Foreshock and Magnetosheath Transients

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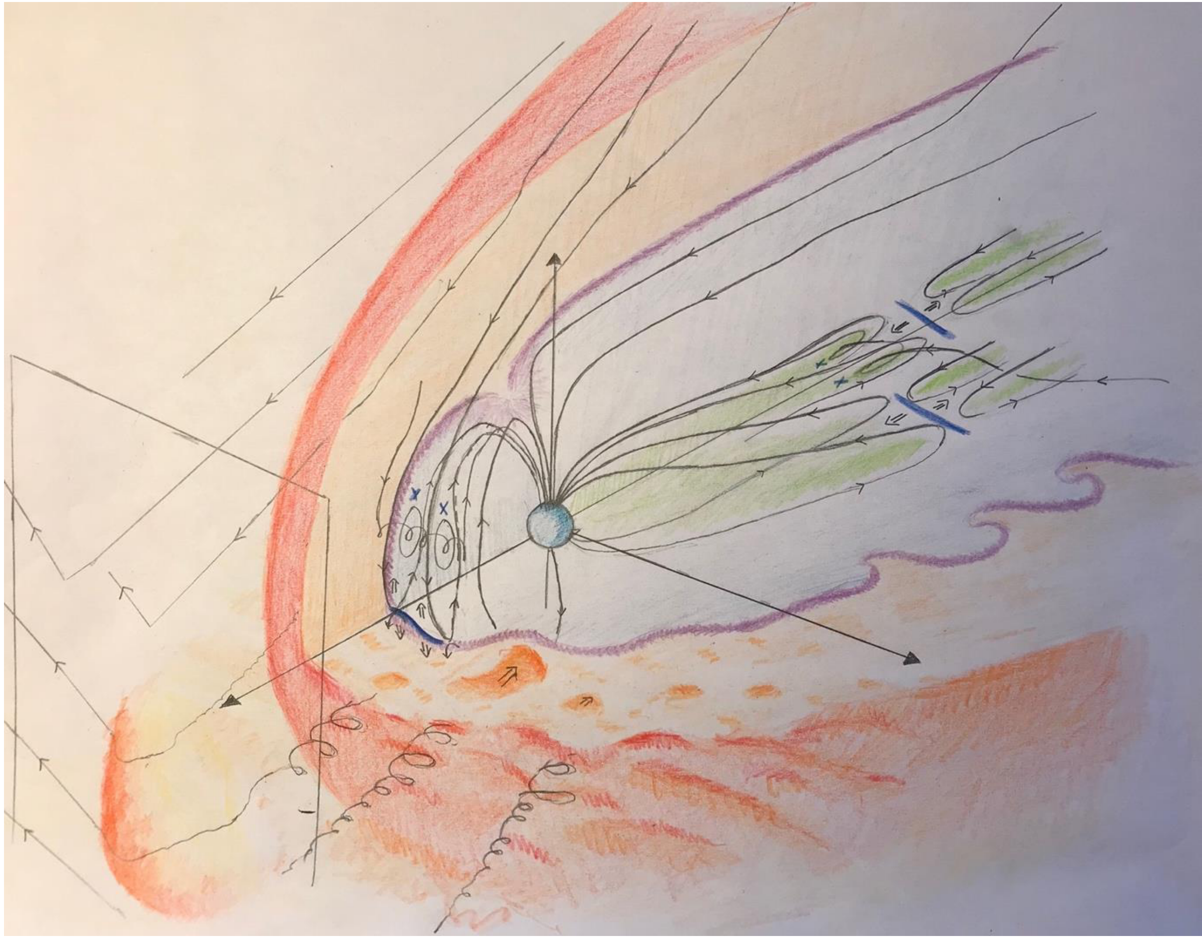
with thanks to Ferdinand Plaschke, Lucile Turc, early-career jet researchers,
ISSI Teams 350 and 465, and many more!

Why do we care?

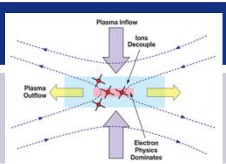
about the foreshock, the bow shock, and the magnetosheath

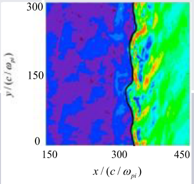
- Process the solar wind before it interacts with the magnetosphere
- Generate structures
- Accelerate particles
- Host fundamental plasma physics processes

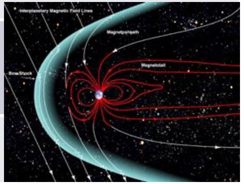


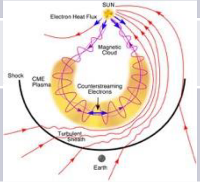
Some spatial scales in heliophysics

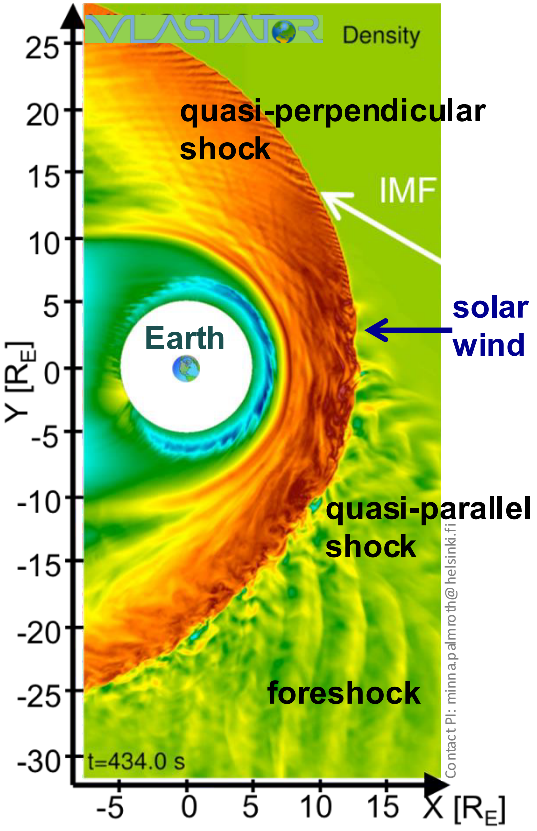
$1d_i^{SW}$ = 100km	$1R_E$ = 6,371km	1 AU = 1.5×10^8km	phenomena	
< $1d_i$			reconnection starts	
10 -100d_i	$1R_E \sim 60d_i^{SW}$		interesting ion kinetics; Earth radius	
100 -1,000d_i	$10R_E$		magnetopause stand-off distance	
	~$50R_E$		Earth's magnetosphere	
	~$235R_E$	0.01 AU	L1 point	
		~0.3 AU	CME	
		1 AU	Earth's distance from the Sun	







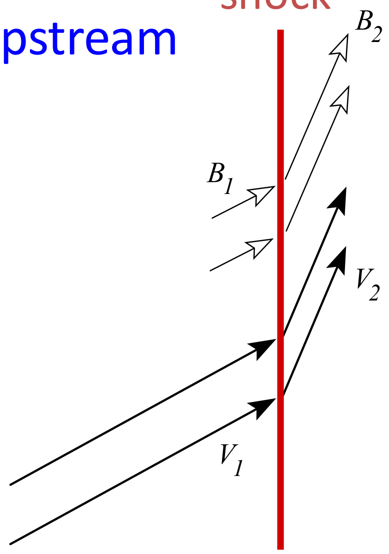




Foreshock outline: from large to small

1. What is a shock? (15-50 R_E)
2. Shock obliquity:
   quasi-perpendicular and quasi-parallel (~20 R_E)
   - Electron and ion foreshocks
3. Foreshock structures
   1. Driven foreshock structures (2-10 R_E)
   2. Intrinsic foreshock structures (1 R_E)
4. Fine structure (10-100 km)
   - Perpendicular shock ripples
   - Reconnection within the shock front

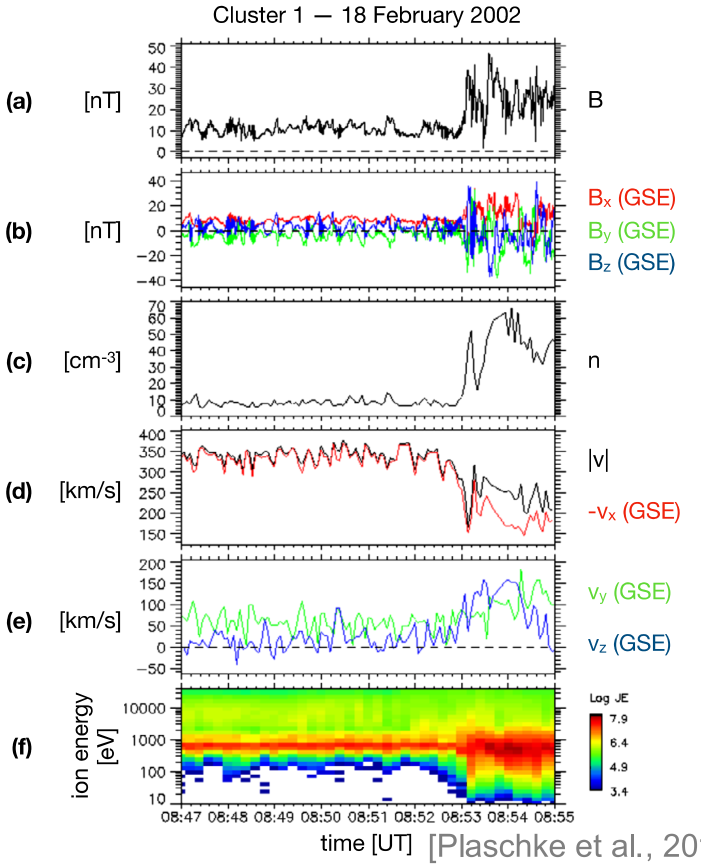
1 What is a space plasma shock?



slower
denser
hotter
higher |B|

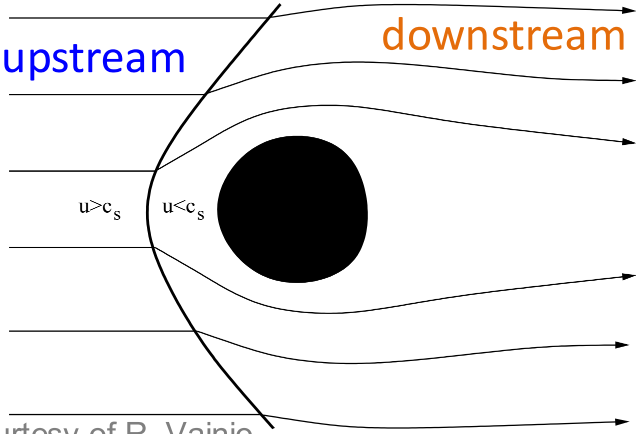
shock: flow speed ↓
speed of information ↑

M_A, M_S, M_f



[Plaschke et al., 2018]

1 Obstacles: magnetospheres

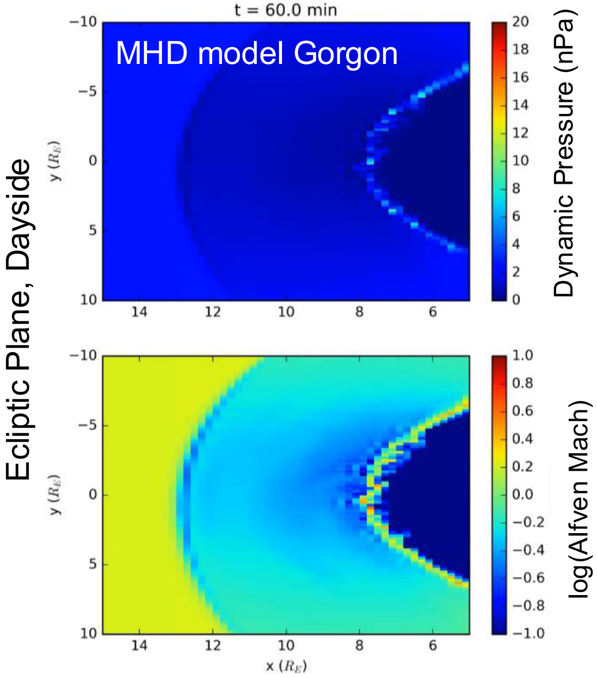


courtesy of R. Vainio

shock: flow speed ↓ speed of information ↑

M_A, M_S, M_f

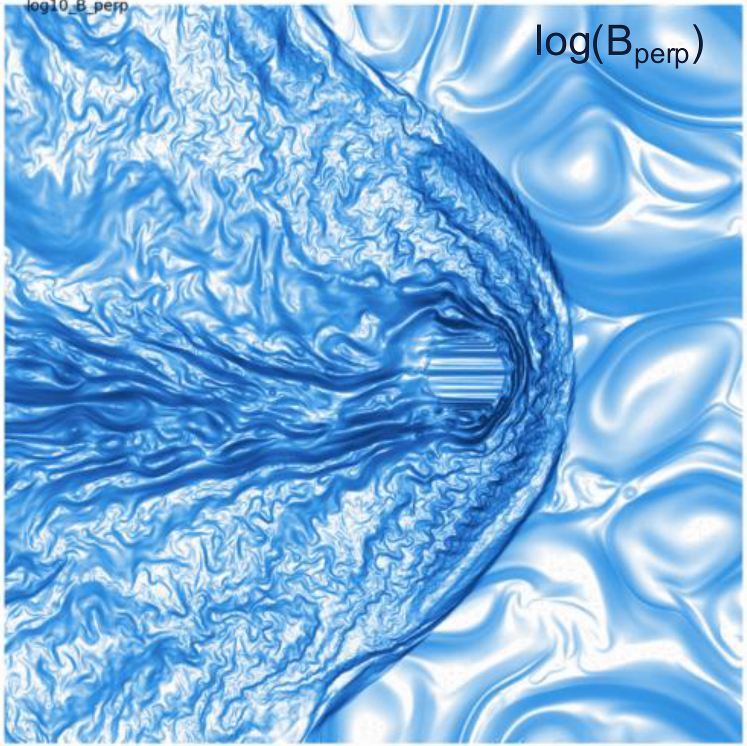
Bow shock position varies mainly with solar wind dynamic pressure



[Mejnertsen et al., 2018]

1 Obstacles: ionospheres, CME flux ropes…

Interaction with an unmagnetized object

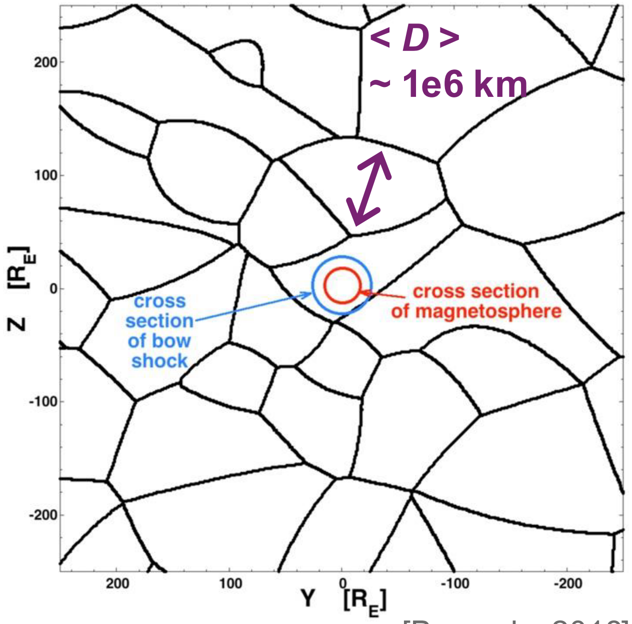


[Menura simulation; E. Behar]

Real solar wind is **turbulent:**
variations in upstream conditions over a range of scales

Solar wind coherence scale (size of flux tubes) 70 - 100 R_E

→conditions across Earth's bow shock often relatively uniform

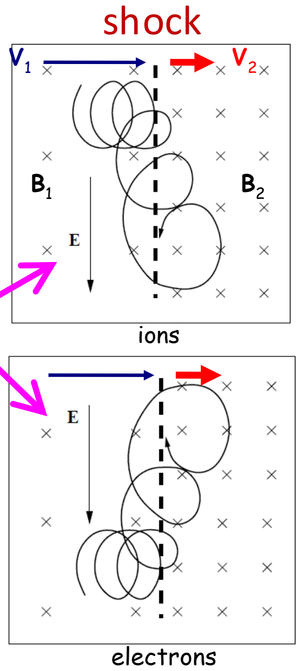


[Borovsky 2018]

1 Particle acceleration 101

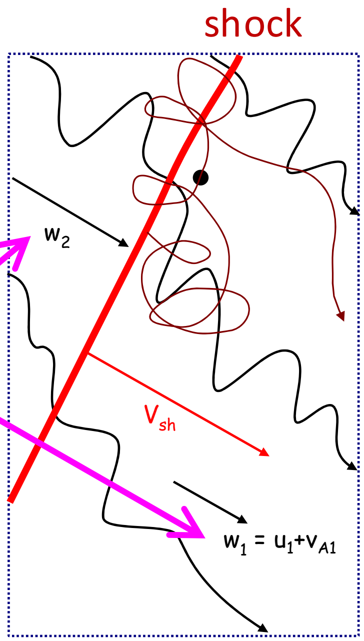
Shock Drift Acceleration

particles gain energy by drifting along/against the convective electric field



Diffusive Shock Acceleration

multiple interactions with waves upstream and downstream lead to multiple shock crossings



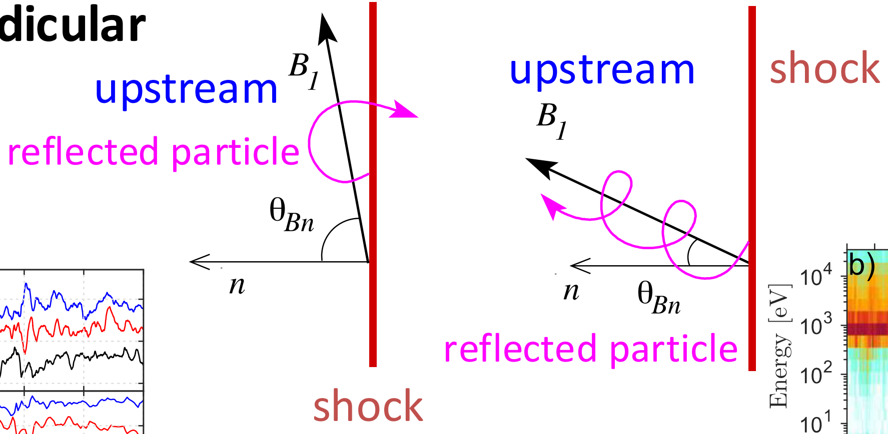
figures: R. Vainio

Earth's bow shock is relatively small:
Under typical solar wind conditions and without an interplanetary seed population, it does not accelerate ions above 200-330 keV

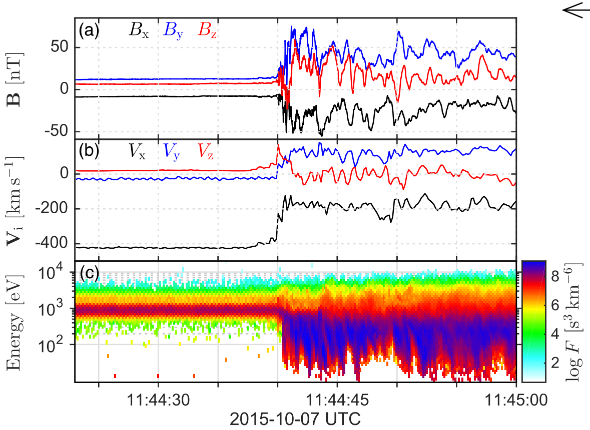
[Meziane et al., 2002]

2 Magnetic field orientation: shock obliquity

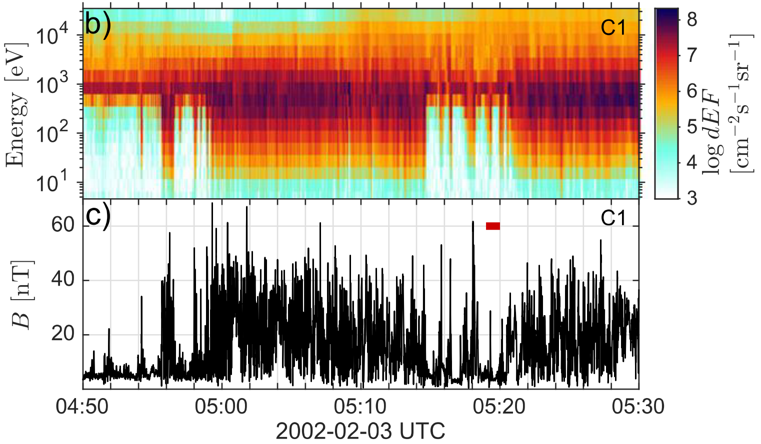
quasi-perpendicular



quasi-parallel



[Johlander, et al., 2016b]

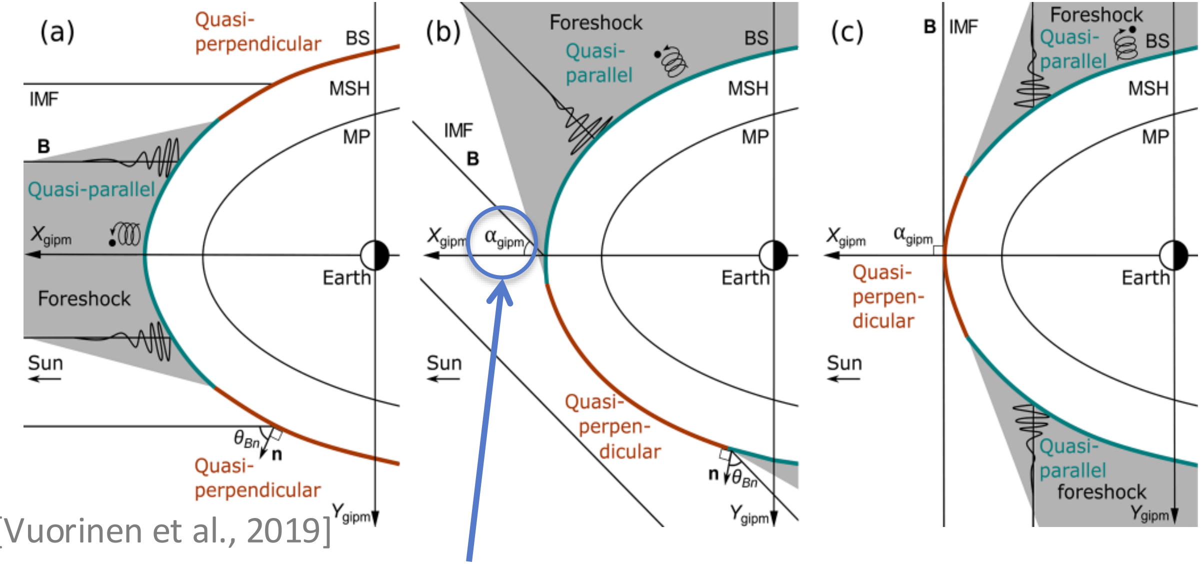


oblique

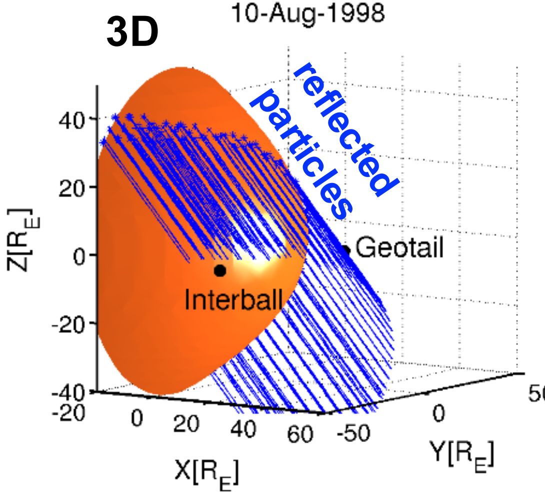
[Johlander et al., 2016a]

2 Curved bow shock

quasi-perpendicular and quasi-parallel regions coexist



[Vuorinen et al., 2019]



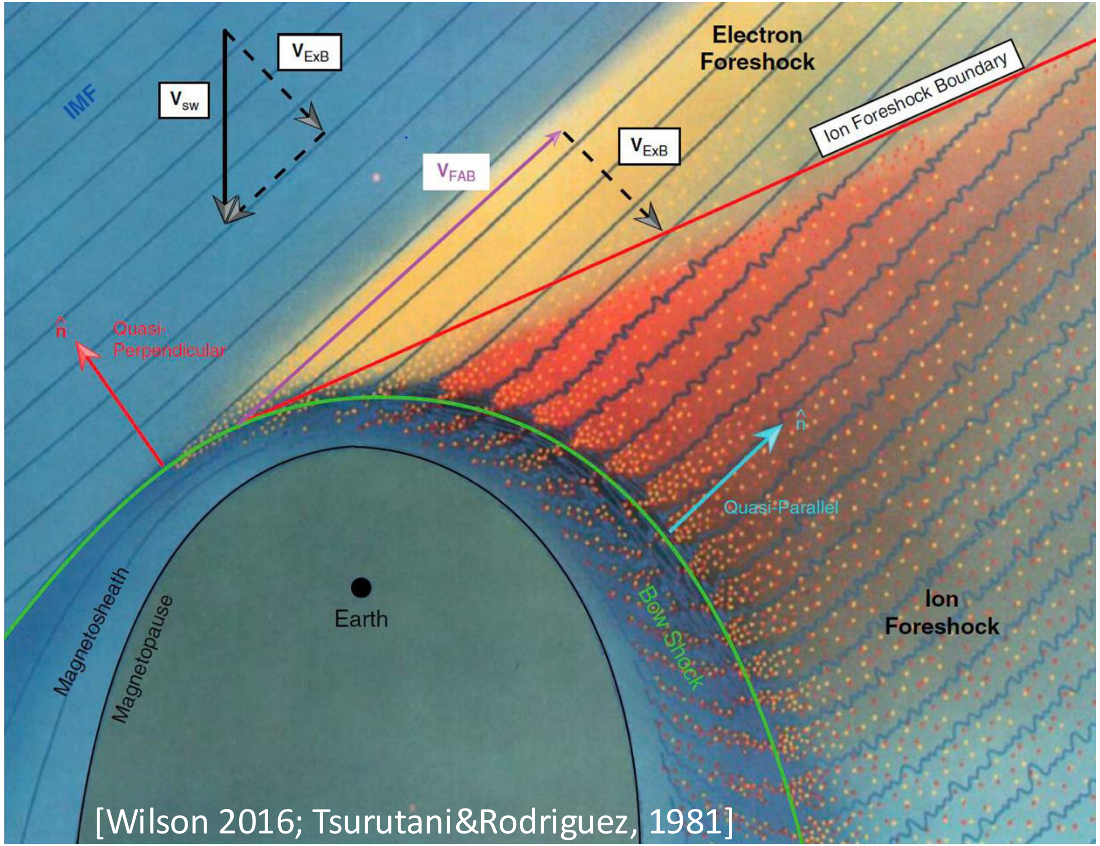
key quantity: IMF cone-angle $\alpha = \mathrm{acos}\left(\frac{B_x}{B}\right) \in [0°, 90°]$

(also for the magnetospheric effects of shock dynamics)

2 Foreshock

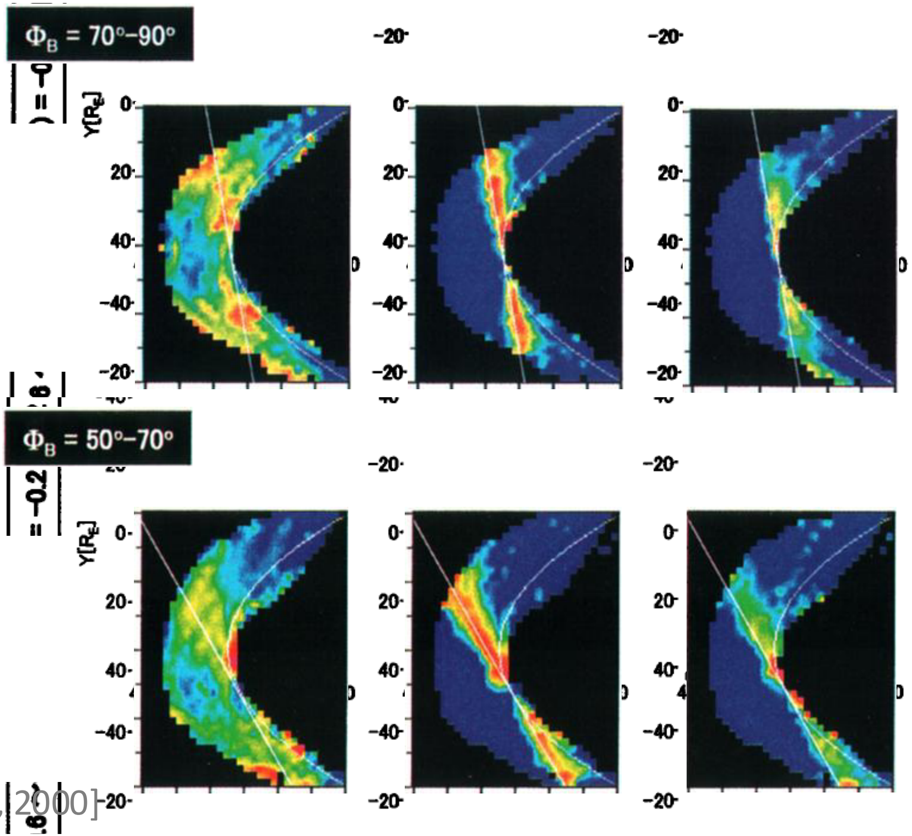
and velocity filter effect

- Foreshock = region upstream of and magnetically connected to the shock and filled with reflected particles and associated instabilities/waves
- (*E x B*)-drift velocity is the same for all particles
  - fastest reflected particles seen closest to the tangent field line
  - separation to electron and ion foreshocks
  - particles reflected at a higher θ_{Bn} will advect to and modify the shock front at a lower θ_{Bn}



2 Electron foreshock

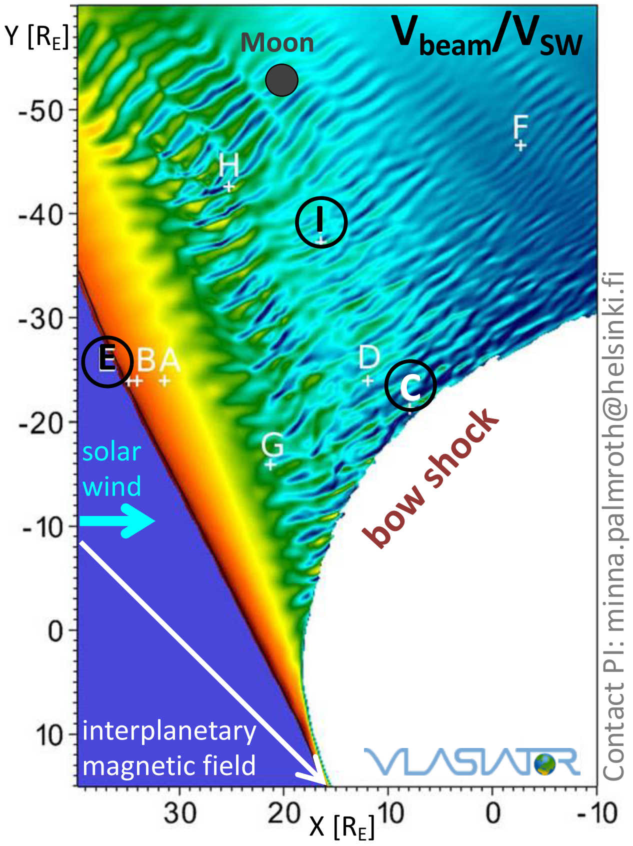
- Electron beams (>1 keV) generate Langmuir waves at the electron plasma frequency, which convert to radio emission at twice the electron plasma frequency
- ISEE-1, Wind, Cluster measurements
- Examples of statistical maps built from Geotail observations [Kasaba et al., 2000]
- Same process as radio emissions from CME-driven shocks in the corona
  - *it's all heliophysics!*

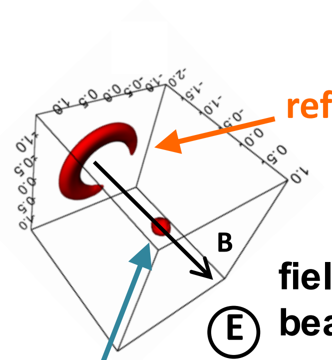


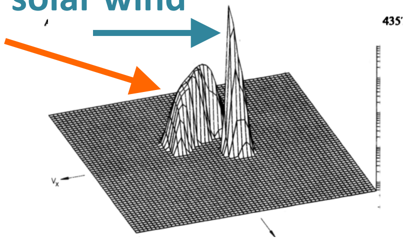
[Kasaba et al., 2000]

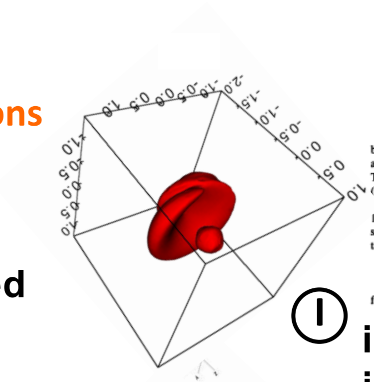
2 Ion foreshock: distribution functions

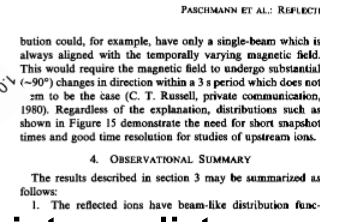
hybrid-Vlasov simulations and ISEE observations









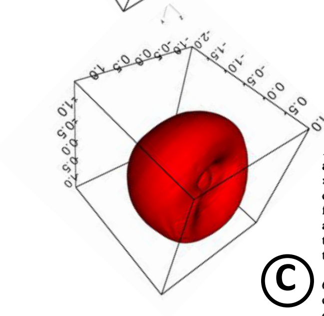

PASCHMANN ET AL.: REFLECTI

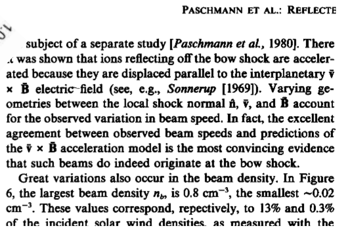
bution could, for example, have only a single-beam which is always aligned with the temporally varying magnetic field. This would require the magnetic field to undergo substantial (~90°) changes in direction within a 3 s period which does not …m to be the case (C. T. Russell, private communication, 1980). Regardless of the explanation, distributions such as shown in Figure 15 demonstrate the need for short snapshot times and good time resolution for studies of upstream ions.

4. OBSERVATIONAL SUMMARY

The results described in section 3 may be summarized as follows:

1. The reflected ions have beam-like distribution func-




PASCHMANN ET AL.: REFLECTE

subject of a separate study [*Paschmann et al.*, 1980]. There was shown that ions reflecting off the bow shock are accelerated because they are displaced parallel to the interplanetary $\bar{v} \times \bar{B}$ electric field (see, e.g., *Sonnerup* [1969]). Varying geometries between the local shock normal $\hat{n}$, $\bar{v}$, and $\bar{B}$ account for the observed variation in beam speed. In fact, the excellent agreement between observed beam speeds and predictions of the $\bar{v} \times \bar{B}$ acceleration model is the most convincing evidence that such beams do indeed originate at the bow shock.

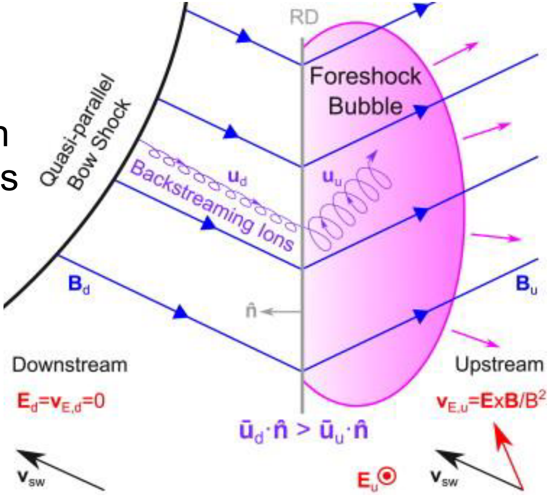
Great variations also occur in the beam density. In Figure 6, the largest beam density n_b, is 0.8 cm^{-3}, the smallest ~0.02 cm^{-3}. These values correspond, repectively, to 13% and 0.3% of the incident solar wind densities, as measured with the

[Kempf et al., 2015; Paschmann et al., 1981]

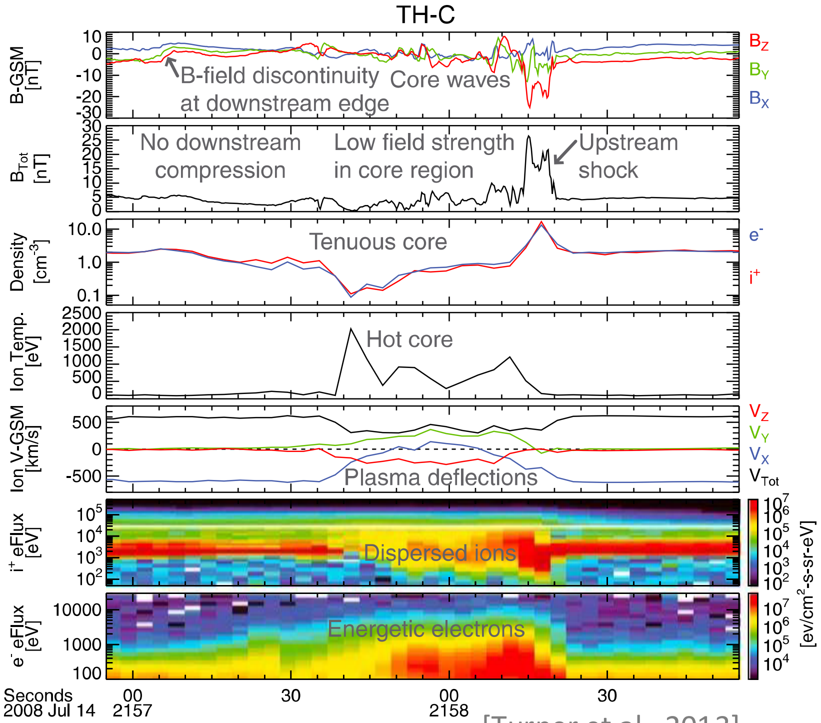
3.1 Driven foreshock structures = non-uniform upstream B-field

foreshock bubbles

- **what:** a hot core of low density, low magnetic field, with an upstream shock
- **driven by** rotational and thin tangential IMF discontinuities [e.g., Liu et al., 2015]
- **size** > 3 R_E
  simulations indicate up to the same size as the whole foreshock [Omidi et al., 2010; Liu et al., 2019]
- **occurrence rate** ~1/day under favorable high solar wind speed conditions [Turner et al., 2013]



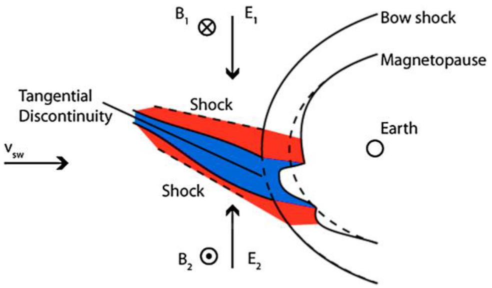
[Archer et al., 2015]



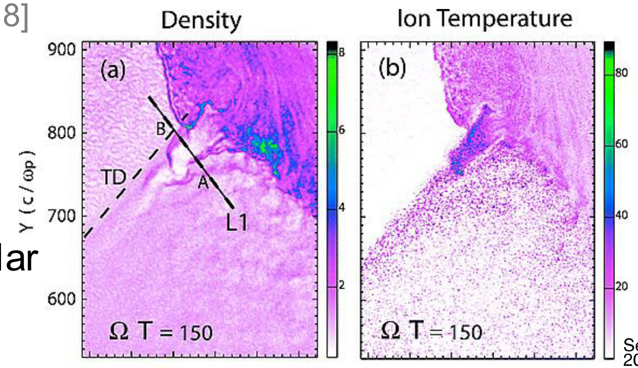
[Turner et al., 2013]

3.1 Driven foreshock structures: hot flow anomalies

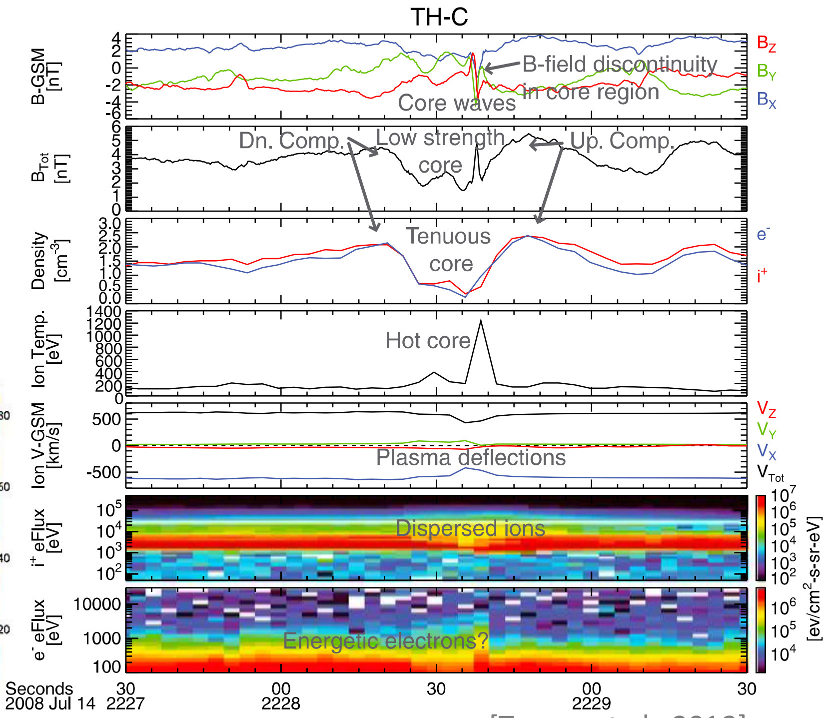
- **what:** suprathermal ions channeled upstream at the **intersection** of a discontinuity with the bow shock, with compressions at its edges
  - AMPTE-UKS: Schwartz et al. [1985]
  - MMS: Schwartz et al. [2018]
- **size a few R_E** increases as it travels across the shock
- **occurrence rate** ~2/h under favorable high solar wind speed conditions [Turner et al., 2013]



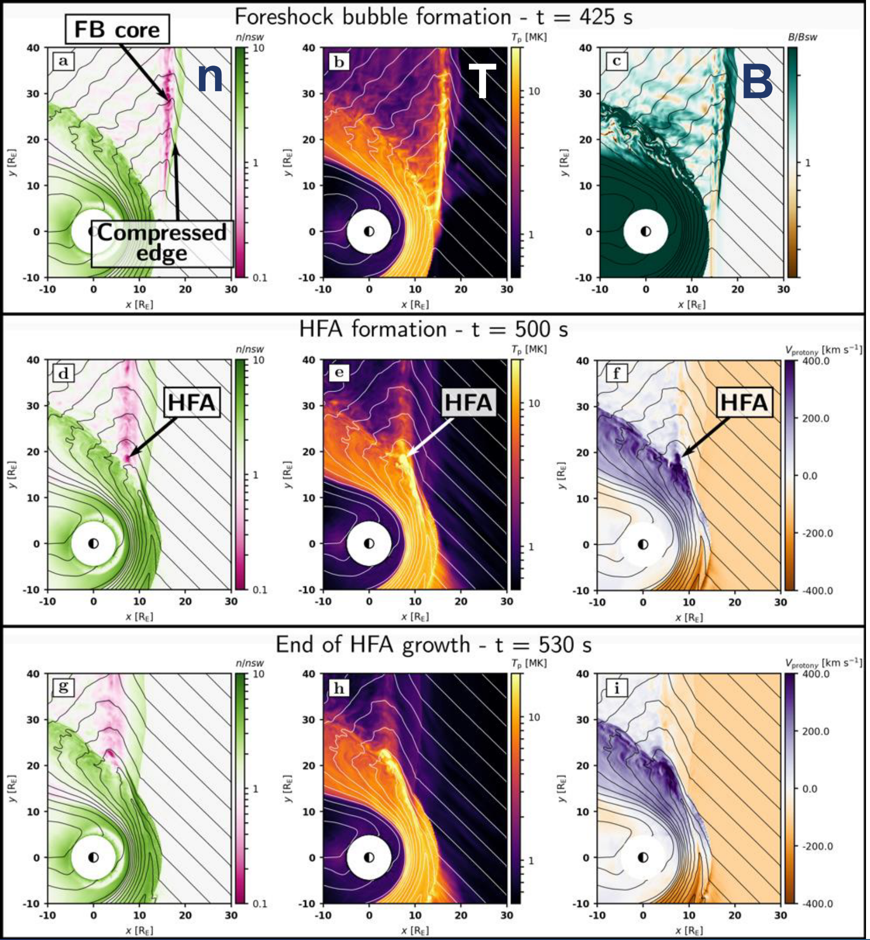
[Eastwood et al., 2015]



[Omidi&Sibeck, 2007]



[Turner et al., 2013]



3.1 Driven foreshock structures

time

An IMF discontinuity may form both a bubble and an HFA, and in observations it's often difficult to distinguish which structure it is.

Main point: a structure with a hot tenuous core driven by a discontinuity.

[Vlasiator simulation, courtesy of L. Turc]

3.1 Driven foreshock structures: key effects

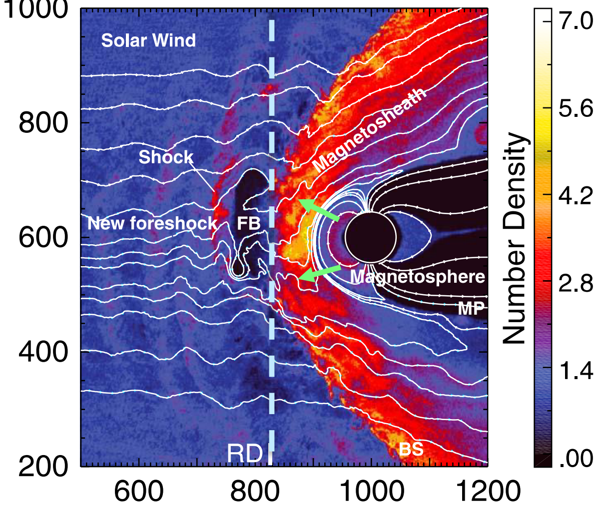
Particle Acceleration

- **Transients with <u>hot, low-density cores</u> and compressional boundaries**
  - leading shock reflects solar wind ions (secondary foreshock) [Liu et al., 2016]
  - occasional ion acceleration [Liu et al., 2017a; Turner et al., 2018]
  - energized ions leak out of the core [Liu et al., 2017b]
  - **electrons almost always energized**, up to 100s of keVs [e.g., Wilson et al., 2016, Liu et al., 2017a,c Raptis et al., 2024, Shi et al., 2025]

Magnetospheric Response

Foreshock Bubble

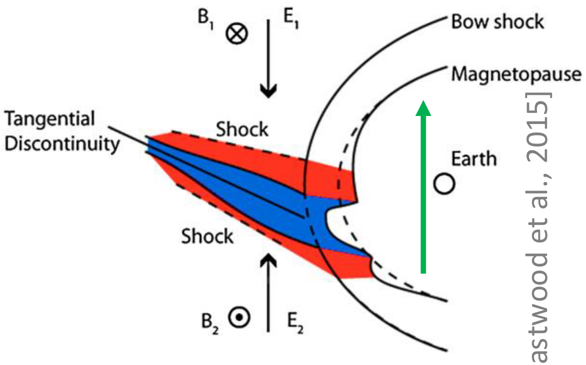
almost global out-in motion



[Turner et al., 2013]

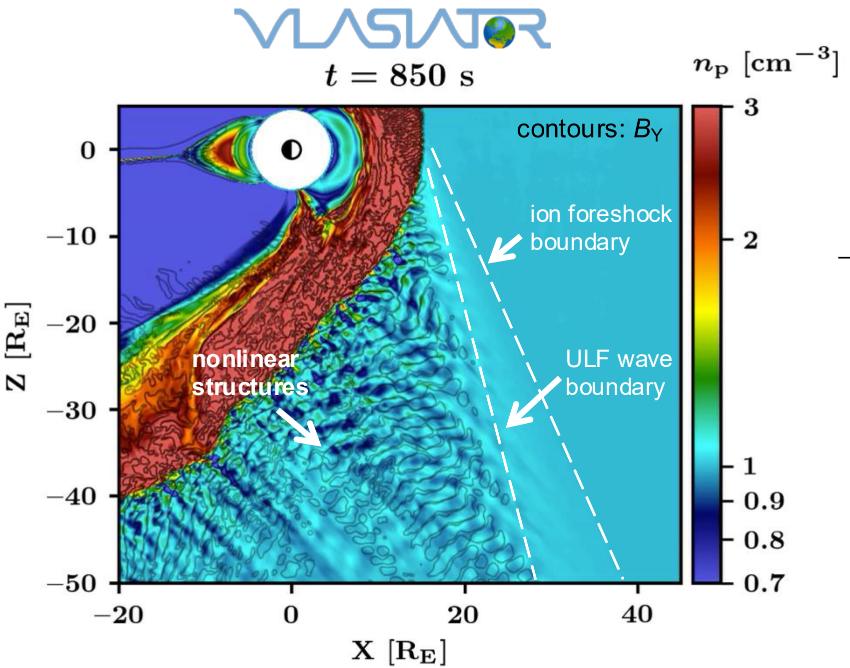
Hot Flow Anomaly

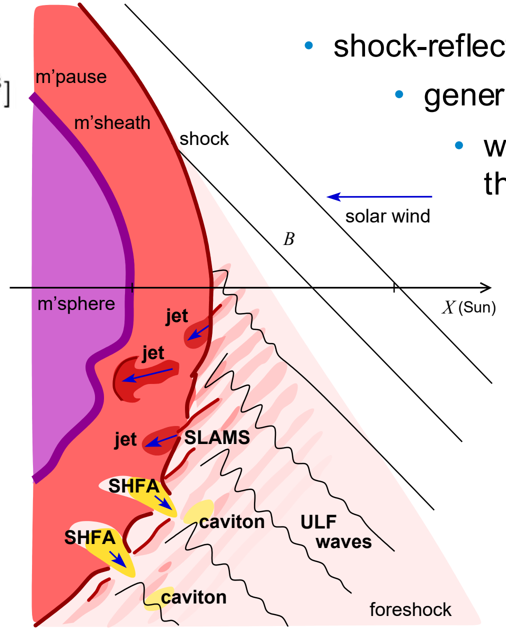
a sweeping bulge



- **magnetospheric waves**
- **aurora**
- **ground-magnetometers**

3.2 Intrinsic foreshock structures: overview





- shock-reflected ions stream against the solar wind
  - generate waves (~30s; **~1*R*$_E$**)
    - waves are advected back towards the shock
      - waves undergo nonlinear interactions with themselves, the ions, and locally generated waves, generating structures:
        - troughs/depressions
          - ***cavitons***
          - ***spontaneous hot flow anomalies***
        - peaks/enhancements
          - ***shocklets***
          - ***short large amplitude magnetic structures (SLAMS)***

Contact PI: minna.palmroth@helsinki.fi; movie by M. Battarbee

3.2 Where it starts: waves

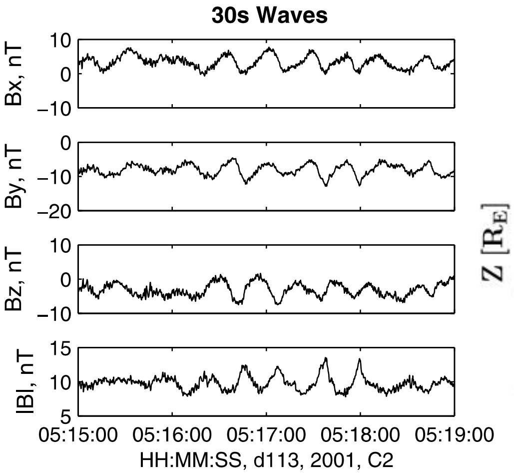
- **focus:** sunward propagating fast magnetosonic waves
- **generated by** right-hand ion-beam instability between SW and reflected ions
- **period** depends on IMF strength and orientation:

$$\omega_{sc} = \frac{qB}{m} \frac{\cos\theta_{Bx}\cos\theta_{Bn}}{\cos\theta_{nx}}$$

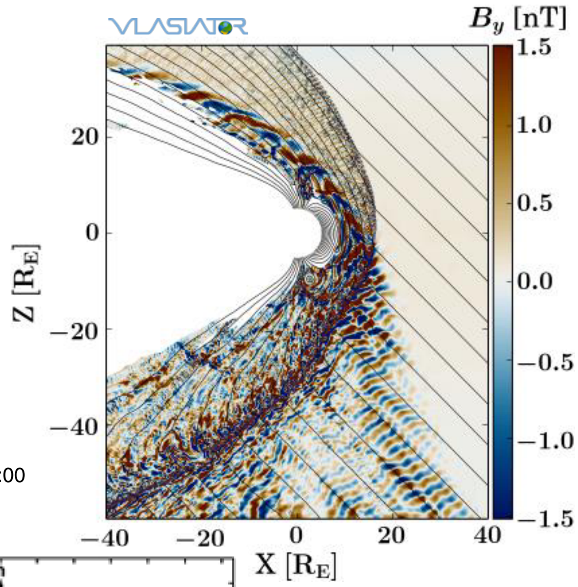
[Takahashi et al., 1984; Le&Russell, 1996]

~30s period at Earth; ~1 R_E wavelength

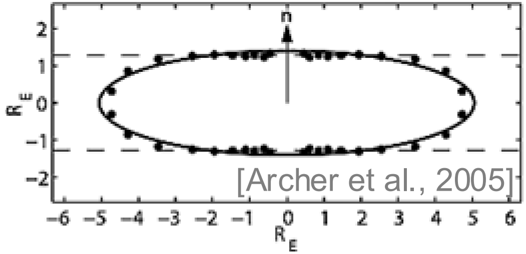
- large amplitude $|\delta \mathbf{B}|/B \sim 1$
- **k** deflected from **B** ~20° due to refraction by spatially varying suprathermal ions
- convected by the solar wind towards the shock, modify it, and transmit into the magnetosphere



[Eastwood et al., 2005]



[Blanco-Cano et al., 2018]

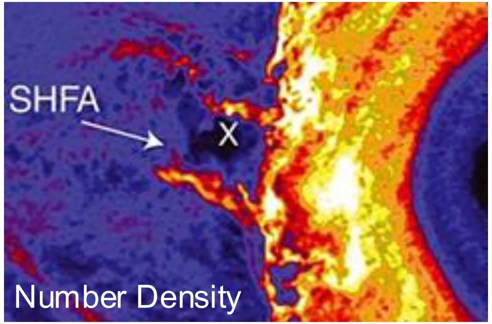


Review:
[Wilson 2016]

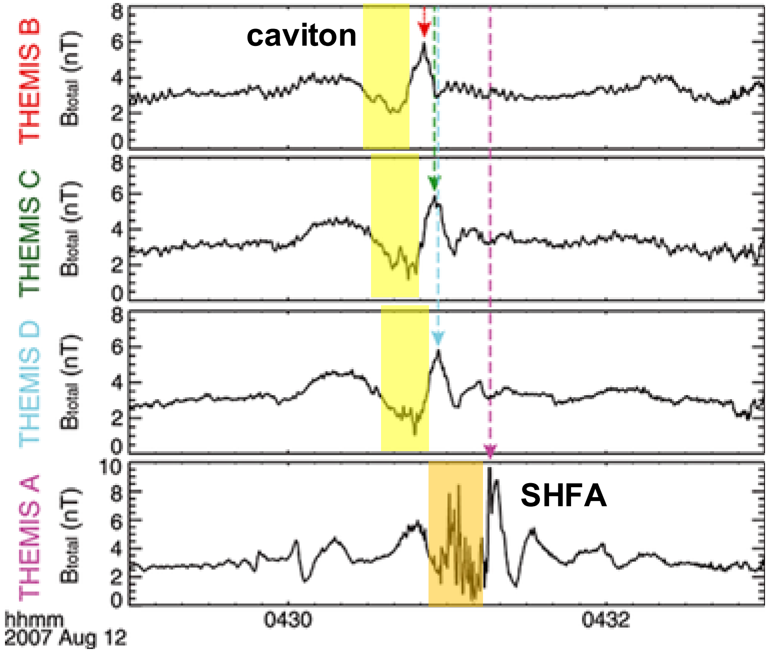
3.2 Troughs: cavitons and spontaneous hot flow anomalies

- **cavitons:** depressions of n and B, but no T increase, with "shoulders" at outer edges
- **where:** deep in the ion foreshock, surrounded by waves [Kajdic et al., 2017]
- **form by** interaction of parallel and obliquely propagating waves [Blanco-Cano et al., 2009]
- **Spontaneous Hot Flow Anomalies:** decrease in n and B, with increase in T
- **form** from cavitons [Zhang et al., 2013]

- **size ~ 1 R_E** same as 30s waves
- **effects:** modify (weaken) the bow shock



[Omidi et al., 2013]



3.2 Peaks: shocklets and SLAMS

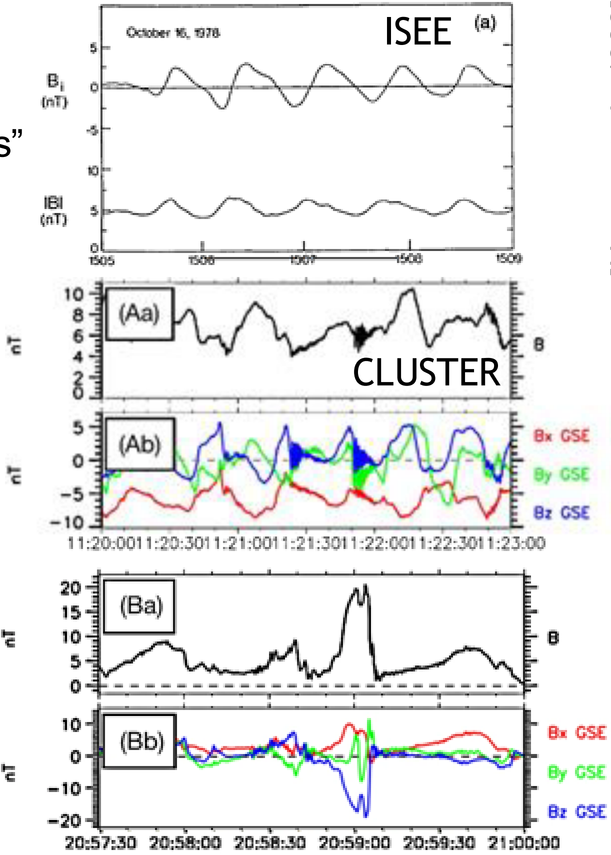
- **"30s waves":** fast magnetosonic waves $|\delta B|/B_0 \sim 1$
- **shocklets:** steepened waves, associated with whistler wave packets and diffuse backstreaming ion distributions, $1 \lesssim |\delta B|/B_0 \lesssim 2$ [e.g., Hoppe et al., 1981]
- **where:** close to the bow shock
- **size ~ 1 R_E** (~30s) [e.g., Le and Russell, 1994]
- **Short Large Amplitude Magnetic Structures (SLAMS):** fast mode pulsations, monolithic, $|\delta B|/B_0 > 2$ (up to 10)
- **where:** close to the bow shock (they are the shock)
- **size > 1000 km** [Lucek et al., 2004; 2008]
- **importance:** ion energization by reflection and trapping
  slow down the incoming flow
  "building blocks" of the quasi-parallel shock

[e.g., Schwartz et al., 1991; 1992; Johlander et al., 2016a]

"30s waves"

shocklets

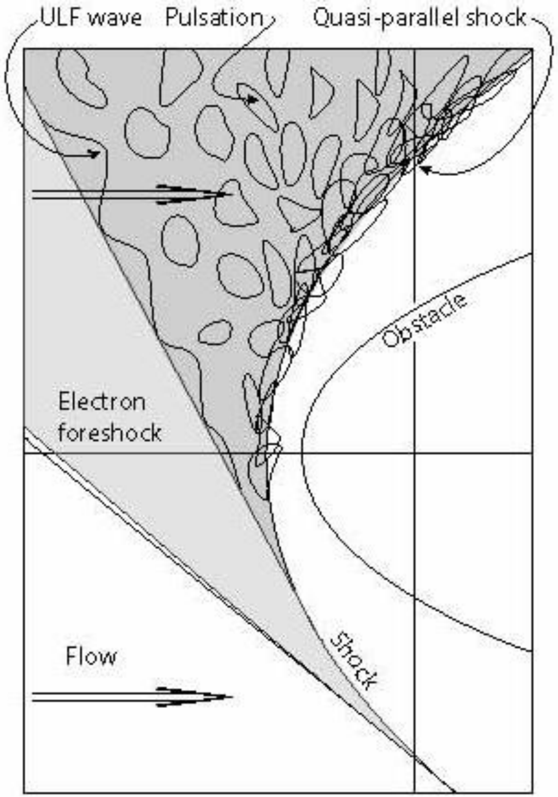
SLAMS



[Hoppe et al., 1983]

[Plaschke et al., 2018]

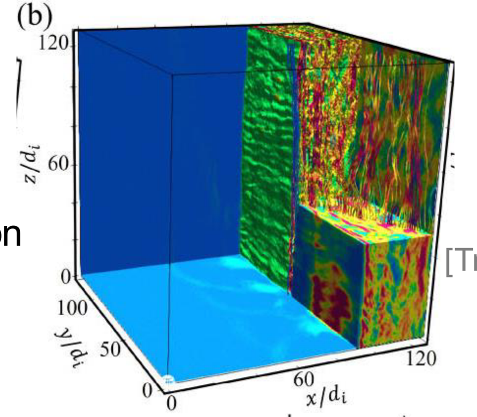
From meso-scale to fine structures



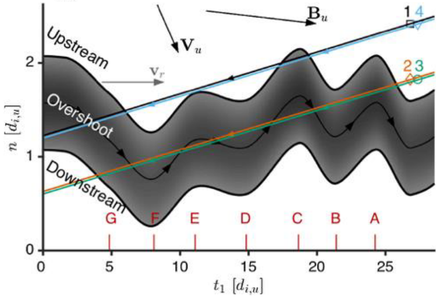
[Treumann&Jaroschek, 2008]

4 Fine structures:
quasi-perp shock surface ripples

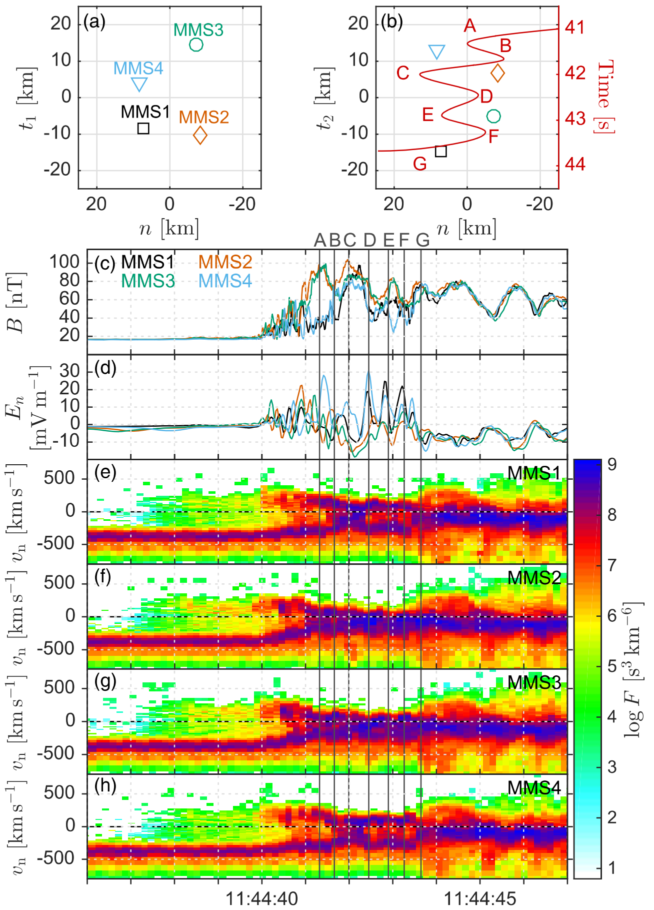
- **Shock non-stationarity:** ripples and reformation
- **Affects** electron acceleration and ion reflection
- Simulation predictions [e.g., Lowe&Burgess 2003]
- Quantitative observations [Johlander et al., 2016b]
  - ripple wavelength **~4 d_{iu} ~ 175 km**
  - ripple amplitude **~0.25 d_{iu} ~ 10 km**]



[Trotta et al., 2023]

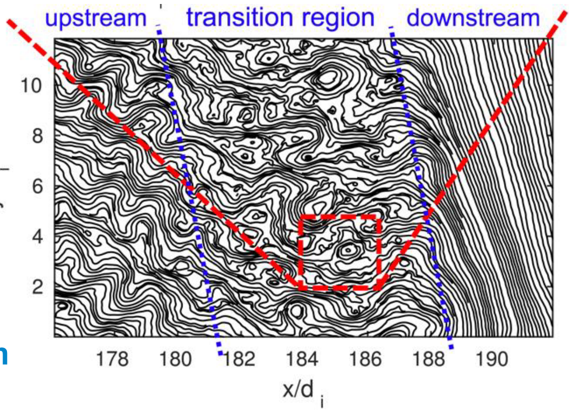


[Johlander et al., 2016b]

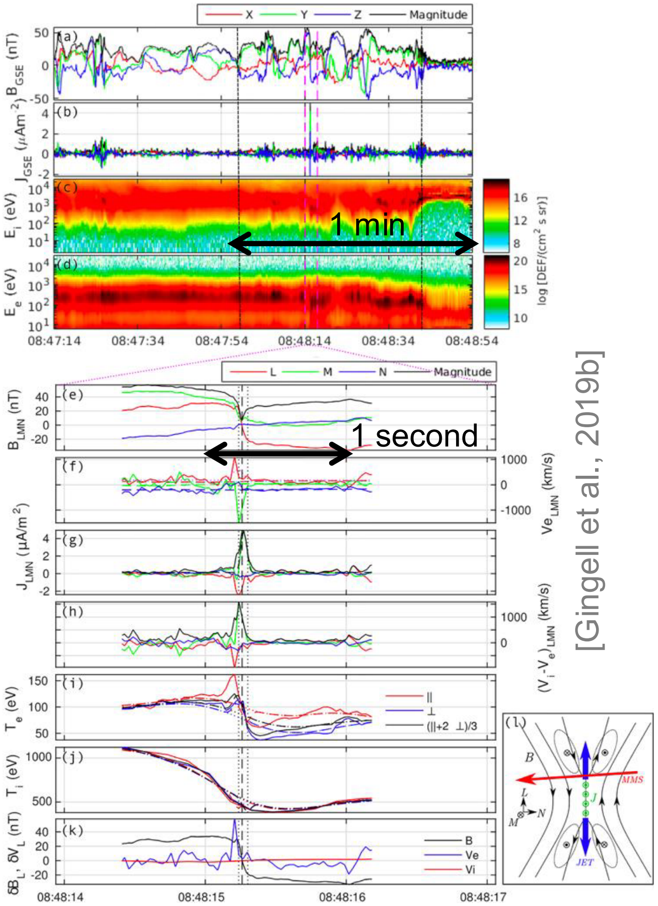


4 Fine structure:
reconnection within the shock front

- First observed at oblique and quasi-parallel geometries
  [Wang et al., 2019;
  Gingell et al., 2019a]
- <u>Statistical observations</u>
  [Gingell et al., 2019b]
  - present for all shock obliquities
  - current sheet widths $\lesssim$**10 d_e ~ 8km**
  - typically feature electron-only reconnection
  - **primary consequence:** relaxing magnetic topology (not heating)
- Simulations
  [e.g., Bohdan et al., 2017; Gingell et al., 2017; Matsumoto et al., 2015]

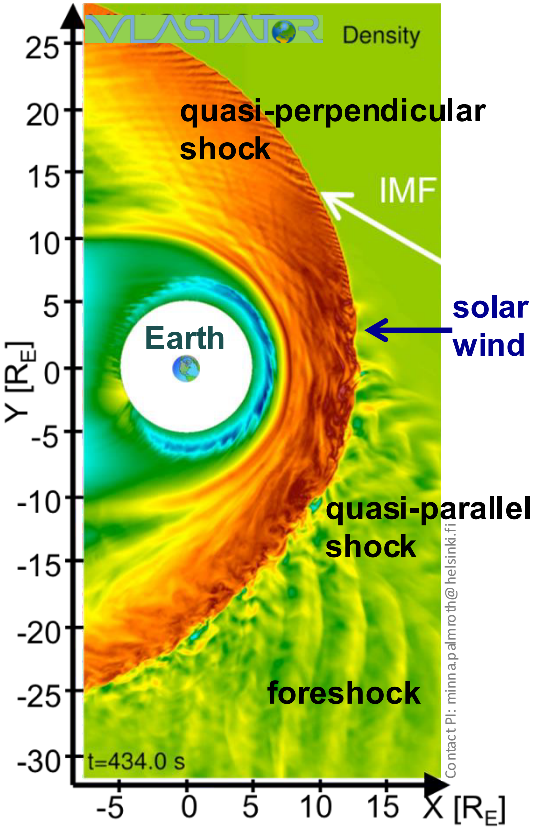


[Gingell et al., 2019a]



[Gingell et al., 2019b]

Magnetosheath outline: from large to small

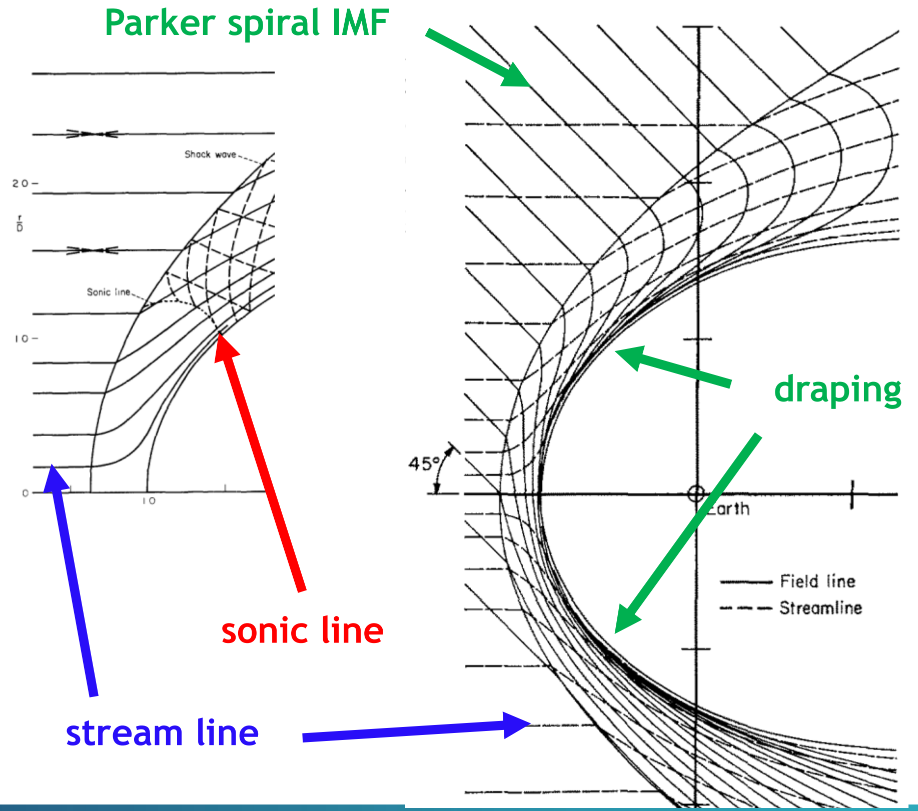


1. Large scale flow and properties (15-50 R_E)
2. Shock obliquity:
   quasi-perpendicular and quasi-parallel sheath (~20 R_E)
3. Magnetopause: (~20 R_E)
   open or closed
4. Instabilities
   mirror modes vs turbulence (10 - 100 km)
   reconnection in turbulence (4 - 100 km)
5. Transient jets (600 km - 1 R_E)

1 Early magnetosheath modelling

Spreiter et al. (1966)

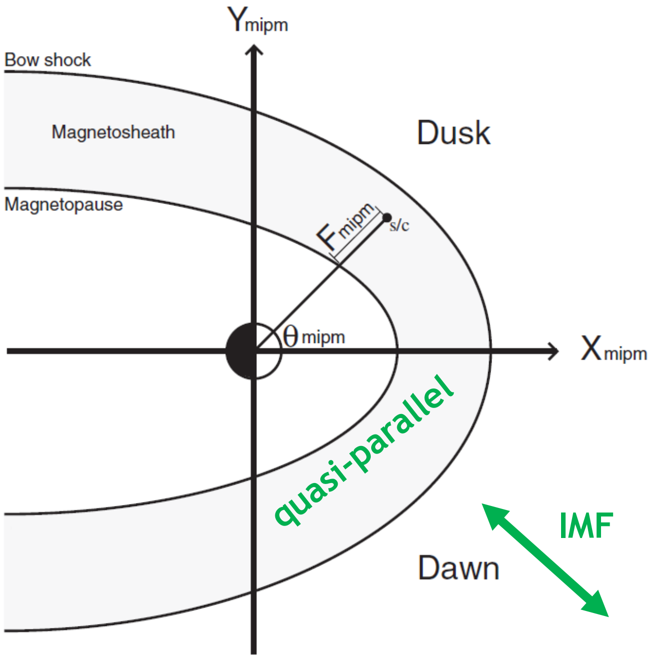
- modelling of flow and shock wave:
  - gas dynamic theory (hydrodynamic)
- magnetopause:
  - tangential discontinuity
  - pressure balance
  - axisymmetric
  - field inside:
    twice the geomagnetic dipole field
- magnetic field:
  - frozen-in, added afterwards



2 Compiled observations:
taking shock obliquity into account

magnetosheath interplanetary medium reference frame: MIPM

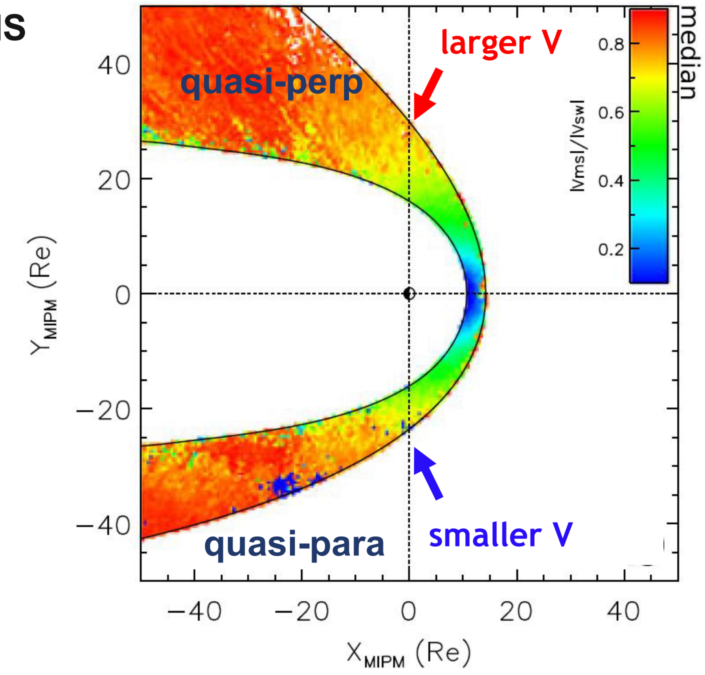
- X:
  - against solar wind flow
  - aberrated Earth-Sun-line
- Y:
  - IMF in X-Y-plane
  - quasi-parallel on –Y side
- bow shock and magnetopause models
  - Verigin et al. (2001)
  - Shue et al. (1998)
- F:
  - radial fractional distance between boundaries

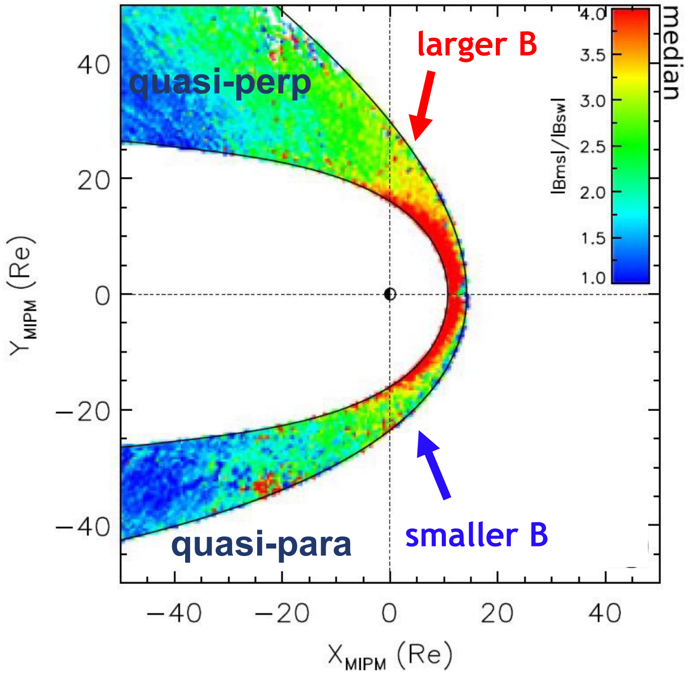


Dimmock and Nykyri (2013)

2 Compiled observations:
velocity and magnetic field differences

THEMIS



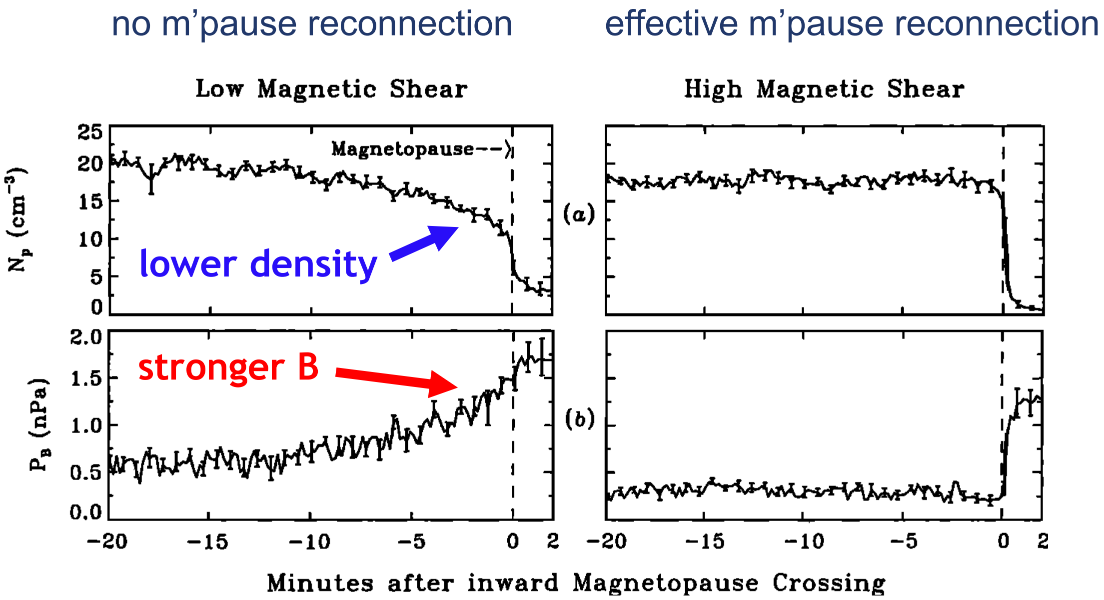


Dimmock and Nykyri (2013)

3 Closed magnetopause leads to plasma depletion layer

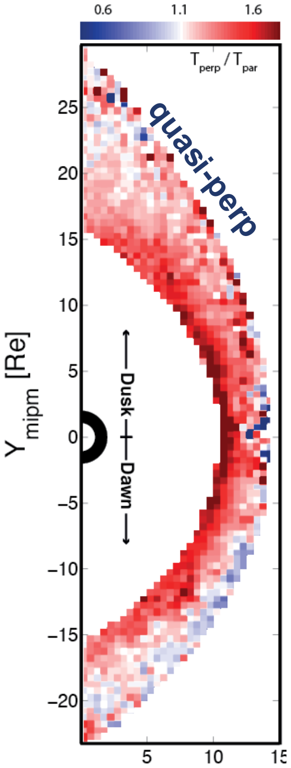
- conditions
  - strongly northward IMF
  - effect enhanced during low M_A

- 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]

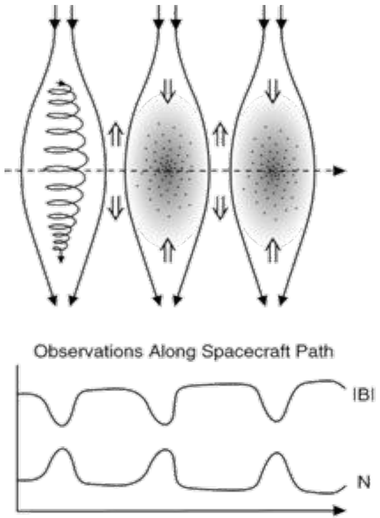
4 Instabilities: quasi-perp sheath mirror modes



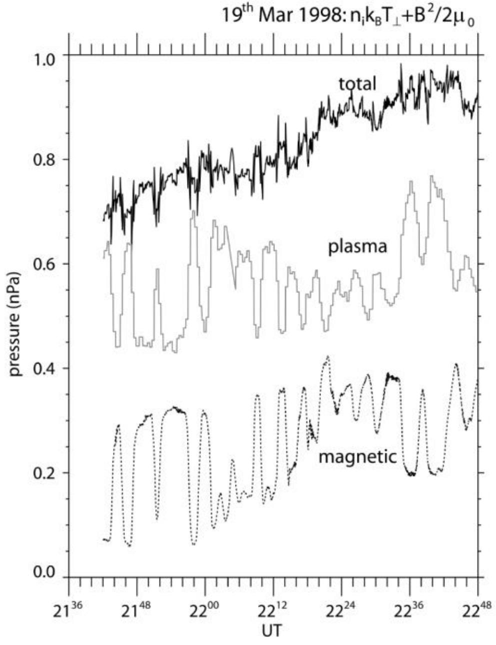
[after Dimmock et al, 2023&2015]

- 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)

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

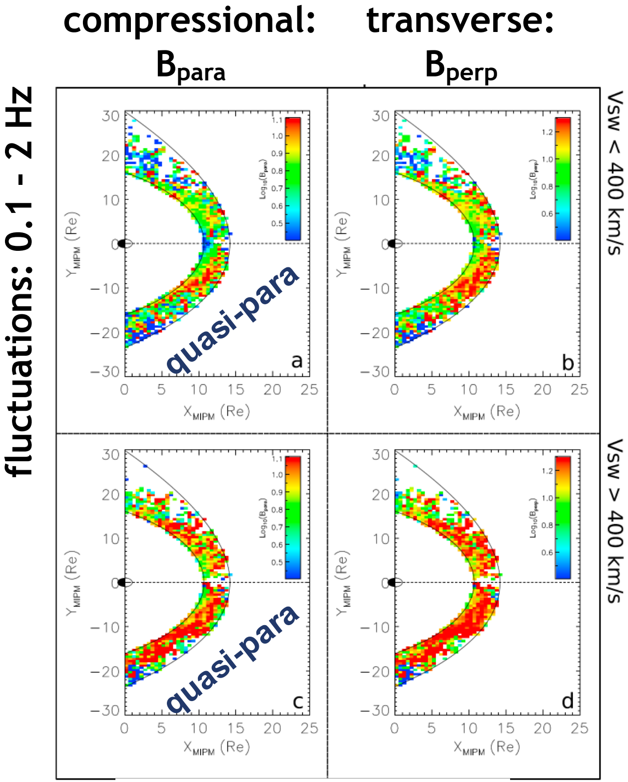


Treumann and Baumjohann (1996)

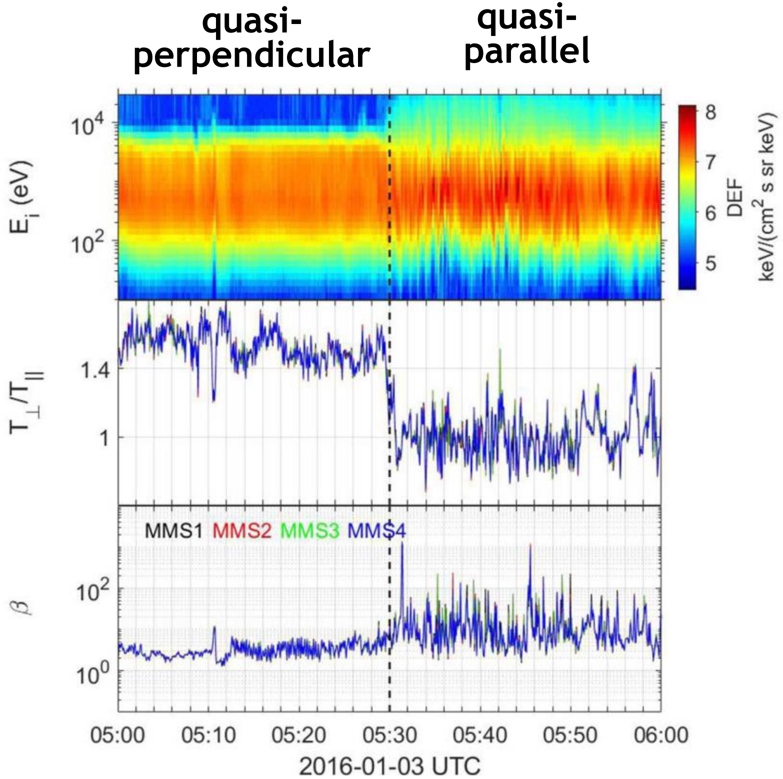


Rae et al. (2007)

4 Turbulent fluctuations: quasi-para sheath has more power



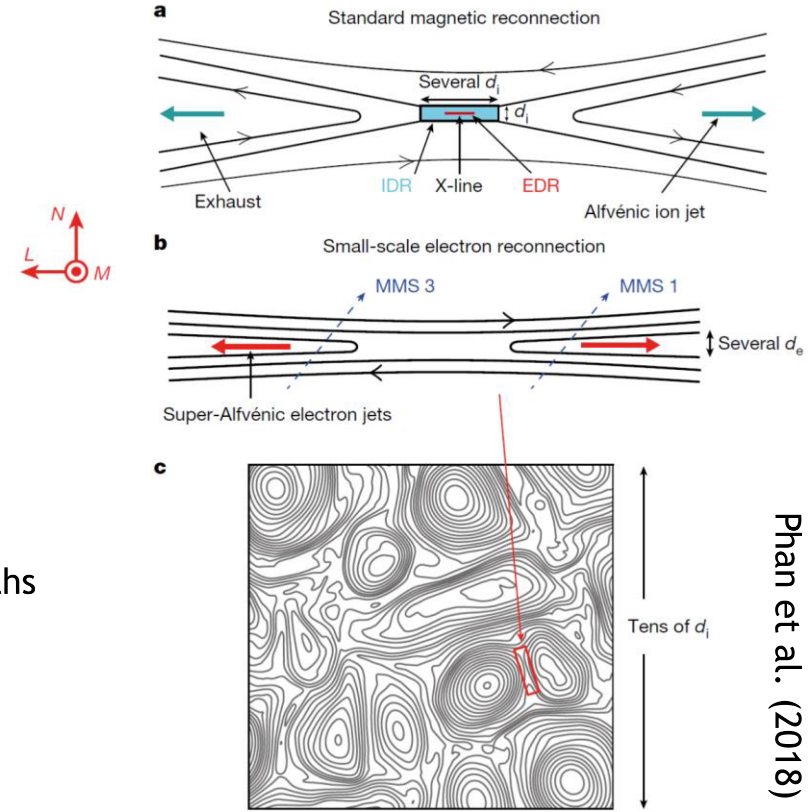
Dimmock et al. (2014)



Yordanova et al. (2020)

4 Turbulent fluctuations: reconnection in 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)

5 Transients:
magnetosheath jets

localised downstream dynamic pressure enhancements: ρV_X^2

size: ~0.5 R_E ~tens of d_i

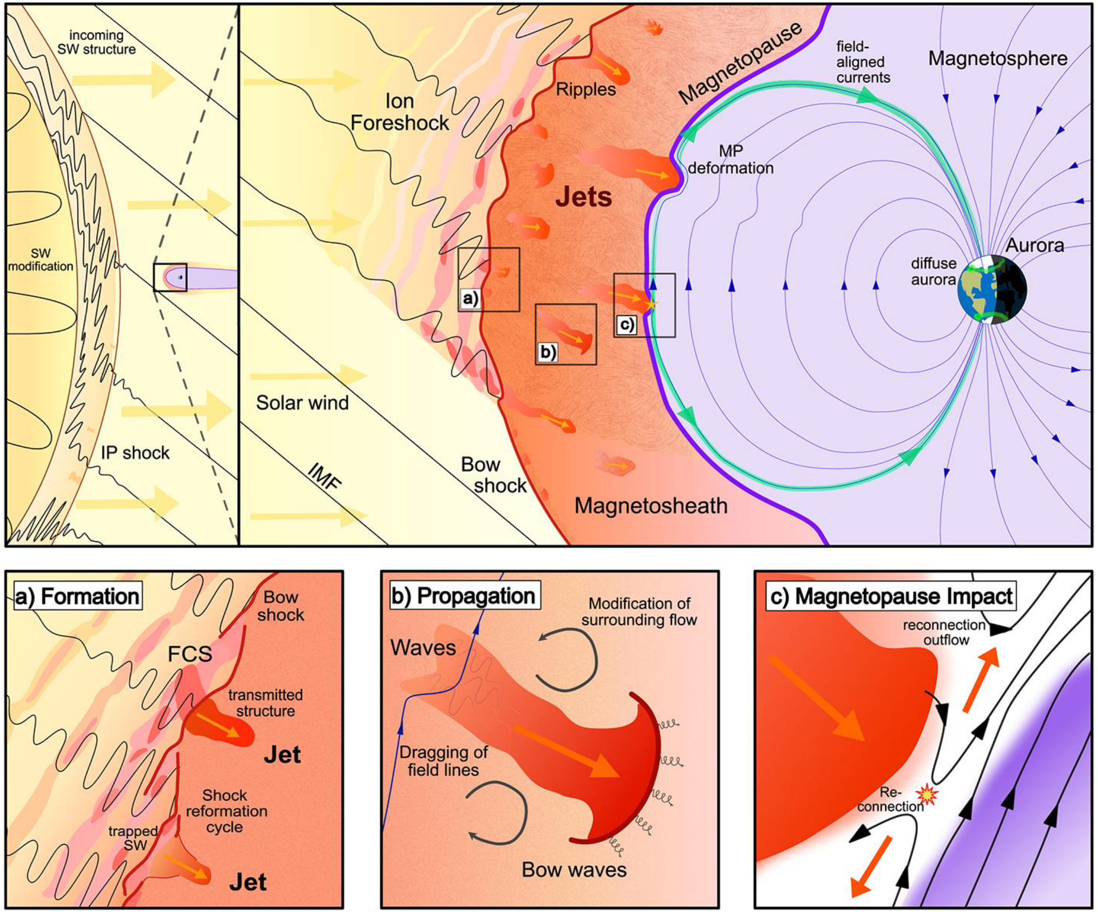
occurrence: ~3 jets/h

from: shock kinetic processes

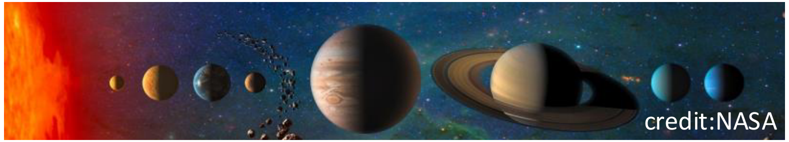
drive: particle acceleration, large amplitude waves, reconnecting current sheets

reviews:

[Plaschke et al., 2018; Kraemer et al., 2025]



[courtesy of F.Koller]



Transient structures near shocks

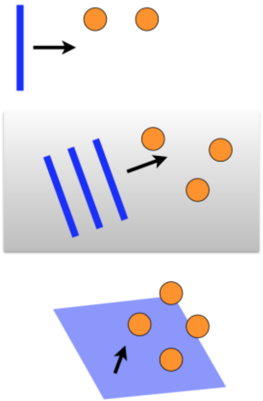
summary

	coronal shocks	interplanetary shocks	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Titan	comets	termination shock
ULFs	?	yes	yes	yes	yes	yes	yes	yes	?	yes	?
shocklets	?	rare	yes?	yes	yes	yes	yes	yes	yes	yes	?
SLAMS	?	no?	yes	yes	yes	yes	yes	yes	?	yes	?
SHFAs	?	?	?	yes	yes	yes	?	?	yes?	?	?
HFAs	?	?	maybe?	yes	yes	yes	yes	yes	?	?	?
FBs	?	?	?	?	yes	?	?	?	?	?	?
jets	?	yes	maybe?	?	yes	yes?	yes?	?	?	?	?

System specific but universal physical processes

[Hietala et al. ISSI 2019]

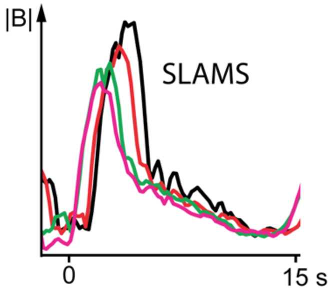
What's next for Earth:
constellation mission



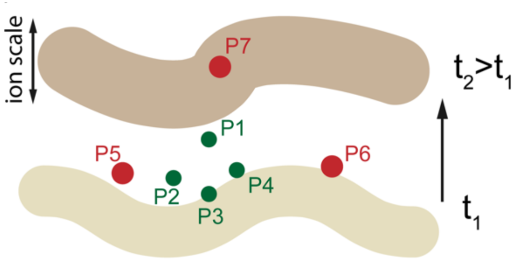
1D motion: 2 spacecraft
e.g., ISEE 1-2

2D motion: 3 spacecraft

3D motion: 4 spacecraft
e.g., CLUSTER, MMS



adapted from [Lucek et al., 2008]



[Plasma Observatory team]

distinguish growth vs motion? *quantify non-planarity?* *measure non-linear gradients?*	**7 spacecraft**

Backups

Shock scales exercise: interplanetary shocks

Each of you will get your own shock event observed by Wind spacecraft at L1 and
explore it at different scales, and
compare with neighbor

How to access and plot data on CDAWeb:

https://cdaweb.gsfc.nasa.gov/

1) Select Wind spacecraft (last in the alphabetic list)
and
magnetic fields (space)

and press “submit”

Shock scales exercise: interplanetary shocks

2) Select WI_H0_MFI (3 sec, 1min and 1 hour)
and
WI_H2_MFI (high res, 11Hz)

and press "submit"

Submit

- [ ] **OMNI_HRO_1MIN:** OMNI Combined, Definitive, 1-minute IMF and Plasma Data Time-Shifted to the Nose of the Earth's Bow Shoc
[Available Time Range: 1981/01/01 00:00:00 - 2025/04/20 23:59:00] Info/DOI Metadata
- [ ] **OMNI_HRO_5MIN:** OMNI Combined, Definitive, 5-minute IMF and Plasma, and Energetic Proton Fluxes, Time-Shifted to the Nose
[Available Time Range: 1981/01/01 00:00:00 - 2025/04/20 23:55:00] Info/DOI Metadata
- [ ] **OMNI_HRO2_1MIN:** OMNI Combined, Definitive 1-minute IMF and Definitive Plasma Data Time-Shifted to the Nose of the Earth's
[Available Time Range: 1995/01/01 00:00:00 - 2025/04/20 23:59:00] Info/DOI Metadata
- [ ] **OMNI_HRO2_5MIN:** OMNI Combined, Definitive 5-minute IMF and Definitive Plasma, and Energetic Proton Fluxes, Time-Shifted t
[Available Time Range: 1995/01/01 00:00:00 - 2025/04/20 23:55:00] Info/DOI Metadata
- [ ] **OMNI2_H0_MRG1HR:** OMNI Combined, Definitive, Hourly IMF and Plasma Data, and Energetic Proton Fluxes, Time-Shifted to th
[Available Time Range: 1963/01/01 00:00:00 - 2025/05/02 11:00:00] Info/DOI Metadata
- [ ] **OMNI_COHO1HR_MERGED_MAG_PLASMA:** OMNI Combined merged hourly magnetic field, plasma and ephermis data - J.H. K
[Available Time Range: 1963/01/01 00:00:00 - 2025/04/29 01:00:00] Info/DOI Metadata
- [x] **WI_H0_MFI:** Wind Magnetic Fields Investigation: 3 sec, 1 min, and hourly Definitive Data. - A. Koval (UMBC, NASA/GSFC)
[Available Time Range: 1994/11/13 00:00:30 - 2025/05/07 23:59:30] Info/DOI Metadata
- [x] **WI_H2_MFI:** Wind Magnetic Fields Investigation, High-resolution Definitive Data - A. Koval (UMBC, NASA/GSFC)
[Available Time Range: 1994/11/13 15:50:26 - 2025/05/07 23:59:59] Info/DOI Metadata
- [ ] **WI_H3-RTN_MFI:** Wind Magnetic Fields Investigation: 3 sec, 1 min, and hourly Definitive Data (RTN). - A. Koval (UMBC, NASA/G
[Available Time Range: 1994/11/13 00:00:30 - 2025/05/07 23:59:30] Info/DOI Metadata
- [ ] **WI_H4-RTN_MFI:** Wind Magnetic Fields Investigation, High-resolution Definitive Data (RTN) - A. Koval (UMBC, NASA/GSFC)
[Available Time Range: 1994/11/13 15:50:26 - 2025/05/07 23:59:59] Info/DOI Metadata
- [ ] **WI_K1-RTN_MFI:** Wind Magnetic Fields Investigation, Key Parameters in RTN [PRELIM] - Andriy Koval (UMBC&GSFC)
[Available Time Range: 2017/01/01 00:00:19 - 2025/05/08 23:58:36] Info/DOI Metadata
- [ ] **WI_K0_MFI:** Wind Magnetic Fields Investigation, Key Parameters [PRELIM] - R. Lepping (NASA/GSFC)
[Available Time Range: 2017/07/01 00:00:00 - 2025/05/11 23:59:32] Info/DOI Metadata
- [ ] **WI_H1_SWE:** Wind Solar Wind Experiment, 92-sec Solar Wind Alpha and Proton Anisotropy Analysis - K. Ogilvie (NASA GSFC)
[Available Time Range: 1994/11/17 19:50:45 - 2025/03/19 23:53:26] Info/DOI Metadata
- [ ] **WI_H1_SWE_RTN:** Solar wind proton and alpha parameters, including anisotropic temperatures, derived by non-linear fitting of th
[Available Time Range: 1994/11/17 19:50:45 - 2025/03/19 23:53:26] Info/DOI Metadata
- [ ] **WI_K0_GIFWALK:** Links to Wind KP pre-generated survey and other plots - Polar-Wind-Geotail Ground System (NASA GSFC)
[Available Time Range: Select dataset for details] Info/DOI Metadata

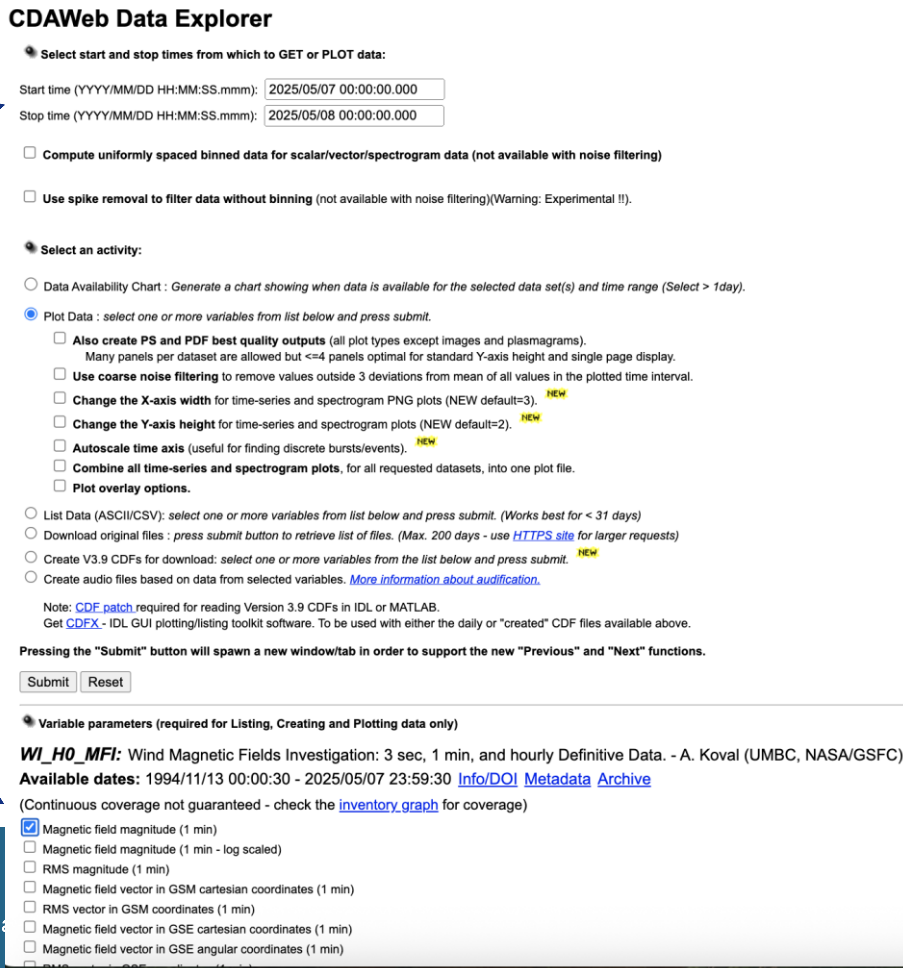
Submit Reset

Shock scales exercise: interplanetary shocks

3) Here you will insert your event time (in a moment)

and here you will select your magnetic field data at different cadences

and press "submit"



Shock scales exercise: interplanetary shocks

Task

- Assume ion inertial length d_i = 100km, and solar wind velocity V_{sw} ~ 500km/s
- **What temporal scales you need to look at** if you're interested in
  a) Reconnection in turbulence
  b) Shock ion kinetic structures
  c) Fluid scales (100-1000 d_i)
  d) Space weather simulation output
     (zoom out until you see the shock driver (CME))

  11Hz, 3s, 1min, or 1 hour cadence?
  How long a window size?

- Make plots for each and discuss with neighbours