CME Expansion as Revealed by Joint Measurements by STEREO, Wind, MESSENGER and Venus Express

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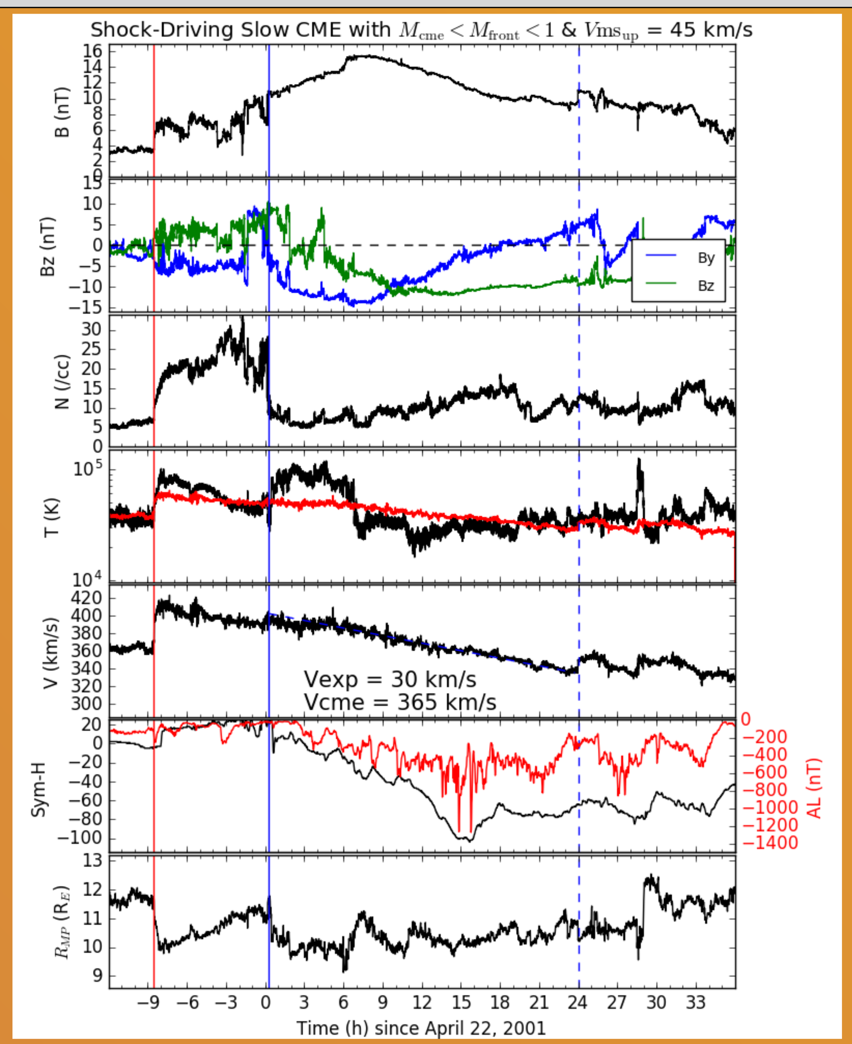
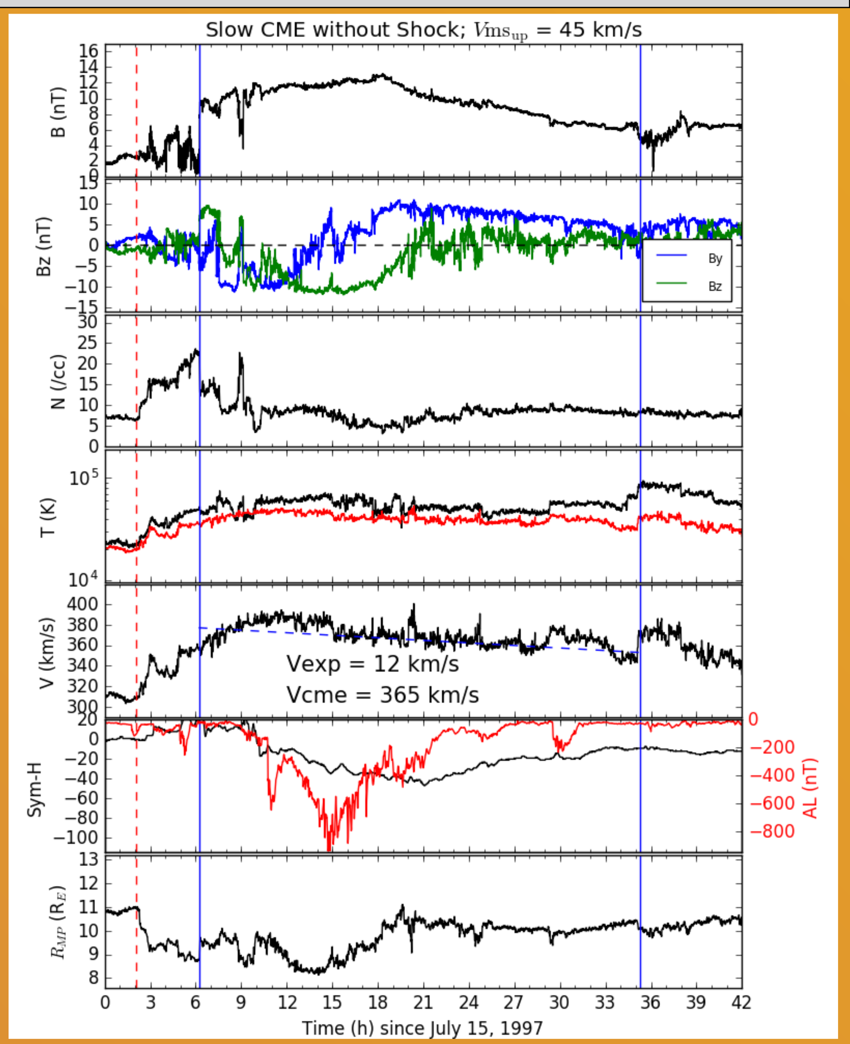
Abstract and Objectives

The radial expansion of magnetic ejecta (ME) has been investigated through the analysis of remote observations, the variation of their properties with radial distance and from local *in situ* plasma measurements showing a decreasing speed profile, as first discussed almost 40 years ago. However, little is known on how local measurements compare to global measurements of expansion and what causes the different expansion properties of different CMEs. Here, we take advantage of 42 CMEs being measured by two spacecraft in radial conjunction to determine how the magnetic field decrease with distance, as a measure of their global expansion. As all these CMEs are also measured near 1 AU by STEREO or Wind, we are able to determine their local expansion from the speed decrease. We find that these two measures have little relation with each other. We also determine the relation between measures of the CME expansion and the CME properties.

CME Expansion Contributes in the Formation of Shocks

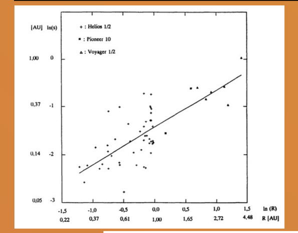


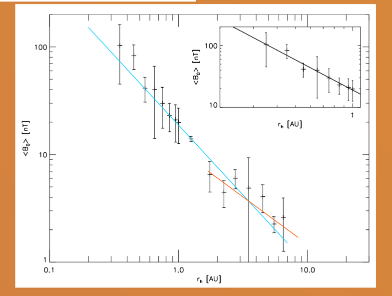


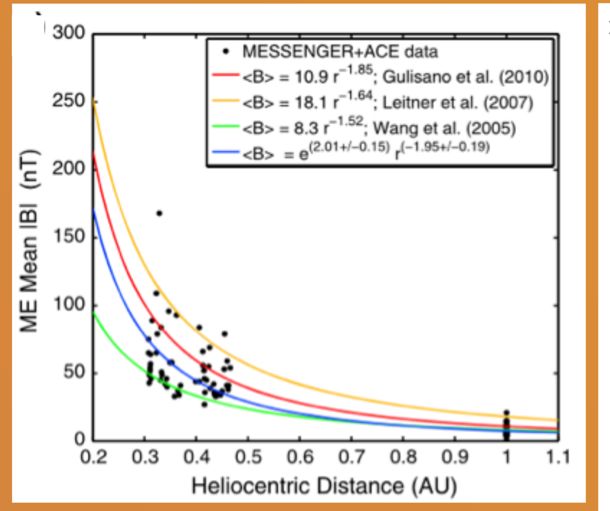
A CME with an average speed under 370 km s^{-1} that nonetheless drove a shock and a similar CME that did not drive a shock at 1 AU. For each CME, we calculated the average speed in the magnetic ejecta, the front speed taking into consideration expansion, the maximum speed and the shock speed. We calculate "Mach" numbers for each of these speeds, using the upstream solar wind and fast magnetosonic speeds. For the CME on the left, expansion contributes to driving the shock ($M_{cme} < M_{front} < 1$), whereas for the one on the right the small expansion speed resulted in no shock (but a wave at 1 AU). *From Lugaz et al., ApJ, 2017*

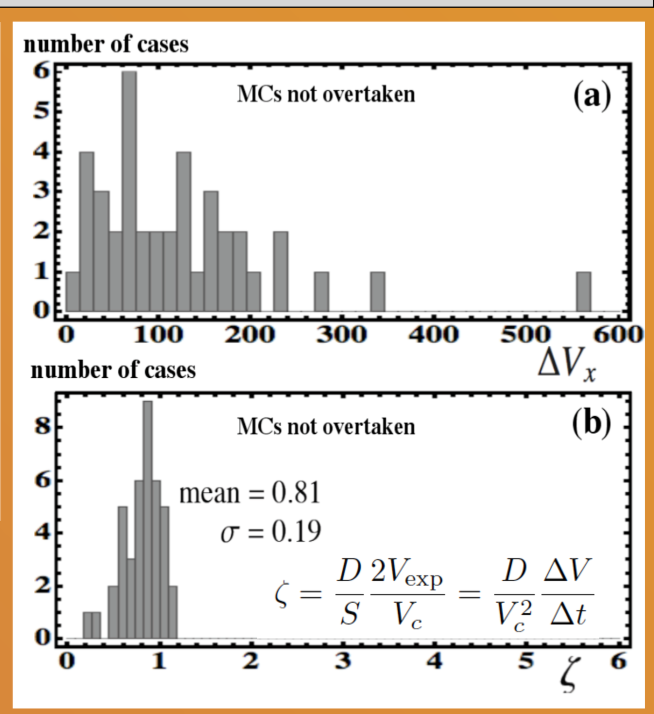
Different Measures of CME Expansion

Past studies reveal that a local measure of the CME expansion, ζ is typically ~ 0.8 for isolated CMEs (Gulisano et al., 2010). Global measures of CME expansion relate the magnetic field strength (maximum or average) as a function of radial distance as r $^{-1.75\pm0.2}$ (Winslow et al., 2015). The increase of CME size with distance can be studied statistically (Bothmer & Schwenn, 1998; Liu et al, 2005; Leitner et al., 2007). Typically, the CME radial size increases as r $^{0.75\pm0.1}$.





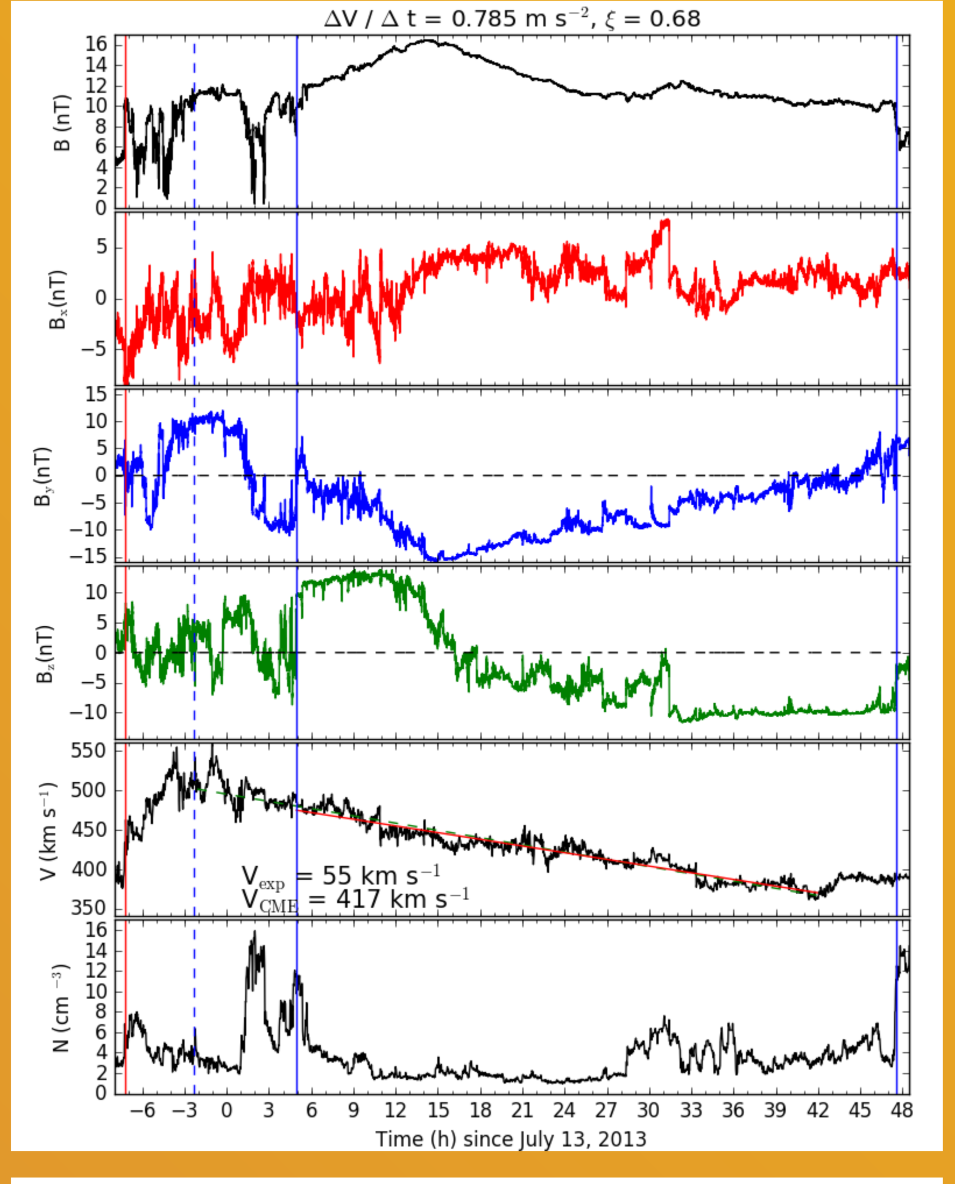


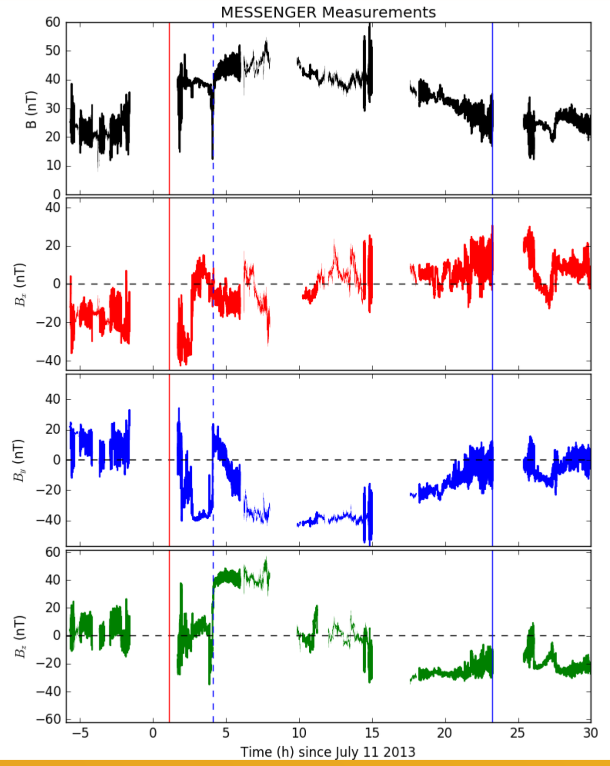


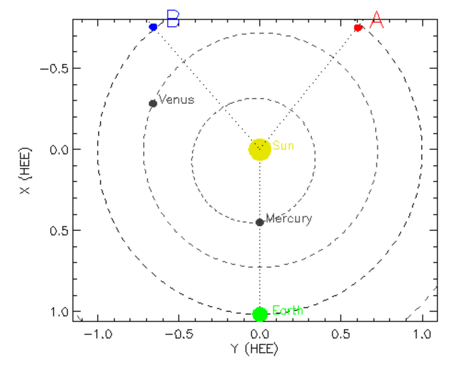
Various past studies of CME expansion based on statistical measures. Left: CME size from Bothmer & Schwenn (1998) and central magnetic field from Leitner et al. (2007). Center: Mean magnetic field from Winslow et al. (2015). Right: Expansion from Demoulin et al., (2010) with data from Gulisano et al., (2010).

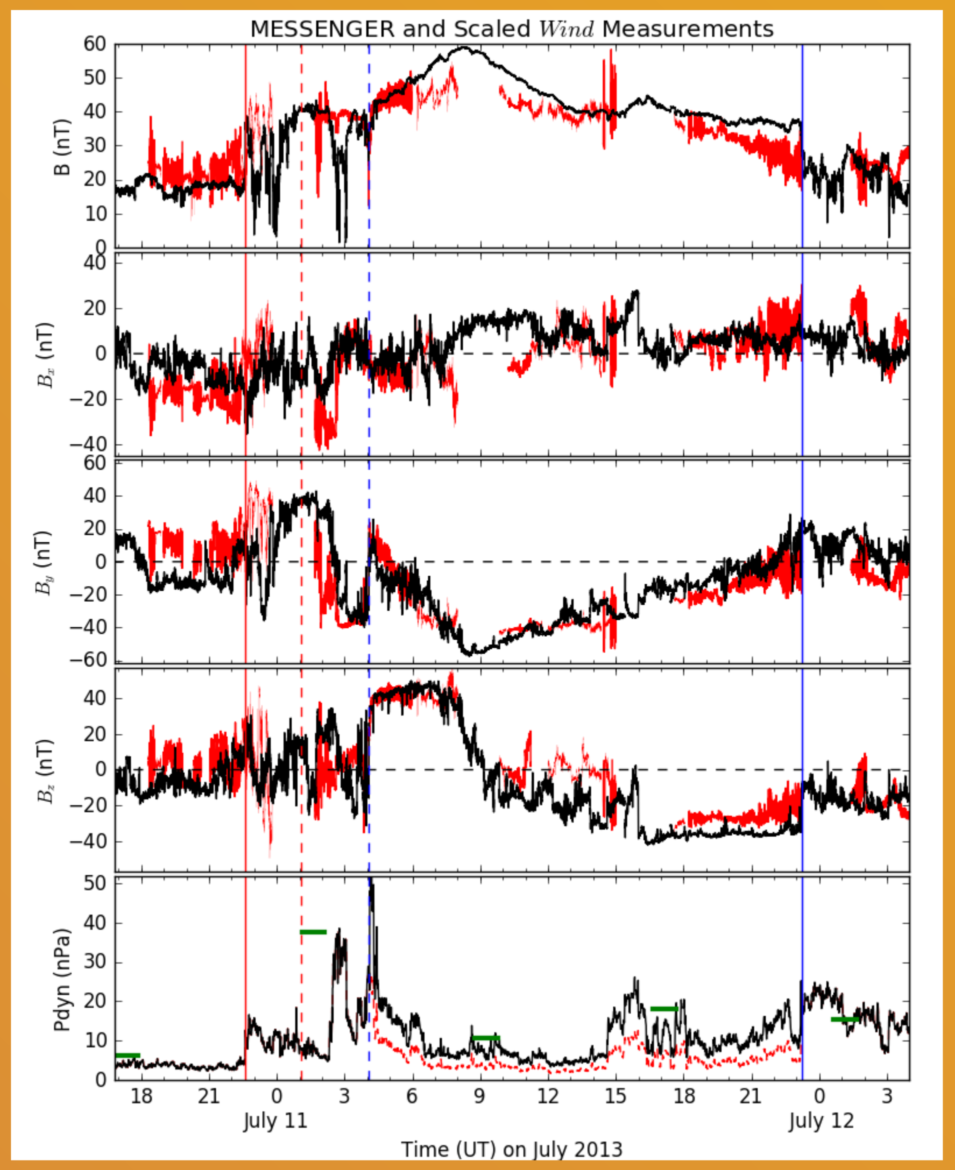
Case Study: 2013 July 13 CME: How do Different Measures of CME Expansion Compare?

We take advantage of a great conjunction event between Mercury and Earth in 2013 July 11-15 (longitudinal alignment within 3°) to highlight our approach of comparing global measures of CME expansion (the exponent decrease of the magnetic field with distance, the exponent increase of the CME size with distance) and local measures (the ratio of expansion speed to CME speed and ζ from Gulisano et al.,2010). *From Lugaz, Winslow, Farrugia, JGRA, 2020.*









<u>Local measures of the CME expansion:</u>
Based on velocity measurements at 1 AU (top left Figure), we estimate ζ = 0.69 ± 0.01. The relation between the expansion speed (55 km s^{-1}) and CME front speed (500 km s^{-1}) is relatively consistent with Owens et al. (2005). ζ is relatively typical (~ 0.8).

<u>Global measures of the CME expansion:</u>
The decrease of the maximum magnetic field in the ejecta from 59 nT at Mercury (0.45 AU) to 16.5 nT at Earth implies a decrease as r $^{-1.6}$. The average magnetic field decrease inside the ejecta implies a decrease with distance as r $^{-1.3}$. These are again typical (~r $^{-1.8}$) or slightly lower.

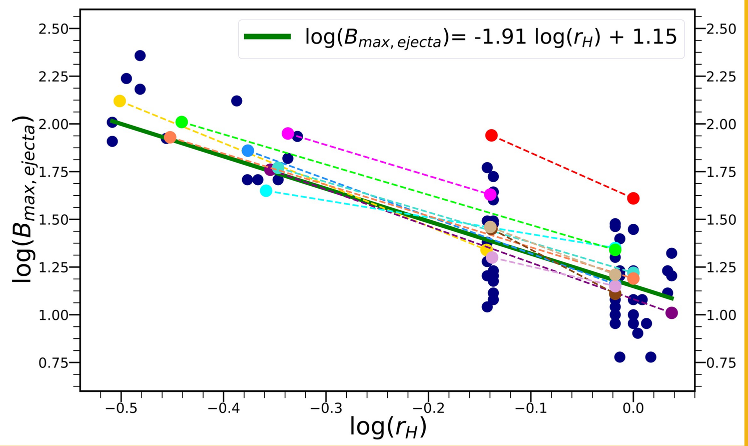
In the bottom left Figure, we overlay MESSENGER measurements with scaled and stretched *Wind* measurements. We attempted to scale differently the different magnetic field components but the match was worse. The scaled dynamic pressure is compared with estimates obtained from the pressure balance at Mercury's magnetopause (Newtonian approximation, green bars).

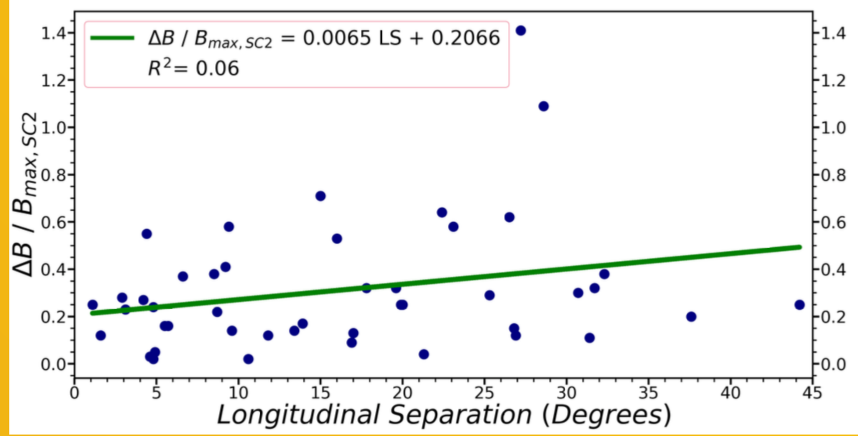
<u>CME duration, size and their increase:</u>
This is a long-duration ejecta: 19.15 hours at Mercury and 42.6 hours at Earth, about twice longer than typical. The CME radial size at 1 AU is estimated as 0.42 AU, while at Mercury it is ~0.25 ± 0.02 AU. This implies an increase of the size with distance as r $^{0.66}$.

Overall, this very large CME is found to expand slowly between 0.45 and 1 AU, indicating that the large size does not correspond to large values of the heliospheric expansion. Comparing the global and local measures of CME expansion, we find that, in agreement with theoretical work, the CME radial size increases approximately as r$^{\zeta}$ and the magnetic field inside the ejecta decreases as r $^{-2\zeta}$.

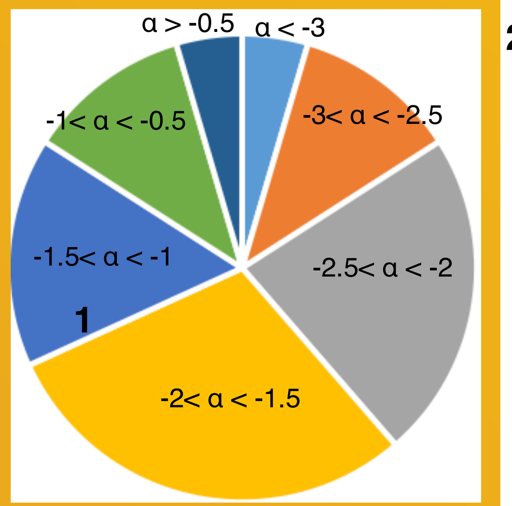
Statistical Comparison: Complexity of CME Expansion

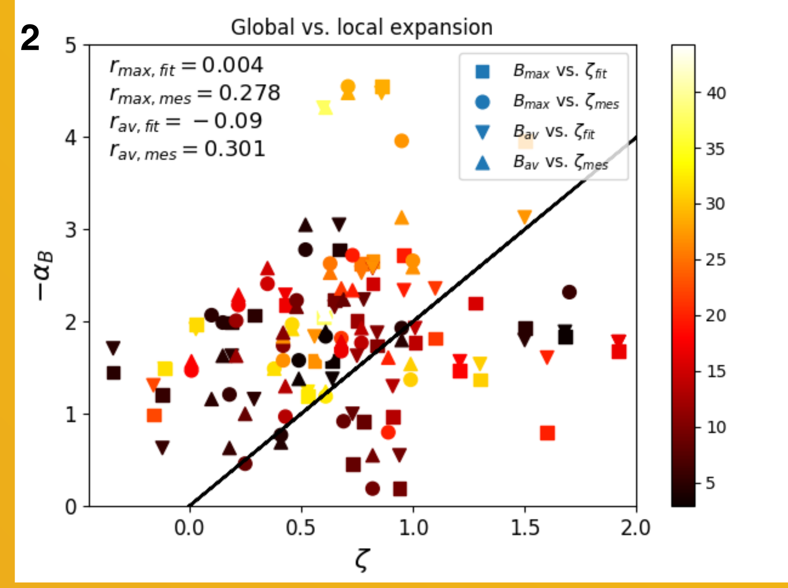
We take advantage of a recent study (Salman, Winslow, Lugaz, JGRA, 2020) identifying 45 CMEs measured in conjunction by two spacecraft in the inner heliosphere (MESSENGER, VEX, ACE/*Wind*, STEREO). For 42 events, there are plasma measurements near 1 AU that allow us to derive the expansion speed and the expansion parameter ζ. For each event, we can also estimate the exponent decrease of the magnetic field as $\alpha = \log(B_2/B_1)/\log(r_2/r_1)$, where the indices 1, 2 refer to the measurements at each of the two spacecraft. *Work submitted to Astrophysical Journal*

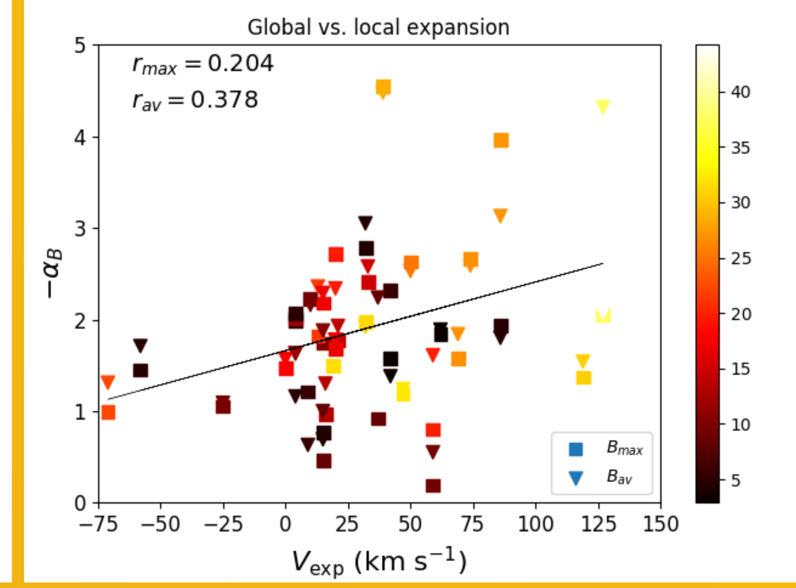




<u>Left</u>: Comparison of general statistical trend for the decrease of the maximum magnetic field in the magnetic ejecta for all 45 CMEs (α_{stat} = -1.91) with 12 random events (measurements of the same CME by two spacecraft plotted with the same color). There can be significant variation from the average trend.
<u>Right</u>: Deviation from the average trend calculated as $\Delta B = |B_{meas,\,SC2} - B_{meas,\,SC1}\,(r_2/r_1)^{-1.91}|$ as compared to the longitudinal separation between the two spacecraft. There is little influence of the longitudinal separation between the spacecraft on the deviation from the average trend. *From Salman, Winslow, Lugaz, JGRA, 2020.*

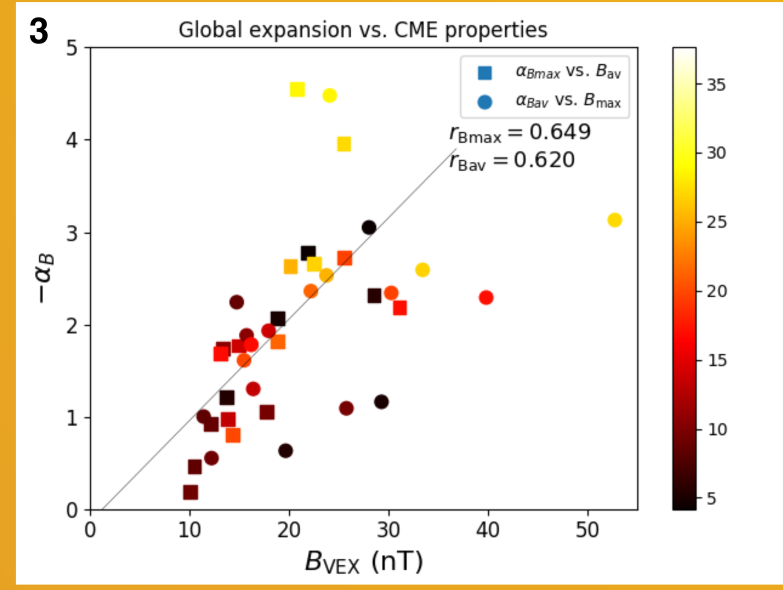


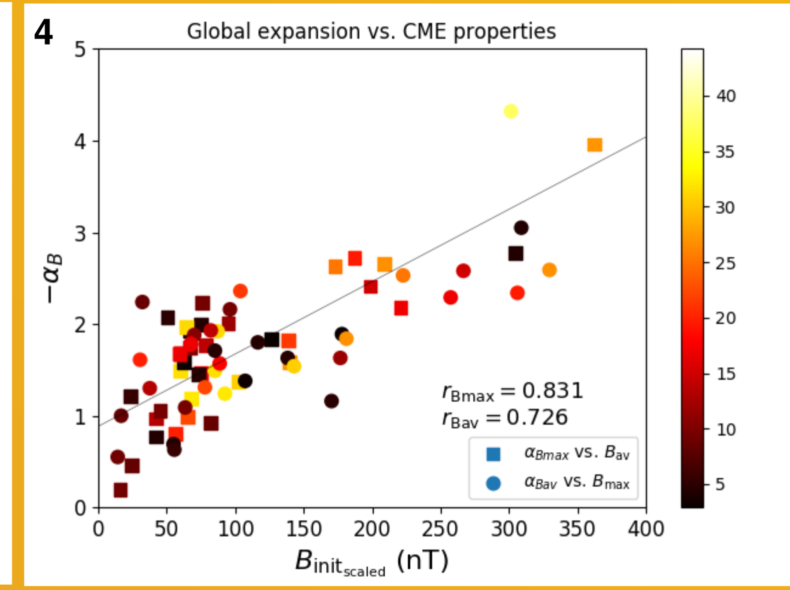


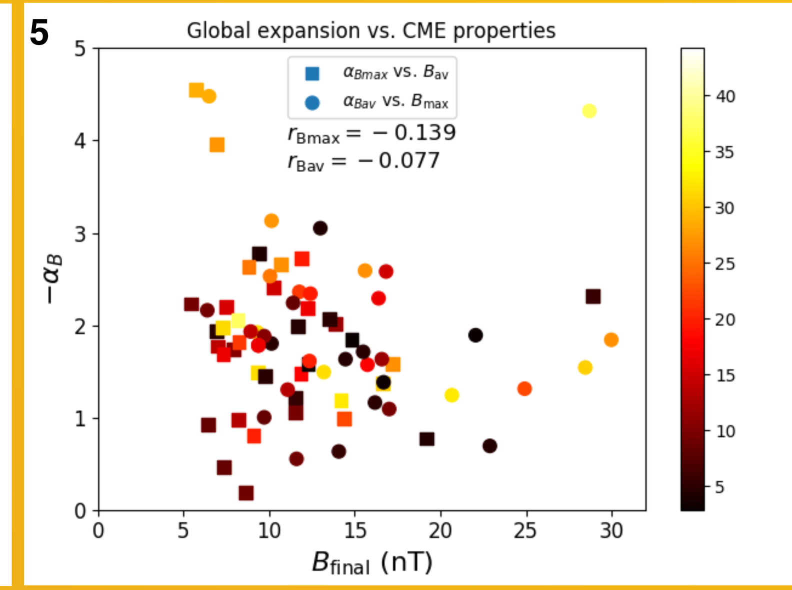


1- Overall, we find that the average value of α is in good agreement with 2ζ. The average is -1.75 (median -1.65), but the standard deviation is 0.84. Less than half of the events are between -1.35 and -2.15.

2- **There is no relation between α and ζ for individual events**, contrary to what we found for the 2013 July CME. The local measure of expansion is not related to the global measure. There is also no relation between the CME expansion speed near 1 AU and α, or between the CME initial speed from coronagraphs and α.





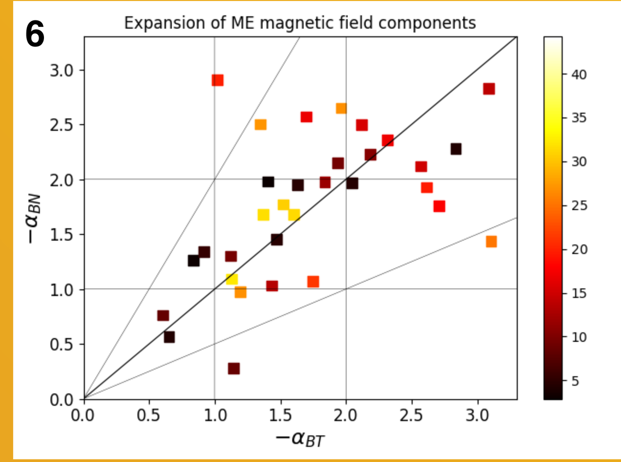


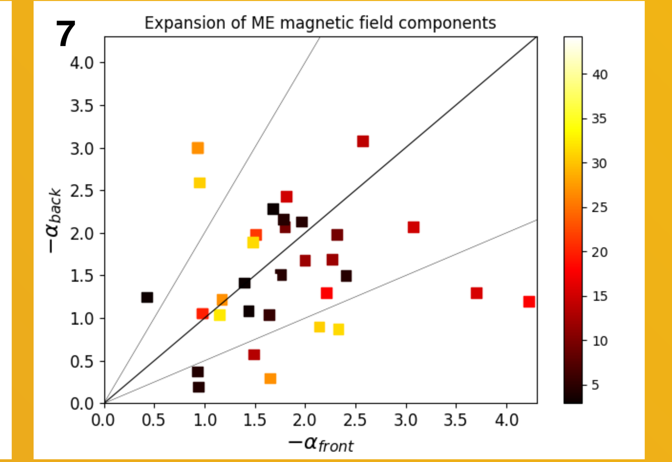
3- There is decent correlation between the magnetic pressure inside the CME (using the maximum magnetic field strength) and α. However, magnetic pressure decreases strongly with distance. Therefore, the relation looks nice for VEX because all measurements are approximately at the same distance. MESSENGER heliocentric distance varies between 0.31 and 0.47 AU. **Overall, this indicates that CMEs with stronger internal magnetic pressures expand faster.**

4- We combine all measurements using a version of the internal magnetic pressure scaled to 0.31 AU. We either use the average magnetic field decrease or the exponent found for each individual CME. This shows a good relationship between the decrease in B and the internal magnetic pressure in the innermost heliosphere.

5- When doing the same thing using the magnetic pressure measured near 1 AU, there is no relation. **Measurements near 1 AU do not reflect the "original" state of CMEs and their global expansion**. The parameter found most correlated with CME global expansion is the CME internal magnetic pressure in the innermost heliosphere: **CMEs expand because of over-pressure** but at 1 AU, they are likely in pressure balance with the solar wind, so that their internal properties are unrelated to the expansion. *From Lugaz et al., submitted.*

Measurements near 1 AU do not reflect the "original" state of CMEs and their global expansion. The parameter found most correlated with CME global expansion is the CME internal magnetic pressure in the innermost heliosphere: **CMEs expand because of over-pressure in the inner heliosphere,** but at 1 AU, they are likely in pressure balance with the solar wind, so that their internal properties are unrelated to the expansion.





6 & 7- **Bonus**: Evolution of normal and tangential and front *vs.* back components of the magnetic field. Most CMEs have a close to 1-1 evolution of the normal *vs.* tangential components. The ratio of the front-to-back expansion is 1.57 ± 1.18 with the magnetic field in the front decreasing faster.