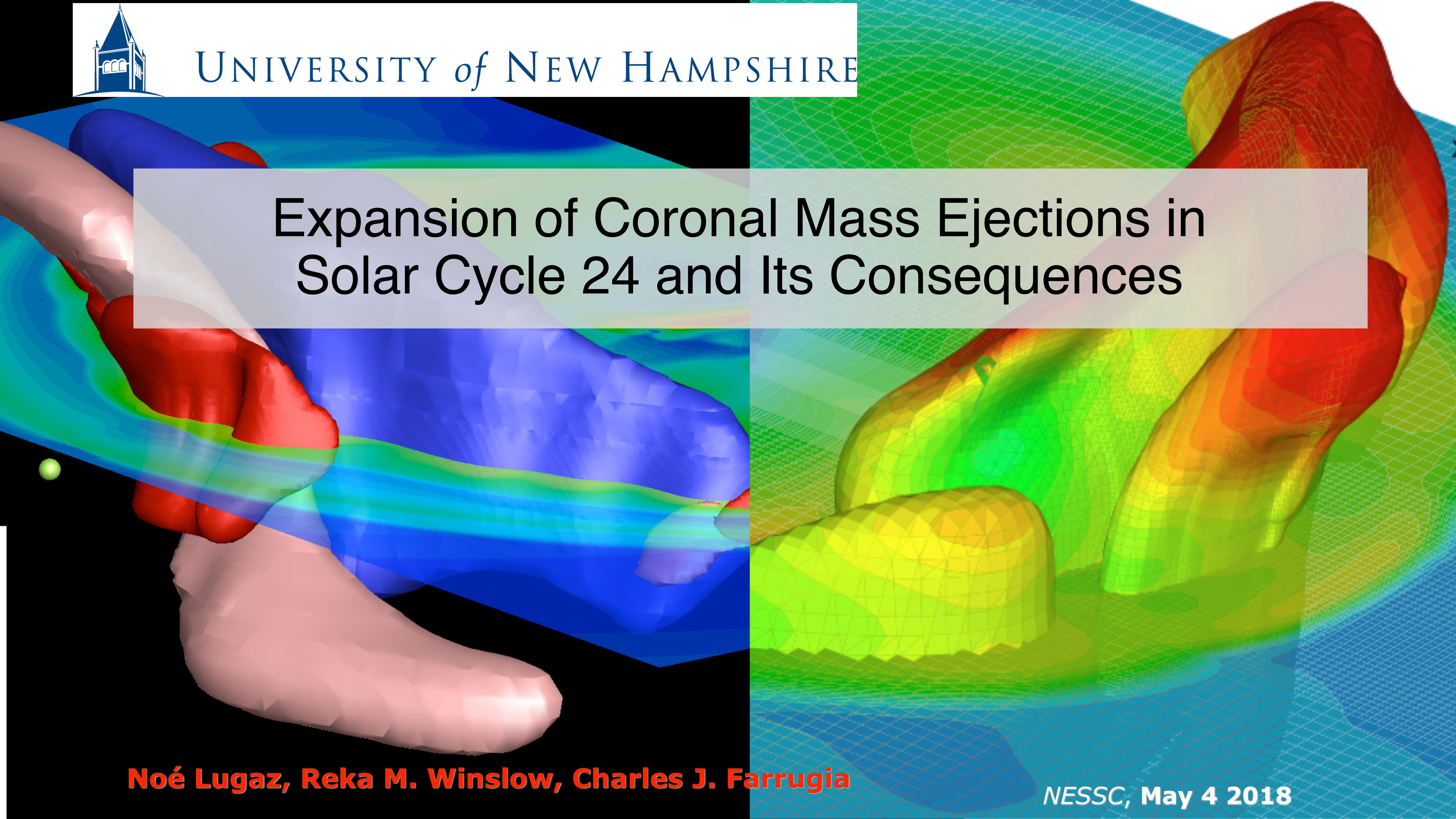
UNIVERSITY of NEW HAMPSHIRE

Expansion of Coronal Mass Ejections in Solar Cycle 24 and Its Consequences



Noé Lugaz, Reka M. Winslow, Charles J. Farrugia

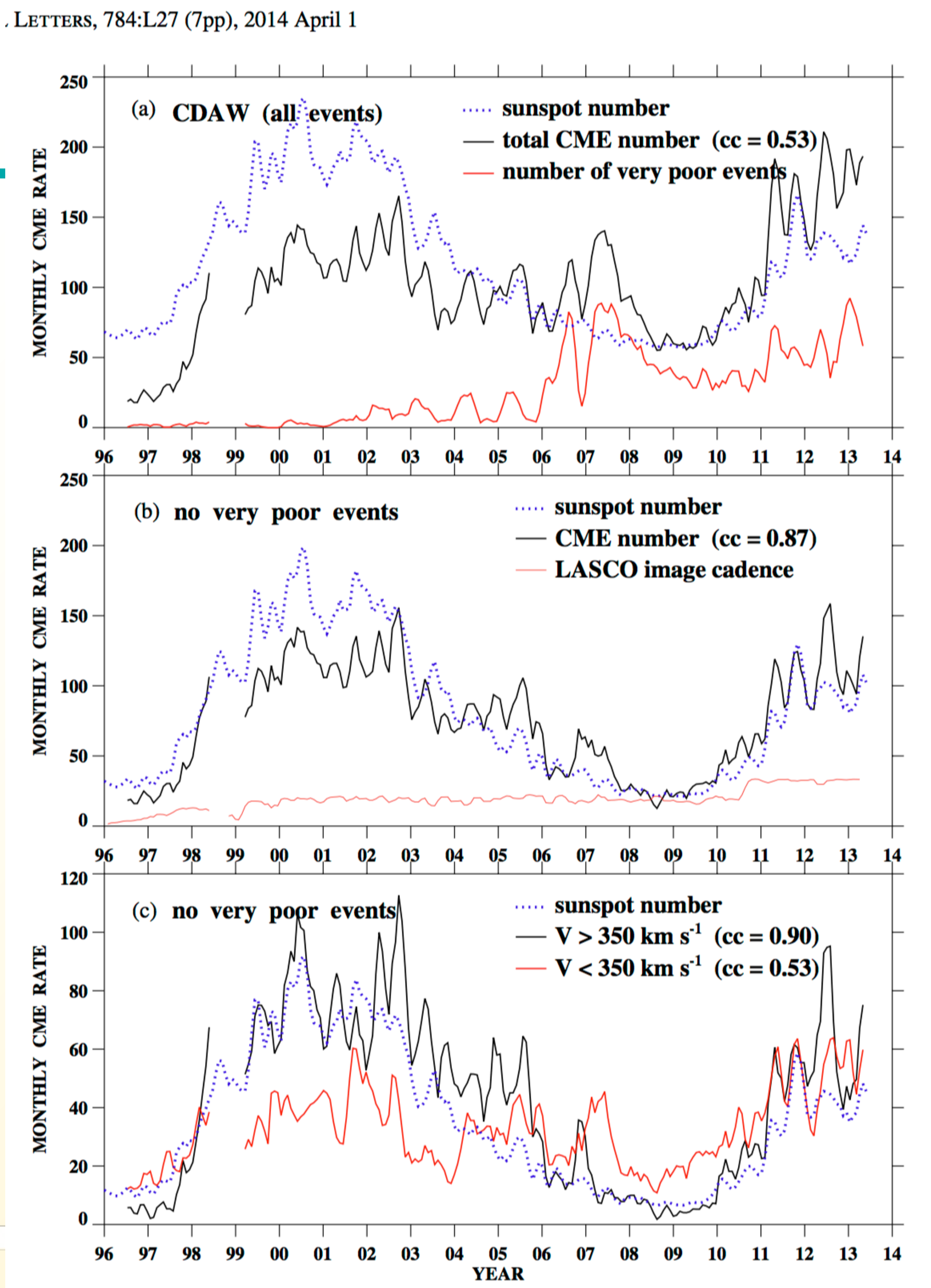
NESSC, **May 4 2018**

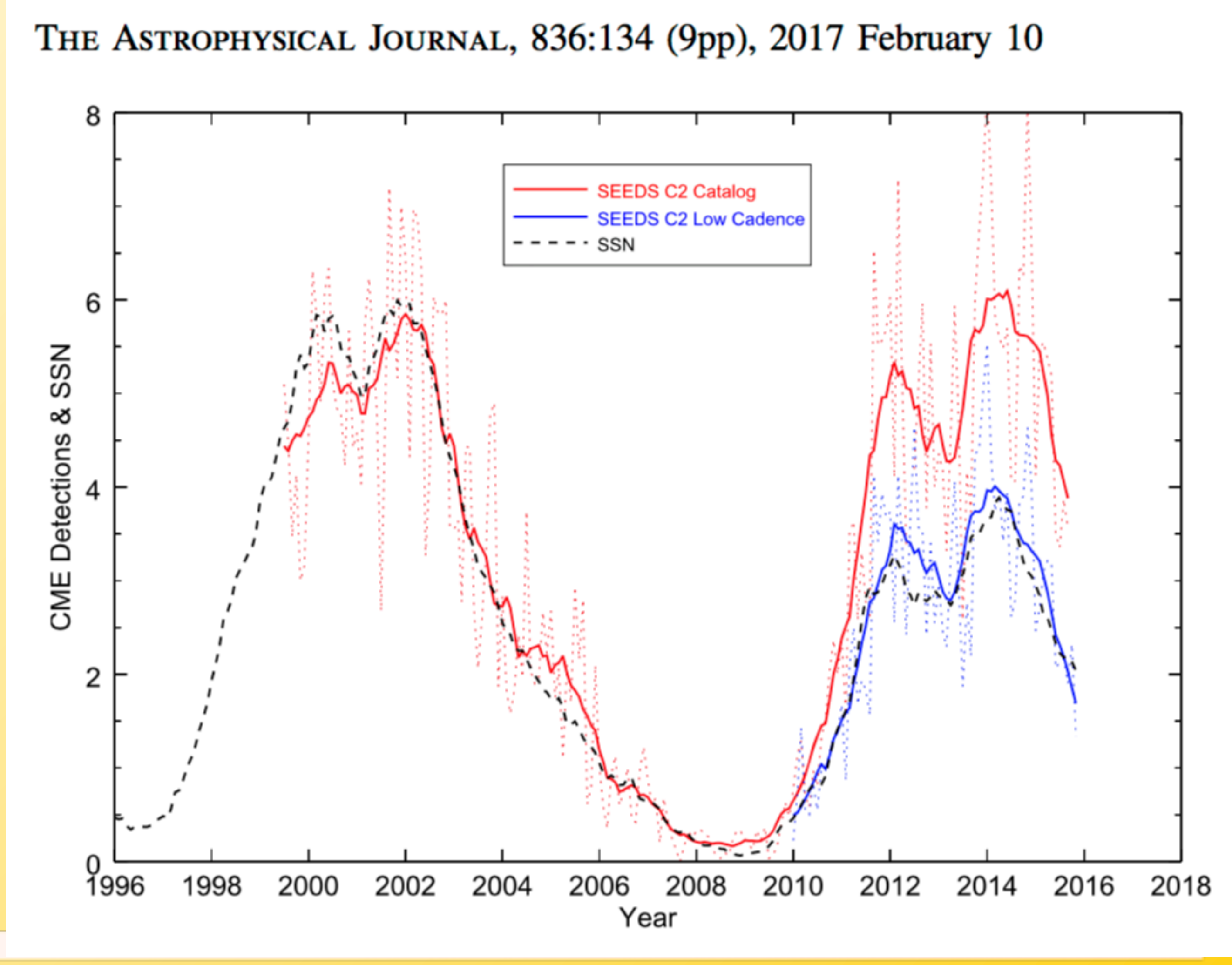
announcement #1:
al" CMEs in SC24

/, in terms of SEPs, geomagnetic storms, etc.

olar activity. The reports about high CME rates from the
sing past correlations. Do **not** use the LASCO catalog.

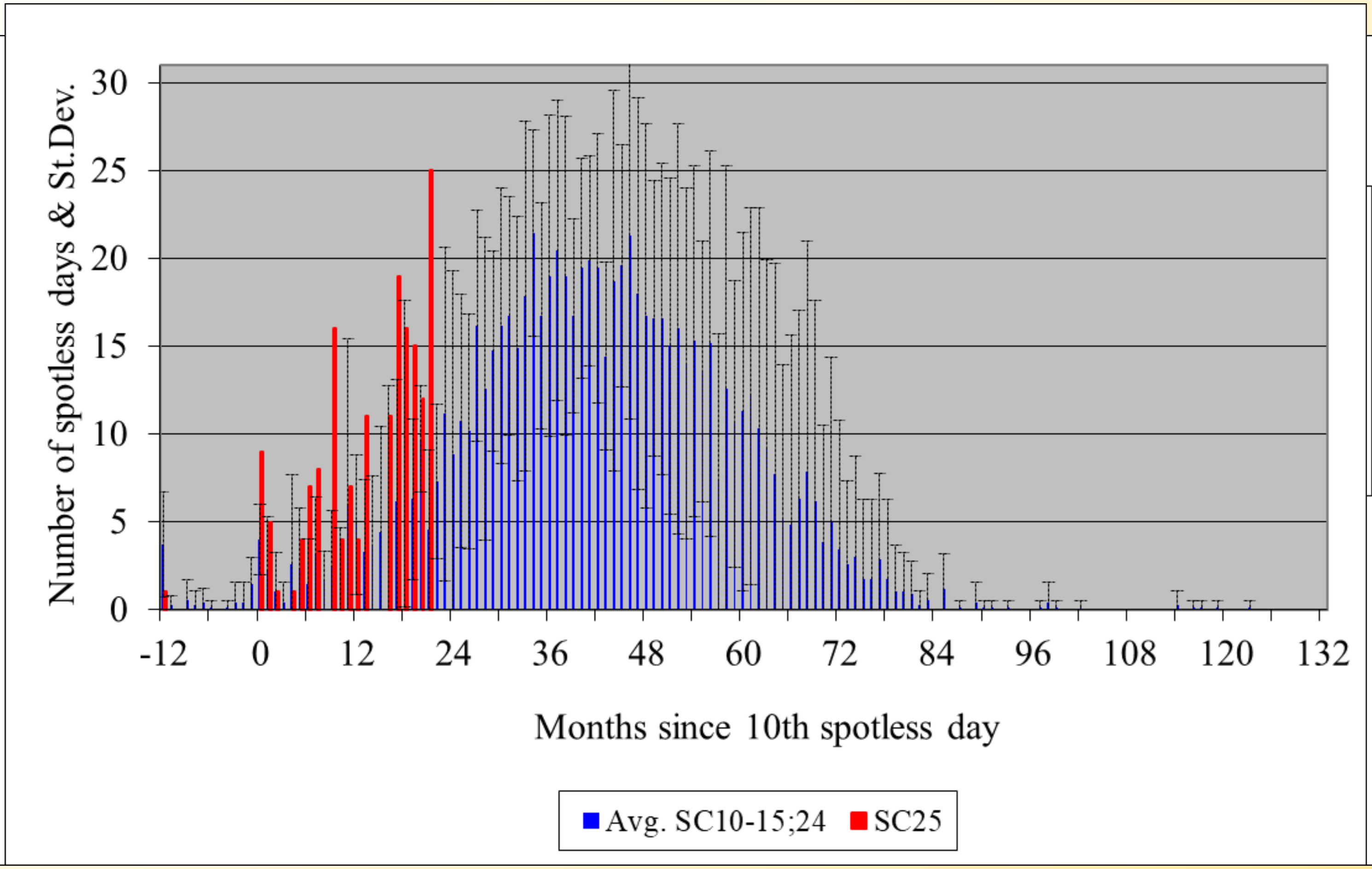
14 - Hess & Colaninno, 2017

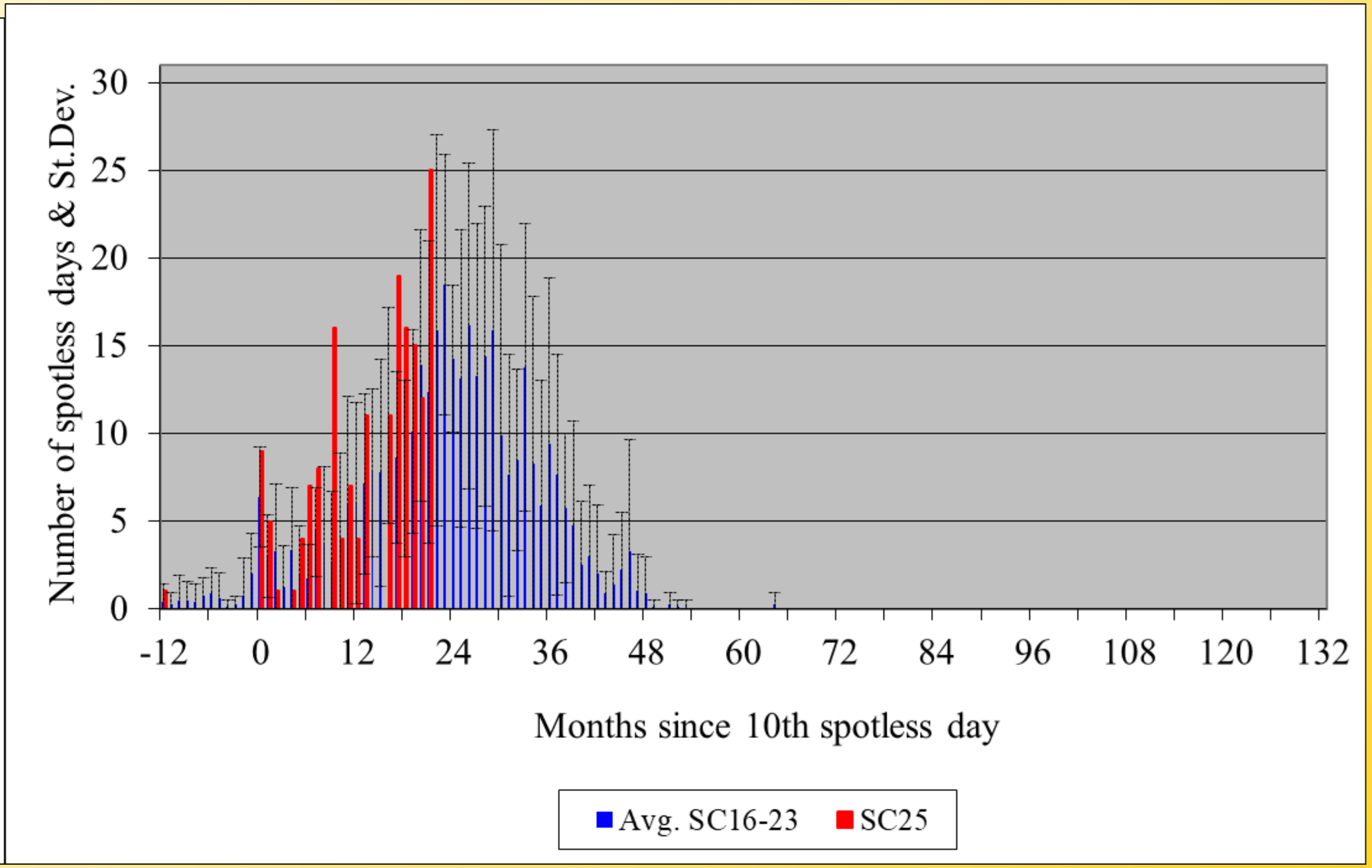




Service announcement #2: SC25?

- SIDC maintains an analysis of sunspot-less days in the current SC24->SC25 transition.
- So far, it seems to indicate the solar minimum may be reach in < 1 year, i.e. a much faster transition than during the last cycle.

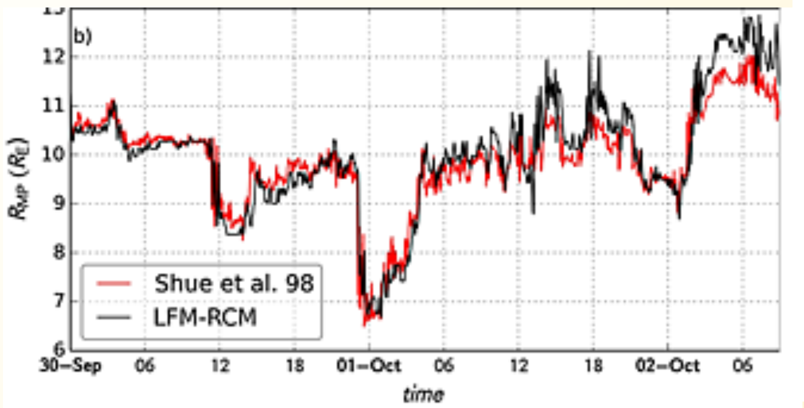


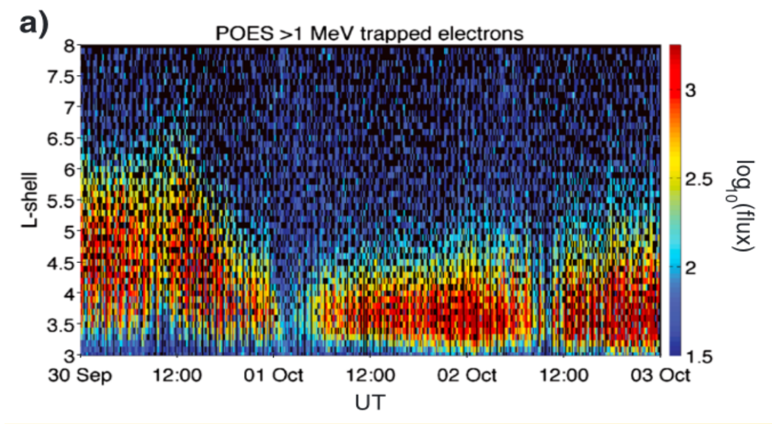


A way to create strong storms in a weak cycle

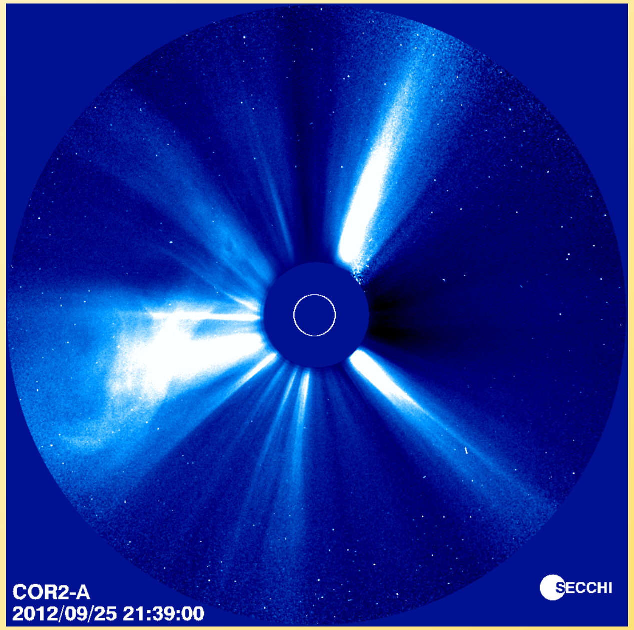
Lugaz *et al.*, **GRL**, 2015
Liu *et al.*, **ApJL**, 2014

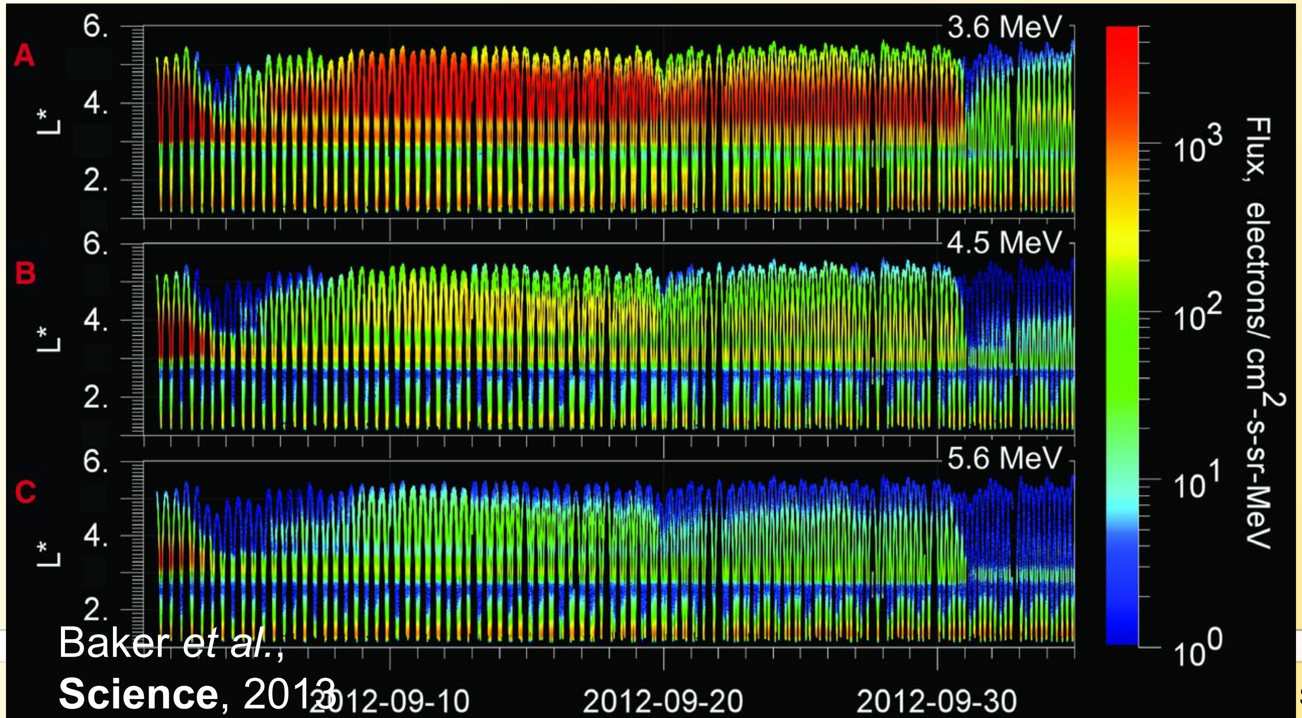
- “In situ […] spacecraft observations reveal an isolated third ring [that] persisted largely unchanged […] for more than 4 weeks before being disrupted (and virtually annihilated) by **a powerful interplanetary shock wave passage**.” D. Baker *et al.*, Science, 2013
- What was really behind this “strong” shock?





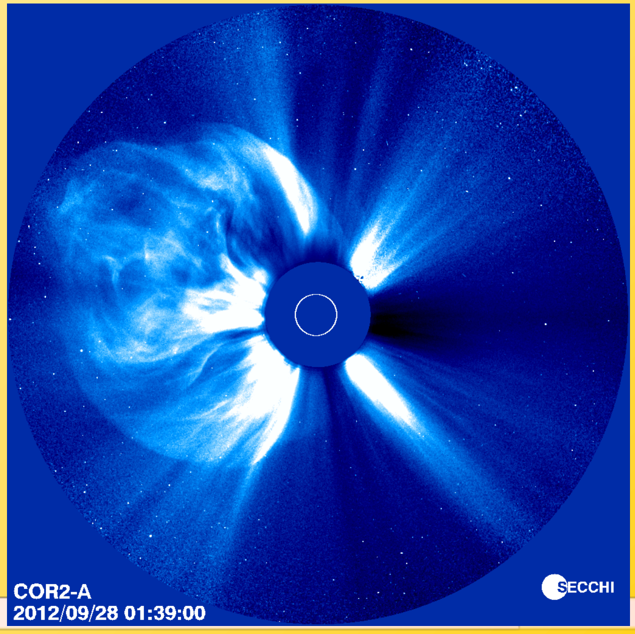
Hudson *et al.*, **GRL**, 2014



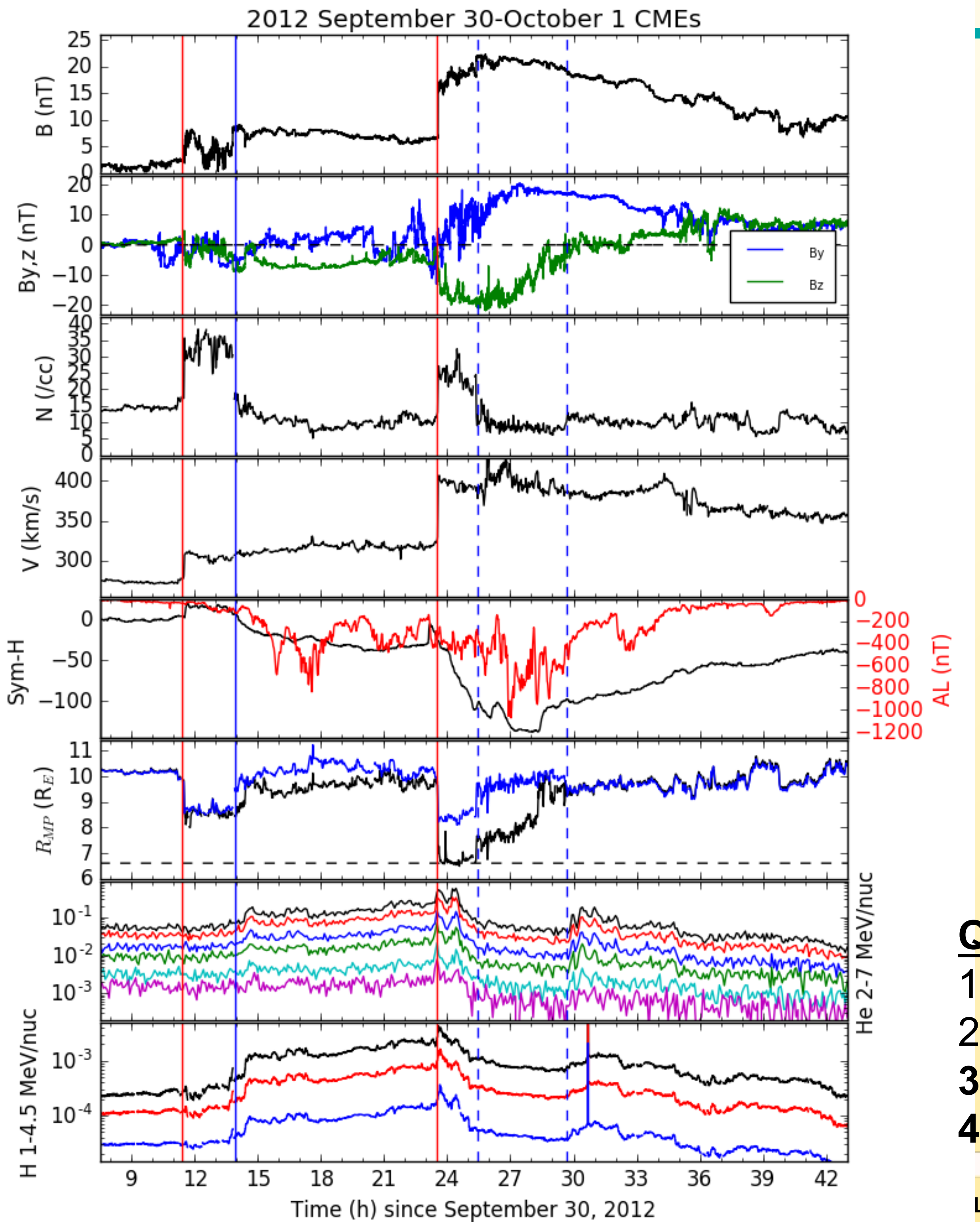


Baker *et al.*, **Science**, 2012

- 2 **interacting** CMEs (Liu et al., 2014; Lugaz et al., 2015)
- Second CME 48 hours after first CME.
- Shock inside previous magnetic ejecta.



What is special about this event?



Lugaz *et al.*, **GRL**, 2015

- **Geo-effects**: Due to shock propagating inside B_Z south. Results in:
  - the main phase of an intense geomagnetic storm.
  - Combination of B_z south and high dynamic pressure results in the magnetopause to reach ~ 6.5 Re (blue curve w/o erosion).
- **IP Causes**:
  - First shock: CME speed of **315 km/s**!!
  - Second shock: CME speed of **370 km/s** (leading edge of 410 km/s)
  - How come? Before shock 1: V_{sw}~ 270 km/s, V_{ms} ~ 40 km/s
    ➡ **315 km/s CME can drive shock!**
  - Before shock 2: V_{sw}~ 320 km/s, V_{ms} ~ 60 km/s
    With 40 km/s radial expansion,
    ➡ **370 km/s CME can drive shock!**

Questions:

1- How common are shocks inside CMEs? (see Lugaz et al.. JGR, 2015)

2- What type of shocks are by themselves geo-effective? (see Lugaz et al., 2016)

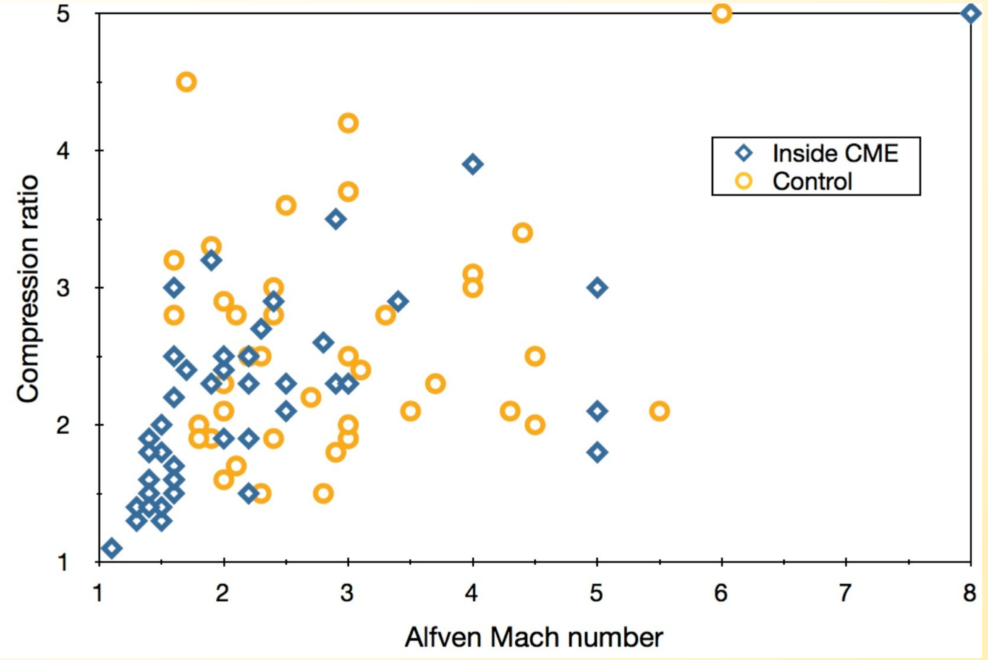
3- How common are shocks driven by very slow CMEs? (next)

4- Are these mostly occurring during the weak SC24? (next)

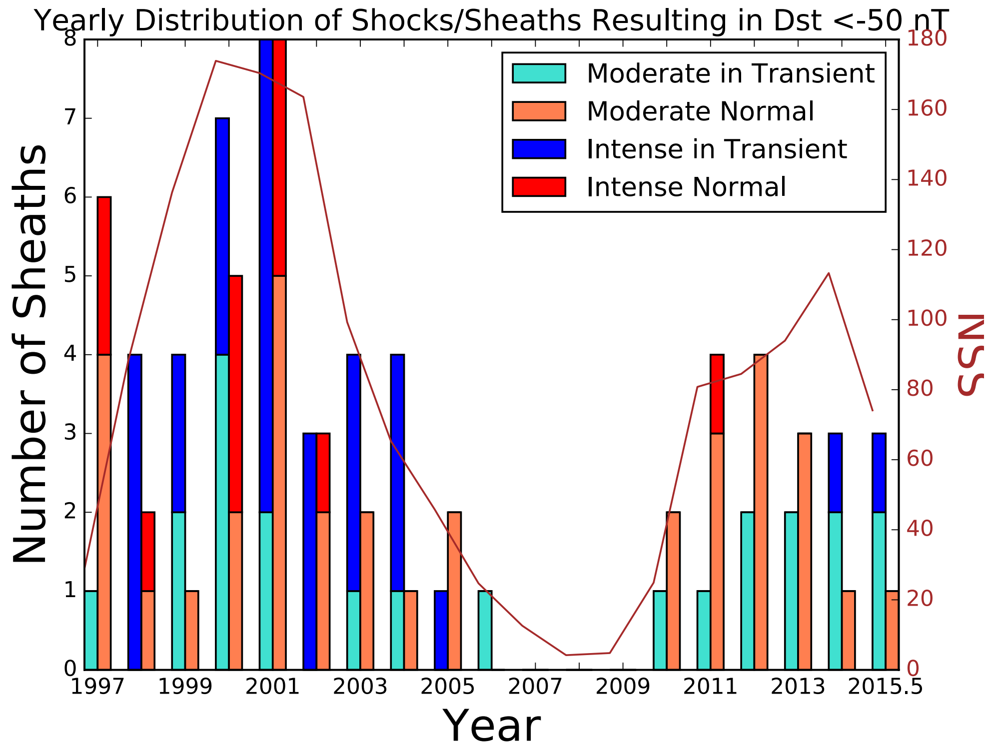
Geo-effectiveness of shocks and shocks inside CMEs

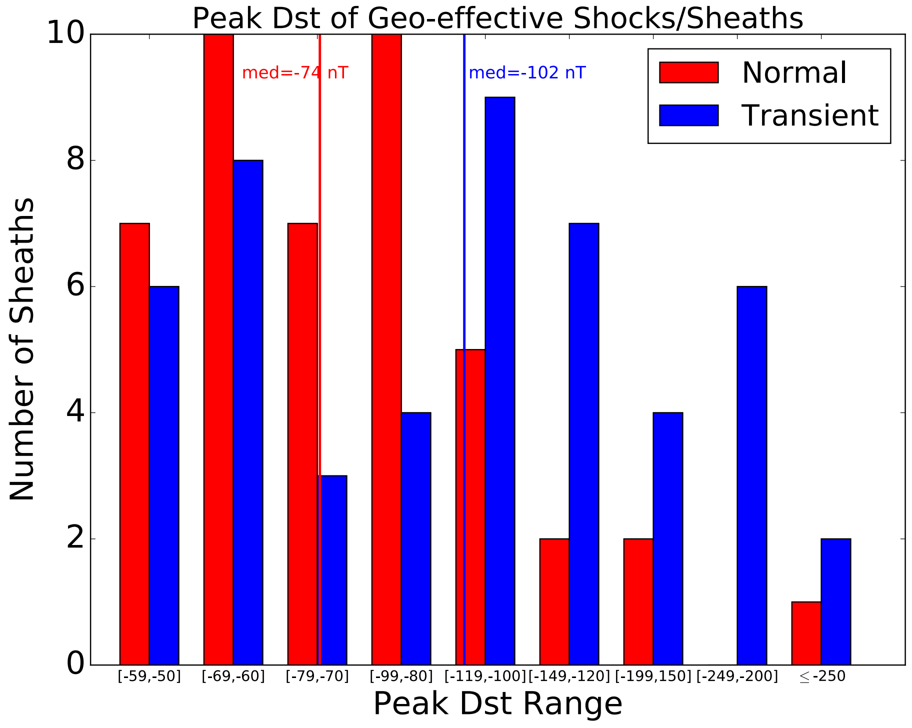
Lugaz *et al.*, **JGR**, 2016

- **Common?** Over SC23, ~15-20% of the shocks at 1 AU propagate inside a CME (Lugaz et al., 2015).
- Not all shocks are equal. But, beware ! Their “properties” (Mach, compression ratio, angle) depend on the upstream conditions. So does their geomagnetic consequences.
- **Causes?** 94 shocks (67 in SC23, 27 in SC24) had a sheath causing a moderate geomagnetic storm.
  - 45 shocks propagated into “nominal” solar wind conditions (“normal” shocks).
  - 49 shocks propagating into a preceding transient (see also, Lugaz et al., JGR, 2015).
- **Shocks inside transients are statistically more geo-effective.**
- ~50% of shocks in CMEs have geo-effective sheaths vs. ~12% of “normal” shocks.



Lugaz *et al.*, **JGR**, 2015





Upstream conditions enabling slow CMEs to drive shocks

Lugaz et al., **ApJ**, 2017

- Straight-forward: slower CMEs are less likely to drive shocks.
- **Questions**: 1- is there a threshold? (ex: CME with speed below 400 km/s don't drive shocks)
  2- Is there a solar dependency of this threshold?
- **Threshold**: CME needs to be faster than the fast magnetosonic speed in the solar wind frame (actually not exactly true, depends on the shock angle).
- On average, this speed is 502 km/s in SC23 and 470 km/s in SC24 (statistically significant).
  New question: Is it affected by the extreme solar minimum in 2006-2009?
- Removing time periods w/ SSN < 50, difference is still here.

Period	V_{sw}	V_a	C_{s1}	C_{s2}	V_{min1}	V_{min2}
Median						
05/1996 - 2007	420	56.3	55.3	47.6	502	497
2008 - 01/2017	394	48.6	53.1	42.3	470	463
07/1997 - 01/2006	426	61.7	55.8	48.9	512	507
10/2010 - 11/2016	399	51.7	53.5	43.3	477	471

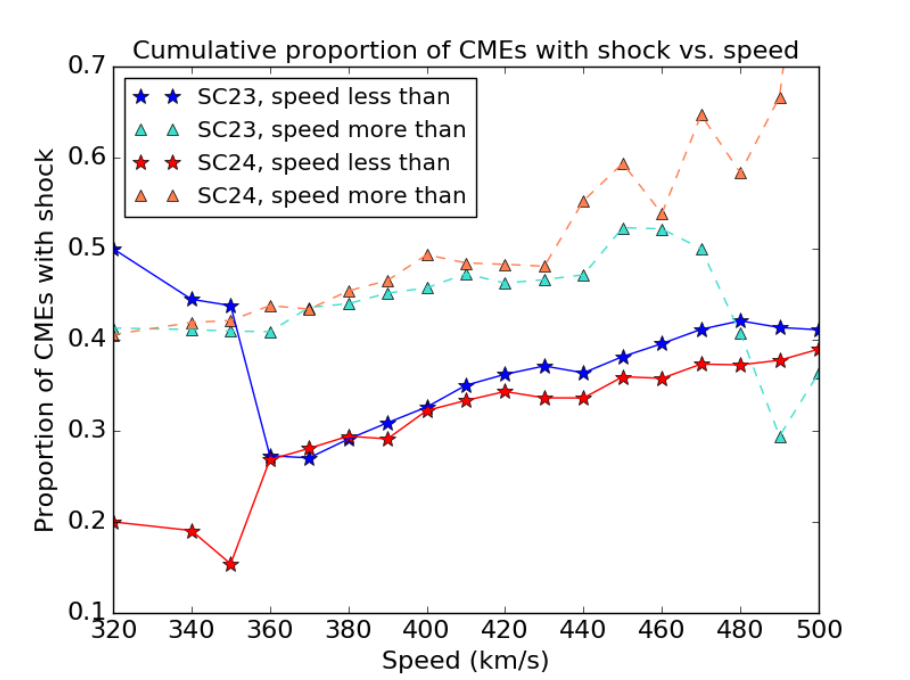
Solar cycle change in proportion of slow CMEs that drive shocks

- The number of days with very (and extremely) low threshold speed for a CME to drive a shock is significantly larger in SC24 than in SC23.

Period	# Days	V_{min} <350	V_{min} <400	V_{min} <450
07/1997 - 01/2006	3128	19	262	764
10/2010 - 11/2016	2250	60	382	838

- **So, do we see more slow CMEs with shocks in SC24 than SC23?**
- **NO**

Speed	Total # of CMEs	05/1996 - 2007		2008- 11/2016	
		CME with shock	%	CME with shock	%
< 370	74	9/33	27%	11/41	27%
370-390	73	12/35	34%	12/38	32%
400-420	71	21/48	44%	12/23	52%
430-450	83	24/57	42%	11/26	42%
460-500	72	24/46	52%	14/26	54%

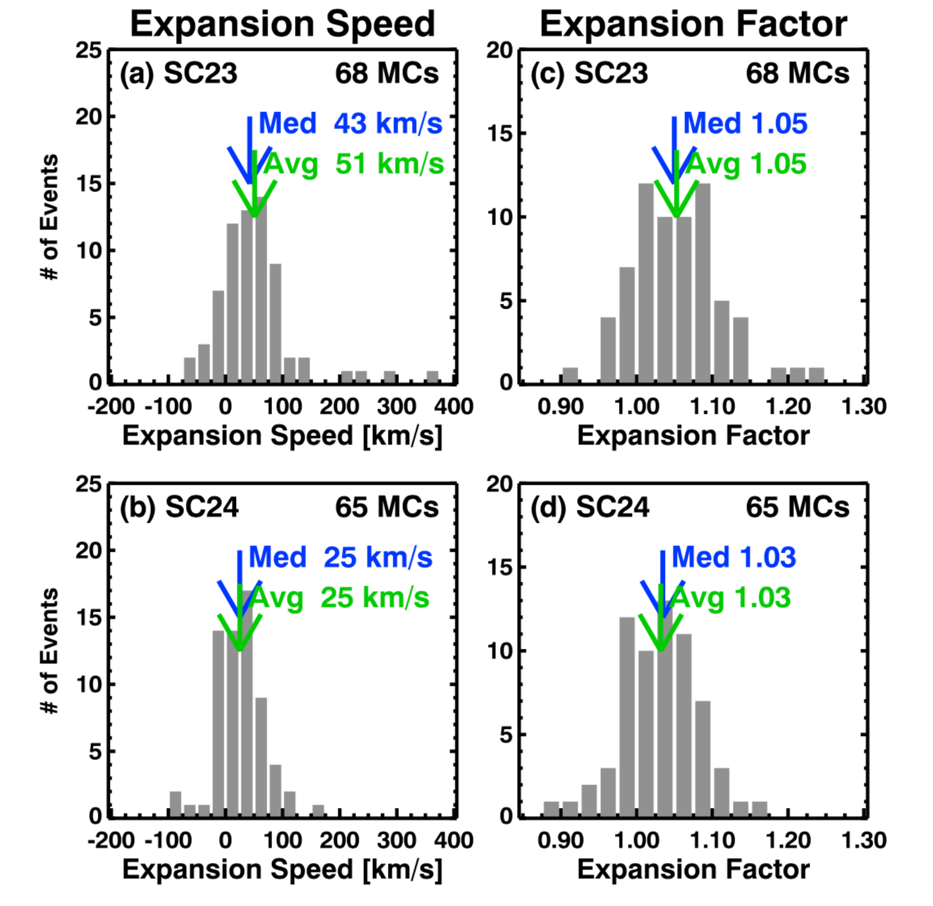


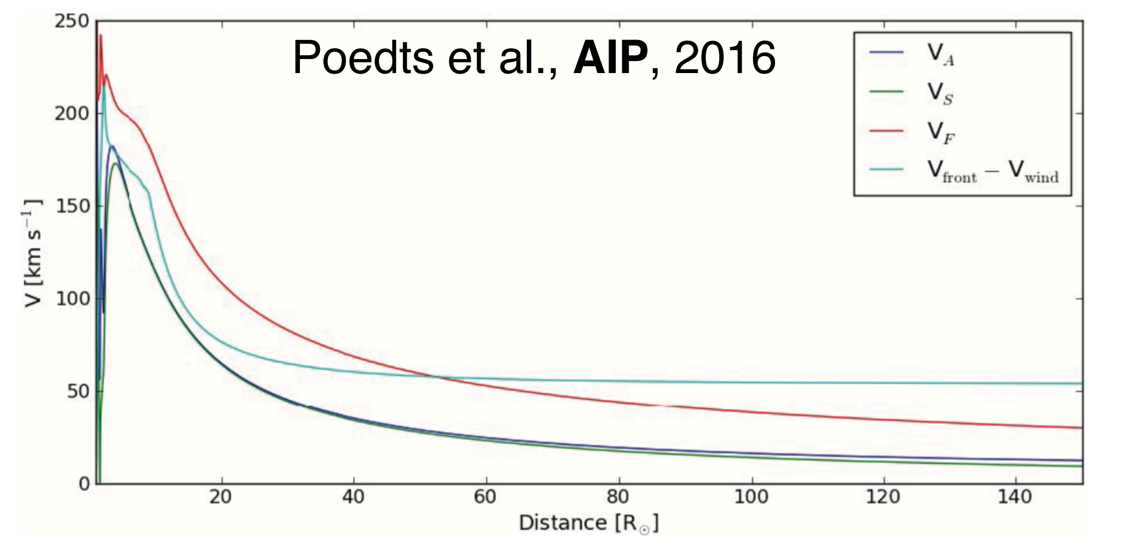
- And, ¼ of very slow CMEs (average speed < 370 km/s) drive shocks!

CME Expansion

- This study is done with the average CME speed. Front speed is what matters!
- Gopalswamy et al. (2015) found that MCs at 1 AU in SC24 have lower expansion speed than MCs during SC23.
- L. Jian et al. (2018) found small decrease in Vexp but larger in Vmax for ICMEs.
- Exact radial dependence(s) of CME expansion, fast magnetosonic speed, solar wind speed and CME “center” speed is not known.

Gopalswamy et al., **JGR**, 2015





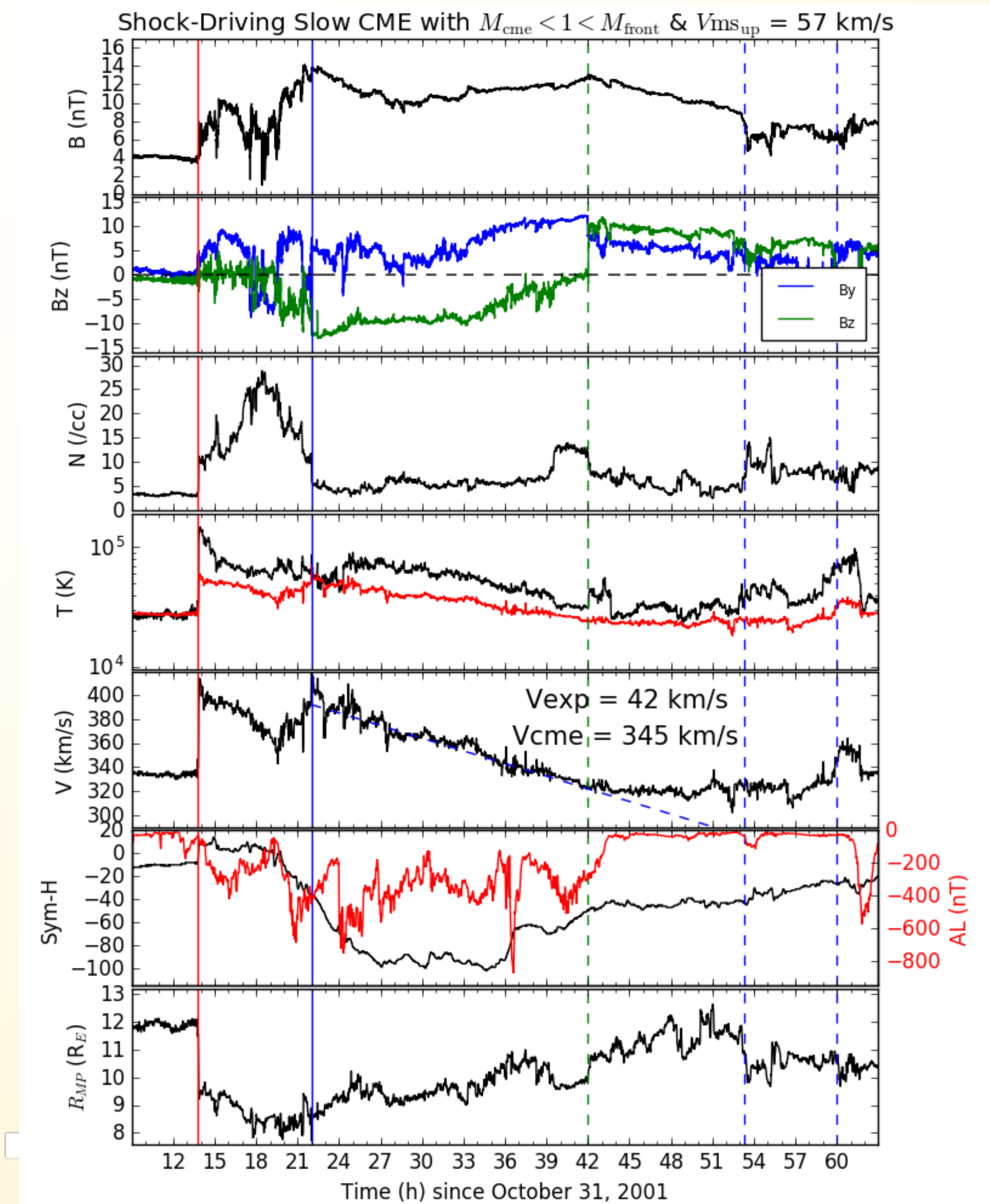
- **Study:** 22 Slowest shock-driving CMEs in SC23/24

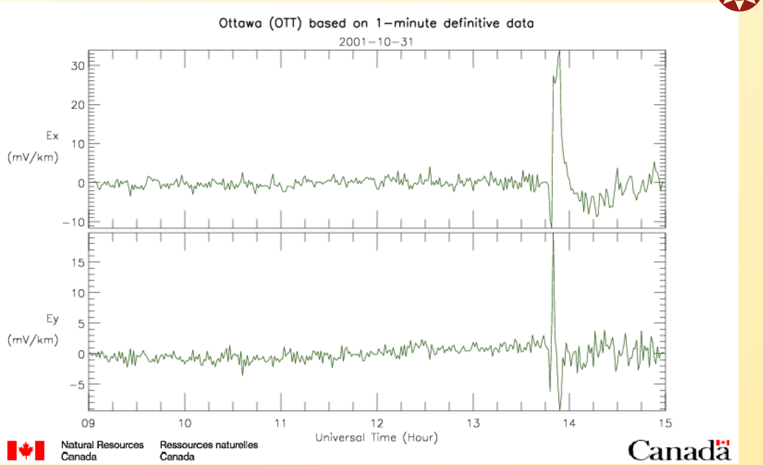
“Mach” number of the CME center, front and maximum speeds

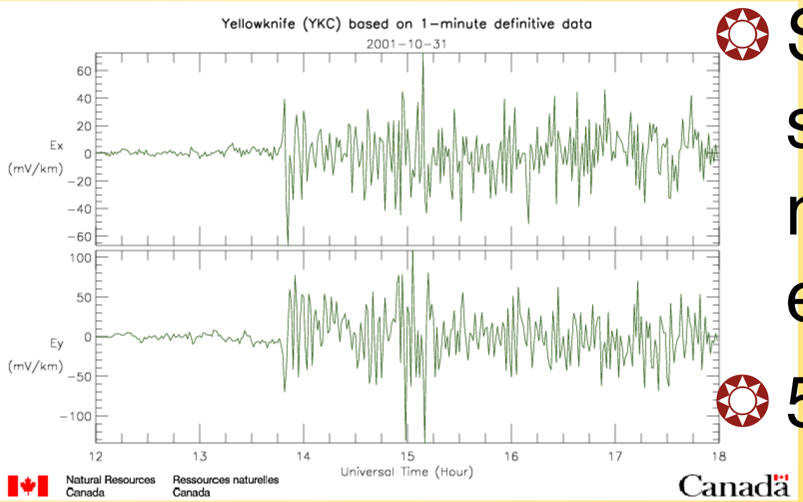
Assuming quasi-perpendicular shock

Shock-Driving Slow CMEs (1)
$M_{cme} < 1 < M_{front}$

Lugaz et al., **ApJ**, 2017

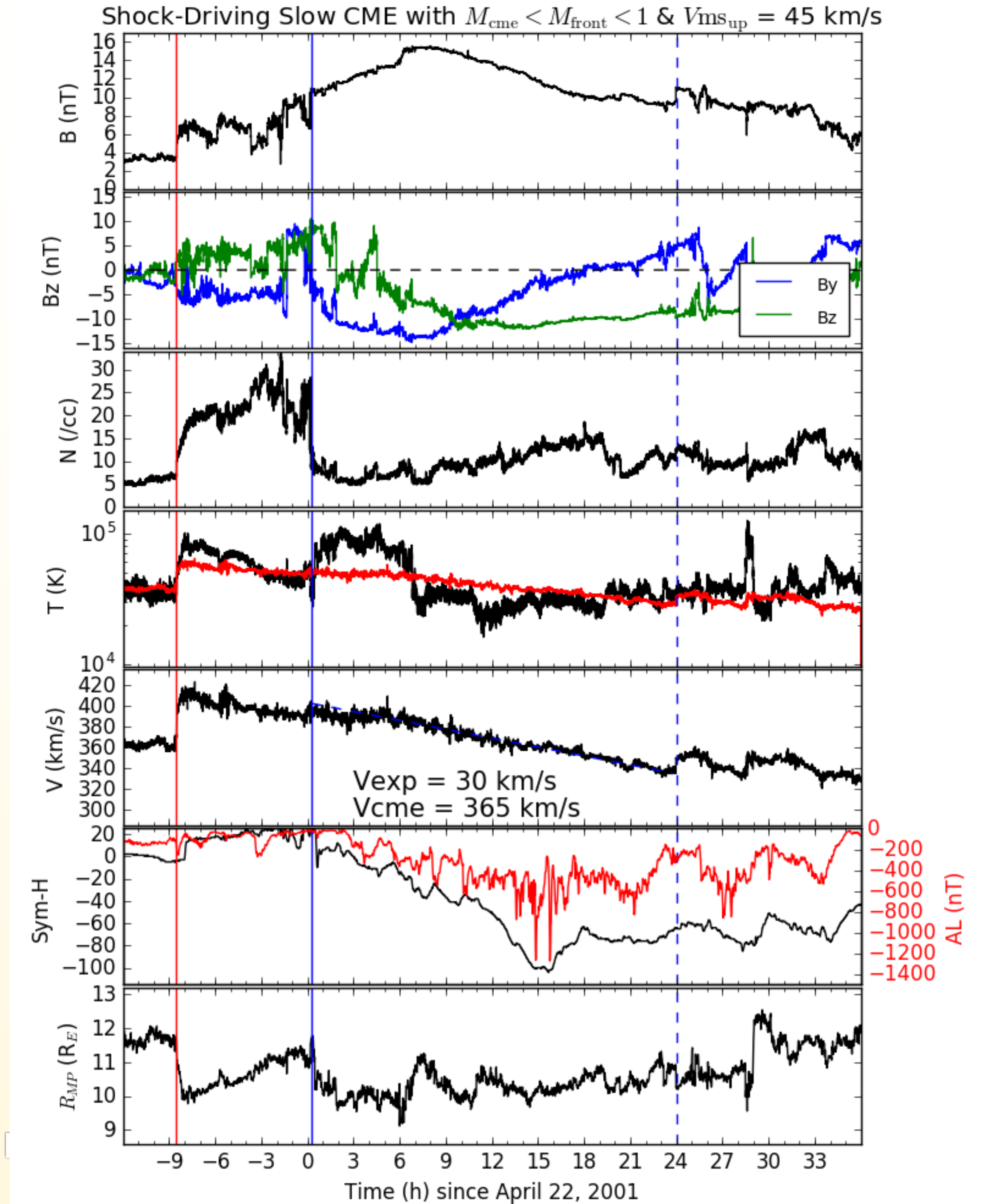


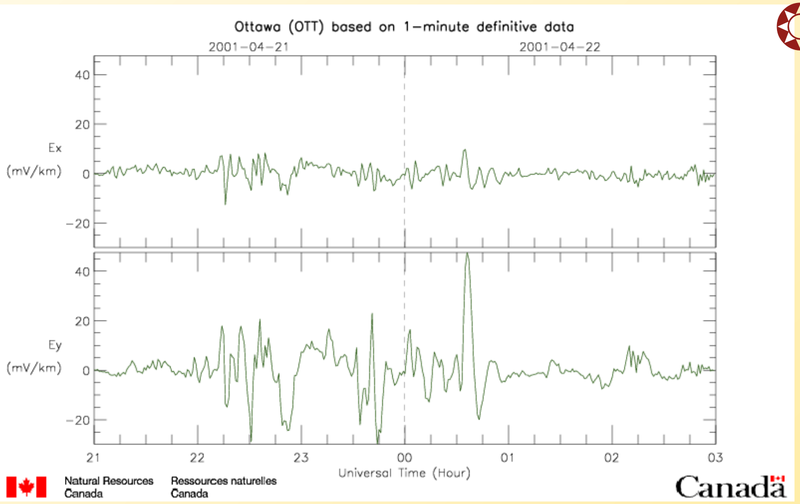




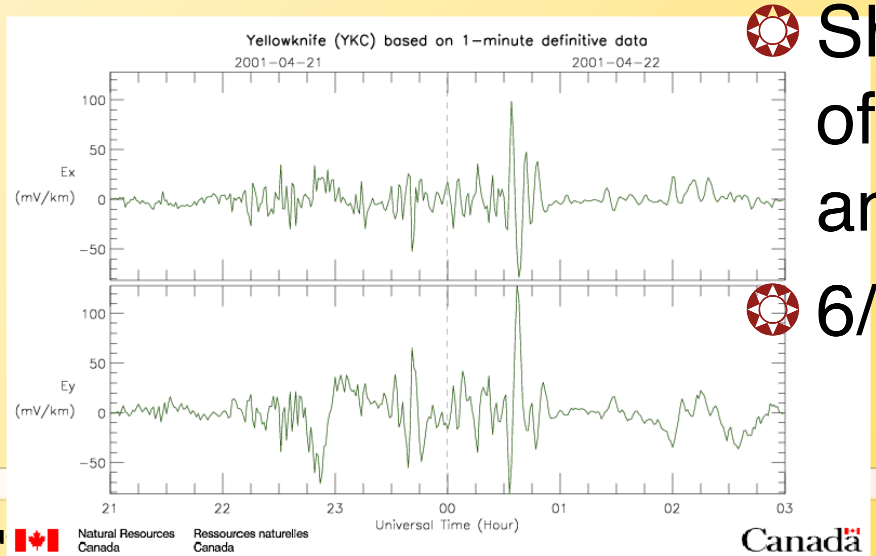
- Shock speed at 1 AU: 415 km/s; CME front 390 km/s
  - Upstream: 330 km/s
  - Fast ms speed: 55 km/s
  - The CME is convected with the solar wind, expansion seems to create the shock.
- ξ ~ 1.25 (large expansion)
- No clear halo
- Shock is due to combination of slow solar wind speed, low magnetosonic speed and CME expansion.
- 5/22 cases like this.

Shock-Driving Slow CMEs (2) $M_{cme} < M_{front} < 1$

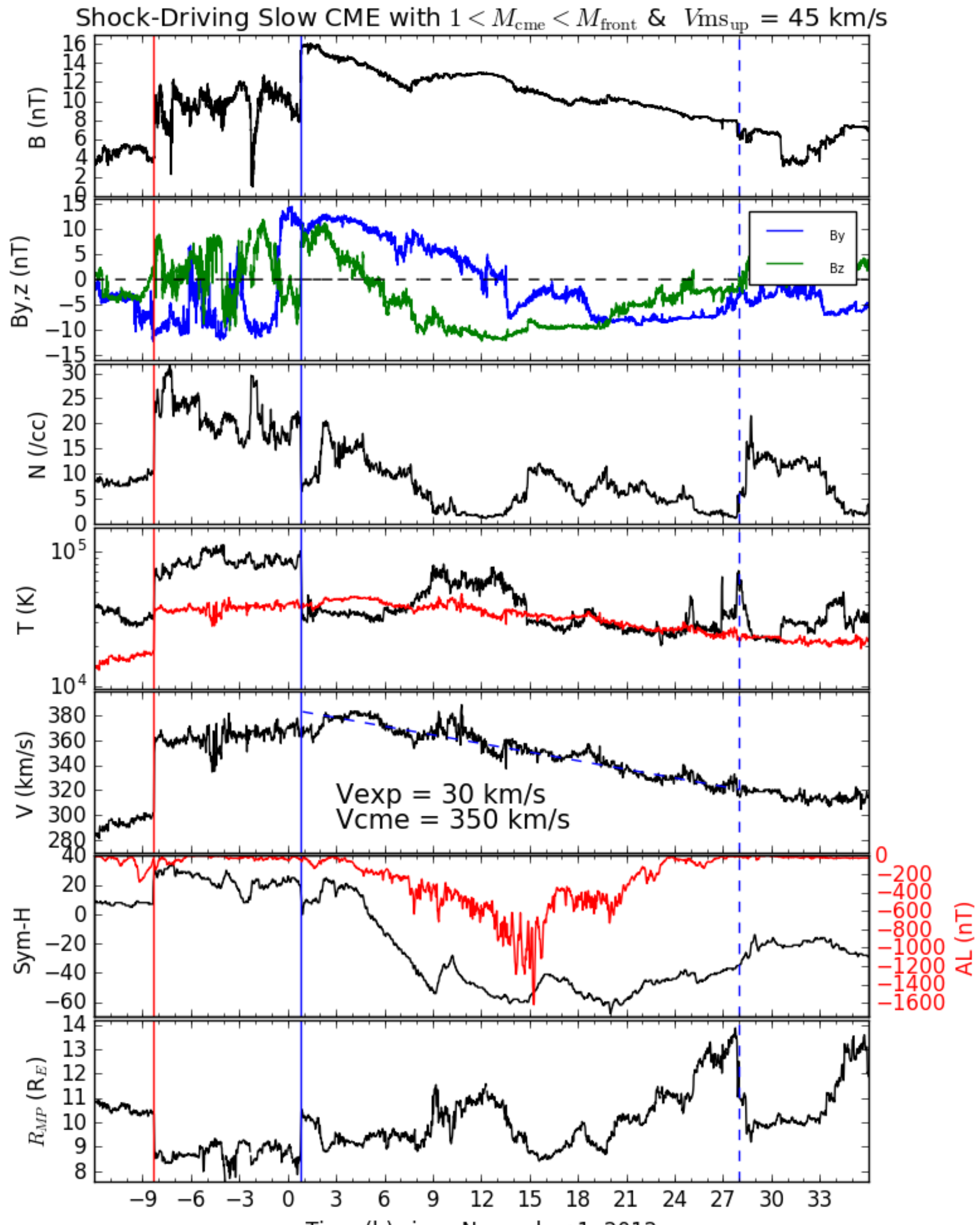


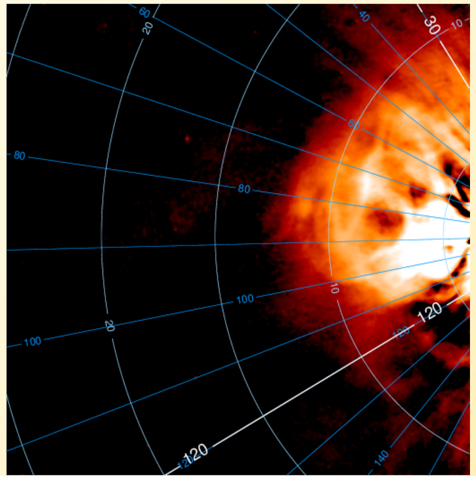


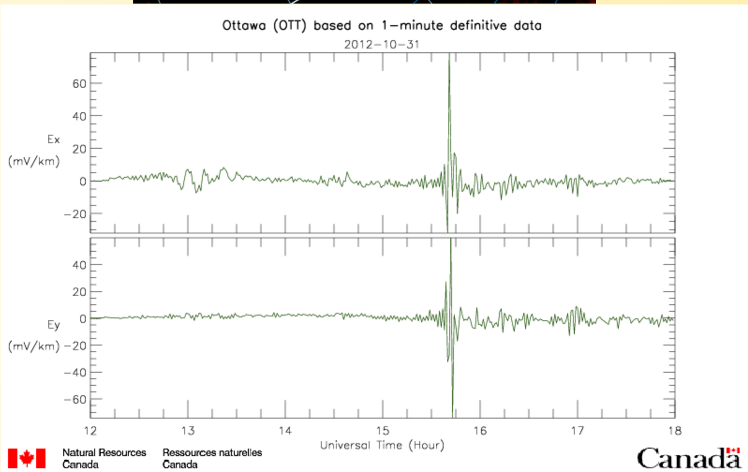
- Shock speed at 1 AU: 380 km/s; CME front 395 km/s
  - Upstream: 360 km/s
  - Fast ms speed: 45 km/s
  - The CME is convected with the solar wind (M_{cme} ~ 0), expansion seems to create the shock.
- $\theta_{Bn} \sim 50°$ explains shock
- $\xi \sim 0.9$ (typical).
- Shock is due to combination of low magnetosonic speed and CME expansion.
- 6/22 cases like this.

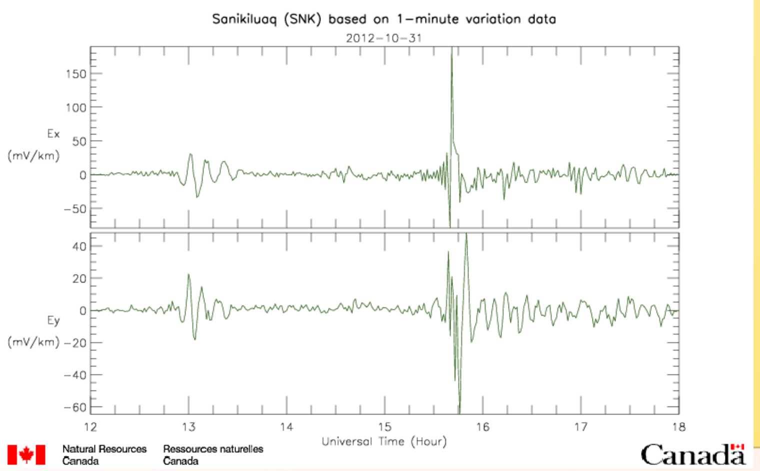


Shock-Driving Slow CMEs (3)
$1 < M_{cme} < M_{front}$



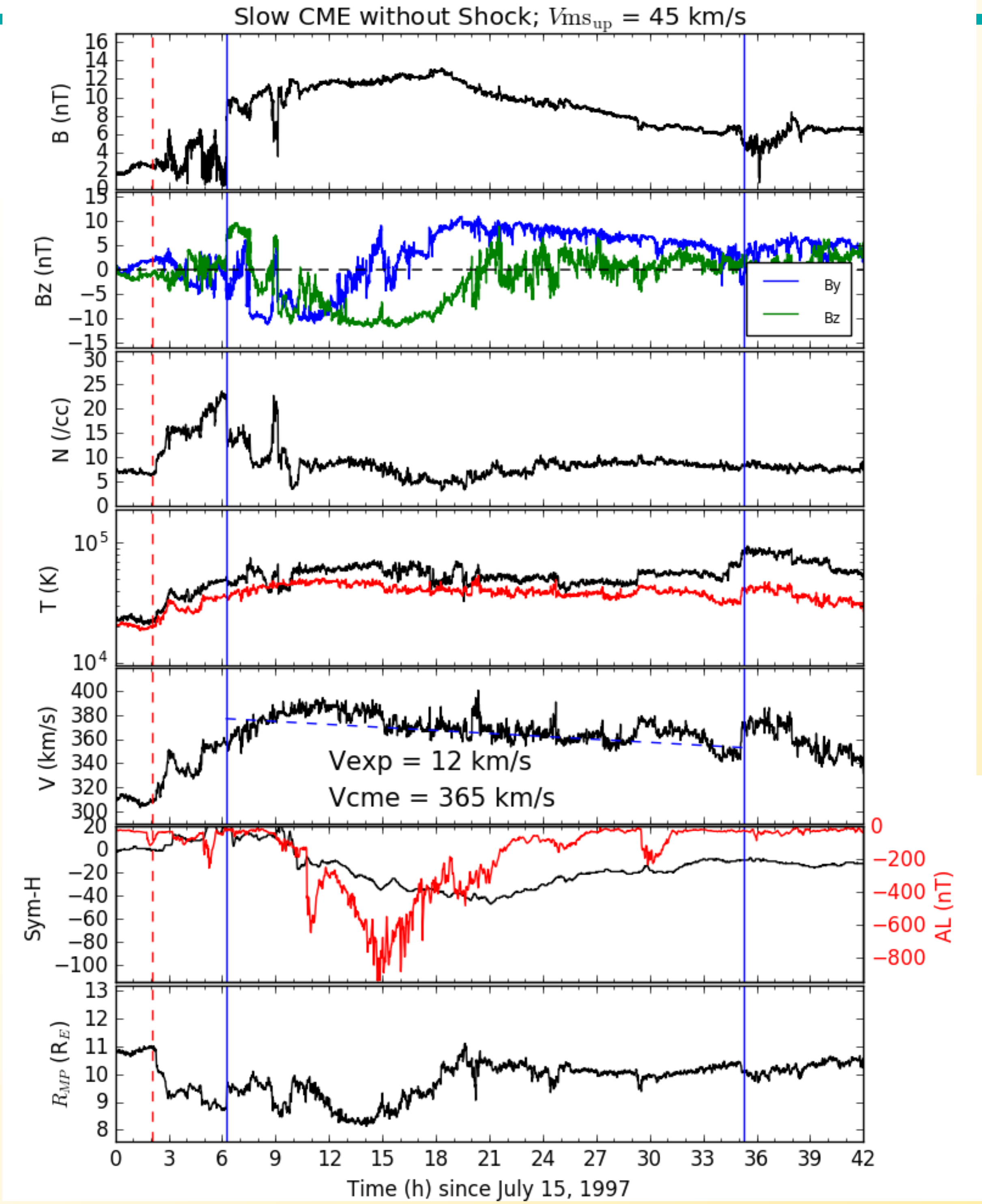




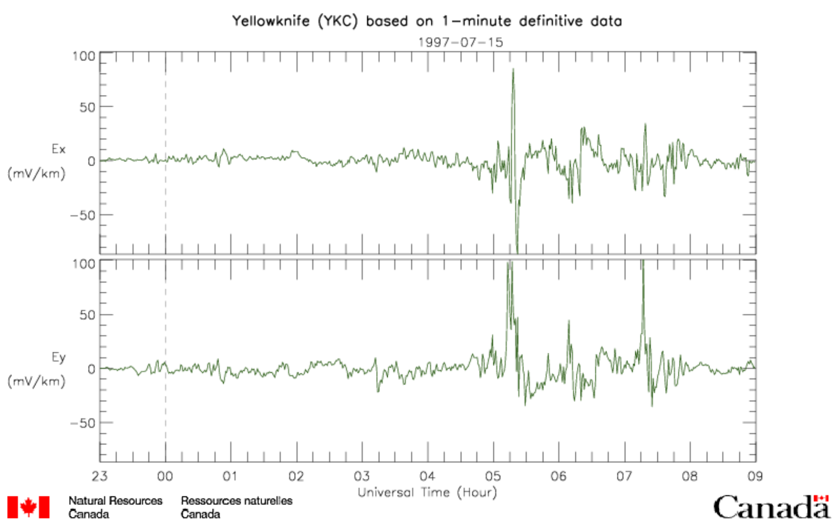


- Shock speed at 1 AU: 390 km/s; CME front 385 km/s
  - Upstream: 290 km/s
  - Fast ms speed: 45 km/s
  - The CME is barely super-fast (M_{cme} ~ 1.3) if we don't consider expansion.
- Halo CME on 10/27 at 14:20
  - 95 hour Sun-Earth propagation for the shock.
  - Average transit speed of 430 km/s.
  - Initial speed of ~420-460 km/s
- 6/22 cases like this.

Slow CME Without Shock



- Slow CME (365 km/s), slow upstream speed, slow magnetosonic speed
  - Upstream: 320 km/s
  - Fast ms speed: 45 km/s
  - Dense sheath preceded by a wave-like feature.
  - CME expansion is very small (ξ ~ 0.3).
- Out of 22 slowest CMEs with shocks, 5 are cases with a complex situation (for example first CME of September 30, 2012) with no simple expansion profile.



Conclusions

- Shocks propagating inside CMEs are a common occurrence at 1 AU.
  - It represents about 15% of the shocks and occurs in about 15% of the CMEs at 1 AU,
  - About half geo-effective shocks/sheaths are due to shocks inside CMEs.
  - Shocks inside CMEs are a great way to make a weak CME geo-effective.
  - Not all shocks are equal. Beware of the upstream conditions.
- Very slow CMEs (V < 350 km/s) sometimes drive shocks.
  - It takes a combination of slow upstream and slow Alfvén speeds, and often high expansion.
  - SC24 has a statistically significant lower threshold for a CME to drive a shock.
  - But slow CMEs drive shocks in the same proportion in SC23 and SC24 (~30% of CMEs below 400 km/s drive a shock). This is based on the CME central speed.
  - Difference in CME expansion can explain why this did not change.
- Looked in details at the 22 slowest CMEs with shocks in the past 20 years: for half expansion speed is critical in the ability of the CME to drive a shock.
- **CME radial expansion can drive shock in the ecliptic.**

Thank you!

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