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Recent STEREO Measurements of CMEs and Shocks

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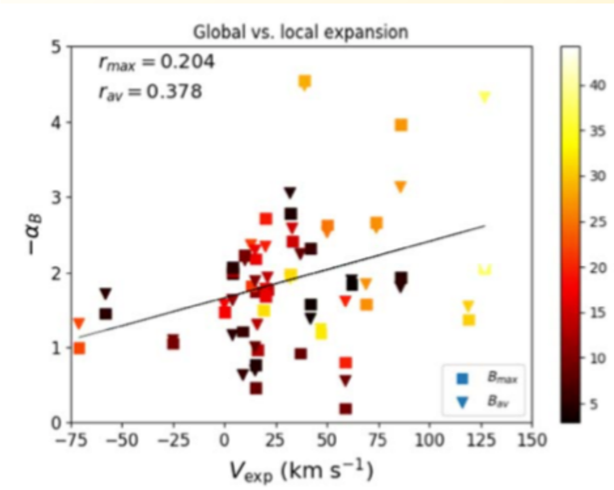
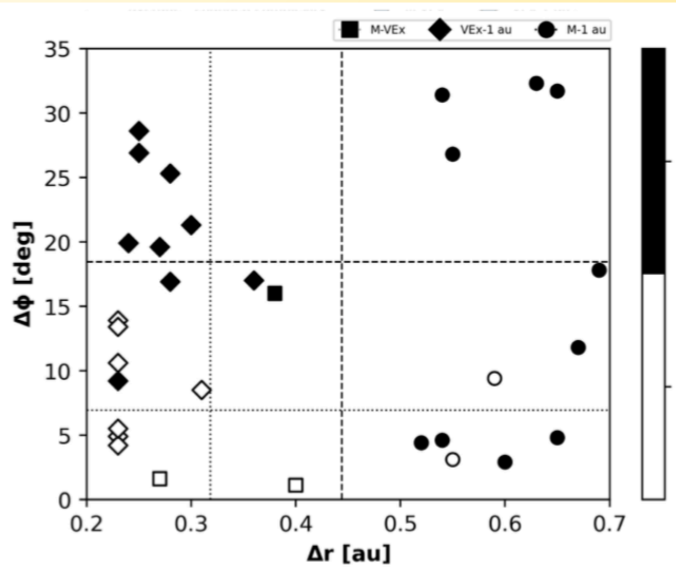
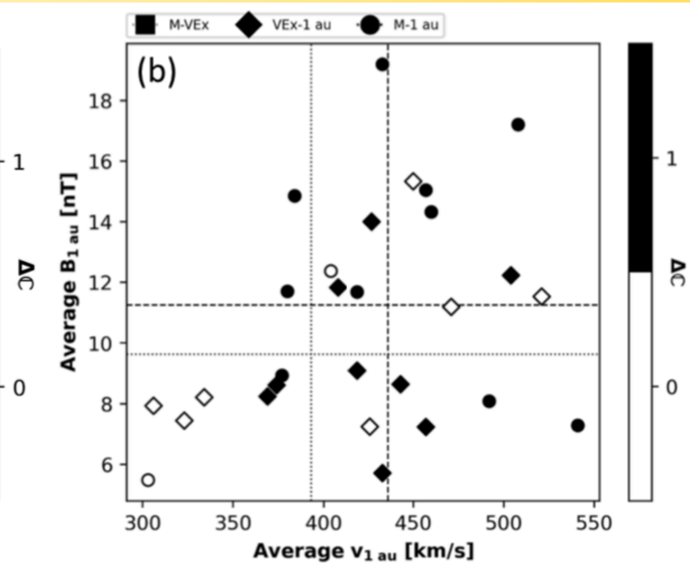
on behalf of A3 and the UNH CME group

Conjunction studies

- Continuation of work from Salman et al. (2020a) that identified 47 conjunction events in the inner heliosphere (33 of which involve STEREO).
- Database used in Lugaz et al. (2020) to investigate CME expansion.
  - Follow-up being worked on by Zhuang et al.
- Database used by Scolini et al. (2022) to investigate changes in CME complexity.

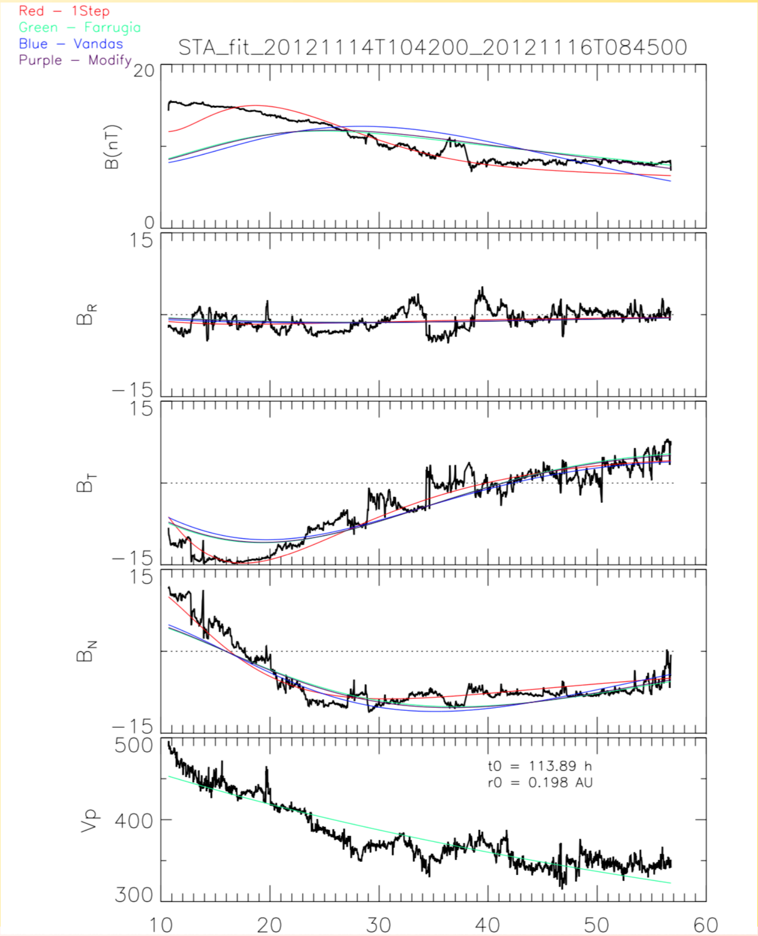






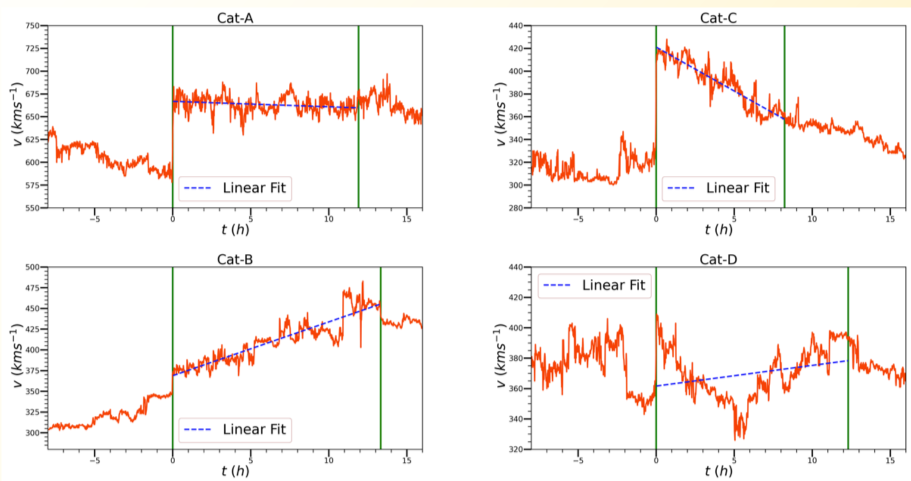
More work on CME expansion

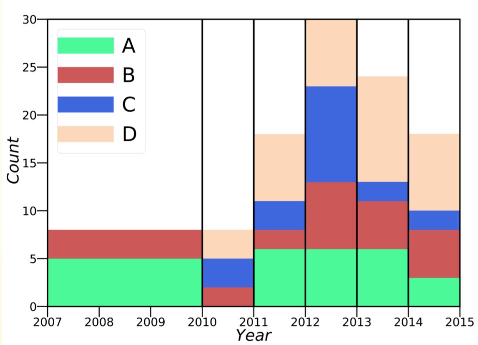
- Can we “reconcile” CME expansion as measured by velocity and the asymmetry in the magnetic field?
- Ongoing work by Wenyuan Yu et al.
- Building on model by Farrugia et al. (1993).
- Does the asymmetry in the magnetic field profile represent the “recent” evolution rather than the evolution since the eruption?
  - Best fit for magnetic field for t_0 = 32 h
  - Best fit for velocity for t_0 = 114 h
  - This would correspond to relaxation towards force-free starting at ~ 0.7 AU

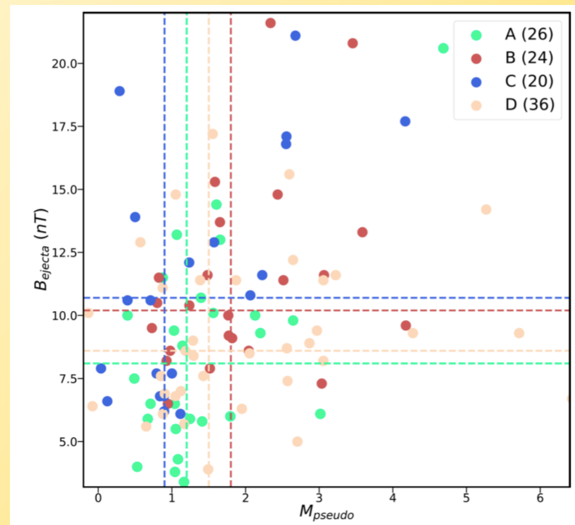


"Statistical" studies of CME properties

- Work presented yesterday by Al-Haddad on non-radial expansion in CMEs
- Salman et al. (2021) used STEREO data to investigate what causes the differences in CME sheath properties. They found that the ME magnetic field strength as well as front speed in the solar wind frame matter most.





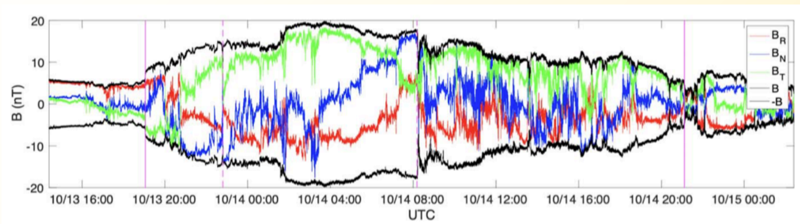


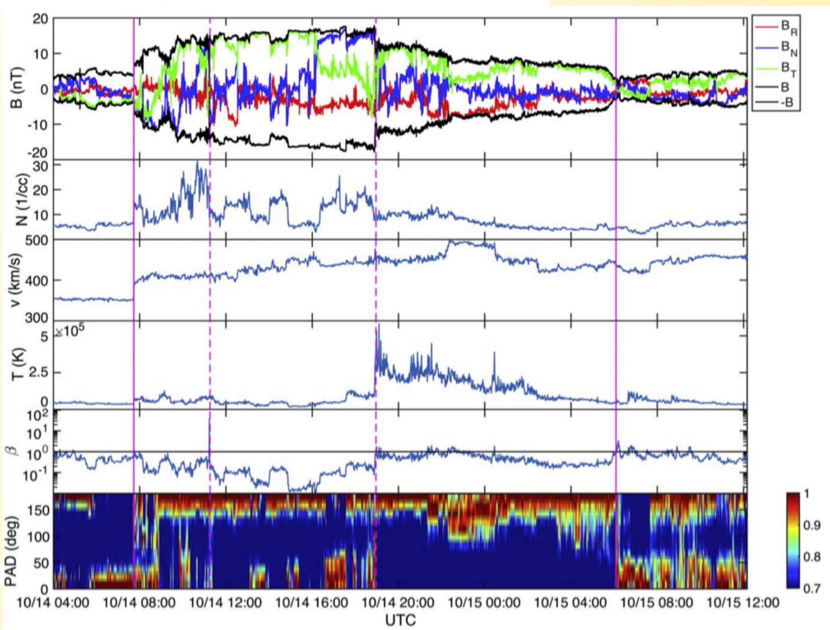
	Average Value				ANOVA
Parameter	Cat-A	Cat-B	Cat-C	Cat-D	P-value
B_{down}/B_{up}	2.31	2.14	2.55	2.44	0.59
N_{down}/N_{up}	3.96	3.02	3.72	3.75	0.29
v_{shock} ($km\,s^{-1}$)	423	464	478	402	0.10
Δv ($km\,s^{-1}$)	76	75	98	77	0.45

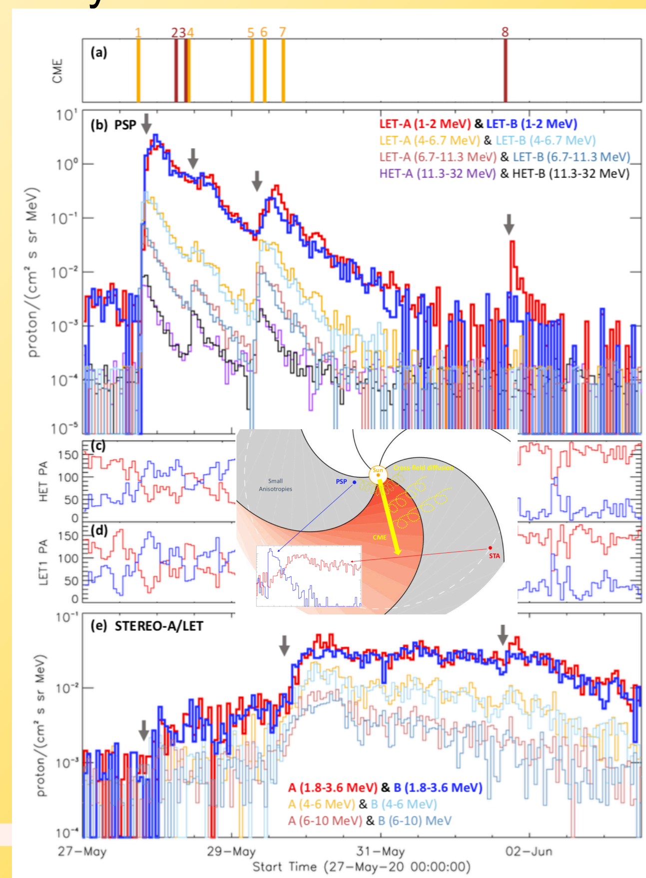
	Average Value				ANOVA
Parameter	Cat-A	Cat-B	Cat-C	Cat-D	P-value
B_{ejecta} (nT)	8.5	11.2	11.5	9.2	**0.02**
N_{ejecta} (cm^{-3})	5.5	6	6.8	4.2	**0.04**
v_{ejecta} ($km\,s^{-1}$)	429	482	446	475	0.27
M_{pseudo}	1.45	1.94	1.33	2.09	0.07

Multi-spacecraft measurements

- Recent multi-spacecraft measurements with PSP and STEREO-A.
  - Winslow et al. (2021b): 0.15 au and ~8° separation
  - Zhuang et al. (2022): 100s keV to few MeV particles accelerated by small CMEs







Rise to solar cycle 25

- The solar minimum of 2007-2009 was extreme (in duration and depth). How was the current solar minimum?
  - Ongoing work by Salman et al (graduated in August 2021).
  - First, looking only at solar wind upstream of CMEs.
  - More or less, same SSN from 2007/01 – 2010/06 and from 2018/01 – 2021/06. Only using STEREO-A measurements.
  - Overall, upstream conditions are similar during this solar cycle as compared to previous one.
  - Need to extend to nominal solar wind conditions and compare with past cycles (extending work of Jian et al., 2011).

Conditions upstream of ~22 CMEs

Parameter	SC24 (2007-2010)	SC25 (2018-2021)
V [kms^{-1}]	357	359
B [nT]	4.1	4.6
N_p [cm^{-3}]	6.5	7.6
V_A [kms^{-1}]	41	42
$V_{f\text{-}ms}$ [kms^{-1}]	47	51

Solar minimum solar wind properties (Jian et al., 2011)

Table 1 Comparison of solar wind parameters for four solar minima.

Solar Min	Period	V ($km\,s^{-1}$)	B (nT)	N_p (cm^{-3})	T_p ($\times 10^3$K)	P_t (pPa)	β
20/21	1976	449 ± 6*	5.56 ± 0.12	8.2 ± 0.3	125 ± 5	43.4 ± 1.7	3.8 ± 0.2
21/22	1986	459 ± 7	5.78 ± 0.14	8.5 ± 0.3	109 ± 5	42.9 ± 1.4	3.4 ± 0.2
22/23	1996	422 ± 4	5.16 ± 0.08	8.0 ± 0.2	84 ± 3	36.0 ± 0.8	3.5 ± 0.1
23/24	July 2008 – June 2009	388 ± 4	4.02 ± 0.08	5.5 ± 0.2	64 ± 3	22.9 ± 0.7	4.1 ± 0.3

Solar Min	Period	V_A ($km\,s^{-1}$)	M_A	V_{MS} ($km\,s^{-1}$)	M_{MS}	P_{dyn} (nPa)	Dst (nT)
20/21	1976	46.6 ± 1.1	12.3 ± 0.3	75.7 ± 1.1	6.01 ± 0.05	2.81 ± 0.07	-13.6 ± 0.9
21/22	1986	48.0 ± 1.4	12.0 ± 0.2	75.2 ± 1.3	6.18 ± 0.05	2.97 ± 0.07	-15.6 ± 1.0
22/23	1996	42.8 ± 0.7	12.1 ± 0.2	69.3 ± 0.7	6.13 ± 0.03	2.44 ± 0.04	-10.9 ± 0.6
23/24	July 2008 – June 2009	40.6 ± 0.8	12.0 ± 0.2	66.0 ± 0.7	5.90 ± 0.03	1.40 ± 0.03	-4.5 ± 0.4

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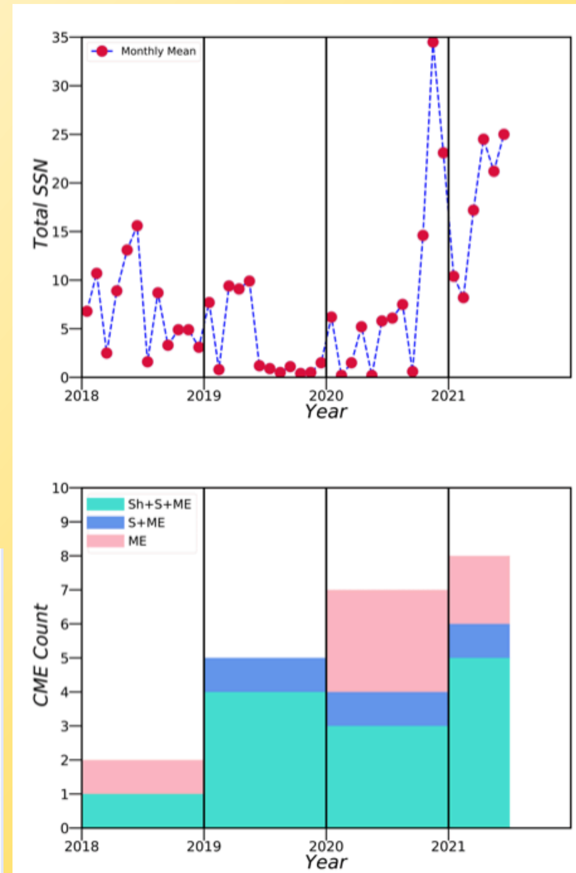
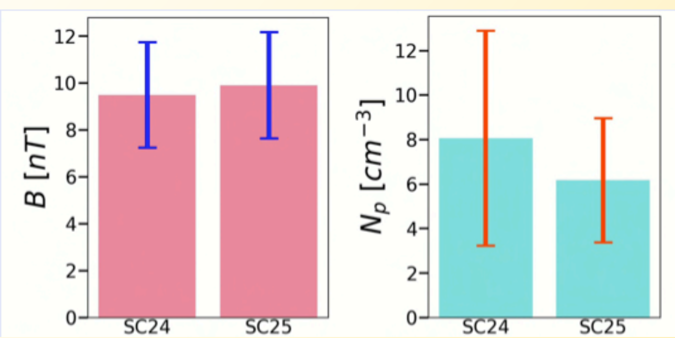
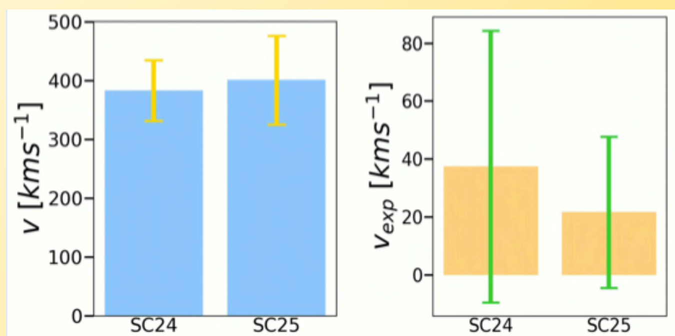
CMEs in 2019-2021

- Comparing CME numbers with 2007-2010, only for STEREO-A
  - 2007: 4, 1, 1 (total, with sheath only, with shock and sheath)
  - 2008: 5, 1, 3
  - 2009: 8, 2, 2
  - 2010 (to June): 6, 2, 2
- Overall, similar number of CMEs
  - Might be a few more shock-driving CMEs in SC25.
  - Properties are overall similar (small number statistics ~22).



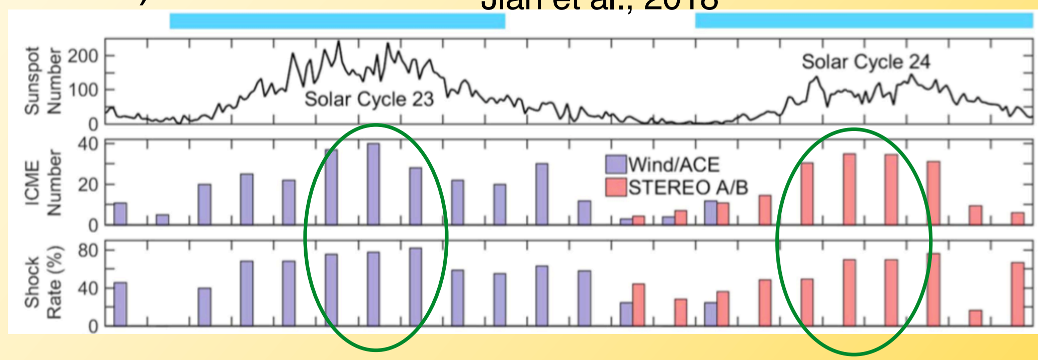




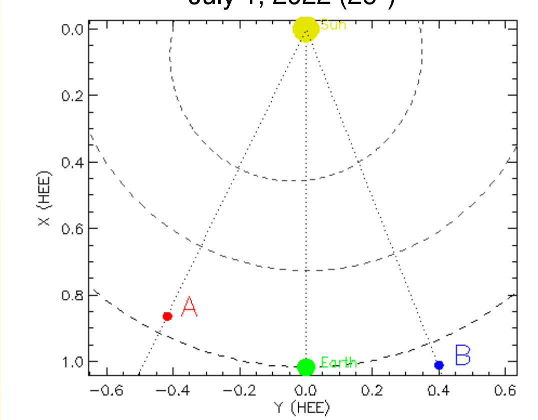
One big change for next few years

- How many CMEs can we expect to measure in situ in the next few years? (*average* of STA, STB and ACE/Wind for 11 years earlier)
  - 2022: ~30 (14 – 35° from the Sun-Earth line)
  - 2023: ~35 (7 – 14°)
  - 2024: ~30 (14 – 29°)
  - 2025: ~25 (29 – 50°)

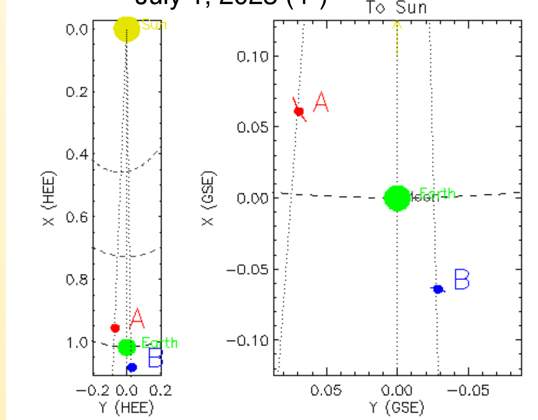
Jian et al., 2018



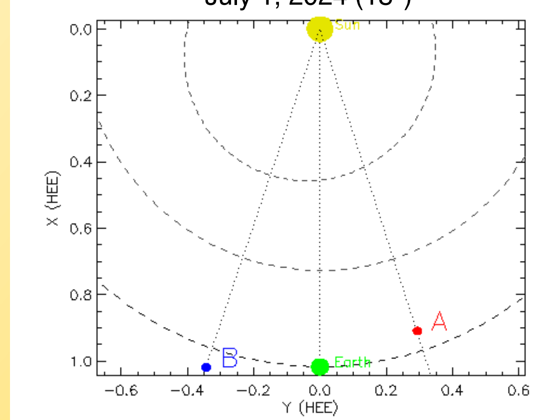
July 1, 2022 (26°)



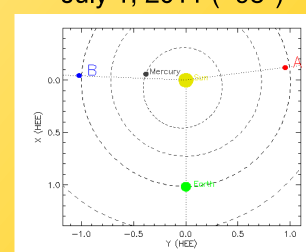
July 1, 2023 (4°)



July 1, 2024 (18°)



July 1, 2011 (~95°)



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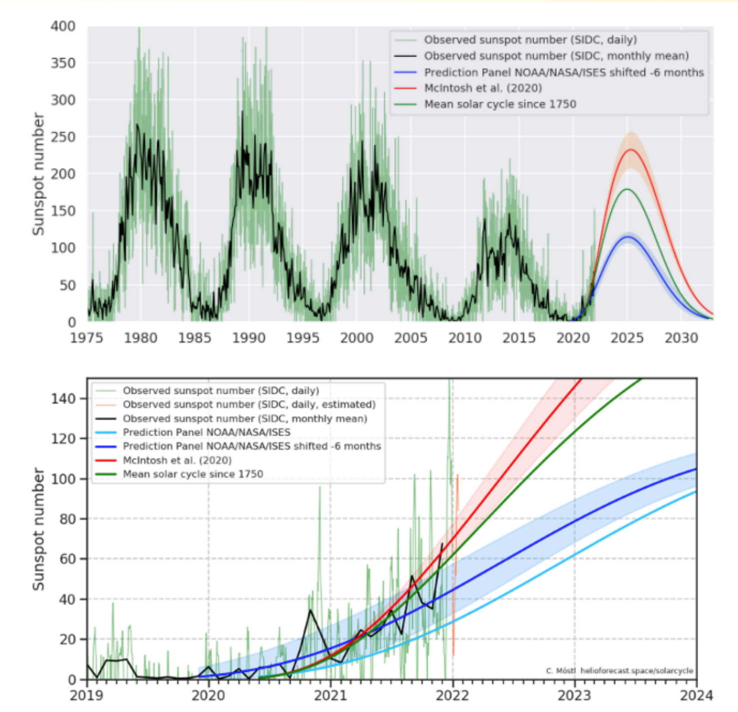
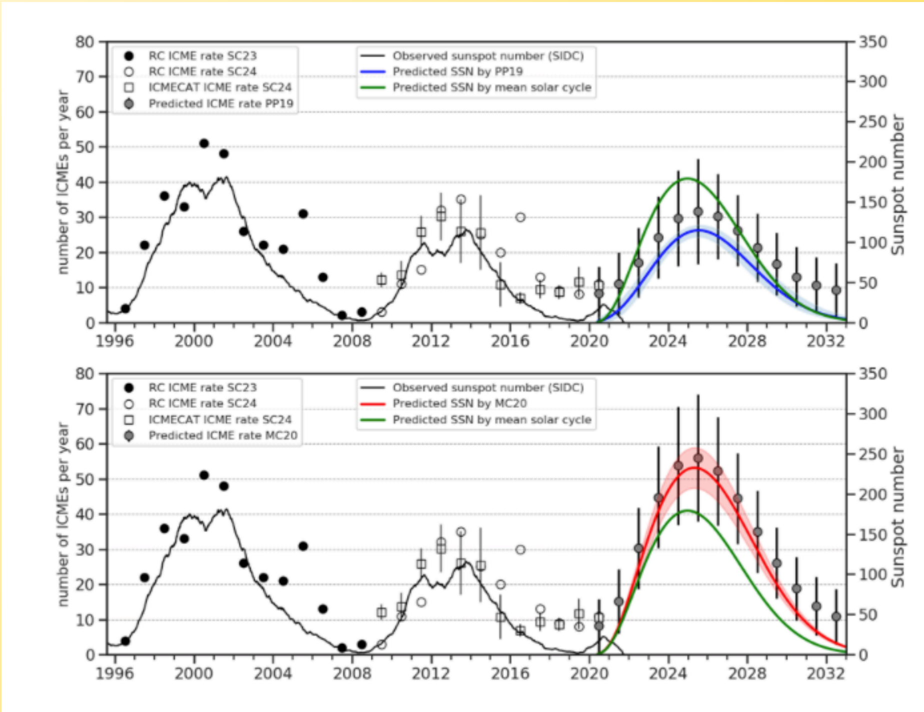
Truth could be even better

- Forecast from Möstl et al (2020) using McIntosh et al. (2020) solar cycle forecast (see helioforecast.space).
- If SC25 is closer to SC23 than SC24, we could get ~50 CMEs in 2023-2025.

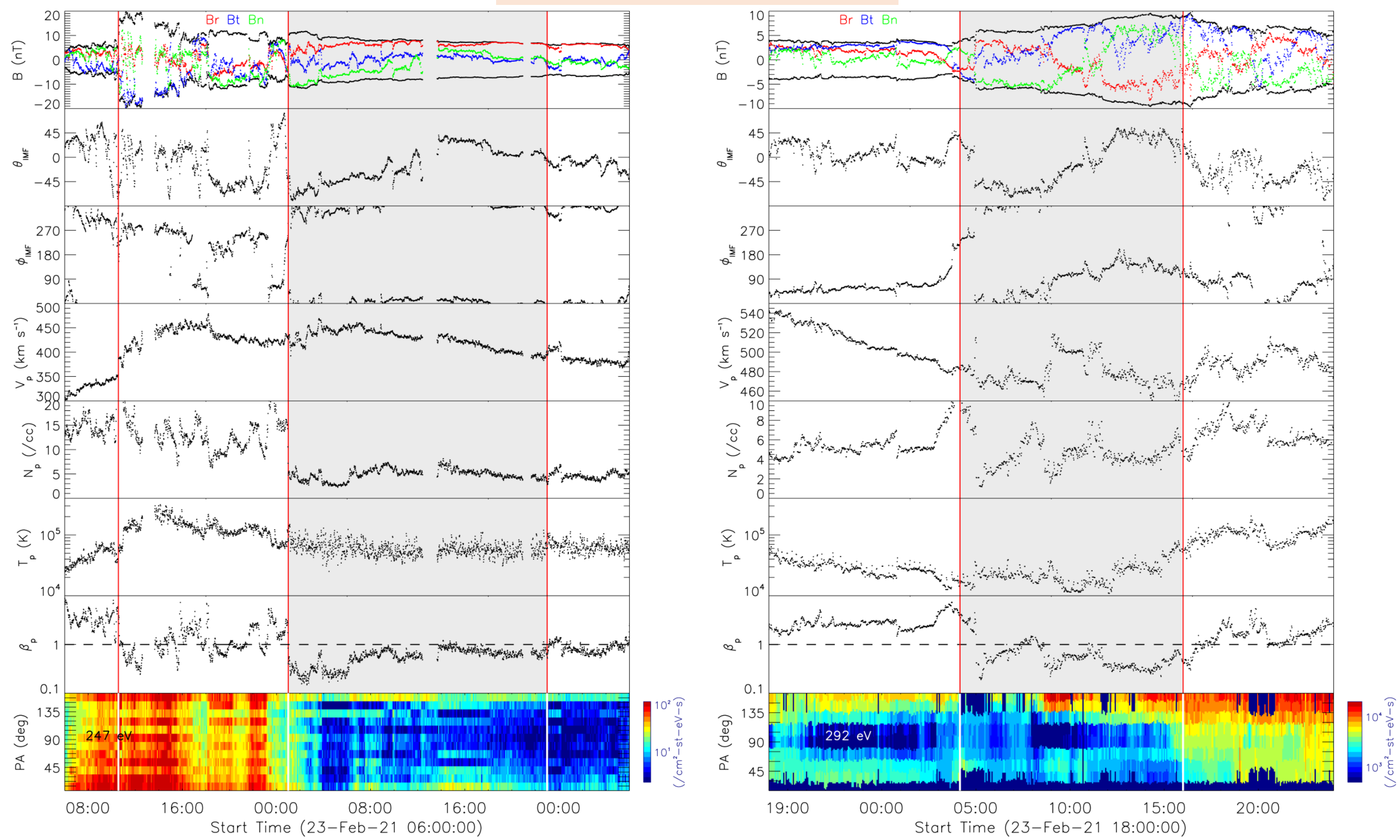




The return of STEREO-A: a preview

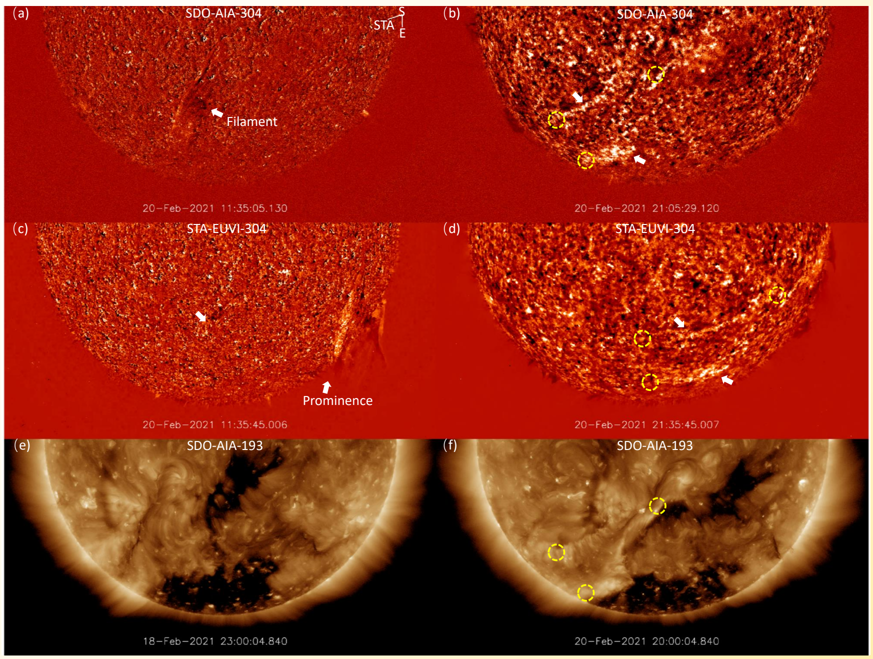
- We already have the first multi-sc measurement of a CME by L1 and STEREO-A in SC24, with separation of ~55° (Lugaz et al., *subm.*).
- Shock and sheath at STEREO-A, ”isolated” ME at Wind.

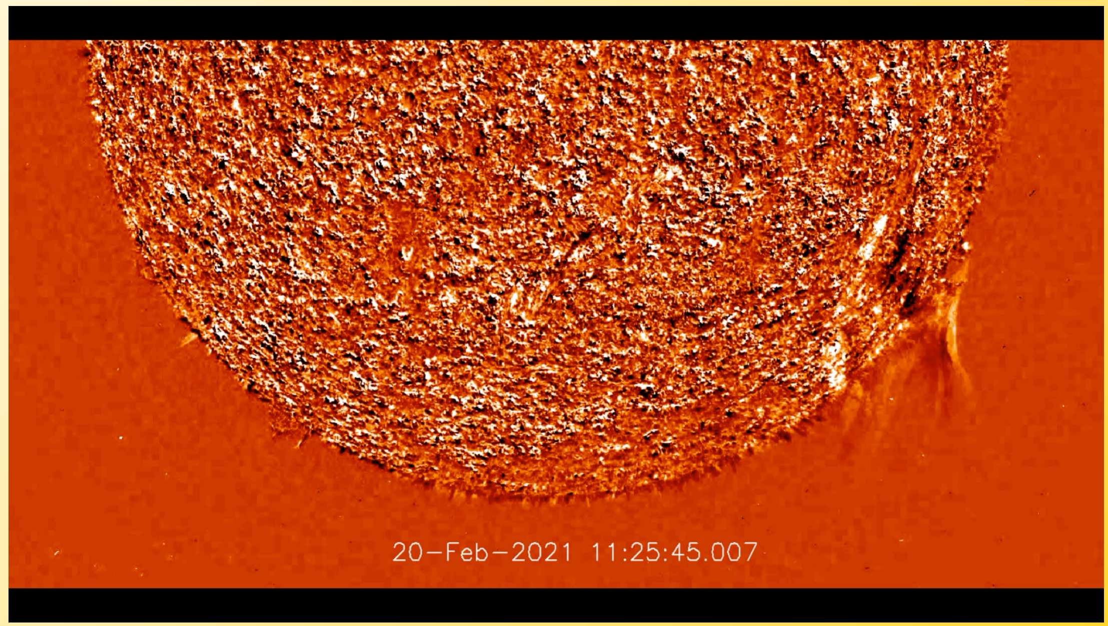
ICME at STEREO-A (left) and *Wind* (right)



February 2021 eruption

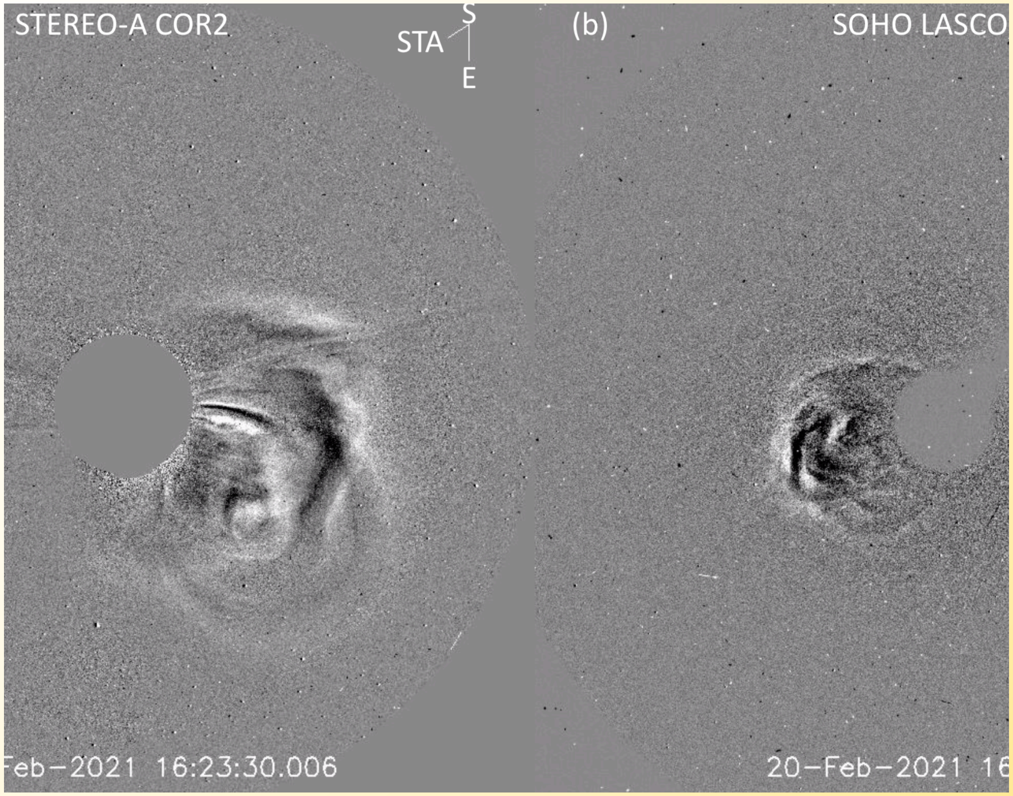
- Filament eruption with clear ribbons
- Close to disk center from Earth (STEREO-A/EUVI view as a near western limb).
- Nearby coronal hole (western leg) as well as dimming/newly open magnetic field.

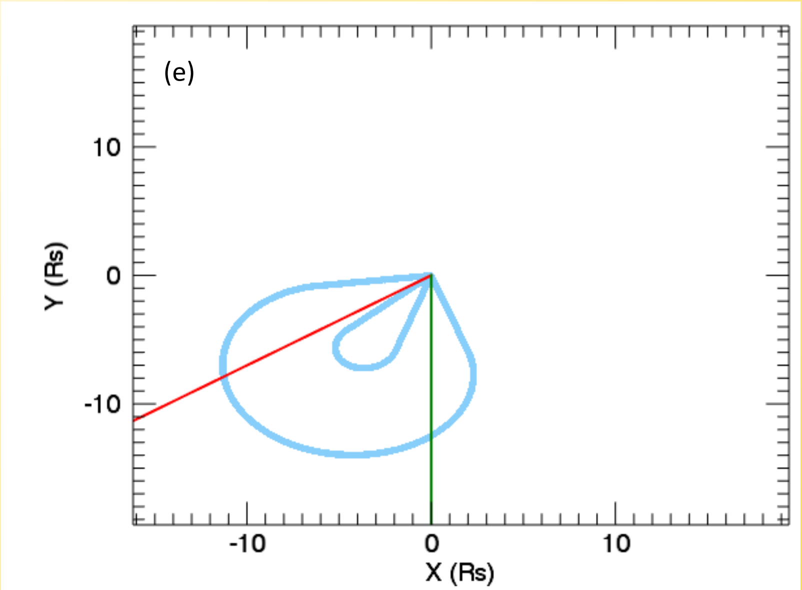




February 2021 eruption

- Close to disk center but clearly directed in-between STEREO-A and Earth in the corona.
- Slightly closer to Sun-STEREOA line ? (more halo)





In situ measurements

- Embedded in the back of a high-speed solar wind stream (HSS) at Wind, well afterwards at STEREO-A.
- Effect of interaction with the HSS: clear BDEs at STEREO-A, mix of single strahl and BDEs at Wind. CME is also faster at Wind than STEREO-A.
- Magnetic field orientation is relatively ”coherent” and consistent with leg crossing at both spacecraft.

ICME at STEREO-A (left) and *Wind* (right)