Shocks Driven by Slow CMEs: Importance of Radial Expansion

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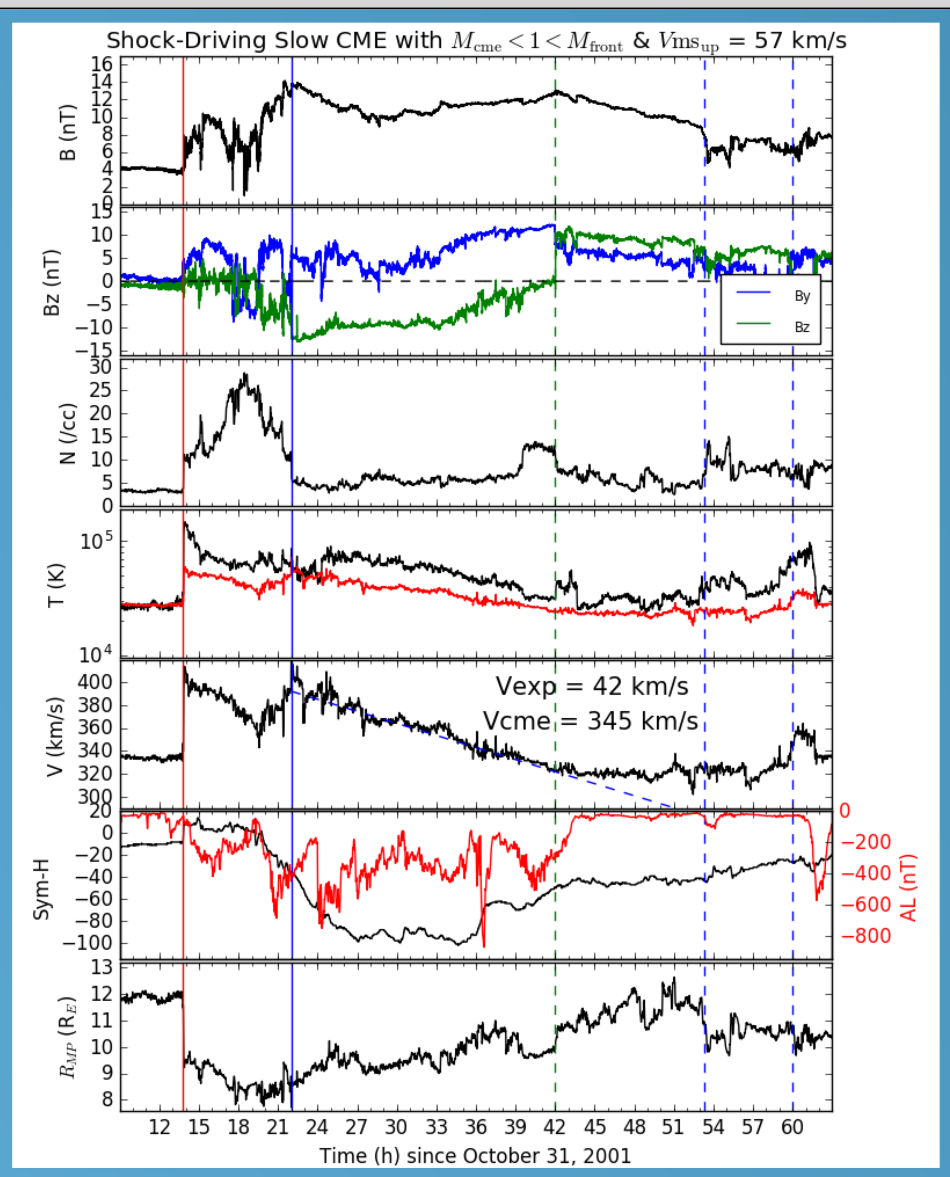
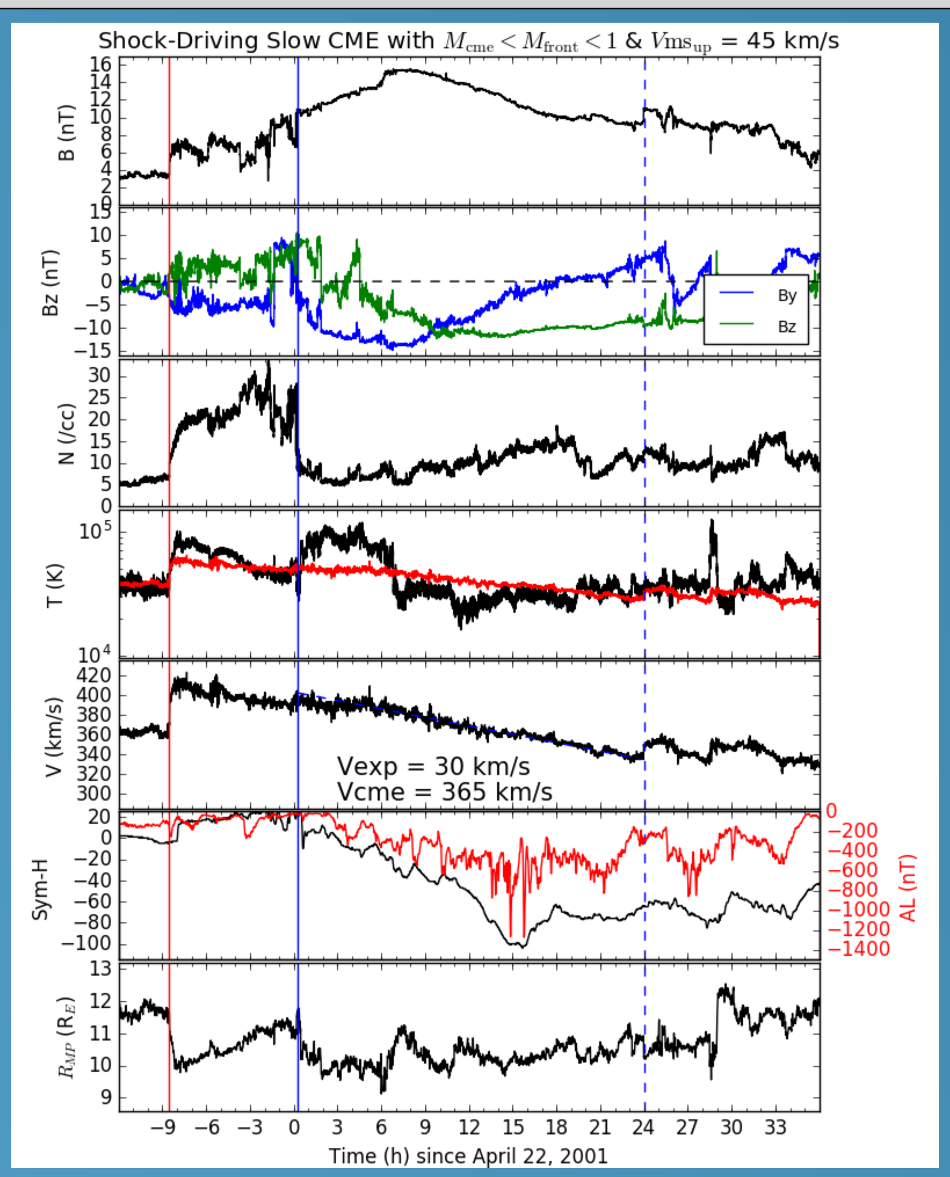
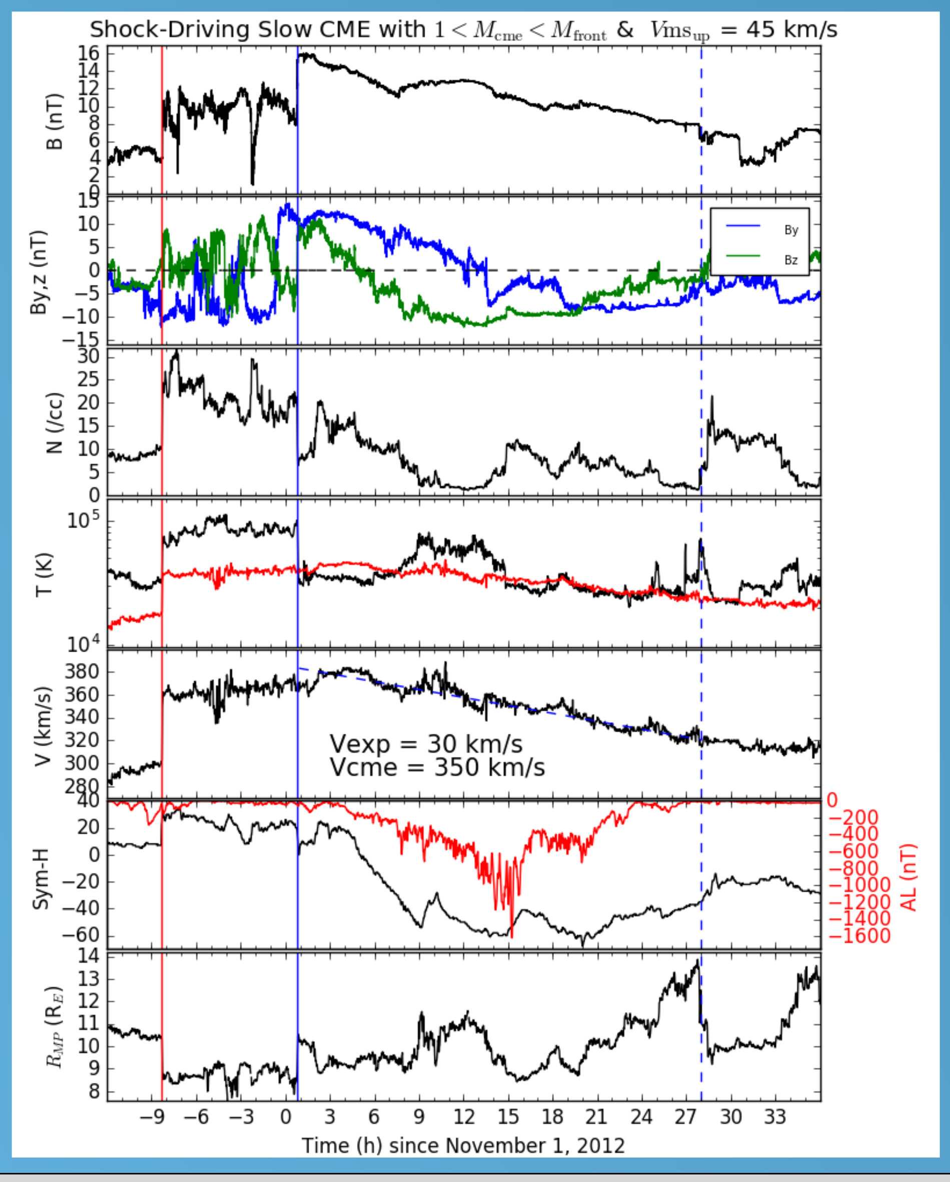
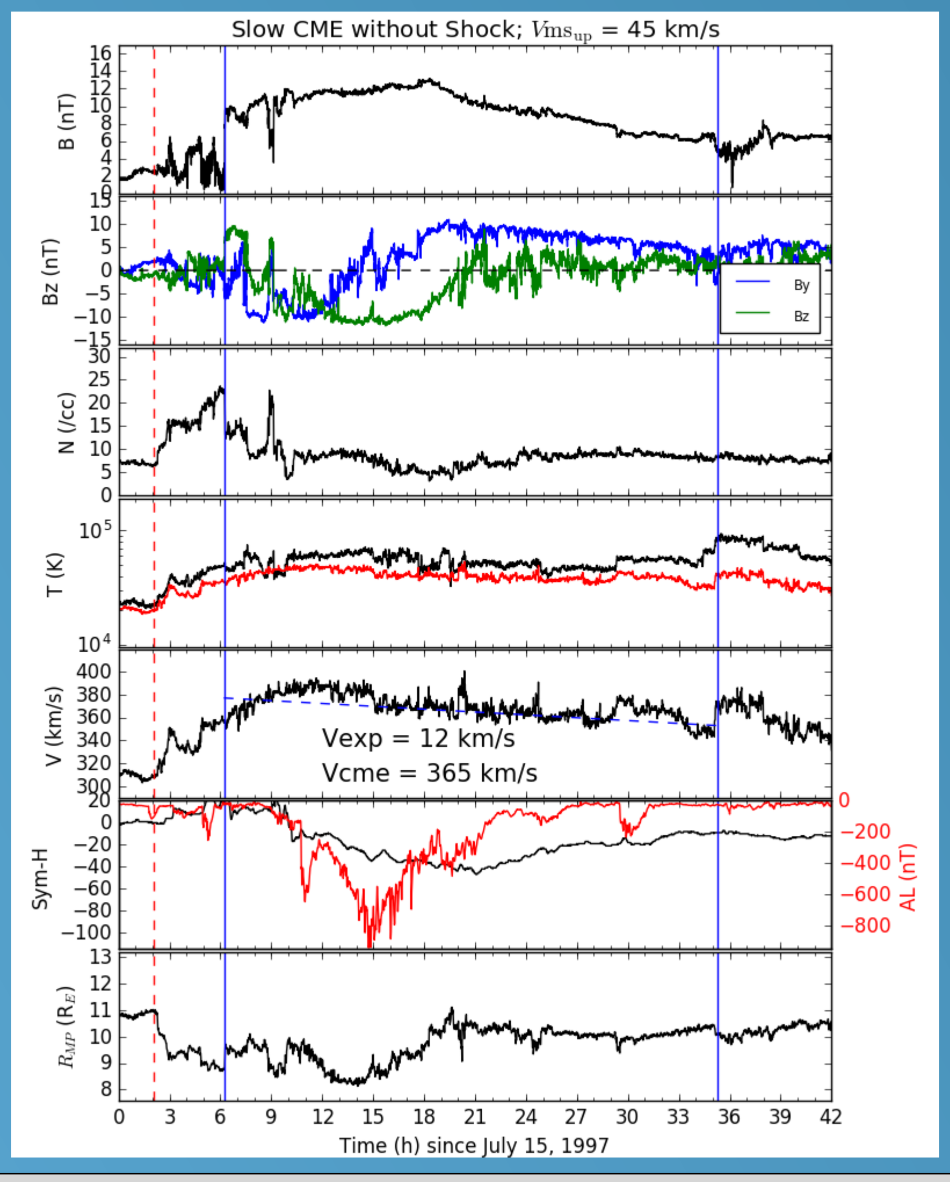
Slow CMEs That Drive Fast Forward Shocks

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. In general, near 1 AU, CMEs with speed greater than about 500 km s^{-1} drive shocks, whereas slower CMEs do not. However, CMEs as slow as 350 km s^{-1} may sometimes, although rarely, drive shocks. We study 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. We also investigate the proportion of all CMEs with speeds under 500 km s^{-1} with and without shocks in solar cycles 23 and 24, depending on the CME speed.









3+1 Examples

Four examples of a CME with an average speed under 370 km s^{-1}: three with a shock, and one without. 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. There are four categories of CMEs with shocks: $M_{cme} < 1 < M_{front}$ (expansion helps drive the shock), $M_{cme} < M_{front} < 1$ (expansion contributes), $1 < M_{cme} < M_{front}$ (expansion strengthens the shock) and complex cases with uneven speeds (often overtaken CMEs).

Slowest Shock-Driving CMEs

Using WIND data from 1996 to 2016, we found 22 CME events with average speed less or equal to 375 km s^{-1} that drove a shock. For about half of them, the propagation Mach number is less than 1, but the addition of expansion contributes to the formation of the shock. Expansion speed and dimensionless parameter (Démoulin et al., 2008) were varied around their typical values, with a few "over-expanding" (~6) CMEs. Expansion always occurred sub-Alfvénically.

Event	Date	t_{shock}	Sheath Δt (h)	CME Start	CME End	$B_{CME\,max}$ (nT)	V_{CME} (km s^{-1})	θ_{Bn}
Average Mach Less than 1 and Front Mach Greater than 1								
1	1998/08/19	18:40	11	08/20 06:00	08/21 20:00	16.5	320	51
2	2001/10/31	13:47	8.2	10/31 20:00	11/02 12:00	13	340	14
3	2009/02/03	19:21	4.6	02/04 00:00	02/04 16:00	11.5	360	74
4	2010/05/28	01:53	17.1	05/28 19:00	05/29 17:00	14.5	355	28
5	2012/09/30	22:19	1.7	10/01 00:00	10/02 00:00	21.5	370	67
Average Mach and Front Mach Less than 1								
6	1997/12/30	01:14	8.8	12/30 10:00	12/31 11:00	14	365	60
7	1998/03/04	11:03	1.8	03/04 13:00	03/06 09:00	12.5	345	35
8	2000/07/26	19:00	7	07/27 02:00	07/28 02:00	8	355	88
9	2001/04/21	15:29	8.8	04/21 23:00	04/23 03:00	15	365	52
10	2011/03/29	15:10	9.1	03/29 23:00	03/31 04:00	14.5	365	77
11	2014/02/15	12:47	15.4	02/16 05:00	02/16 16:00	17.5	375	88
Average Mach and Front Mach Greater than 1								
12	1997/05/26	09:09	7	05/26 16:00	05/27 10:00	11	335	57
13	1997/12/10	04:33	14.1	12/10 18:40	12/12 00:00	16	350	69
14	2002/03/18	13:14	17.2	03/19 05:00	03/20 16:00	21.5	370	39
15	2012/10/31	14:28	9.1	11/01 00:00	11/02 03:00	15.5	350	86
16	2014/08/19	05:49	10.2	08/19 16:00	08/21 05:00	21	360	85
17	2016/01/18	21:21	12.7	01/19 10:00	01/21 00:00	17	360	55
No Clear Expansion								
18	1998/06/13	19:18	8.6	06/14 04:00	06/15 06:00	12	345	32
19	2010/02/10	23:58	8.5	02/11 08:00	02/12 03:00	8.5	360	61
20	2012/01/21	04:02	2	01/21 06:00	01/22 08:00	12.5	330	81
21	2012/09/30	10:15	3.8	09/30 14:00	09/30 20:00	8	315	77
22	2016/11/09	05:45	18.2	11/10 00:00	11/10 16:00	13	360	88

Event	V_{exp}	V_{sw}	V_{ms}	V_{cme}	V_{front}	V_{max}	V_{shock}	M_{cme}	M_{front}	M_{max}	M_{shock}	V_{exp}/V_{cme}	ξ
1	32	275	45	320	350	350	325	0.99	1.65	1.65	1.8	0.10	0.92
2	42	320	57	345	400	400	415	0.35	1.2	1.2	2.1	0.12	1.26
3	27	305	65	360	400	400	375	0.83	1.4	1.4	1.2	0.075	1.85
4	25	315	48	355	390	390	295	0.84	1.6	1.6	1.4	0.070	0.53
5	35	320	58	370	400	420	450	0.86	1.4	1.7	2.9	0.095	0.79
6	0	320	58	365	375	410	370	0.78	0.95	1.6	1.95	0	1.1
7	40	350	51	345	390	390	440	-0.10	0.78	0.78	2.2	0.12	0.72
8	20	350	50	360	370	400	415	-0.10	0.20	0.81	1.3	0.056	0.82
9	30	360	46	365	390	415	370	0.11	0.65	1.2	1.6	0.082	0.89
10	25	330	63	365	385	405	395	0.56	0.87	1.2	1.8	0.068	0.6
11	32	375	70	375	405	450	470	0	0.43	1.1	2	0.085	1.08
12	20	285	41	335	360	360	335	1.2	1.8	1.8	1.4	0.060	0.80
13	20	285	60	350	375	390	390	1.1	1.5	1.7	2.2	0.057	0.57
14	42	295	52	370	420	480	515	1.4	2.4	3.6	4.1	0.11	2.7
15	30	290	45	350	370	380	390	1.3	1.8	2.0	2.2	0.086	0.78
16	45	295	51	360	415	430	270	1.3	2.4	2.7	1.3	0.12	1.03
17	15	300	58	360	385	385	355	1.05	1.5	1.5	1.9	0.042	0.32
18	0	315	64	345	350	385	270	0.47	0.55	1.1	1.7	0	-
19	2	300	53	360	365	380	315	1.1	1.2	1.5	1.8	0.0056	-
20	2	305	56	330	330	330	335	0.45	0.45	0.45	1.4	0.0060	-
21	-5	270	38	315	310	320	350	1.2	1.05	1.3	2.0	-0.016	-0.6
22	-15	295	50	360	345	375	360	1.3	1	1.6	1.4	-0.042	-0.58

22 Slowest Shock-Driving CMEs from 1996 to 2016 measured by Wind.
The examples shown in the left side of the poster are events #2, 9 and 15. CME identification is from Richardson & Cane (2010). Shock identification and analysis is from IPShocks.fi (Kilpua et al., 2015). The dimensionless expansion parameter, ξ, is calculated using the slope of the velocity curve where the velocity is approximately linear.
Shocks with $V_{shock} < V_{front}$ occur typically because the shock is oblique.

Solar Cycles 23 vs. 24

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 1-day data to determine the minimum speed, V_{min}, required to form a shock (sum of the solar wind and fast magnetosonic speeds). 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 CMEs. All other things equal, slow CMEs should be more likely to drive a shock in SC24 than SC23. Next, we determine the percentage of CMEs with shocks depending on the CME speed.

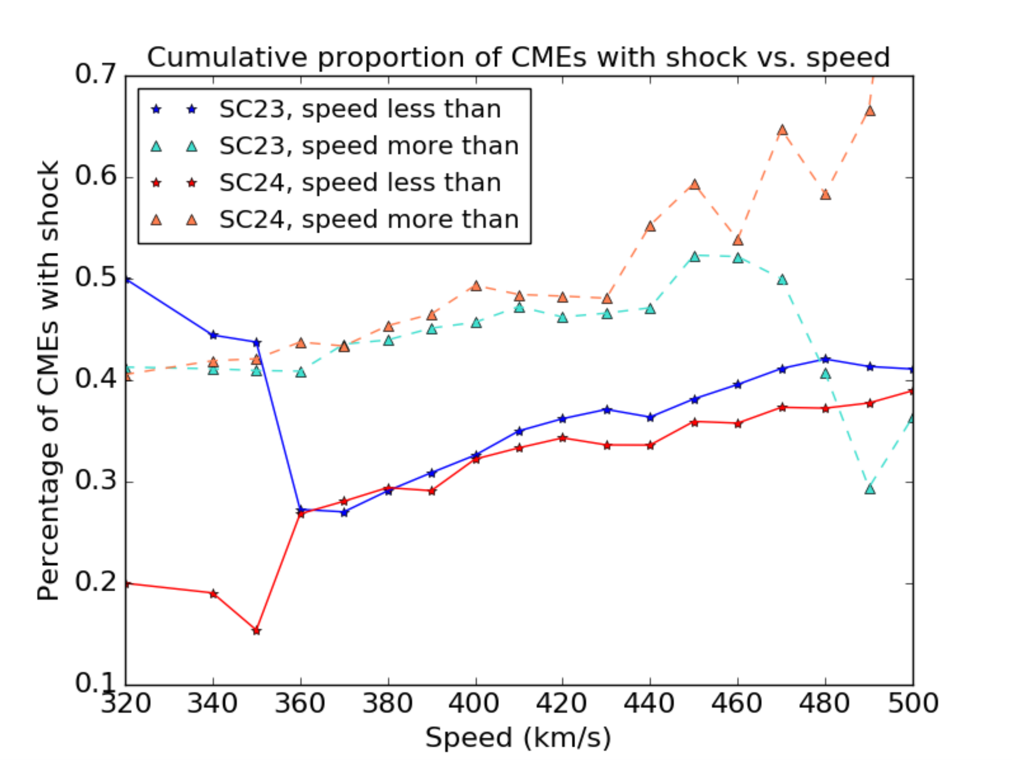
Period	V_{sw}	V_a	C_{s1}	C_{s2}	V_{min1}	V_{min2}
Median						
05/1996 - 2007	420	56.3	55.3	47.6	502	497
2008 - 01/2017	394	48.6	53.1	42.3	470	463
07/1997 - 01/2006	426	61.7	55.8	48.9	512	507
10/2010 - 11/2016	399	51.7	53.5	43.3	477	471

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 and Characteristics Speeds and Day when Shocks with Slow Speeds May Form for the SC23 and 24
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 Richardson and Cane (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. Note that SC24 had more of the slowest CMEs (< 370 km s^{-1}) but fewer of the slightly faster ones (400-500 km s^{-1}).



Cumulative proportion of CMEs with shocks depending on CME average speed
Solid: CMEs with speed less than X with shock
Dash: CMEs with speed between X and 500 with shock

Discussion and Conclusions

•~25% of the slowest CMEs from 1996 to 2016 drive a shock. If CME radial expansion did not contribute to the formation of theses shocks, one would expect this number to be smaller. Other potential explanations include: bias in detecting CMEs with shocks, and erosion of non-shock driving slow CMEs as compared to shock-driving CMEs. We estimate for the 22 slowest CMEs that expansion increases the Mach number by 0.44, on average, from 0.77 for the propagation Mach to 1.2 for the front Mach. Excluding complex events, there is a 0.58 increase from 0.73 to 1.32. This means that the expansion contributes about 40% to the front Mach number.
• For these slow CMEs, slow solar wind speed, low fast magnetosonic speed and "large" expansion must occur for a shock to form.
• There is no significant difference in the proportion of CMEs with shocks or without shocks depending on their speed in SC24 compared to SC23. However, a 490 km s^{-1} CME in SC24 should, on average, drive a shock, while it should not in SC23.
• This lack of difference can be explained if the expansion speed of CMEs is less at 1 AU in SC24 than it was in SC23. A 450 km s^{-1} would have, for example, a 520 km s^{-1} front speed in SC23 but only 470 km s^{-1} front speed in SC24.
•Gopalswamy et al. (2014, 2015) reported that MCs in SC24 had an expansion speed of 25 km s^{-1} vs. 51 km s^{-1} in SC23. If this holds for all CMEs, rather than only MCs, this could explain the lack of change in the ability of slow CMEs to drive shocks.