The Alpha-proton Differential Flow in the Alfvénic Young Solar Wind

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Questions we want to answer

- **How does the differential flow change with solar wind speed at Parker Solar Probe (PSP) encounter distances?**
- **How does the differential velocity vary across the critical Alfvén Surface (CAS)?**
- **What are the effects of Alfvénic fluctuations like switchbacks on the differential velocity?**

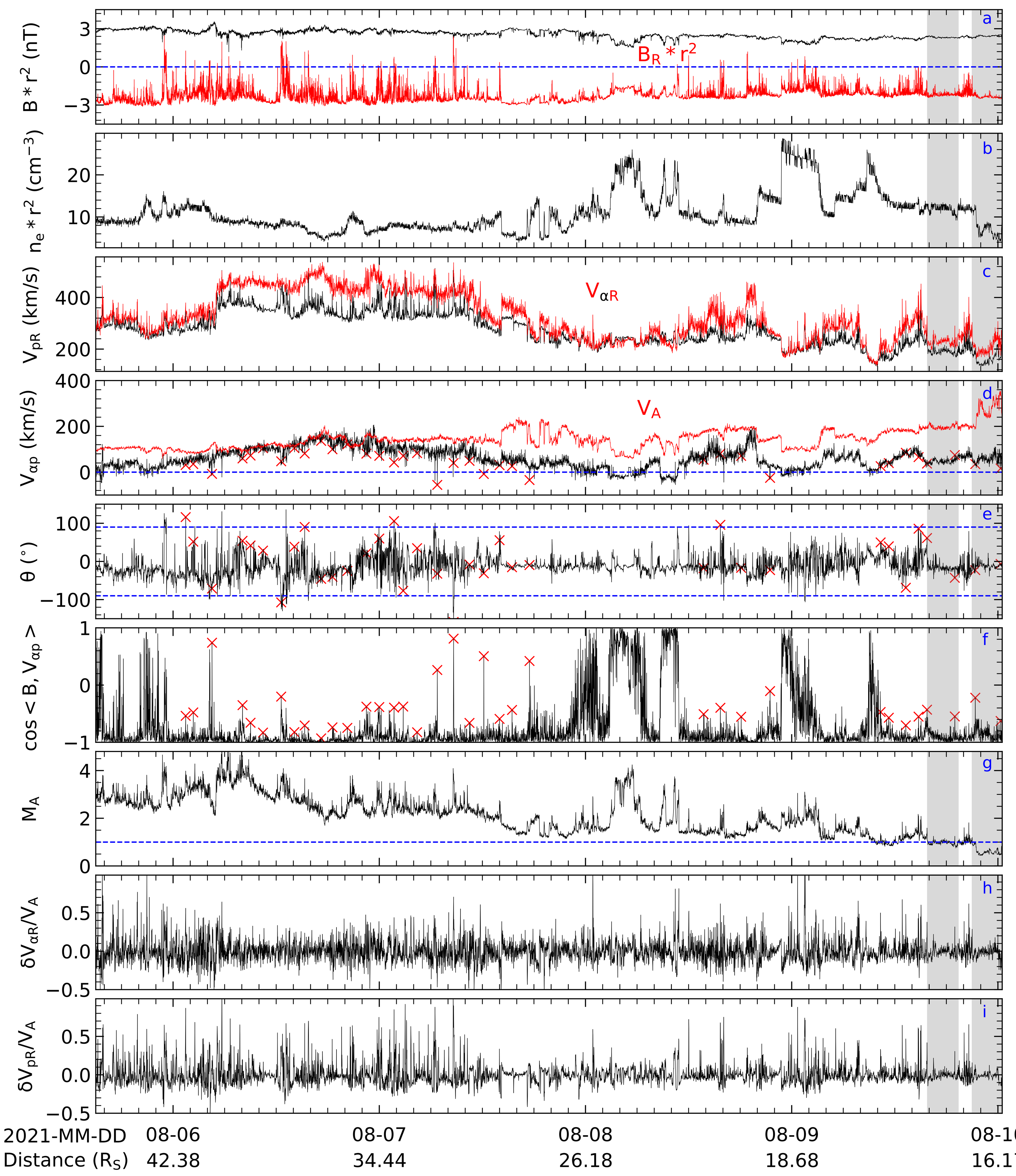
Background

- $V_{\alpha p}$ provides key insights into ion acceleration and heating in the solar wind.
- PSP offers the opportunity to study $V_{\alpha p}$ below the CAS.
- PSP has observed switchbacks near the Sun, and the impact of such structures at this distance on $V_{\alpha p}$ is worth further investigating.

Important Concepts

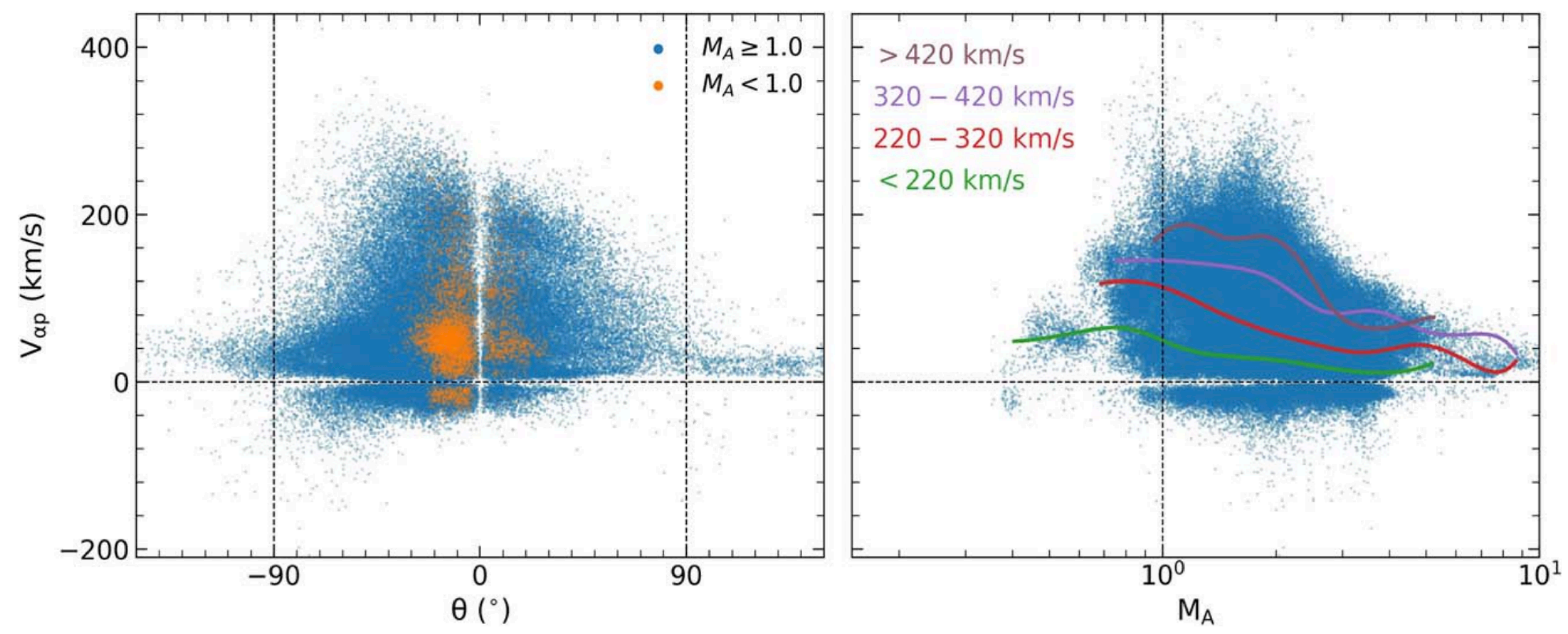
- $|V_{\alpha p}| = \mathrm{sign}(|V_\alpha| - |V_p|)|V_\alpha - V_p|$.
- **Low Mach-number Boundary Layer (LMBL)**: A region in the pristine solar wind with increased Alfvén radius and suppressed switchbacks, likely originating from the peripheral areas within an coronal hole where open magnetic fields rapidly diverge. Proposed by *Liu et al. (2023)*.

Key Findings



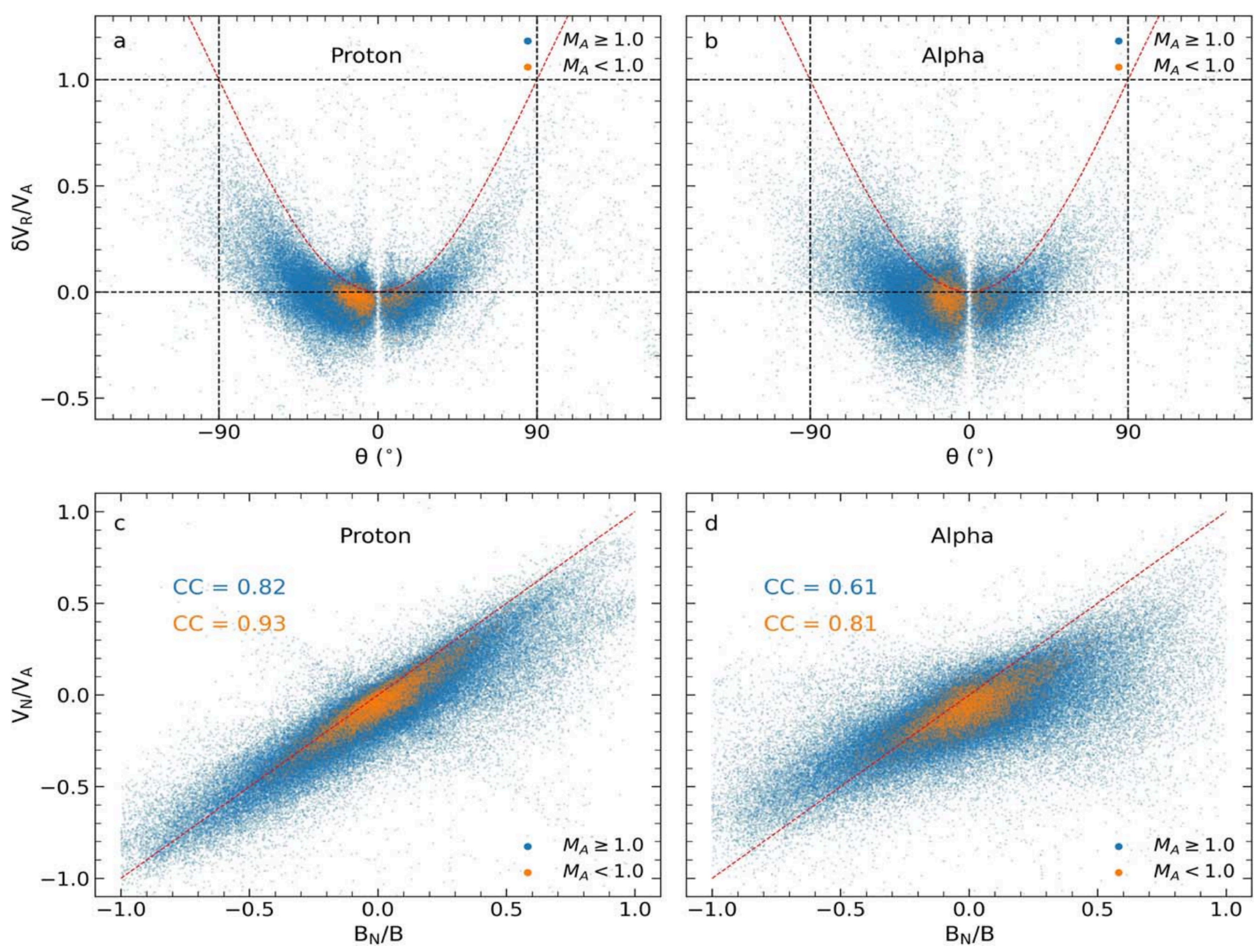
In situ measurements of Encounter 9.

- In fast solar wind, $V_{\alpha R} > V_{pR}$; in slow solar wind, $V_{\alpha R} \sim V_{pR}$.
- When $M_A < 1$, $V_{\alpha p}$ is **notable** even in slow solar wind (LMBL feature).
- Generally, $V_{\alpha p} < V_A$, and $V_{\alpha p}$ is aligned with **B**.
- **Deviations of the alignment** are related to **switchbacks** and **associated velocity fluctuations**.
- δV_{pR}: one-sided; $\delta V_{\alpha R}$: more two-sided. Alphas experience weaker modulation by Alfvénic waves.



Measurements of $V_{\alpha p}$ as functions of magnetic field deflection angle (left) and radial Alfvén Mach number (right).

- $V_{\alpha p}$ decreases with increasing $|\theta|$; and at a fixed M_A, it increases with V_{sw}.
- $M_A < 1$, θ is small. Existence of large $V_{\alpha p}$ in sub-Alfvénic solar wind suggests fast-wind-like features (LMBL).
- $V_p < 420$ km/s, $V_{\alpha p}$ increases below CAS and then decreases above the CAS. $V_p > 420$ km/s, this preferential acceleration extends above the CAS. Possible reasons: (1) **stronger and more diverse preferential acceleration of alpha particles in the fast solar wind**,(2) **Coulomb collision is more negligible in the fast solar wind**.



Effects of Alfvénic fluctuations on protons (left) and alphas (right).

Proton:

- Follow $dV_R/dV_A = 1 - \cos\theta$; $M_A < 1$: trend less evident.
- Strong correlation between B_N/B and V_N/V_A both below and above the CAS (CC = 0.93 and 0.82), indicating strong modulation by Alfvén fluctuations both in super(sub)-Alfvénic solar wind.

Alphas:

- Do not quite follow $dV_R/dV_A = 1 - \cos\theta$.
- Strong correlation between B_N/B and V_N/V_A below the CAS (0.81), indicating strong modulation. Weakened correlation above the CAS (0.61), isolated from Alfvénic waves.

Conclusion

- **Alphas generally stream faster than protons**, with $\mathbf{V_{\alpha p}}$ aligned with **B** and limited by V_A. In slower solar wind, alphas occasionally stream slower. As V_p increases, $V_{\alpha p}$ rises but stays below V_A.
- An overall $\mathbf{V_p}$ **enhancement when** $\mathbf{M_A \lesssim 2}$ is observed, indicating **strong alpha preferential acceleration in this region, especially in the fast solar wind.**
- Alfvénic fluctuations cause deviations from magnetic field alignment, large field deflections, and velocity drops. $M_A < 1$: These fluctuations strongly affect protons and alphas; $M_A > 1$: this affection weakens for alphas but remains strong for protons.

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