Radial Evolution of Coronal Mass Ejections in the Inner Heliosphere: Catalog and Analysis (DOI: 10.1029/2019JA027084)

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Abstract

Our knowledge of the properties of Coronal Mass Ejections (CMEs) in the inner heliosphere is constrained by the relative lack of plasma observations between the Sun and 1 AU. We present a comprehensive catalog of 47 CMEs measured in situ measurements by two or more radially aligned spacecraft (MESSENGER, *Venus Express*, STEREO, or *Wind*/ACE). We estimate the CME impact speeds at Mercury and Venus using a drag-based model (DBM) and present an average propagation profile of CMEs (speed and deceleration) in the inner heliosphere. We find that CME deceleration continues past Mercury's orbit but most of the deceleration occurs between the Sun and Mercury. We examine the exponential decrease of the maximum magnetic field strength with heliocentric distance using two approaches: a statistical method and analysis from individual conjunction events. Findings from both the approaches are on average consistent with previous studies but show significant event-to-event variability. We also find the expansion of the CME sheath to be well fit by a linear function. However, we observe the average sheath duration and its increase to be fairly independent of the initial CME speed, contradicting commonly held knowledge that slow CMEs drive larger sheaths. We also present an analysis of the 3 November 2011 CME observed in longitudinal conjunction between MESSENGER, *Venus Express*, and STEREO-B focusing on the expansion of the CME and its correlation with the exponential fall-off of the maximum magnetic field strength in the ejecta.

Objective

- Comprehensive catalog of CMEs observed in conjunction between radially aligned spacecraft in the inner heliosphere.
- Evolution of general CME properties: from its eruption to being measured at/near L1.

Approach

- We examine each CME listed in the following catalogs*.
- For each CME measured by spacecraft1 (SC1: MESSENGER or *Venus Express*), we compare its longitudinal separation with spacecraft2 (SC2: *Venus Express or* STEREO or *Wind*/ACE) during the event.
- Only selective longitudinal separations (≤35°) are considered (it increases the probability of the spacecraft observing both the sheath and the ejecta).

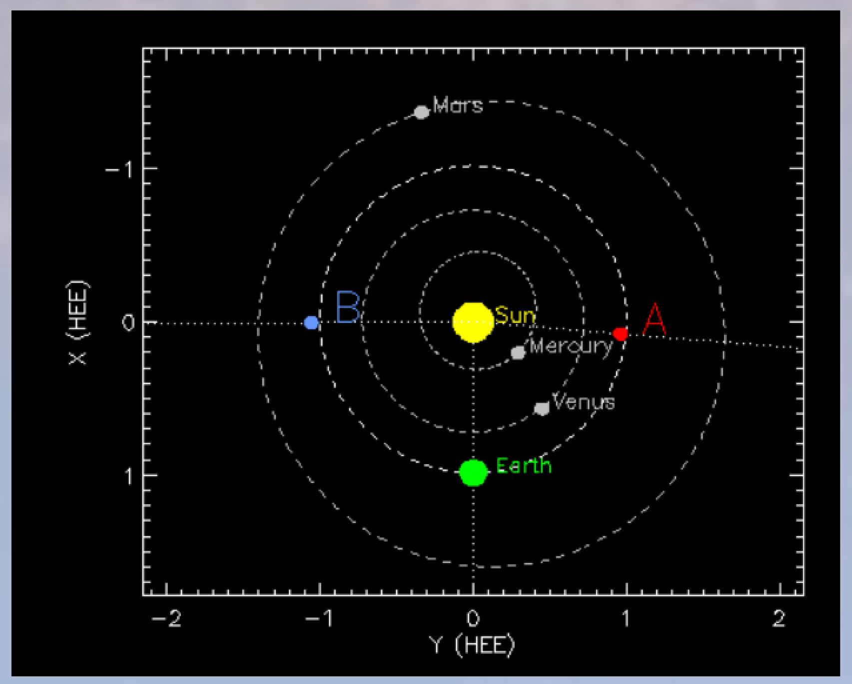


Fig: Positioning of inner heliosphere planets and spacecraft on 1 January 2011 (*Image credit: STEREO SCIENCE CENTER*).

- If CME signatures are measured by SC2 within an expected interval after the initial measurement at SC1, we list the CME as a possible conjunction event.

*Catalogs:

- MESSENGER: Mercury (2011-2015): [1,2]
- *Venus Express* : Venus (2006-2013): [3]
- STEREO: near Earth (2007-2016): [4]
- ACE/ *Wind:* L1 (1996-2018): [5]

Identifying the CME at the Sun

- We examine each CME in the LASCO CME catalog up to a period of 3-5 days prior to its measurement at SC1.
- We approximate the CME propagation direction using three field of views: LASCO (SOHO) and COR2 (STEREO) observations and compare it with the relative positioning of the spacecraft.

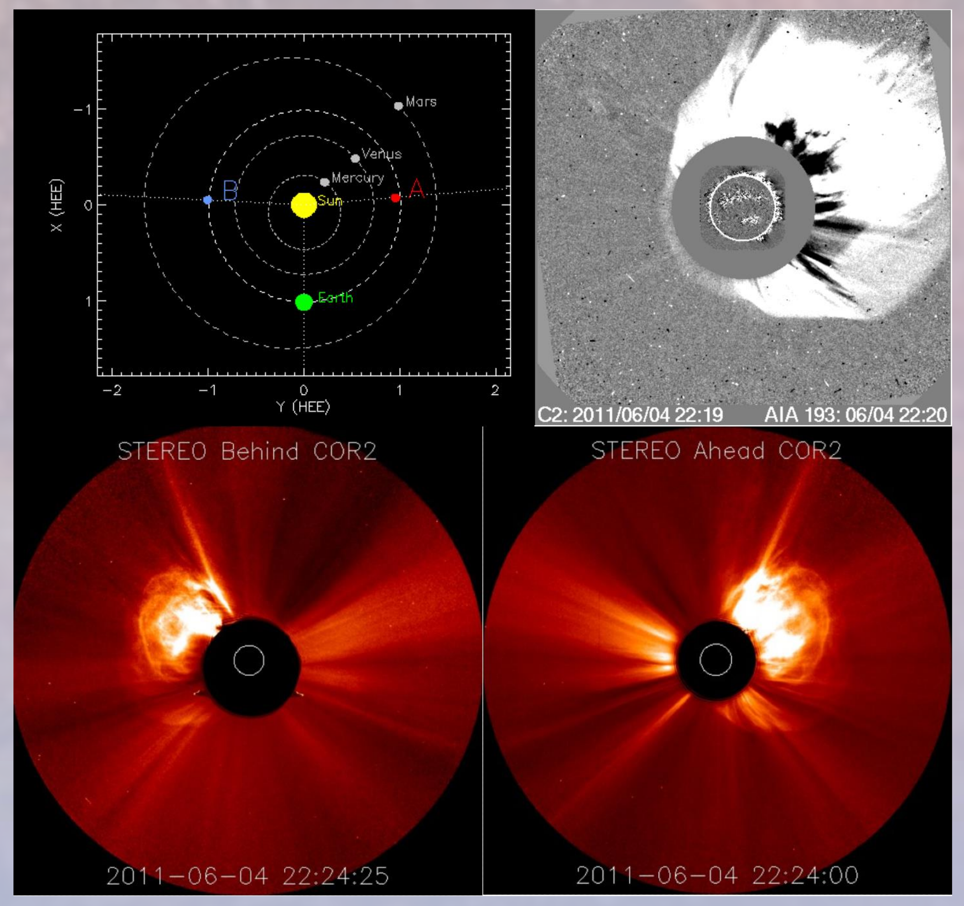


Fig: Positioning of inner heliosphere planets and spacecraft during the 4 June 2011 CME event and LASCO and COR2 observations of the CME (Image credit: *CDAW Data Center*).

- For candidates satisfying the directional requirement, we compare the initial speed at the Sun with the speed measured near Earth and the average transit speeds between the Sun to SC1 and SC1 to SC2 for consistency.
- Then we compare the DBM estimated arrival times at the spacecraft with database timings to select the best possible candidate(s).

We list 47 CME events observed in conjunction with 2 events having three point measurements (4 June 2011 and 3 November 2011 CMEs).

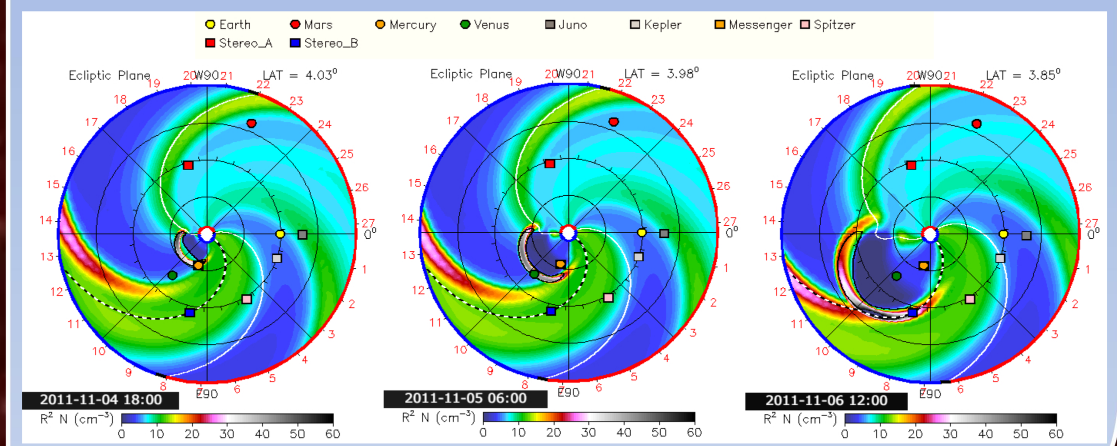
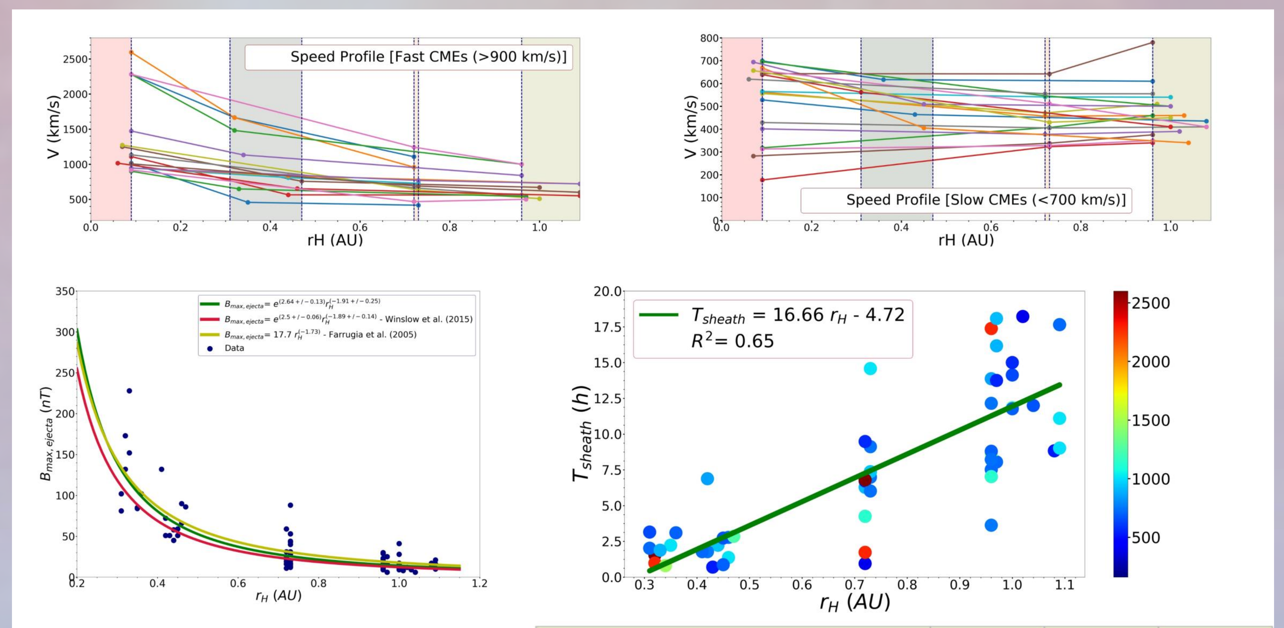


Fig: WSA-ENLIL model simulation with CME cone extension of the 3 November 2011 CME: when it reached Mercury (left), Venus (middle) and STEREO-B (right). (Image credit: *CCMC*)

Evolution of CME Properties

- Taking advantage of conjunction, we estimate the CME impact speed at Mercury/Venus using the DBM [6].
- Using the initial speed from coronagraphs and the solar wind speed measured near 1 AU, three estimates for the impact speed at Mercury/Venus are found (later averaged) by adjusting the drag coefficient in the DBM to match:
  1) The CME arrival time near L1.
  2) The Maximum CME speed near L1.
  3) The CME arrival time at Mercury/Venus.
- We categorize CMEs based on initial speeds (Fast: >900 km/s, Intermediate: 700-900 km/s, Slow: <700 km/s).



	Sun-Spacecraft2	Su-M	M-VEx	VEx-L1
Speed Variation in % (F, I, S)	46, 24, 5			
Average Deceleartion (in m/s^2)		12.3	8.1	0.3
Note: Su=Sun, M=MESSENGER, VEx= Venus Express, F=Fast, I =Intermedite, S=Slow				

Fig: Speed profile (in km/s) for fast and slow CMEs with speed estimations/measurements at three distinct points in space (top panel), correlation of the maximum magnetic field strength in the ejecta (in nT) and sheath duration (in hour) with heliocentric distance (in AU, middle panel), and statistical results (bottom panel).

- Fast (slow) CMEs observe on average a 46% (5%) decrease in speeds from the Sun to SC2.
- Most of this deceleration for fast CMEs occurs between the Sun and Mercury (30%).
- More than 80% of the exponent decrease of the maximum magnetic field strength (B_{max}) in the ejecta lie outside the 95% Confidence Interval of the statistical fit, confirming the heterogenous nature of individual CME events.
- Intercept of the linear fit approximates that the formation of CME sheaths to start at ~0.24 AU.
- Average sheath duration of fast (slow) CMEs is 1.74 (2.22) hours at Mercury, 7.30 (6.57) hours at Venus and 13.74 (10.98) hours near L1, which contradicts commonly held knowledge that slow CMEs correspond to larger sheaths.

A Sample Conjunction Event

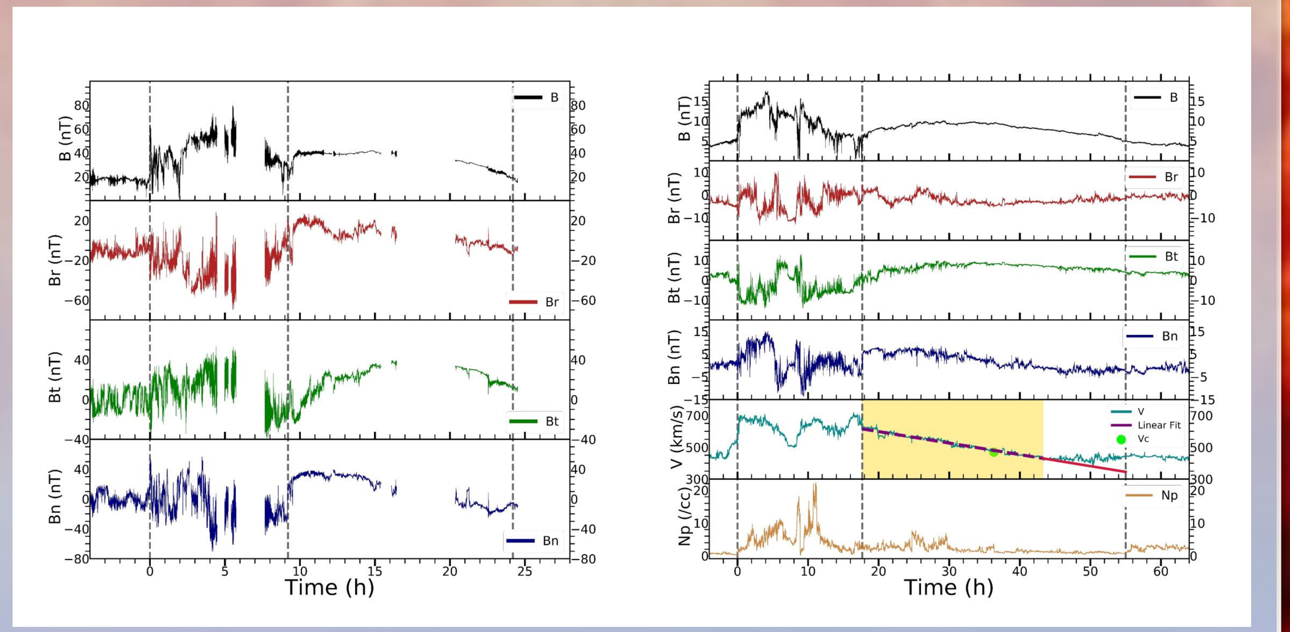


Fig: Measurements of the 3 November 2011 CME at MESSENGER (left), and at STEREO-B (right).

- $B_{max,sheath}$ / $B_{max,ejecta}$ at MESSENGER:1.86, at ST-B:1.8.
- The exponent decrease (α) of B_{max} in the ejecta with distance ($B_{max} \sim r^{\alpha}$) from MESSENGER (0.44 AU) to ST-B (1.09 AU) is -1.61.
- Expansion speed [(V_{front}:617) – (V_{back}:446)/2] is ~86 km/s at ST-B, representing an expanding CME.

Concluding Remarks

- 58-67% of the total speed variation of CMEs happen sunward of Mercury's orbit.
- CME deceleration continues beyond Mercury's orbit, at least to Venus's orbit.
- $B_{max,sheath}$ / $B_{max,ejecta}$ is found to remain mostly constant at distinct points in the inner heliosphere.
- CME-to-CME variability is not well represented by fits.
- The sheath duration is found to be fairly independent of the initial CME speed throughout the inner heliosphere.

References

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Acknowledgments

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