



Characterizing the Impact of Alfvén Wave Forcing in Interplanetary Space on the Distribution of Near-Earth Solar Wind Speeds

B. L. Alterman

Heliophysics Science Division, NASA, Goddard Space Flight Center, Greenbelt, MD 20771, USA; b.l.alterman@nasa.gov

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Abstract

Broadly, solar wind source regions can be classified by their magnetic topology as intermittently and continuously open to the heliosphere. Early models of solar wind acceleration do not account for the fastest, nontransient solar wind speeds observed near-Earth, and energy must be deposited into the solar wind after it leaves the Sun. Alfvén wave energy deposition and thermal pressure gradients are likely candidates, and the relative contribution of each acceleration mechanism likely depends on the source region. Although solar wind speed is a rough proxy for solar wind source region, it cannot unambiguously identify source region topology. Using near-Sun observations of the solar wind’s kinetic energy flux, we predict the expected kinetic energy flux near Earth. This predicted kinetic energy flux corresponds to the range of solar wind speeds observed in the fast solar wind and we infer that the solar wind’s near-Sun kinetic energy flux is sufficient to predict the distribution of the fastest, nontransient speeds observed near Earth. Applying a recently developed model of solar wind evolution in the inner heliosphere, we suggest that the acceleration required to generate this distribution of the fastest, nontransient speeds is likely due to the continuous deposition of energy by Alfvén wave forcing during the solar wind’s propagation through interplanetary space. We infer that the solar wind’s Alfvénicity can statistically map near-Earth observations to their source regions because the Alfvén wave forcing that the solar wind experiences in transit is a consequence of the source region topology.

Unified Astronomy Thesaurus concepts: Fast solar wind (1872); Alfvén waves (23); Interplanetary particle acceleration (826)

1. Introduction

The solar wind is a stream of charged particles that continuously leaves the Sun. In 1957, L. Biermann (1957) first observed it from observations of comet tails. The following year, E. N. Parker (1958) showed that the solar wind is necessarily supersonic and that its speed transitions from subsonic to supersonic by converting thermal energy to kinetic energy at distances of $\sim 5 R_S$, where R_S is the Sun’s radius. This distance is often referred to as the “sonic point.” This supersonic transition is necessary for the solar wind to obtain the minimum speed required to escape the Sun’s gravitational pull (E. N. Parker 1958; N. Meyer-Vernet 2007). However, the mechanism that converts the solar plasma’s thermal energy into kinetic energy does not provide sufficient energy for the solar wind to reach the asymptotic, fastest, nontransient speeds observed near Earth. Additional energy must be deposited into the solar wind above the sonic point for it to reach the asymptotically fastest, nontransient speeds observed near Earth (E. Leer & T. E. Holzer 1980; T. E. Holzer & E. Leer 1980, 1981; V. H. Hansteen & M. Velli 2012; C. P. Johnstone et al. 2015).

Detailed analysis of the solar wind in the inner heliosphere and near Earth show that slow and fast speed winds have distinct properties. For example, the wave modes carried by the plasma also differ in fast and slow winds (E. Marsch & C.-Y. Y. Tu 1990). In fast wind, fluctuations in the components of the solar wind velocity and magnetic field are highly correlated, while fluctuations in the plasma density and magnetic field magnitude are minimal (J. W. Belcher et al. 1969; J. W. Belcher & L. Davis 1971), as is

typical of Alfvénic fluctuations (H. Alfvén 1942, 1943). In slow wind, compressive fluctuations are also often observed. Non-thermal features like helium and heavy ion temperatures in excess of mass proportionality with hydrogen ($T_s/T_H > m_s/m_H$) and speeds along the magnetic field in excess of hydrogen are often observed in fast wind but are absent in slow wind (J. C. Kasper et al. 2008, 2017; L. Berger et al. 2011; P. J. Tracy et al. 2015, 2016; M. O. Stakhiv et al. 2016; B. L. Alterman et al. 2018; T. Ďurovcová et al. 2019; J. L. Verniero et al. 2020, 2022; K. G. Klein et al. 2021). Fast and slow winds also have different chemical and compositional signatures (J. Geiss et al. 1995a, 1995b; R. von Steiger et al. 2000; F. Xu & J. Borovsky 2015; H. Fu et al. 2015, 2017; L. Zhao et al. 2017, 2022; T. Ervin et al. 2024). Remote observations show that changes in these chemical and compositional signatures reflect the magnetic topology of the solar wind’s source regions on the Sun (D. H. Brooks et al. 2015; D. Baker et al. 2023). Solar wind with fast speeds is typically associated with source regions that have magnetic fields that are radial and continuously open to the heliosphere (Y.-M. Wang & N. R. J. Sheeley 1990; J. L. Phillips et al. 1994; J. Geiss et al. 1995b; C. N. Arge et al. 2013). In contrast, sources of slow wind have more complex magnetic field topologies and are only intermittently open to interplanetary space (E. Antonucci et al. 2005; S. K. Antiochos et al. 2011; N. U. Crooker et al. 2012; L. Abbo et al. 2016; D. Baker et al. 2023).

These differences in solar wind properties and their association with solar wind speed have led to a general identification of near-Earth slow wind with $v_{sw} < 400 \text{ km s}^{-1}$ with intermittently open source regions and $v_{sw} > 600 \text{ km s}^{-1}$ with continuously open source regions (B. Bavassano & R. Bruno 1991; R. Schwenn 2006; H. Fu et al. 2018; B. L. Alterman & R. D’Amicis 2025).



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However, this classification by speed is known to be imprecise (R. D’Amicis et al. 2021b; S. L. Yardley et al. 2024), especially in the intermediate speed range $v_{\text{sw}} = 400\text{--}600 \text{ km s}^{-1}$. This imprecision is likely because the maximum speed attainable by solar wind from intermittently open regions is greater than the minimum speed of solar wind born in continuously open regions (B. L. Alterman & R. D’Amicis 2025), which is a proposed source of the Alfvénic slow wind (e.g., R. D’Amicis & R. Bruno 2015). The Alfvénic slow wind is a subset of solar wind with slow speeds most similar to solar wind from intermittently open source regions, but other properties that are more similar to fast wind from continuously open source regions (R. D’Amicis & R. Bruno 2015; R. D’Amicis et al. 2021a, 2021b, 2019, 2016; S. L. Yardley et al. 2024).

The minimum solar wind speed observed in the near-Sun environment follows a Parker-like trend (N. E. Raouafi et al. 2023). These observations also display high levels of Alfvénic fluctuations, irrespective of solar wind speed (N. E. Raouafi et al. 2023). The processes accelerating the solar wind during transit through interplanetary space to speeds in excess of Parker’s prediction differ based on the solar wind’s source region. Solar winds originating in continuously open source regions are accelerated by the deposition of energy carried by Alfvén waves (J. C. Perez et al. 2021; J. S. Halekas et al. 2023; Y. J. Rivera et al. 2024), while solar winds born in intermittently open source regions are accelerated by thermal and electric pressure gradients (J. S. Halekas et al. 2022, 2023; Y. J. Rivera et al. 2025). This in situ acceleration can be described by the isopoly solar wind model (J.-B. Dakeyo et al. 2022) that includes Alfvén wave forcing (C. Shi et al. 2022) in which the solar wind follows a Parker-like isotropic expansion in the corona out to some distance r_0 , and, at heights $r > r_0$, the acceleration decreases and the solar wind follows a polytropic expansion. Depending on the source region and therefore relevant in situ acceleration mechanism (Y. J. Rivera et al. 2024, 2025), this critical distance r_0 varies between $6.5 R_S$ and $11.5 R_S$, and the polytropic index varies between $\gamma = 1.3$ and 1.41 .

The solar wind’s total energy flux (W) is independent of solar wind speed (v_{sw}) and solar activity (G. Le Chat et al. 2012). It consists of the flux of kinetic (W_K), thermal (W_H), and gravitational potential energy (W_G) along with the electric coupling between ionized hydrogen and electrons (W_e), the flow of energy associated with waves in the plasma (W_A), and the heat flux (Q) (B. D. G. Chandran et al. 2011; D. Telloni et al. 2023), the latter of which is negligible far above the sonic point (D. Telloni et al. 2023). As shown by Parker Solar Probe (hereafter Probe; N. J. Fox et al. 2015) and Solar Orbiter (hereafter Orbiter; D. Müller et al. 2013, 2020), W_K must become an increasing fraction of W with increasing distance from the Sun due to the solar wind’s in transit acceleration (M. Liu et al. 2021; D. Telloni et al. 2023; Y. J. Rivera et al. 2024, 2025). We show that the radial scaling of the kinetic energy flux derived from early Probe results (M. Liu et al. 2021) is sufficient to account for the fast wind peak in the distribution of solar wind speeds observed near Earth. Comparing this with the results of the isopoly model as applied to the conjunction between Probe and Orbiter in 2022 February (Y. J. Rivera et al. 2024), we infer that the solar wind acceleration due to Alfvén wave forcing observed below the orbit of Venus continues out to Earth. Comparing these observations to the range of speeds over which solar wind observations from continuously open source regions become

the dominant source of near-Earth solar wind (B. L. Alterman & R. D’Amicis 2025, B. L. Alterman & R. D’Amicis 2025, in preparation), the range of speeds solar wind from continuously open source regions would reach near Earth in the absence of Alfvén wave forcing, and the impacts of magnetic field topology on solar wind acceleration in the middle corona, we infer that solar wind Alfvénicity is a better predictor of solar wind source region than speed because it is driven by the magnetic field topology of the source region.

2. Observations

We use observations of ionized hydrogen (protons) and fully ionized helium (alpha particles) from the Wind spacecraft Faraday cups (K. W. Ogilvie et al. 1995) collected near-Earth and outside of Earth’s magnetosphere for which the fitting algorithms return physically meaningful velocities, densities, and temperatures of hydrogen and helium (J. C. Kasper et al. 2006). We select data from the declining phase 23 or 24 (R. D’Amicis et al. 2021a) when continuously open source regions are confined to the Sun’s polar region and intermittently open source regions are confined to the Sun’s equatorial region (R. von Steiger et al. 2000; R. Schwenn 2006; D. J. McComas et al. 2008), leading to distinct slow and fast wind peaks in the solar wind speed distribution (B. Bavassano & R. Bruno 1991). This results in more than 0.75 million distinct solar wind observations of both hydrogen and helium collected over 1828 days.

3. Analysis

Figure 1 plots the distribution of the solar wind speed (v_{sw}) from the time period selected in 5.38 km s^{-1} wide bins. For visual clarity, this histogram has been smoothed (A. Savitzky & M. J. E. Golay 1964; P. Virtanen et al. 2020), and values below 10^{-4} are not plotted. This has no impact on our results or interpretation.

To estimate the location of the fast and slow wind components of the near-Earth v_{sw} distribution, we select data with speeds $v_{\text{sw}} < 400 \text{ km s}^{-1}$ and $v_{\text{sw}} > 600 \text{ km s}^{-1}$ and fit each peak with a Gaussian distribution $g(x) = A \cdot \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$ with amplitude A , mean μ , and standard deviation σ . This data selection yields approximately 400,000 distinct slow wind and just over 73,000 fast wind observations. A figure with the histogram and fits is included in the supplemental material. Table 1 summarizes the derived fit parameters. The speeds of the peaks are $v_{\text{slow}} = 355 \pm 44 \text{ km s}^{-1}$ and $v_{\text{fast}} = 622 \pm 58 \text{ km s}^{-1}$, where we quote the standard deviation of the distribution instead of the fit parameter uncertainty. These ranges are highlighted with turquoise and labeled. As slow and fast wind are broadly considered to originate in different types of source region, there must be a speed below which intermittently open source regions are the dominant source of solar wind in the distribution and above which continuously open source regions are the dominant source. We estimate this speed $v_i = 484 \pm 34 \text{ km s}^{-1}$ as the range of speeds over which the Gaussians fit to both the fast and slow subsets intersect, when the uncertainties on all fit parameters are propagated. Figure 1 indicates v_i in pink. Table 2 summarizes all speeds derived and quoted in this work.

M. Liu et al. (2021) show that near-Sun observations of the solar wind’s total and kinetic energy flux obey power laws of

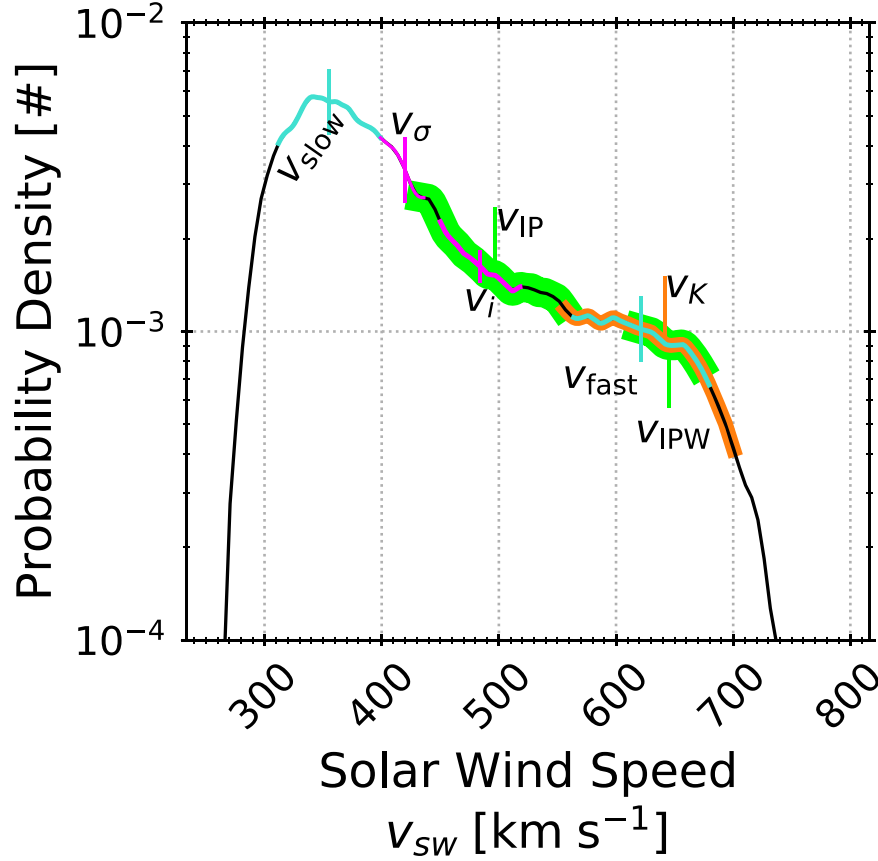


Figure 1. Probability density function (PDF) of the solar wind speed during the declining phase of solar activity. The turquoise regions are the slow and fast wind peaks, labeled v_{slow} and v_{fast} . The pink regions indicate v_{σ} and v_i . v_{σ} is the range of speeds over which $\nabla_{v_{\text{sw}}} A_{\text{He}}$ decreases as the Alfvénicity increases. v_i is the range of speeds over which Gaussians fit to the slow and fast wind distributions intersect. The range of speeds near Earth predicted from observations of the near-Sun kinetic energy flux is highlighted in orange and labeled v_K . Green regions indicate the speeds derived using the isopoly model without (v_{IP}) and with (v_{IPW}) Alfvén wave forcing. Table 2 summarizes these values.

Table 1

Parameters Characterizing the Gaussians Fit to the Slow and Fast Wind Peaks in Figure 1

Gaussian Fit Parameters for Solar Wind Speed Distributions			
Parameter	Units	Slow Peak	Fast Peak
Center (μ)	[km s ⁻¹]	355 ± 1	622 ± 2
Width (σ)	[km s ⁻¹]	44 ± 2	58 ± 2
Amplitude (A)	[10 ⁻³]	5.9 ± 0.1	1.05 ± 0.01

the form

$$f(R) = c \left(\frac{R}{R_s} \right)^b. \quad (1)$$

Table 3 summarizes the coefficient c and exponent b derived by M. Liu et al. (2021). Combining both power laws yields a near-Earth kinetic energy flux estimate $W_K = 0.64 \pm 0.02 \text{ mW m}^{-2}$.

The kinetic energy flux is given by Equation (2), where ρ_s is the mass density for a given species and v_s is its speed:

$$W_{K,s} = \frac{1}{2} \rho_s v_s^3. \quad (2)$$

We calculate the total W_K from near-Earth observations considering helium and hydrogen. If we assume the electrons, hydrogen, and helium move at the same speed, quasi-neutrality

implies that the electron contribution to the kinetic energy flux is on the order of 0.05% and therefore negligible.

Figure 2 plots the frequency of near-Earth solar wind observations as a function of solar wind speed and kinetic energy flux. Because the slow solar wind is observed markedly more frequently near Earth than fast wind, each column has been normalized to its maximum value so that this sampling artifact is removed. To extract the trend of W_K as a function of v_{sw} , we bin the data in 10 km s⁻¹ wide speed intervals and fit each column with a log-normal distribution. Figure 3 is an example of one such fit. We use a log-normal distribution because the distribution tails are asymmetric and enhanced on the side of the distribution corresponding to higher W_K . The resulting fit parameters are plotted in black. The central trend (dashed-dotted line) is the peak from these 1D fits. The thick black line on top of the dash-dotted line is the range of speeds corresponding to v_{fast} observed near Earth. The shaded region bounded by thin black lines corresponds to their widths. Only distributions up to 740 km s⁻¹ are well described by a log-normal distribution. This is unsurprising because we select data from solar minima and these speeds correspond to the region of Figure 1 where the probability density function (PDF) of v_{sw} decreases markedly. The horizontal orange region is the range of near-Earth values predicted above using near-Sun observations (M. Liu et al. 2021). As the orange region intersects the solid black lines below 740 km s⁻¹, this has no impact on our conclusions.

Table 2
Ranges of Speeds Derived and Referenced in this Letter

Summary of Speed Ranges		
Symbol	Speed Range	Description
v_{IPW}	620–671	Near-Earth speed predicted from the isopoly model with Alfvén wave forcing.
v_{fast}	622 ± 58	Peak of the fast wind distribution observed near Earth.
v_K	557–700	Near-Earth speed predicted from near-Sun kinetic energy flux observed by Probe.
v_{IP}	434–554	Near-Earth speed predicted from the isopoly model without Alfvén wave forcing for the source region conditions consistent with the fast wind peak observed near Earth.
v_i	484 ± 34	Speeds at which Gaussians fit to the fast and slow wind distributions overlap.
v_σ	399–436	Speed range identified by B. L. Alterman & R. D’Amicis (2025, in preparation) as the transition between fast and slow wind, accounting for the helium abundance, normalized cross helicity, and solar wind compressibility.
v_{slow}	355 ± 44	Peak of the slow wind distribution observed near Earth.

Note. All units are in km s^{-1} .

Table 3

Parameters from the Radial Scalings in Equation (1) for the Total Energy Flux and Kinetic Energy Flux Fraction from M. Liu et al. (2021, Their Figure 6)

Radial Scaling Parameters for the Solar Wind Energy Flux			
Energy Flux	Symbol	Coefficient c	Exponent b
Total	W	52.1 ± 1.4	-1.92 ± 0.007
KE Fraction	W_K/W	0.04 ± 0.001	0.41 ± 0.007

To calculate the speeds at which the near-Sun estimate of the near-Earth kinetic energy flux (W_{est}) and the observed near-Earth kinetic energy flux (W_{obs}) intersect, we have constructed a spline representation of W_{obs} (dashed-dotted line in Figure 2) and calculated the speeds at which it intersects W_{est} , $v_K = 642 \text{ km s}^{-1}$. Figure 2 shows that the minimum speed at which these two values for W_K intersect corresponds to the upper bound on the W_{obs} trend and the minimum of W_{est} . The maximum corresponds to the intersection of the maximum value W_{est} and the lower bound on W_{obs} . Applying the same spline method to these intersections as above, we determine that this range of speeds corresponds to $v_{\text{sw}} = 557\text{--}700 \text{ km s}^{-1}$. Figure 1 plots v_K as a vertical orange bar and highlights the full range of values in orange.

The difference between $v_{\text{fast}} = 622 \text{ km s}^{-1}$ and the center of the v_K range of values is 20 km s^{-1} . The maximum value for v_i is 518 km s^{-1} , which is 39 km s^{-1} slower than the minimum of v_K and almost twice as large as the difference between the central v_{fast} and v_K values. In other words, the near-Earth fast solar wind speeds predicted from near-Sun observations of W_K correspond well with v_{fast} observed near Earth. Although this range of predicted near-Earth speeds is wider than the v_{fast} peak, it is well separated from the range of speeds v_i for which slow and fast solar winds are both observed to have a nontrivial contribution in the near-Earth environment.

Assuming the conjunction between Probe and Orbiter that was described by the isopoly model with Alfvén wave forcing (Y. J. Rivera et al. 2024) is representative of the evolution in the transit of solar wind from magnetically open sources, we use the range of values that account for the fit uncertainties on the Alfvén-wave-forcing profile along with the uncertainties on γ to calculate that the corresponding range of expected speeds near Earth ($212 R_S$) for this event is $v_{\text{IPW}} = 620\text{--}671 \text{ km s}^{-1}$ with a central value of 645 km s^{-1} . The slowest v_{IPW} corresponds to the largest γ and weakest Alfvén-wave-forcing profile, while the fastest v_{IPW} corresponds to the smallest γ and

the strongest forcing profile. This range of v_{IPW} falls within the range of speeds given by v_{fast} and v_K . Figure 1 labels this range of speeds v_{IPW} and highlights it in green.

The temperature in the isothermal layer consistent with Y. J. Rivera et al.’s (2024) observations, and the isopoly that includes Alfvén wave forcing is $T_o = 1.7 \text{ MK}$. To determine the range of temperatures in the isothermal layer corresponding to v_{fast} , we minimize the absolute value of the difference between the near-Earth speed predicted from the isopoly model and the fast wind peak $|v_E(T_o, f_0, \gamma) - v_{\text{fast}}|$ over the ranges $\gamma = 1.41 \pm 0.02$ and $f_0 = 0.012 \pm 0.002$ in units of $GM_\odot/R_\odot^2$ from Y. J. Rivera et al. (2024), where f_0 sets the strength of the Alfvén-wave-forcing profile. Using $v_{\text{fast}} = 622 \pm 58 \text{ km s}^{-1}$, the range of isothermal layer temperatures is $T_o = 1.34\text{--}1.85 \text{ MK}$ with a central value of $T_o = 1.6 \text{ MK}$, which are consistent with UVCS observations (S. R. Cranmer 2020) and exceed the estimates of T_o from exospheric theory using near-Sun electron observations (J. S. Halekas et al. 2022). The corresponding Alfvén-wave-forcing strengths are $f_0 = 1.2 \times 10^{-2}$, 1.22×10^{-2} , and 1.18×10^{-2} . The polytropic index is $\gamma = 1.41$ in all cases. Under the isopoly model, the near-Earth speeds corresponding to these T_o in the absence of Alfvén wave forcing is $v_{\text{IP}} = 434\text{--}554 \text{ km s}^{-1}$ with a central value of 497 km s^{-1} . Figure 1 labels this range of speeds v_{IP} and highlights it in green.

The helium abundance is given by the helium-to-hydrogen number density ratio in units of percent $A_{\text{He}} = 100 \times n_{\text{He}}/n_{\text{H}}$. In the slow wind, A_{He} is highly variable below 4.19%, and $\nabla_{v_{\text{sw}}} A_{\text{He}} > 0$ (B. L. Alterman & R. D’Amicis 2025; B. L. Alterman et al. 2025). In fast wind, the helium abundance is fixed at $A_{\text{He}} = 4.19\%$, which is 49% of the photospheric abundance, and the gradient is flat (B. L. Alterman & R. D’Amicis 2025; B. L. Alterman et al. 2025). This change in $\nabla_{v_{\text{sw}}} A_{\text{He}}$ is one composition signature suggesting that slow solar wind originates in intermittently open source regions, while fast wind originates in continuously open source regions (B. L. Alterman & R. D’Amicis 2025, Section 4.3 and references therein). Fitting a bilinear function of $A_{\text{He}}(v_{\text{sw}})$, B. L. Alterman & R. D’Amicis (2025) define the speed and abundance at which this change of gradient occurs as the saturation point with saturation speed v_s and saturation abundance A_s . They show that v_s decreases as the Alfvénicity increases, while A_s increases with increasing Alfvénicity. Considering the solar wind Alfvénicity as a proxy for the magnetic field topology above the sonic point, B. L. Alterman & R. D’Amicis (2025) argue that the dependence of v_s and A_s

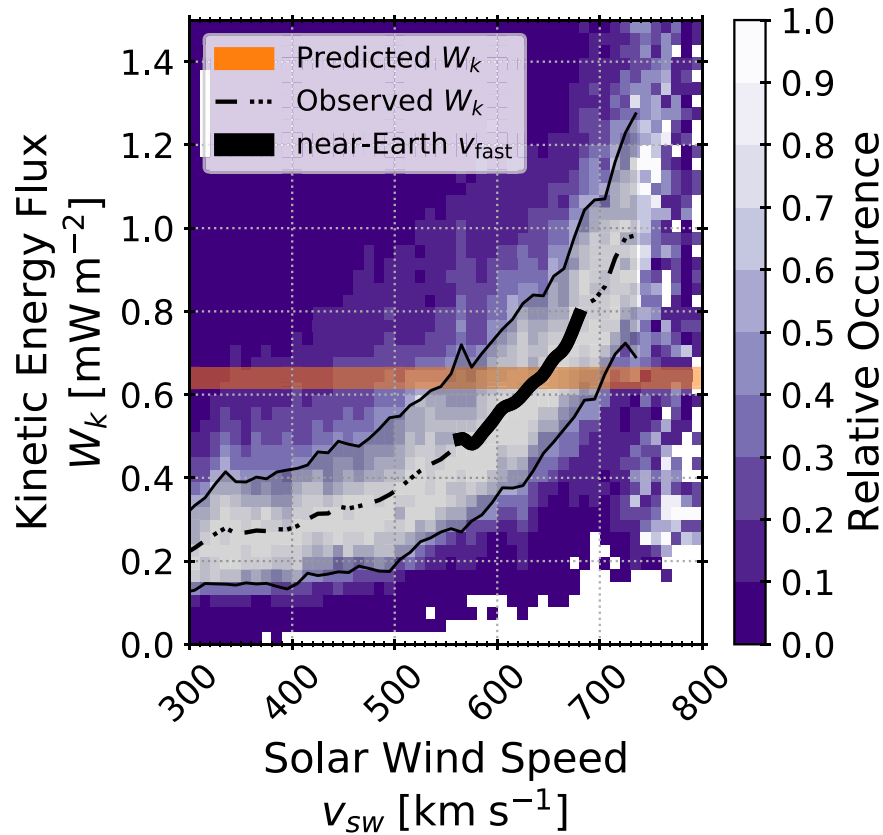


Figure 2. A 2D heat map showing the frequency of observations as a function of solar wind speed and kinetic energy flux observed near Earth. Because slow solar wind is observed more frequently than fast solar wind (Figure 1), each column in the heat map is normalized to its maximum value to remove this sampling artifact. The black dashed–dotted line is the central value in each column; the black solid lines are the spread of values. The region highlighted with a thick black line corresponds to v_{fast} . The orange horizontal band is the range of kinetic energy fluxes predicted near Earth from Probe observations of the radial scaling of the total and kinetic energy fluxes during Encounters 1, 2, 4, and 5.

on Alfvénicity is consistent with solar wind observed at 1 au and originating in continuously open source regions having a minimum v_{sw} less than the maximum v_{sw} for solar wind observed at 1 au and born in intermittently open source regions. B. L. Alterman & R. D’Amicis (2025, in preparation) show that the unexpected presence of compressive fluctuations in fast wind modifies v_s and A_s . Accounting for these effects, the range of speeds over which solar wind from continuously open sources becomes a significant component of the near-Earth solar wind speed distribution is $v_\sigma = 399\text{--}436\text{ km s}^{-1}$, which is just faster than the fastest v_{slow} and overlaps with v_{IP} by 2 km s^{-1} (B. L. Alterman & R. D’Amicis 2025, in preparation). Figure 1 plots this range of speeds in pink and labels it v_σ , as σ is a common symbol for the Alfvénicity.

4. Discussion

Recent observations suggest that differences in the speed of solar wind from intermittently and continuously open source regions begin to develop in the middle corona at heights above the Sun’s surface $2\text{--}3.5 R_\odot$ (N. Ngampoopun et al. 2025). In continuously open field regions, the speed is highly correlated with magnetic field geometry, while it is not in intermittently open field regions (Y.-M. Wang & N. R. J. Sheeley 1990; N. Ngampoopun et al. 2025). Above the middle corona, the minimum speed of near-Sun solar wind is consistent with Parker’s isothermal solar wind model (E. N. Parker 1958; N. E. Raouafi et al. 2023). During propagation through

interplanetary space, solar wind from intermittently open source regions is accelerated by thermal pressure gradients (Y. J. Rivera et al. 2025). In contrast, solar wind from continuously open source regions is accelerated by both thermal pressure gradients and Alfvén wave forcing (Y. J. Rivera et al. 2024, 2025). Theory and observations suggest that the physical mechanisms generating Alfvén waves and producing the energy necessary to accelerate the solar wind during interplanetary propagation are common to intermittently and continuously open source regions and they are sufficient to accelerate the solar wind to the speeds v_{fast} observed near Earth (L. A. Fisk & N. A. Schwadron 2001; L. A. Fisk 2005; L. A. Fisk & J. C. Kasper 2020; G. P. Zank et al. 2020; P. F. Wyper et al. 2022; S. D. Bale et al. 2023; N. E. Raouafi et al. 2023).

The solar wind’s Alfvénicity is a more reliable predictor of solar wind source region than speed (C. Tu et al. 1992; R. D’Amicis et al. 2021a). The Alfvénicity quantifies whether the dominant wave modes in the plasma correspond to high correlations between the velocity and magnetic field components in the absence of density compressions and fluctuations in the magnetic field magnitude (J. W. Belcher et al. 1969; J. W. Belcher & L. Davis 1971; R. Bruno & V. Carbone 2013; R. D’Amicis et al. 2021a, 2021b). Such signatures are considered to be indicative of the presence of Alfvén waves (H. Alfvén 1942, 1943). Fast solar wind from magnetically open sources has a high Alfvénicity. Solar wind from magnetically closed sources does not display a

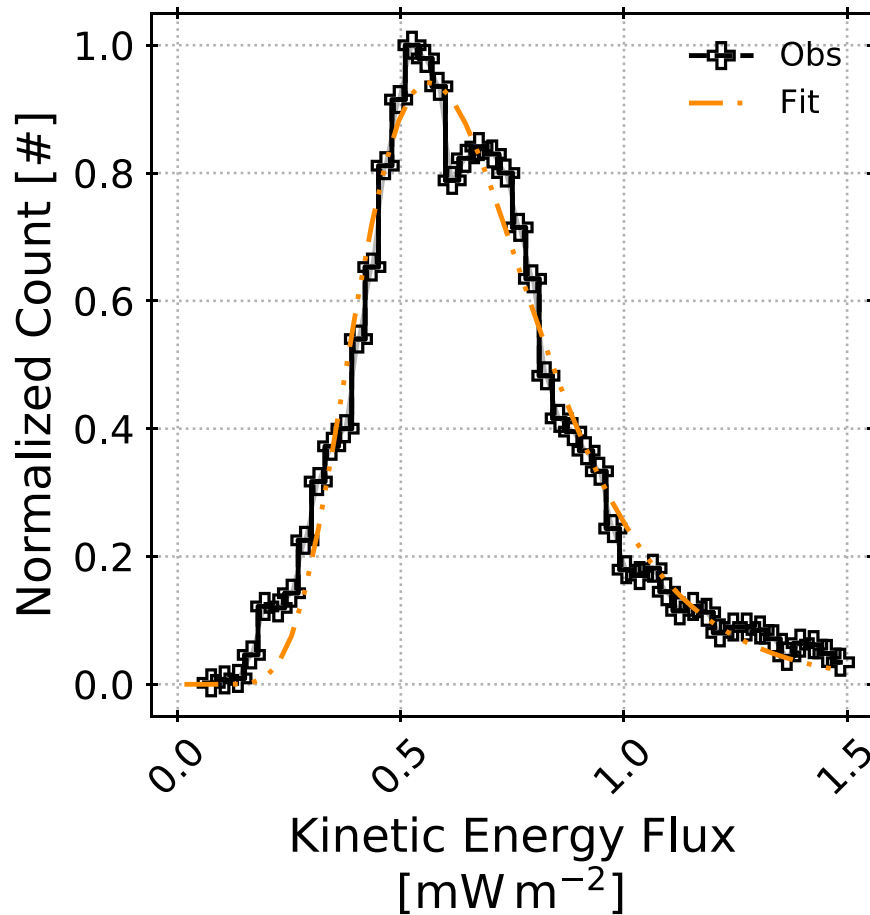


Figure 3. An example of the log-normal distribution fit to observations of solar wind speeds observed near Earth in the range of speeds 620–630 km s^{−1}. The binned observations are in black. The fit is plotted in a dashed–dotted orange line.

preferred Alfvénicity, which means that it can carry a wide range of fluctuations and waves (R. D’Amicis et al. 2021b; B. L. Alterman & R. D’Amicis 2025). The Alfvénicity of fluctuations carried by solar wind from intermittently open sources decays during solar wind propagation through interplanetary space, while the Alfvénicity of solar wind from continuously open source regions does not (E. Marsch & C.-Y. Y. Tu 1990). Large-scale motion of the Sun’s corona is likely a key source of solar wind Alfvén waves (L. A. Fisk & N. A. Schwadron 2001; L. A. Fisk 2005; J. C. Kasper et al. 2019) and can drive the solar wind’s Alfvénicity. When the solar wind speed is larger than the Alfvén speed, this is no longer the case. This height is the Alfvén radius, nominally $\sim 20 R_S$ (J. C. Kasper et al. 2021), well above the middle corona where differences in solar wind speed based on the magnetic topology of source regions begin to develop.

We have estimated the range of near-Earth fast wind speeds $v_{\text{fast}} = 622 \pm 58 \text{ km s}^{-1}$ and slow wind speeds $v_{\text{slow}} = 355 \pm 44 \text{ km s}^{-1}$ using the distribution of v_{sw} observed by the Wind spacecraft during the declining phase of solar activity when continuously and intermittently open source regions are heliographically stratified. B. L. Alterman & R. D’Amicis (2025, in preparation) and B. L. Alterman & R. D’Amicis (2025) suggest that the minimum speed at which solar wind from continuously open source regions becomes a nontrivial component of the distribution of v_{sw} observed near Earth is $v_{\sigma} = 399\text{--}436 \text{ km s}^{-1}$. To naively estimate the range of the

slowest speeds over which solar wind from continuously open source regions becomes the primary component of near-Earth observations, we have calculated the speed $v_i = 484 \pm 34 \text{ km s}^{-1}$, the range of speeds over which Gaussians fit to the slow and fast wind distributions intersect.

Empirically derived radial scalings of the solar wind’s kinetic energy flux (M. Liu et al. 2021) lead to a predicted near-Earth speed $v_K = 557\text{--}700 \text{ km s}^{-1}$. v_K spans the range of fast wind speed v_{fast} and exceeds v_i . This suggests that the radial evolution of the solar wind’s kinetic energy flux is sufficient to account for the statistical range of fast solar wind speeds observed near Earth.

The range of near-Earth solar wind speeds predicted by a solar wind model that includes both thermal pressure gradients and Alfvén wave forcing (Y. J. Rivera et al. 2024) is $v_{\text{IPW}} = 620\text{--}671 \text{ km s}^{-1}$, which overlaps with the central values of both v_{fast} and v_K but is significantly narrower than both. Under this same model, near-Earth solar wind with speeds v_{fast} would only reach speeds $v_{\text{IP}} = 434\text{--}554 \text{ km s}^{-1}$ if it was not accelerated by Alfvén wave forcing during transit through interplanetary space. The range of isothermal temperatures used to derive v_{IP} varies by 38%, while the strength of Alfvén-wave-forcing profiles varies by 3% and the polytropic index remains fixed at $\gamma = 1.41$. This suggests that the range of near-Earth fast wind speeds is sensitive to the temperature boundary conditions, while it is insensitive to the overall strength of the forcing profile and the in situ heating.

The speed range v_{IP} is at least 35 km s^{-1} faster than the maximum v_{slow} , spans v_i is 10 km s^{-1} slower than the slowest v_{fast} , and overlaps v_{σ} by at most 2 km s^{-1} , which is less than 50% the width of a single bin in the PDF of v_{sw} in Figure 1. This suggests that Alfvén wave forcing of the solar wind continues out beyond the orbit of Venus, consistent with observations of the decay of Alfvénic structures (e.g., switchbacks) as the solar wind propagates through interplanetary space (A. P. Rasca et al. 2021; A. Tenerani et al. 2021).

In this work, we have de facto declared that speed differences or overlaps on the order of $\lesssim 10 \text{ km s}^{-1}$ near Earth are insignificant. The size of the histogram bins used to generate Figure 1 is 5.38 km s^{-1} . The full range of nontransient v_{sw} observed at $212 R_S$ is $v_{\text{sw}} = 200\text{--}800 \text{ km s}^{-1}$. A speed range of 10 km s^{-1} is approximately 1.7% of this 600 km s^{-1} range. The maximum range of speeds covered by v_{slow} to v_K is $v_{\text{sw}} = 311\text{--}700 \text{ km s}^{-1}$. A speed range of 10 km s^{-1} is approximately 2.6% of this 389 km s^{-1} span. The observations from Wind near Earth consist of two 913 day intervals collected during the declining phase of solar activity, separated by at least 8.5 years and ending in 2018. The speed estimate v_K is derived from near-Sun observations collected over four different 12 day intervals spanning 2018–2022 (M. Liu et al. 2021), which spans the end of the declining phase of solar cycle 24 and minimum 25. The model proposed by Y. J. Rivera et al. (2024) is developed using 1 hr and 40 minutes of Probe observations that correspond to 10 hrs of Orbiter observations collected over the course of 2 days in 2022, during the rising phase of solar cycle 25. Given that this work compares four different sets of observations, collected over four different ranges of time, at different phases of solar activity and at different radial distances, we have performed our analysis using the widest possible ranges of values that account for the uncertainties on all derived speeds and model parameters. Only using the central or mean values would only reduce the ranges of speeds and improve our results. As such, a speed difference or overlap on the order of two histogram bin widths seems negligible. We infer that Alfvénicity is a reliable predictor of source region because solar wind from continuously open source regions is accelerated in transit by Alfvén wave forcing, while solar wind from intermittently open source regions is not, and the presence or absence of Alfvén wave forcing during interplanetary propagation is a consequence of the magnetic field topology at the source region.

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ORCID iDs

B. L. Alterman  <https://orcid.org/0000-0001-6673-3432>

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