

organism - [who obs model discuss] → who methodology results discuss

Estimating the uncertainty on potential field models to understand the sources of the slow Alfvénic solar wind

JACK D. COLLARD^{1,2}, TAMAR ERVIN^{1,2}, JIA HUANG², MINGZHE LIU², SAMUEL T. BADMAN³,
YEIMY J. RIVERA⁴, PETE RILEY⁴, KAI JAFFAROVE^{1,2}, ORLANDO M. ROMEO², STUART D. BALE^{1,2},
ROBERTO LIVI⁴, PHYLLIS L. WHITTLESEY², ALI RAHMATI² AND DAVIN E. LARSON²

¹Department of Physics, University of California, Berkeley, Berkeley, CA 94720-7300, USA

²Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA

³Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA

⁴Predictive Science Inc. San Diego, CA, USA

ABSTRACT

Using observations from Parker Solar Probe Encounters 4 to 21, we identify hundreds of streams of slow Alfvénic solar wind (SASW) and connect them to their coronal origins through a combination of Potential Field Source Surface (PFSS) modeling and ballistic backmapping. This mapping procedure depends on user-defined inputs such as the photospheric magnetogram choice, source surface height, and solar wind speed profile used for ballistic propagation to connect the spacecraft position with the model. We quantify the uncertainty that these parameters introduce into the estimated footpoint locations for all identified streams. We find that source surface height is the largest source of uncertainty, with a median total footpoint uncertainty of approximately 1.8° across all streams. Using the mapped footpoints, we characterize the source regions of the streams through their expansion factor, magnetic field strength, EUV intensity, and proximity to the open-closed magnetic boundary. We find that SASW consistently traces back to regions near coronal hole boundaries rather than to coronal hole interiors. Overall, these results support an origin for SASW near coronal hole boundary regions, while providing a statistical estimate of the mapping uncertainty associated with traditional solar wind connectivity methods.

1. INTRODUCTION

The solar wind is a supersonic outflow that continually expands from the solar corona through the inner heliosphere (Parker 1958). Decades of spacecraft observations have taken in-situ measurements of the plasma parameters associated with the solar wind, finding a large range in measured densities, speeds, and temperatures (Neugebauer & Snyder 1962, 1966; McComas et al. 2001). While the solar wind evolves as it radially expands through the heliosphere (Shi et al. 2022a; Maksimovic et al. 2020; Dakeyo et al. 2022), work has shown that some of the variation in plasma parameters can be tied to the topological source region(s) on the solar surface that the plasma parcel spent time in (e.g. Laming 2015, 2017). Splitting the solar wind into defined categories based on in-situ plasma measurements provides a pathway towards understanding the relationship between the source region and the subsequent plasma observed.

The fast solar wind (FSW; speeds above 500 km s^{-1} at 1 AU) has been shown to originate in coronal hole (CH) regions, where open magnetic field lines allow for plasma flow out through the heliosphere (Hundhausen 1972; McComas et al. 1998, 2008). However, the origin of the slow solar wind (SSW) remains an unresolved question in heliophysics, with multiple proposed sources (Abbo et al. 2016; Viall & Borovsky 2020). Work has also identified a subset of slow solar wind that is highly Alfvénic at times, known as slow Alfvénic solar wind (SASW; Marsch et al. 1981; D’Amicis et al. 2011). The SASW exhibits elemental and heavy ion compositional signatures (Stansby et al. 2020a; Ervin et al. 2024b) similar to the FSW. Alpha-to-proton density ratios within these streams are also similar to the FSW (Ervin et al. 2024b,a; Alterman & D’Amicis 2025). As compositional signatures are typically driven by solar source (e.g.

lots of references should be "e.g., ..."

Hundhausen 1968; Landi et al. 2012), these similarities suggest that some SASW streams may share a common origin with fast wind from CHs. Observations from closer to the Sun have shown that the SASW may originate from multiple sources (Ervin et al. 2024a) and that alpha-to-proton density ratios may vary between the SASW and FSW (Huang et al. 2025).

Work has shown that the SASW exhibits turbulence characteristics, such as spectral scalings and breakpoints between inertial and injection scales, similar to those of the fast wind (Perrone et al. 2020). A relationship between Alfvénicity and spectral index has also been shown (Chen et al. 2013; Podesta & Borovsky 2010; Bowen et al. 2018; Ervin et al. 2025), where more Alfvénic wind streams show spectral scalings closer to $-3/2$ at 1 AU. Differences in solar source region, and proximity to large-scale structures like the heliospheric current sheet (Chen et al. 2021; Shi et al. 2022b), potentially also drive differences in the observed turbulence properties. The solar wind shows a poorly developed inertial range close to the Sun, with spectral scalings $\sim -3/2$, steepening to $\sim -5/3$ as the wind expands (Alberti et al. 2020; Chen et al. 2020; Sioulas et al. 2023). We therefore would expect the near-Sun SASW to show spectral scalings of $-3/2$ consistent with these results.

Recent works have mapped SASW streams to their estimated sources, often finding that these streams map to open-field regions near CH boundaries, including small CHs, overexpanded boundary regions, and, in some cases, non-CH structures or CH-active region complexes (Yardley et al. 2024; Ervin et al. 2024b; D’Amicis et al. 2021; Panasenco et al. 2020; D’Amicis et al. 2025; Ervin et al. 2024a). Estimating the solar source relies on coronal magnetic field modeling to extrapolate the photospheric magnetic field and connect in-situ observations to their sources. A computationally efficient method to do this magnetic field extrapolation is the Potential Field Source Surface (PFSS; Altschuler & Newkirk 1969) model, coupled with some method of projecting the spacecraft trajectory down to the model’s outer boundary (typically 2 - 3 $R_{\odot}$). The PFSS model and propagation methods include a variety of user inputs that introduce uncertainties into the inferred connectivity (Koukras et al. 2025; Ervin et al. 2024a; Dakeyo et al. 2024a). These modeling methods allow us to quantify source region properties, and measure the magnetic expansion near the coronal base which has been tied to solar source region (e.g. Wang et al. 2009). These models have been used extensively to connect near-Sun observations to their estimated solar origins (Badman et al. 2020, 2022). Understanding the impacts of these uncertainties on our interpretation of the resulting sources is vital for a complete picture of solar wind origins.

We take a statistical approach to studying the characteristics of SASW streams. Using Parker Solar Probe (PSP; Fox et al. 2016) observations from January 27, 2020 to October 1, 2024 (Encounters 4-21), we map hundreds of streams back to their estimated source using PFSS modelling and ballistic propagation, while quantifying uncertainties from model inputs. For each modeled stream we extract source region parameters including expansion factor, footpoint magnetic field strength, EUV intensity, and distance to the nearest CH boundary to estimate a solar source. We look at the inertial range spectral scaling of magnetic field spectra for the SASW finding scalings of $\sim -3/2$ as expected for highly Alfvénic wind. We find that the majority of these streams map to near the open-closed boundary.

2. OBSERVATIONS

Parker Solar Probe (PSP; Fox et al. 2016) has been flying through the inner heliosphere making measurements of fields and plasma properties since launching in 2018. These observations allow us to study solar wind streams at various heliocentric distances, from different sources. The FIELDS (Bale et al. 2016) suite makes high-cadence measurements of the magnetic and electric fields. We use observations from the fluxgate magnetometer (MAG) to produce turbulent spectra. The ion electrostatic analyzer (SPAN-I; Livi et al. 2022) takes measurements of the 3d velocity distribution function (VDF) of ions in the solar wind. We use partial moments calculated from the measured 3d distribution function at a cadence of 3.5 seconds. It is important to note that SPAN-I has a limited field-of-view due to occultation by the spacecraft and thermal protection system, and thus these are partial moments of the VDF which can lead to large underestimations in density (N_p), while the velocity (v_p) is less effected (Livi et al. 2022). To account for this, we calculate the maximum proton density ($N_{p,max}$) over a 1-minute rolling window used for derived parameters requiring the proton density.

In this study we focus on studying the SASW, and thus a measure of the Alfvénicity is required. We use the normalized cross helicity (σ_C) as a proxy for Alfvénicity. $\sigma_C = \pm 1$ corresponds to pure Alfvén waves propagating sunward (+1) or anti-sunward (-1). Cross helicity is calculated following Equation 1 using the merged dataset, and $N_{p,max}$ (Ervin et al. 2024c):

estimate power spectra

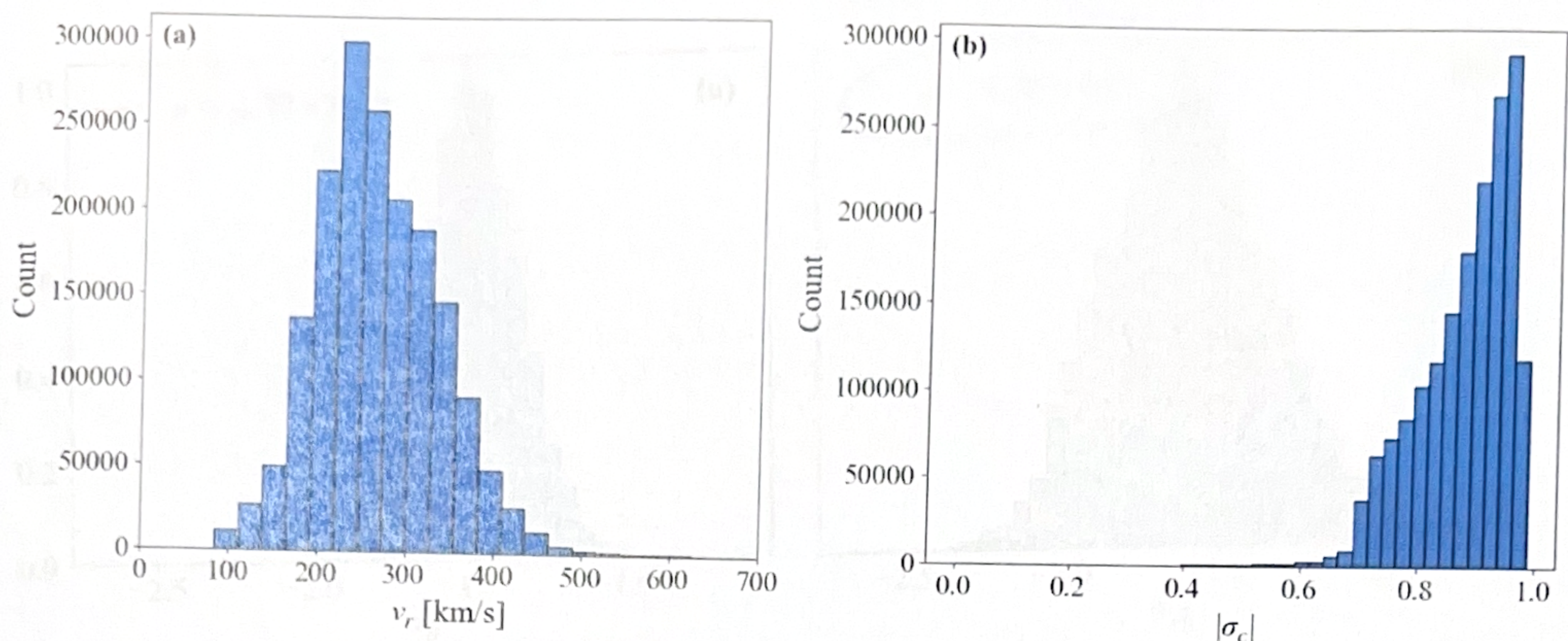


Figure 1. Distributions of the in-situ parameters used to identify SASW. Panel (a) shows the distribution of radial solar wind speed, v_r , for all SASW intervals. Panel (b) shows the distribution of the absolute value of the cross helicity, $|\sigma_C|$.

$$\sigma_C = \frac{\langle E^+ \rangle - \langle E^- \rangle}{\langle E^+ \rangle + \langle E^- \rangle} \quad (1)$$

where $E^\pm$ is the energy of the Elsässer variables:

$$\delta \mathbf{z}^\pm = \delta \mathbf{v} \mp \delta \mathbf{b} \text{ sign}(\langle B_r \rangle). \quad (2)$$

$\delta \mathbf{v}$ and $\delta \mathbf{b}$ are fluctuations in the velocity vector $\mathbf{v}$ measured by SPAN-I and the Alfvén speed $\mathbf{b} = \mathbf{B} / \sqrt{\mu_0 m_p N_{p,\max}}$ calculated as $\delta \mathbf{x} = \mathbf{x}(t) - \langle \mathbf{x}(t) \rangle$ for both $\mathbf{v}$ and $\mathbf{b}$. $\text{sign}(\langle B_r \rangle)$ accounts for the polarity of the background magnetic field, $\langle \dots \rangle$ represents an average over a 60-minute non-overlapping window chosen to cover the full spectral features of the inertial range (Ervin et al. 2024c) and capture multiple correlation times (Parashar et al. 2020). We define Alfvénic wind to have $\langle |\sigma_C| \rangle \geq 0.7$ over the stream (D’Amicis & Bruno 2015). Following Ervin et al. (2024a), we identify streams as “slow” and “Alfvénic” provided that $v_r \leq v_{\text{thresh},r}$ and $\langle |\sigma_C| \rangle \geq 0.7$ for at least 30-minutes to qualify as a SASW stream. We identify 646 SASW streams, amounting to ~ 1500 hours of PSP observations. Figure 1 shows an overview of the in-situ classification parameters (v_r and σ_C) associated with the SASW parameterization.

Figure 1 displays the in-situ radial velocity (v_r) and cross helicity ($|\sigma_C|$) values for all of the identified SASW intervals. The radial velocity distribution in panel (a) peaks at $\sim 250 \text{ km s}^{-1}$, with a majority of values falling within the slow-wind regime defined by our heliocentric distance-based threshold. Panel (b) shows that the distribution of $|\sigma_C|$ values are skewed toward 1.0, with most intervals $\gtrsim 0.8$, consistent with highly Alfvénic fluctuations. These distributions reflect that we are indeed observing slow, Alfvénic wind streams.

2.1. Spectral Scaling

For each of the identified streams, we estimate the inertial range spectral scaling of both the trace and magnitude magnetic field spectra. Spectra are computed from the FIELDS/MAG full-cadence 3-axis magnetic field observations over 1-minute non-overlapping windows for each of the 646 streams using a fast Fourier transform (FFT). Thus for a stream of length 30-minutes, we would compute 30 different trace and magnitude spectra via the FFT where each spectra is denoted $E(f)$. We compute trace spectra as a sum of the power spectra over each of the three-axes, and compute magnitude spectra as a FFT of $|B|$. Spectra are fit in log-log space via least-squares on a frequency range of 0.015 to 0.25 Hz to compute the spectral index α such that $E(f) \propto f^\alpha$. Resulting spectral indices for the trace and magnitude spectra are shown in Figure 2.

Figure 2(a) reports the indices associated with the trace spectra (α_B) and Figure 2(b) shows indices associated with magnitude spectra ($\alpha_{|B|}$). $\alpha_B \sim -1.49 \pm 0.16$ while the magnitude spectra shows slightly steeper indices with

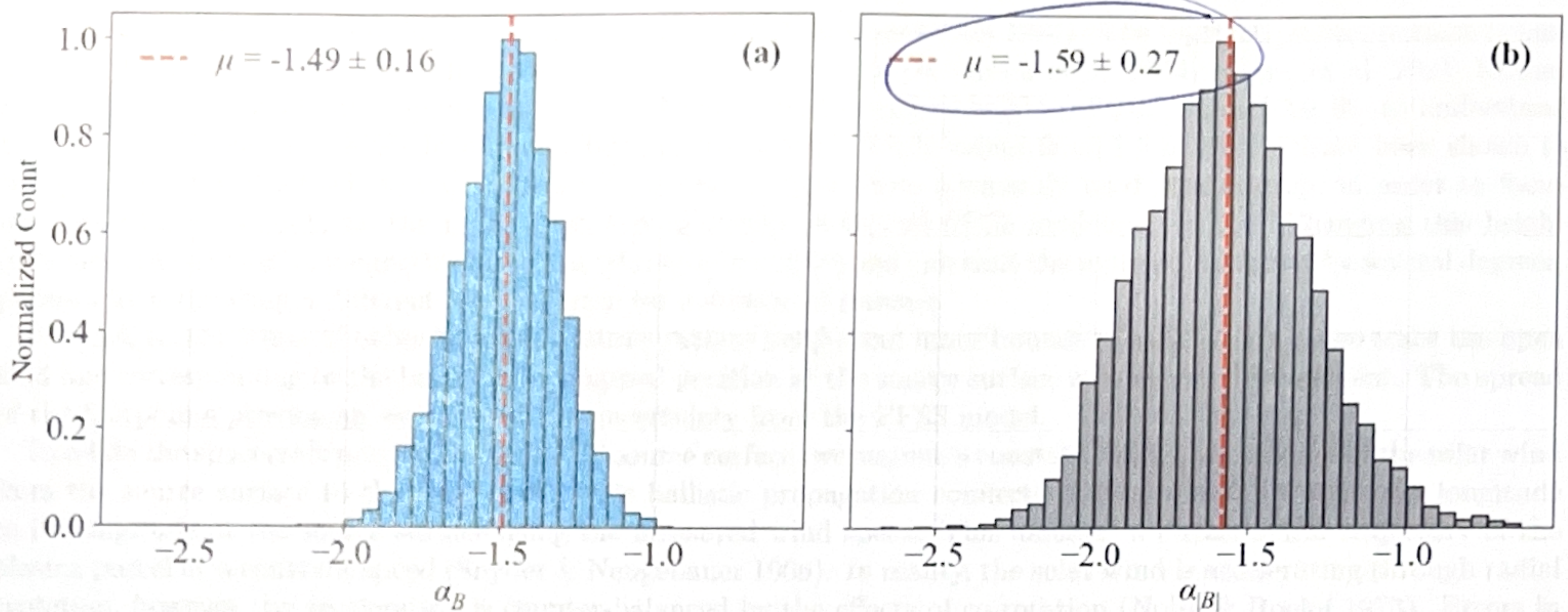


Figure 2. Distributions of inertial-range spectral indices derived from magnetic field power spectra calculated within the identified SASW intervals over 1-minute non-overlapping windows. Panel (a) shows the distribution of spectral indices derived from the trace magnetic field spectrum, α_B . Panel (b) shows the distribution of spectral indices derived from the magnetic field magnitude spectrum, $\alpha_{|B|}$. The red dashed lines indicate the mean values for each distribution which are also reported in the legend alongside the standard deviation.

$\alpha_{|B|} \sim -1.59 \pm 0.27$. Therefore, this result indicates that the SASW observed in the near-Sun environment shows spectral scalings of $-3/2$, which is consistent with previous works for high cross helicity wind (Ervin et al. 2025; Bowen et al. 2018).

→ better to say "one consistent with..." (or not inconsistent with!)

3. MODELING

To determine the coronal source regions of the solar wind streams observed by PSP, we use a two-step procedure that combines ballistic-propagation with a PFSS model. The PFSS model extrapolates the photospheric field outwards, modeling the large scale structure of the coronal magnetic field. Ballistic propagation is used to connect the spacecraft trajectory down to the model's outer boundary for field line tracing to produce estimated source footpoints. This allows us to link in-situ measurements to specific locations on the solar surface while quantifying the uncertainties introduced by the modeling assumptions. PFSS assumes the corona is current-free and therefore satisfies $\nabla \times \mathbf{B} = 0$, allowing the magnetic field to be expressed as the gradient of a scalar potential. The magnetic field is extrapolated following the current-free assumption from an inner boundary condition, an observed photospheric magnetic field, to an outer boundary, the source surface height (R_{ss}). At this height, the magnetic field is forced to be purely radial.

Despite the magnetostatic (current-free) assumption and the forcing of a radial field at R_{ss} , PFSS models have been shown to map the global distribution of open and closed magnetic flux reasonably well and provide similar predictions of footpoint locations in comparison with more physically driven, magnetohydrodynamic type models (e.g. Badman et al. 2020, 2021, 2023; Ervin et al. 2024c; Riley et al. 2006). In addition to the physical assumptions, PFSS models require user inputs, with each introducing uncertainty into the extrapolated fields and thus the estimated connectivity of the spacecraft. ~~Constant solar wind parameters~~

The lower boundary of the PFSS model is determined by an observation of the photospheric magnetic field, in this study we use GONG magnetograms (Harvey et al. 1996) with the ADAPT flux transport model (Worden & Harvey 2000) applied (ADAPT-GONG). As the solar magnetic field undergoes evolution over a variety of temporal and spatial scales, extrapolations with different photospheric magnetic field observations will produce different results. Therefore, estimating source footpoints from one magnetogram does not well reflect the entire stream of interest. Therefore, for each stream we use five magnetograms centered around the mean event time (mean, ± 6 hr, ± 12 hr). This allows for estimation of the sensitivity of the footpoint to magnetic flux evolution on the solar surface.

The model's outer boundary, the source surface height, which defines the radius at which the field is forced to become radial, is another user choice. R_{ss} values between 1.5 and 3 $R_{\odot}$ have been shown to best reproduce in-situ

yes!
not uncertainty

measurements of the neutral line and magnetic field timeseries (Hoeksema 1984). The ‘optimal’ source surface height has also been shown to evolve with solar cycle (Schatten et al. 1969; Arden et al. 2014; Huang et al. 2024; Kumar et al. 2025). We repeat the mapping using three different source surface heights of 2.0, 2.5, and 3.0 $R_{\odot}$ to understand the effect of source surface height on our estimated footpoints. While values from 1.5 to 3.0 $R_{\odot}$ have been shown to be optimal, we restrict our tested range to 2.0-3.0 $R_{\odot}$, values more commonly used in literature, in order to focus our uncertainty estimate on the range most representative of typical PFSS modeling choices. Changing this height influences the amount of magnetic expansion (Huang et al. 2024) and can shift the mapped footpoint by several degrees, potentially estimating a different source region for a stream of interest.

For each combination of outer boundary source surface height and inner boundary magnetogram, we trace the open field line corresponding to the ballistically mapped position at the source surface and record the footpoint. The spread of the footpoints provide an estimate of the uncertainty from the PFSS model.

To relate the spacecraft position to the PFSS source surface, we assume a constant radial propagation of the solar wind from the source surface to the spacecraft. This ballistic propagation connects the spacecraft’s Carrington longitude to its longitude at the source surface using the measured wind speed. This assumes a Parker spiral trajectory of the plasma parcel at a constant speed (Snyder & Neugebauer 1966). In reality, the solar wind is accelerating through radial evolution, however the acceleration is counter-balanced by the effects of co-rotation (Nolte & Roelof 1973). Errors in the ‘constant speed assumption’ have been shown to be of smaller magnitude than error associated with uncertainty in the PFSS (Neugebauer et al. 2002; Ervin et al. 2024a), and to increase as a function of heliocentric distance (Dakeyo et al. 2024a). As PSP is close to the Sun, this uncertainty source is also expected to be minimal due to the small propagation distance between the solar wind source and the spacecraft. *↑ you can estimate this*

In this work, we use the in-situ solar wind speed measured by PSP/SPAN-I as the ‘constant speed’ input into the ballistic propagation model. To account for uncertainty in the velocity measurement, we perform error estimation at each timestamp via Monte-Carlo sampling. We introduce an estimated error of 4% to account for the estimated uncertainty in the SPAN-I velocity measurement (3% ; Livi et al. 2022) and account for other systematic uncertainties. Therefore, at each timestamp, we generate a distribution of possible source surface longitudes for the propagation of the spacecraft trajectory down to the source surface height.

The total mapping uncertainty for each stream comes from these user inputs for both the ballistic propagation and PFSS modeling. To combine these uncertainties, we calculate the pooled standard deviation across all realizations generated from the uncertainty in v_{sw} used for ballistic propagation, the choice of source surface height, and magnetogram selection.

Figure 3 illustrates this mapping procedure for a representative solar wind stream observed during PSP Encounter 7 (January 17, 2021). Panel (a) presents the mean estimated photospheric footpoint locations (red) for this stream, with the total longitudinal and latitudinal uncertainties (white). These footpoints are overlaid on an EUV observation of the corona (from SDO/AIA at 193 Å) taken at the midpoint of the stream interval. Panels (b), (c), and (d) show the in-situ measurements of the radial solar wind speed V_r , radial magnetic field B_r , and the magnitude of the cross helicity $|\sigma_C|$, respectively, for this stream.

Figure 4 displays the individual contributions to the total footpoint location uncertainty for same stream as in Figure 3. Each panel focuses on a single source of uncertainty. We obtain these values by decomposing the total uncertainty into the contributions from (a) ballistic backmapping, (b) source surface height, and (c) magnetogram selection. Once again, the estimated footpoints are shown in red with the respective uncertainty bars in white, overlaid on the same SDO/AIA image. As expected, we see that the largest uncertainty comes from the choice of source surface height (Ervin et al. 2024a).

We can then examine the total longitudinal and latitudinal uncertainty for all 646 identified SASW streams, shown in Figure 5. Most of the population has relatively small uncertainty that sits in the dense corner of the figure, with median uncertainties of 1.80° in longitude and 1.83° in latitude. However, both distributions are skewed toward much larger values, with 5th to 95th percentile ranges of 0.18° to 19.4° in longitude and 0.19° to 30.5° in latitude. The extended, structured tails that reach larger uncertainties are likely due to differences in the model inputs, such as the magnetogram choices, producing large changes in magnetic connectivity for specific streams specifically when streams map near the open-closed boundary and a change in connectivity jumps over a larger, closed structure. Overall, most of the identified source region footpoints appear to be stable under common variations in model inputs, demonstrating the ballistic propagation and PFSS model pipeline to be generally reliable. However, the small subset of points with substantially larger uncertainties is notable and should be interpreted more carefully.

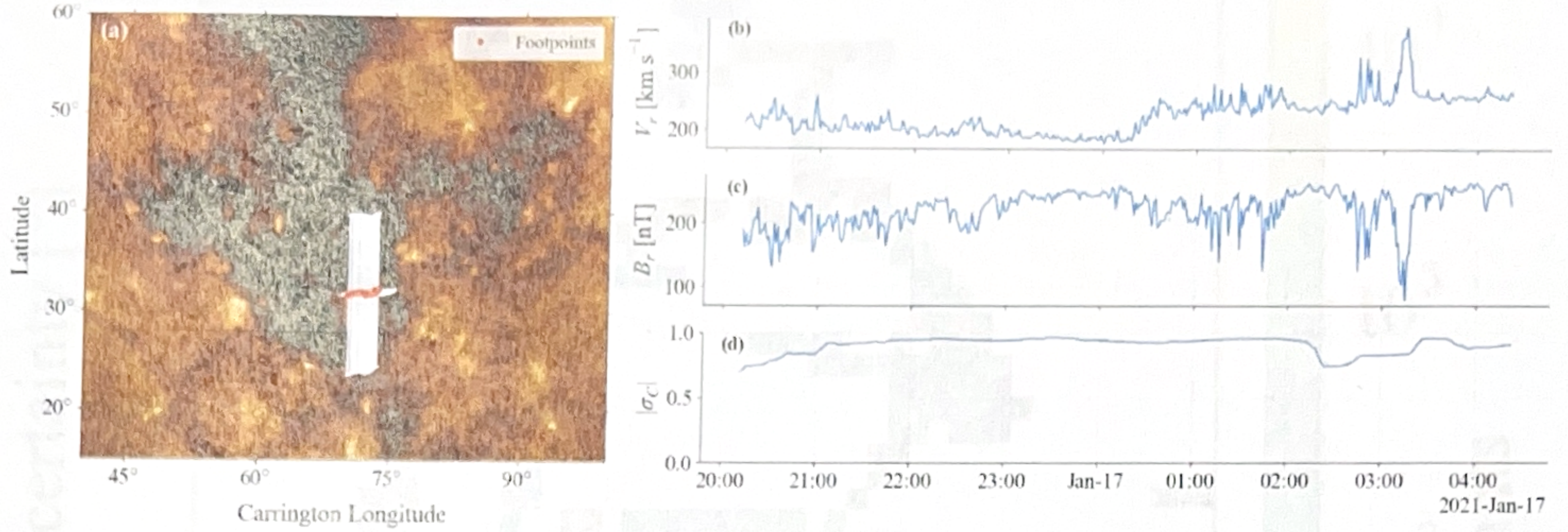


Figure 3. Panel (a) shows the estimated footpoint locations for a representative identified SASW stream on January 17, 2021 plotted over a SDO/AIA 193 Å image taken near the midpoint of the interval. The red markers indicate the mean footpoint locations and the white bars show the overall longitudinal and latitudinal uncertainty. Panels (b)-(d) show the timeseries of the corresponding in-situ measurements during the stream interval, including the radial speed v_r , radial magnetic field B_r , and the absolute value of the cross helicity $|\sigma_C|$.

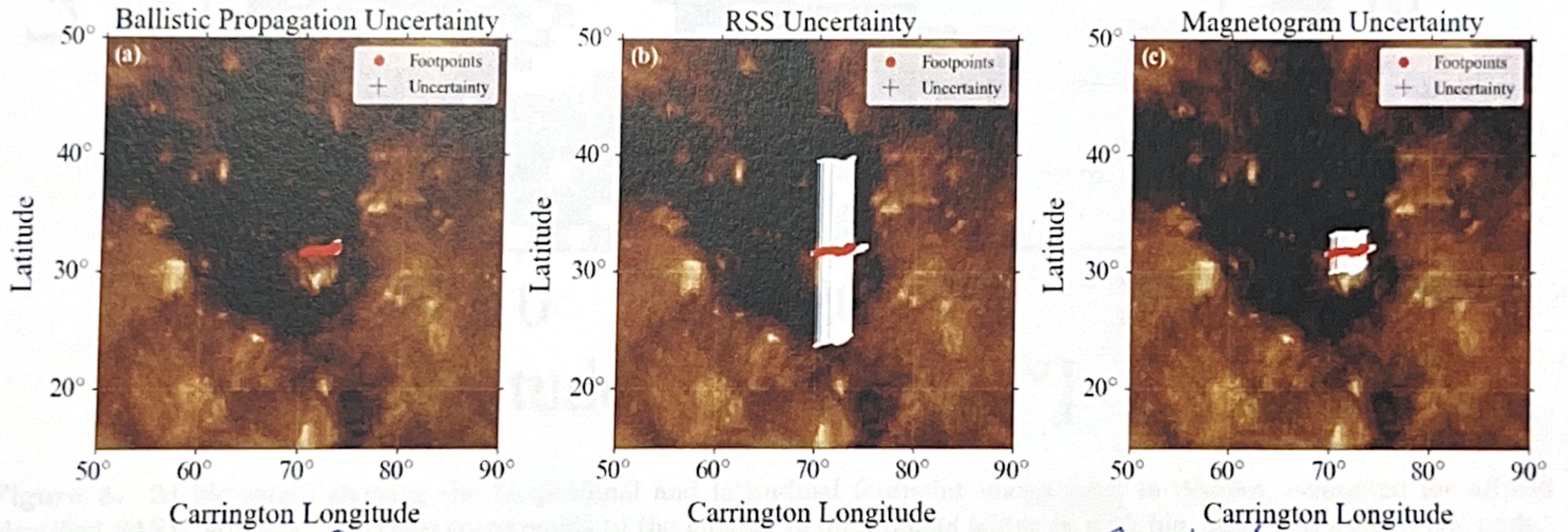


Figure 4. Figure illustrating the individual contributions to the estimated footpoint uncertainty for the stream shown in Figure 3. Each Panel shows the mapped foot point location in red with various uncertainties in white depending of the source of error. The background image in each panel is the same SDO/AIA 193 Å observation used in Figure 3. Panel (a) shows the uncertainty associated with ballistic backmapping. Panel (b) shows the uncertainty due to different choices of PFSS source surface heights. Panel (c) presents the uncertainty from magnetogram selection.

3.1. Source Region Parameters

We use our mapped photospheric footpoint estimates for each solar wind stream to extract source region parameters to characterize the magnetic topology and environment of the originating coronal region. We derive these parameters using the PFSS model output and remote observations that are transformed into the same Carrington coordinate system.

The magnetic expansion factor, f_s , is obtained directly from the PFSS solution for the open magnetic field line connected to the mapped source surface position. It is defined as

$$f_s = \left(\frac{R_0}{R_1} \right)^2 \frac{B_R(R_0, \lambda_0, \phi_0)}{B_R(R_1, \lambda_1, \phi_1)} \quad (3)$$

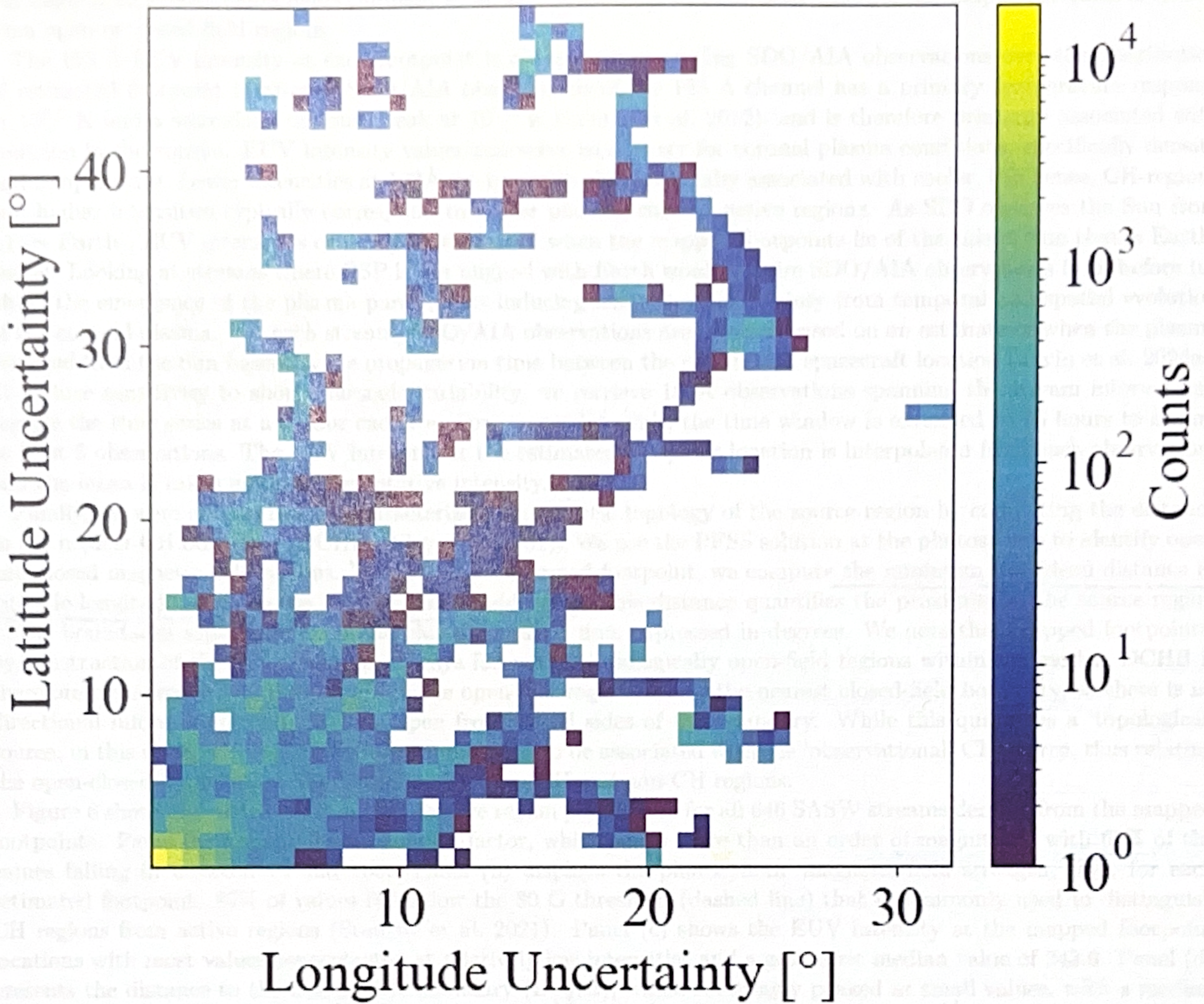


Figure 5. 2d histogram showing the longitudinal and latitudinal footpoint uncertainty, in degrees, computed for all 646 identified SASW streams. The color corresponds to the number of data points falling in each bin, shown on logarithmic scale.

where R_0 and R_1 correspond to the photospheric and source surface radii, respectively, and B_R is the radial magnetic field at latitude λ and longitude ϕ . The expansion factor quantifies how much an open magnetic flux tube diverges between the photosphere and the source surface (Wang & Sheeley 1990, 1997). Smaller f_s values indicate weaker magnetic expansion. There is an (empirically) established anti-correlation between solar wind speed and expansion factor (Wang & Sheeley 1990) that has been shown to be strongest for solar-minimum fast wind emerging from CH-like structures, across heliocentric distances (Dakeyo et al. 2024b). Fast, CH-origin wind typically has small expansion factors (Wang & Sheeley 1990), while small CHs and their boundaries have been shown to produce larger expansion factors (Wallace et al. 2020; Ervin et al. 2024b) and potentially slower wind speeds (Leer & Holzer 1980; Wang et al. 2012; Stansby et al. 2020b).

The photospheric magnetic field strength, B_0 , is determined by sampling the photospheric magnetogram at the estimated footpoint location for each mapped field line. The field strength at the footpoint is an important diagnostic of the source region, as open-field CH regions are often characterized by relatively weak photospheric fields, while active regions exhibit stronger fields. Previous studies have shown that a threshold of 30 G can be used to distinguish

Remember to
(consistently) use
the map as
David Stansby?

CH fields from active region fields (Stansby et al. 2021), allowing us to identify whether our mapped streams originate from open or closed field regions.

The 193 Å EUV intensity at each footpoint is obtained by sampling SDO/AIA observations over the distribution of estimated footpoint locations. SDO/AIA observations of the 193 Å channel has a primary temperature response at $10^{6.2}$ K and a secondary response peak at $10^{7.3}$ K (Lemen et al. 2012), and is therefore primarily associated with emission in the corona. EUV intensity values can serve as a proxy for coronal plasma conditions, specifically density and temperature. Lower intensities at 193Å are typically observationally associated with cooler, less dense, CH-regions and higher intensities typically correspond to hotter plasma, such as active regions. As SDO observes the Sun from L1 ($\sim$ Earth), EUV intensities can only be extracted when the mapped footpoints lie of the side of Sun that is Earth-facing. Looking at streams where PSP is not aligned with Earth would require SDO/AIA observations from before (or after) the emergence of the plasma parcel, thus inducing additional uncertainty from temporal and spatial evolution of the coronal plasma. For each stream, SDO/AIA observations are selected based on an estimate of when the plasma emerged from the Sun based on the propagation time between the corona and spacecraft location (Ervin et al. 2024a). To reduce sensitivity to short-timescale variability, we retrieve 193Å observations spanning the stream interval and sample the time series at a 3-hour cadence. For shorter intervals, the time window is extended to 15 hours to ensure at least 5 observations. The EUV intensity at the estimated footpoint location is interpolated from each observation, and the mean is taken as the representative intensity.

Finally, we were able to further characterize the magnetic topology of the source region by computing the distance to the nearest CH boundary (DCHB; Riley et al. 2001). We use the PFSS solution at the photosphere to identify open and closed magnetic field regions. Then, for each mapped footpoint, we compute the minimum Euclidean distance in latitude-longitude space to the nearest closed-field pixel. This distance quantifies the proximity of the source region to the boundaries separating open and closed magnetic flux, expressed in degrees. We note that mapped footpoints, by construction of the PFSS solution, always fall within topologically open-field regions within the model. DCHB is therefore measured outward from within the open-flux region toward the nearest closed-field boundary, so there is no directional information distinguishing open from closed sides of the boundary. While this quantifies a ‘topological’ source, in this work, we consider the open flux region to be associated with the ‘observational’ CH-source, thus relating the open-closed boundary to the boundary between CH and non-CH regions.

Figure 6 shows the distribution of these source region parameters for all 646 SASW streams derived from the mapped footpoints. Panel (a) presents the expansion factor, which spans more than an order of magnitude, with 61% of the values falling in between 10 and 100. Panel (b) displays the photospheric magnetic field strength, $|B_0|$, for each estimated footpoint. 85% of values fall below the 30 G threshold (dashed line) that is commonly used to distinguish CH regions from active regions (Stansby et al. 2021). Panel (c) shows the EUV intensity at the mapped footpoint locations with most values concentrated at relatively low intensities and a geometric median value of 243.6. Panel (d) presents the distance to the nearest CH boundary (DCHB), which is strongly peaked at small values, with a median value of 0.86 ± 0.54 degrees.

Inferences? How about correlating the >30G streams in the other 3 panels? Assoc with large EUV, small EF, ...?

4. DISCUSSION

Ervin et al. (2025) reported spectral indices for ambient (Alfvénic and non-Alfvénic) wind streams in PSP Encounters 4 - 14, fitting 115,348 trace and magnitude spectra finding fits of $\alpha_B \sim -1.55 \pm 0.38$ and $\alpha_{|B|} \sim -1.28 \pm 0.61$. Our fitted trace spectral index $\alpha_B \sim -1.49$ is consistent with their result $\alpha_B \sim -1.55$, and prior results connecting fast, highly Alfvénic wind to $\sim -3/2$ spectral scalings (Chen et al. 2010). We show that this $-3/2$ scaling occurs in the near-Sun wind for SASW streams as well, consistent with prior results at near-Sun distances (Shi et al. 2021; Sioulas et al. 2023) and at 1 AU that connect the presence of coherent magnetic structures with $\sigma_B \sim -1$ (Bowen et al. 2018).

Our magnitude scaling $\alpha_{|B|} \sim -1.59$ is steeper than the $\alpha_{|B|} \sim -1.28 \pm 0.61$ reported in Ervin et al. (2025) for ambient wind observed by PSP. Dunn et al. (2023) has shown that in compressible fluctuations can lead to a steepening of $\alpha_{|B|}$ to $-5/3$, however additional work looking at the SASW dataset is necessary for definitive conclusions.

The source region parameters derived from PFSS mapping and remote observations indicate that SASW streams originate from open magnetic flux regions near CH boundaries. The footpoint magnetic field strengths mostly fall below 30 G, which has been found to be the threshold separating CH wind from active region sources in GONG magnetogram measurements (Stansby et al. 2021).

The EUV intensity distribution also supports this interpretation. In Ervin et al. (2024a), SASW footpoint intensities were compared to the distribution of intensities across full-disk AIA images, showing that SASW generally occupied

(or did you delete?)

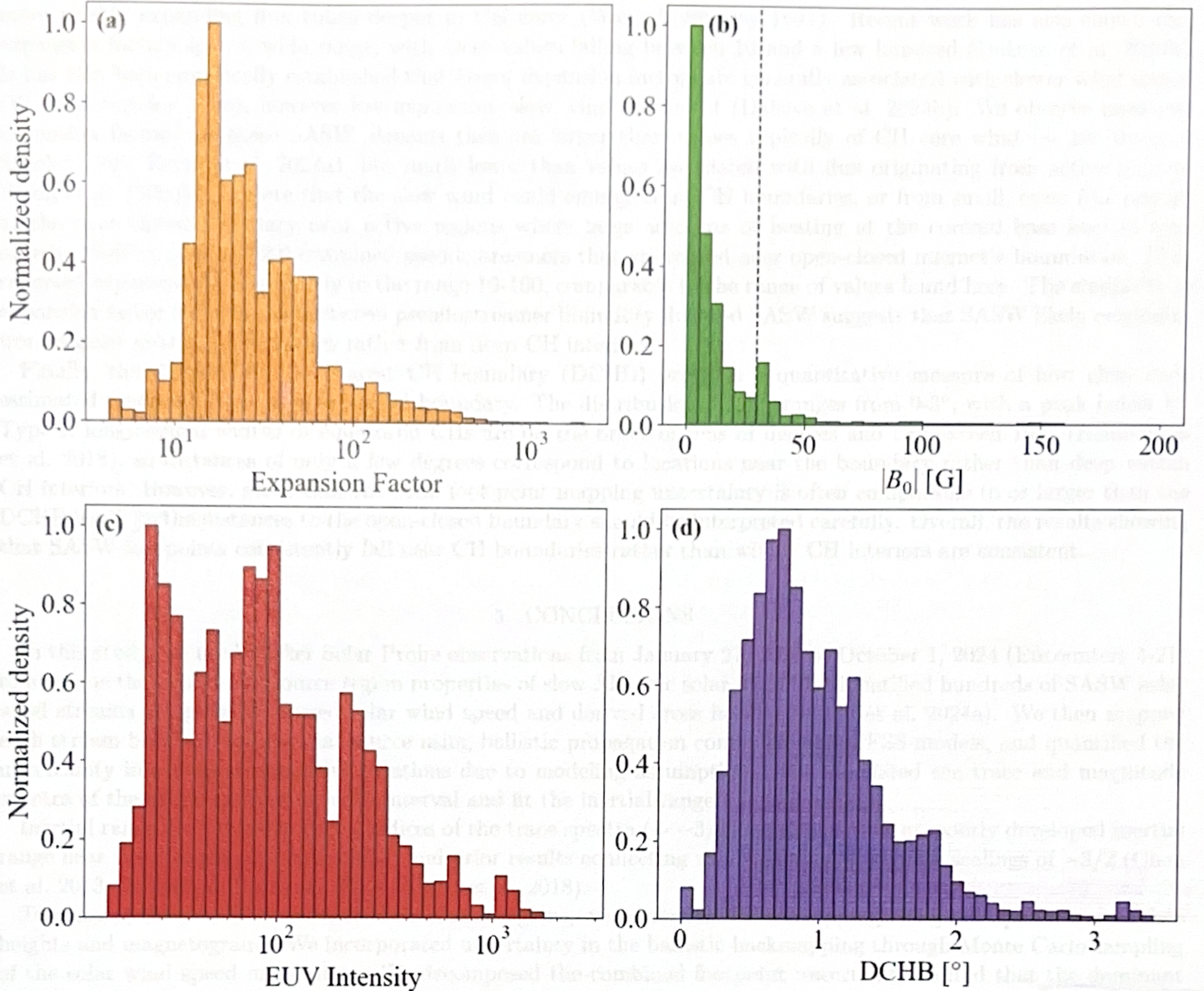


Figure 6. Distributions of derived source region parameters for all identified SASW streams. Panel (a) shows the magnetic expansion factor, f_s , associated with each mapped footpoint. Panel (b) shows the magnetic field strength at the mapped footpoint location, $|B_0|$, extracted from the corresponding magnetogram. The dashed vertical line marks the 30 G threshold to distinguish CH and active region wind streams. Panel (c) presents the EUV intensity at 193 Å taken at the mapped footpoint locations from SDO/AIA observations. Panel (d) shows the calculated distance to the nearest CH boundary (DCHB) from the mapped footpoint location.

the lower intensity portion of the distribution. Similarly, we find the SASW footpoints in this study form a similar low-intensity distribution with the majority of intensities falling below 10^3 . These lower values are consistent with cooler, darker, CH regions rather than bright active regions. However, the distribution spans a broader range than the distribution for fast solar wind (Ervin et al. 2024a), suggesting that SASW does not always originate deep within CH cores, but from regions near the open-closed boundary. It is important to note that projection effects, and brighter active regions can both preclude our ability to see the “true” source of the wind in EUV observations, and thus combining intensity values with other metrics is necessary.

The magnetic expansion factors further supports CH boundary origins for SASW. We find a median expansion factor of 58.4 with a majority of values ranging from 10-100. Prior studies have shown slow solar wind to be associated with rapidly diverging flux tubes located closer to CH boundaries (Ervin et al. 2024a), while fast solar wind emerges from

more weakly expanding flux tubes deeper in CH cores (Wang & Sheeley 1997). Recent work has also shown that expansion factors span a wide range, with most values falling between 10 and a few hundred (Dakeyo et al. 2024b). It has also been empirically established that larger expansion factors are generally associated with slower wind speeds (Wang & Sheeley 1990), however low expansion, slow wind does exist (Dakeyo et al. 2024b). We observe moderate expansion factors for these SASW streams that are larger than values typically of CH core wind (~ 10 ; Wang & Sheeley 1997; Ervin et al. 2024a), but much lower than values associated with flux originating from active regions. Wang et al. (2009) postulate that the slow wind could emerge from CH boundaries, or from small, open flux regions at the open-closed boundary near active regions where large amounts of heating at the coronal base lead to slow speeds. Wallace et al. (2020) examined pseudostreamers that are rooted near open-closed magnetic boundaries. They reported expansion factors mostly in the range 10-100, comparable to the range of values found here. The similarity in expansion factor distributions between pseudostreamer boundary flux and SASW suggests that SASW likely originates from regions near CH boundaries rather than deep CH interiors.

Finally, the distance to the nearest CH boundary (DCHB) provides a quantitative measure of how close each estimated footpoint is to an open-closed boundary. The distribution mostly ranges from $0-3^\circ$, with a peak below 1° . Typical longitudinal widths of equatorial CHs are on the order of tens of degrees and can exceed 100° (Heinemann et al. 2018), so distances of only a few degrees correspond to locations near the boundary rather than deep within CH interiors. However, given that the total foot point mapping uncertainty is often comparable to or larger than the DCHB itself, the distances to the open-closed boundary should be interpreted carefully. Overall, the results showing that SASW footpoints consistently fall near CH boundaries rather than within CH interiors are consistent.

5. CONCLUSIONS

In this study, we used Parker Solar Probe observations from January 27, 2020 to October 1, 2024 (Encounters 4-21) to examine the in-situ and source region properties of slow Alfvénic solar wind. We identified hundreds of SASW solar wind streams using the measured solar wind speed and derived cross helicity (Ervin et al. 2024a). We then mapped each stream back to their coronal source using ballistic propagation combined with PFSS models, and quantified the uncertainty in estimated footpoint locations due to modeling assumptions. We calculated the trace and magnitude spectra of the magnetic field for each interval and fit the inertial range spectral indices.

Inertial range fits showed spectral indices of the trace spectra ($\sim -3/2$) consistent with an poorly developed inertial range near the Sun (Sioulas et al. 2023) and prior results connecting wind with $\sigma_R \sim -1$ with scalings of $-3/2$ (Chen et al. 2013; Podesta & Borovsky 2010; Bowen et al. 2018).

To connect the SASW streams to their source regions, we performed PFSS mapping using multiple source surface heights and magnetograms. We incorporated uncertainty in the ballistic backmapping through Monte Carlo sampling of the solar wind speed uncertainty. We decomposed the combined footpoint uncertainty to find that the dominant contributor to mapping error is the assumed PFSS source surface height, followed by magnetogram selection, with relatively small contributions from ballistic propagation. Across the full sample of 646 streams, we find median total footpoint uncertainties of 1.80° in longitude and 1.83° in latitude, with a subset of streams with much larger uncertainties exceeding 20° .

The source-region parameters derived from the mapped footpoints indicate that SASW streams primarily originate from open magnetic flux regions near the open-closed (observationally CH) boundaries. The magnetic expansion factors span a broad range of values, consistent with moderately expanding flux tubes, larger than those typically associated with CH core wind but smaller than those associated with active region sources. The footpoint magnetic field strengths mostly fall below the 30 G threshold associated with CH wind (Stansby et al. 2021), the lower EUV intensities correspond with CH sources. In addition, the mapped footpoints fall within a few degrees of the PFSS open-closed boundary. Together, these indicate that SASW is most commonly connected to open magnetic flux near the open-closed boundary (observationally CH-AR boundaries) rather than deep within regions of open flux (observationally CH structures).

Future work using more sophisticated models and a larger dataset could improve the statistics on this work. Other parameters such as elemental composition to study the first ionization potential (FIP; Laming 2015) effect and heavy ion charge states could provide additional insight into sources and release mechanisms. Observations from Solar Orbiter over a range of heliocentric distances could be used to do so. Complimentary studies of the proton specific entropy, which has shown to be a proxy for charge state ratios (Pagel et al. 2004; Nakhleh et al. 2026; Collard et al. 2025), could be done with both the PSP and Solar Orbiter near-Sun datasets.

*Only became the bands ya set of
if used in the bands ya set of
Magnetism might*

6. ACKNOWLEDGMENTS

J.C. and T.E. acknowledge funding from NASA contract NNN06AA01C. T.E. acknowledges funding from The Chuck Lorre Family Foundation Big Bang Theory Graduate Fellowship. J.H. acknowledges the support by NASA grant 80NSSC23K0737.

The FIELDS and SWEAP experiments on the Parker spacecraft was designed and developed under NASA contract NNN06AA01C. We acknowledge the NASA Parker Solar Probe Mission, the FIELDS team led by S. D. Bale, and the SWEAP team led by M. Stevens for use of data.

This research used version 4.1.6 of the SunPy open source software package (Community et al. 2020), and made use of HelioPy, a community-developed Python package for space physics (Stansby et al. 2022).

Software: Astropy (Astropy Collaboration et al. 2013, 2018, 2022), heliopy (Stansby et al. 2022), matplotlib (Hunter 2007), numpy (Harris et al. 2020), pandas (Wes McKinney 2010), sunkit-magex (Stansby et al. 2020), pySPEDAS (Angelopoulos et al. 2019), scipy (Virtanen et al. 2020), spiceypy (Annex et al. 2020), SunPy (Community et al. 2020)

REFERENCES

- Abbo, L., Ofman, L., Antiochos, S. K., et al. 2016, SSRv, 201, 55, doi: 10.1007/s11214-016-0264-1
- Alberti, T., Laurenza, M., Consolini, G., et al. 2020, ApJ, 902, 84, doi: 10.3847/1538-4357/abb3d2
- Alterman, B. L., & D'Amicis, R. 2025, ApJL, 982, L40, doi: 10.3847/2041-8213/adb48e
- Altschuler, M. D., & Newkirk, G. 1969, SoPh, 9, 131, doi: 10.1007/BF00145734
- Angelopoulos, V., Cruce, P., Drozdov, A., et al. 2019, Space Science Reviews, 215, 9, doi: 10.1007/s11214-018-0576-4
- Annex, A., Pearson, B., Seignovert, B., et al. 2020, The Journal of Open Source Software, 5, 2050, doi: 10.21105/joss.02050
- Arden, W. M., Norton, A. A., & Sun, X. 2014, Journal of Geophysical Research (Space Physics), 119, 1476, doi: 10.1002/2013JA019464
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123, doi: 10.3847/1538-3881/aabc4f
- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, ApJ, 935, 167, doi: 10.3847/1538-4357/ac7c74
- Badman, S. T., Bale, S. D., Martínez Oliveros, J. C., et al. 2020, ApJS, 246, 23, doi: 10.3847/1538-4365/ab4da7
- Badman, S. T., Bale, S. D., Rouillard, A. P., et al. 2021, A&A, 650, A18, doi: 10.1051/0004-6361/202039407
- Badman, S. T., Brooks, D. H., Poirier, N., et al. 2022, ApJ, 932, 135, doi: 10.3847/1538-4357/ac6610
- Badman, S. T., Riley, P., Jones, S. I., et al. 2023, Journal of Geophysical Research (Space Physics), 128, e2023JA031359, doi: 10.1029/2023JA031359
- Bale, S. D., Goetz, K., Harvey, P. R., et al. 2016, SSRv, 204, 49, doi: 10.1007/s11214-016-0244-5
- Bowen, T. A., Mallet, A., Bonnell, J. W., & Bale, S. D. 2018, ApJ, 865, 45, doi: 10.3847/1538-4357/aad95b
- Chen, C. H. K., Bale, S. D., Salem, C. S., & Maruca, B. A. 2013, The Astrophysical Journal, 770, 125, doi: 10.1088/0004-637X/770/2/125
- Chen, C. H. K., Horbury, T. S., Schekochihin, A. A., et al. 2010, PhRvL, 104, 255002, doi: 10.1103/PhysRevLett.104.255002
- Chen, C. H. K., Bale, S. D., Bonnell, J. W., et al. 2020, ApJS, 246, 53, doi: 10.3847/1538-4365/ab60a3
- Chen, C. H. K., Chandran, B. D. G., Woodham, L. D., et al. 2021, A&A, 650, L3, doi: 10.1051/0004-6361/202039872
- Collard, J. D., Ervin, T., Dewey, R. M., et al. 2025, arXiv e-prints, arXiv:2511.14938, doi: 10.48550/arXiv.2511.14938
- Community, T. S., Barnes, W. T., Bobra, M. G., et al. 2020, The Astrophysical Journal, 890, 68, doi: 10.3847/1538-4357/ab4f7a
- Dakeyo, J. B., Badman, S. T., Rouillard, A. P., et al. 2024a, A&A, 686, A12, doi: 10.1051/0004-6361/202348892
- Dakeyo, J.-B., Maksimovic, M., Démoulin, P., Halekas, J., & Stevens, M. L. 2022, The Astrophysical Journal, 940, 130, doi: 10.3847/1538-4357/ac9b14
- Dakeyo, J. B., Rouillard, A. P., Réville, V., et al. 2024b, A&A, 691, A77, doi: 10.1051/0004-6361/202451272
- D'Amicis, R., & Bruno, R. 2015, ApJ, 805, 84, doi: 10.1088/0004-637X/805/1/84
- D'Amicis, R., Bruno, R., & Bavassano, B. 2011, Journal of Atmospheric and Solar-Terrestrial Physics, 73, 653, doi: 10.1016/j.jastp.2011.01.012
- D'Amicis, R., Bruno, R., Panasenco, O., et al. 2021, A&A, 656, A21, doi: 10.1051/0004-6361/202140938
- D'Amicis, R., Velli, M., Panasenco, O., et al. 2025, A&A, 693, A243, doi: 10.1051/0004-6361/202451686

- Dunn, C., Bowen, T. A., Mallet, A., Badman, S. T., & Bale, S. D. 2023, *ApJ*, 958, 88, doi: 10.3847/1538-4357/ad03ef
- Ervin, T., Jaffarove, K., Badman, S. T., et al. 2024a, *ApJ*, 975, 156, doi: 10.3847/1538-4357/ad7d00
- Ervin, T., Bale, S. D., Badman, S. T., et al. 2024b, *ApJ*, 969, 83, doi: 10.3847/1538-4357/ad4604
- . 2024c, *ApJ*, 972, 129, doi: 10.3847/1538-4357/ad57c4
- Ervin, T., Mallet, A., Eriksson, S., et al. 2025, *ApJL*, 992, L11, doi: 10.3847/2041-8213/ac0b56
- Fox, N. J., Velli, M. C., Bale, S. D., et al. 2016, *SSRv*, 204, 7, doi: 10.1007/s11214-015-0211-6
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357, doi: 10.1038/s41586-020-2649-2
- Harvey, J. W., Hill, F., Hubbard, R. P., et al. 1996, *Science*, 272, 1284, doi: 10.1126/science.272.5266.1284
- Heinemann, S. G., Temmer, M., Hofmeister, S. J., Veronig, A. M., & Vennerström, S. 2018, *ApJ*, 861, 151, doi: 10.3847/1538-4357/aac897
- Hoeksema, J. T. 1984, PhD thesis, Stanford University, California
- Huang, J., Larson, D. E., Ervin, T., et al. 2025, *ApJL*, 986, L28, doi: 10.3847/2041-8213/ade0ac
- Huang, Z., Tóth, G., Huang, J., et al. 2024, *ApJL*, 965, L1, doi: 10.3847/2041-8213/ad3547
- Hundhausen, A. J. 1968, *Space Science Reviews*, 8, 690, doi: 10.1007/BF00175116
- Hundhausen, A. J. 1972, *Coronal Expansion and Solar Wind*, doi: 10.1007/978-3-642-65414-5
- Hunter, J. D. 2007, *Computing in Science & Engineering*, 9, 90, doi: 10.1109/MCSE.2007.55
- Koukras, A., Dolla, L., & Keppens, R. 2025, *A&A*, 694, A134, doi: 10.1051/0004-6361/202244327
- Kumar, S., Srivastava, N., Talpeanu, D.-C., et al. 2025, *Journal of Space Weather and Space Climate*, 15, 24, doi: 10.1051/swsc/2025021
- Laming, J. M. 2015, *Living Reviews in Solar Physics*, 12, 2, doi: 10.1007/lrsp-2015-2
- Laming, J. M. 2017, *ApJ*, 844, 153, doi: 10.3847/1538-4357/aa7cf1
- Landi, E., Gruesbeck, J. R., Lepri, S. T., Zurbuchen, T. H., & Fisk, L. A. 2012, *ApJ*, 761, 48, doi: 10.1088/0004-637X/761/1/48
- Leer, E., & Holzer, T. E. 1980, *J. Geophys. Res.*, 85, 4681, doi: 10.1029/JA085iA09p04681
- Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, *SoPh*, 275, 17, doi: 10.1007/s11207-011-9776-8
- Livi, R., Larson, D. E., Kasper, J. C., et al. 2022, *The Astrophysical Journal*, 938, 138, doi: 10.3847/1538-4357/ac93f5
- Maksimovic, M., Bale, S. D., Berčič, L., et al. 2020, *ApJS*, 246, 62, doi: 10.3847/1538-4365/ab61fc
- Marsch, E., Rosenbauer, H., Schwenn, R., Muehlhaeuser, K.-H., & Denskat, K. U. 1981, *J. Geophys. Res.*, 86, 9199, doi: 10.1029/JA086iA11p09199
- McComas, D. J., Ebert, R. W., Elliott, H. A., et al. 2008, *Geophys. Res. Lett.*, 35, L18103, doi: 10.1029/2008GL034896
- McComas, D. J., Goldstein, R., Gosling, J. T., & Skoug, R. M. 2001, *SSRv*, 97, 99, doi: 10.1023/A:1011826111330
- McComas, D. J., Riley, P., Gosling, J. T., Balogh, A., & Forsyth, R. 1998, *J. Geophys. Res.*, 103, 1955, doi: 10.1029/97JA01459
- Nakhleh, A. J., Viall, N. M., Lepri, S. T., & Raines, J. M. 2026, *Journal of Geophysical Research: Space Physics*, doi: 10.1029/2025JA034762
- Neugebauer, M., Liewer, P. C., Smith, E. J., Skoug, R. M., & Zurbuchen, T. H. 2002, *Journal of Geophysical Research (Space Physics)*, 107, 1488, doi: 10.1029/2001JA000306
- Neugebauer, M., & Snyder, C. W. 1962, *Science*, 138, 1095, doi: 10.1126/science.138.3545.1095.a
- . 1966, *J. Geophys. Res.*, 71, 4469, doi: 10.1029/JZ071i019p04469
- Nolte, J. T., & Roelof, E. C. 1973, *SoPh*, 33, 241, doi: 10.1007/BF00152395
- Pagel, A. C., Crooker, N. U., Zurbuchen, T. H., & Gosling, J. T. 2004, *Journal of Geophysical Research (Space Physics)*, 109, A01113, doi: 10.1029/2003JA010010
- Panasenco, O., Velli, M., D'Amicis, R., et al. 2020, *ApJS*, 246, 54, doi: 10.3847/1538-4365/ab61f4
- Parashar, T. N., Goldstein, M. L., Maruca, B. A., et al. 2020, *The Astrophysical Journal Supplement Series*, 246, 58, doi: 10.3847/1538-4365/ab64e6
- Parker, E. N. 1958, *ApJ*, 128, 664, doi: 10.1086/146579
- Perrone, D., D'Amicis, R., De Marco, R., et al. 2020, *A&A*, 633, A166, doi: 10.1051/0004-6361/201937064
- Podesta, J. J., & Borovsky, J. E. 2010, *Physics of Plasmas*, 17, 112905, doi: 10.1063/1.3505092
- Riley, P., Linker, J. A., & Mikić, Z. 2001, *J. Geophys. Res.*, 106, 15889, doi: 10.1029/2000JA000121
- Riley, P., Linker, J. A., Mikić, Z., et al. 2006, *ApJ*, 653, 1510, doi: 10.1086/508565
- Schatten, K. H., Wilcox, J. M., & Ness, N. F. 1969, *SoPh*, 6, 442, doi: 10.1007/BF00146478
- Shi, C., Velli, M., Bale, S. D., et al. 2022a, *Physics of Plasmas*, 29, 122901, doi: 10.1063/5.0124703
- Shi, C., Velli, M., Tenerani, A., Réville, V., & Rappazzo, F. 2022b, *ApJ*, 928, 93, doi: 10.3847/1538-4357/ac558b

- Shi, C., Velli, M., Panasenco, O., et al. 2021, *A&A*, 650, A21, doi: 10.1051/0004-6361/202039818
- Sioulas, N., Huang, Z., Shi, C., et al. 2023, *ApJL*, 943, L8, doi: 10.3847/2041-8213/acaeff
- Snyder, C. W., & Neugebauer, M. 1966, *The Solar Wind* (Pergamon Press)
- Stansby, D., Baker, D., Brooks, D. H., & Owen, C. J. 2020a, *A&A*, 640, A28, doi: 10.1051/0004-6361/202038319
- Stansby, D., Green, L. M., van Driel-Gesztelyi, L., & Horbury, T. S. 2021, *Solar Physics*, 296, 116, doi: 10.1007/s11207-021-01861-x
- Stansby, D., Matteini, L., Horbury, T. S., et al. 2020b, *MNRAS*, 492, 39, doi: 10.1093/mnras/stz3422
- Stansby, D., Yeates, A., & Badman, S. 2020, *Journal of Open Source Software*, 5, 2732, doi: 10.21105/joss.02732
- Stansby, D., Rai, Y., Argall, M., et al. 2022
- Viall, N. M., & Borovsky, J. E. 2020, *Journal of Geophysical Research (Space Physics)*, 125, e26005, doi: 10.1029/2018JA026005
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *Nature Methods*, 17, 261, doi: 10.1038/s41592-019-0686-2
- Wallace, S., Arge, C. N., Viall, N., & Pihlström, Y. 2020, *The Astrophysical Journal*, 898, 78, doi: 10.3847/1538-4357/ab98a0
- Wang, Y. M., Grappin, R., Robbrecht, E., & Sheeley, N. R., J. 2012, *ApJ*, 749, 182, doi: 10.1088/0004-637X/749/2/182
- Wang, Y.-M., Ko, Y.-K., & Grappin, R. 2009, *The Astrophysical Journal*, 691, 760, doi: 10.1088/0004-637X/691/1/760
- Wang, Y. M., & Sheeley, N. R., J. 1990, *ApJ*, 355, 726, doi: 10.1086/168805
- . 1997, *Geophys. Res. Lett.*, 24, 3141, doi: 10.1029/97GL53305
- Wes McKinney. 2010, in *Proceedings of the 9th Python in Science Conference*, ed. Stéfan van der Walt & Jarrod Millman, 56 – 61, doi: 10.25080/Majora-92bf1922-00a
- Worden, J., & Harvey, J. 2000, *Solar Physics*, 195, 247, doi: 10.1023/A:1005272502885
- Yardley, S. L., Brooks, D. H., D'Amicis, R., et al. 2024, *Nature Astronomy*, doi: 10.1038/s41550-024-02278-9