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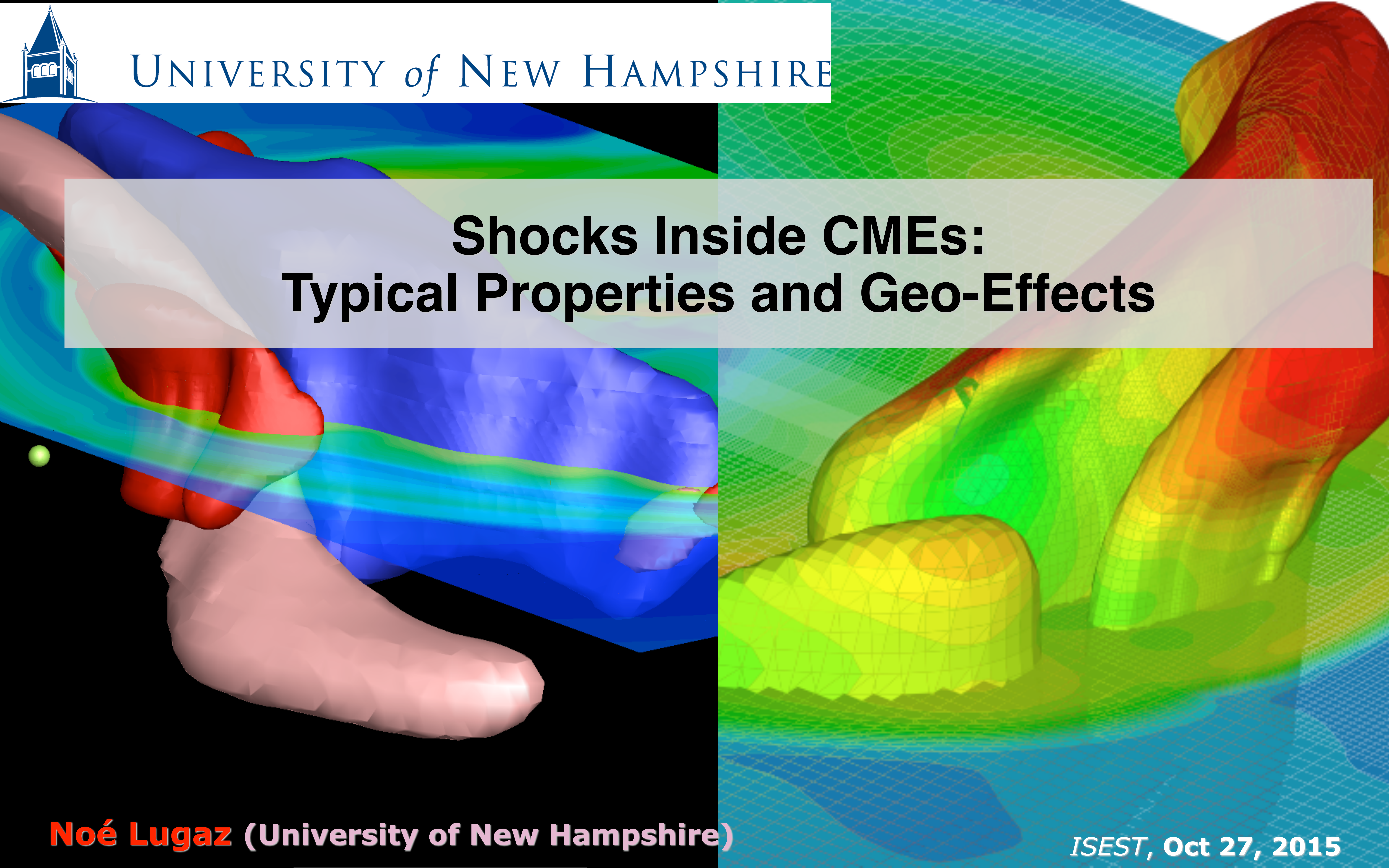

Shocks Inside CMEs:
Typical Properties and Geo-Effects

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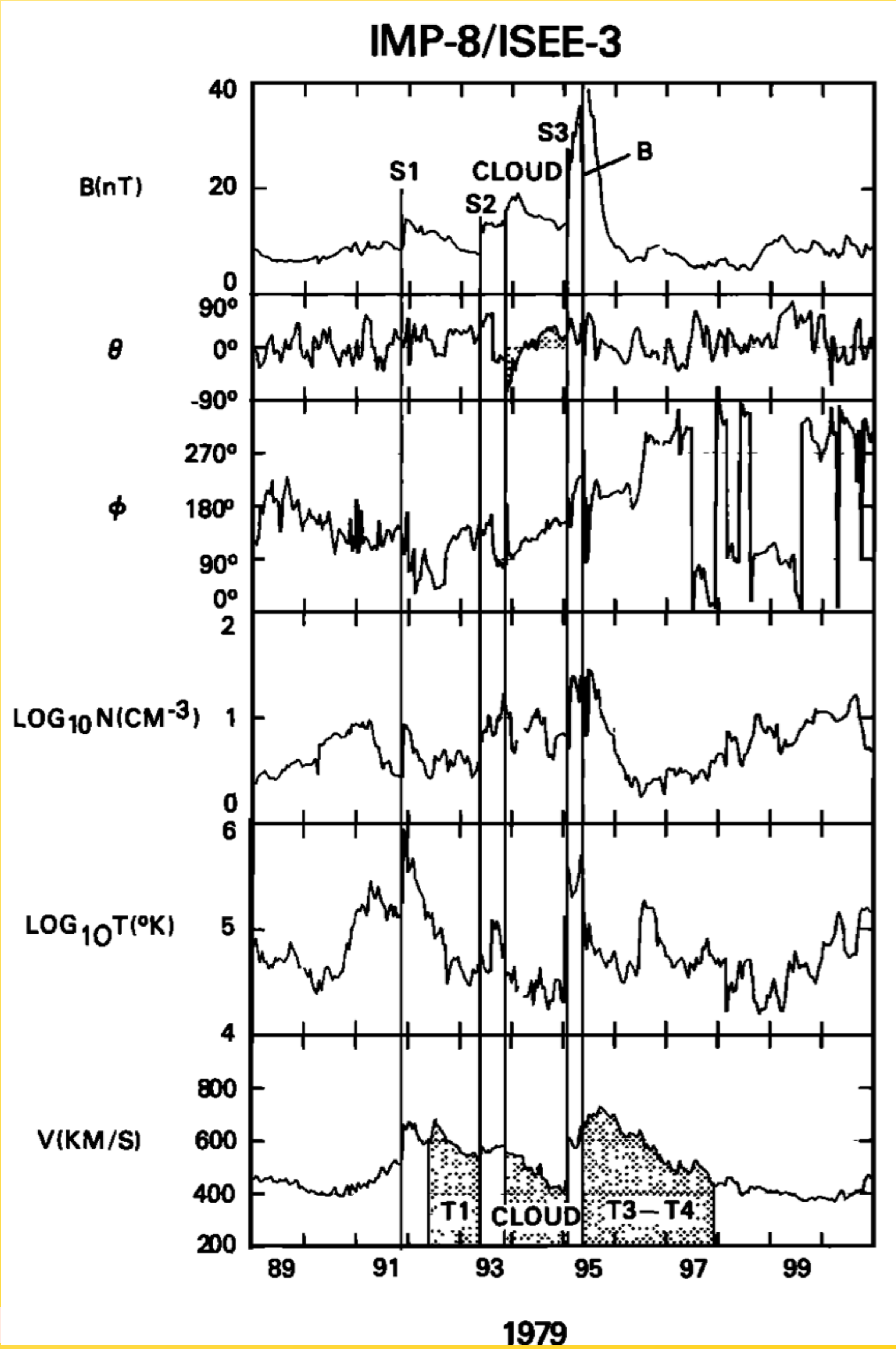
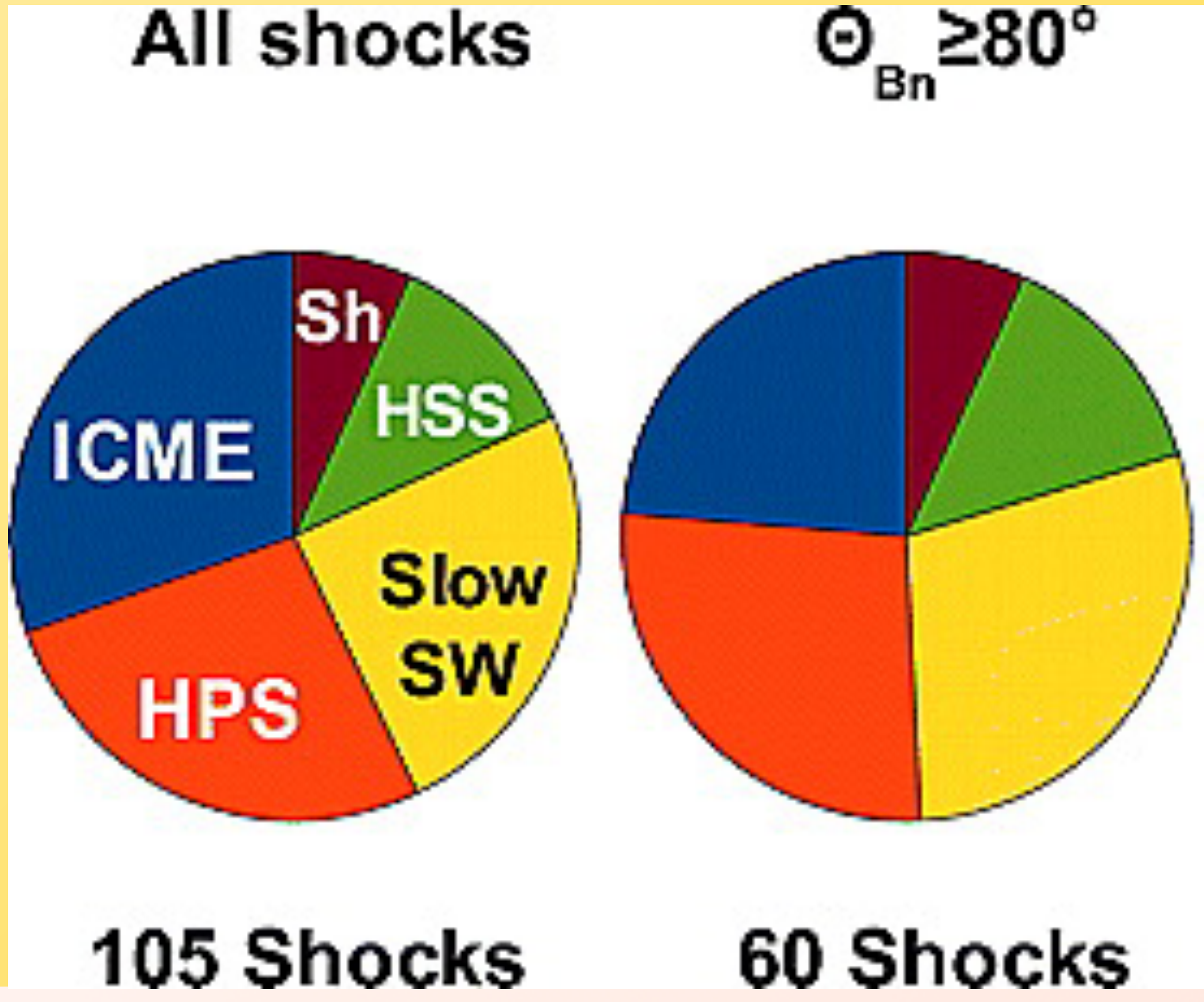
ISEST, Oct 27, 2015

Shocks inside CMEs

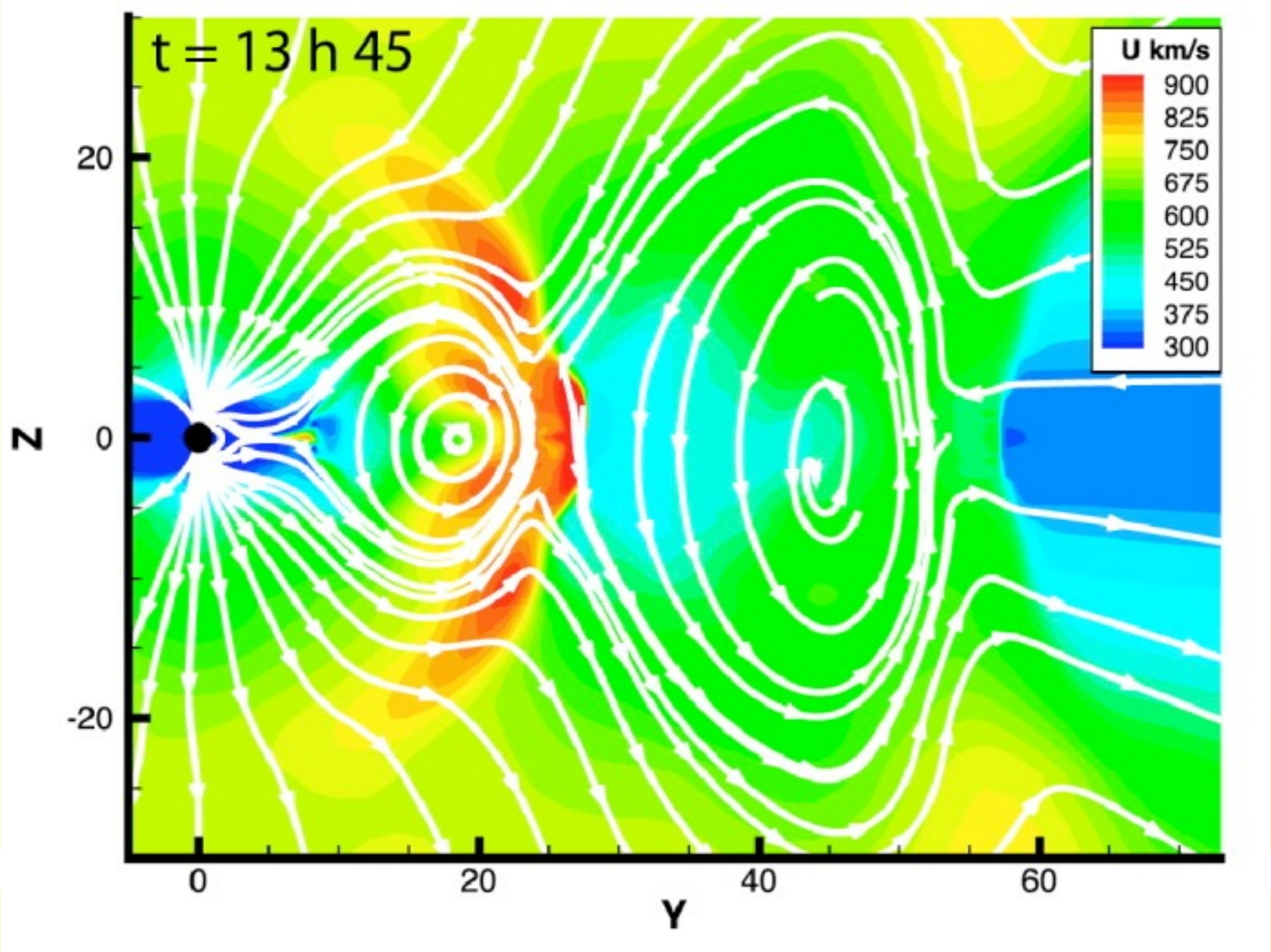
- Shocks inside CMEs have been known for 30+ years (e.g., see Ivanov, 1982) and some studies indicate that they may lead to strong geo-effects.
- Simulations reveal that fast-mode forward shocks can propagate through a MC.
- Richardson & Cane (2010b) found that ~30% of quasi-perp shocks are propagating inside a CME or closely following one. Collier et al. (2007) found that 8/82 MCs in SC23 have shocks propagating inside them.
- Zhang et al. (2007) found 9/88 intense geomagnetic storm in SC23 due to shock inside CMEs.



Richardson & Cane, JGR, 2010



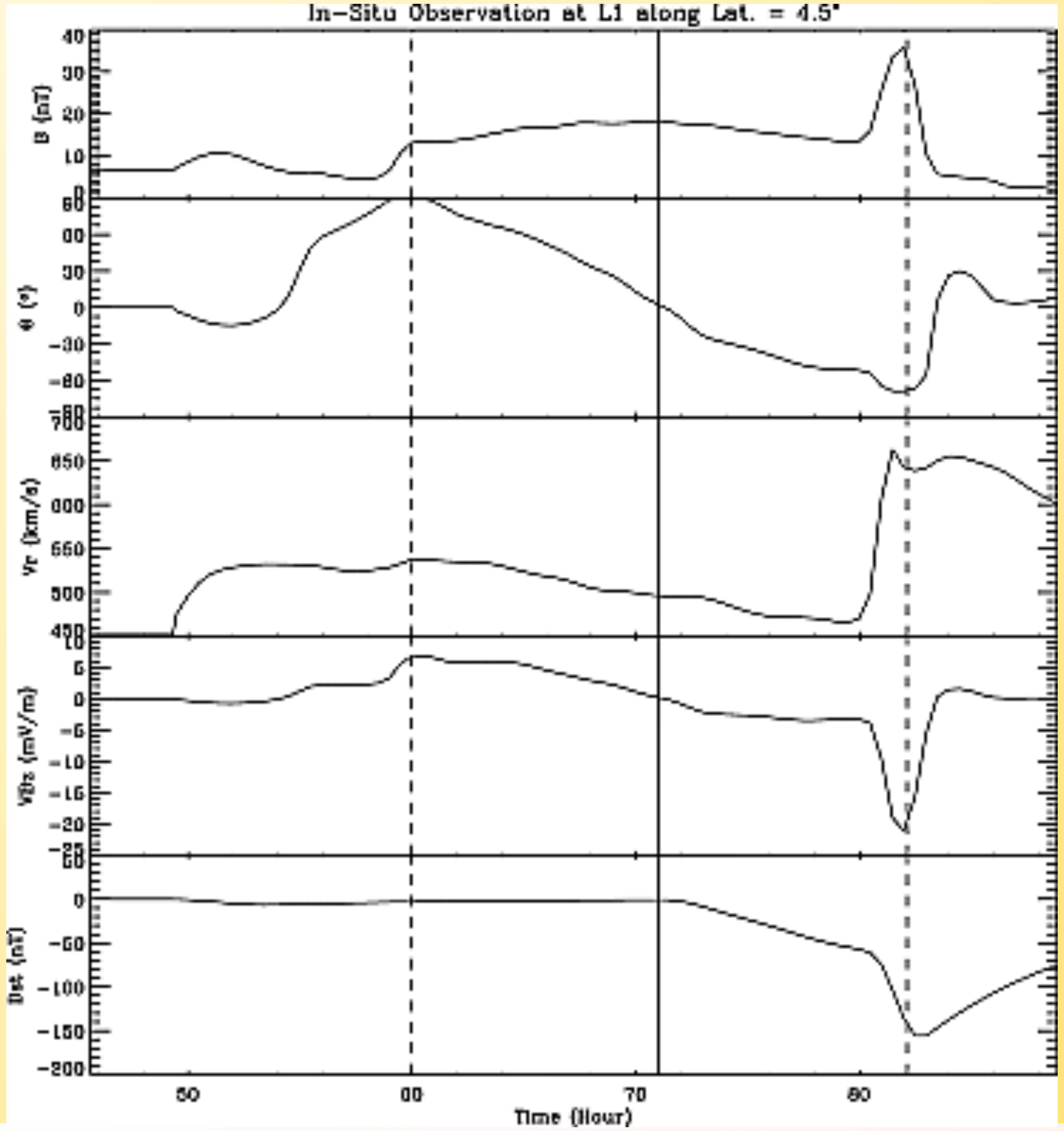
Lugaz *et al*, ApJ, 2005



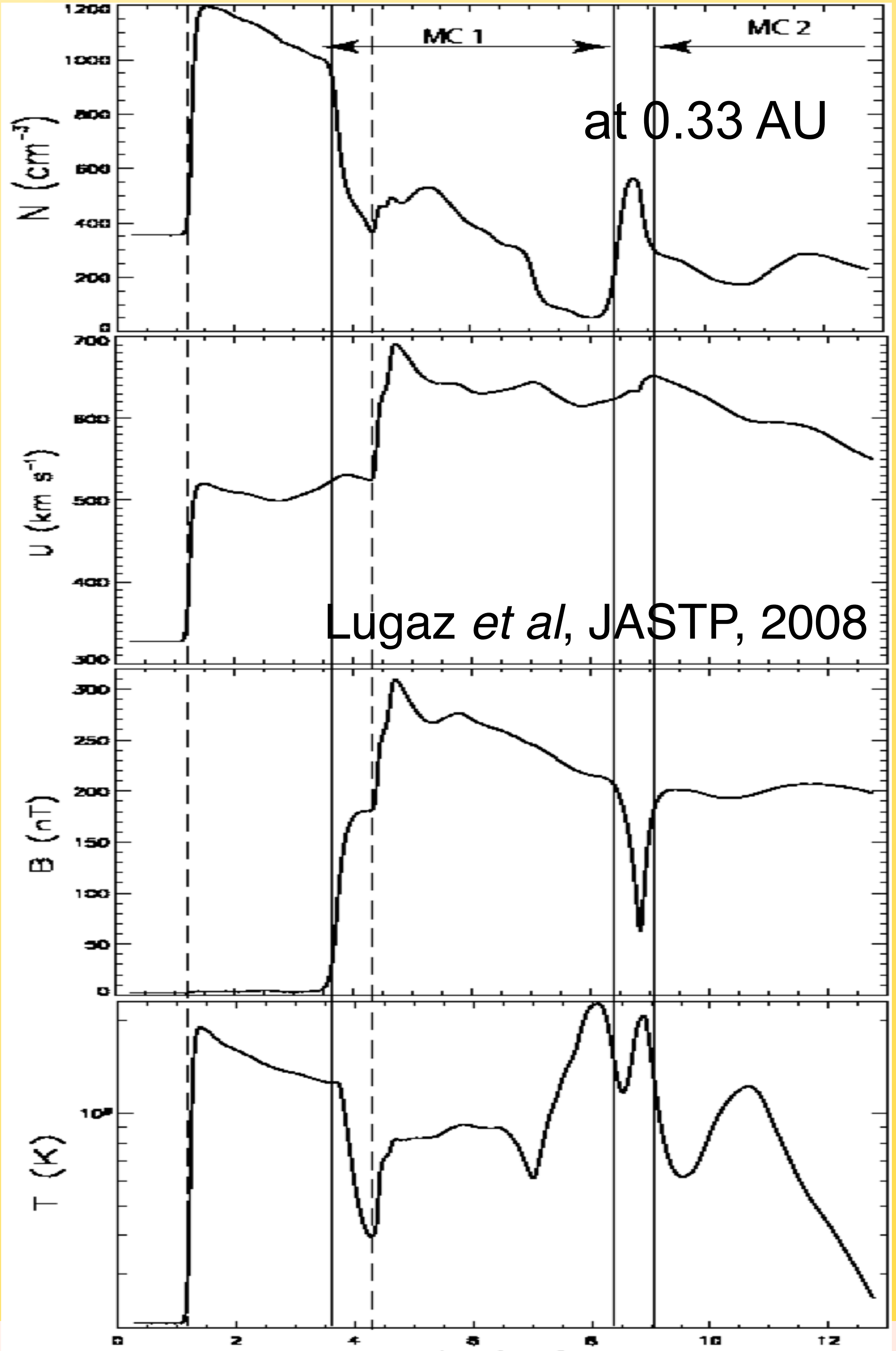
Burlaga *et al.*, JGR, 1987

Numerical Simulations

- Past work reveal that fast-mode forward shocks can propagate through a MC.
- Shock weakens but is still able to compress the magnetic field by a factor ~2.
- Complex shock evolution due to changes in upstream conditions.



Xiong *et al*, JGR, 2006



at 0.33 AU

Lugaz *et al*, JASTP, 2008

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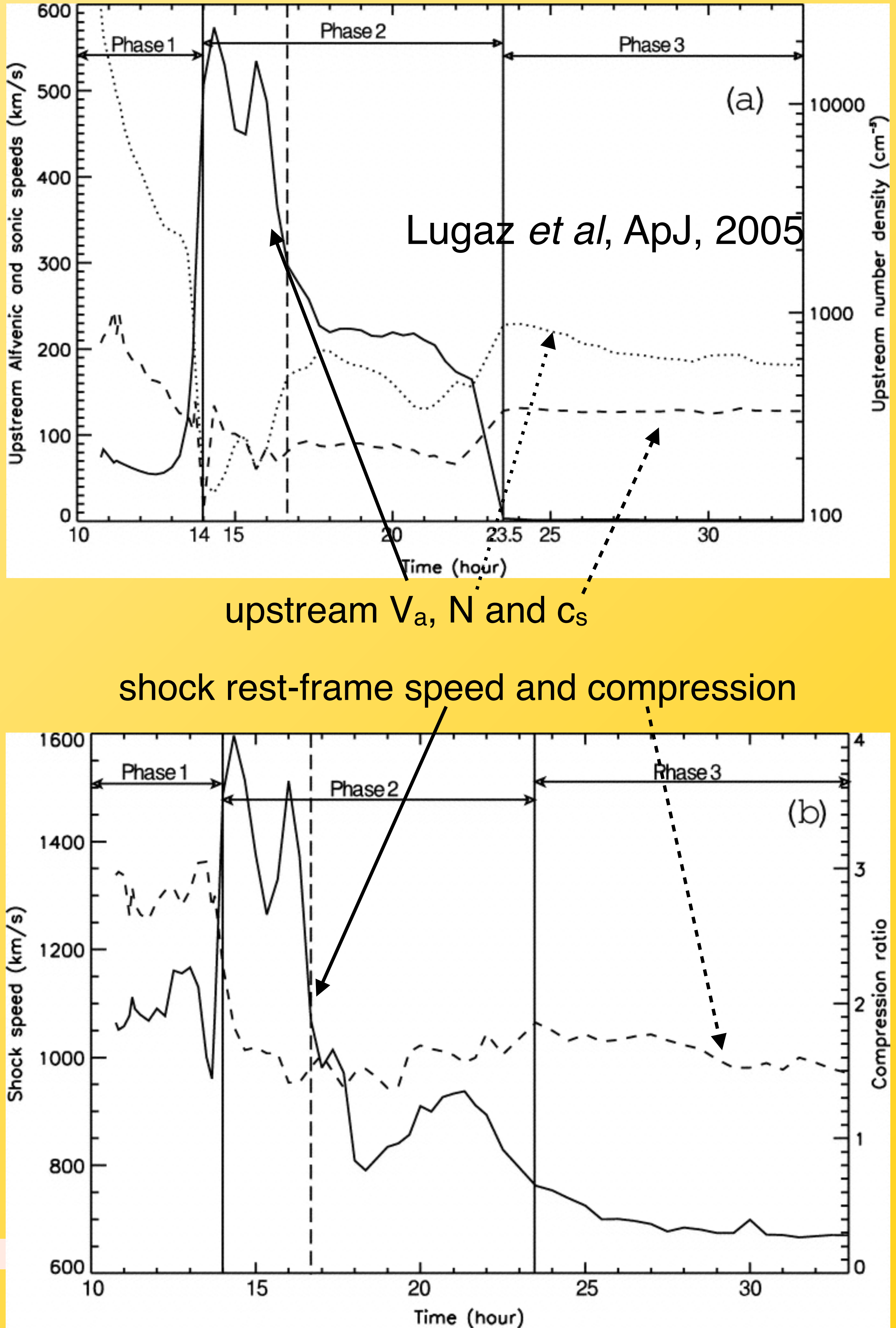


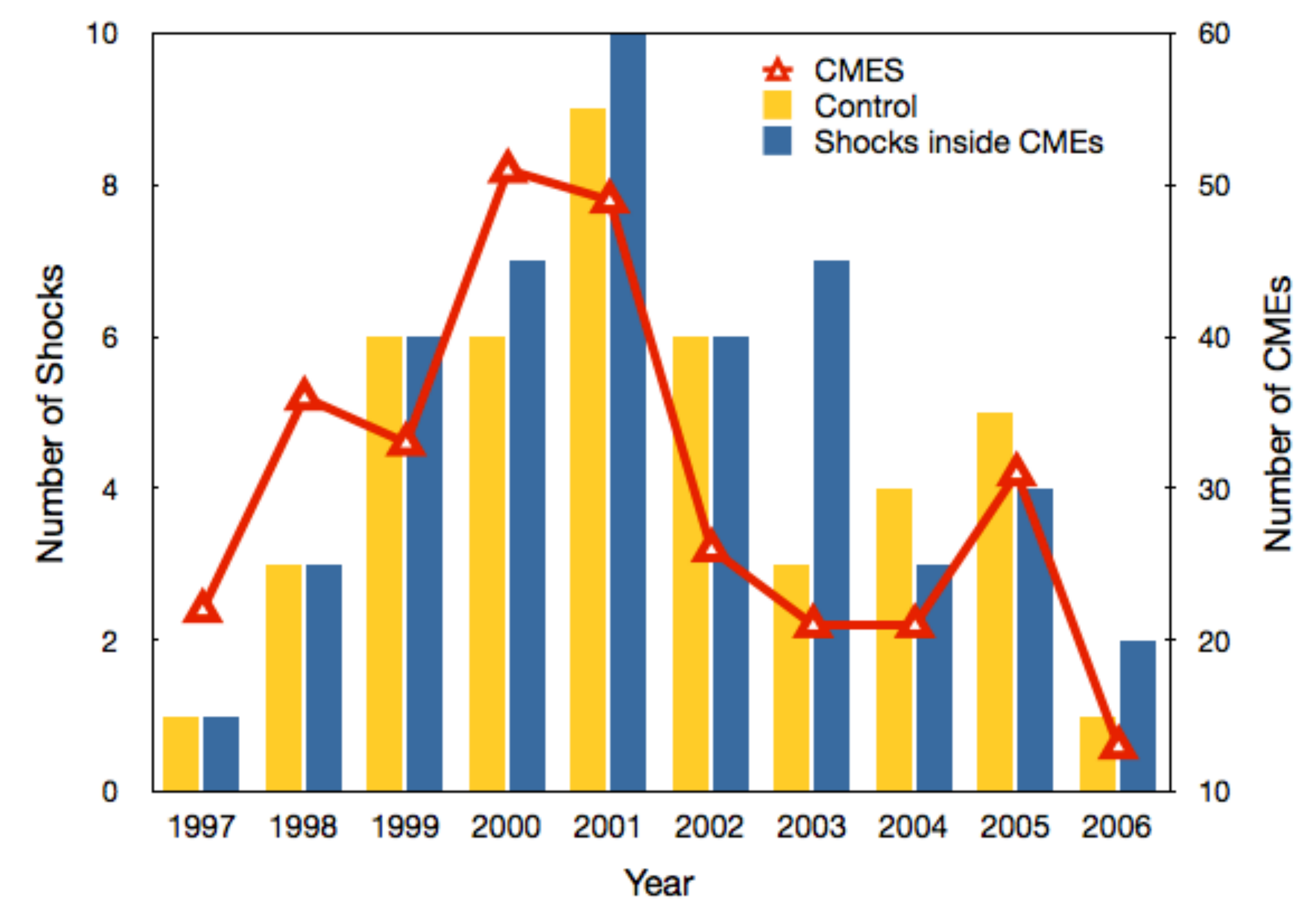
Lugaz *et al*, ApJ, 2005

upstream V_a, N and c_s

shock rest-frame speed and compression

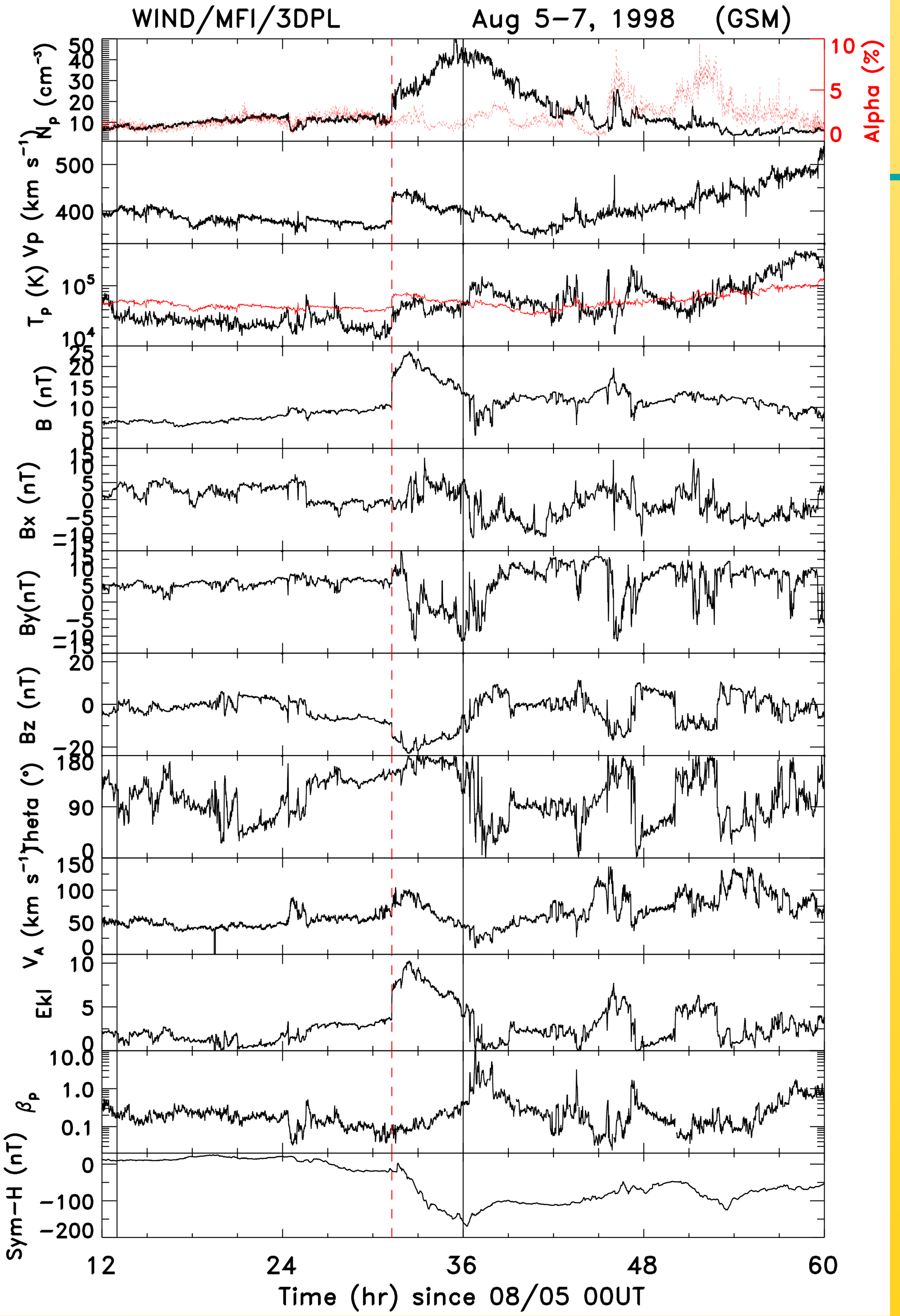
Statistical study

- Combined list of shocks at ACE (UNH) and at Wind (CfA) with list of CMEs measured at L1 (Richardson & Cane, 2010) for solar cycle 23.
- ~60 “shocks” identified inside CMEs or closely following them.
  - Removed dubious shocks and CMEs with properties close to average solar wind.
- List of **49 shocks propagating inside CMEs** or at the back boundary of a CME.
  - Created a “control sample” of 45 shocks with a similar yearly distribution.
  - 21 shocks were identified by R&C, 2010b.
  - # of shocks inside CMEs has solar cycle dependence;
  - ~70% are quasi-perpendicular;
  - 10 cases when SSN < 50;
  - ~15% of CMEs have a shock inside them.;
    - For 2003 (few CMEs but clustered in time), 30% of CMEs had a shock propagating through them.
  - ~15-20% of the shocks at 1 AU propagate inside a CME.
  - Lugaz et al., **JGR**, 2015, “*Shocks Inside CMEs…*”



Typical case
August 6, 1998

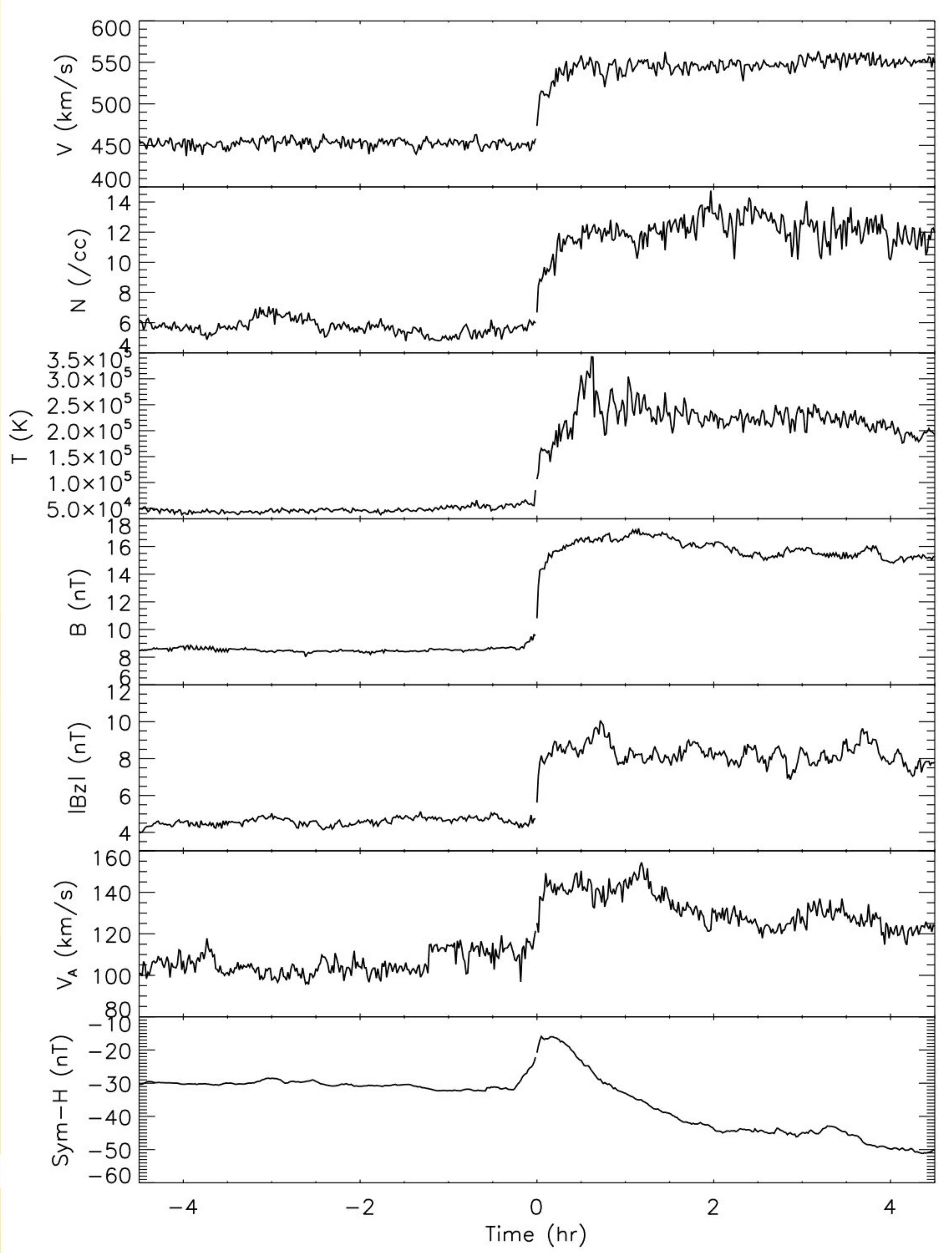
- Slow CME starting around 13:00 with low temperature, higher B field.
  - Back end of CME pretty clear at 36 h with short interval of low B and high β, reminiscent of interaction region as described by Wang *et al.* (2003).
- Shock inside CME at 30.6 h.
  - Quasi-perp shock with a compression ratio ~1.8, V_{shock} = 460 km/s and M_{ms} ~ 1.5
  - Upstream conditions: β ~ 0.07; V_a ~ 70 km/s; V_{sw} ~ 370 km/s; B ~ 10 nT.
- Intense geo-magnetic storm:
  - Doubling of B + increase of V => **tripling of coupling function to ~ 10 mV/m**
  - Sym-H decreases from -20 nT at 30h to -169 nT at 36h, clearly associated with the compression from the shock.

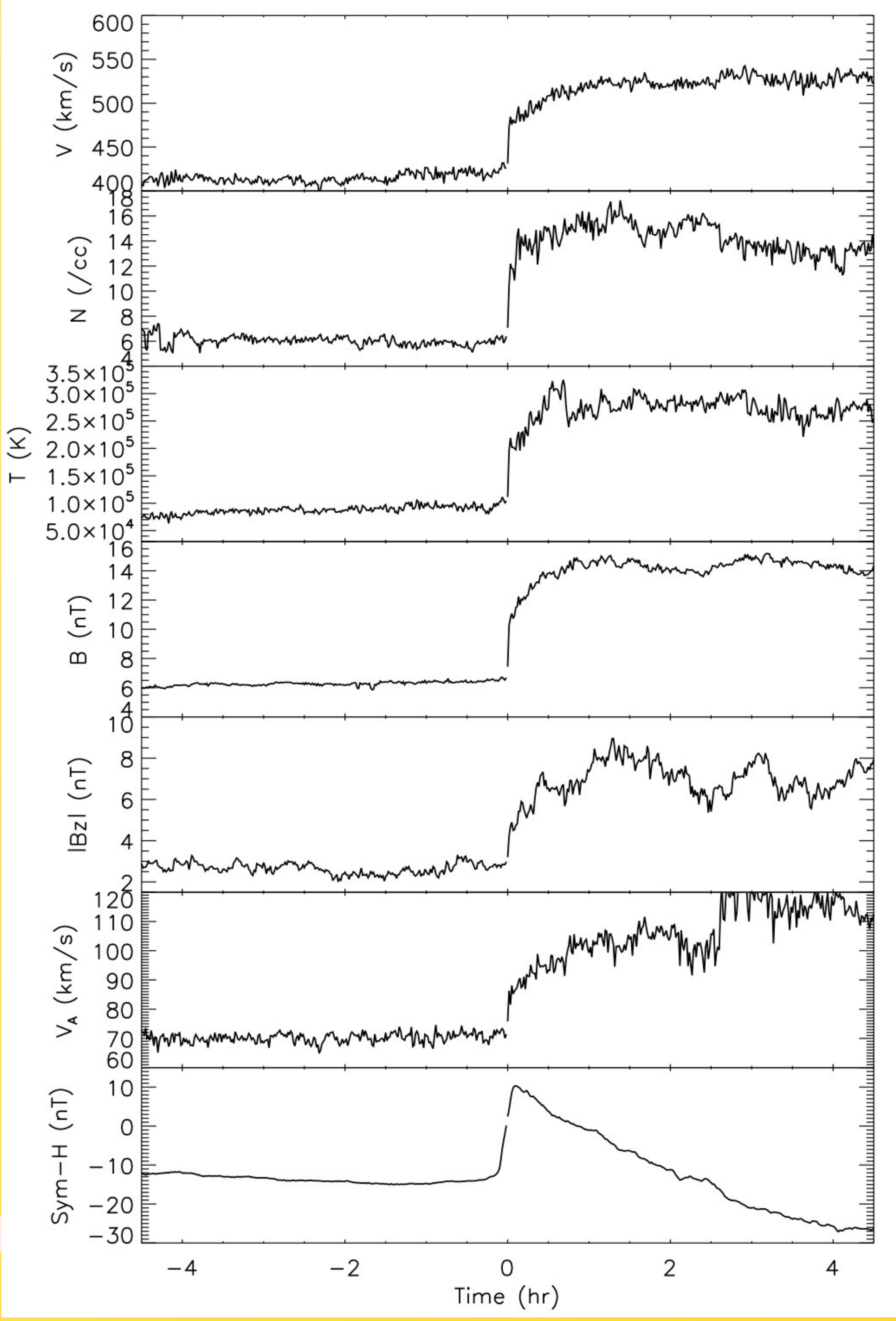


Superposed Epoch Analysis

- Shocks propagating into weak and relatively slow CMEs (B ~ 8.5 nT, V ~ 450 km/s).
- Small changes in upstream conditions may have a large impact on the Mach number. A shock with a speed of 600 km/s would have a Mach number of 2.7 for “normal” conditions vs 1.4 for conditions as encountered inside CMEs.
- On average, a moderate storm and a weaker SI.

Shocks inside CME

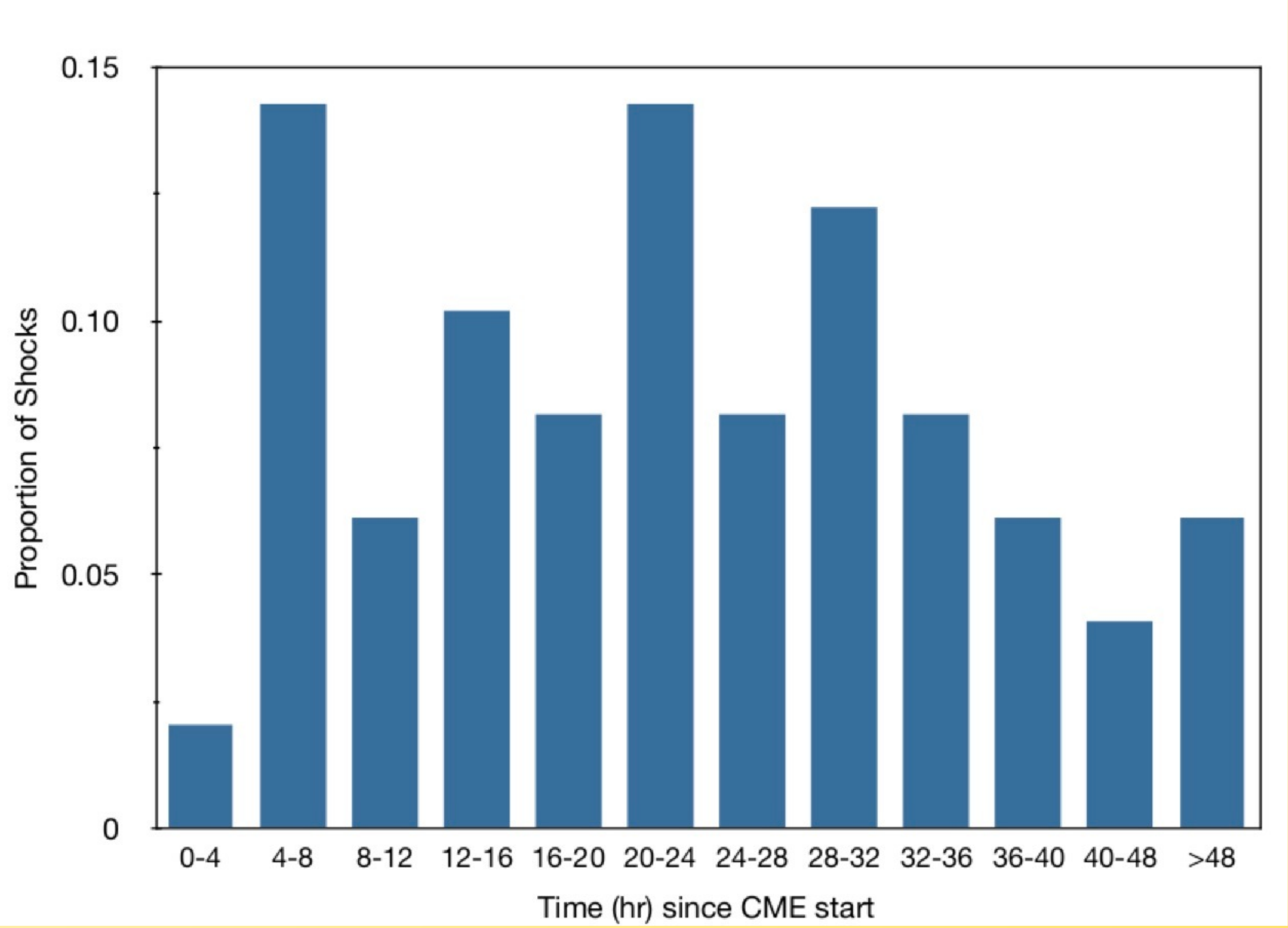


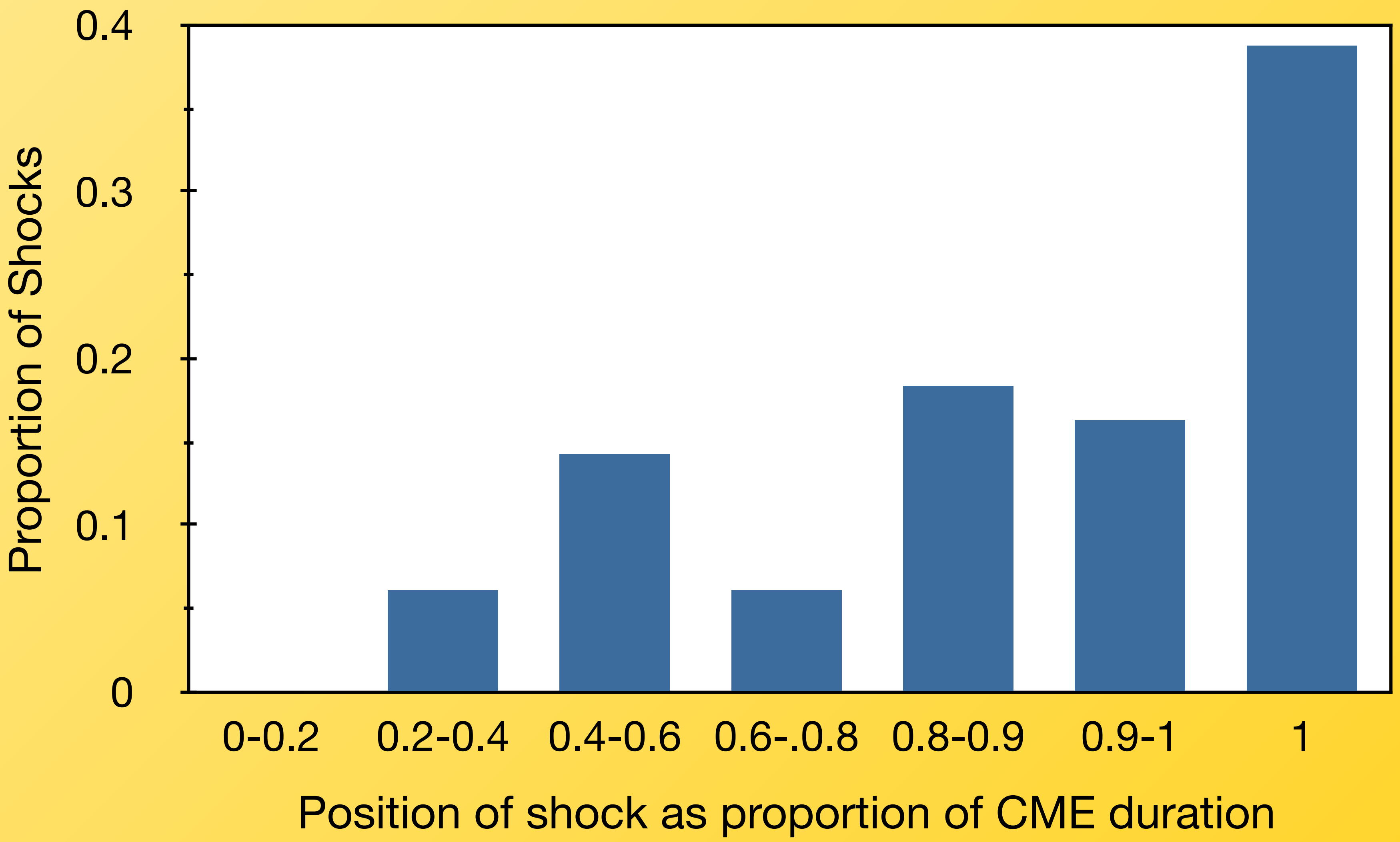


Control Sample

Detailed comparison
Shock position

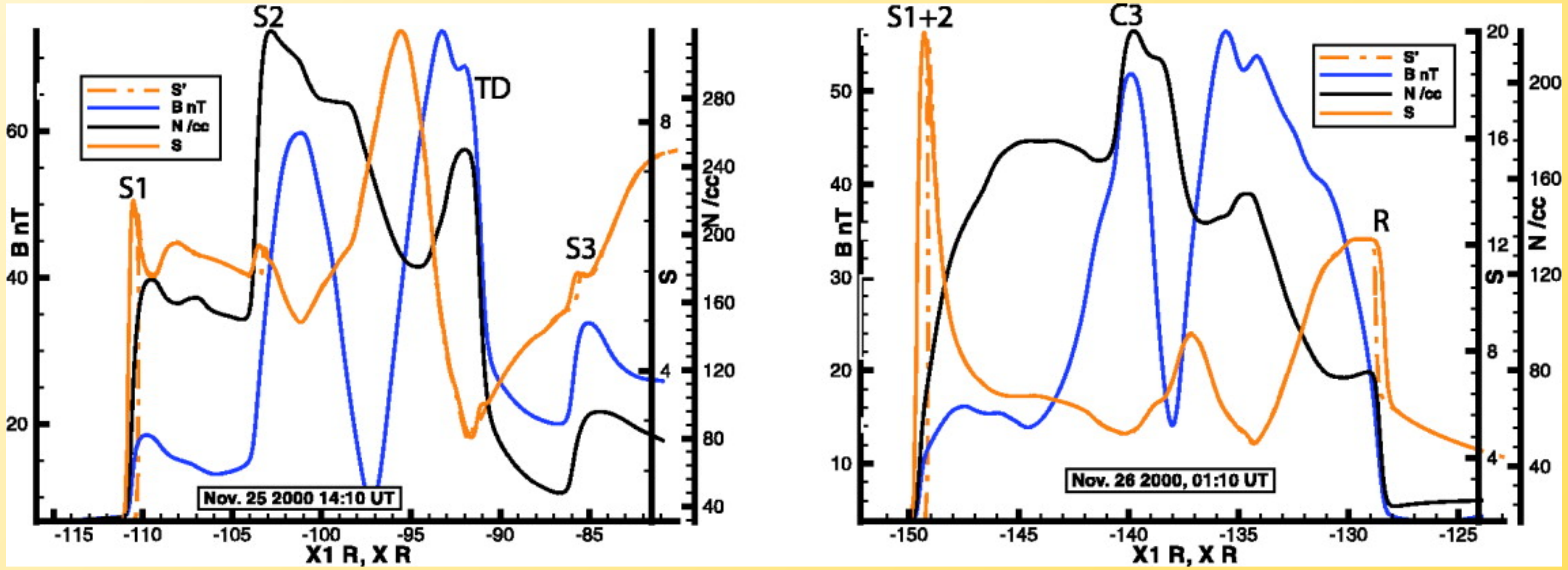
- Most shocks occur in the back part of the CME (average 24h after CME start).
  - CME average duration is 30 hours, only 1/3 of shocks occur within 16 hours of CME start.
  - Uniform distribution is not expected because the back of the CME has been compressed.
  - Often hard to identify back of CME, 1/3 of shocks occur at the CME back.
  - Strongly non-uniform distribution indicates that not all shocks can survive through a CME.
    - Two causes: expansion of CME (speed in front typically 100-200 km/s faster than back) and peak of V_a usually towards the middle of the CME.



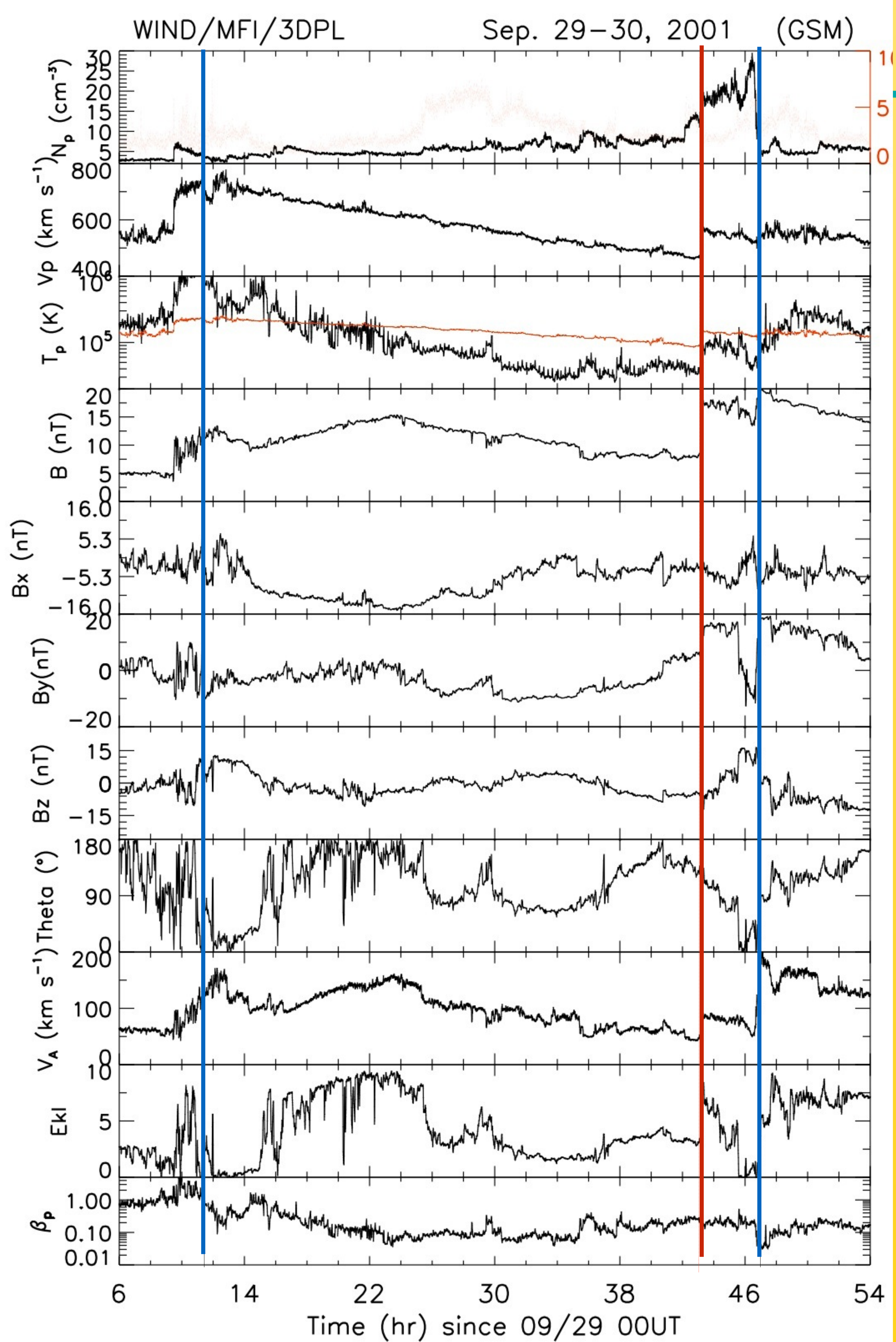


Shock near the back of a CME: Sep 30, 2001

- Example of a 700 km/s shock propagating within a few hours of a long and fast CME.
  - Shock is slower than the front of the CME,
  - Alfvén speed peaks at 150 km/s close to the center of the cloud as compared to 50 km/s in the back.
  - Shock will not remain a fast magneto-sonic shock throughout its propagation.

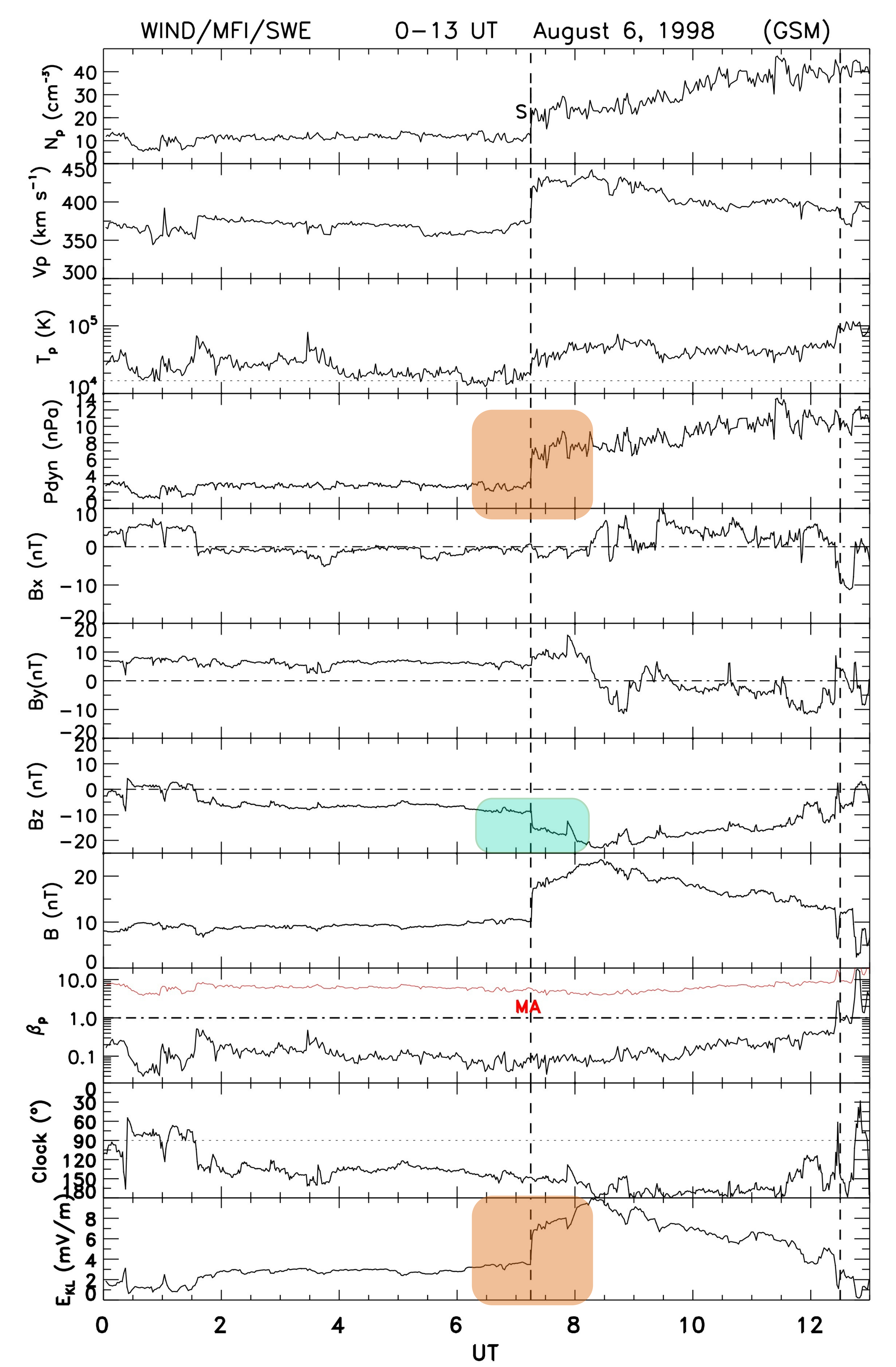


Lugaz et al. (2007): in this simulation, the third shock (S3) becomes a compression wave (C3) due to the large Alfven speeds encountered. See also measurements discussed in Wang et al. (2003)

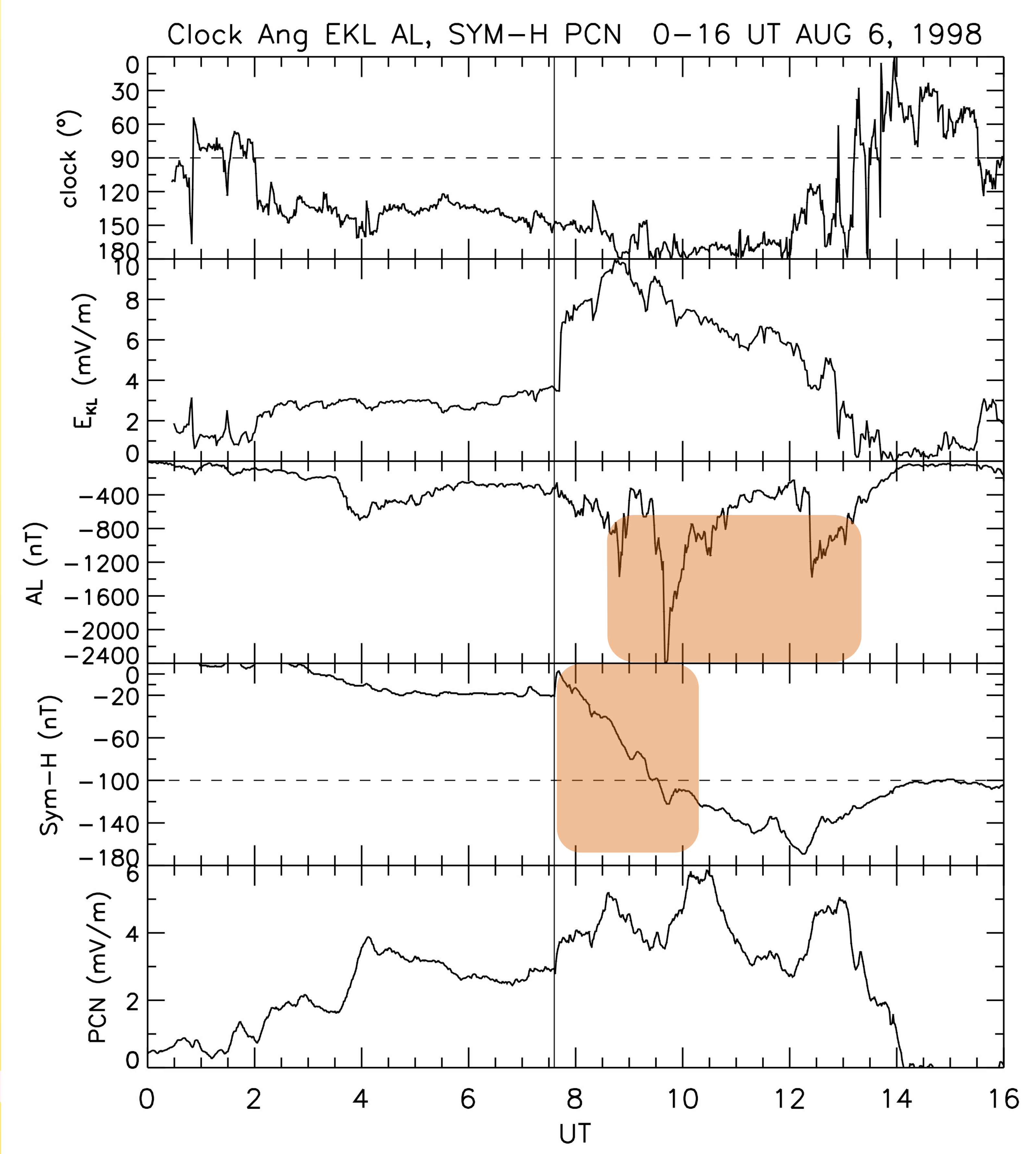


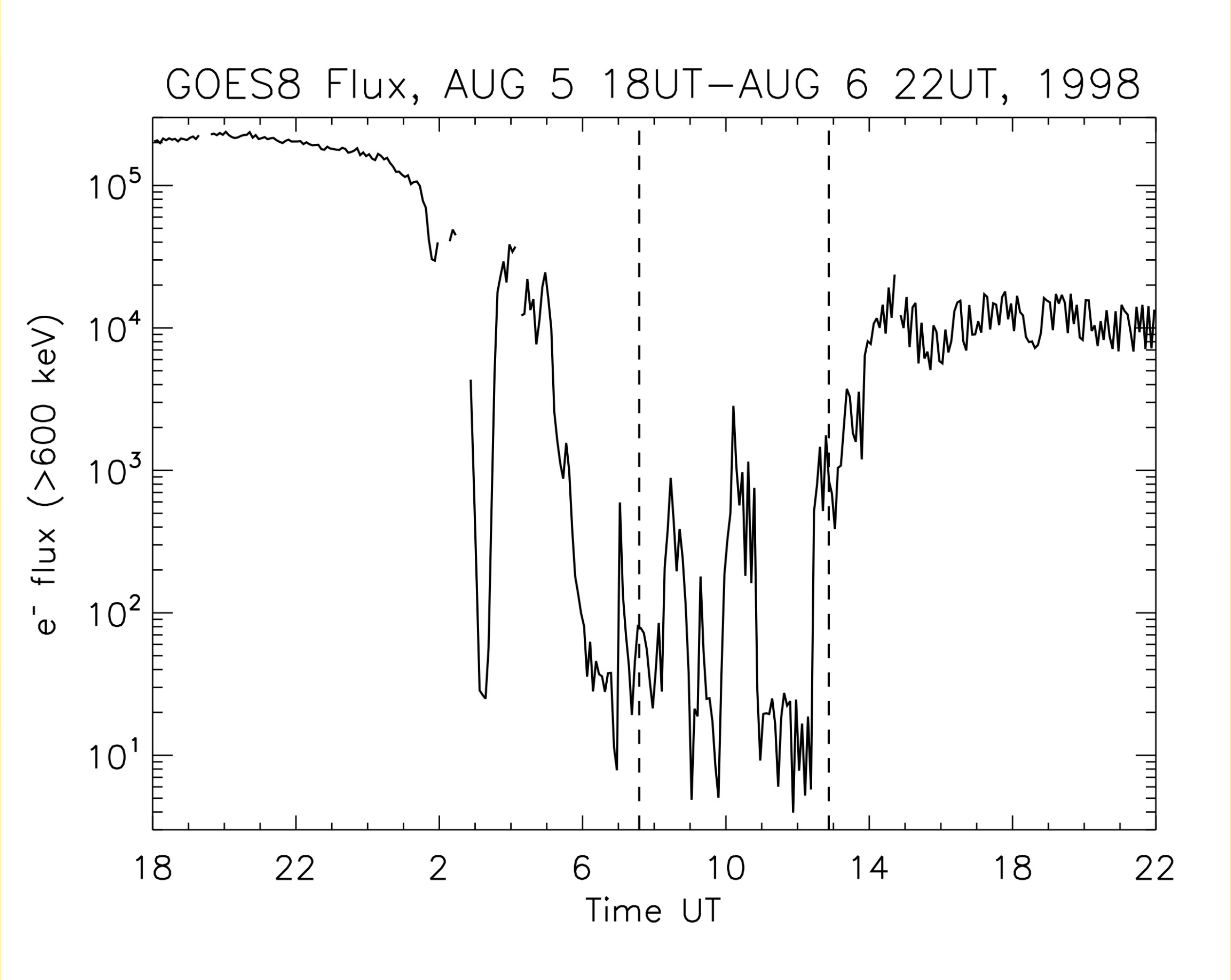
Geo-effect: August 1998 event

- Weak CME (B ~10 nT, V ~ 370 km/s) and weak shock (V ~ 470 km/s, M_{ms} ~1.6)



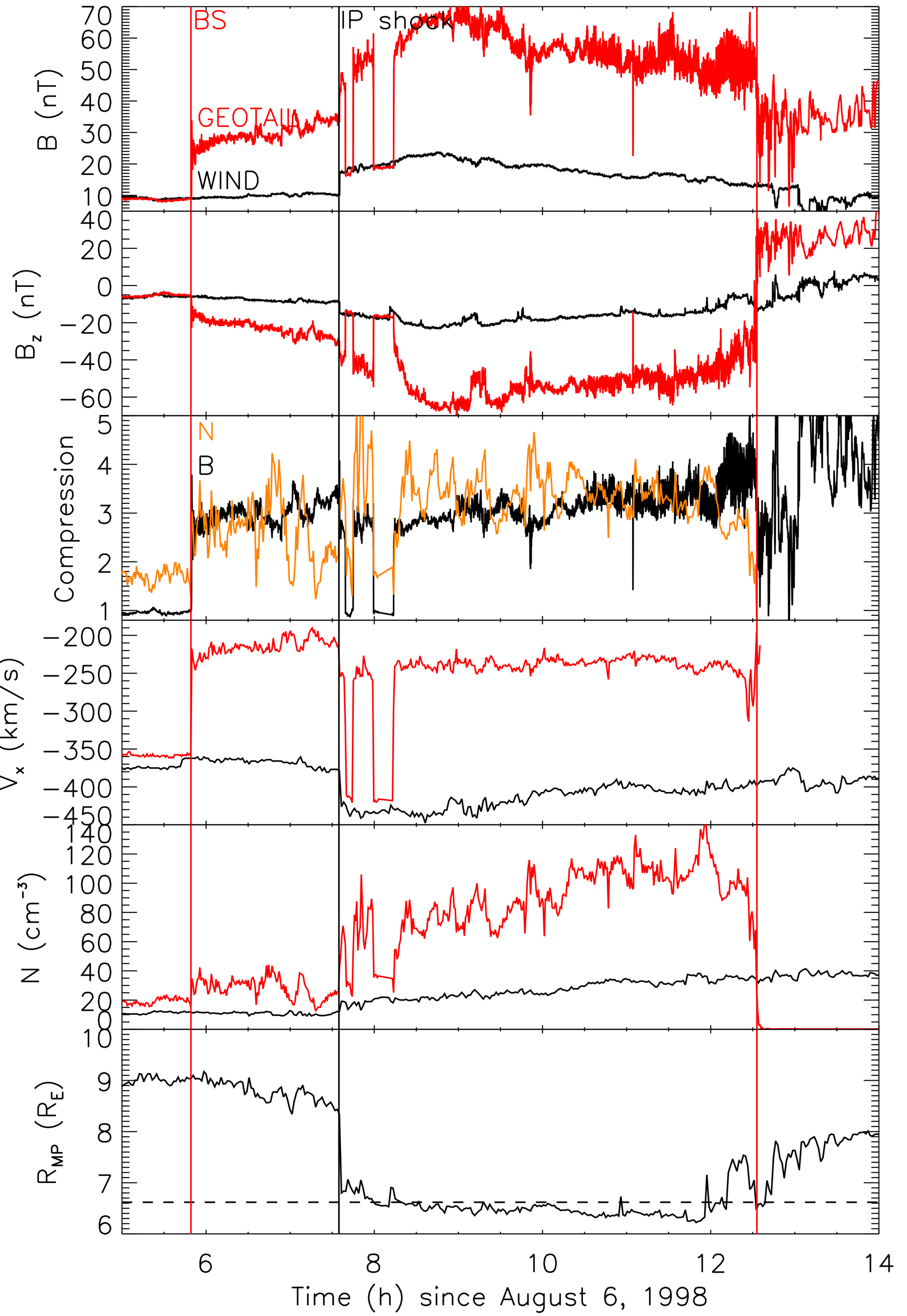
- Dual effects: **increase dawn-to-dusk electric field and dynamic pressure**.
- Followed by substorms and rapid decrease in Sym-H.



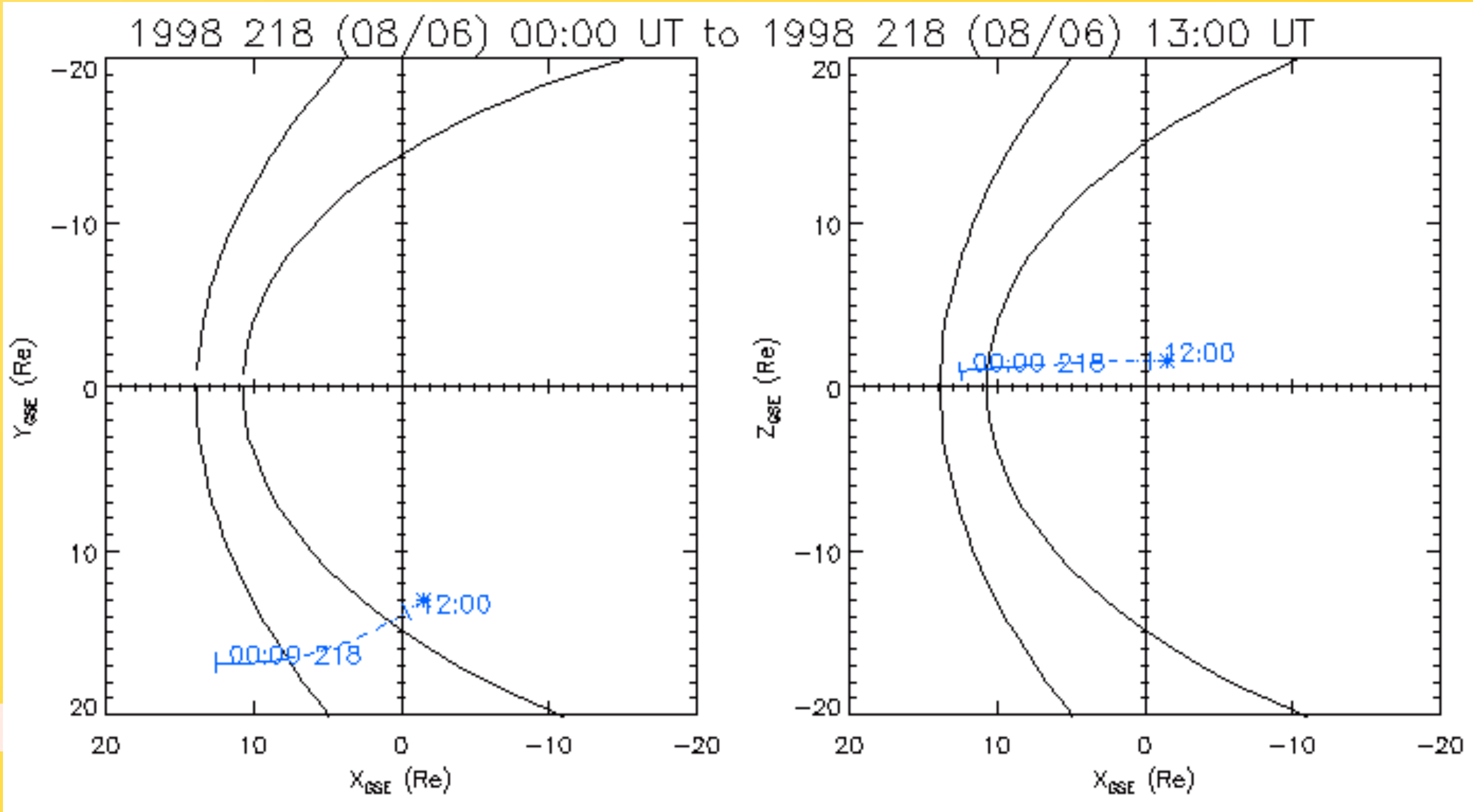


- Large drop of energetic e^- at GOES, recovery as the CME ends.

Effects on magnetosheath (MSH)



- Geotail in the MSH ~ 2 h before IP shock arrival.
- Clear look at the MSH response to high P_{dyn}, high B_z, medium to low M_a (~5) solar wind.
- Multiple BS crossings after IP shock, consistent with Earthward motion of MP by about 2–3 R_E.
- Geotail crossed the MP into the MSP at the end of the main phase of the storm.
- Highly magnetized MSH (higher than MSP), but also very dense.
- Simultaneous increases in Pdyn and southward Bz at the shock result in MP nose at GEO orbit for ~4.5 hours.



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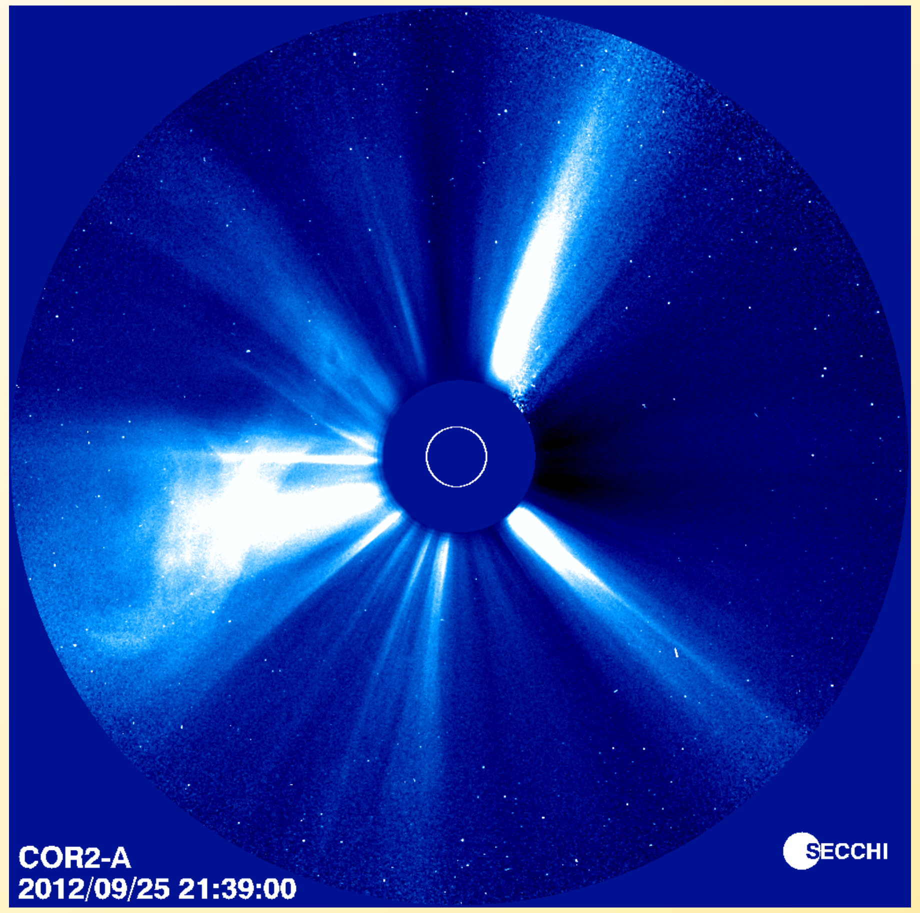
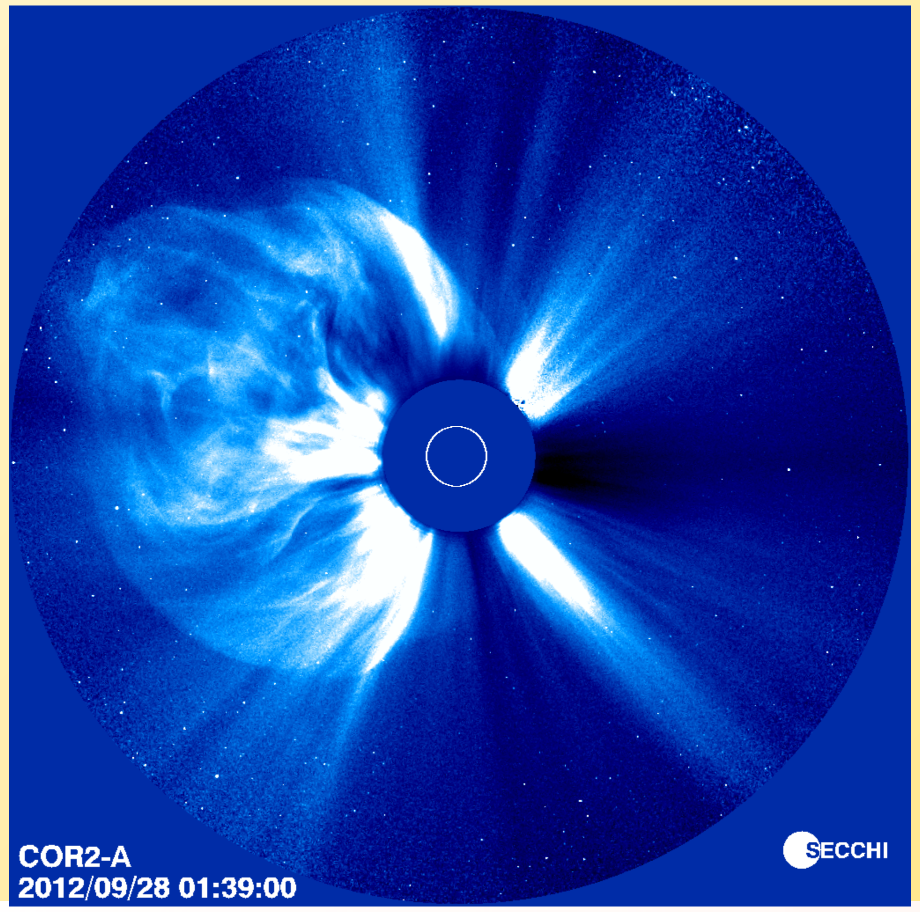
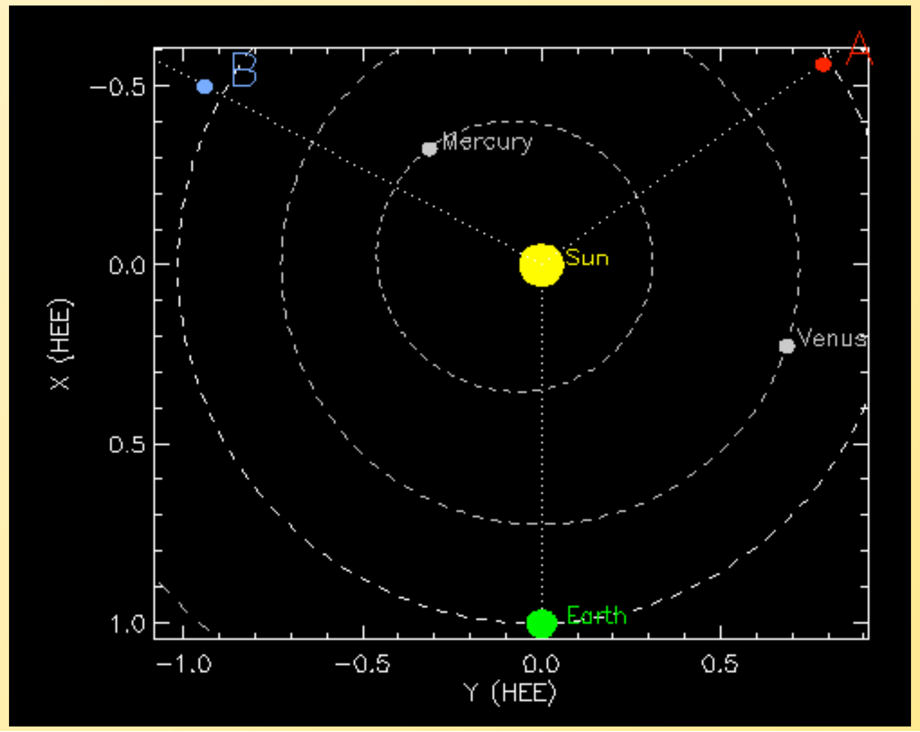
Another example: September 30, 2012

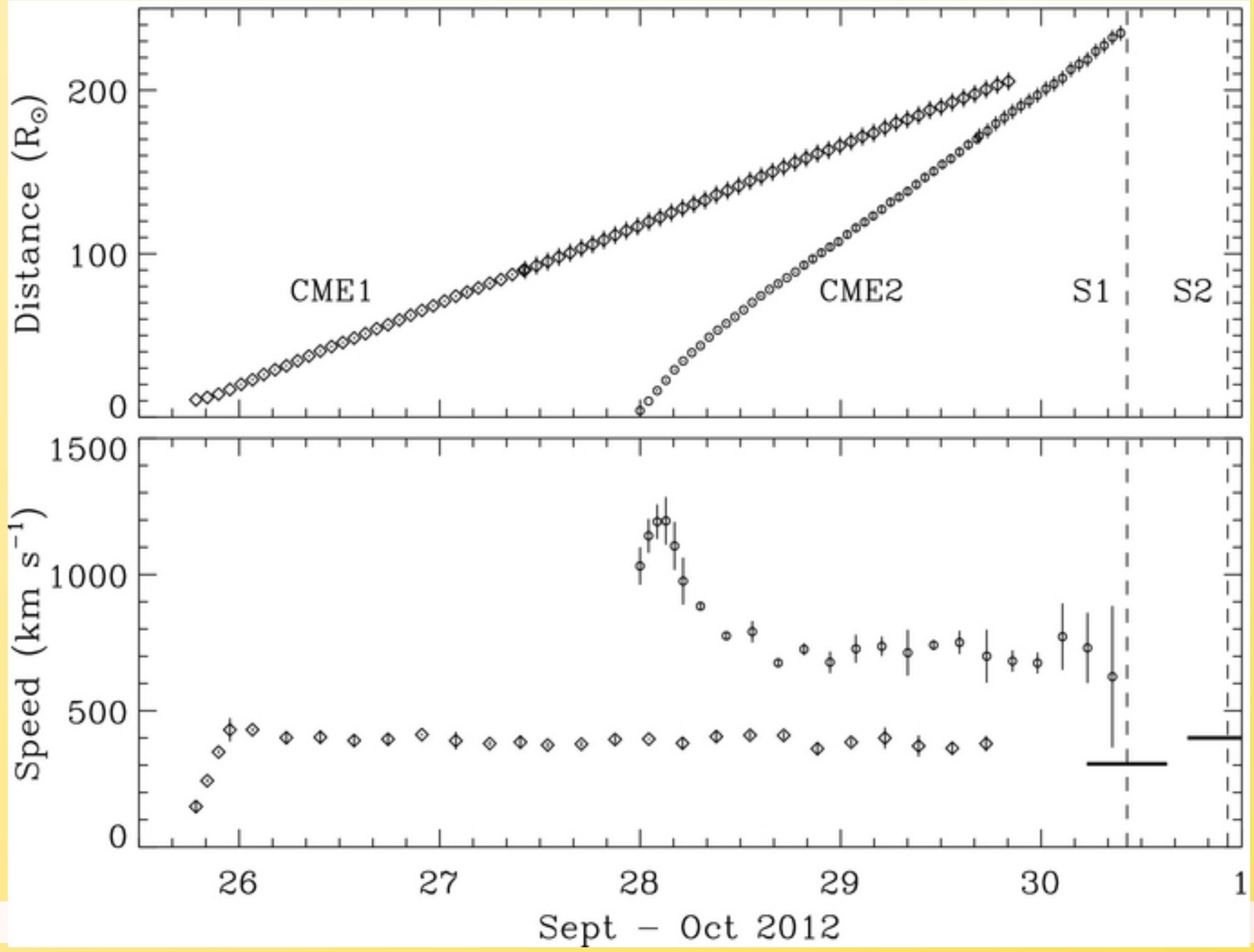
- Small blow-out CME overtaken by fast CME, launched ~48h later.
- Can be followed with STEREO/SECCHI to 1 AU.

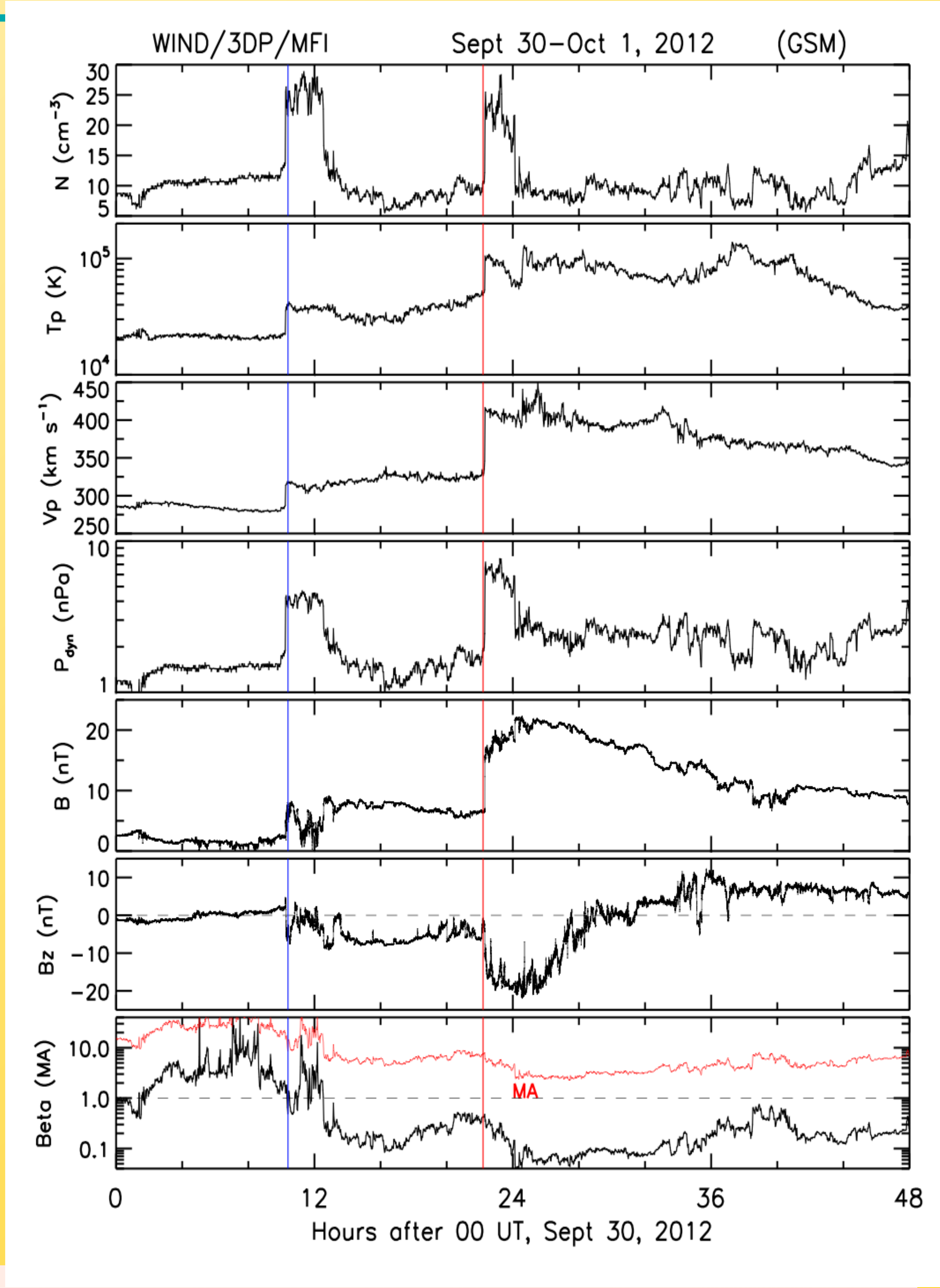






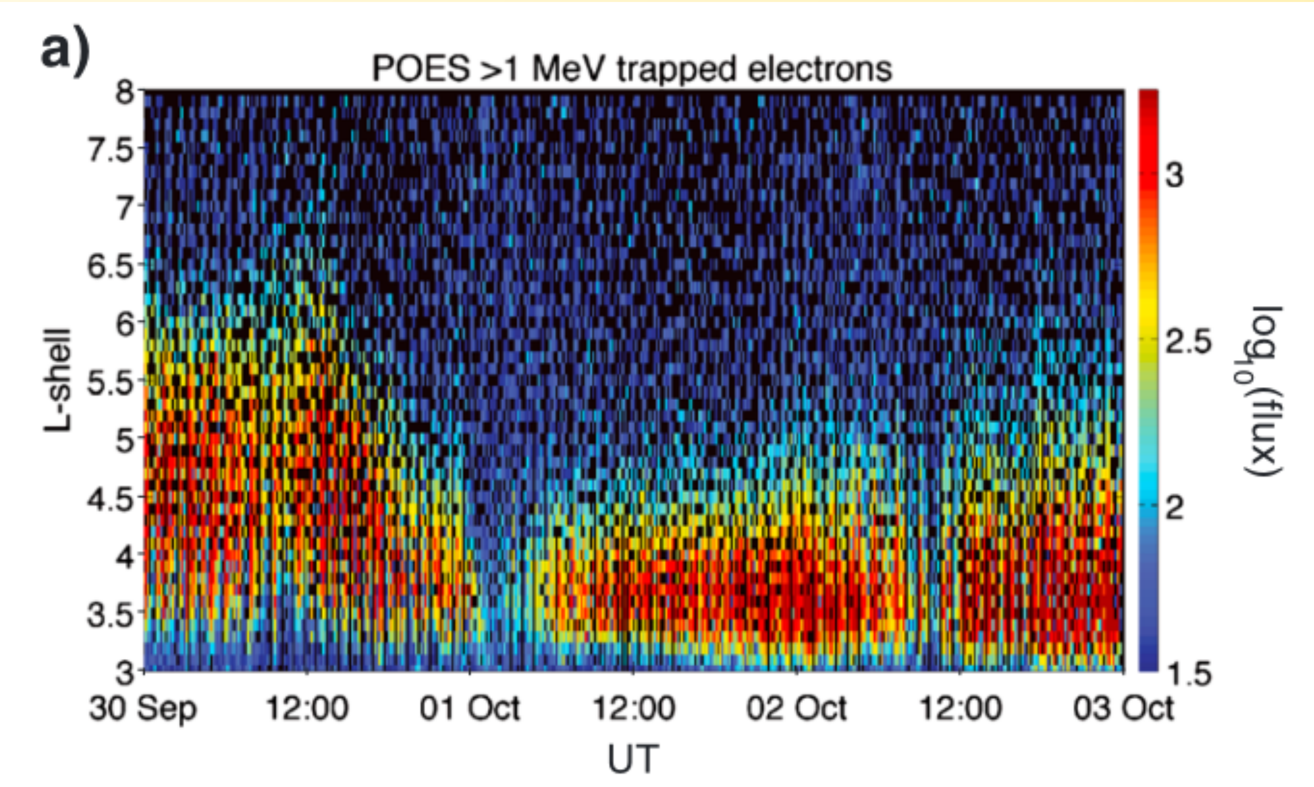
Ying Liu *et al*, ApJ, 2014

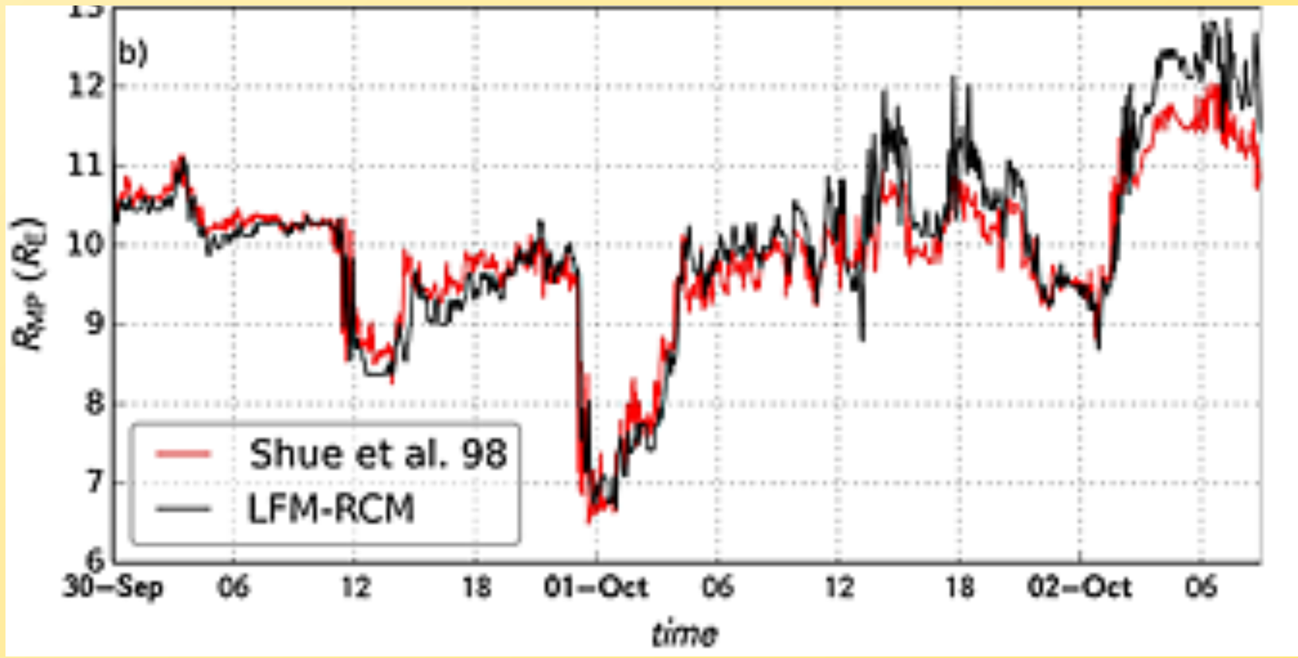




September 30, 2012

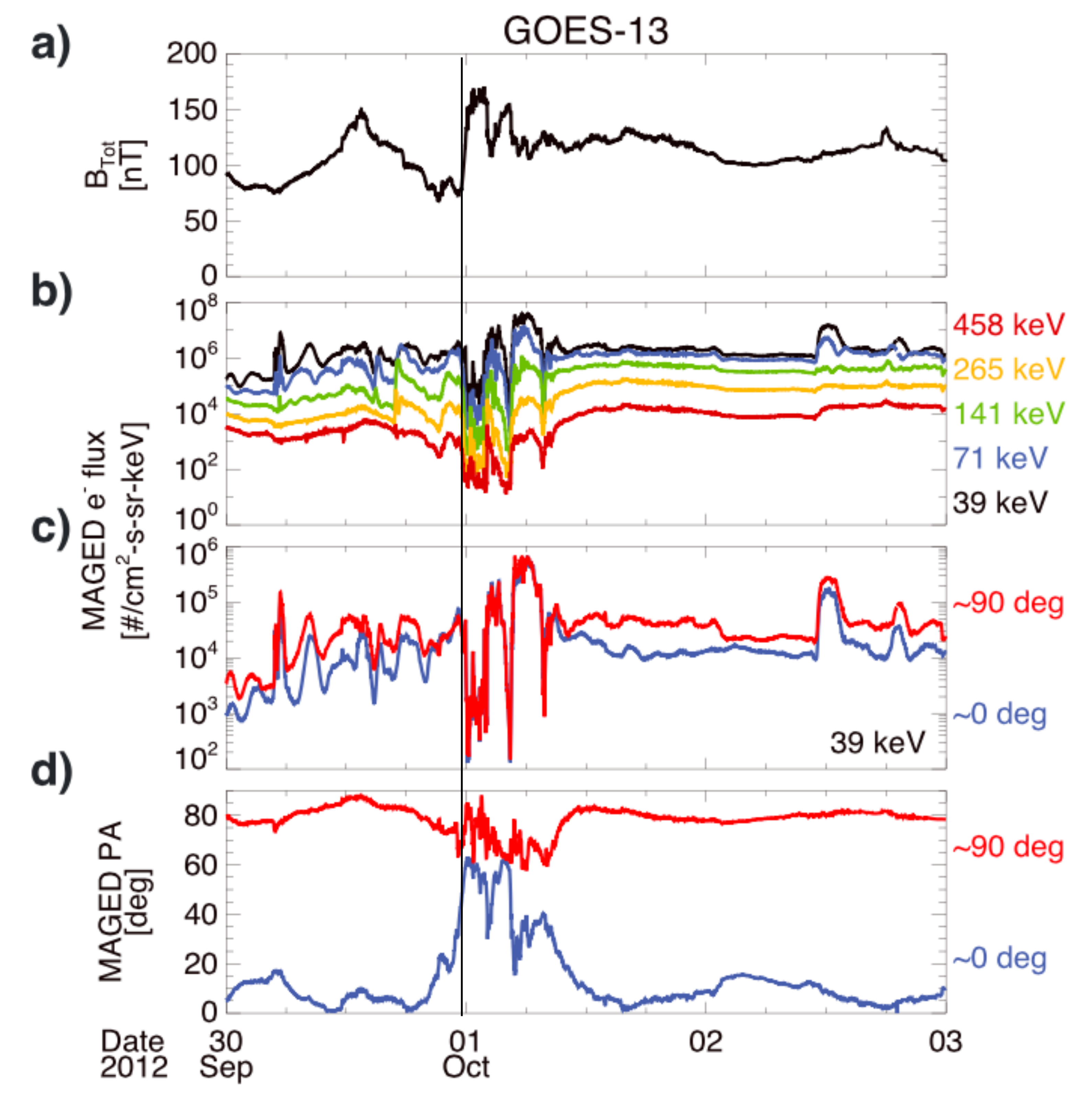
- Maybe this event rings a bell?
  - "Observations reveal an isolated third ring […] of high-energy (>2 MeV) electrons that […] persisted largely unchanged […] for more than 4 weeks before being disrupted (and virtually annihilated) by **a powerful interplanetary shock wave passage**." Baker *et al.,* Science, 2013

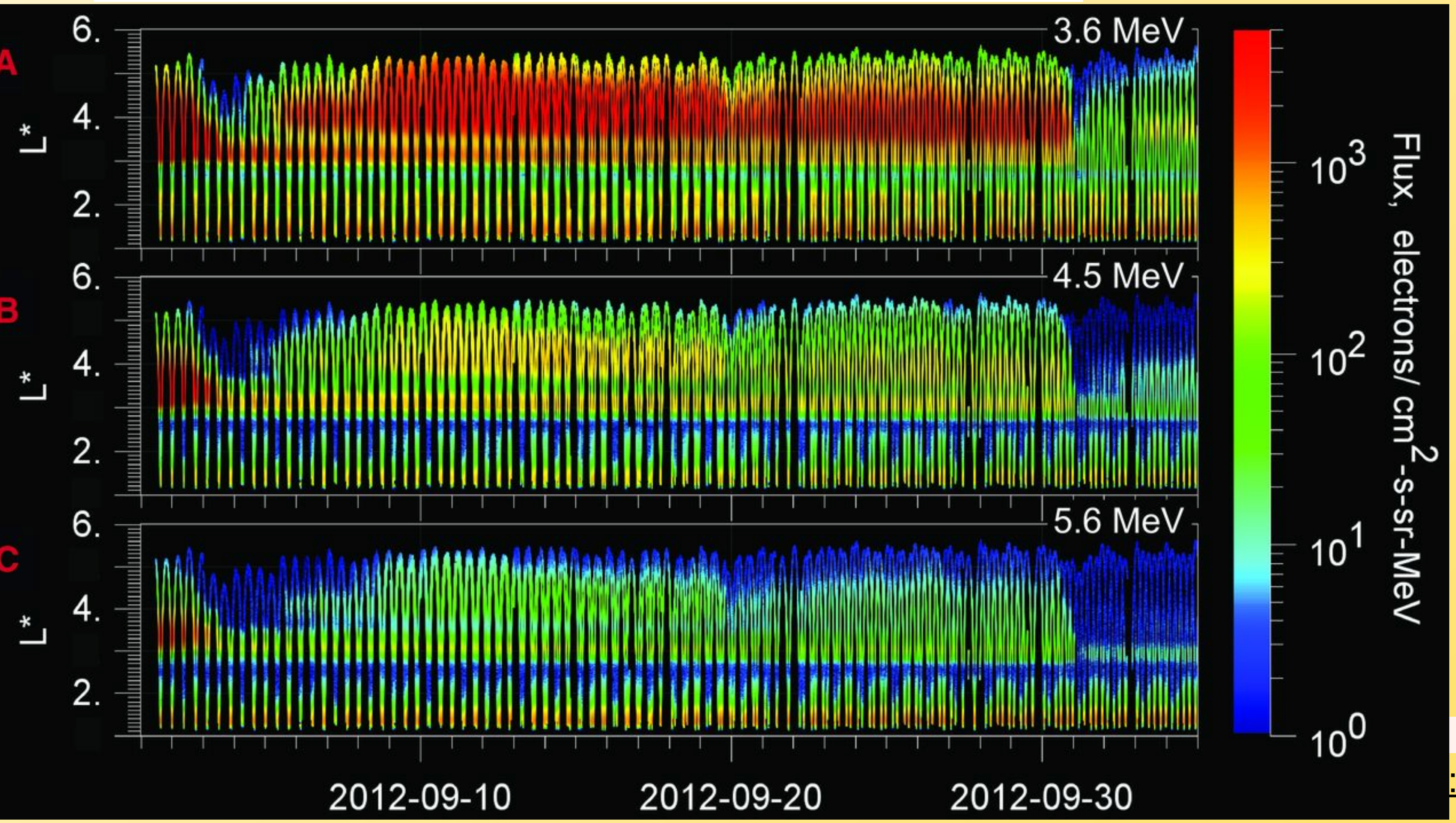




Hudson *et al.*, **GRL**, 2014

Turner *et al.*, **JGR**, 2014





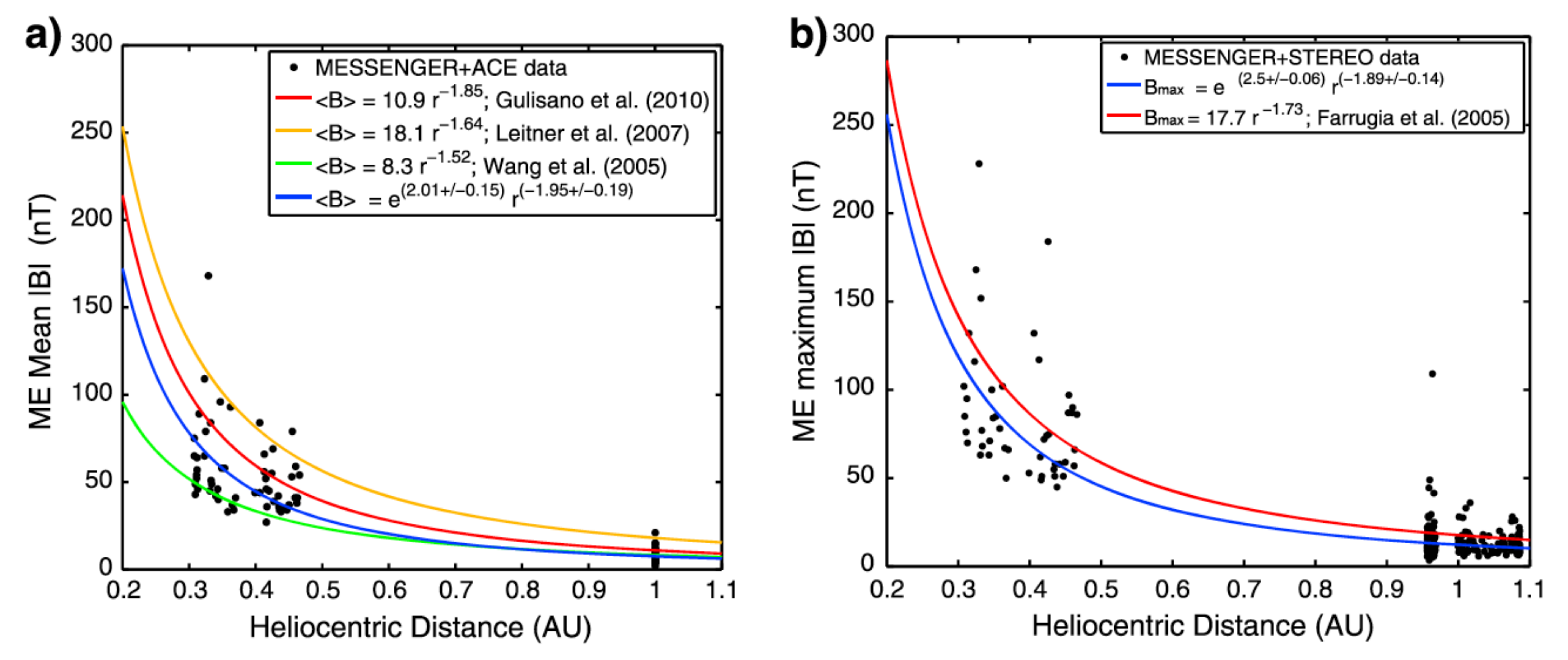
“Reverse” study

- Work in Progress: **which types of shocks are geo-effective?**
- Starting for existing lists of intense geomagnetic storms in SC23
  - Zhang et al (2007) list: 9/88 due to shocks inside CMEs, 12/88 due to shock/sheath, 9/88 to multiple shocks -> 30/88 intense geomagnetic storms are due to shocks.
  - From our list, 5 newly identified shocks inside CMEs, so **14/30 geo-effective shocks are shocks inside CMEs** (including 2 listed as multiple shocks), 6/30 are due to multiple shocks and 9/30 to single shocks into normal sw conditions (1 actually CIR)
  - Echer et al (2008) list: 22 shocks/sheath, 3 complex, 1 compressed CME, 1 SH/HCS -> 27/90 intense geomagnetic storms due to shocks.
  - From our list, 9/22 shocks + 3 complex + 1 compr. CME + 1 SH/HCS are shocks within CMEs -> **14/27 geo-effective shocks are due to shocks inside CMEs,** 10 to “normal” shocks.
- We all know shocks can be geo-effective, and they are second only to magnetic clouds in causing intense geo-magnetic storms. However, **~50% of (intense) geoeffective shocks are in fact propagating within a previous CME.**
- 14/50 shocks inside CMEs lead to intense geomagnetic storms (28%).
- ~10/~200 “normal” shocks lead to intense geomagnetic storms (5%).

Conclusions

- Shocks propagating inside CMEs are a common occurrence at 1 AU (~50 during SC 23).
  - It represents about 15% of the shocks and occur in about 15% of the CMEs at 1 AU,
  - Associated with 19 out of the intense geo-magnetic storms in SC23 (within 12 h of shock).
- Shocks inside CMEs are typically **fast and weak**.
- These shocks propagate inside weak and relatively slow CMEs with B ~ 8-10 nT, speed of ~ 450 km/s and Alfvén speed ~ 100 km/s.
- Median compression is about 2. Increase in electric field ~3.
- Most shocks are measured in the back 75% of the CME (as measured by its duration). This may indicate that **not all shocks are able to survive throughout a CME**:
  - CME expansion means that upstream speed increase by about 30-40% throughout the CME,
  - In many CMEs, the Alfvén speed peaks in the center of the ejecta.
- Shocks inside CMEs are a great way to make a weak CME geo-effective.
- Combine characteristics of shocks and ejecta: **simultaneous increase in dynamic pressure and B field** => large earthward motion of the MP, potential for MP shadowing.
- **Not all shocks are equal. Beware of the upstream conditions!**

Thank you!



Winslow et al. (JGR, 2015): 61 CMEs from 0.31 AU to 0.47 AU in 03/2011 to 09/2014
Similar (very slightly steeper than previous study from SC21 w/ Helios)

Thanks to Charlie Farrugia, Liu Ying, Chuck Smith, Nathan Schwadron,
Harlan Spence, Chia-Lin Huang, Chip Manchester, Tamas Gombosi,
and everyone else!

"Recent" studies have been made possible by the following grants:
NSF AGS0639335, AGS0819653, AGS1239699, AGS1239704 and
NASA NNX08AQ16G, NNX13AH94G and NNX15AB87G.