Decoupling CME Properties from Solar Cycle Effects and Heliocentric Distance

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Background & Motivation

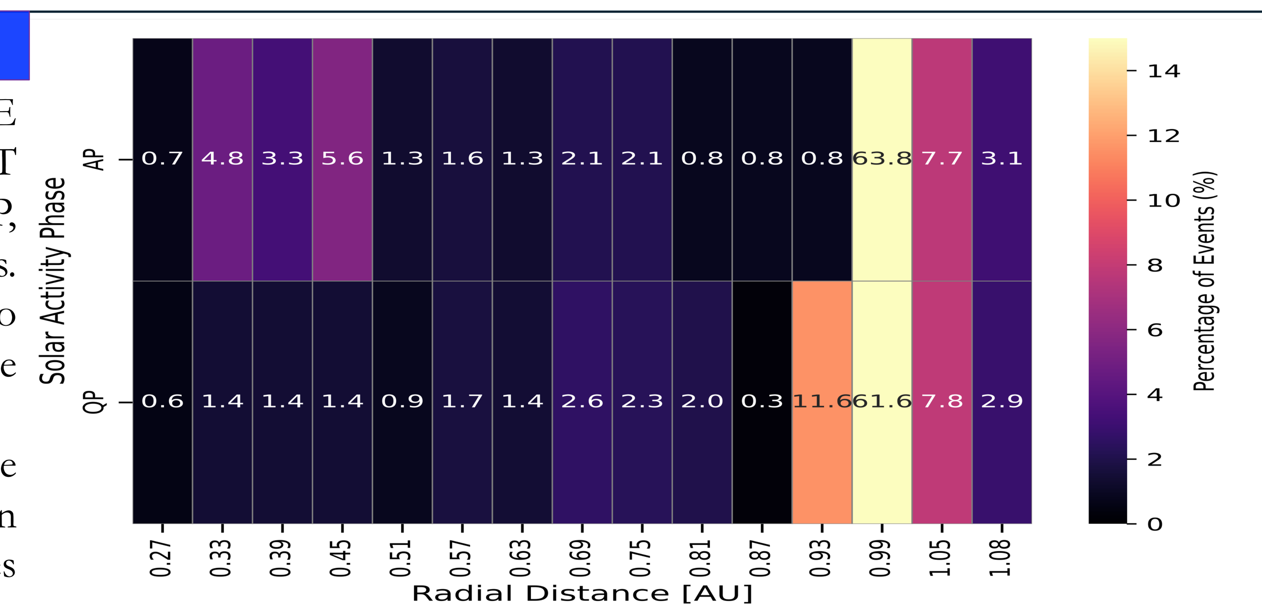
CMEs evolve continuously as they propagate through the heliosphere, causing their temporal properties to change with heliocentric distance. At the same time, CME properties are known to vary with solar-cycle activity, yet most previous studies have examined radial evolution and solar-cycle effects independently. As a result, it remains unclear whether observed CME trends are driven primarily by propagation effects, solar-cycle conditions, or a combination of both. Understanding this distinction is essential for improving CME evolution models and space-weather forecasting.

Using multi-spacecraft observations from 1995–2024, we compare the radial evolution of CME magnetic, plasma, and temporal properties during Active Phase (AP) and Quiet Phase (QP) solar-cycle conditions.

Data & Method

We analyzed nearly three decades of multi-spacecraft CME observations from the extended HELIO4CAST ICMECAT catalog, incorporating measurements from Solar Orbiter, PSP, STEREO-A/B, Wind, MESSENGER, and Venus Express. Magnetic-field and plasma data were transformed into RTN/MVA coordinates, resampled to a uniform 1-minute cadence, and grouped into 15 heliocentric-distance bins.

Events were classified into AP and QP events using solar-cycle phase intervals defined in our previous study, enabling an investigation of how CME magnetic and plasma properties evolve with distance under different solar-cycle influence.



Duration Evolution with Distance & SC phase

Figures 1 and 2 present the heliocentric evolution of CME substructure durations. Figure 1 shows the sheath duration, while Figure 2 shows the magnetic ejecta (ME) duration for Active Phase (AP) and Quiet Phase (QP) events. **CME substructure durations increase with heliocentric distance.** Sheath duration evolution is statistically identical for both AP and QP events (p-interaction}=0.95; F-test p=0.55). ME duration also increases with distance, consistent with continuous CME expansion, while AP–QP differences remain only marginally significant (F-test p=0.060).

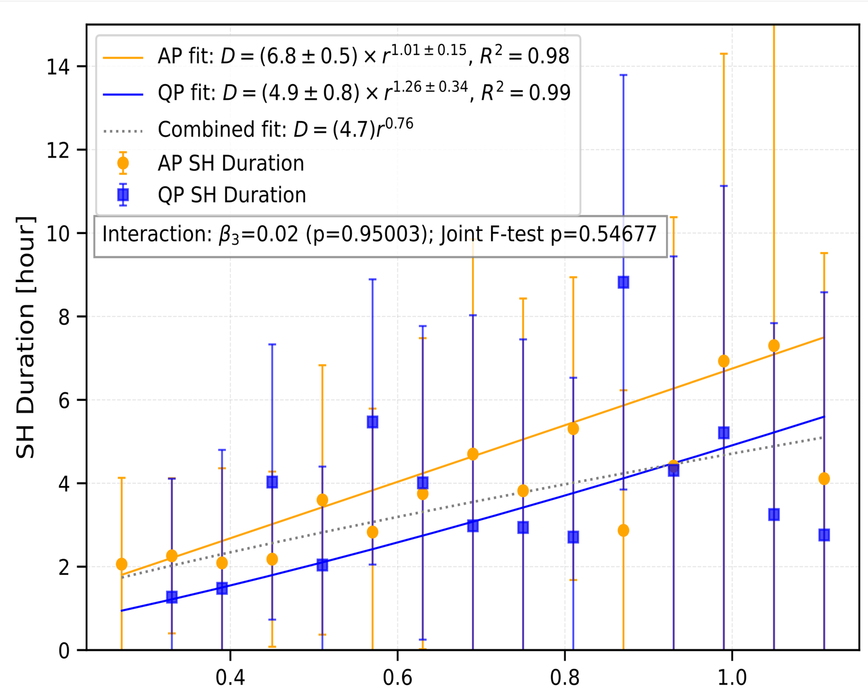


Figure 1: SH Duration in AP and QP vs Helio-Dist.

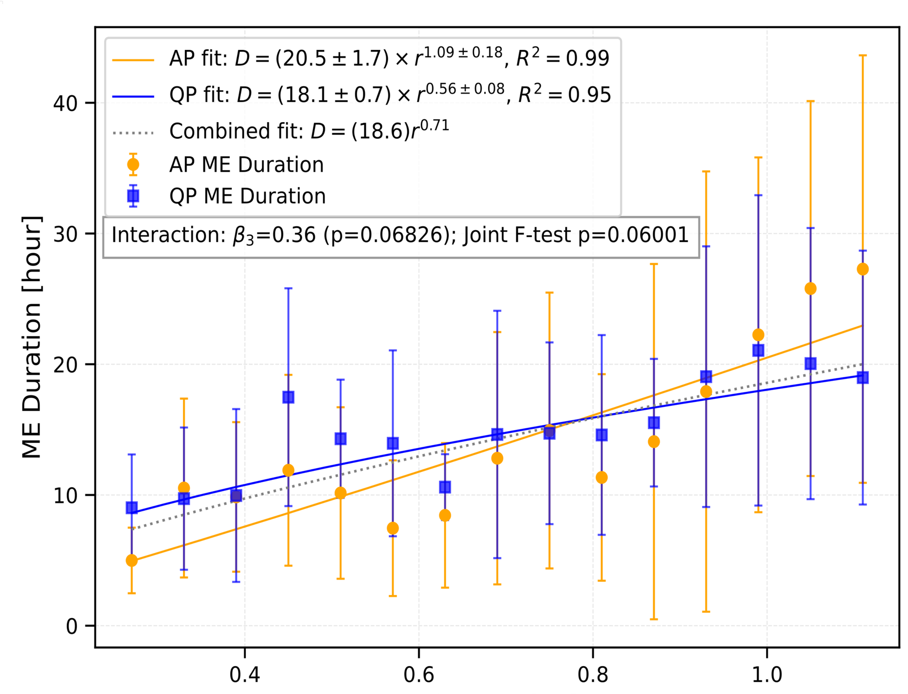


Figure 2: ME Duration in AP and QP vs Helio-Dist.

B_ME Evolution with distance & SC phase

Figures 3–5 show the radial evolution of the ME magnetic field for AP and QP CMEs, including the mean field (B_{ME}) front and rear field strengths, and the sheath-to-ME field ratio (B_{SH}/B_{ME}). The mean, front, and rear ME magnetic fields all decrease with heliocentric distance, consistent with progressive CME expansion during heliospheric propagation.

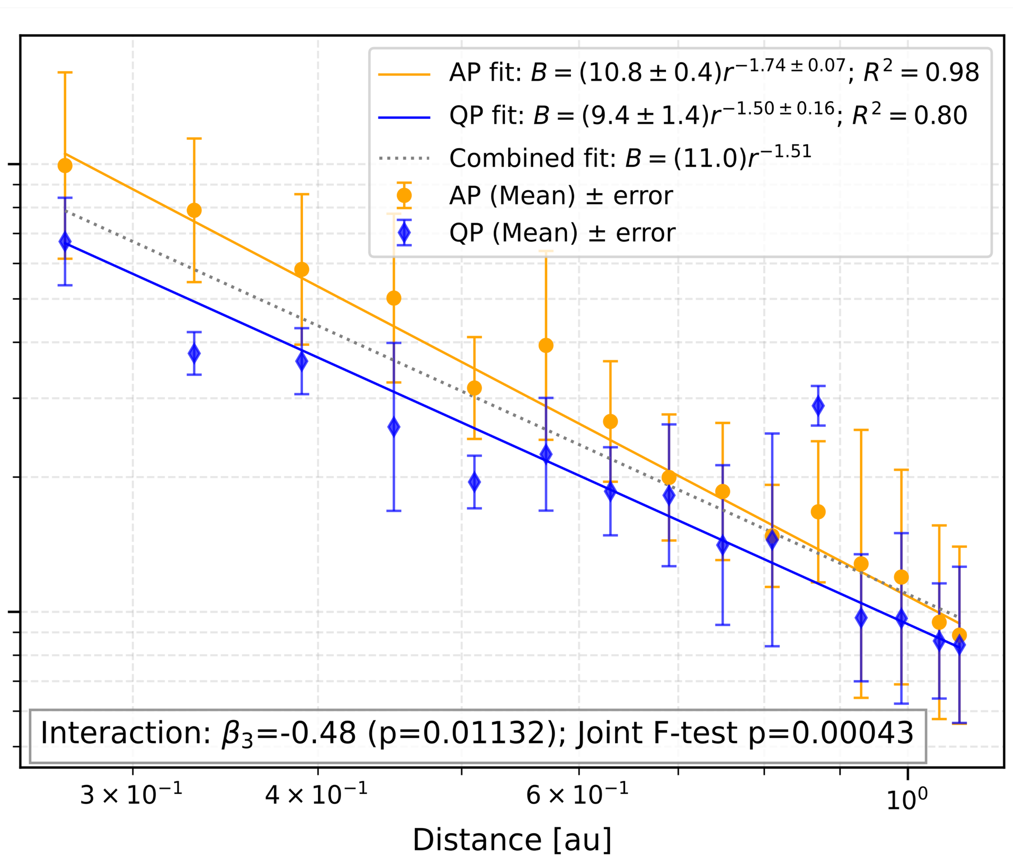


Figure 3: **B_ME** in AP and QP vs Helio-Dist.

- AP CMEs exhibit a steeper magnetic-field decay than QP CMEs in both the front and rear ME.
- The rear magnetic field decays faster than the front, suggesting continued evolution of CME internal structure.
- The AP and QP decay exponents are consistent with previously reported CME magnetic-field scaling laws, including: Yakub(2026): B ∝ $r^{-1.46}$, Good(2019) : B ∝ $r^{-1.78}$, Farrugia(2007) : B ∝ $r^{-1.73}$, Davies(2021) : B ∝ $r^{-1.68}$, Moestl(2026): B ∝ $r^{-1.57}$, Henneson(2020): B ∝ $r^{-1.51}$, Wang(2005): B ∝ $r^{-1.53}$
- The B_{SH}/B_{ME} remains close to **unity** throughout the observed heliocentric range, indicating that the sheath and magnetic ejecta (ME) maintain comparable magnetic field strengths during propagation.

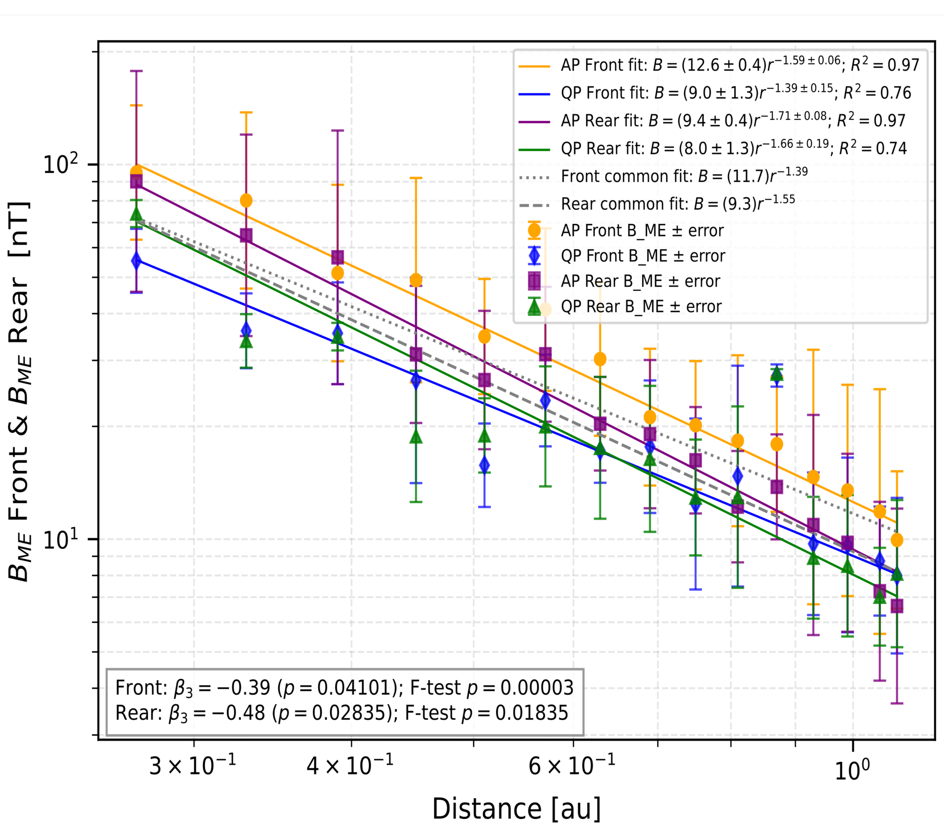


Figure 4: $\mathbf{B_{front}}$ **&** $\mathbf{B_{rear}}$ Duration in AP and QP vs Helio-Dist.

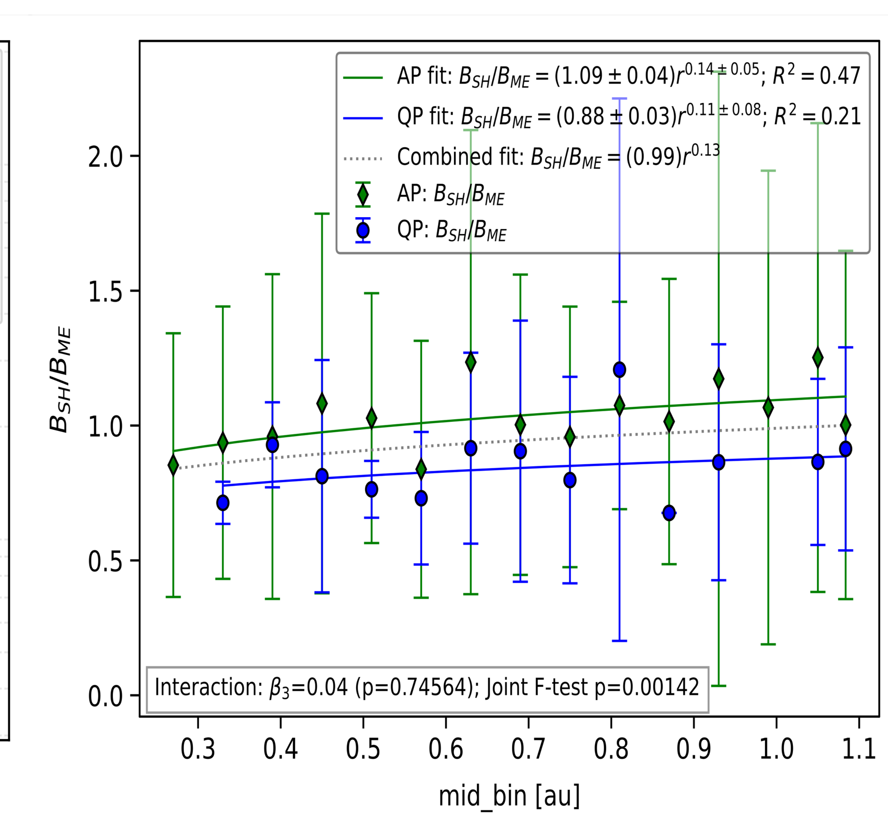


Figure 5: $\mathbf{B_{SH}/B_{ME}}$ in AP and QP vs Helio-Dist.

MVA Field components: Axial (Bj) and Poloidal (Bk) Field Evolution

The axial and poloidal magnetic field components; (|Bj| & (|Bk) decrease with heliocentric distance during AP and QP, which consistent with magnetic flux-rope expansion during propagation.

Their decay exponents are within the range of the reported results by previous studies such as: Yakub(2026) Bj ∝ $r^{-1.48}$, Wenyuan(2024): Bj_{front} ∝ $r^{-1.79}$, Bj_{rear} ∝ $r^{-1.79}$ and Yakub(2026) Bk ∝ $r^{-1.52}$. **The axial-field evolution remains largely independent of solar-cycle phase.**

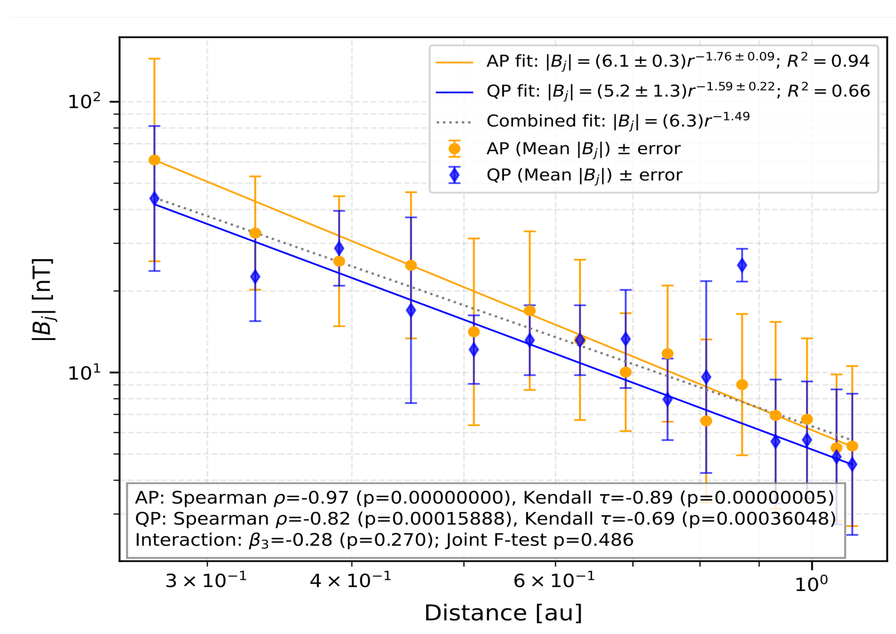


Figure 6: $|\mathbf{B_k}|$ in AP and QP vs Helio-Dist.

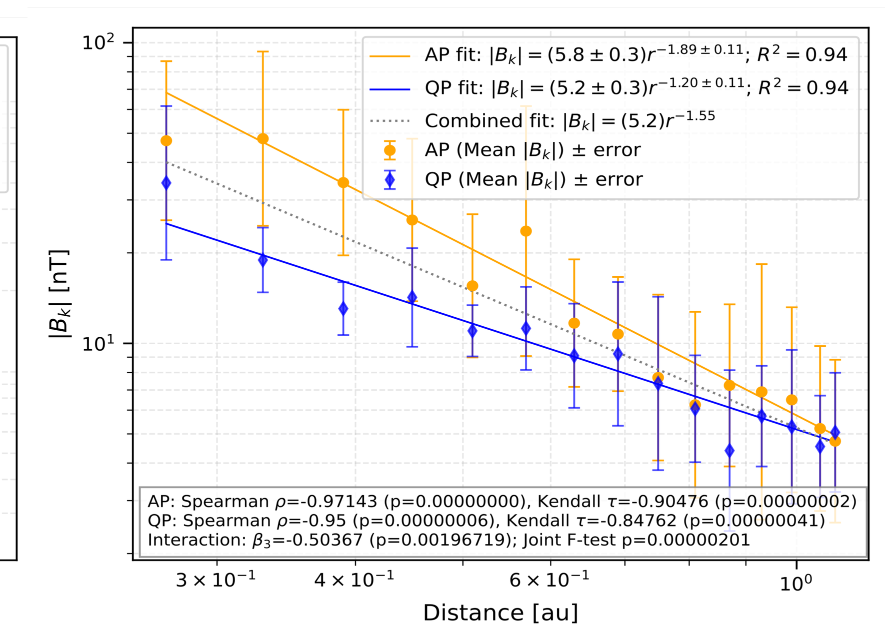


Figure 7: $|\mathbf{B_j}|$ in AP and QP vs Helio-Dist.

Plasma Parameter Evolution: Density (Np), Bulk Speed (Vp) & Expansion Speed (Vexp)

Here we look at how the plasma properties of CME in AP and QP vary over distance. Figure 7 presents the Np and Figures 8 and 9 are for bulk speed and the expansion speed as the events propagates and Figure 10 gives dimensionless expansion rate (ζ) evolution.

- Np decreases with heliocentric distance for both AP and QP CMEs.
- The QP density decay agrees with previously reported CME density scalings ($r^{-2.4}$) , whereas the shallower AP trend indicates that AP CMEs retain higher proton densities over larger heliocentric distance.
- The bulk velocity in AP CMEs remain faster (~ 450 km s^{-1}) than QP CMEs (~ 390 km s^{-1}) throughout heliospheric propagation. The weak AP deceleration and slight QP acceleration toward 1 AU are consistent with the ICME–solar-wind speed convergence reported by Jian(2018).
- The V_{exp} increases more rapidly with heliocentric distance in QP CMEs than in AP CMEs, implying that QP events experience stronger apparent expansion during propagation through the inner heliosphere.
- After normalizing for propagation speed, CME duration, and heliocentric distance, both AP and QP events exhibit similar values of ζ.

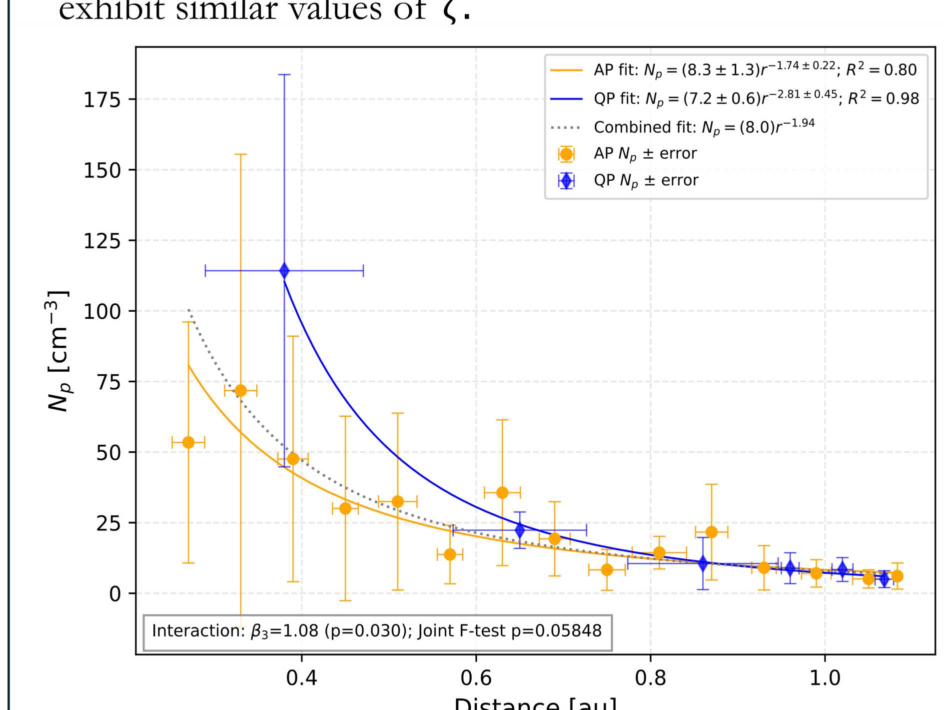


Figure 7: **Np** in AP and QP vs Helio-Dist.

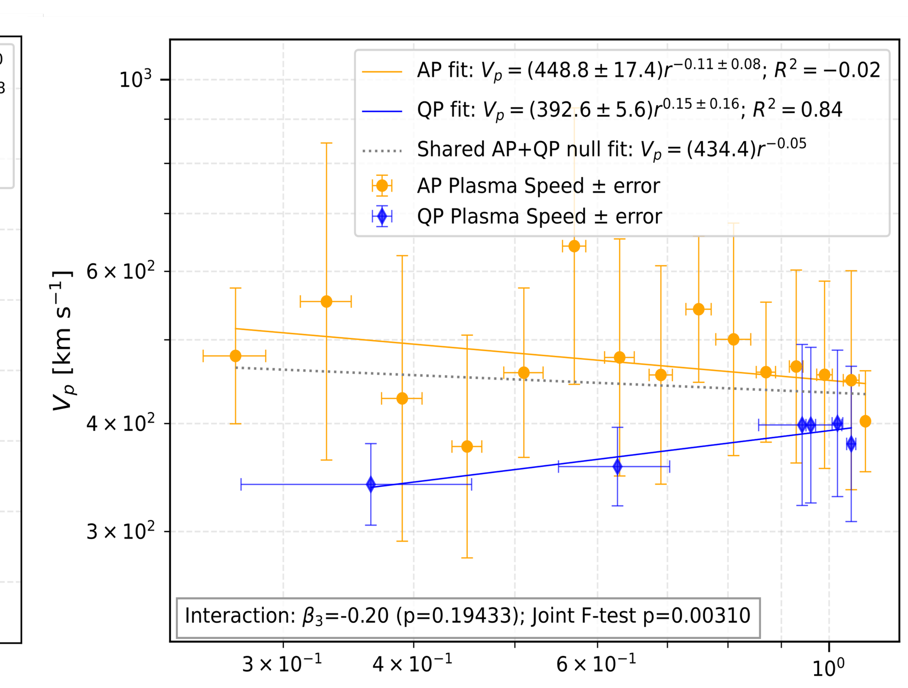


Figure 8: **Vp** in AP and QP vs Helio-Dist.

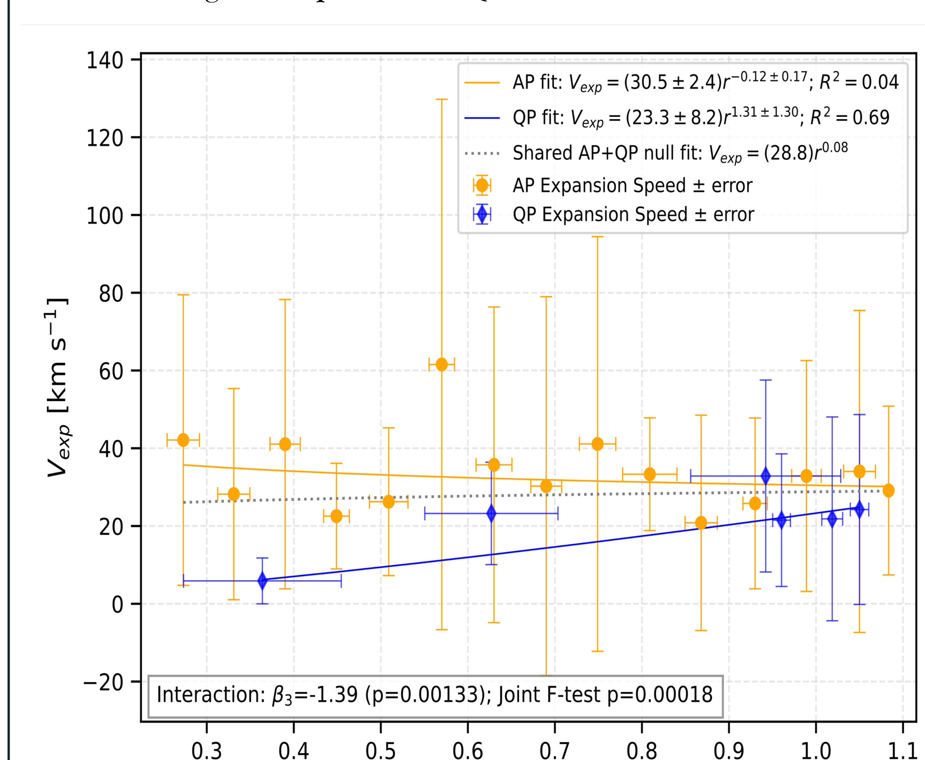


Figure 9: **Vexp** in AP and QP vs Helio-Dist.

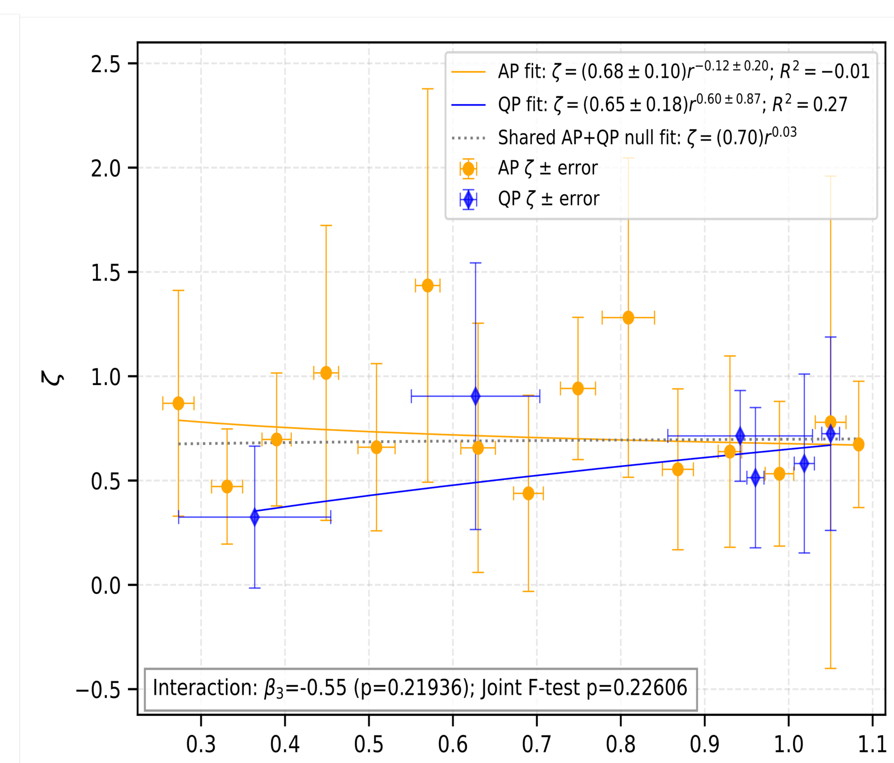


Figure 10: **Dimensionless Vexp Rate** in AP and QP vs Helio-Dist.

Study's Key Takeaways:

- Sheath and magnetic-ejecta durations increase with heliocentric distance; however, only for the ME, does it exhibit stronger appreciable solar-cycle dependence.
- Solar cycle phase influences not only the overall decay of CME magnetic field strength, but also the evolution of its internal magnetic structure, with AP CMEs exhibiting stronger magnetic field weakening throughout the ejecta.
- **The axial magnetic field (|** $\mathbf{B_j}$ **|) shows no significant solar-cycle dependence in its radial evolution, whereas the poloidal magnetic field (|** $\mathbf{B_k}$ **|) does, with AP CMEs exhibiting substantially faster field decay than QP CMEs.**
- AP and QP CMEs exhibit similar radial evolution of B_{SH}/B_{ME} , but AP events maintain consistently larger sheath-to-ME magnetic field ratios, indicating stronger sheath compression.

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