Geometry of Magnetic Fluctuations near the Sun from the Parker Solar Probe

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Abstract

Solar wind magnetic fluctuations exhibit anisotropy due to the presence of a mean magnetic field in the form of the Parker spiral. Close to the Sun, direct measurements were not available until the recently launched Parker Solar Probe (PSP) mission. The nature of the anisotropy and geometry of the magnetic fluctuations play a fundamental role in dissipation processes and in the transport of energetic particles in space. Using PSP data, we present measurements of the geometry and anisotropy of the inner heliosphere magnetic fluctuations, from fluid to kinetic scales. The results are surprising and different from 1 au observations. We find that fluctuations evolve characteristically with size scale. However, unlike 1 au solar wind, at the outer scale, the fluctuations are dominated by wavevectors quasi-parallel to the local magnetic field. In the inertial range, average wavevectors become less field aligned, but still remain more field aligned than near-Earth solar wind. In the dissipation range, the wavevectors become almost perpendicular to the local magnetic field in the dissipation range, to a much higher degree than those indicated by 1 au observations. We propose that this reduced degree of anisotropy in the outer scale and inertial range is due to the nature of large-scale forcing outside the solar corona.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Interplanetary turbulence (830); Magnetic fields (994); Solar corona (1483)

1. Introduction

As the solar wind expands from the corona into interplanetary space, the solar magnetic field systematically gives up control of the coronal plasma, and in situ dynamical processes, such as turbulence, begin to manifest. In particular, when the flow speed exceeds the local Alfvén speed (known as the Alfvén critical point), the magnetically controlled outer corona transforms into the kinetic-energy-dominated solar wind, and large-scale, more isotropic turbulence starts to develop (DeForest et al. 2016a). This inner heliosphere solar wind, outside the Alfvén critical region, is sometimes called dynamically young or nascent solar wind. The Parker Solar Probe (PSP), even during its first five orbits, provides the first opportunity to study the young solar wind with in situ data (McComas et al. 2007; Fox et al. 2016).

Plasma turbulence, in the presence of a mean magnetic field, exhibits several types of anisotropies (Shebalin et al. 1983), including wavevector anisotropy and variance anisotropy (Parashar et al. 2016; Matteini et al. 2020). In the solar wind, the Parker spiral (Parker 1958) acts as a mean magnetic field, and therefore, both anisotropies are observed (Horbury et al. 2012; Oughton et al. 2015). Further, since the magnetic fluctuations are distributed over a broad range of length scales, the nature of anisotropy changes across scales. The spatial scales can be roughly grouped into three broad categories, from largest to smallest—outer scale or energy-containing scale, inertial range, and kinetic scale. Here, we study the nature of wavevector anisotropy near the Sun across this wide range of scales.

We perform a slab+2D decomposition, which approximates the anisotropy in solar wind as the superposition of slab and 2D fluctuations (Zank & Matthaeus 1992, 1993; Oughton 1993; Bieber et al. 1996; Zank et al. 2017). The slab model assumes that wavevectors ($k$) are parallel to $B_0$, and the 2D model assumes that $k$ is perpendicular to $B_0$. From incompressibility, the slab fluctuations are strictly transverse to $B_0$. Clearly, the slab+2D framework is highly idealized, with excitations restricted to modes either on the $k_\parallel$ axis or in the $k_z = 0$ plane. Thus, most of k-space is unpopulated, which may appear as an oversimplification. Measurements and simulations show that turbulence power lies in between with a nontrivial distribution. Various models for this power distribution are discussed in the community (Shebalin et al. 1983; Sridhar & Goldreich 1994; Goldreich & Sridhar 1995; Galtier et al. 2000). Nevertheless, the slab+2D model has fared very well in matching observations, suggesting that it captures the important elements of the physics.

1 au solar wind observations indicate superposition of both slab and 2D fluctuations from the Maltese–Cross plots (Matthaeus et al. 1990). Using the technique developed in Bieber et al. (1996; which became known as the Bieber test), several studies (e.g., Smith et al. 2006; Hamilton et al. 2008; Podesta et al. 2009; Osman & Horbury 2009; Leamon et al. 1998a; 1998b) have now established that 2D fluctuations represent the dominant component (~80% of the total energy) at this heliocentric distance. However, wind speed and latitude variation show some variability (Smith 2003; Dasso et al. 2005). The nature of slab and 2D fluctuations close to the Sun are not well known (Cranmer 2018; Adhikari et al. 2020). Here, we study the relative strength of the slab and 2D components in the inner heliosphere from outer scale to the ion kinetic range.

We analyze PSP data within the first five solar encounters (defined as the period when the spacecraft is within 0.25 au; Guo et al. 2021). Following Bandyopadhyay et al. (2020a), Chen et al. (2021), and Parashar et al. (2020), we divide each encounter into intervals of about 1.5 hours in duration, spanning several correlation lengths (see Table 1). We use publicly available Level-2 PSP/Fields Experiment (FIELDS) flux-gate magnetometer (MAG; Bale et al. 2016, 2019) data for the correlation and inertial scale and Level-3 “moments” data from the Solar Probe Cup (SPC; Kasper et al. 2016, 2019; Case et al. 2020) in the PSP/Solar Wind Electrons Alphas and

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Protons (SWEAP) archives to obtain proton density and radial speed.

2. Correlation Scale Anisotropy

We begin by evaluating the 2D correlation function $R(r_\perp, r_\parallel)$ as a function of spatial scales parallel and perpendicular to $B_0$ to infer the nature of the anisotropy at the outer scale. We rotate the magnetic field data into a mean field coordinate system for each interval (Belcher & Davis 1971, 197; Bieber et al. 1996). In this coordinate system, $\tilde{z} = B_0/|B_0|$ defines the mean field unit vector, $\tilde{y} = -\tilde{z} \times \tilde{R}/|\tilde{z} \times \tilde{R}|$, where $\tilde{R}$ is the radial direction, and $\tilde{x} = \tilde{y} \times \tilde{z}$. The two-point correlation function is defined as $R(r) = (\hat{b}(x) \cdot \hat{b}(x + r))$. Near the Sun, due to the low ratio of the Alfvén speed to solar wind speed, Taylor’s hypothesis may not always be valid, especially at electron scales (Huang & Sahraoui 2019). Through the first five encounters, Taylor’s frozen-in hypothesis is moderately maintained (Chasapis et al. 2019); here we limit our analyses to magnetohydrodynamic (MHD) and ion kinetic scales. Therefore, we calculate the spatial lag $r$ from temporal lag $\tau$, using $r = V_{SW} \tau$ (Taylor 1938; Jokipii 1973). Here $V_{SW}$ is the mean solar wind speed in each interval. We employ a Blackman–Tukey technique (Blackman & Tukey 1958; Matthaeus & Goldstein 1982) to compute the correlation functions $R(r)$ for different values of the spatial lag $r$, with the maximum lag chosen as one-fifth of the interval length. Then, we project the spatial separation $r$ (radial, as it emerges from a frozen-in flow) onto a 2D mesh spanned by $r_\parallel(=r \cos \theta)$; where $\theta$ is the angle between $\tilde{R}$ and $B_0$ and $r_\perp(=r \sin \theta)$ (Matthaeus et al. 1990; Dasso et al. 2005, 200; Weygand et al. 2009; Osman et al. 2011) and accumulate the estimates of $R(r)$ onto it.

Figure 1 shows the correlation function contour levels obtained from the first five encounters of PSP. The figure indicates both slab and 2D fluctuations. The four-quadrant plot is produced by reflecting the data across the axes from the first quadrant. In order to combine data from different intervals, we have normalized the fluctuations to the variance (e.g., Milano et al. 2001).

Correlation lengths in the various angular bins (from $(r_\perp, r_\parallel)$ bins using $\tan \theta = r_\perp/r_\parallel$) can be estimated as the values of $r$ where the decreasing function $R(r)$ drops by exponential ($R(0)/e$; Smith et al. 2001). We consider all of the points in the angular bin $0^\circ \leq \theta \leq 25^\circ$ to calculate the parallel correlation length $L_\parallel$ and those in $75^\circ \leq \theta \leq 90^\circ$ to calculate the perpendicular correlation length $L_\perp$ fluctuations, respectively (Table 2).

Our results show that the correlation length along the magnetic field is ~40% smaller than that in the perpendicular direction. This result indicates that the outer scale fluctuations are anisotropic, and the slab component is dominant at the outer scale. Although near-Earth observations have earlier shown that slab fluctuations can dominate or be comparable to 2D fluctuations at large scales, those observations were obtained only for fast wind (Dasso et al. 2005; Weygand et al. 2011). Slow wind exhibits a dominant 2D component at the outer scale, and the ratio $L_\parallel/L_\perp > 1$ (Ruzi et al. 2010, 2011a, 2011b, 2014; Zhou & He 2021). PSP has sampled mostly slow wind during its first five solar encounters. Therefore, our result is in contrast with the 1 au observations. This suggests that the near-Sun slow wind is actually similar to fast wind at 1 au. This slow wind has had more time to evolve than the fast wind, so the two show significantly distinct properties at 1 au.

3. Inertial Range Anisotropy

Following Bieber et al. (1996) and Hamilton et al. (2008), we compute the ratio of energy associated with the slab ($E_s$) and 2D ($E_2$) components from the ratio of the spectra of the two perpendicular components, $P_{xx}$ and $P_{yy}$, and their power law index $q$:

$$P_{yy} = \frac{k_s^{-4q} + r' \left( \frac{2}{1 + |q|} \right) k_2^{-4q}}{k_x^2 - k_2^2}$$

where $k_2 = 2\sigma f/V_{SW} \cos \theta$ and $k_s = 2\sigma f/V_{SW} \sin \theta$, $f$ is the frequency in the spacecraft frame, and $r' = E_s/E_2$. One obtains from Equation (1)

$$r' = \left[ \tan \theta \right]^{-4q} \left( \frac{\rho_s}{\rho_x} - \frac{1}{2} \right) \left( \frac{1 + |q|}{\rho_s} \right)$$

where $r = E_s/(E_s+E_2) = 1/(1+r')$ is the fraction of energy contained in the slab component within the selected frequency band.
Power Law Indexes for Trace Spectra
\[ \langle q \rangle \pm \sigma_q \] Slab Energy Fraction \[ \langle r \rangle \pm \sigma_r \]

\[ -1.5646 \pm 0.0004 \] \[ 0.546 \pm 0.009 \]

Table 5
Averaged Parameters and Uncertainties in the Ion Kinetic Range

\[ \langle q \rangle \pm \sigma_q \] Slab Energy Fraction \[ \langle r \rangle \pm \sigma_r \]

\[ -2.109 \pm 0.003 \] \[ 0.136 \pm 0.003 \]

4. Kinetic Scale Anisotropy

To probe the nature of anisotropy in the dissipation range, we use SCaM data product of the FIELDS suite, which merges MAG and search-coil magnetometer (SCM) measurements (Bowen et al. 2020). This data set resolves the ion kinetic range sufficiently above the noise floor (signal-to-noise ratio $>5$; Huang et al. 2021). Due to an SCM anomaly in March 2019, the full SCaM data are available only for the first encounter. Therefore, our kinetic range analysis is limited to 2018 November 4 through 2018 November 7.

In the dissipation range, two distinct frequency bands are seen at the inner heliosphere from PSP (Huang et al. 2021): (i) an ion transition range ($f \sim 2-9$ Hz) and (ii) an ion kinetic range between the ion and electron scales ($f \sim 10-60$ Hz). Here, we fit the ion kinetic range in the band 10–60 Hz. We divide into 15-minute subintervals and calculate the energy partition to gather statistics. From Table 3, we find that the slab fraction is only $\sim 10\%$.

We note here that the average index in the kinetic range is different than previous results at 1 au (e.g., Huang & Sahraoui 2019) and the first PSP perihelion (Duan et al. 2021; Huang et al. 2021). A possible reason is that here we selected only intervals where the index of $P_{xx}$ and $P_{yy}$ were similar and then calculated the average, while the other studies calculated the total power spectrum without any such restrictions.

Figure 3 shows the average values of $P_{yy}/P_{xx}$ in the ion kinetic range for bins of $\theta$, along with the minimum $\chi^2$ curve. The resulting best-fit value of $r$ is consistent with the value obtained from the average analysis and it is smaller than the slab fraction energy computed for the inertial scale in the previous section. This result is consistent with most previous studies at 1 au (Podesta 2009; Sahraoui et al. 2010; Horbury et al. 2012) and the inner heliosphere (Duan et al. 2021), showing that the fluctuations become more anisotropic at small scales.
5. Discussion

Simulations show that the Maltese–Cross type patterns with the simultaneous presence of slab and 2D fluctuations do not arise naturally in a turbulent plasma, and such observations are possibly a consequence of either the initial condition or of averaging over different parcels of wind with each component (Ghosh et al. 1998). The PSP data, analyzed in the near-Sun environment where the solar wind has had less time to develop, shows more about the origin of the slab and 2D components (Zhu et al. 2020; Duan et al. 2021).

We propose the following scenario, which is summarized in Figure 4, to explain our new results. In the sub-Alfvénic solar corona, below the Alfvén region, the plasma is essentially quasi-2D (Zank et al. 2018, also see Matthaeus et al. 1999b, 1999a; Dmitruk et al. 2002; Verdini et al. 2009; Cranmer & Winebarger 2019). Therefore, the increase of the slab fraction in the outer scale and inertial range from PSP, compared to 1 au, suggests that there might be a transition region just beyond the Alfvén critical point, where the slab component is introduced and possibly amplified. The slab component is expected to increase due to the nature of mechanical forcing on the plasma parcels, presumably at large length scales. This slab forcing may be due to the shear, Kelvin–Helmholtz-like roll ups or waves (DeForest et al. 2016b; Ruffolo et al. 2020). It is possible that PSP is sampling outer part of this plasma.

Once the slab fluctuations are introduced at the forcing scales (outer scale), they eventually cascade to the inertial and kinetic scales, but that takes time. This may explain why PSP observations show increased slab fractions at the outer and inertial scales, but a reduced slab fraction at the kinetic range. Later, on the way to 1 au, most of the slab energy is converted to 2D energy via the anisotropic cascade at the inertial range. In the kinetic range, the 2D fraction is preferably dissipated and so the dissipation range is left with increased slab energy at 1 au. Later PSP orbits and future remote sensing and in situ missions such as the Polarimeter to UNify the Corona and Heliosphere (PUNCH) and Solar Orbiter will shed more light on these explanations.

The results of this paper provide new constraints on inner heliosphere plasma fluctuations that heat the solar wind and modulate the transport of Solar Energetic Particle (SEP; Giacalone et al. 2006; Ruffolo et al. 2008; Klein & Dalla 2017). Quantification of the 2D and slab energy ratio is crucial for understanding SEP propagation close to the Sun (Bieber et al. 1996; Droge 2003; Ruffolo et al. 2008; McComas et al. 2016; Bandyopadhyay et al. 2020b).

The correlation length and its anisotropy are important parameters for understanding the dynamics of a plasma system (Bandyopadhyay et al. 2018, 2019) and for determining whether the parameters of numerical models match those of...
the space plasmas that they model (Usmanov et al. 2014, 2018; Adhikari et al. 2019). The direct estimation of parallel and perpendicular correlation scales also provides key inputs for solar wind models.

Turbulence-transport-based solar wind models (Adhikari et al. 2015, 2017; Zank et al. 2017, 2018) often use 2D/slab decomposition. The results presented here are critical for these models. Finally, we expect that our results will eventually improve the day-to-day forecasting of space weather.

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