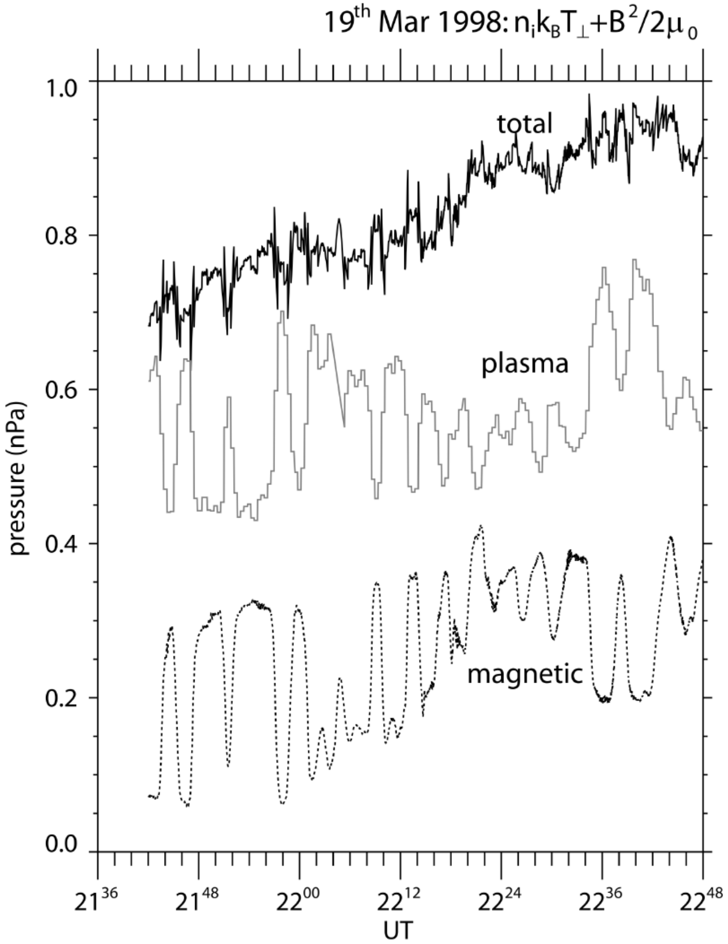
MIRROR MODES

- ion T anisotropy:
  $T_{perp} > T_{para}$
  - high beta: mirror modes
    - spatially periodic pattern of "magnetic bottles"
    - B and n anti-correlated, slow-mode type disturbance, pressure balance
    - no motion in plasma rest frame
    - size: several ion gyroradii, hundreds of km
  - Laitinen et al. (2010):
    - modulation of MP reconnection by mirror modes (beta variations)

$$\frac{T_\perp}{T_\parallel} > 1 + \frac{1}{\beta_\perp}$$



Treumann and Baumjohann (1996)



Rae et al. (2007)

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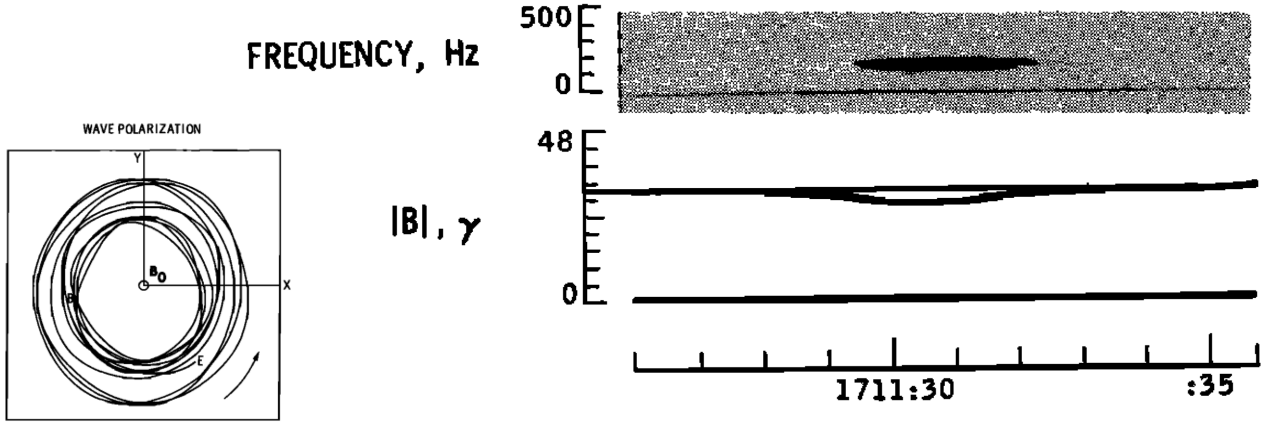
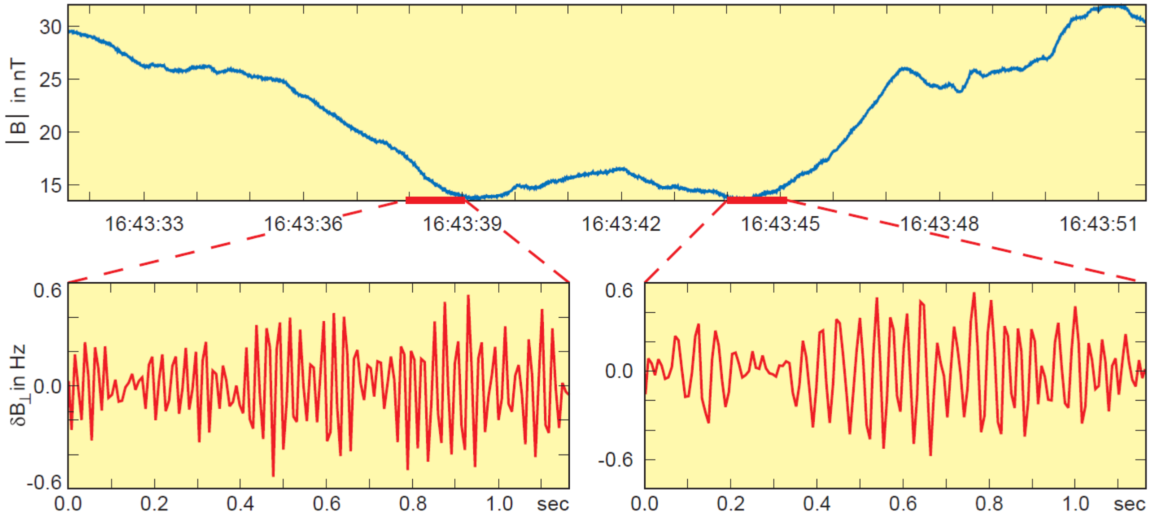
INSIDE MIRROR MODES: LION ROARS

- lion roars
  - whistler waves
  - right-hand polarized EM waves in the plasma rest frame
  - propagate parallel to B
  - correlate with decreases in B
  - bursts/packets ~1s
  - amplitudes ~0.1nT
  - frequencies ~100Hz
    - fraction of electron cyclotron frequency
  - caused by …
    - electron temperature anisotropy?
    - electron heat flux?



Smith and Tsurutani (1976)



Baumjohann et al. (1999)

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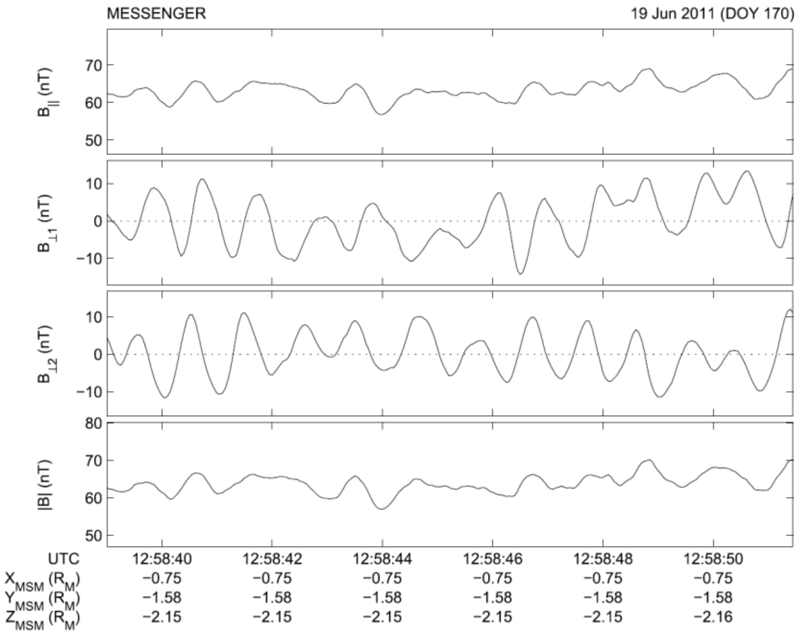
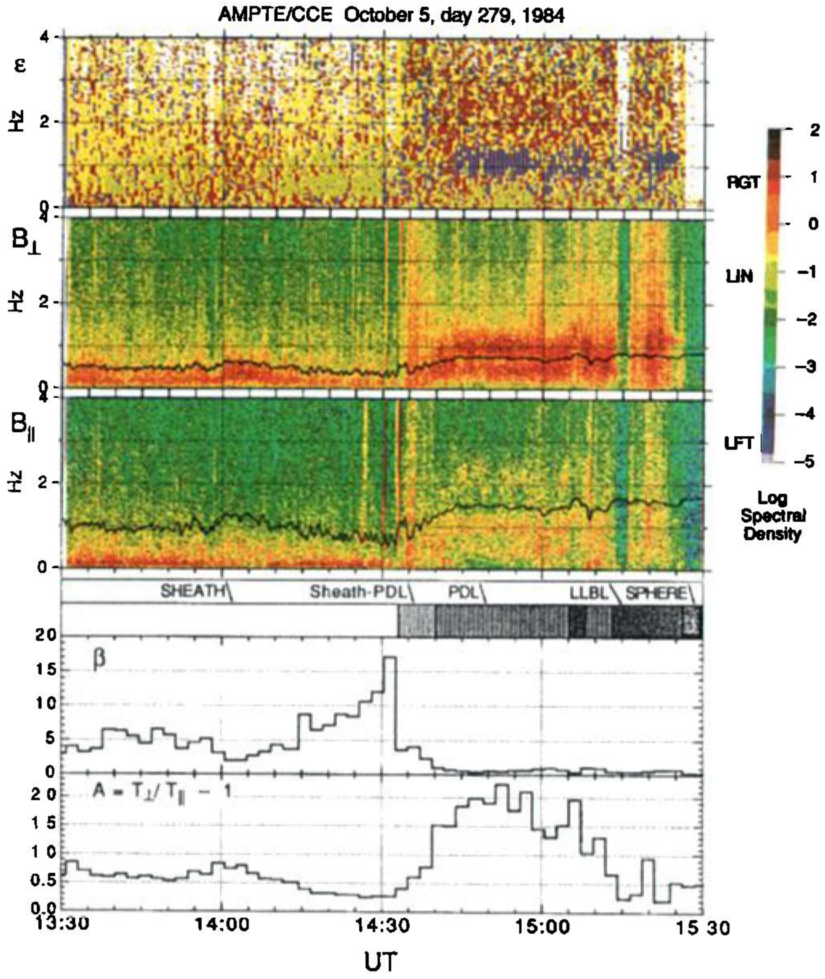
ION CYCLOTRON WAVES

- ion T anisotropy:
  $T_{perp} > T_{para}$
  - low beta: ion cyclotron waves
    - transverse left-hand circularly polarized waves
    - below ion cyclotron frequency in plasma frame
    - parallel to B
  - EMIC waves in PDL
    - B compression
    - T anisotropy



Sundberg et al. (2015)



Anderson et al. (1991)

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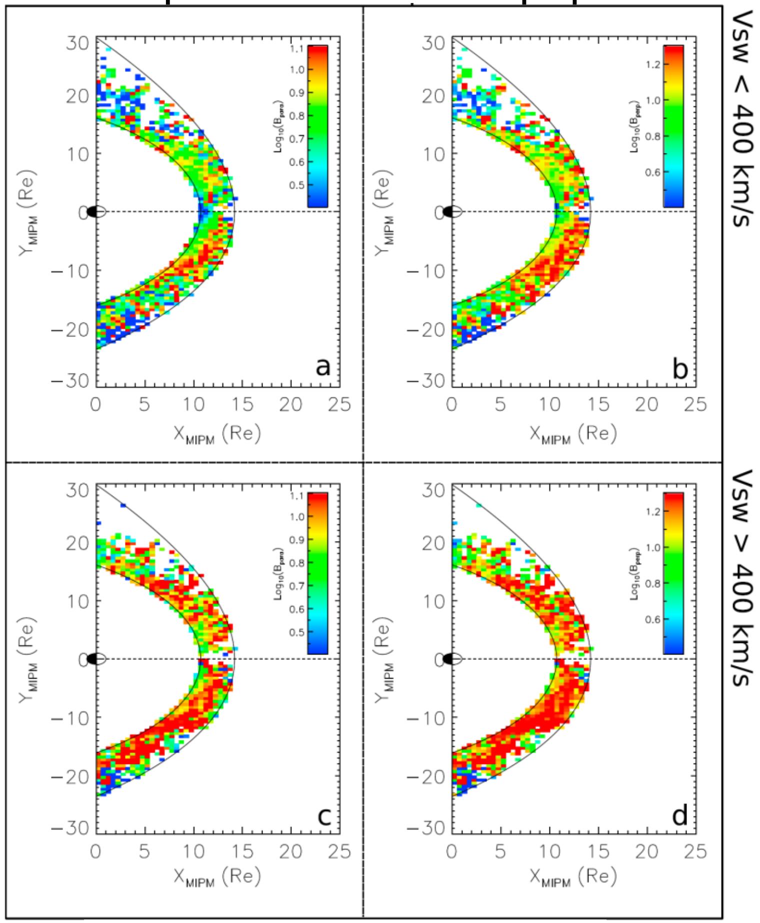
TURBULENT FLUCTUATIONS

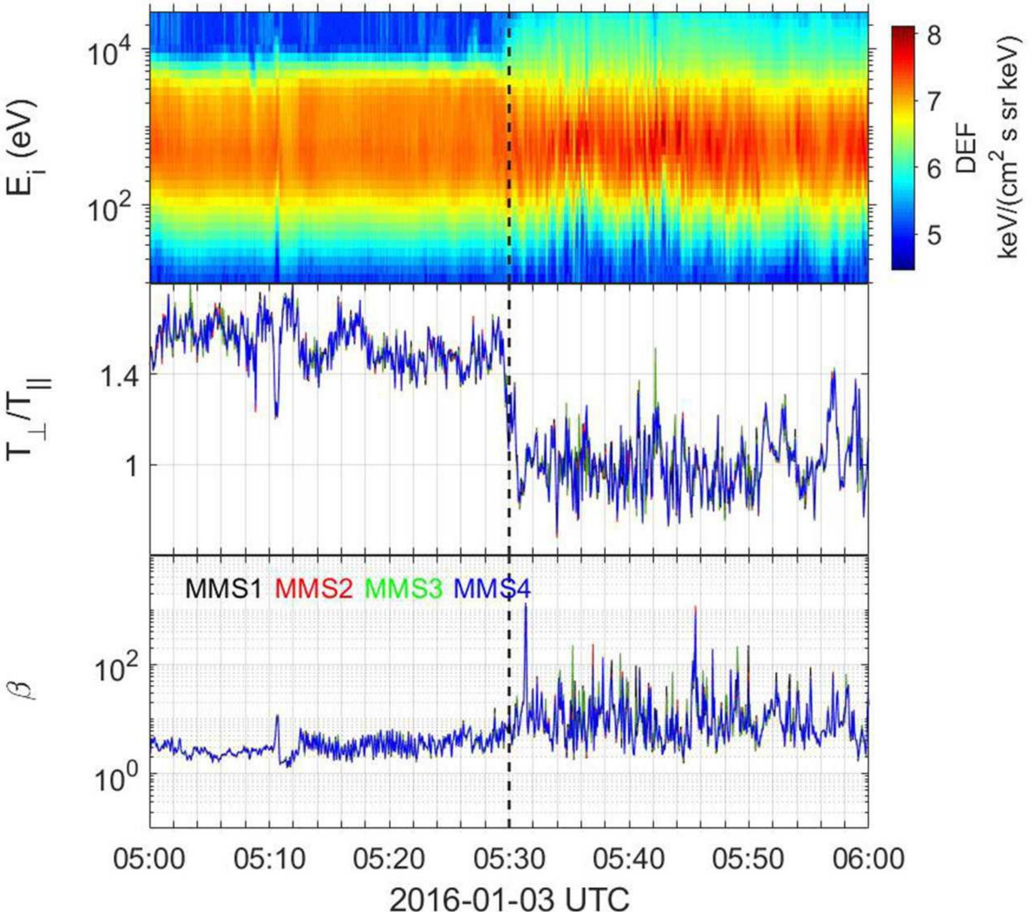
fluctuations: 0.1 - 2 Hz

compressional: B_{para} transverse: B_{perp}



Dimmock et al. (2014)

quasi-perpendicular quasi-parallel



Yordanova et al. (2020)

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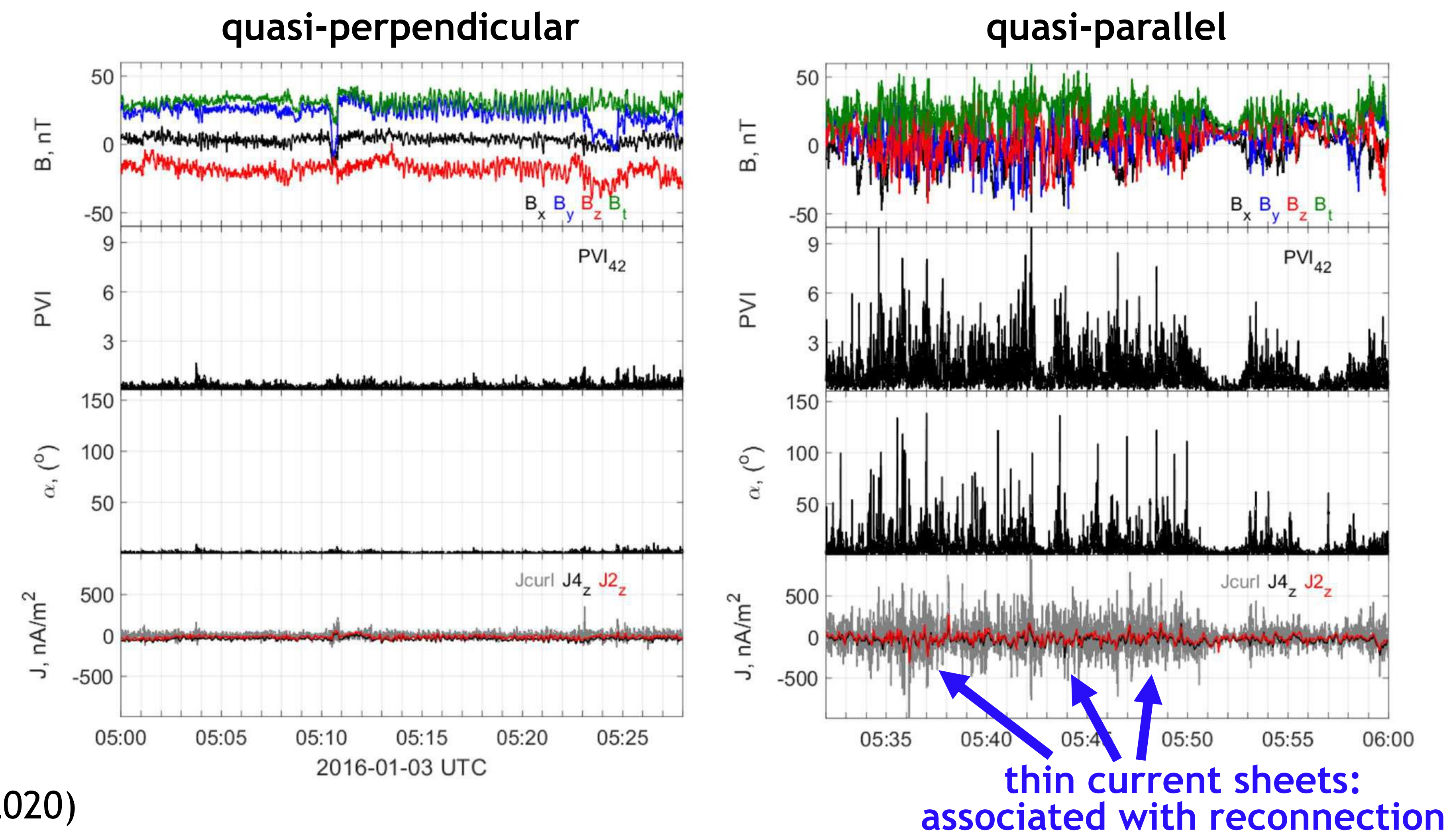
TURBULENT FLUCTUATIONS

partial variance of increments:

$$PVI_{ij}(t) = \sqrt{\frac{|\Delta \boldsymbol{B}_{ij}(t)|^2}{\langle|\Delta \boldsymbol{B}_{ij}|^2\rangle}}$$

field rotation between S/C:



Yordanova et al. (2020)

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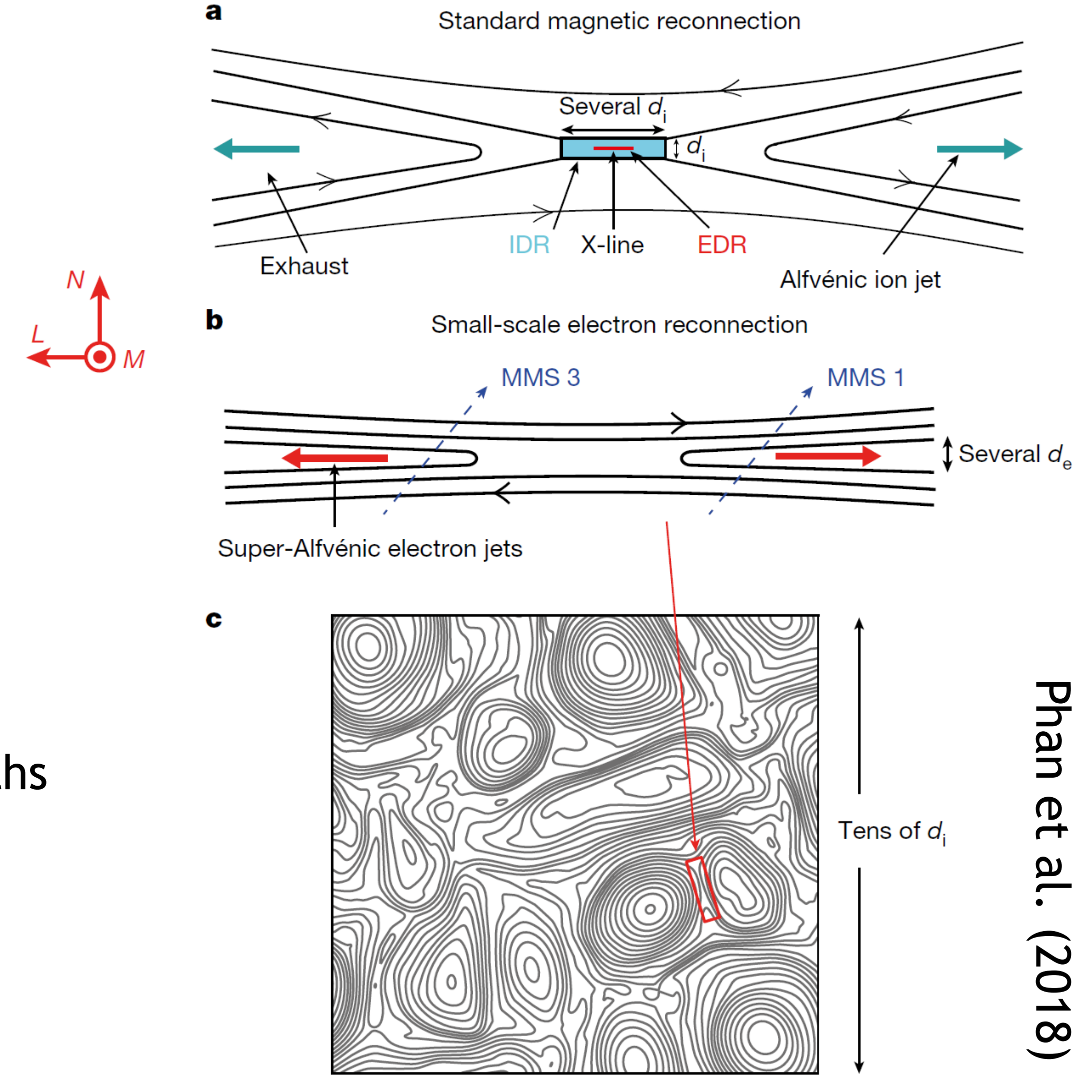
RECONNECTION AT THIN CURRENT SHEETS

- Cluster observations
  - Retino et al. (2007)
    - current sheet scale: ion inertial length d_i = 1s = 100km
    - in situ evidence of reconnection and crossing of the ion diffusion region
- MMS observations
  - Vörös et al. (2017)
  - Phan et al. (2018): electron-only reconnection
    - current sheet scale: few electron inertial lengths 4 d_e = 45ms = 4km
    - intense electron outflow and current
    - J*E‘ > 0
    - no ion-scale current layer, no ion jets



Phan et al. (2018)

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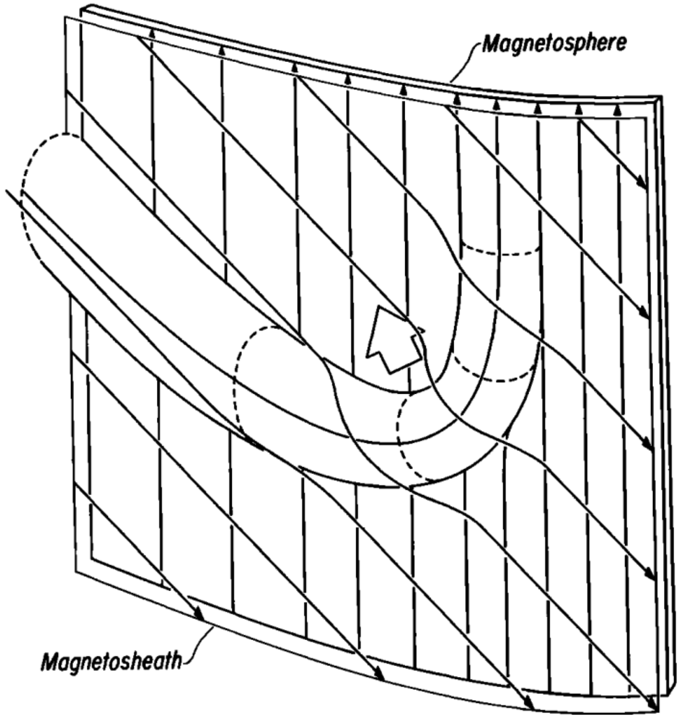
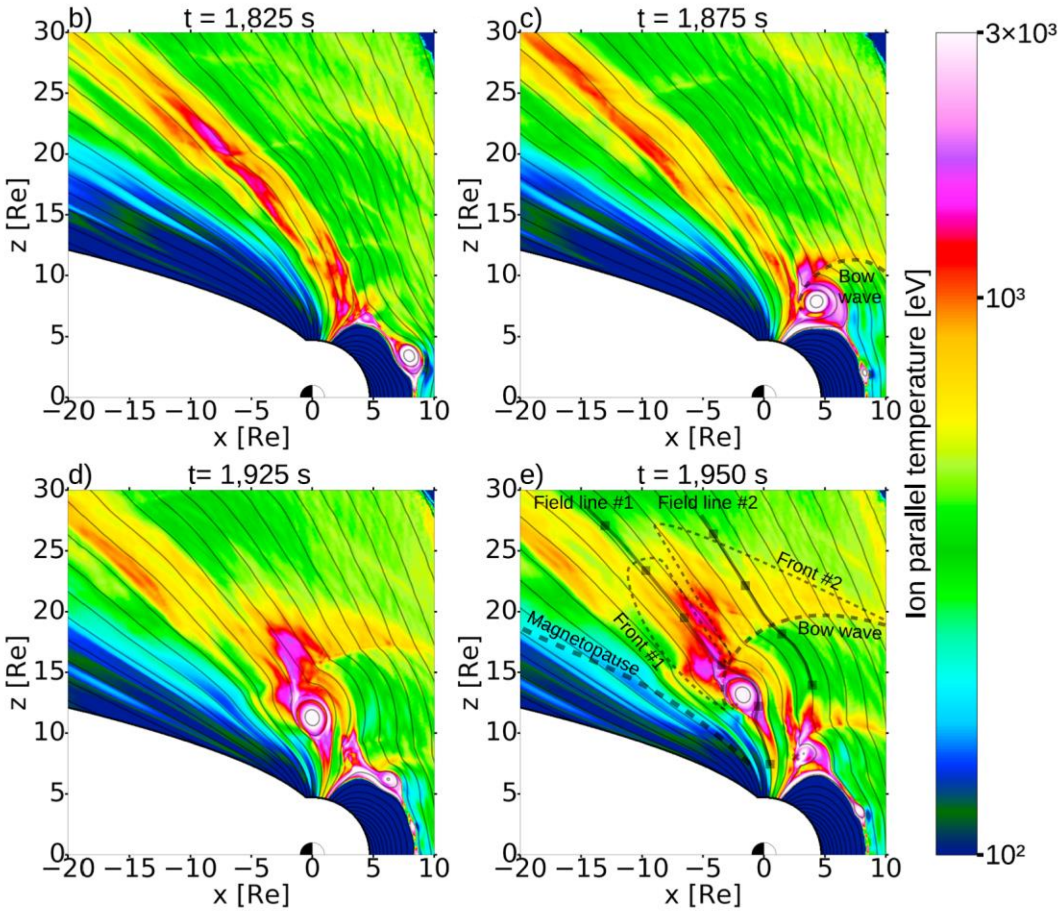
FLUX TRANSFER EVENTS

- flux transfer events
  - drive fast mode bow waves
  - accelerate ions to 30 keV
  - time-energy dispersive ion signatures



Russell and Elphic (1979)



Jarvinen et al. (2018)

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OUTLINE

1. global structures
   - distributions
   - asymmetries
   - PDL
   - currents

2. local processes
   - mirror modes
   - lion roars
   - ion cyclotron waves
   - turbulence
   - reconnection
   - FTE bow waves

3. external transients

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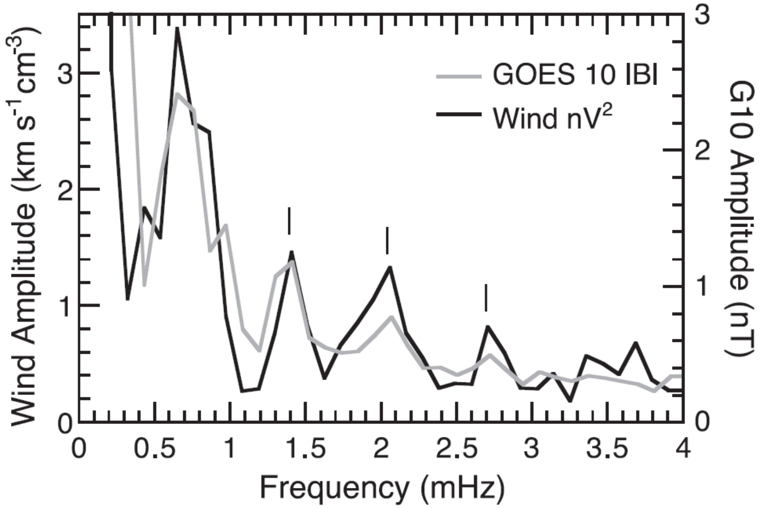
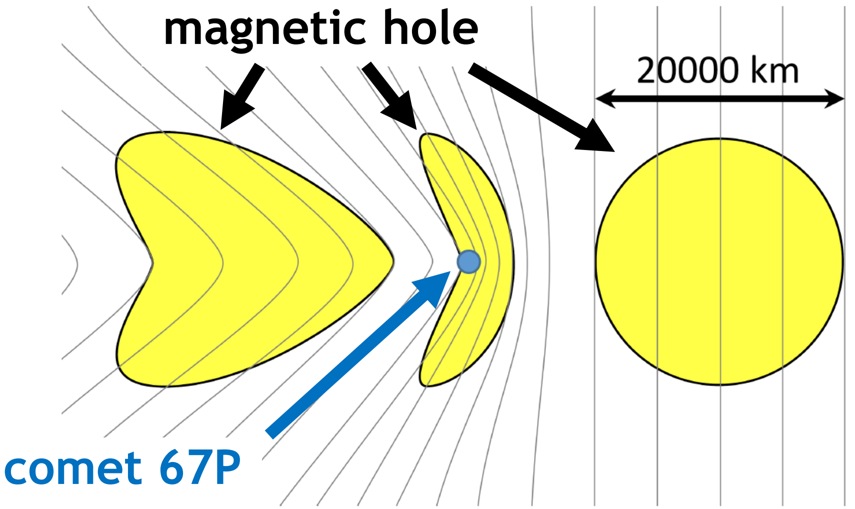
SOLAR WIND VARIATIONS

- IMF variations
  - change in foreshock location
  - MP expanded downstream of Q-para shock: e.g., Suvorova et al. (2010)
- pressure variations
  - single pulse: e.g., Sibeck (1990)
  - periodic, 5 – 15 minute periods, e.g. Sibeck et al. (1989), Kepko et al. (2002)
- CME magnetic clouds
  e.g., Turc et al. (2013, 2014, 2017)
- SW magnetic holes
  e.g., Karlsson et al. (2015), Plaschke et al. (2018)



Kepko et al. (2002)



Plaschke et al. (2018)

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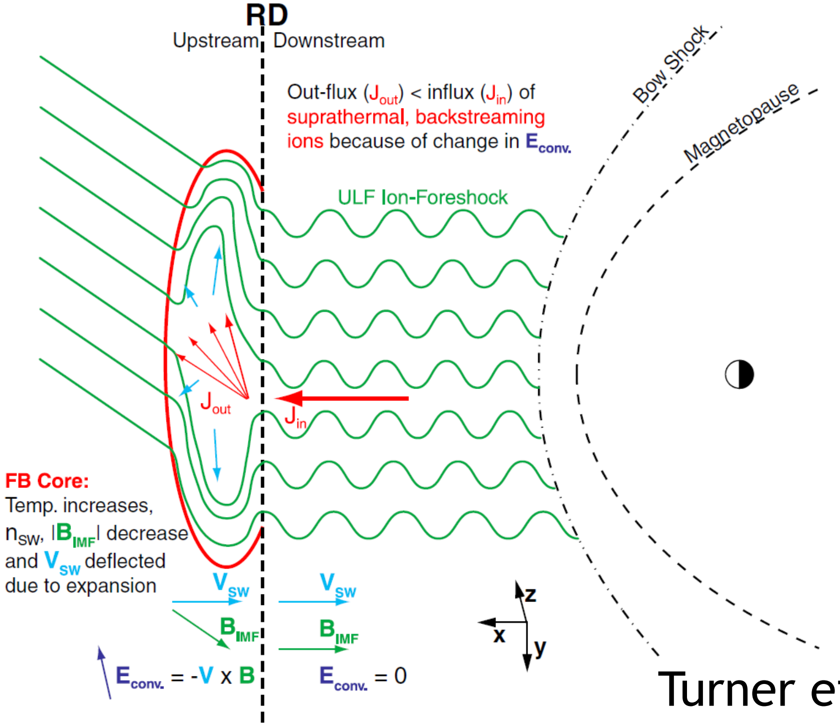
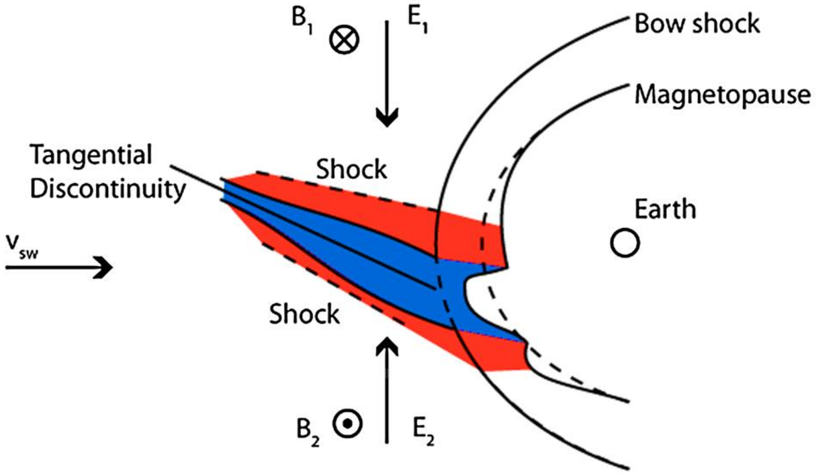
FORESHOCK TRANSIENTS

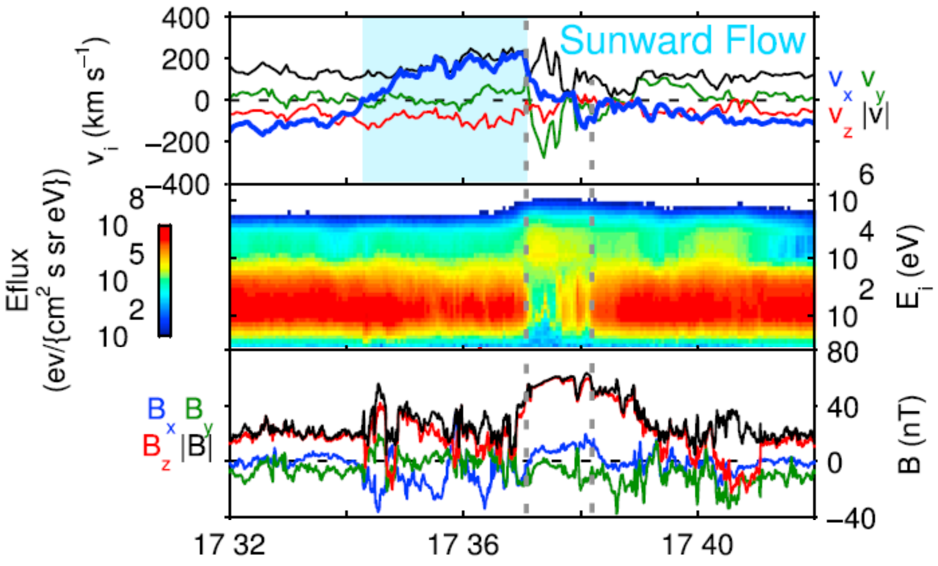
- hot flow anomalies (HFAs) and foreshock bubbles (FBs)
  - hot, tenuous plasma inside
  - can cause severe pressure disturbances in the magnetosheath



Turner et al. (2013)



Eastwood et al. (2015)



Archer et al. (2014)

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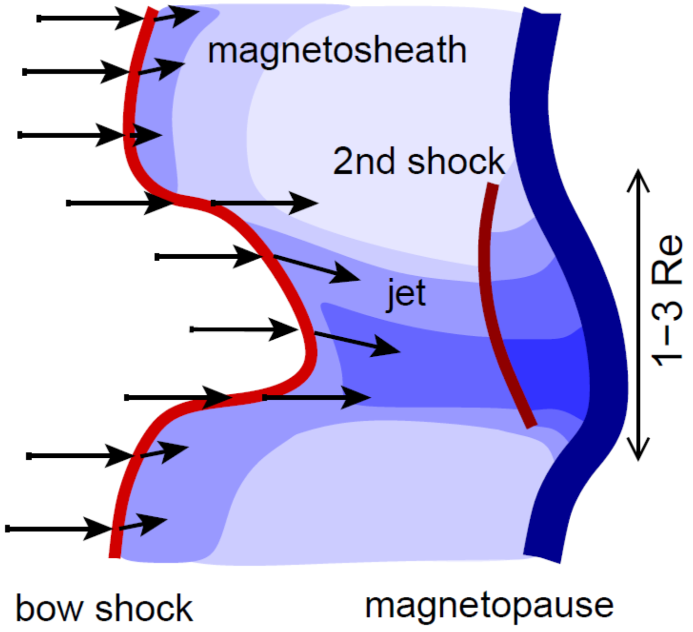
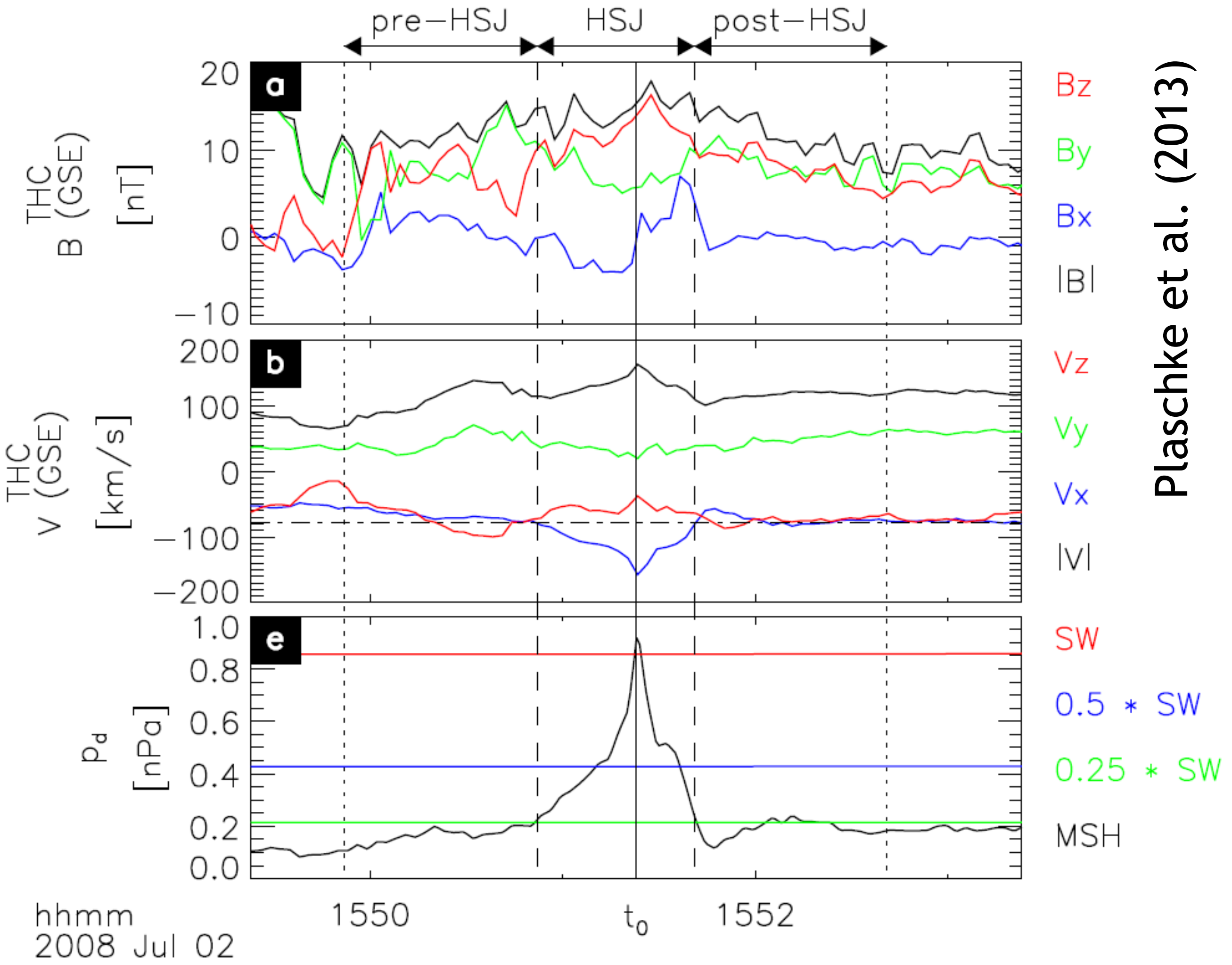
HIGH-SPEED JETS

- high-speed jets
  - local enhancements in dynamic pressure
  - occurrence mainly in quasi-parallel magnetosheath, downstream of an undulated shock

Hietala et al. (2012)





Plaschke et al. (2013)

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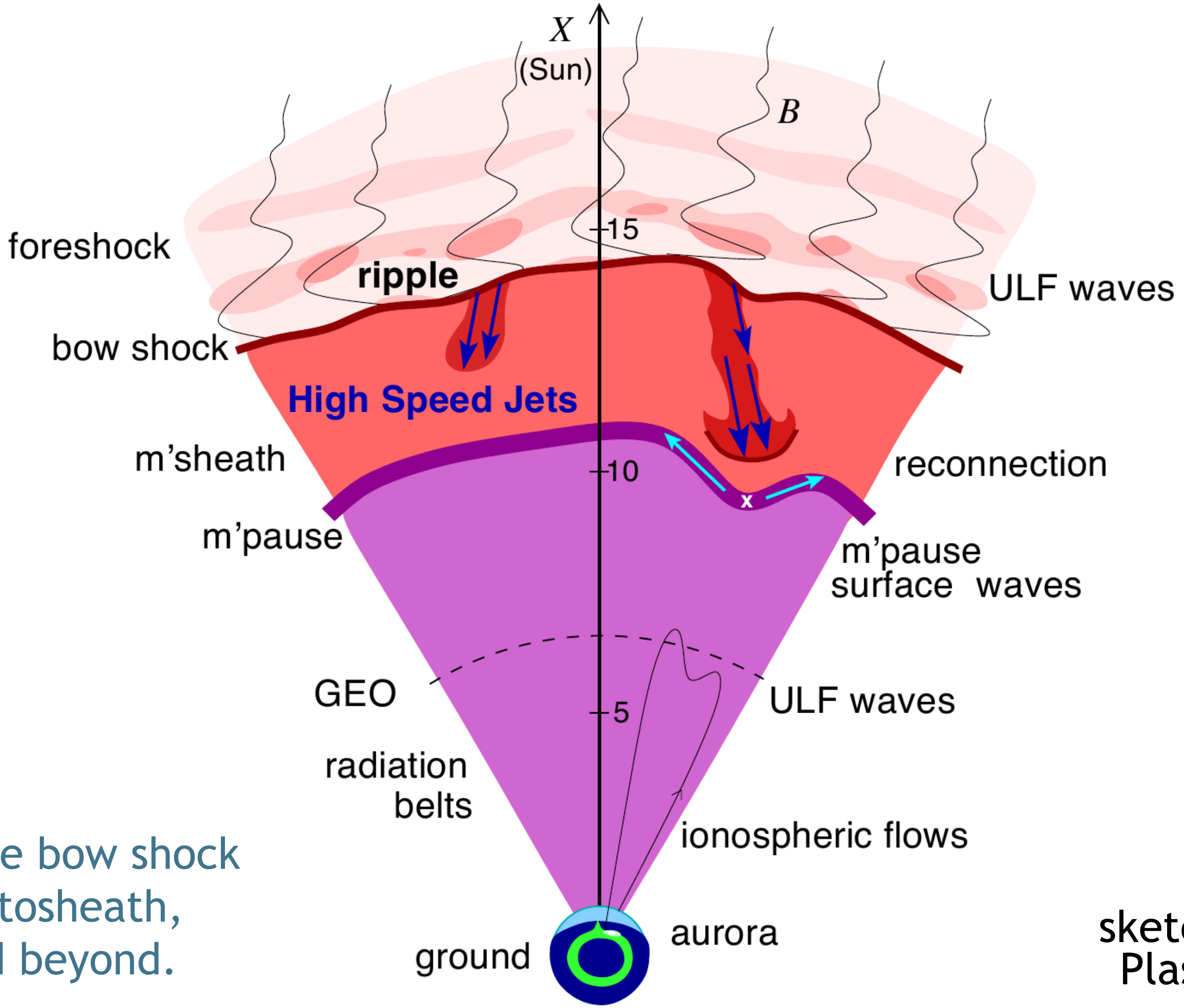
HIGH-SPEED JETS



Jets connect processes
in the foreshock and at the bow shock
with effects in the magnetosheath,
at the magnetopause, and beyond.

sketch by H. Hietala in
Plaschke et al. (2018)

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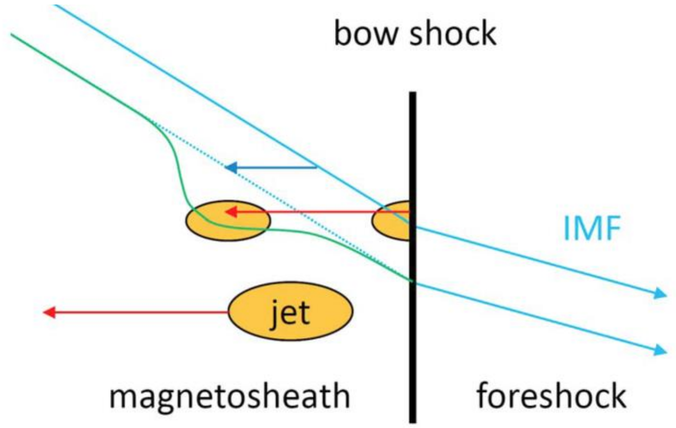
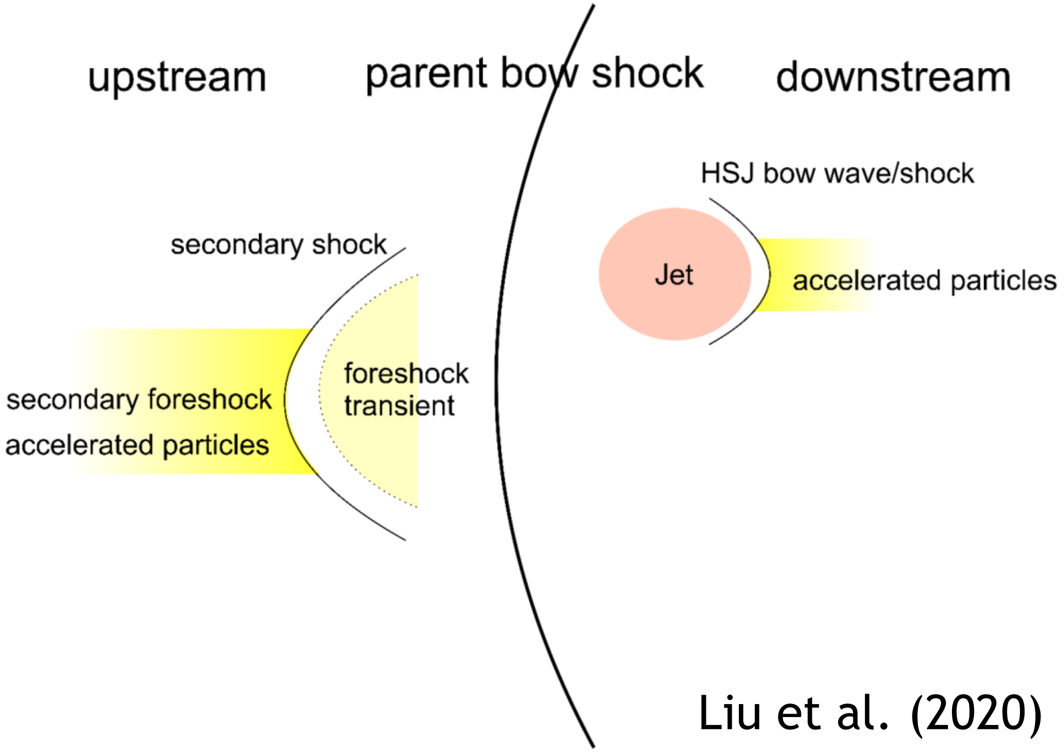
JET INTERACTION WITH AMBIENT PLASMA

jets modify/straighten magnetic fields

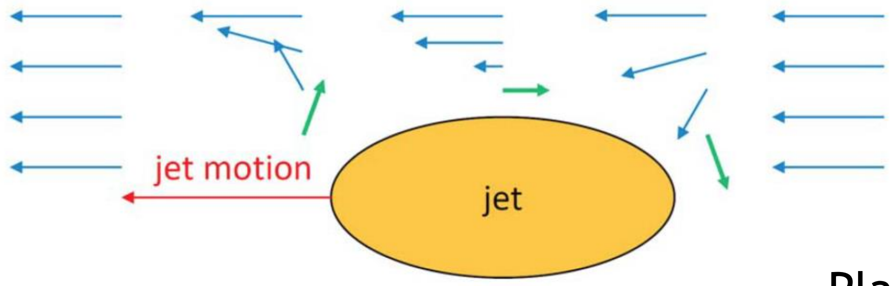


jets accelerate particles at jet-driven bow waves



Liu et al. (2020)

jets cause vortical motion of plasma



Plaschke et al. (2017, 2018, 2020)

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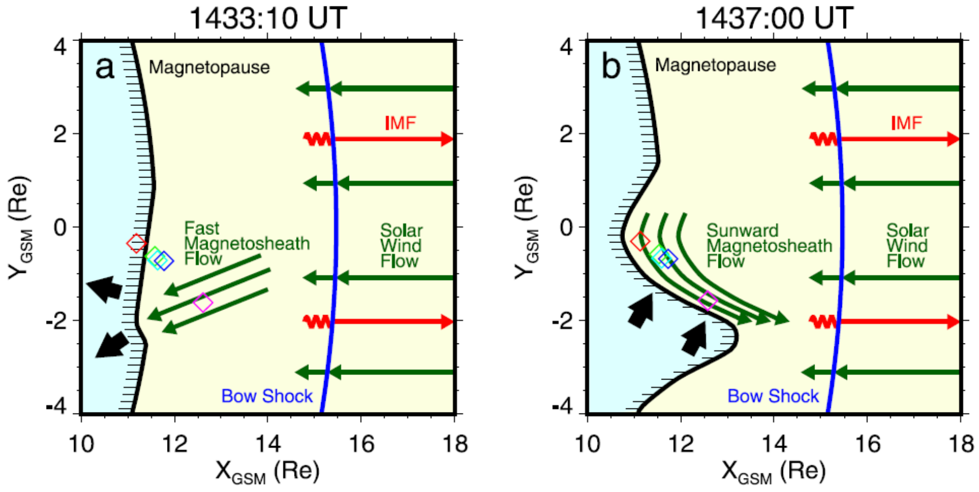
JET IMPACT

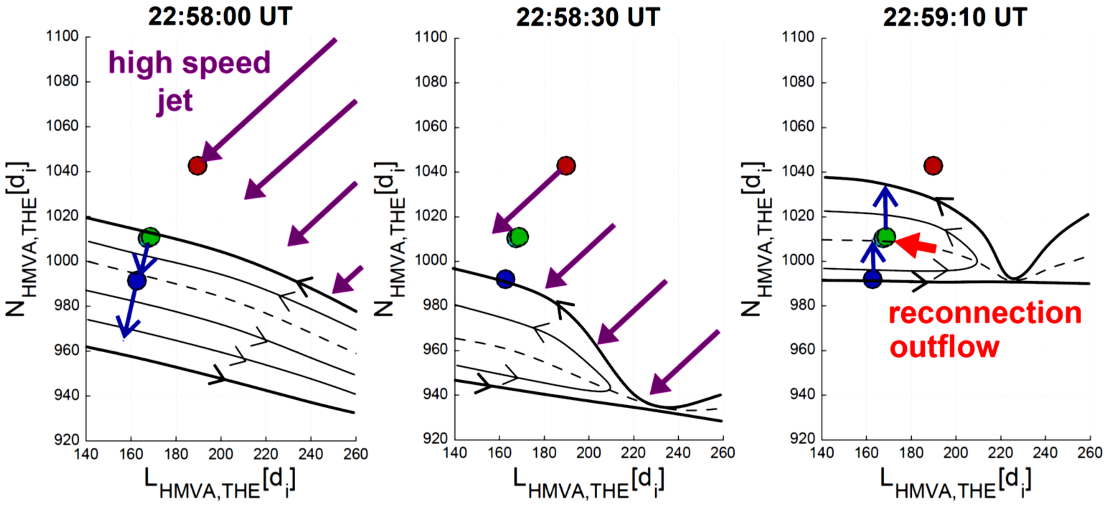
- jets are very common (Plaschke et al., 2016)
  - dayside magnetopause impact rate of LARGE jets with cross-sections > 2 R_E
    - in general: once every 20 minutes
    - under low IMF cone angle conditions: once every 6.5 minutes



Shue et al. (2009)

- jets can strongly indent the magnetopause

- jets can cause magnetopause reconnection
  - current sheet compression
  - change in magnetic field geometry
- jets can trigger substorms (Nykyri et al., 2019)



Hietala et al. (2018)

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   - reconnection
   - FTE bow waves
3. external transients
   - solar wind
     - IMF variations
     - pressure pulses
     - CME MCs
     - magnetic holes
   - foreshock transients
     - HFAs
     - FBs
   - jets

May apply to other planets and comets!

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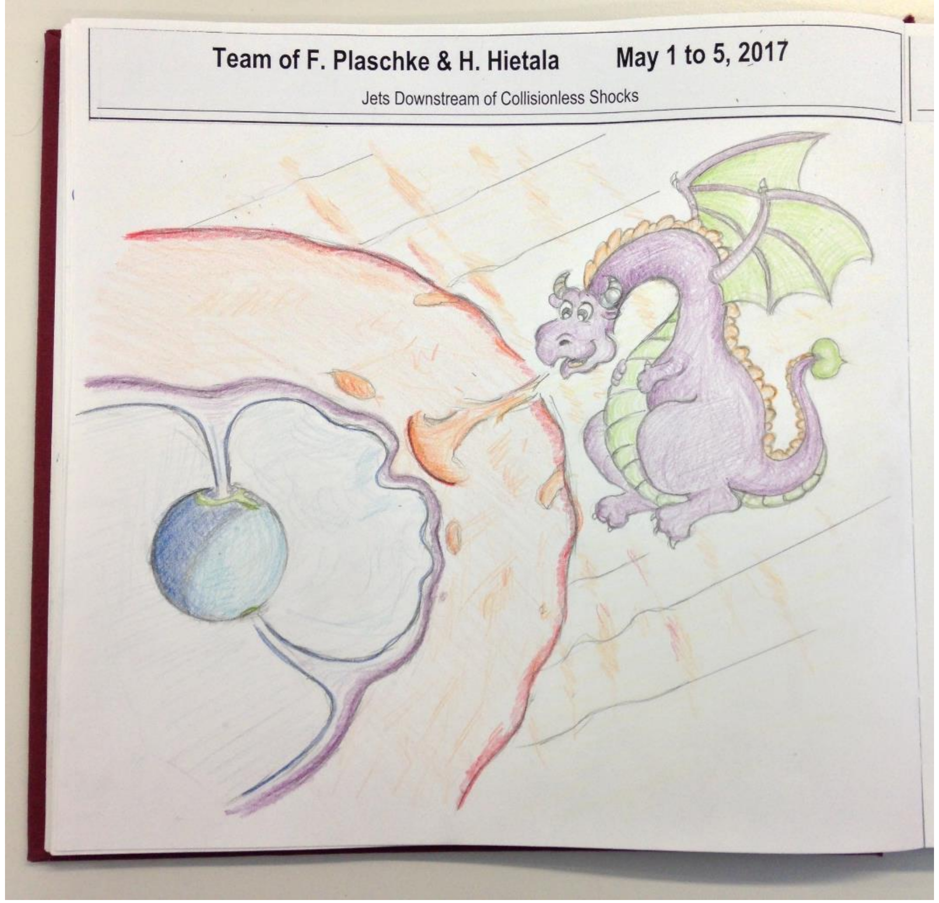
   - solar wind
     - IMF variations
     - pressure pulses
     - CME MCs
     - magnetic holes
   - foreshock transients
     - HFAs
     - FBs
   - jets



drawing by H. Hietala
ISSI team 350, 2nd meeting

Thank you very much!

THIS PRESENTATION IS BEING RECORDED!