In situ shock analysis

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Outline and learning outcomes

- What does an interplanetary shock look like in spacecraft observations
- Shock parameter estimation
  - What are the basic parameters
    - shock normal vector
    - shock speed
      -> shock obliquity and Mach numbers
  - MHD theory to estimates in practise
    - how to apply
    - merits and caveats

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Introduction

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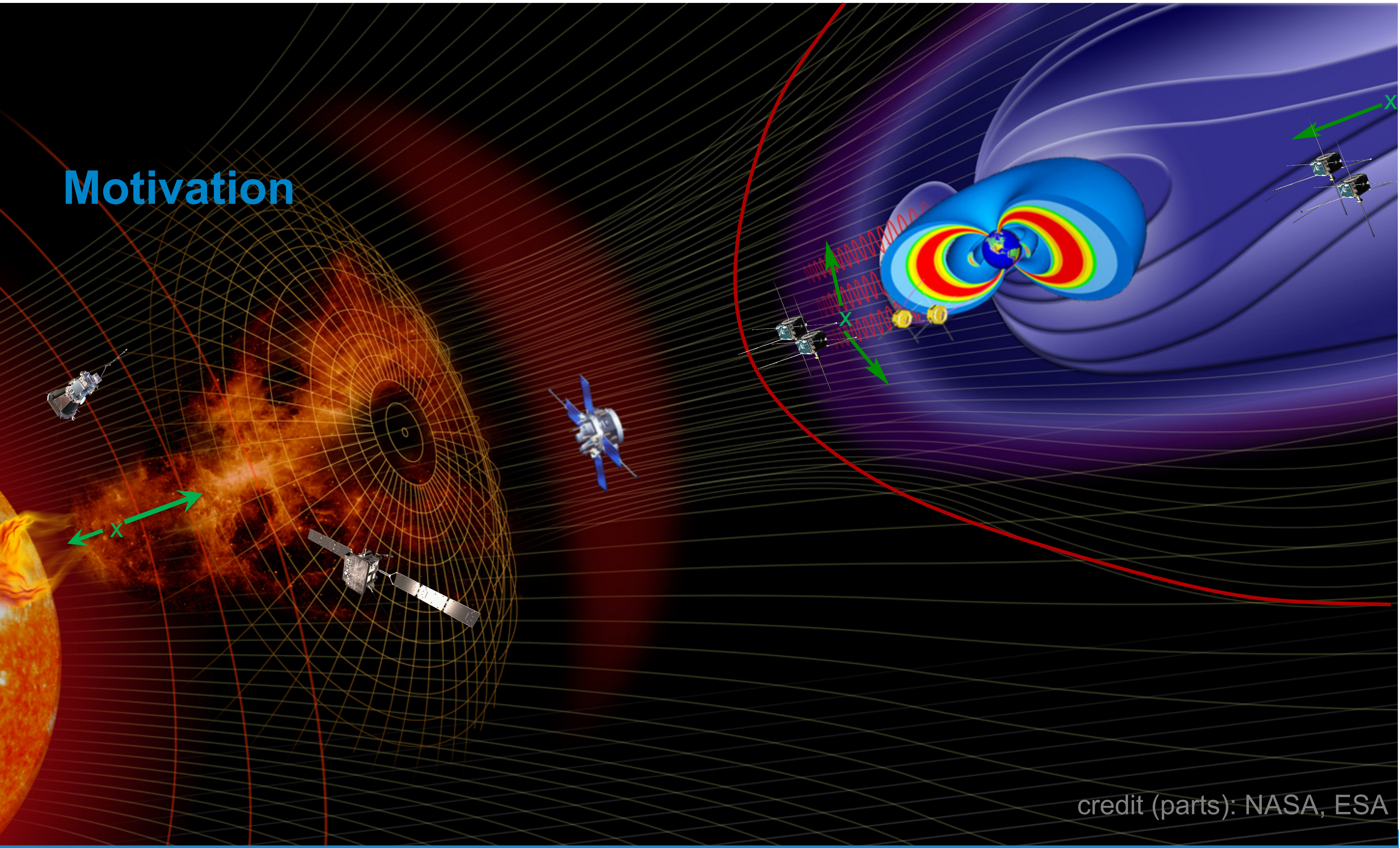
Motivation



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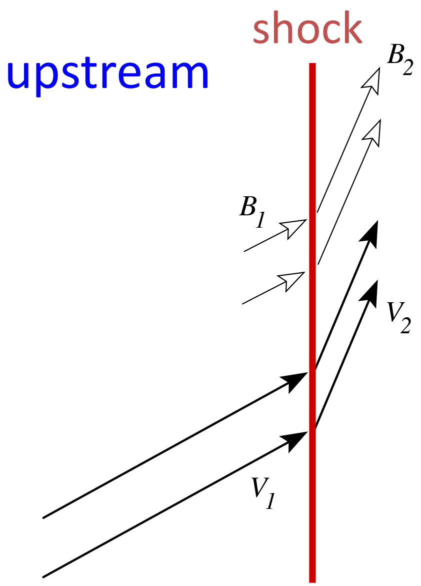
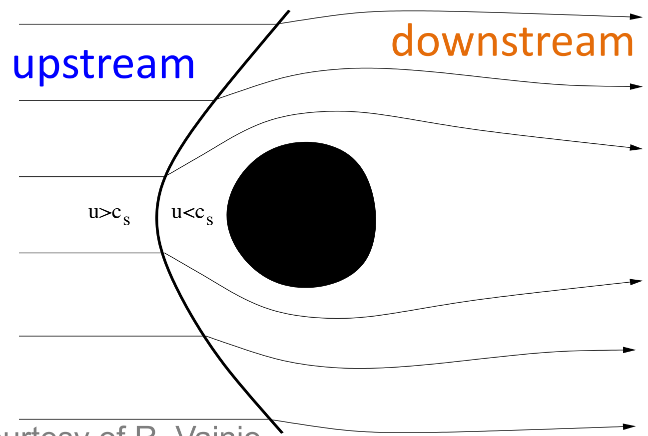
What is a space plasma shock?



downstream

slower
denser
hotter
higher |B|



courtesy of R. Vainio

shock: flow speed ↓
speed of information ↑

M_A, M_S, M_f

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Shocks in observations

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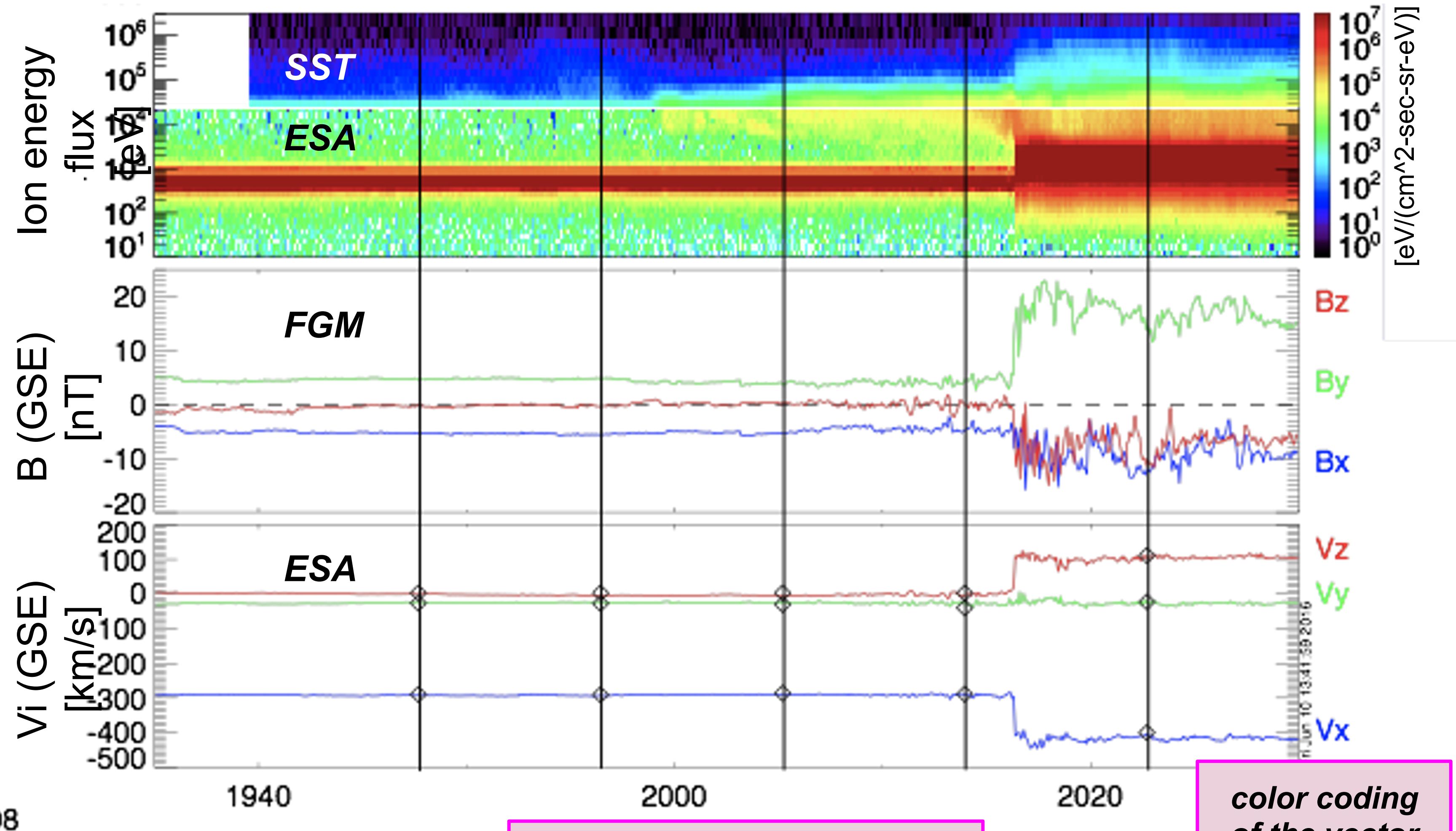
What does an interplanetary shock look like using *in situ* observations?

theta$_{Bn}$ ~ 60 deg
M_A ~ 4.9

Interplanetary shock passing over ARTEMIS in the solar wind



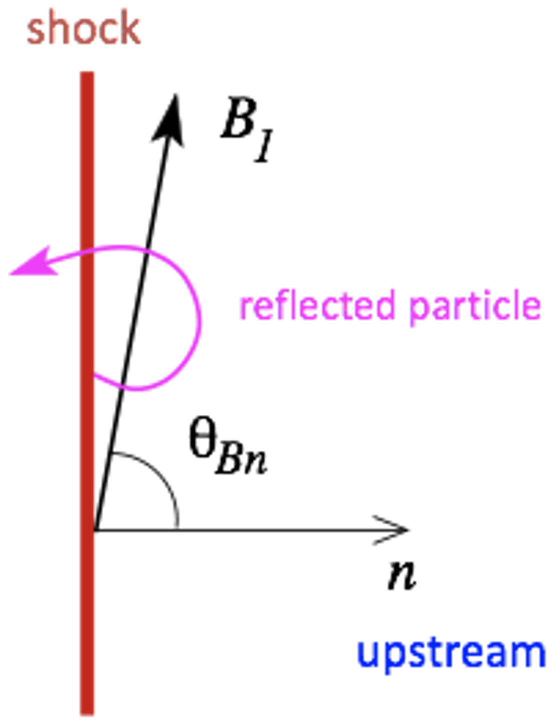
date and time

Universal Time (UT)

color coding of the vector components

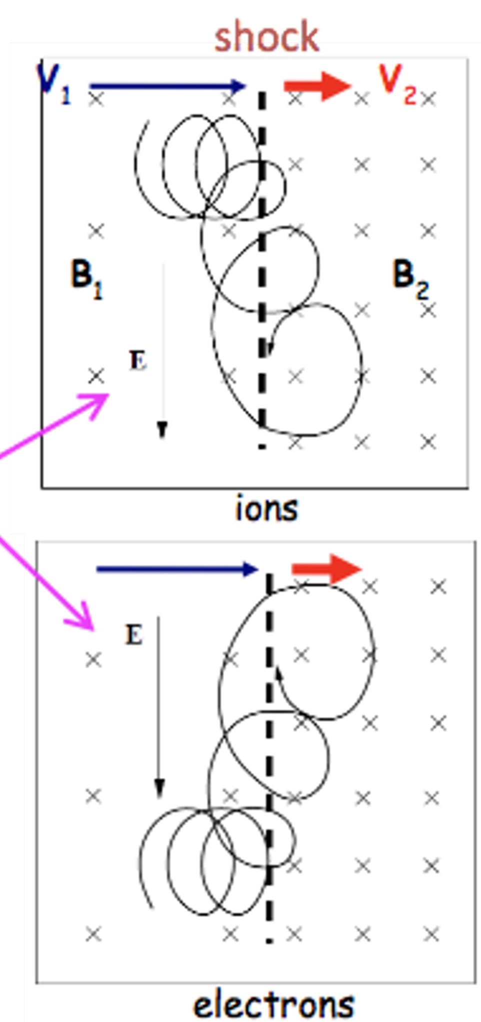
Upstream magnetic field orientation: shock obliquity

quasi-perpendicular



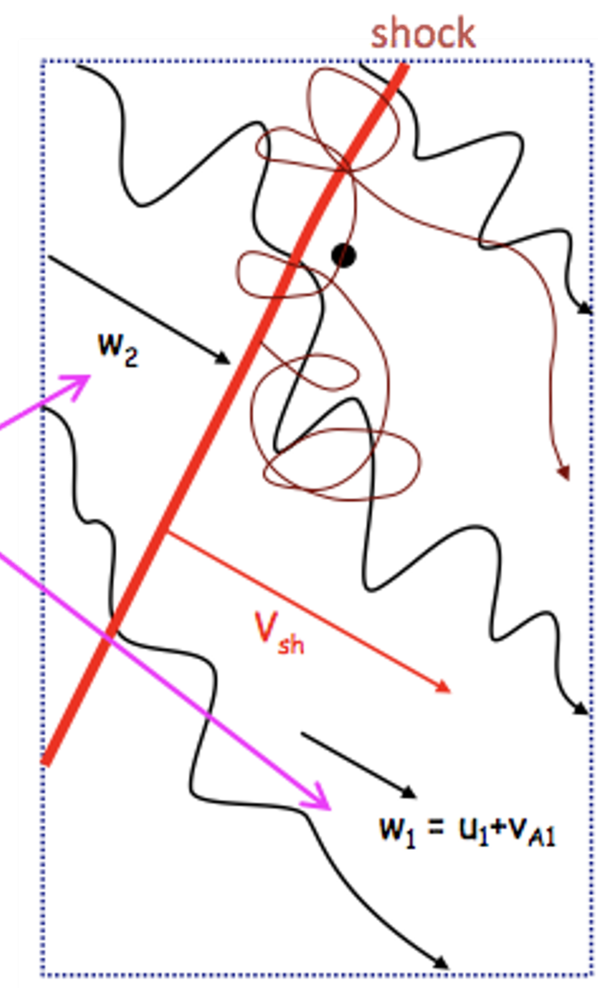
Particle acceleration: sneak peek

Shock Drift Acceleration



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

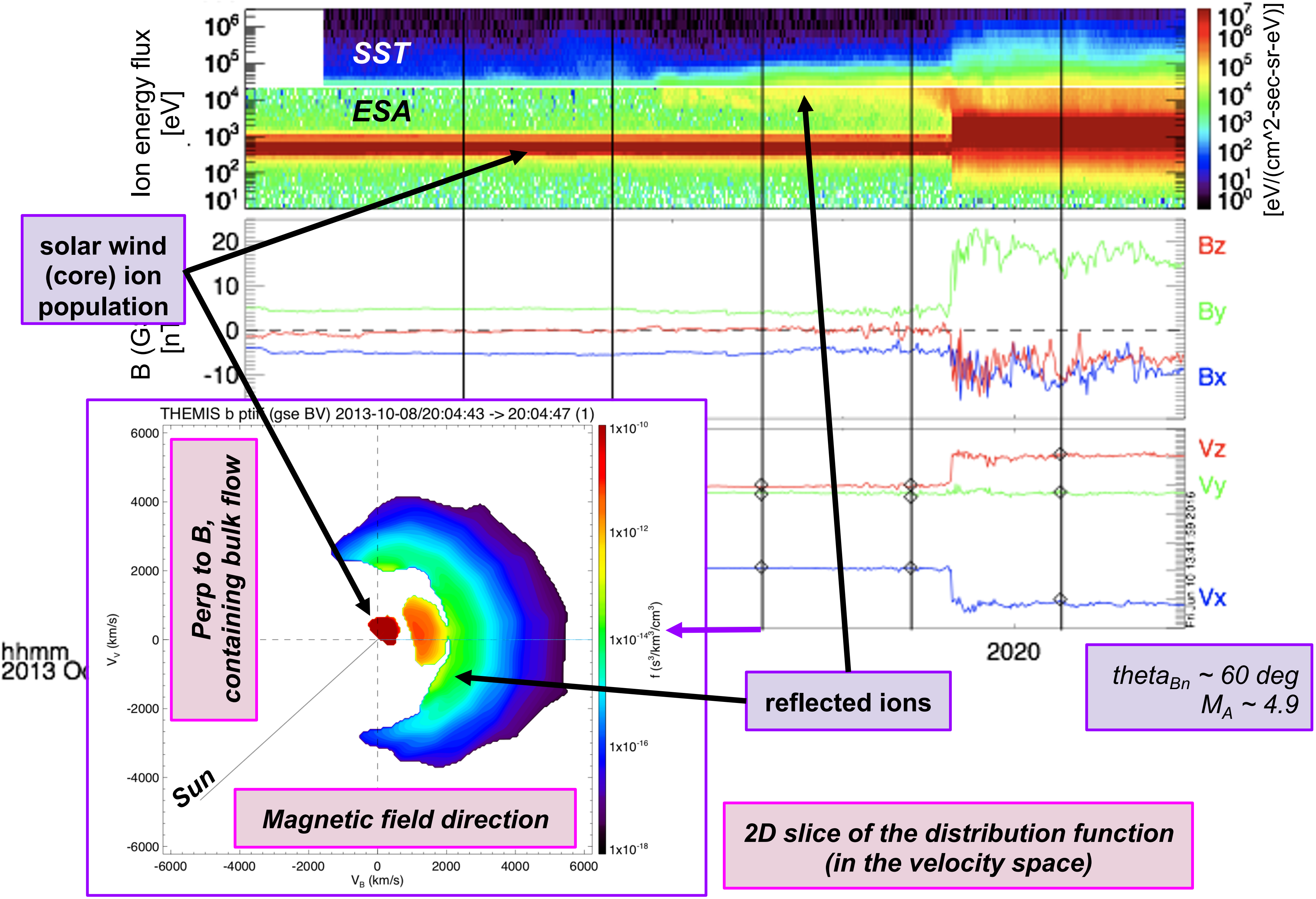
Diffusive Shock Acceleration



interactions with waves upstream and downstream

figures: R. Vainio

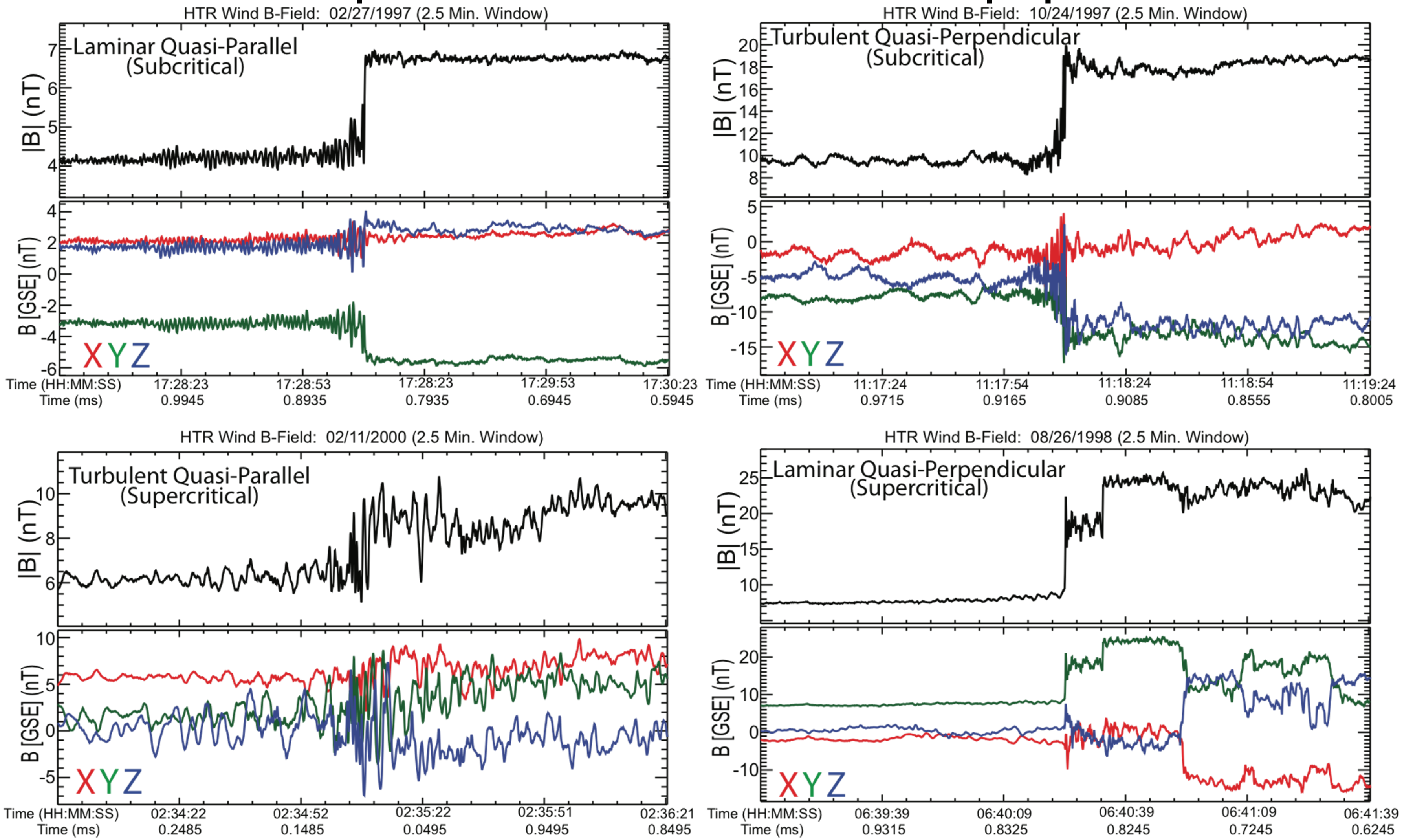
Interplanetary shock passing over ARTEMIS in the solar wind



Examples of shocks with different obliquity

Interplanetary shocks: Wind

Quasi-parallel | **Quasi-perpendicular**

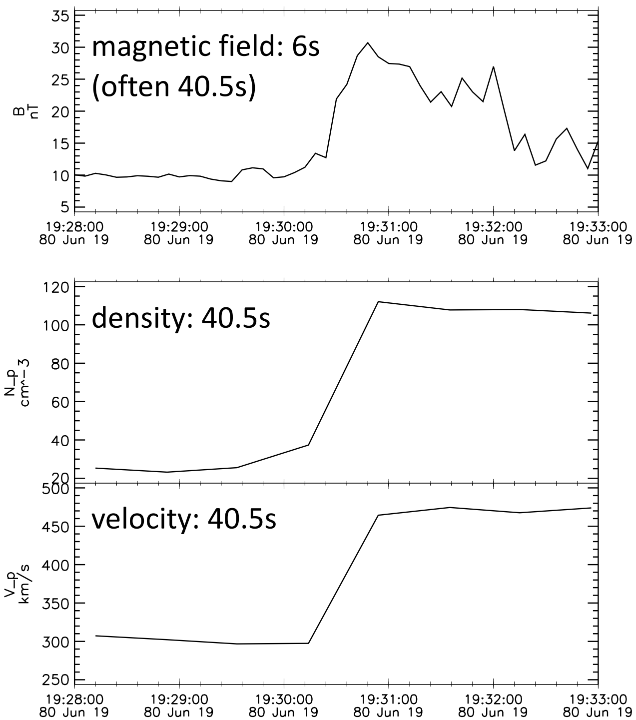


[Wilson, PhD thesis, 2010]

Temporal cadence of the measurements influences your interpretation

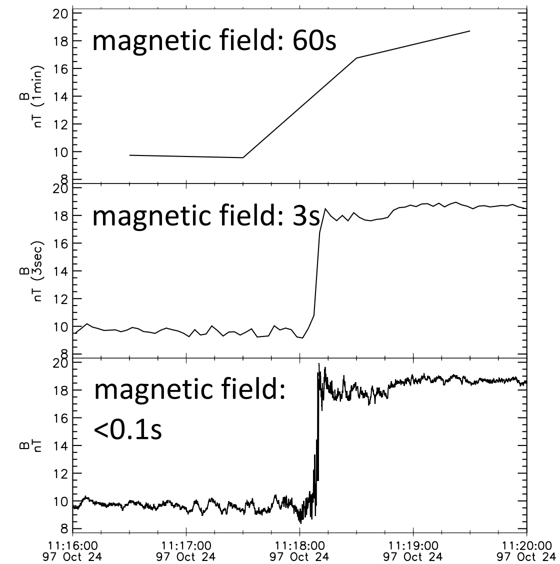
PAST

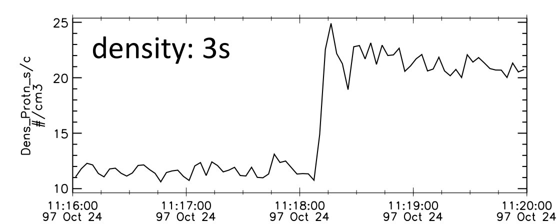
HELIOS data (1970s and 80s)



PRESENT

Example with near-Earth data (WIND)





FUTURE

Solar Orbiter burst mode: 128 vectors/s magnetic field data, 1s plasma and particle data.

Parameter estimation

- We want to estimate the shock normal vector and the shock speed
  - These will allow us to estimate the shock obliquity and Mach number
  - These will allow us to put characterise the shock and put the other observations in context

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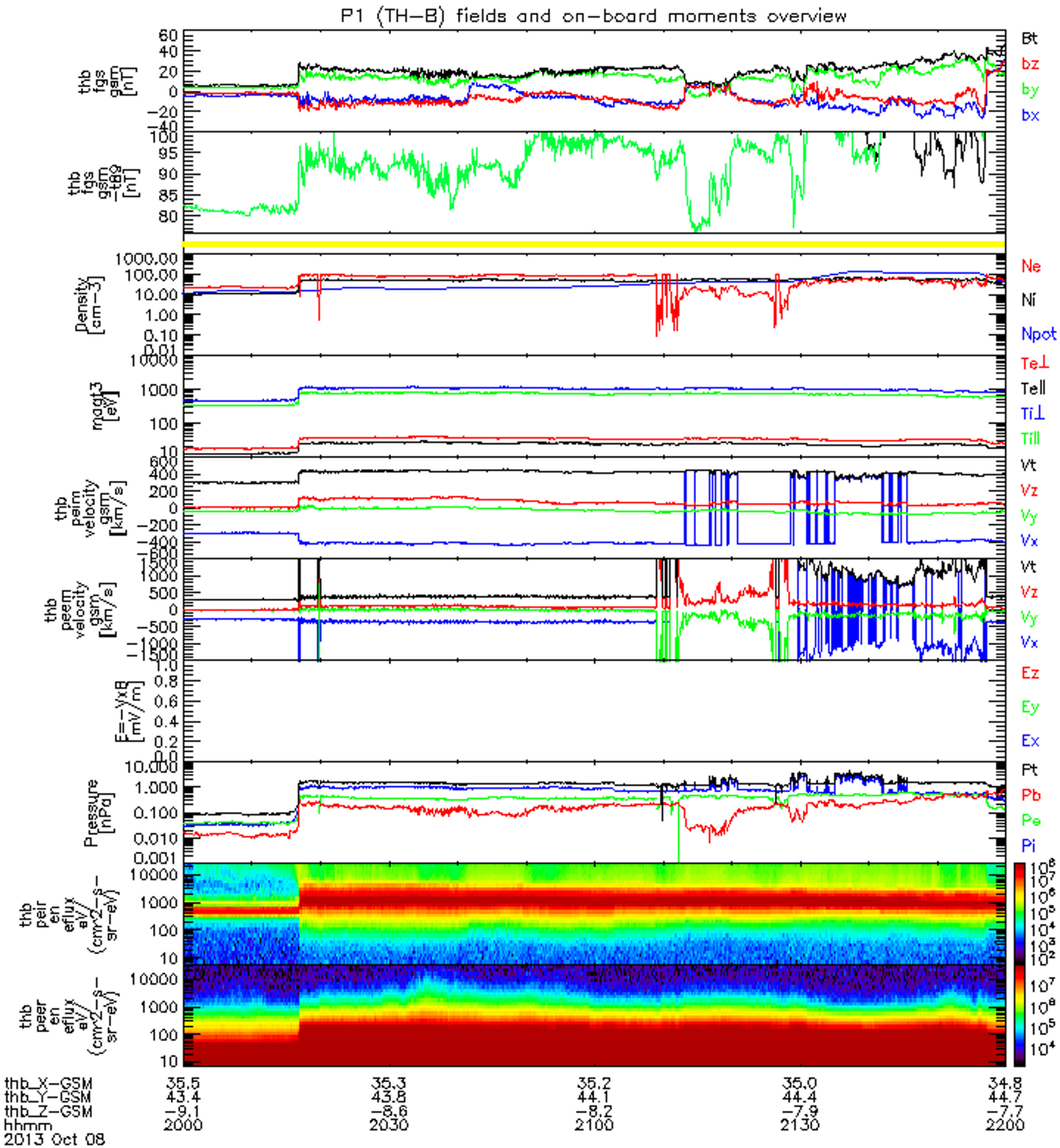
What do we have?
(1) spacecraft data



ARTEMIS shock example again

Observations are never perfect

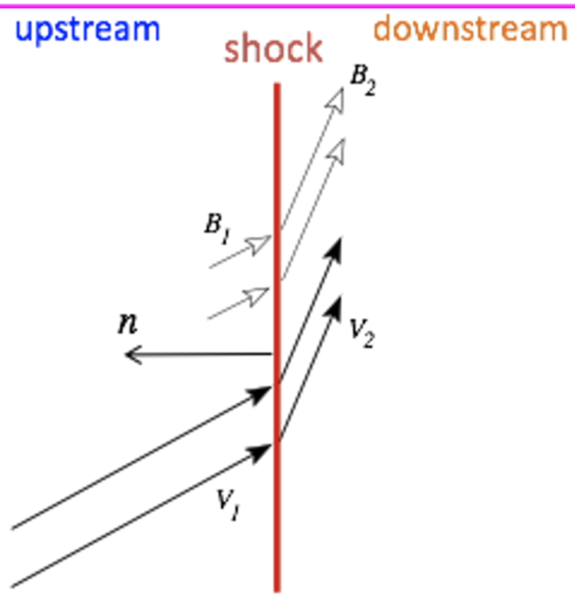
- Data gaps
- Non-ideal instrument performance due to
  - Sensitivity
  - Plasma region
  - Contamination
  - Calibration
  - (26 known issues for THEMIS ESA alone)

What do we have?

(2) Rankine-Hugoniot jump conditions from ideal MHD

$$
\begin{aligned}
[\rho_m V_n] &= 0 && \text{conservation of mass} \\
[\rho_m V_n^2 + P + \frac{B_t^2}{2\mu_0}] &= 0 \\
[\rho_m \mathbf{V}_t V_n - \frac{\mathbf{B}_t B_n}{\mu_0}] &= 0 && \text{conservation of momentum} \\
[\frac{1}{2}\rho_m V^2 V_n + \frac{\gamma P}{\gamma - 1} V_n + \frac{B_t^2}{\mu_0} V_n - \frac{\mathbf{V}_t \cdot \mathbf{B}_t}{\mu_0} B_n] &= 0 && \text{conservation of energy} \\
[B_n] &= 0 && \text{B is divergence-free} \\
[\mathbf{V}_t B_n - \mathbf{B}_t V_n] &= 0. && \text{induction equation (} E_t \text{ continuous)}
\end{aligned}
$$

$$0 = \{\mathbf{F}(0^+) - \mathbf{F}(0^-)\} \cdot \mathbf{n} \equiv \mathbf{F}_2 \cdot \mathbf{n} - \mathbf{F}_1 \cdot \mathbf{n} \equiv [\mathbf{F} \cdot \mathbf{n}]$$



What assumptions did we make?

- infinitely thin
  (shock layer is a “black box”)
- infinitely extended
  (essentially 1D)
- planar
  (not curved, rippled,...)
- time-stationary
  (no time variations)
- laminar flows
  (no waves, turbulence, ...)

Shock normal: co-planarity methods

Rankine-Hugoniot equations:

The upstream and downstream magnetic field vectors are in the same plane as the shock normal:

$$\mathbf{n} = \pm \frac{(\mathbf{B}_2 \times \mathbf{B}_1) \times (\mathbf{B}_2 - \mathbf{B}_1)}{|(\mathbf{B}_2 \times \mathbf{B}_1) \times (\mathbf{B}_2 - \mathbf{B}_1)|}$$

Similar equations using also velocity vectors ("mixed-mode"):

$$\hat{\boldsymbol{n}}_{MX1} = \pm \frac{(\boldsymbol{B}_u \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}}{|(\boldsymbol{B}_u \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}|}$$

$$\hat{\boldsymbol{n}}_{MX2} = \pm \frac{(\boldsymbol{B}_d \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}}{|(\boldsymbol{B}_d \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}|}$$

$$\hat{\boldsymbol{n}}_{MX3} = \pm \frac{(\Delta \boldsymbol{B} \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}}{|(\Delta \boldsymbol{B} \times \Delta \boldsymbol{V}^{\mathrm{arb}}) \times \Delta \boldsymbol{B}|}$$

Notes:

- use upstream and downstream **average** values (to remove waves)
- **vary** the averaging windows (systematically and in a manner consistent with the data cadence)
- do **not** include the shock layer (but stay close to it)
- magnetic field data at higher cadence and accuracy than plasma data
  -> magnetic co-planarity method often preferable to the mixed-mode method

single sc methods

Shock speed: mass flux algorithm

Rewrite the conservation of mass across the shock front

$$[\rho_m V_\mathrm{n}] \quad = \quad 0$$

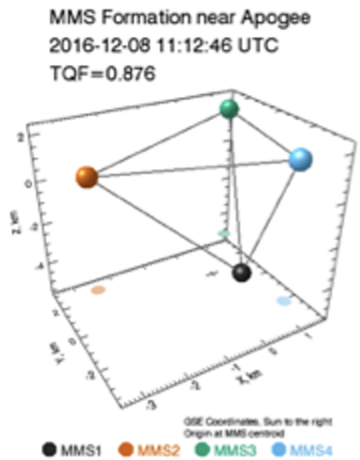
using the velocities measured in the spacecraft frame:

$$\boxed{V_\mathrm{sh}^\mathrm{sc} = \frac{(\rho_{m2}\mathbf{V}_2^{sc} - \rho_{m1}\mathbf{V}_1^{sc}) \cdot \mathbf{n}}{\rho_{m2} - \rho_{m1}}}$$

Notes:

- the shock speed is along the shock normal
- need to estimate shock normal first
- vary the up and downstream averaging windows
- do not include the shock layer
- only as good as your plasma measurements

Shock normal and speed: 4-spacecraft method



Cluster, MMS, lucky conjunctions, ...

$$\frac{(\mathbf{r}_1 - \mathbf{r}_\alpha) \cdot \mathbf{n}}{V_{\mathrm{sh}}^{\mathrm{sc}}} = (t_1 - t_\alpha) \quad \alpha = 2 \dots 4$$

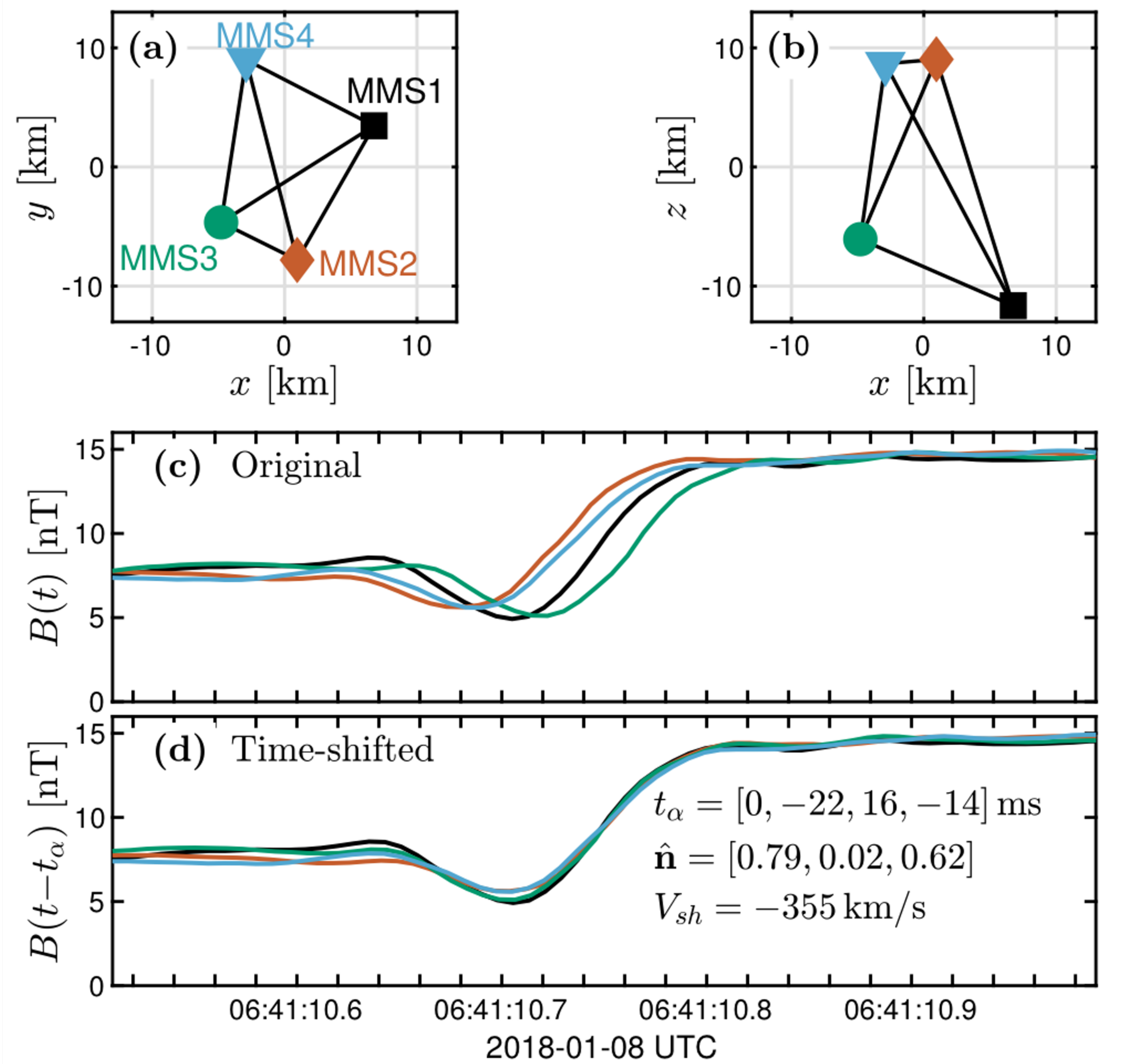
Notes:

- **Merit 1:** only requires data of spacecraft location and timing of a structure from, e.g., magnetic field
- **Merit 2:** gives both the normal and the speed at the same time
- **Merit 3:** you can compare the result with four single sc normals
- **Caveat 1:** spacecraft must be non-co-planar (a good tetrahedron)
- **Caveat 2:** assumes that the shock is planar at the scale of the tetrahedron
- **Caveat 3:** identifying the same structure at 4 different spacecraft can be difficult and subjective

multi sc methods

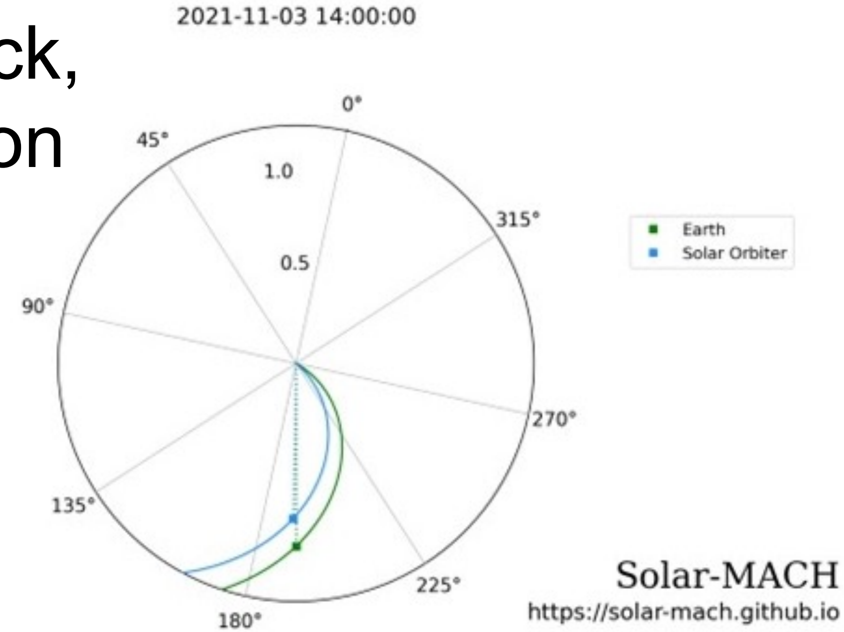
Example: 4-spacecraft timing method, an MMS interplanetary shock crossing

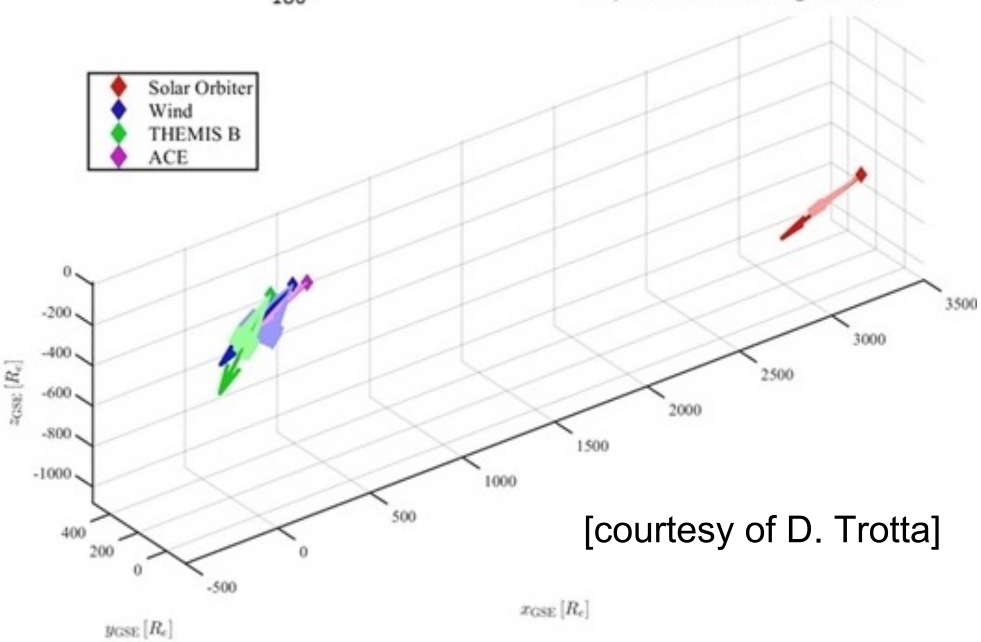
[Johlander, PhD thesis, 2019]



Example:
multi-spacecraft timing check, SolarOrbiter – L1 conjunction

$$\frac{(\mathbf{r}_1 - \mathbf{r}_\alpha) \cdot \mathbf{n}}{V_{\mathrm{sh}}^{\mathrm{sc}}} = (t_1 - t_\alpha) \qquad \alpha = 2 \ldots 4$$



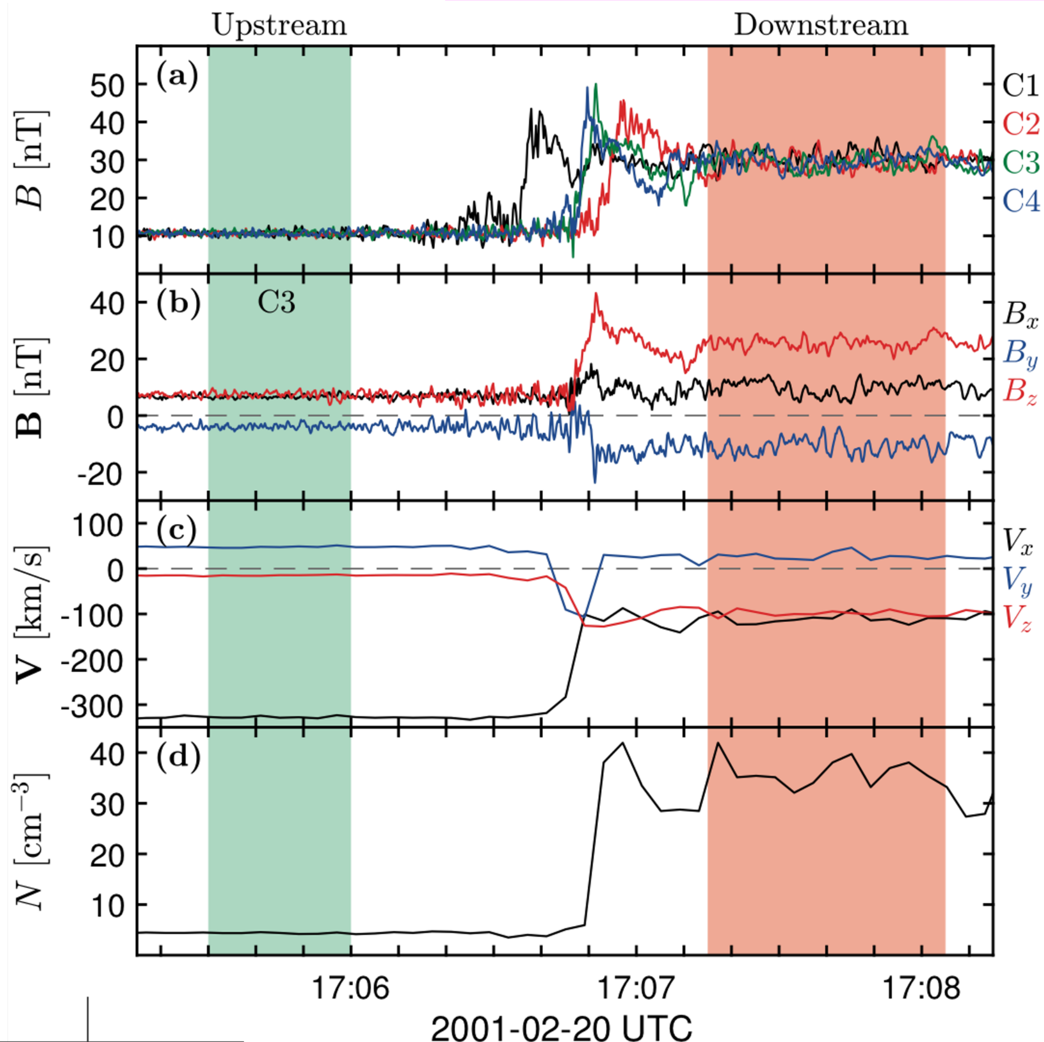


[courtesy of D. Trotta]

Example:
Comparing different methods, a Cluster bow shock crossing

[Johlander, PhD thesis, 2019]

Parameter	Value
$\mathbf{B}_u$	$(6.7, -3.9, 7.4)$ nT
$\mathbf{B}_d$	$(9.9, -11.1, 25.7)$ nT
N_u	$4.4\,\mathrm{cm}^{-3}$
N_d	$36.3\,\mathrm{cm}^{-3}$
$\mathbf{V}_u$	$(-327, 48, -15)$ km/s
$\mathbf{V}_d$	$(-111, 28, -99)$ km/s



Normal vectors		**Speeds**	
Timing	(0.93, -0.21, -0.29)	Timing	28 km/s
B coplanarity	(0.97, -0.10, -0.21)	Mass flux	-49 km/s
V coplanarity	(0.93, -0.09, -0.36)	Tangential **E**	36 km/s
Mixed mode	(0.96, -0.14, -0.22)	Shock foot th.	25 km/s
Bow shock model[a]	(0.97, -0.06, -0.23)		

[a] Model by [Farris et al., 1991].

Mach number

Mach number: Dimensionless number characterising the fluid flow *M*.

Sound speed $V_S = \sqrt{\gamma k_B T / m}$

Alfven speed $V_A = \sqrt{B^2 / \mu_0 \rho_m}$

Slow and fast mode magnetosonic speeds:

$$V_{\substack{s\\f}}^2 = \frac{1}{2}(V_S^2 + V_A^2) \mp \frac{1}{2}\sqrt{(V_S^2 + V_A^2)^2 - 4V_S^2 V_A^2 \cos^2\theta},$$

The relevant Mach number for shock formation is the ratio between the component of upstream plasma velocity parallel to the shock wave vector (shock normal) V_{1n} evaluated in the reference frame moving with the shock and the phase velocity of the wave mode in the plasma frame.

$$M_{f1} = (\boldsymbol{V}_1^{sc} - V_{sh}^{sc}\,\boldsymbol{n})\cdot\boldsymbol{n} / V_{f1}$$

Notes: most shocks are fast mode shocks

4.4 Is it a shock? - an analysis recipe

1) Estimate the **shock normal** (with various methods)
2) Calculate the **shock obliquity** θ_{Bn}
   (the angle between shock normal and the upstream magnetic field)
3) Estimate the **shock speed** (using the various normals from step 1)
   check timing with other sc
   [iterate steps 1-3]
4) Shift your velocity observations **into the frame moving with the shock**
5) Calculate **the component of the upstream velocity normal to the shock**
   sanity check: the plasma should be flowing into the shock, not away from it
6) Estimate **the fast magnetosonic speed**
   a) Estimate ion (and electron) temperatures (these will have large uncertainties) and combine into a single MHD plasma temperature
   b) Calculate sound speed and Alfven speed
   c) Calculate the fast magnetosonic wave speed using the θ_{Bn} (from step 2)
7) Mach number: calculate **the ratio between the upstream velocity normal to the shock and the fast magnetosonic wave speed** (you will have several)
   -for the discontinuity to be a shock, the fast mode Mach number should be >1
   -additional check: the ratio with the normal outflow velocity should be <1
8) Report the range(s) of values you got

Not every jump is shock

examples of what else is out there

- No plasma flow across the discontinuity: $V_n = 0$
  - contact discontinuity
    - two plasmas at different densities and temperatures next to each other
    - all other quantities constant
  - tangential discontinuity
    - pressure and B field change but maintain pressure balance
    - example: magnetopause (when it's not reconnecting)
- No compression: density, $|B|$ and V_n are constant
  - rotational discontinuity
    - tangential magnetic field changes sign
    - a large amplitude Alfven wave

And these do not accelerate particles

Summary

- There are shocks all around, all the time
  - We care because they can accelerate particles
- A shock looks like a jump in spacecraft data
  - But not all jumps are shocks
- You can use MHD theory to construct estimates of the shock properties:
  - start with shock normal and speed

BUT

- a lot of assumptions which may not hold in reality go into both the theory and the application

further reading: Paschmann and Daly, "Analysis Methods for Multi-Spacecraft Data", ISSI SR, 2000

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Thank you

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Backups

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How do you define "zero", "constant", and "no change" in practice?

10:1 rule

- if $V_n < 0.1V_{tot}$ it is practically 0
- if $B_n < 0.1B_{tot}$ it is practically 0
- ...

- if the change in $V_n < 0.1\ V_{tot}$ it is practically constant
- if the change in $B_n < 0.1\ B_{tot}$ it is practically constant
- ...

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