



Alpha-Proton Relative Drift: Implications for the Origins and Dynamics of the Solar Wind

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Received 2024 September 17; revised 2024 November 28; accepted 2024 December 12; published 2025 January 2

Abstract

Helium nuclei (alpha particles) strongly influence the momentum and energy balance in the solar wind, comprising up to 20% of the solar wind mass density. In fast Alfvénic wind at heliocentric distances greater than 0.3 au, the alpha particles' bulk flow speed is systematically different to that of the protons. This relative drift speed is of unknown origin and is often close to the local Alfvén wave speed. Novel Parker Solar Probe measurements of the solar wind below 0.3 au show that, closer to the Sun, the alpha-proton drift speed remains on the order of $100\text{--}200\text{ km s}^{-1}$, even where the Alfvén speed is greater than 600 km s^{-1} . This relative speed is quantitatively similar to oxygen-hydrogen drift speeds observed in the transition region by remote sensing, suggesting similar selective acceleration processes in the corona. Due to the relative speed of the Alfvén wave to each particle population close to the Sun, the alphas fluctuate with velocity amplitudes comparable to those of the protons, altering the energy balance of the wave. As a result, alpha particles carry a significant fraction of the total kinetic energy in Alfvénic fluctuations in the near-Sun solar wind. The alpha-proton drift speed is comparable to the proton speed in the near-Sun wind, making the bulk flow of the alpha particles a significant contribution to the kinetic energy flux. These heavy-ion dynamics provide new observational constraints on quantifying the energy budget of the solar wind and the magnetic field evolution through the heliosphere.

Unified Astronomy Thesaurus concepts: Fast solar wind (1872); Solar wind (1534); Solar physics (1476); Space plasmas (1544); Alfvén waves (23)

1. Introduction

The solar wind is formed by the continuous escape of plasma from the solar atmosphere, with abundant populations of protons and alpha particles, and trace amounts of heavier ions. The alpha particles form 1%–5% of the total number density of the solar wind, depending on multiple factors, resulting in a maximum of 20% of the total mass density (M. R. Aellig et al. 2001; J. C. Kasper et al. 2007). The alpha particles and heavier ions in the wind share similar bulk velocities (R. von Steiger et al. 1995), often traveling faster than the bulk proton velocity. This speed difference between the heavy ions and protons, the “ion drift,” is greater in solar wind with higher Alfvénic wave activity, often the faster wind (E. Marsch et al. 1982b; P. Mostafavi et al. 2022; H. Ran et al. 2024). While the origins of the drift are not yet known, the similar speeds of the heavy ions suggest selective acceleration processes dependent on mass to charge ratios in the origin of the solar wind, such as ion-cyclotron wave resonance (E. Marsch et al. 1982a; J. V. Hollweg & P. A. Isenberg 2002; J. A. Araneda et al. 2009; P. A. Isenberg & B. J. Vasquez 2009; V. L. Galinsky & V. I. Shevchenko 2012), Alfvénic turbulent heating (Y. Q. Hu et al. 2000; Y. G. Maneva et al. 2013; E. Marsch 2018), or reconnection (A. V. Artemyev et al. 2014; S. D. Bale et al. 2023; D. Duan et al. 2023).

The solar wind accelerates away from the Sun and displays a variety of bulk proton velocities: from $\sim 400\text{ km s}^{-1}$ in the slow wind to $\sim 700\text{ km s}^{-1}$ in the fast when measured near Earth (M. Neugebauer & C. W. Snyder 1962; S. R. Cranmer 2009; L. Abbo et al. 2016). Among other differences, the slow

wind emerges from a variety of locations on the solar surface (U. Feldman et al. 2005; D. Stansby et al. 2020) and is accelerated in large part by coronal pressure or electric potential (E. Leer et al. 1982; J. S. Halekas et al. 2022), while the fast typically is magnetically linked to coronal holes (R. Bruno & V. Carbone 2013; S. R. Cranmer et al. 2017) and is additionally accelerated by Alfvén wave/turbulent evolution and coronal reconnection though the relative contribution of each is unclear (J. S. Halekas et al. 2023; N. E. Raouafi et al. 2023a; Y. J. Rivera et al. 2024).

Alfvénic fluctuations are observed in the solar wind by the (anti)correlation of ion velocity and magnetic field fluctuations. These magnetic fluctuations are often observed to be noncompressive, with the local magnetic field strength not varying (eg. L. Matteini et al. 2015). The amplitude of the corresponding velocity fluctuations for each ion population depends on how quickly the wave travels in the rest frame of each (B. E. Goldstein et al. 1995; L. Matteini et al. 2015; M. D. McManus et al. 2022). In the rest frame of a cold plasma composed of ions traveling at the same speed (the single fluid approximation), as is typical of non-Alfvénic slow wind, these fluctuations propagate at the Alfvén speed, $v_A = \frac{B_0}{\sqrt{\mu_0 \rho}}$, in which B_0 is the background magnetic field strength, μ_0 is the vacuum permeability, and ρ is the total mass density.

It has long been known that in the Alfvénic fast wind beyond 0.3 au, the ions heavier than protons exhibit drifts in the local magnetic field direction, constrained by the Alfvén speed (E. Marsch et al. 1982b; B. E. Goldstein et al. 1995; S. P. Gary et al. 2000) due to the excitation of wave and particle anisotropic instabilities (E. Marsch & S. Livi 1987; S. P. Gary et al. 2000; D. Verscharen et al. 2013, 2015; L. Ofman et al. 2023). Due to this relative speed, the alphas and heavy ions often do not engage in the wave motions to the same extent as the protons (E. Marsch et al. 1982b; B. E. Goldstein et al. 1995;



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L. Matteini et al. 2015). When the drift speed is close to the Alfvén speed, the heavy ions “surf” the wave, experiencing little to no Alfvénic fluctuations.

Thanks to Parker Solar Probe (PSP; N. J. Fox et al. 2016), it is now possible to investigate the origins and evolution of the alpha drift using in situ measurements at distances as close as $10 R_{\odot}$. Earlier works on characterizing the alpha drift at these distances have focused on comparison between solar wind speeds (P. Mostafavi et al. 2022; H. Ran et al. 2024). In this work, we consider only the evolution of the fast wind to investigate the state and consequences of the alpha drift in the near-Sun environment.

2. Data

Analyzing Encounters 10–16, we use Solar Probe Analyzer for Ions (SPAN-I) moments (J. C. Kasper et al. 2016; R. Livi et al. 2022) for particle data, and FIELDS MAG data (S. D. Bale et al. 2016) downsampled to the SPAN data frequency for measurements of the magnetic field. Due to the constraints of the instrument placement on the spacecraft, SPAN-I does not always fully observe the velocity distribution of the solar wind in the solar equatorial plane. As a result, SPAN-I can provide spurious observations of the plasma density, and we use the FIELDS Radio Frequency Spectrometer Quasi-Thermal Noise (M. Pulupa et al. 2017; M. Moncuquet et al. 2020) measurements of the electron number density as an approximation of the solar wind density in order to calculate a local Alfvén speed, $v_A = B_0 / \sqrt{\mu_0 \sum_i n_i m_i} \approx B_0 / \sqrt{\mu_0 n_e m_p}$. In the same manner as P. Mostafavi et al. (2022) and H. Ran et al. (2024), we select only data with a resolvable maximum in the angular distribution of the SPAN-I instrument.

We compare the PSP data to Solar Orbiter (S. Müller et al. 2013) data at solar distances greater than $70 R_{\odot}$. We fit two peaks to Solar Wind Analyzer Proton and Alpha Particle Sensor (SWA PAS) energy flux distributions (C. J. Owen et al. 2020) to estimate the radial proton and alpha speeds and use the observations of the Solar Orbiter Magnetometer instrument (T. S. Horbury et al. 2020) with the SWA PAS number density moments to provide an estimate of the local Alfvén speed.

We calculate the local Alfvén speed using the 20 minute rolling average of the background magnetic field and plasma density. While several methods have historically been used to estimate the drift speed, we use $|v_{\alpha p}| = |v_{\alpha} - v_p|$ as the fast wind exhibits almost entirely outward-accelerated alpha particles (E. Marsch et al. 1982b; P. Mostafavi et al. 2022).

Recently, the acceleration of the solar wind has been empirically characterized for a range of distances spanning from the outer corona to the termination shock by B. A. Maruca et al. (2023). They found that for distances less than 0.7 au, the radial evolution of the wind speed was fit by the power law $v_p \propto R^{0.157 \pm 0.071}$. As the solar wind at PSP perihelia has yet to accelerate to the speeds observed at Solar Orbiter or Earth, we use this power law to differentiate between the fast and slow winds at PSP and Solar Orbiter in a self-consistent manner. We fit the power law to measurements by PSP using fast (slow) wind speeds of >600 (<300) km s^{-1} at Earth, which is not significantly slower than known values (U. Feldman et al. 2005). To consider just the Alfvénic solar wind, we choose time periods for which the correlation coefficient between velocity and magnetic field fluctuations for the proton population is greater than 0.7.

3. Results

3.1. Encounter 15

The evolution of the solar wind can be observed distinctly in the comparison between PSP and Solar Orbiter observations during radial lineups of the two spacecraft (R. Laker et al. 2021; D. Telloni 2023). The two spacecraft sample the same streams of Alfvénic wind during 2023 March 15–20, after the PSP perihelion during Encounter 15. The time series data for this lineup are shown in Figure 1. Due to the speed of PSP at perihelion, the spacecraft exhibits an apparent counter-rotation relative to Solar Orbiter when viewed from the surface of the Sun. This causes Solar Orbiter to cross the structure in the reverse order of PSP.

The decrease of the magnetic field magnitude and fluctuation amplitude is evident between PSP within $25 R_{\odot}$ and Solar Orbiter beyond $110 R_{\odot}$ in the top row of Figure 1. The acceleration of the solar wind is similarly visible in the second row of Figure 1, with slow wind accelerating from 200 to 350 km s^{-1} and fast wind from >400 to $>500 \text{ km s}^{-1}$. The darker line segments in plots on the left of the figure highlight the data selected as fast wind at PSP, which are used in this analysis.

The bottom two rows of Figure 1 show comparisons of the alpha drift and the Alfvén speed. As the Solar Orbiter data are energy flux values, the resulting speed fits are aligned to the radial direction. In order to lessen the effect of switchbacks and fluctuations, on the right of Figure 1(c) we plot the 1 hr median value of the alpha drift divided by $\cos(\theta_{BR})$, where θ_{BR} is the magnetic field angle to the radial direction, and Alfvén speed for these data. The data show the decrease in Alfvén speed from greater than 200 km s^{-1} at PSP to under 100 km s^{-1} at Solar Orbiter. The alpha drift speed is then constrained due to the Alfvén speed, showing the greatest difference in the fast wind stream measured by PSP during March 18 00:00–06:00 and by Solar Orbiter during March 19. The ratio of the alpha drift to the Alfvén speed in Figure 1(d) reflects this constraint, rising from around 0.5 at PSP to unity at Solar Orbiter. The radial evolution of the alpha drift compared to the Alfvén speed is the focus of this study.

3.2. Radial Scaling

Figure 2 plots the observed radial evolution of the alpha drift and the local Alfvén speed for fast Alfvénic wind during Encounters 10–16. Due to the field-of-view constraints on PSP plasma measurements, the alpha drift statistics at distances greater than $30 R_{\odot}$ are based on limited data. We only plot radial bins with more than 10 data points to avoid spurious points. The average drift speed measured at $50 R_{\odot}$ is consistent with the maximum alpha drift speeds observed previously at 0.3 au by the Helios probes, around 150 km s^{-1} (E. Marsch et al. 1982b), marked by a horizontal line in Figure 2.

The evolution of the Alfvén speed is in line with the expected radial trend for a radial magnetic field of $\frac{1}{R}$, shown by the dotted line (M. Velli et al. 1991; J. Squire et al. 2020). Interestingly, at solar distances below $22 R_{\odot}$, the average speed of the alpha drift remains on the order of $100\text{--}200 \text{ km s}^{-1}$, while the Alfvén speed increases significantly. The radial evolution of the alpha drift seems uncoupled from that of the Alfvén speed within $50 R_{\odot}$.

By directly comparing the alpha drift speed against the local Alfvén speed, we normalize the comparison between different

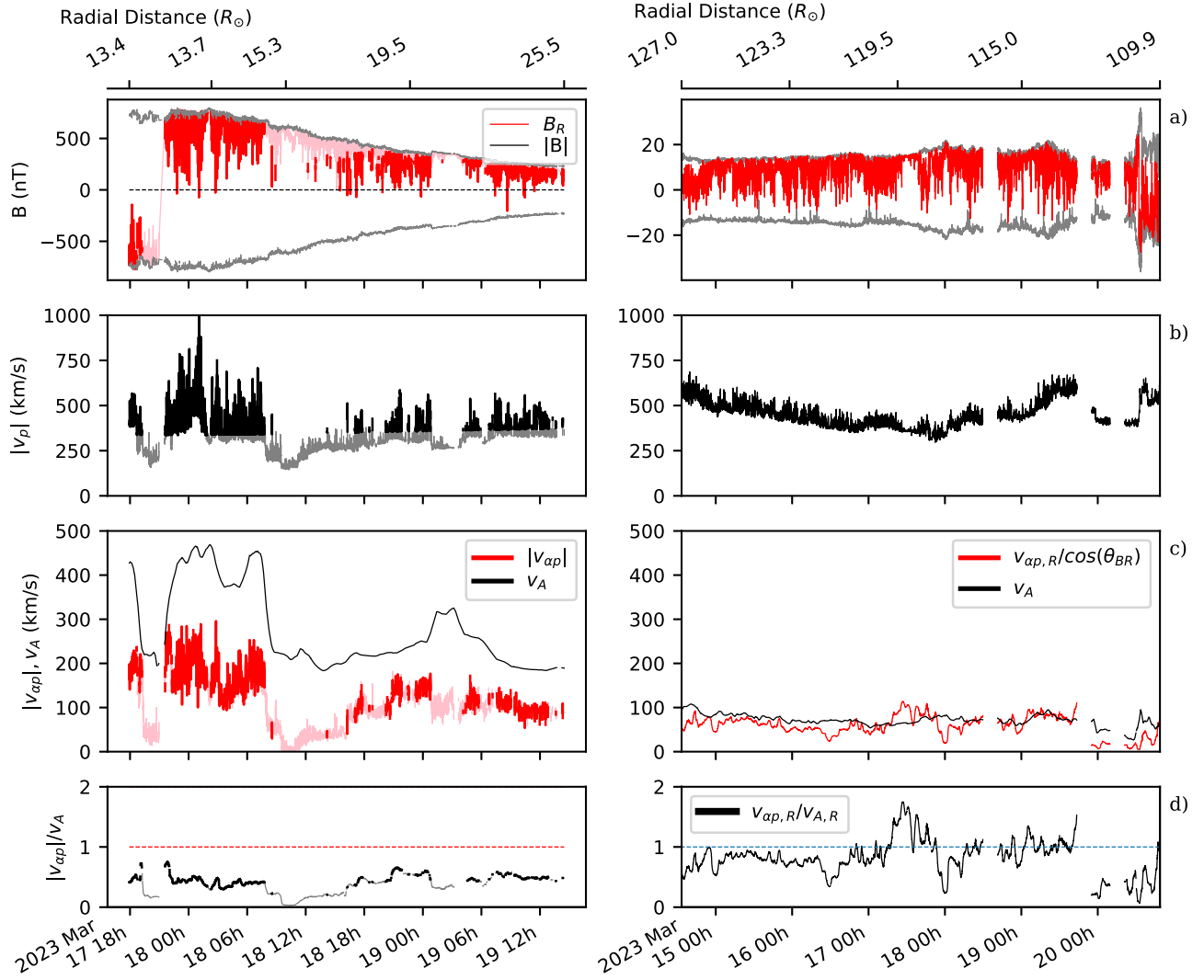


Figure 1. Magnetic field and particle time series data at PSP (left) and at Solar Orbiter (right) during a radial lineup in 23 March. Row (a) shows magnetic field measurements (magnitude and radial component). Row (b) shows proton speed. Row (c) shows alpha drift and Alfvén speed, and row (d) shows ratio of alpha drift speed to Alfvén speed. Lines are bold during the times that fit the Alfvénic fast wind condition at PSP and are therefore included in the analysis.

streams of fast wind over multiple perihelia. To account for the variation in a number of samples at different Alfvén speeds, Figure 3 plots and compares the 1D histograms of alpha drift speed, such that the color is normalized by the number of samples of the modal drift speed observed at a given Alfvén speed.

It can be seen that the alpha drift speed diverges from the Alfvén speed, from around 100 km s^{-1} . There appears to be a slight upward gradient at higher Alfvén speeds, which suggests a decrease of the alpha drift with distance. We can firmly state that at PSP perihelia, the alpha–proton drift is not yet limited by the Alfvén speed in the fast wind.

3.3. Wave Dynamics

When alpha particles do not drift at the Alfvén speed, they can no longer be assumed to surf the wave. We consider the comparison of the velocity fluctuation amplitudes of the alphas with the protons as a marker for the partition of the kinetic energy between the particle species and attempt to understand the interaction of the Alfvén wave with both populations in the manner described by B. E. Goldstein et al. (1995) and L. Matteini et al. (2015).

The phase speed of the wave relative to the i th population can be found using the correlation between the velocity fluctuations of that population, δv_i , and the magnetic field fluctuations, $\delta \mathbf{B}$, with a factor B_0 , the background magnetic field strength:

$$v_{\text{ph},i} = \mp \frac{\delta v_i}{\delta \mathbf{B}} B_0. \quad (1)$$

Applied to the alpha and proton populations, subscript α and p , respectively,

$$\frac{\delta v_p}{v_{\text{ph},p}} = \frac{\delta v_\alpha}{v_{\text{ph},\alpha}} = \mp \frac{\delta \mathbf{B}}{B_0}. \quad (2)$$

Due to the noncompressive nature of the wave, $\delta \mathbf{B}$ is confined to a sphere of constant radius, B_0 , shown by the bottom circle of Figure 4. This causes concentric spheres in velocity space for the ion populations, offset from the origin in the Sun's frame due to their initial velocities in the solar wind. As the radius of each sphere is the phase speed of the wave relative to each population, the shared central velocity is that of the wave's propagation. The spherical polarization of the wave suggests the de

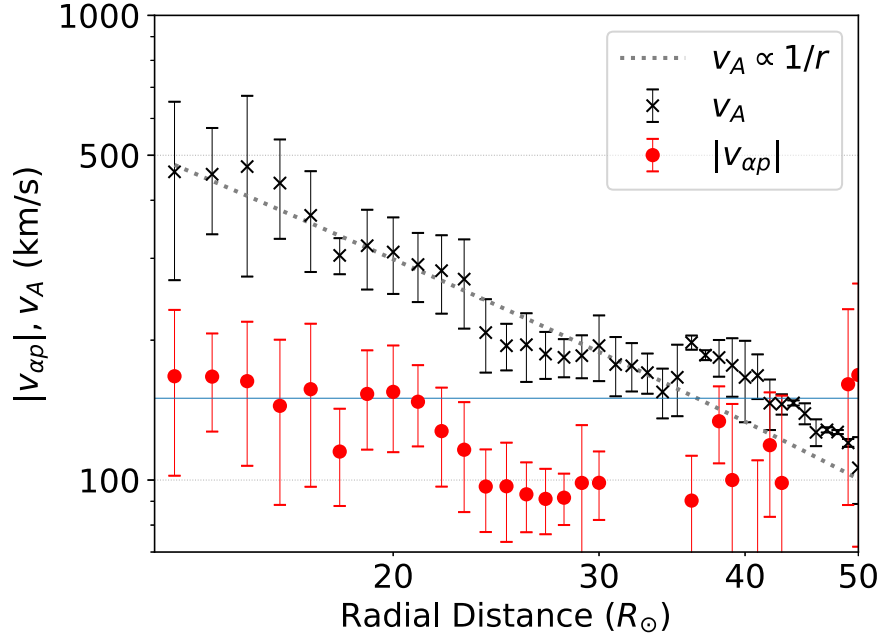


Figure 2. A log–log plot of radially binned means and standard deviations of the Alfvén speed and alpha drift speed in the Alfvénic fast wind. The dotted line shows a $1/R$ trend for the Alfvén speed, and the straight blue line marks 150 km s^{-1} .

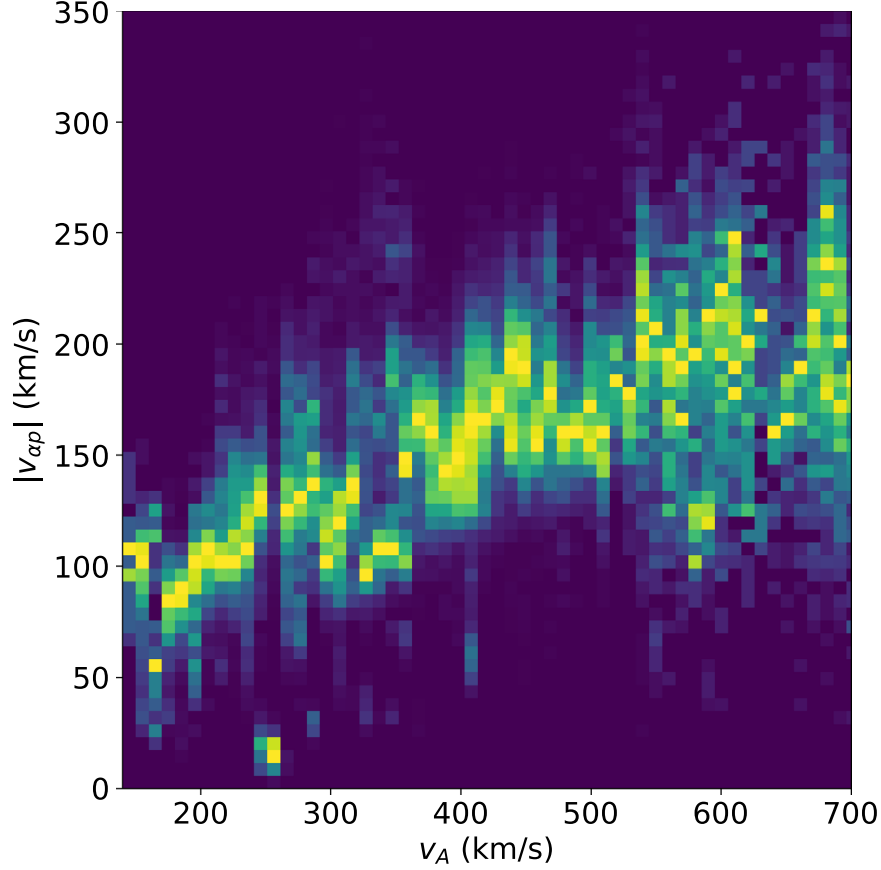


Figure 3. 1D histograms comparing alpha drift and Alfvén speed, colors normalized in vertical columns.

Hoffmann–Teller frame, defined with no motional electric field, as an obvious candidate for the frame of the wave itself (L. Matteini et al. 2015; Z. Němeček et al. 2020; M. D. McManus et al. 2022).

As the alphas are accelerated antisunward along the local magnetic field (the same direction as the wave propagation), $v_{\text{ph},\alpha} = v_{\text{ph},p} - |v_{\alpha p}|$. Thus, the drift speed and the wave’s phase speed constrain the relative amplitudes between the two ion

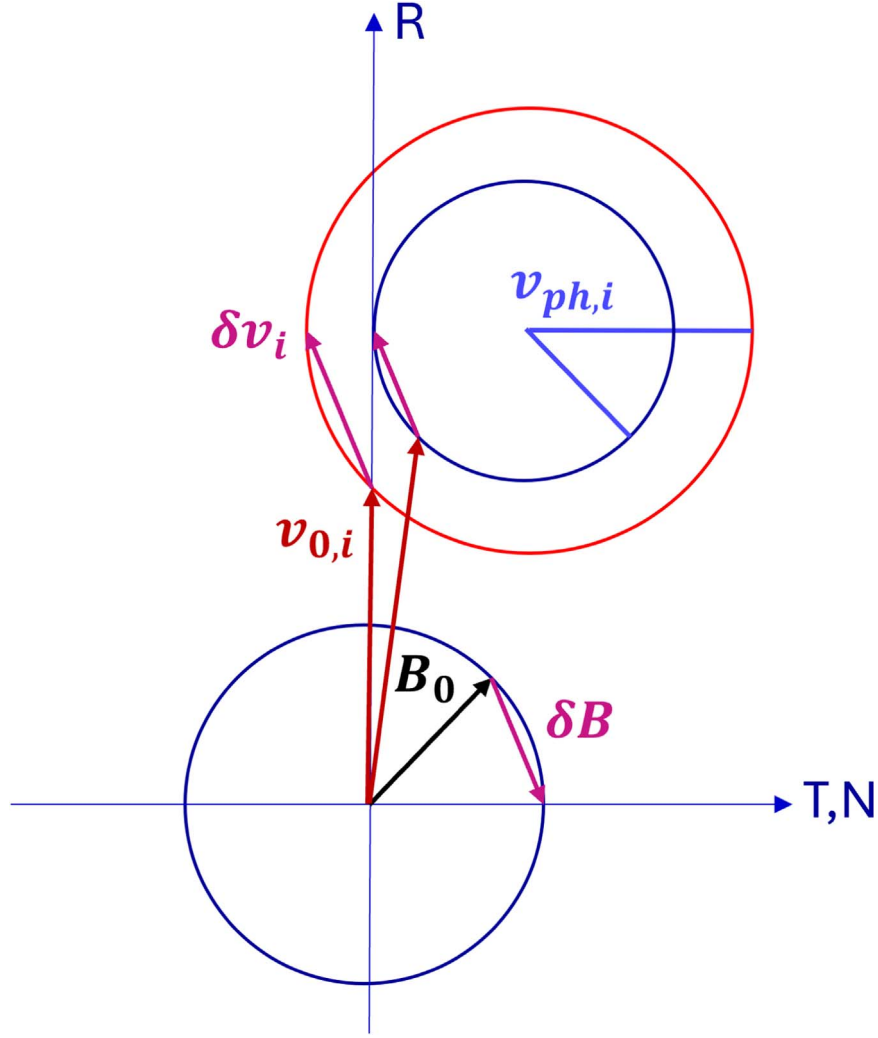


Figure 4. Velocity variations for multiple species due to an Alfvén wave. Vectors for background (subscript 0) and wave magnetic field and velocity directions have been drawn, with circles representing the spherically polarized velocity fluctuations and magnetic field.

populations:

$$\frac{\delta v_\alpha}{\delta v_p} = \frac{v_{ph,p} - |v_{\alpha p}|}{v_{ph,p}}. \quad (3)$$

Fluctuation amplitudes are found from the data by taking the 20 minute rolling standard deviation of the velocities, σ , in the N direction of the RTN heliocentric coordinate system. The 20 minute timescale is long enough to examine large-amplitude Alfvén waves without significant risk of mixing wind streams of different origins (e.g., J. S. Halekas et al. 2023). Due to a lack of reliable fluctuation data far from the Sun, we limit the following analysis to distances below $30 R_\odot$.

Studying the evolution of velocity fluctuations in Figure 5(a), we find the alpha and proton populations oscillating with similar amplitudes close to the Sun. This is in contrast to further distances at which the alpha populations surf the wave, experiencing oscillation amplitudes much smaller than those of the protons. The proton velocity fluctuation amplitude increases from 40 to 100 km s^{-1} along a radial trend of $R^{-1.0}$, plotted by the red dashed line. This trend is steeper than the $R^{-0.5}$ expected from the Wentzel, Kramers, and Brillouin approximation of Alfvénic fluctuations (M. Velli et al. 1991; R. Grappin & M. Velli 1996; J. Squire et al. 2020), due in part to the timescale (20 minutes) for

the variance measurement. The steepening of the radial trend at shorter timescales is discussed regarding the magnetic variances by A. Tenerani et al. (2021). The alphas' amplitude increase is controlled both by the radial evolution of the Alfvén wave amplitude and the speed of the alpha population relative to the wave. As a result, the radial trend fitted is not indicative of a single physical process.

Figure 5(b) shows the radially binned means of the ratio of velocity fluctuation amplitudes between the alphas and protons. We expect the relative amplitudes to tend asymptotically to unity near the Sun, where $v_{\alpha p} \ll v_{ph,p} \approx v_{ph,\alpha} \approx v_A$, and this seems to be the case within $17 R_\odot$. The downward trend of the alpha fluctuation amplitude signals the evolution toward surfing the wave at greater distances from the Sun.

4. Discussion

4.1. Origins of the Drift

We found that the alpha–proton drift is not controlled by the Alfvén speed in Alfvénic fast solar wind at small heliocentric distances, in contrast to the surfing observed at greater distances. The unconstrained drift speed is on the order of $100\text{--}200 \text{ km s}^{-1}$ with a mean of 170 km s^{-1} at $13 R_\odot$, which is quantitatively similar to observations of oxygen ion drift near

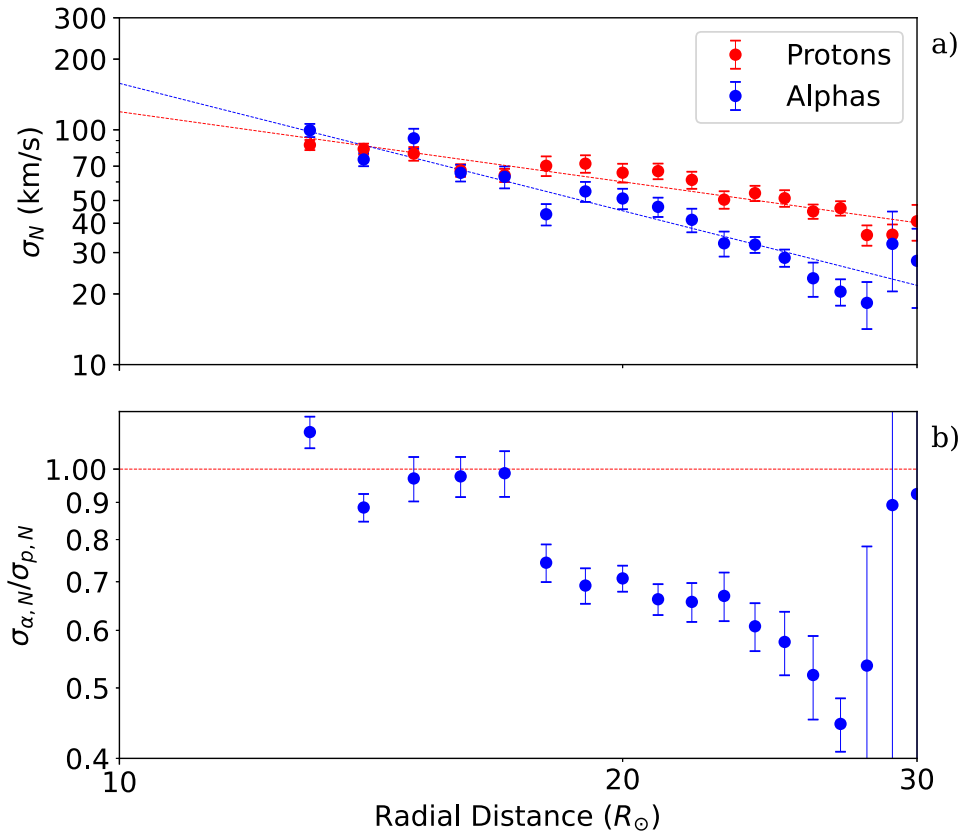


Figure 5. Radially binned means and standard errors of (a) the rms velocity fluctuation amplitudes of the proton and alpha populations and (b) the ratio of alpha fluctuation amplitudes to proton amplitudes.

the transition region from SOHO UVCS (S. R. Cranmer et al. 1998). It seems likely that all heavy ions experience an initial additional acceleration in the low corona compared to the protons, and the resulting speed difference is either maintained or coincidentally recovered by the time the ions are constrained by the decelerating Alfvén speed.

The initial acceleration of the ion drift may be due to reconnection events (A. V. Artemyev et al. 2014; S. D. Bale et al. 2023; D. Duan et al. 2023), which are predicted to accelerate the heavy ions preferentially, though the exact accelerated values are highly dependent on different resonant processes. Indeed, S. D. Bale et al. (2023) and N. E. Raouafi et al. (2023b) have found strong evidence for the significance of reconnection jetting accelerating the fast solar wind in the low corona, with observed proton jets at $\sim 150 \text{ km s}^{-1}$. S. D. Bale et al. (2023) noted that signatures of this reconnection acceleration are visible in the alpha particle distributions at PSP during Encounter 10.

The dependence of the alpha-proton drift speed on Alfvén speed measured by PSP in Figure 3 may be related to processes occurring during the evolution of each fast wind stream. Treating the Alfvén speed as decreasing monotonically away from the Sun for any given stream, the positive correlation then suggests that the ion drift decreases as the solar wind propagates away from the Sun.

Between 13 and 20 $R_{\odot}$, the drift speed causes an additional bulk kinetic energy flux contribution from the alphas as large as 40% that of the protons, with a mass flux of the alphas equal to 20% that of the protons. This has at least two possible

consequences. First, the alpha drift could contribute to the heating of the solar wind as the decreasing Alfvén speed constrains the alpha drift speed, exciting the fast-magnetosonic/whistler and Alfvén/ion-cyclotron instabilities (e.g., S. P. Gary et al. 2000; D. Verscharen & B. D. G. Chandran 2013; D. Verscharen et al. 2015). Second, the decrease of the alpha drift with distance could also result in an acceleration of the proton population due to momentum conservation (e.g., D. Verscharen et al. 2015). The observations presented here on where and at which speeds the heavy ions are constrained by the instabilities related to the Alfvén speed may aid in modeling the total energy flux budget of the fast solar wind.

4.2. Evolution of the Alfvén Wave

In this work, we showed that the velocity fluctuation amplitude of the alpha particles is already similar to that of the protons in the young solar wind at 13 $R_{\odot}$ from the Sun (see Figure 5) due to the relative speed of each species with respect to the Alfvén wave. These observations in turn demonstrate the significance of the alpha particles in the fluctuating kinetic energy balance of the Alfvén wave and highlight the importance of the application of multifluid theory in the near-Sun solar wind (E. Marsch & D. Verscharen 2011; L. Matteini et al. 2015).

The Alfvén wave energy flux is estimated to contribute 20%–40% of the total energy flux in the young fast solar wind, which leads to the acceleration and heating of the fast wind through turbulent dissipation and mechanical processes

(J. S. Halekas et al. 2023; Y. J. Rivera et al. 2024). The increased velocity amplitudes experienced by the heavy ions contribute kinetic energy in the Alfvénic fluctuations according to their proportional mass density (up to 20%). As a result, we expect the alpha particles and heavy ions to contribute significantly in the energy partition of the Alfvén wave within $13 R_{\odot}$. This contribution will need to be taken into account when modeling the evolution of Alfvén waves from the Sun's corona to the solar wind.

5. Summary

This work has examined the alpha-proton drift on a large scale using PSP Encounters 10 through 16. The drift speed was found to be on the order of $150 \pm 50 \text{ km s}^{-1}$, uninhibited by the Alfvén wave speed in the fast solar wind at PSP perihelia. The difference between the drift speed and the Alfvén wave speed causes the proton and alpha fluctuation amplitudes to become similar within $30 R_{\odot}$. Due to the drift speed, alpha particles contribute significant kinetic energy to both the bulk motion and Alfvénic fluctuations of the young fast solar wind. Further analyses of energy and Alfvénic motion in the inner heliosphere discussed should not neglect the heavy ions.

Acknowledgments

The PSP data used here are publicly available on NASA CDAWeb, <https://cdaweb.gsfc.nasa.gov/index.html/>, and the Solar Orbiter data are available on the ESA Solar Orbiter Archive, <https://soar.esac.esa.int/soar/>. Parker Solar Probe was designed, built, and is now operated by the Johns Hopkins Applied Physics Laboratory as part of NASA's Living with a Star (LWS) program (contract NNN06AA01C). Solar Orbiter is a space mission of international collaboration between ESA and NASA, operated by ESA. Solar Orbiter magnetometer operations are funded by the UK Space Agency (grant ST/T001062/1).

This work is supported by the Science and Technology Facilities council (STFC) of the UK under studentship ST/X508433/1 and grants ST/X002098/1 and ST/W001071/1. This study has received funding from the European Unions Horizon 2020 research and innovation program under grant agreement No. 101004159 (SERPENTINE, <http://www.serpentine-h2020.eu>). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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