Altered solar wind – magnetosphere interaction at low Mach number

Benoit Lavraud

IRAP/CNRS, Toulouse, France

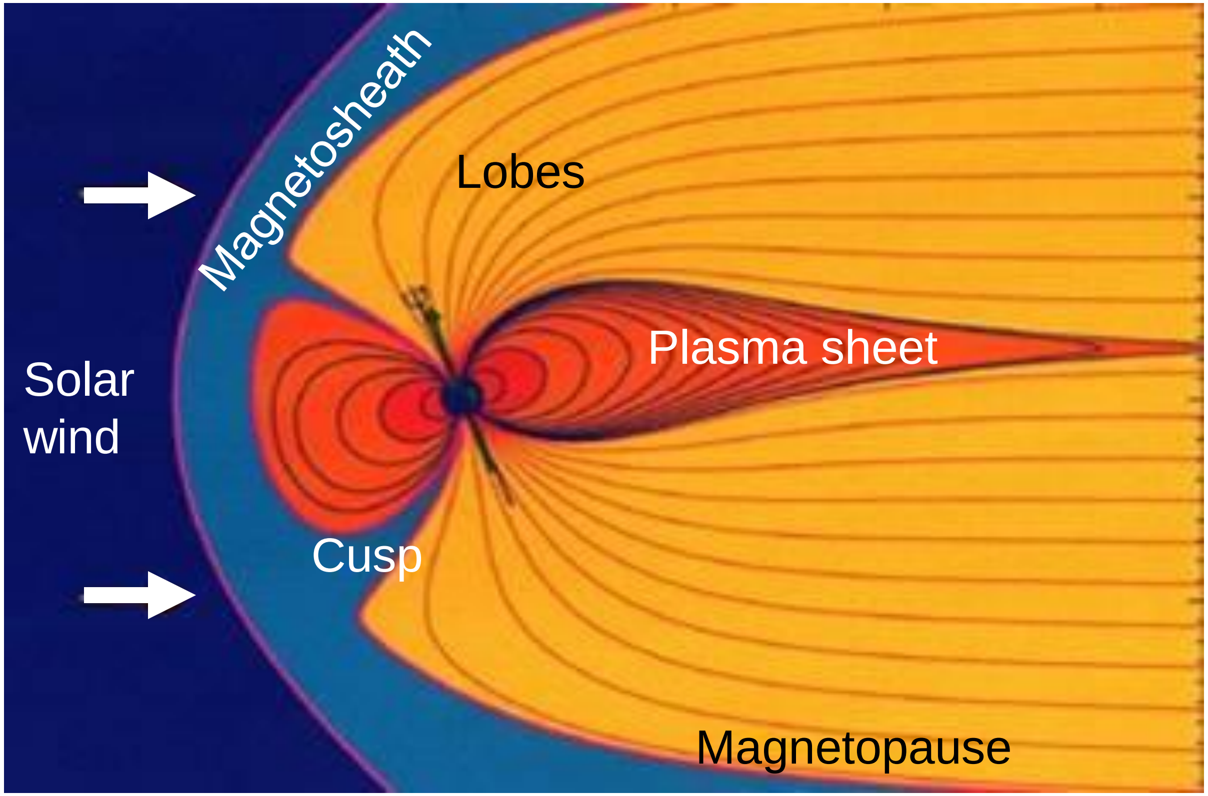
Geospace Revisited 2014, Rhodes, September 2014

OUTLINE

- Introduction and motivation
- Magnetosheath β properties
- Asymmetric flows in the magnetosheath
- Asymmetric magnetopause shape
- Sunward magnetosheath flows
- Formation of Alfvén wings
- Other expected effects
- Conclusions

MOTIVATION :

An “unknown” or “over-looked” magnetosphere



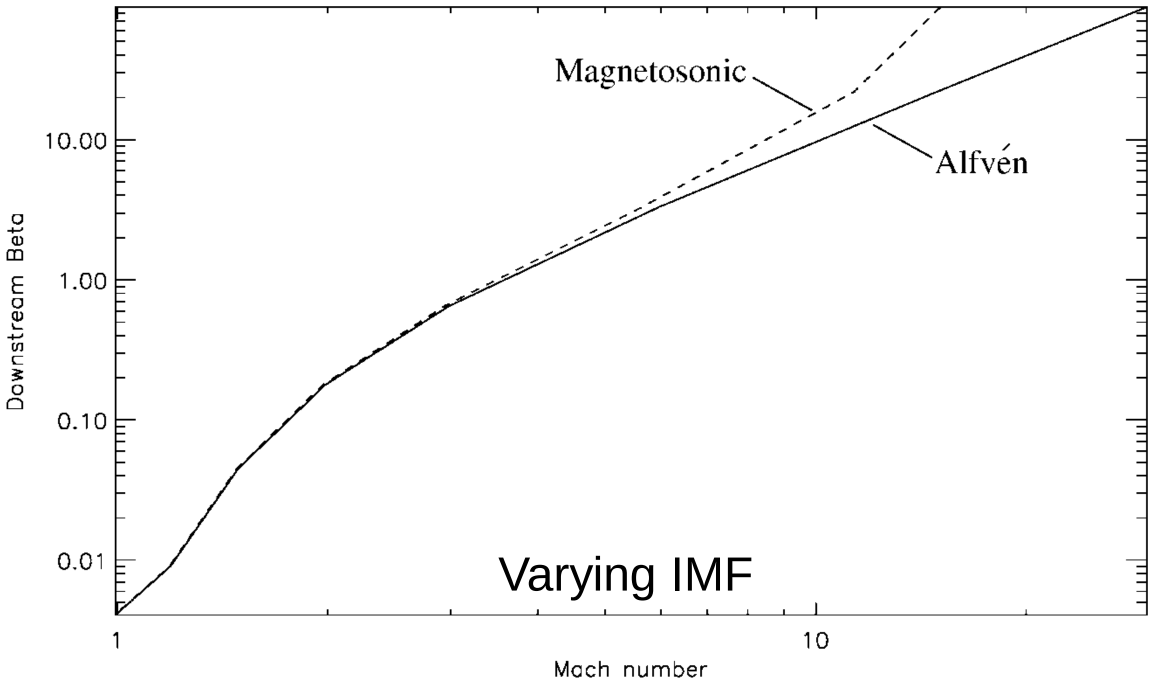
High Mach number
=
High-β magnetosheath

Low Mach number
=
Low-β magnetosheath

- **Pivotal role of magnetosheath**
- **Implications for CME-driven storms**

Magnetosheath β as a function of SW Mach number

Perpendicular shock case

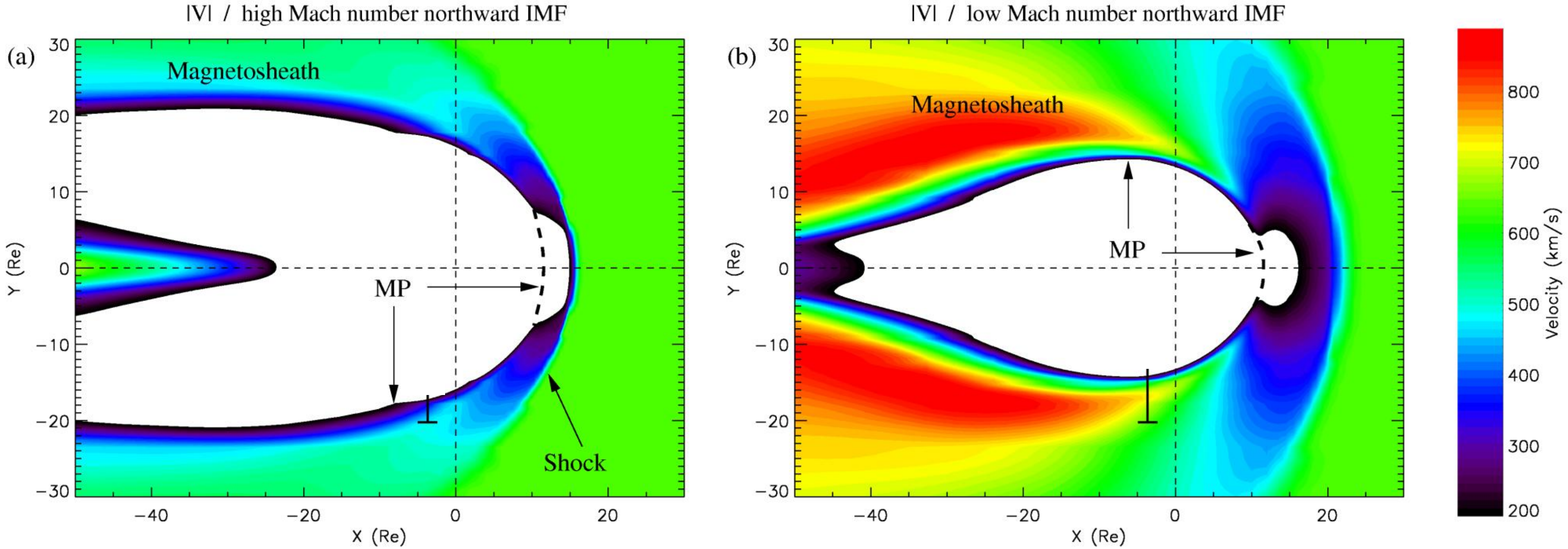


- Rankine-Hugoniot shock Jump conditions
- $M_{MS} = V_{SW} / \sqrt{(V_A^2 + V_S^2)}$
- $M_A = V_{SW} / V_A$
- $M_A > M_{MS}$

→ Low-β magnetosheath prevails during low Mach numbers: Magnetic forces become important/dominant

Magnetosheath flow dependence on Mach number

Equatorial planes

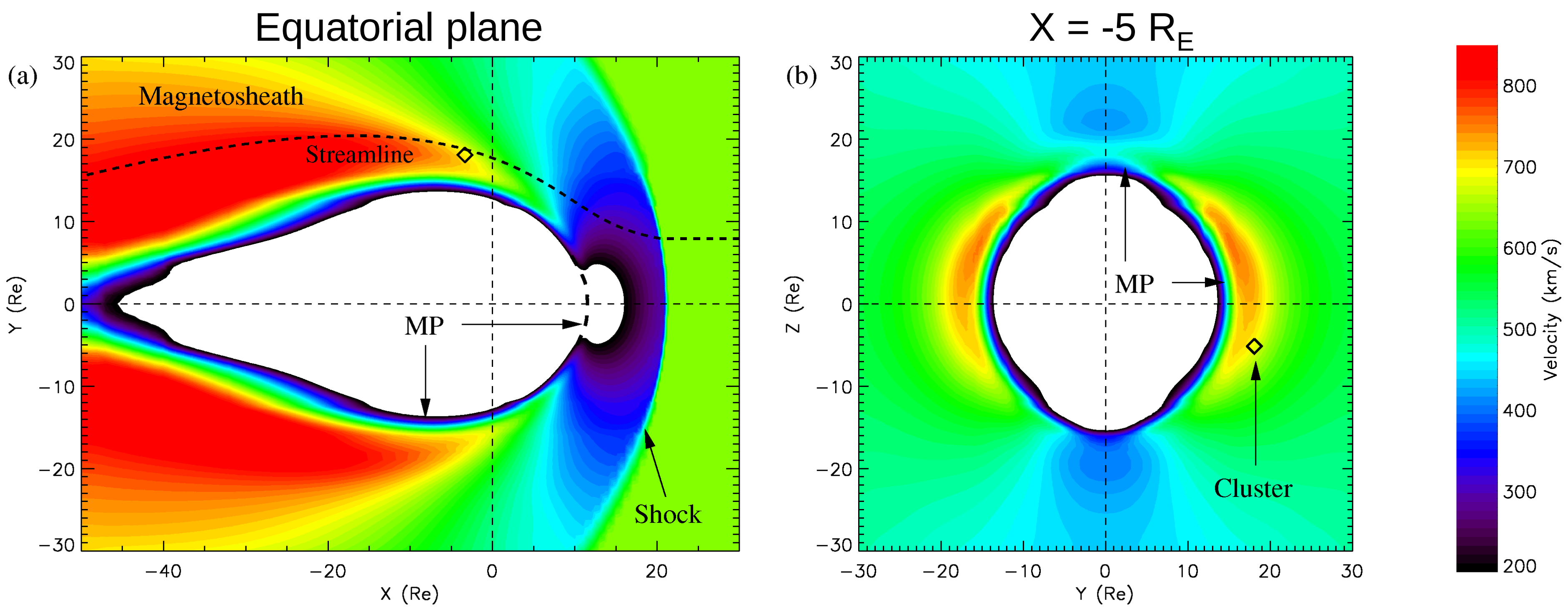


Global MHD simulations (BATS-R-US)
for high and low Mach numbers

→ Strong flow acceleration : increasing for decreasing M_A

See also *Chen et al.* [1993], *Rosenqvist et al.* [2007]

Magnetosheath flow acceleration and asymmetry



Global MHD simulation (BATS-R-US)
for low Mach number ($M_A = 2$)

→ Asymmetric flow acceleration, along the flanks only:
a magnetic "slingshot" effect?

Mechanism of magnetosheath flow acceleration

- Steady state momentum equation:

$$\rho(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\nabla \boldsymbol{p} + \boldsymbol{j}\times\boldsymbol{B}$$

- Magnetic forces

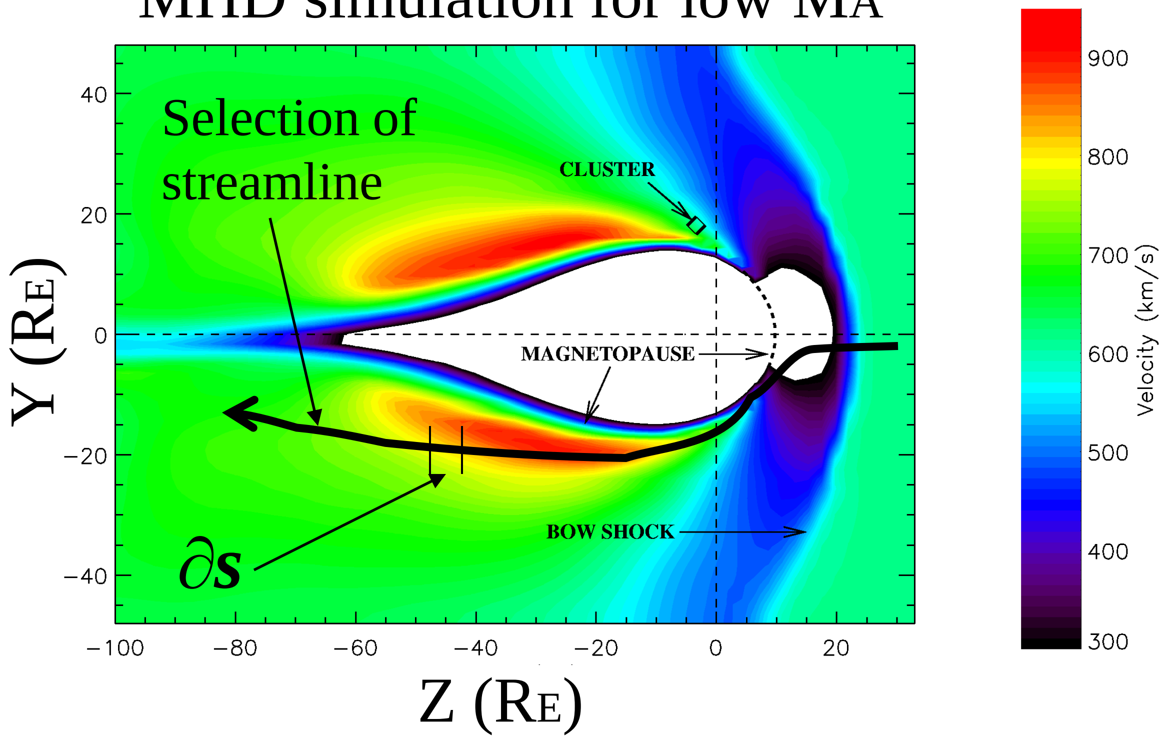
$$\boldsymbol{j}\times\boldsymbol{B} = \frac{1}{\mu}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B} - \nabla\left(\frac{\boldsymbol{B}^2}{2\mu}\right)$$

- Integration of forces:

$$\frac{\partial v}{\partial s} = A_{\nabla p} + A_{\nabla B} + A_{CurvB}$$

(~10% 45% 45%)

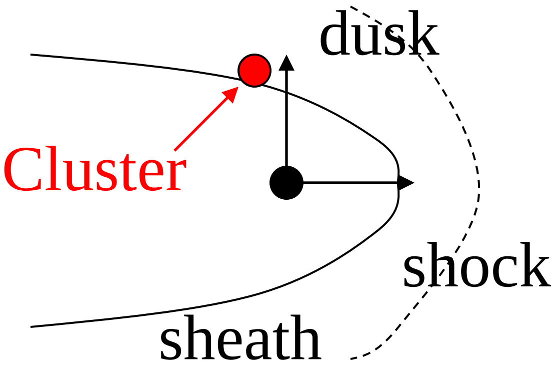
MHD simulation for low MA



Note: Not a simple analogy to a “slingshot”, magnetic pressure gradient as important as tension force

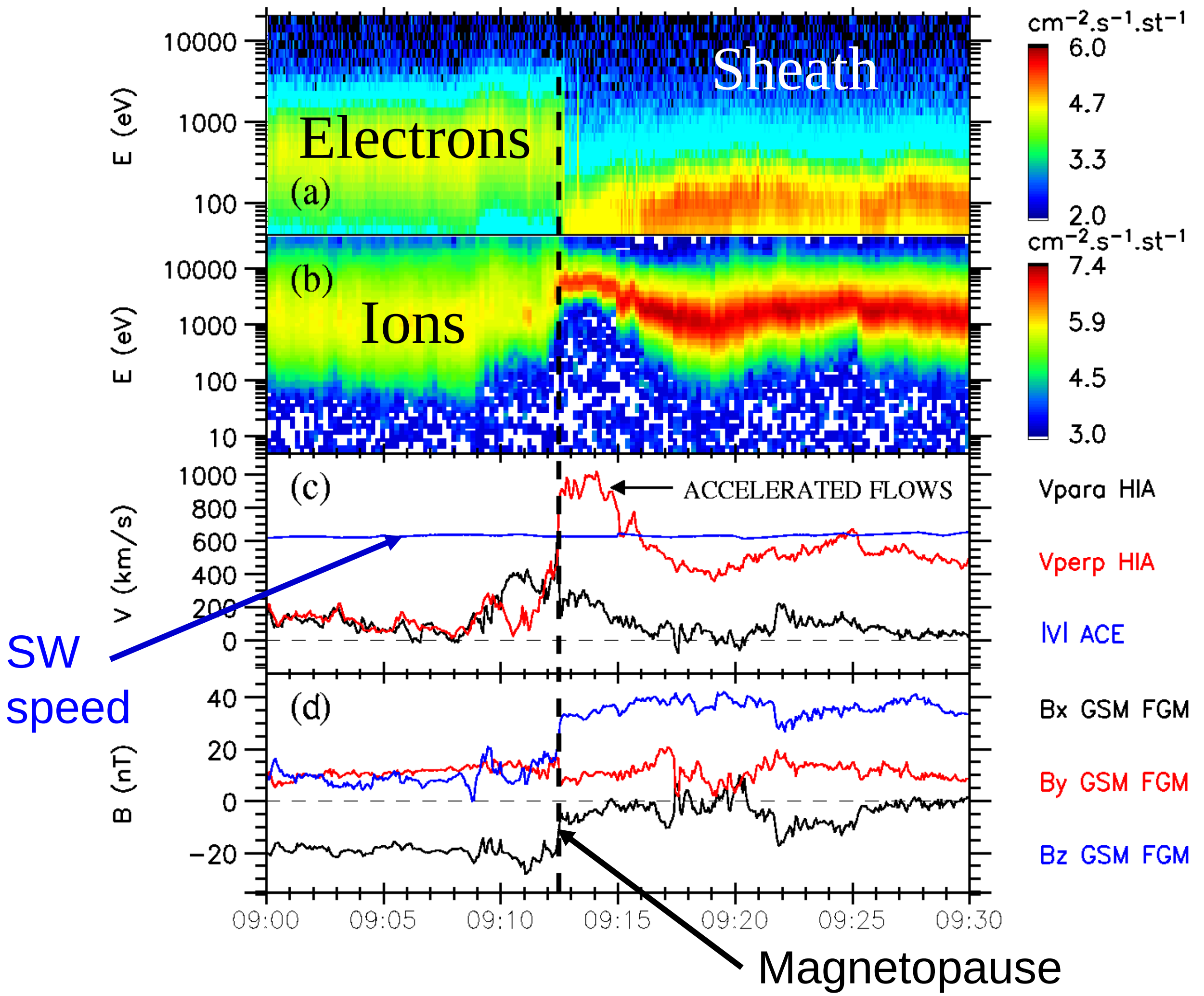
→ We can estimate the contribution of each force:
J x B **acceleration dominates at low Mach numbers**

Observation of such magnetosheath flow jets



- Solar wind observations:
  IMF large and north
  SW density low

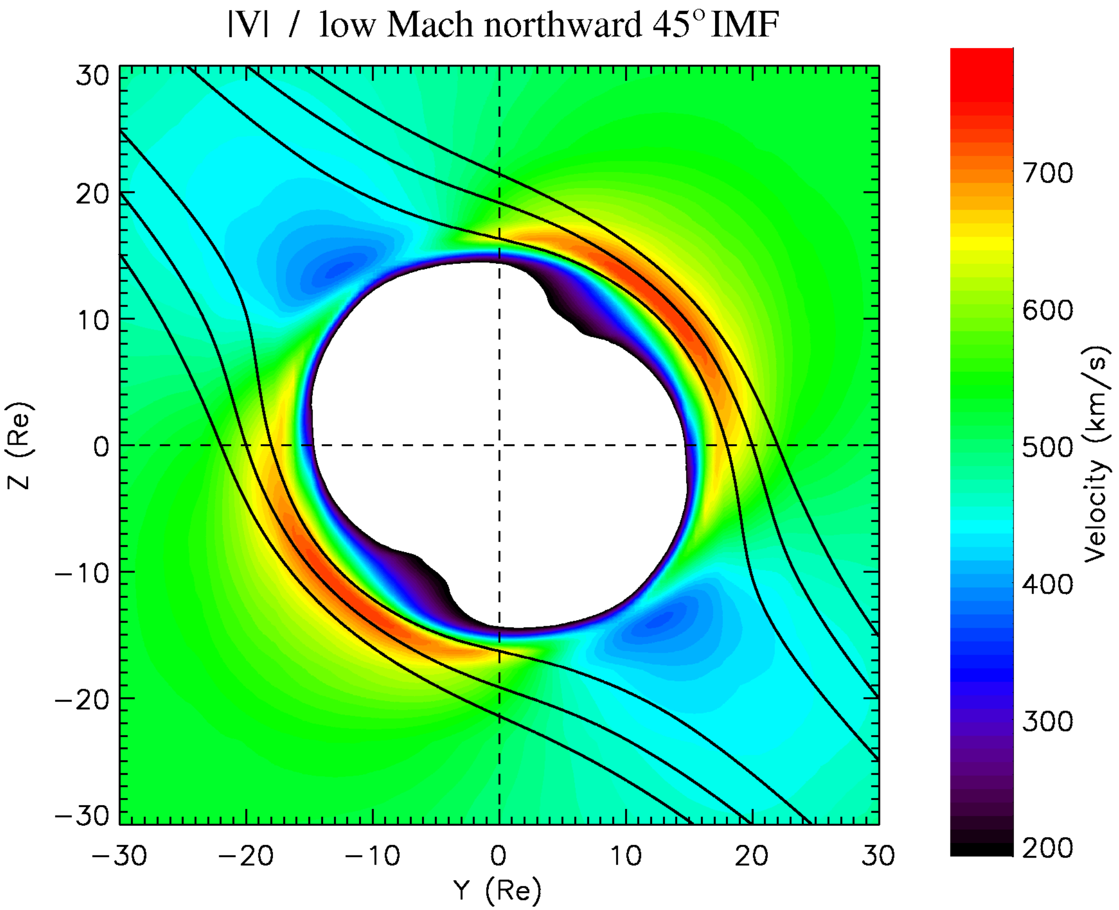
- Cluster observations:
  Flows ⊥ B field
  outside MP
  Up to 1040 km/s while
  SW is only 650 km/s



→ Flows not associated with reconnection and 60% > SW

Flow asymmetry: role of IMF direction

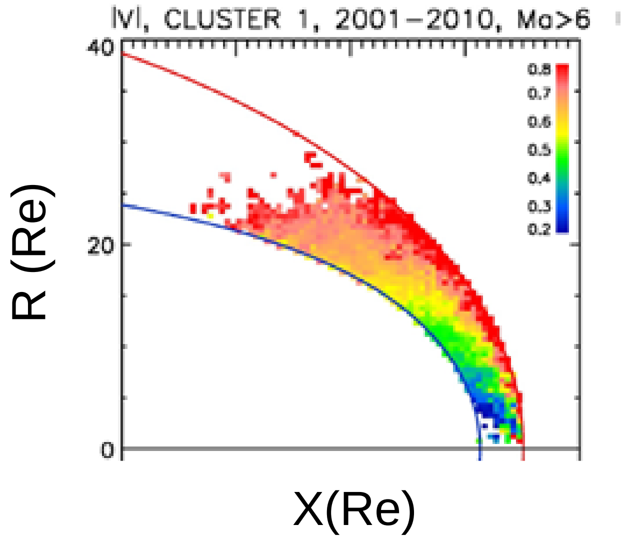
Flow magnitude and sample field lines from MHD simulations (X = -5 R_E)



→ The enhanced flow location follows the IMF orientation

+ additional anomalous flow deflections [*Nishino et al*., 2008]

Statistics of magnetosheath flows

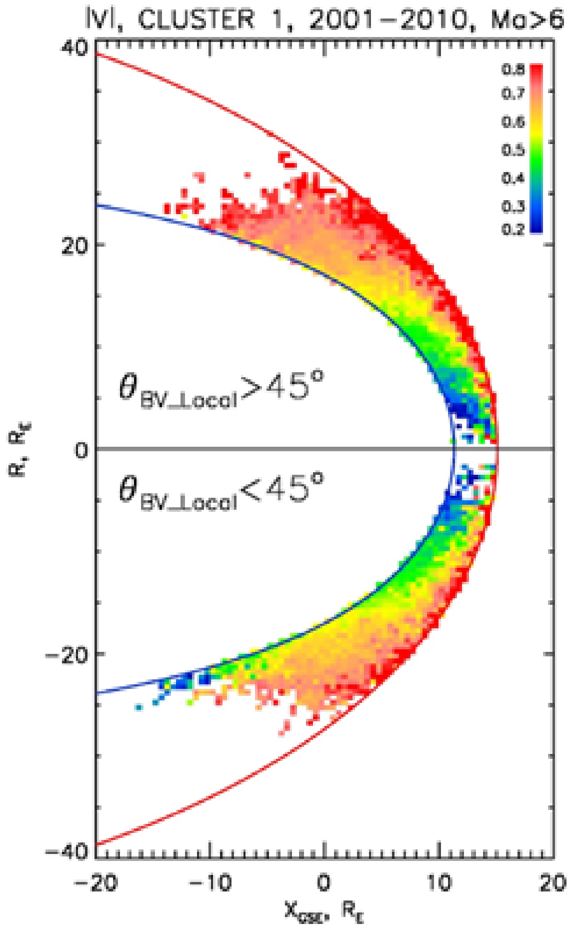


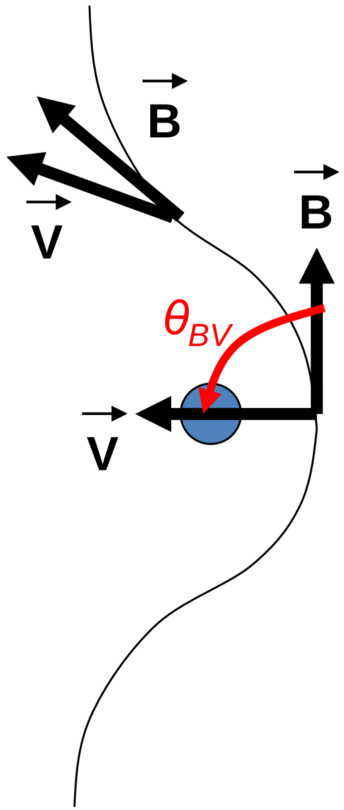
- Use of all Cluster data in years 2001 – 2010
- Data binned in *Verigin et al.* (2006) magnetosheath reference frame
- Solar wind data from OMNI

Statistics of magnetosheath flows

Data when local B is perp. to local V

Data when local B is para to local V





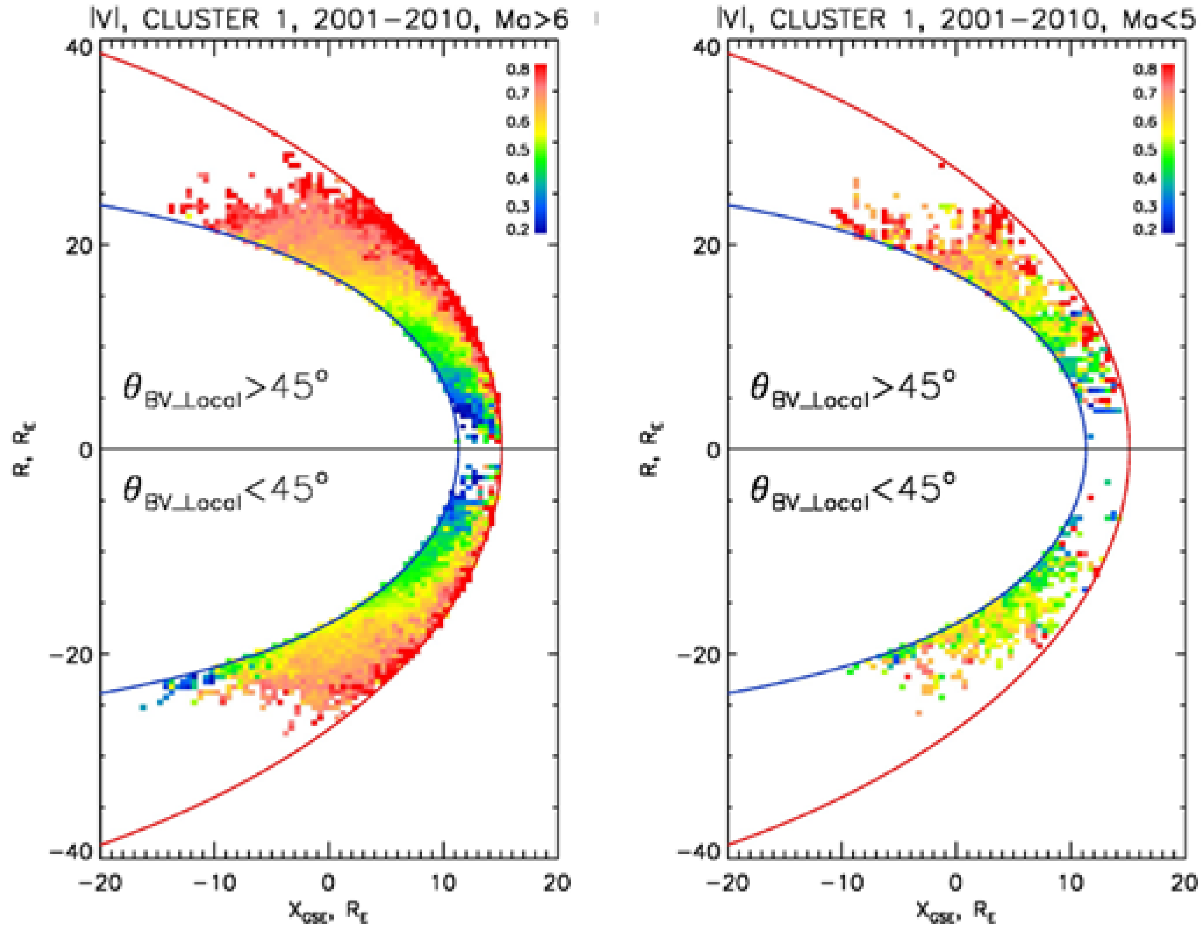
$M_A > 6$

→ Magnetosheath flows are symmetric for high Mach number

Statistics of magnetosheath flows

Data when local B is perp. to local V

Data when local B is para to local V



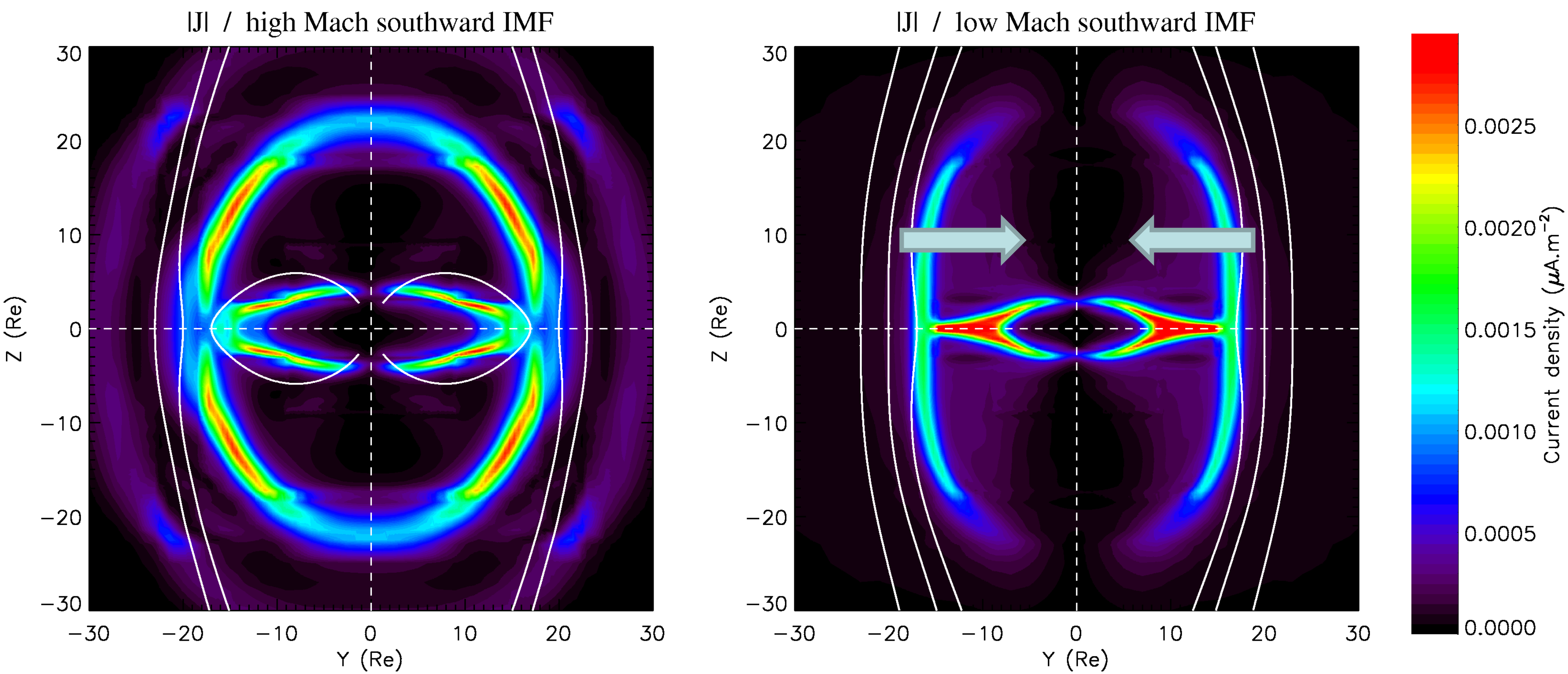
$M_A > 6$

$M_A < 5$

→ Strong asymmetry confirmed by statistics for low M_A

Magnetopause asymmetry: role of magnetic forces

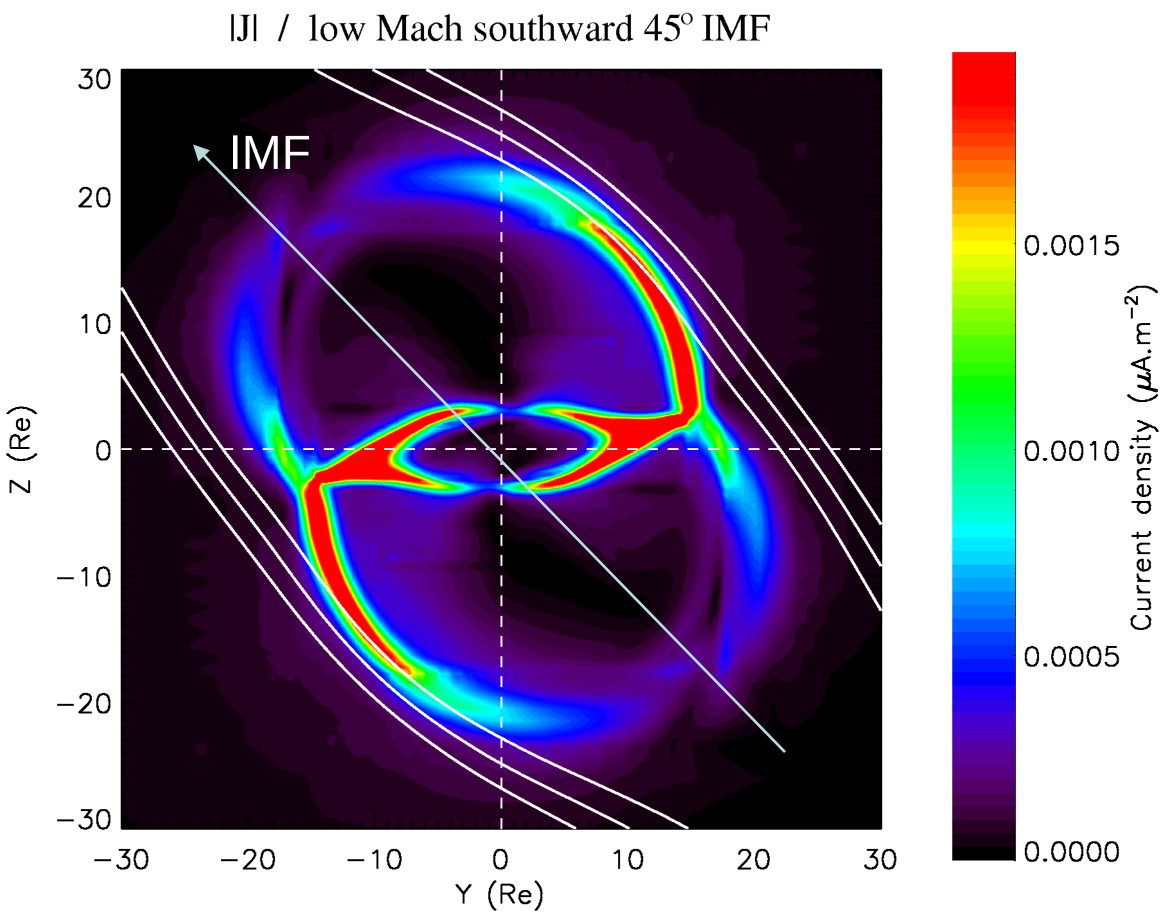
Current magnitude and sample field lines from MHD simulations ($X = -5\ R_E$)



→ The magnetopause is squeezed owing to enhanced magnetic forces in the magnetosheath

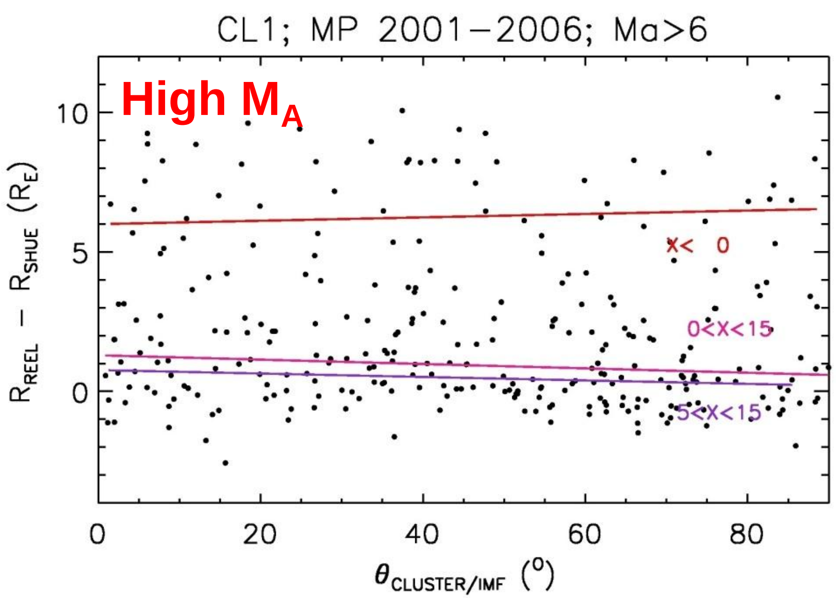
Magnetopause asymmetry: role of IMF direction

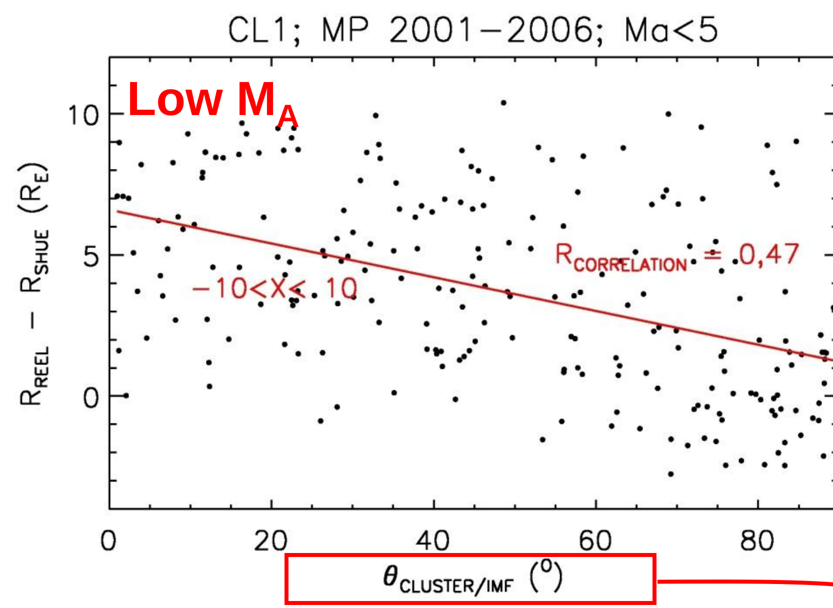
Current magnitude and sample field lines from MHD simulation (X = -5 R_E)



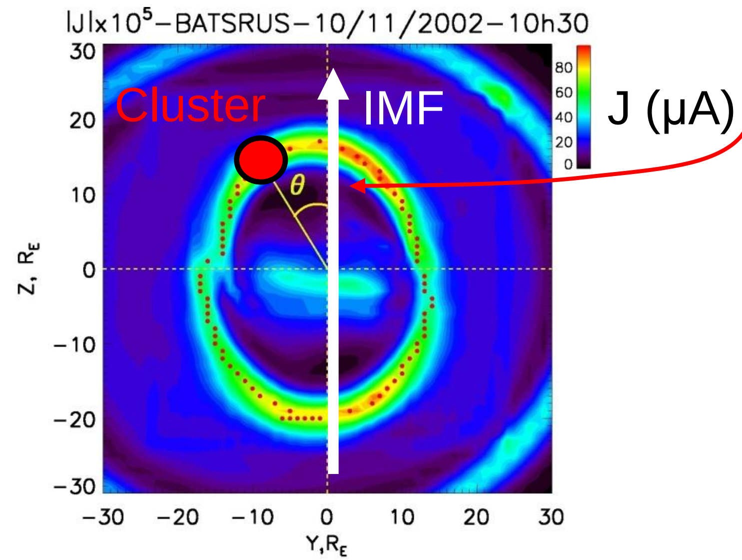
→ The magnetopause squeezing follows the IMF orientation

Magnetopause asymmetry: observations



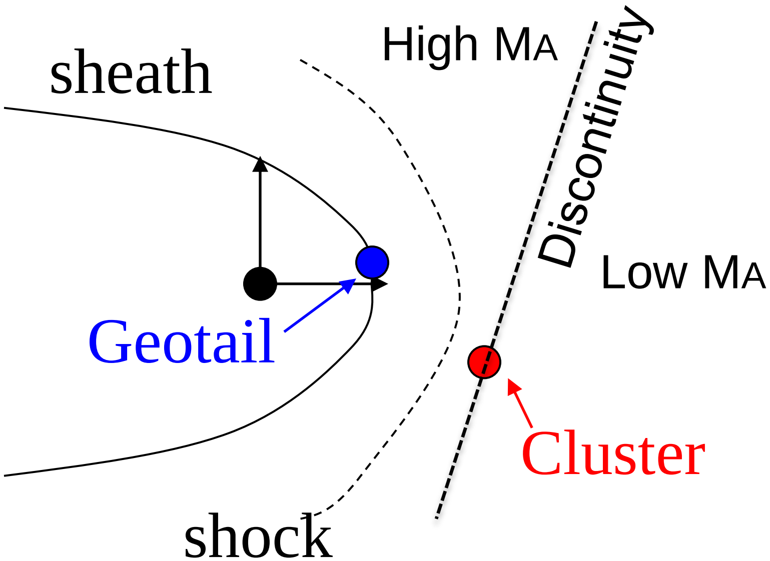


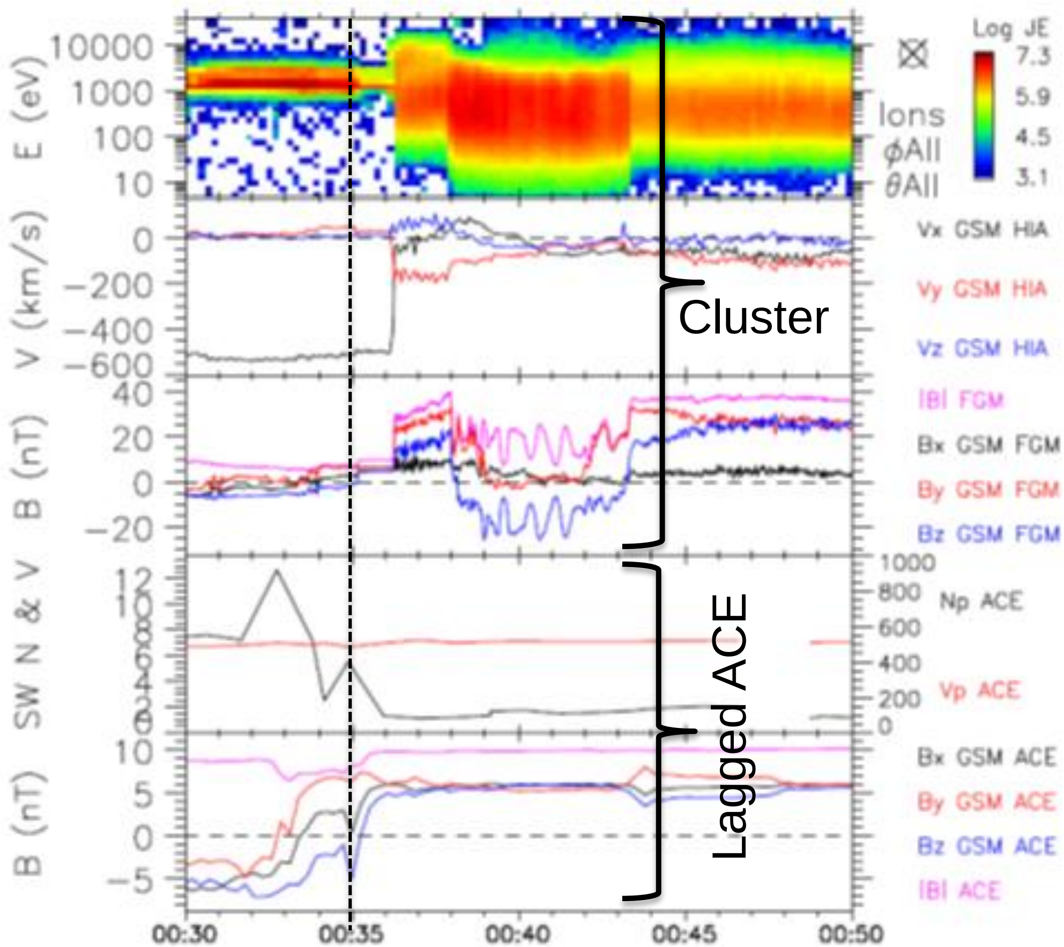
- 297 MP crossings with MA > 6
  from the list of Wang et al. [2006]
- 241 MP crossings with MA < 5
  from data mining with AMDA
- Solar wind from OMNI



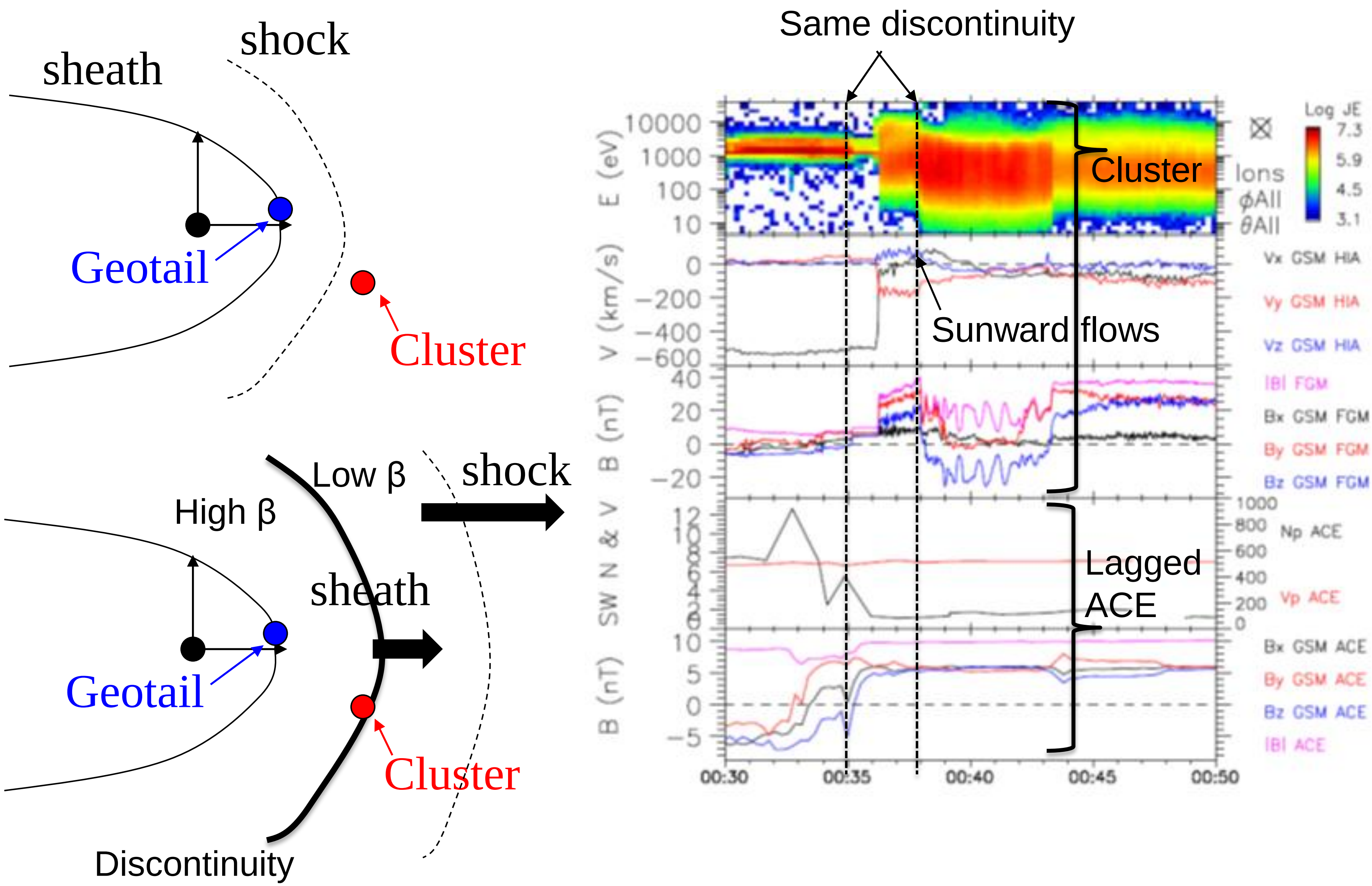
→ Statistical confirmation of magnetopause squeezing

Extreme retreat of bow shock and sunward sheath flows





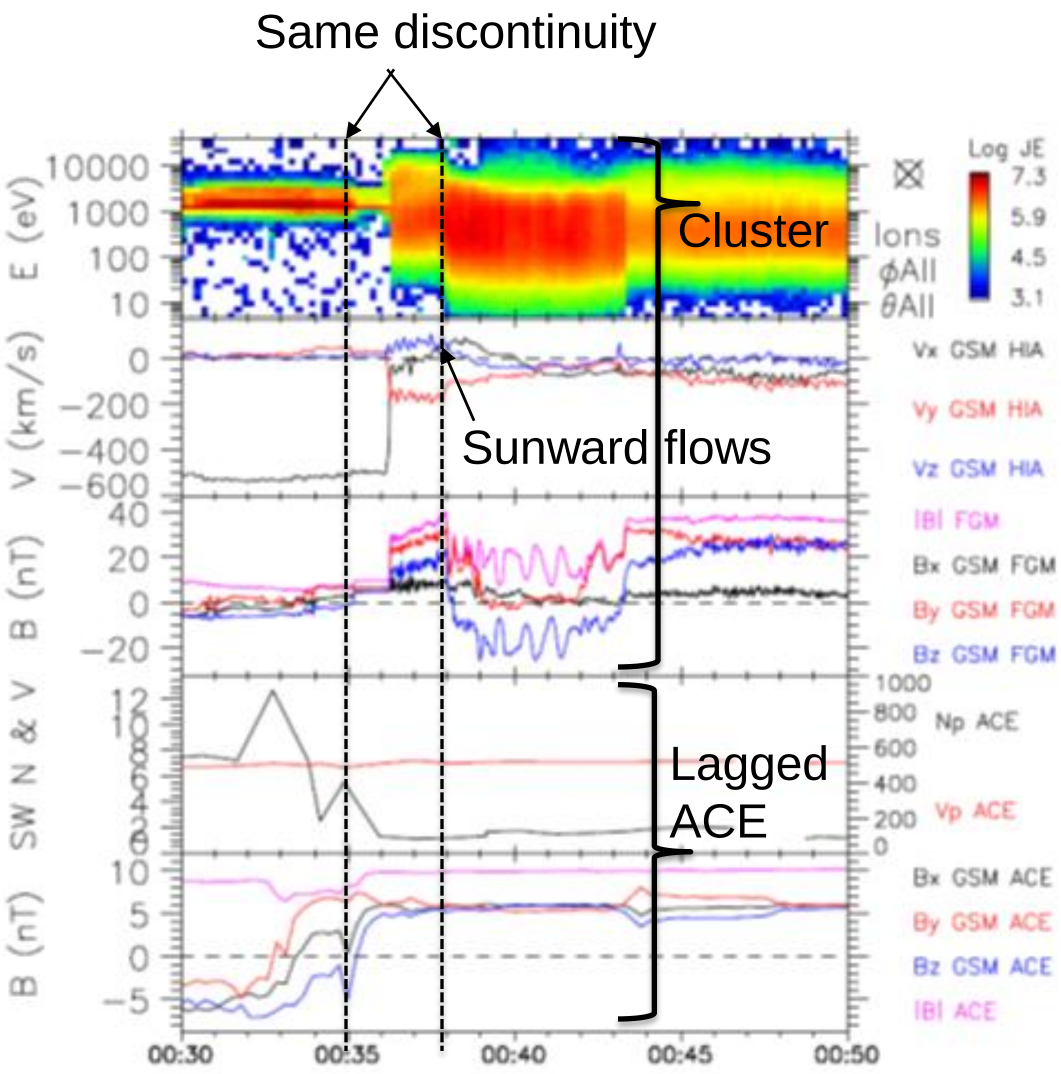
Extreme retreat of bow shock and sunward sheath flows



Extreme retreat of bow shock and sunward sheath flows

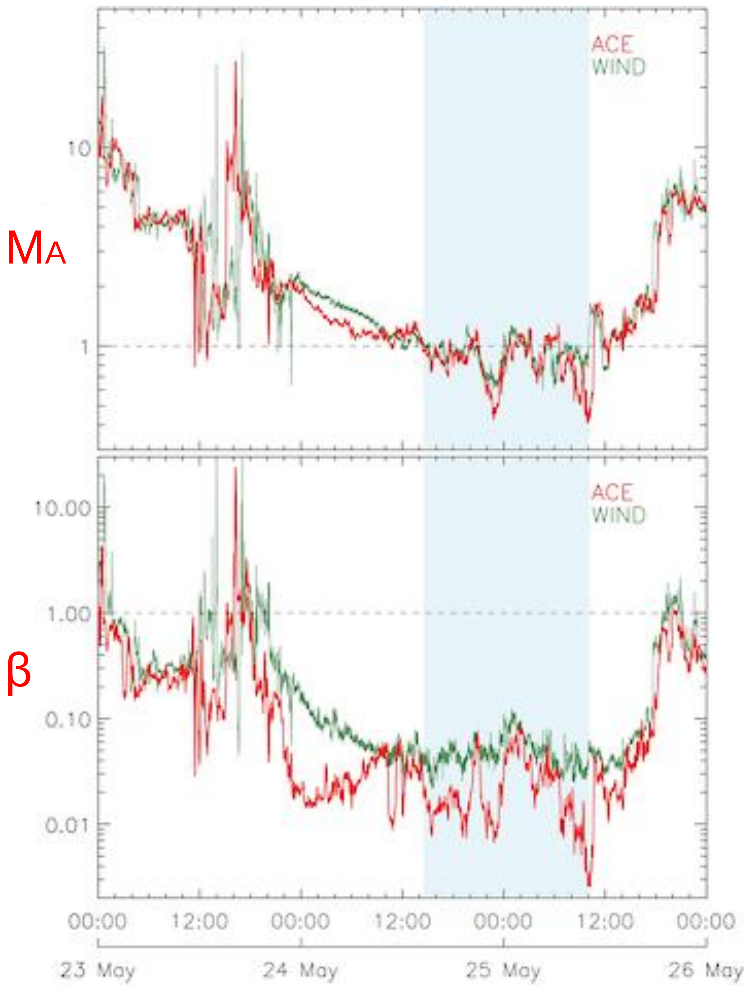
→ **Extreme (akin to HFA) bow shock and sheath dynamics if fast M_A variations**

Note: first sunward sheath flow observed at Jupiter (Siscoe, 1971)



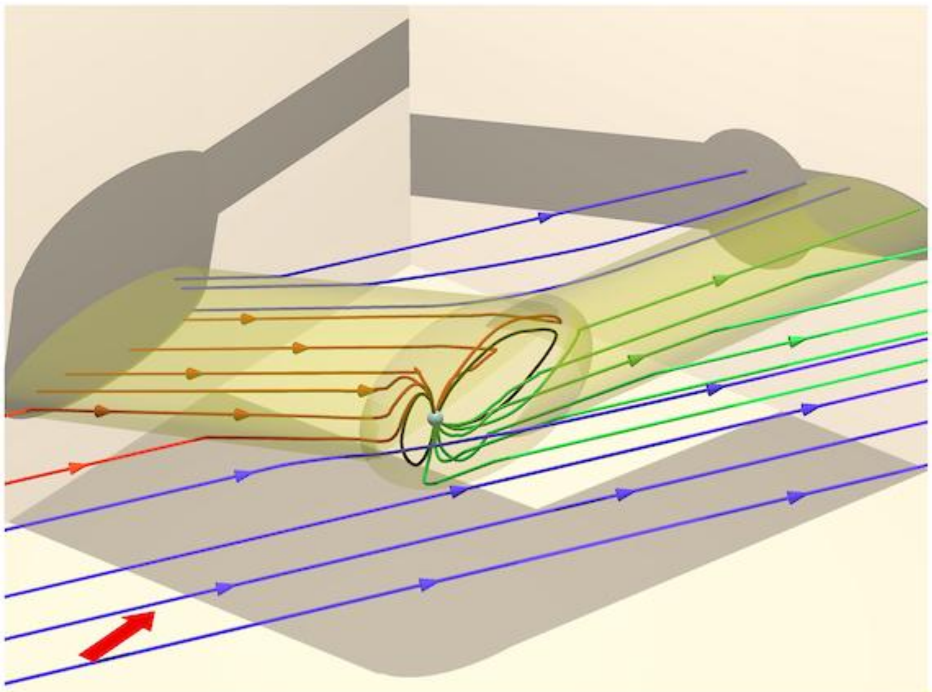
Formation of Alfvén wings at Earth

On 24-25 May 2002, during a CME the Alfvén Mach number reached 0.4



Chané et al. [2012]

3D schematic of expected Alfvén wing structure



→ Alfvén wings are expected under such extreme low M_A

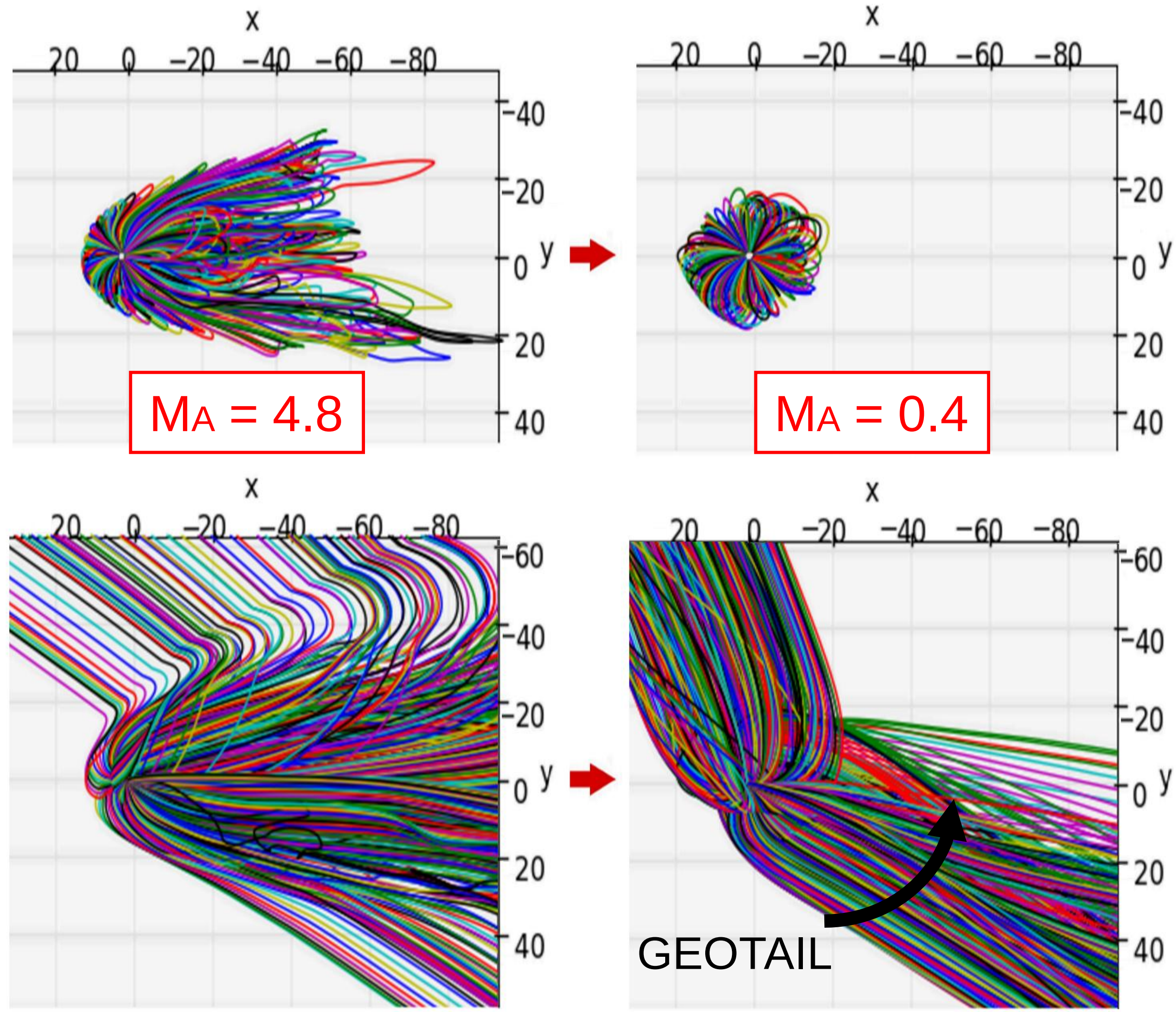
Formation of Alfvén wings at Earth

Observations and simulations for 24-25 May 2002 during M_A = 0.4

Chané et al. [2014]

- GGCM simulations of Alfvén wing
- GeoTail observations consistent with simulations
- Both data and simulation show very low activity

→ Alfvén wings do occur at Earth
(rarely though…)



SOME OTHER LOW M_A EFFECTS

- Possibly faster KH instability onset at flanks
- Changes to dayside reconnection rate
- Cross-polar cap potential saturation
- Global sawtooth oscillations
- Plasma depletion layer (disappears at high M_A)
- Heating at bow shock (Ti/Te)
- Drifts and losses to the magnetopause (radiation belts and ring current)
- Bow shock acceleration and reflection

else …

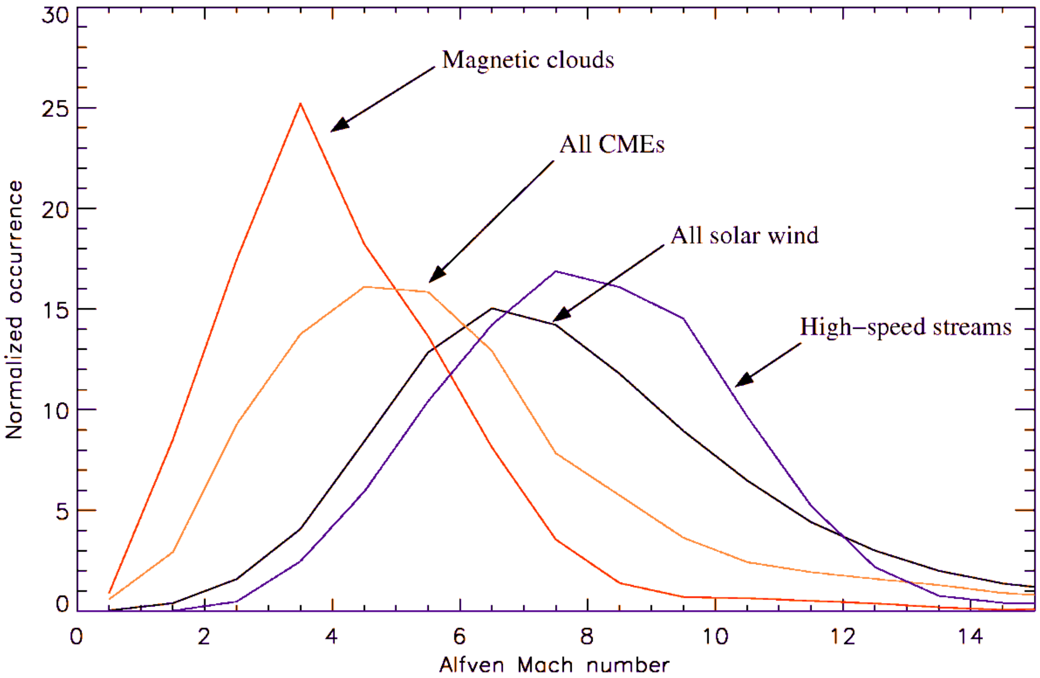
CONCLUSIONS

- SW – magnetosphere interaction is significantly altered at low Mach number
- It is mediated by a buffer region: the magnetosheath
- All these effects are thus important during CME-driven storms
- They must occur at other magnetospheres (Mercury: low M_A and no ionosphere Moons, e.g., like Io in sub-Alfvenic flows)

Acknowledgments

Joe Borovsky (Space Science Institute)
Aaron J. Ridley (Univ. Michigan, USA)
Emmanuel Chané (KU Leuven, Belgium)
Jimmy Raeder (Univ. New Hampshire)
Janet Kozyra (Univ. Michigan, USA)
Maria M. Kuznetsova and CCMC
(NASA GSFC, USA)
and Cluster teams

Occurrence distribution of solar wind Mach numbers



- Binning of OMNI dataset

- Lists from:
  CMEs: Cane and Richardson [2003]
  MCs: Lepping et al. [2006]
  HSS: *Borovsky and Denton* [2006]

See also:
Gosling et al. [1987]
Borovsky and Denton [2006]

→ CMEs, and particularly the subset of magnetic clouds, have low Mach numbers

Extreme retreat of bow shock and sunward sheath flows