CME Radial Expansion and CME-CME Interaction

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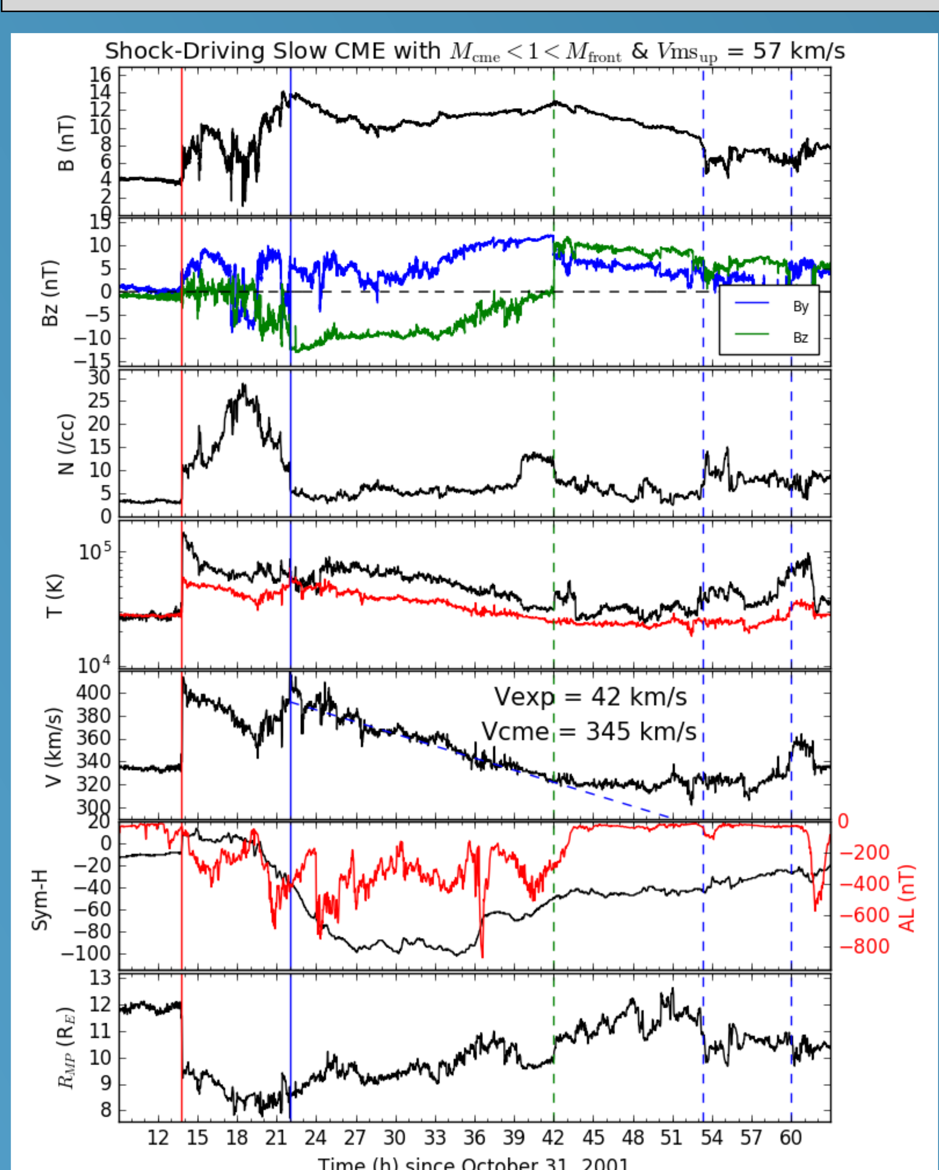
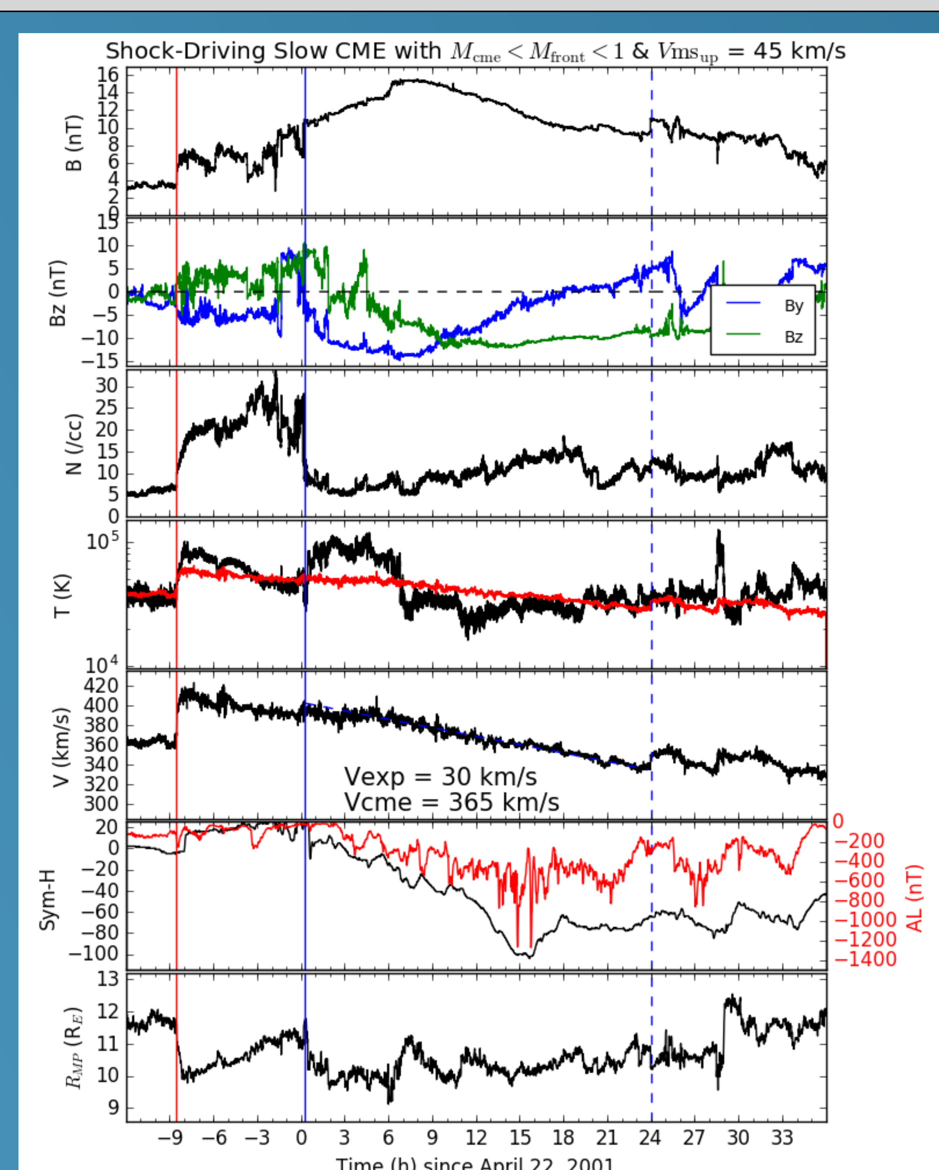
Slow CMEs That Drive Fast Forward Shocks

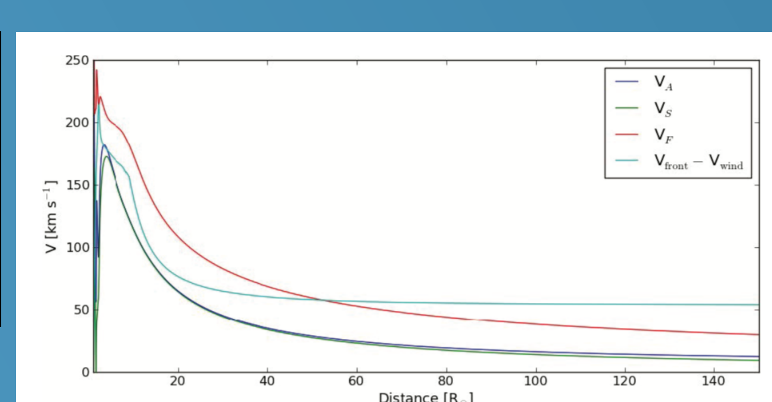
Coronal mass ejections (CMEs) may disturb the solar wind either by overtaking it, or by expanding into it, or both. CMEs whose front moves faster in the solar wind frame than the fast magnetosonic speed, drive shocks. CMEs as slow as 350 km s^{-1} may sometimes, although rarely, drive shocks. We studied these slow CMEs with shocks and investigate the importance of CME radial expansion in contributing to their ability to drive shocks and in enhancing shock strength in Lugaz et al., ApJ, 2017. For such slow CMEs, the shock may form in the inner heliosphere, once the Alfvén speed decreases.





Two examples of a CME with an average speed under 370 km s^{-1} that nonetheless drove a shock. For each CME, we calculated the average speed in the magnetic ejecta, the front speed taking into consideration expansion, the maximum speed and the shock speed. We calculate "Mach" numbers for each of these speeds, using the upstream solar wind and fast magnetosonic speeds. For the CME on the left, expansion helps drive the shock ($M_{cme} < 1 < M_{front}$), for that on the right, expansion contributes ($M_{cme} < M_{front} < 1$).

Outstanding questions: Jian et al. (2008) found that proportion of CMEs with shock increases from 1/2 to 2/3 from Venus to Earth. **How much does CME expansion matter? What about the fast magnetosonic speed evolution?**



Right: Simulation work by Poedts, Pomoell & Zuccarello, AIP Conf. Proc., 2016.

Solar Cycles 23 vs. 24 vs. 25?

SC24 is weaker in terms of solar wind speed and IMF strength at 1 AU than previous cycles. This should affect the ability of slow CMEs to form a shock. We used OMNI data to determine the minimum speed, V_{min}, required to form a shock. V_{min} is about 35 km s^{-1} lower in SC24 than it was in SC23 (statistically significant) and this difference holds if we exclude the quietest periods when there was no CME. Therefore, slow CMEs should be more likely to drive a shock in SC24 than SC23. However, there is no significant difference in the proportion of CMEs with shocks or without shocks depending on their speed in SC24 compared to SC23. This can be explained if the expansion speed of CMEs is less at 1 AU in SC24 than it was in SC23, as found for MCs by Gopalswamy et al. (2014, 2015). **What will happen in the rest of SC24 and SC25?**

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

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

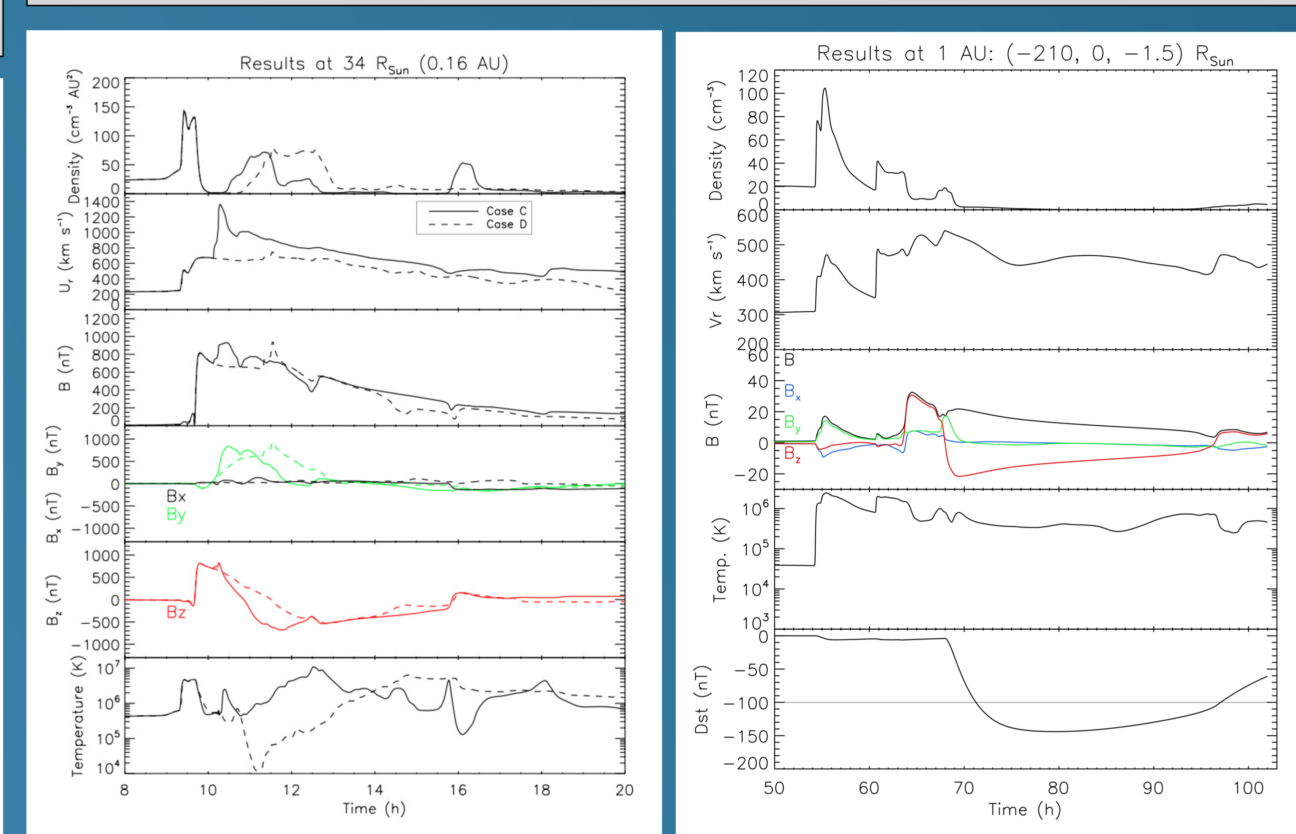
Median Solar Wind & Characteristics Speeds
Top: Solar Wind (V_{sw}), Alfvén (V_a), ion-acoustic (C_s) with two versions of the electron temperature (not part of OMNI) and minimum front speeds to form a shock ($V_{min} = V_{sw} + \sqrt{(V_a^2 + C_s^2)}$). All speeds are in km s^{-1}.
Bottom: Number of days with low V_{min}

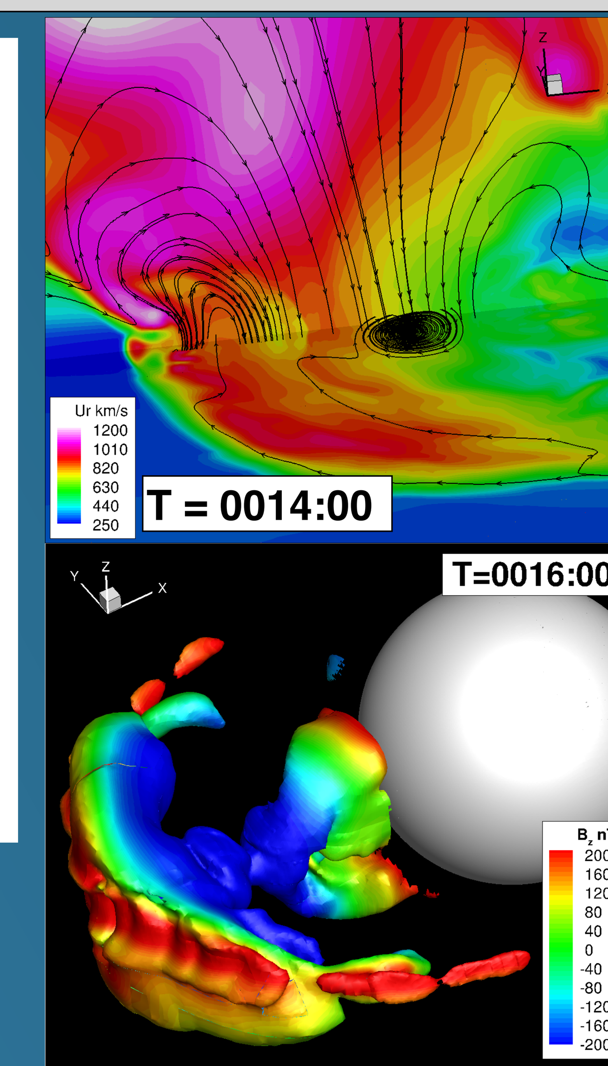
Speed	Total # of CMEs	05/1996 - 2007		2008- 11/2016	
		CME with shock	%	CME with shock	%
< 370	74	9/33	27%	11/41	27%
370-390	73	12/35	34%	12/38	32%
400-420	71	21/48	44%	12/23	52%
430-450	83	24/57	42%	11/26	42%
460-500	72	24/46	52%	14/26	54%

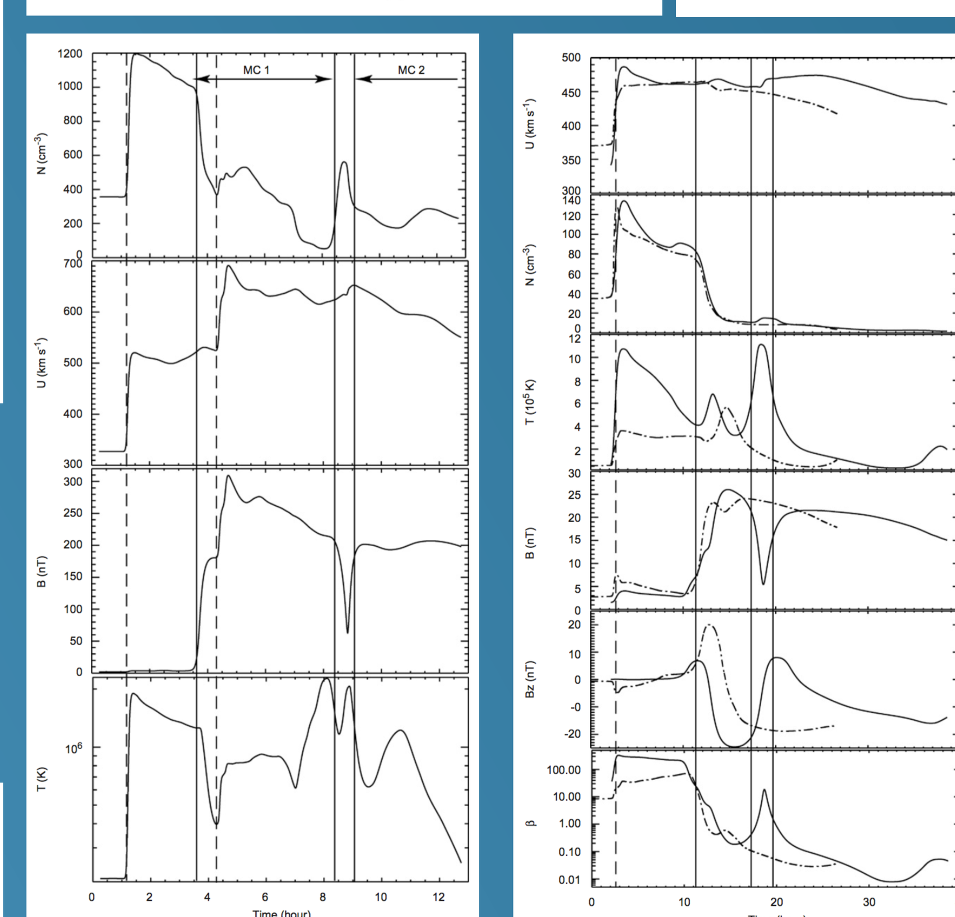
Percentage of Slow CMEs with Shocks
We used the average magnetic ejecta speeds from R&C (2010) and the list of shocks measured by ACE and Wind from Kilpua et al. (2015). The percentage of slow CMEs driving a shock is almost the same for SC23 and SC24, indicating that another effect must balance the lower V_{min} in SC24.

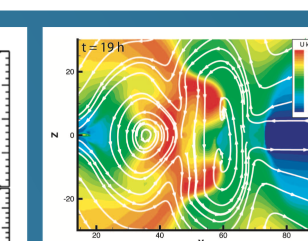
CME-CME Interaction

At Earth, the main structures resulting from CME-CME interaction are complex ejecta, multiple-MC events and shock propagating inside CMEs (see Lugaz et al., Solar Physics, 2017). Most interactions are "completed" in the sense that the resulting structure has a uniform speed profile, except for instances of shocks inside CMEs. Measurements in the inner heliosphere shall reveal series of non-interacting CMEs as well as additional cases of shock propagating inside CMEs.





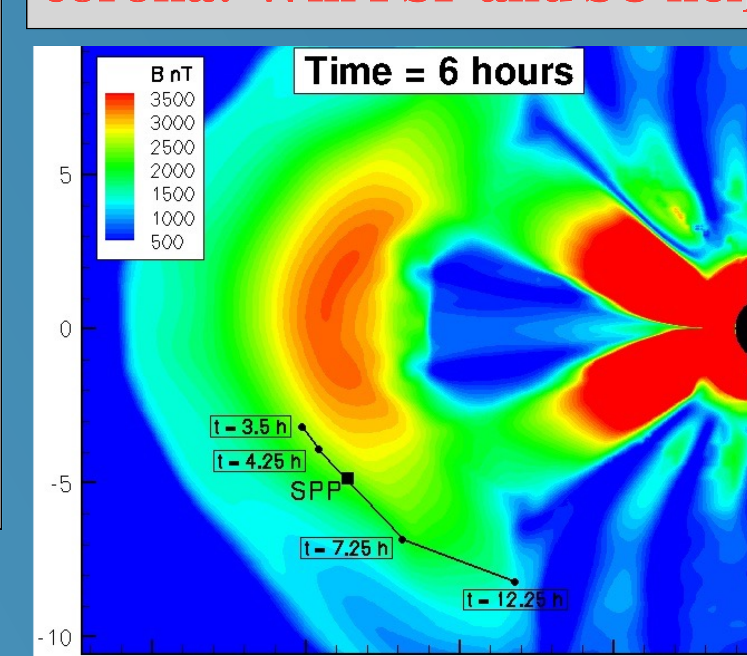


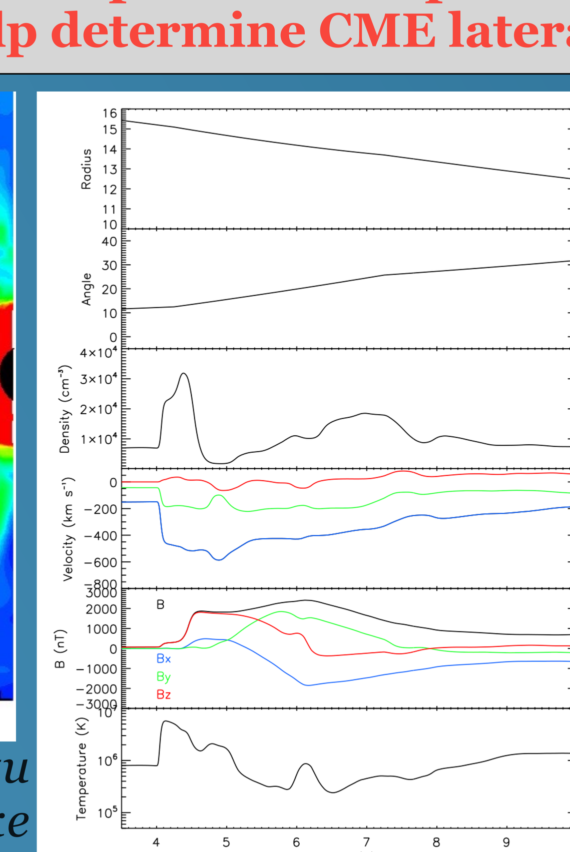


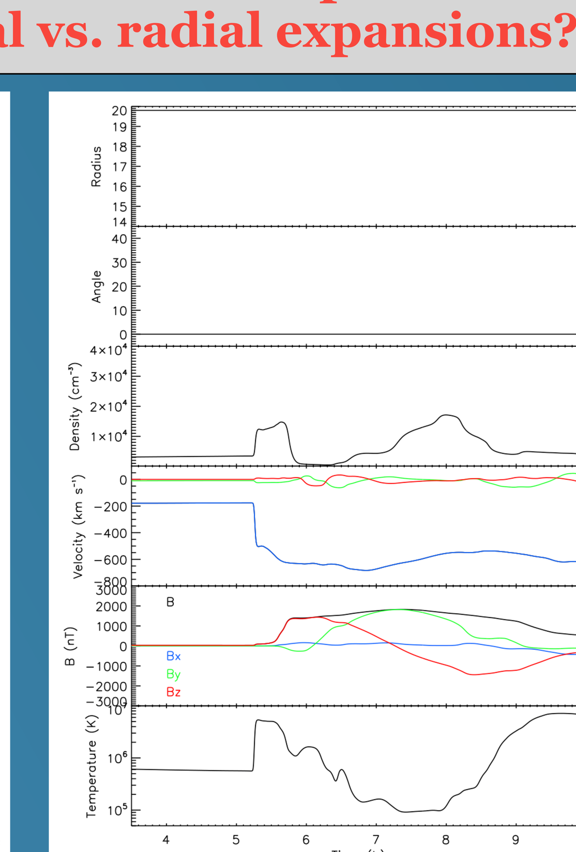
Top: In situ measurements of 2 interacting CMEs of different orientations at 0.16 AU and at 1 AU and corresponding 3-D views close to 0.16 AU (from Lugaz et al., ApJ, 2013 and GRL, 2014).
Bottom: In situ measurements of 2 interacting CMEs at 0.33 AU with the shock propagating inside MC1 and at 1 AU corresponding to a multiple-MC event (from Lugaz et al., JASTP, 2008).
How often do CME-CME interaction occurs in the inner heliosphere?

Bonus Topic: CME Expansion (2)

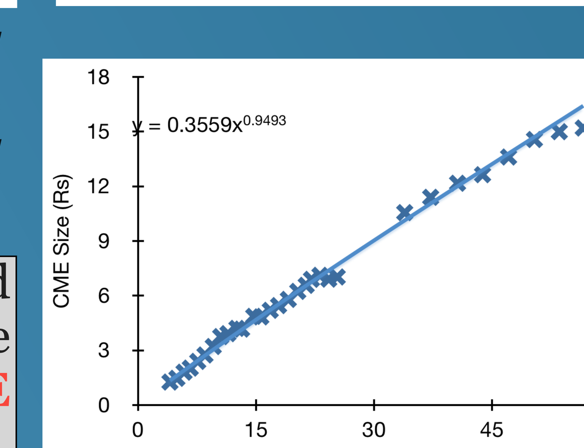
For measurements very close to the Sun, measured CME expansion measured may be extreme. In addition, CME aging and expansion will need to be taken into account when doing fitting and reconstruction. Close to perihelion, PSP and SO will travel at speeds of a few tenths of R_{Sun} per hour. During CME crossings, the s/c may move across ~20% of the CME radius. **How does CME expansion compare to the Alfvén speed in the corona? Will PSP and SO help determine CME lateral vs. radial expansions?**







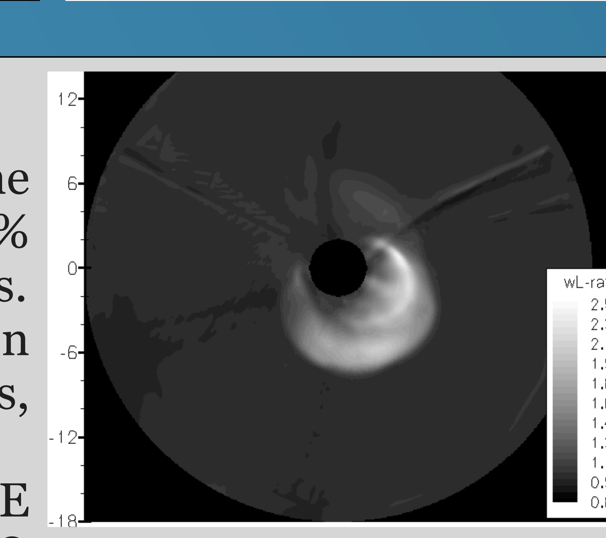
Top: Simulated CME in situ measurements for a PSP-like orbit near perihelion (middle) & measurements by a stationary s/c (right). The CME speed and magnetic field profiles are significantly different due to the spacecraft angular motion. Bottom right: Simulated CME radial size in the corona and inner heliosphere.



Additional questions: How does radial expansion measured *in situ* compare to expansion measured remotely? Evidence of CME axis? **Are we ready to analyze CME measurements in the corona & inner heliosphere?**

Discussion and Conclusions

• CME expansion: 25% of the slowest CMEs from 1996 to 2016 drove a shock. We estimate for the 22 slowest CMEs that radial expansion increases the Mach number by 0.44, on average, from 0.77 for the propagation Mach to 1.2 for the front Mach. This means that the expansion contributes about 40% to the front Mach number. Question for PSP/SO: how do expansion and Alfvén speeds change with distance? Fund my HGI proposal for further studies.
• CME expansion, solar cycles and *in situ* measurements: The difference in CME expansion in SC24 vs. SC23 has direct consequences on the proportion of CMEs with shock. What will happen in SC25? For PSP/SO measurements, one needs to find ways to distinguish between CME internal properties, aging effects and expansion effects. Measurements in the inner heliosphere may allow to determine CME curvature and lateral expansion.
• CME-CME interaction: Earth is so positioned that *in situ* measurements show the results of CME-CME interaction for most cases. This is because CME speeds become more similar as they propagate, decreasing the opportunity for interactions. By making measurements closer to the Sun, PSP and SO will reveal what exactly happens to shock waves propagating inside ejecta, how much reconnection and erosion occurs between CMEs and may help determining the momentum exchange between CMEs as they collide.



Solar Orbiter synthetic coronagraph image of a Earth-directed CME.