Magnetic and Velocity Fluctuations in the Near-Sun Region from 0.1–0.3 au Observed by Parker Solar Probe

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Abstract

The fluctuations observed in the slow solar wind at 1 au by the WIND spacecraft are shown by recent studies to consist of mainly magnetic-field directional turning and magnetic-velocity alignment structure (MVAS). How these structures are created has been a question because the nature of the fluctuations in the near-Sun region remains unknown. Here, we present an analysis of the measurements in the slow solar wind from 0.1–0.3 au by Parker Solar Probe during its first six orbits. We present the distributions in the $\sigma_{vb} - \sigma_r$ plane of both the occurrence and average amplitudes of the fluctuations, including the magnetic field, the velocity, and the Elsässer variables, where $\sigma_{vb}$ is the correlation coefficient between the magnetic and velocity fluctuations multiplied by the opposite sign of the radial component of the mean magnetic field and $\sigma_r$ is the normalized residual energy. We find that the dominant composition is the outward-propagating Alfvénic fluctuations. We find Alfvénic fluctuations with $\sigma_{vb} > 0.95$, in which the amplitudes of $z^r$ reach 60 km s$^{-1}$ and those of $z^f$ are close to the observational uncertainty. We also find a region with high $\sigma_{vb}$ and moderate minus $\sigma_r$ in which the fluctuations are considered MVAS being magnetic dominated with the amplitude of magnetic fluctuations reaching 60 km s$^{-1}$. We provide empirical relations between the velocity fluctuation amplitude and $\sigma_{vb}$. The comparison between these results and those observed at 1 au may provide some clues as to the nature and evolution of the fluctuations.

Unified Astronomy Thesaurus concepts: Slow solar wind (1873); Interplanetary turbulence (830)

1. Introduction

The identification of both fast solar wind originating from coronal holes and slow solar wind related to the streamer belt regions has been accepted for decades (e.g., McComas et al. 2008; Abbo et al. 2016). The slow solar wind typically has a low degree of Alfvénicity, being more strongly intermixed with structures of non-Alfvénic nature (Tu & Marsch 1995). The complexity of the composition of the fluctuations in the slow wind makes it more difficult to study. The nature of the fluctuations in the slow wind has long been a major research topic in the study of solar wind turbulence.

In situ measurements show that some slow solar wind bears some signatures of the fast solar wind (e.g., Zhao et al. 2009; D’Amicis & Bruno 2015; Perrone et al. 2020). Some slow solar wind are found to be highly Alfvénic (D’Amicis & Bruno 2015; Wang et al. 2019). Pure Alfvén waves are presented in the solar wind though very rare. Tu & Marsch (1993) found pure Alfvén waves at 0.3 au and Wang et al. (2012) found pure Alfvén waves at 1 au, but both in the fast solar wind. No pure Alfvén wave has yet been reported to exist in the slow solar wind. It remains unknown if the low degree of Alfvénicity in the slow wind found by WIND observations at 1 au and by Helios observations from 0.3–1 au (Tu & Marsch 1995) originates from the near-Sun region.

Tu & Marsch (1991) proposed the concept of magnetic-field directional turning (MFDT) for the first time, as being a kind of static magnetic structure with constant velocity, magnetic-field magnitude, and proton density. MFDT is convected by the solar wind and nearly has no velocity fluctuations, leading to the low values of the correlation between the magnetic and velocity fluctuations and highly negative normalized residual energy $\sigma_r$. The existence of MFDT is confirmed by Bavassano et al. (1998) and Bruno et al. (2007). The magnetic flux rope structure has a low $\sigma_c$ and also a highly negative $\sigma_r$ observed by Ulysses (Chen et al. 2018; Zhao et al. 2019) and Parker Solar Probe (PSP; Zhao et al. 2020, 2021). The relation between MFDT and magnetic flux rope needs to be studied. Tu et al. (2016) presented two cases with high correlation between the magnetic field and velocity fluctuations and low Alfvén ratio. Wang et al. (2020) suggested the concept of magnetic-velocity alignment structure (MVAS), which is magnetic-dominated structures with high correlation between magnetic-field fluctuations and velocity fluctuations.

Wang et al. (2020) investigated both MFDT and MVAS and analyzed their pixel averaged amplitude distributions of the fluctuations in the $C_{vb}$–$\sigma_r$ plane in the slow solar wind using WIND measurements at 1 au, where $C_{vb}$ is the correlation coefficient between magnetic-field and velocity fluctuations multiplied by the sign of the $x$ component of the mean field in geocentric solar ecliptic coordinates. Wang et al. (2020) found these fluctuations show the features of MFDT and MVAS in different $C_{vb}$ and $\sigma_r$ regions. They identified MFDTS with $|C_{vb}| < 0.55$ and $\sigma_r \in (-1, 0)$ and MVASs with $|C_{vb}| > 0.85$ and $\sigma_r \in (-0.9, -0.2)$. The amplitude distributions of velocity and magnetic field both illustrate a vertical stripe feature for MVAS, while the amplitude distributions of magnetic field present a horizontal stripe feature for MFDTS. The level contours of the pixel average amplitudes of Elsässer variables show “U” and “W” shapes, indicating comparable amplitudes.
between the fluctuations with outward and inward sense. Very few intervals show features of Alfvénic fluctuations with $|C_{vb}| > 0.9$ and $\sigma_r \sim 0$. The number of intervals with outward sense is much larger than that with inward sense. However, one does not know if these features obtained at 1 au can find their prototypes in the near-Sun region. We also do not know how the structures in the slow wind originate. The amplitudes behavior of the fluctuations in the near-Sun region have not been studied yet.

The PSP mission provides an opportunity to investigate the fluctuations in the near-Sun region inside 0.3 au (Fox et al. 2016). Zhu et al. (2020) analyzed the wave composition properties of the solar wind turbulence within 0.3 au and found that the outward Alfvén mode dominates over the whole range of scales and distances and the wavevectors shift to quasi-perpendicular directions as the scale decreases. Zhao et al. (2021) searched for the magnetic flux rope structures in the solar wind to within the closest distance to the Sun of 0.13 au and analyzed their relation to the streamer belt and heliospheric current sheet crossing. D’Amicis et al. (2021) presented the cover observations performed at different heliocentric distances for the Alfvénic slow wind from 0.17–1 au. Panasenko et al. (2020) showed that the Alfvén waves may be an important part of most of the nascent solar wind and they can survive out to greater distances based on the analysis of PSP measurements and an evolving potential field extrapolation model. In this study, we utilize the PSP measurements with an time resolution of 0.8738 s from 0.1–0.3 au in the slow solar wind and analyze in the $C_{vb}$–$\sigma_r$ plane the distribution of occurrence and average amplitude of magnetic field, velocity, and Elsässer variables. We find both new features and similarities in comparison with the results at 1 au. We construct an empirical relationship between the amplitudes and $C_{vb}$. Our results unveil the nature of the slow solar wind fluctuations, help in understanding their evolution, and also provide an experimental basis for future theoretical and numerical studies. This paper is organized as follows. In Section 2, we describe the data and method. In Section 3, we show the results of the number distribution and average amplitude distributions. In Section 4, we discuss our results and draw conclusions.

### 2. Data and Method

In the present study, we use the data observed by PSP from 0.1–0.3 au during the first six orbits from 2018 October 31 to 2020 August 31. The magnetic field $B$ is measured by the fluxgate magnetometer (MAG) in the FIELDS instrument suite (Bale et al. 2016) and the proton moments are derived from the measurements by the Solar Probe Cup (Case et al. 2020) in the Solar Wind Electrons, Alphas, and Protons (SWEAP; Kasper et al. 2016) instrument suite. The moments including proton number density $n_p$ and proton bulk velocity $V$ are used. We select the intervals with the measurements at a high resolution of 0.8738 s and cut these data into non-overlapping 6 minute intervals. We only reserve the intervals with no individual data gaps longer than 6 s and total data gap shorter than 5% of 6 minutes. We focus on the slow solar wind with the average velocity $V_0 < 450$ km s$^{-1}$. We require that $B_0/B_0 > 0.5$ to keep the intervals with $B_0$ quasi-parallel to the radial direction. We further require that the square root of the variance matrix trace of the velocity fluctuations be larger than 9 km s$^{-1}$, which is the median uncertainty for the nonradial components of the proton bulk velocity (Case et al. 2020). After these criteria, we obtain 5232 intervals.

We calculate the magnetic-field compression $S_B = \sqrt{\sigma_B^2/B_0^2}$ as defined by Bruno et al. (2007) and the relative magnitude fluctuation $F_B = \langle |B_0| - |B_{min}| / |B_0| \rangle$ for each interval, where $\sigma_B$ is the variance of the magnetic-field magnitude fluctuations, $|B_{min}|$ is the minimum value of the magnetic magnitude, and $B_0$ is the average magnetic field for each 6 minute interval. We require that $S_B < 0.03$, $F_B < 0.4$ following by Wang et al. (2020) to avoid the large structures, which removes 24.7% intervals. As a result, we obtain 3938 intervals for further investigation. None of the time period for these 3938 intervals is close to heliospheric current sheet crossings shown by Zhao et al. (2021). We also cut the data into non-overlapping 10 minute intervals. After setting the same criteria, we obtain 2090 intervals. The analyses for the 10 minute intervals do not alter the validity of the results, as we checked. Therefore, we only present the results for 6 minute intervals.

For each selected interval, $\delta V_A$ and $\delta v$ are obtained from the times series subtracted by their time averages as

$$\delta V_A(t) = V_A(t) - V_A \tag{1}$$

$$\delta v(t) = V(t) - V_0 \tag{2}$$

Here, $V_A = B / \sqrt{4\pi n_p m_p}$ is the magnetic field in Alfvén units, $n_p$ is the time average of the proton number density, and $m_p$ is the proton mass. The normalized residual energy $\sigma_r$ and the correlation coefficient $C_{vb}$ between $\delta V_A$ and $\delta v$ are defined as

$$\sigma_r = \frac{\langle \delta v^2 \rangle - \langle \delta v \rangle^2}{\langle \delta v \rangle^2 + \langle \delta v \rangle^2} \tag{3}$$

$$C_{vb} = \frac{\langle \delta v \cdot \delta v \rangle}{\langle \delta v^2 \rangle \langle \delta v \rangle} \tag{4}$$

which are dimensionless parameters to reflect the nature of solar wind fluctuations (Tu & Marsch 1995; Wang et al. 2020). Here, the angled bracket $\langle \rangle$ denotes an ensemble time average. The positive (negative) sign of $C_{vb}$ refers to the positive (negative) correlation between $\delta V_A$ and $\delta v$. In order to distinguish the outward sense of the fluctuations from the
inward sense, we use $C_{vb}'$ instead of $C_{vb}$ in the following analysis (Wang et al. 2020). $C_{vb} = -C_{vb} \cdot B_R/|B_R|$, where $B_R$ is the $R$ component of $B_\theta$ in the RTN coordinates ($R$ is the direction from the Sun to the spacecraft, $T$ is cross product of the solar rotation axis, and $R, N$ completes the right-handed coordinates). Therefore, the positive (negative) value of $C_{vb}'$ corresponds to the outward (inward) sense.

We obtain the square root of the variance matrix trace of $\delta v_A$, $\delta v$, $z^+$, and $z^-$ as their fluctuation amplitudes. The $z^\pm$ are defined as

$$z^\pm = \delta v \pm \frac{C_{vb}}{|C_{vb}'|} \cdot \delta v_A.$$  \hspace{1cm} (5)

This definition ensures that $z^+$ always refers to the dominated fluctuations, whether it is the Elsässer variable propagating parallel or anti-parallel to the background magnetic-field line.

We obtain the 2D joint number distribution of $C_{vb}'$ and $\sigma_r$ in the $C_{vb}'$–$\sigma_r$ plane with 40 × 40 pixels. The pixels with less than four intervals are discarded for statistical purposes. The pixel average fluctuation amplitudes and corresponding standard errors normalized by the averaged amplitudes are calculated. We construct empirical relations to describe the fluctuation amplitudes with respect to $C_{vb}'$ and $\sigma_r$. The results are presented in the next section.

3. Results

Figure 1 shows the 2D joint number distribution of $C_{vb}'$ and $\sigma_r$ for the selected intervals in the slow solar wind. All the intervals have $C_{vb}' > 0$, which means that the selected intervals all have the outward sense. Most intervals have $C_{vb}' > 0.5$. $\sigma_r$ spreads from −0.6 to 0.4 with a few intervals with $\sigma_r$ as low as −0.8 and as high as 0.9. The peak of the number distribution centers around $C_{vb}' \sim 0.9$ and $\sigma_r \sim 0$, indicating the dominance of Alfvénic fluctuations with an outward-propagating direction.

Figure 2 presents the pixel average amplitude of $\delta v_A$ and $\delta v$ as a function of $C_{vb}'$ and $\sigma_r$. It illustrates the vertical stripe feature of the amplitude $\delta v$, suggesting that the amplitude $\delta v$ is controlled by $C_{vb}'$ and has little dependence on $\sigma_r$. The magenta rectangle denotes the region with $C_{vb}' > 0.95$. With the parameters in the magenta rectangle region, the intervals have a very high correlation between magnetic-field and velocity fluctuations and an approximately equal magnetic energy and kinetic energy ($\sigma_r \sim 0$). We can see that the pixel average amplitudes of $\delta v_A$ and $\delta v$ for the Alfvénic fluctuations with $C_{vb}' > 0.95$ are approximately 50 km s$^{-1}$. The black rectangle region denotes the region with $C_{vb}' > 0.75$ and $\sigma_r \in (-0.6, -0.3)$. With the parameters in the black rectangle region, the intervals have a high correlation between magnetic-field and velocity fluctuations, but the fluctuations are magnetic dominated. The dominance of magnetic fluctuations can be clearly seen from the pixel average amplitudes of $\delta v_A$ and $\delta v$. The average amplitudes of $\delta v_A$ are over 40 km s$^{-1}$ and can reach 60 km s$^{-1}$, while the average amplitudes of $\delta v$ are below 40 km s$^{-1}$. This black rectangle region denotes the MVAS, whose features are clearly demonstrated by the pixel average amplitudes of $\delta v_A$ and $\delta v$ in the $C_{vb}'$–$\sigma_r$ plane (Wang et al. 2020). For the region with $C_{vb}' > 0.75$ and velocity-dominated fluctuations, both the distributed range and the fluctuation amplitudes are small. The part of fluctuations is to be further investigated in the future.

Figure 3 demonstrates the pixel average amplitude of $z^+$ and $z^-$ in the $C_{vb}'$–$\sigma_r$ plane. As pointed out in Section 2, $z^+$ represents the dominant fluctuations. Since $C_{vb}' > 0$, the dominant fluctuations all have outward sense. Therefore, $z^-$ represents the fluctuations with outward sense. In the Alfvénic fluctuations with $C_{vb}' > 0.95$ region, the amplitudes of dominant outward fluctuations $z^+$ reach 60 km s$^{-1}$, while the amplitudes of inward fluctuations $z^-$ are around the uncertainty of the velocity detection. In the MVAS region, the amplitudes of $z^+$ reach 60 km s$^{-1}$, while the amplitudes of $z^-$ are around 30 km s$^{-1}$. Outside this region, the amplitudes of $z^-$ are just above the margin of the observational uncertainty.

Figure 4 shows the standard errors ($\sigma$) normalized to the average amplitude ($E$) for $\delta v_A$ in the $C_{vb}'$–$\sigma_r$ plane. The normalized standard errors are smaller than 0.2, indicating the average amplitudes are reliable. The distribution for $\delta v_A$, $\delta v$, $z^+$ and $z^-$ are similar.
In Figure 5, the dots show the values of the average velocity amplitude for each pixel in the \( \mathcal{C}_{vb} - \sigma \) plane, with the x-axis denotes \( \mathcal{C}_{vb} \). We can see that the average velocity amplitude increases as the \( \mathcal{C}_{vb} \) increases at \( \mathcal{C}_{vb} > 0.55 \), while at a given \( \mathcal{C}_{vb} \), the dots spread over a limited range. This is consistent with the vertical stripe feature of the average velocity amplitude distribution in the \( \mathcal{C}_{vb} - \sigma \) plane. We thus construct empirical relations between the average velocity amplitude \( A_v \) and \( \mathcal{C}_{vb} \), assuming that \( A_v \) does not depend on \( \sigma \). We perform the linear fits using the dots in three ranges \( \mathcal{C}_{vb} > 0.85 \), \( 0.55 < \mathcal{C}_{vb} < 0.85 \), and \( \mathcal{C}_{vb} < 0.55 \), respectively. The results of the fits are also shown with the corresponding rms error \( \sigma_f \). \( \mathcal{C}_{vb} > 0.85 \) and \( \mathcal{C}_{vb} < 0.55 \) are marked by the two vertical dotted lines.

The empirical relations are illustrated in the panel (b) of Figure 6, displaying the similarity to the observational result shown in the right panel of Figure 2. Figure 6(b) illustrates that \( A_v \) does not change with \( \sigma \), but increases as \( \mathcal{C}_{vb} \) increases. The physical effects responsible for this feature needs to be addressed in the future. Based on the empirical relations between \( A_v \) and \( \mathcal{C}_{vb} \), we predict the distributions of the average velocity amplitude of velocity fluctuations \( A_v \) and \( \mathcal{C}_{vb} \) as follows:

\[
A_v = \begin{cases} 
130.3 \mathcal{C}_{vb} - 82.8, & \text{for } \mathcal{C}_{vb} > 0.85, \\
35.9 \mathcal{C}_{vb} - 4.5, & \text{for } 0.55 < \mathcal{C}_{vb} < 0.85, \\
7.7 \mathcal{C}_{vb} + 12.5, & \text{for } \mathcal{C}_{vb} < 0.55.
\end{cases}
\]
amplitude of $\delta v_A$ and $z^\pm$ ($A_b$ and $A_\pm$), respectively, in the $C'_{vb}-\sigma_r$ plane using the following equations:

$$A_b = A_b \sqrt{(1 - \sigma_r)/(1 + \sigma_r)},$$

$$A_\pm = A_b \sqrt{r_A + 1 \pm 2|C_{vb}|/r_A},$$

where the Alfvén ratio $r_A$ is related to $\sigma_r$ by $r_A = (1 + \sigma_r)/(1 - \sigma_r)$. We present the empirical relations of $A_b$ and $A_\pm$ as a functions of $C'_{vb}$ and $\sigma_r$ in Figure 6. We can clearly find the consistence between the predictions of the empirical relations and the observations.

4. Conclusions and Discussion

In the present study, we perform analyses for the fluctuations in the slow solar wind from 0.1–0.3 au in the $C'_{vb}-\sigma_r$ plane on both the number distribution of the selected data intervals and the pixel averaged amplitude distributions of magnetic field, velocity, and the Elsässer variables using PSP measurements. We find that the Alfvénic fluctuation events dominate the number distribution. In the average amplitude distribution we find a region denoting the Alfvénic fluctuations with $C'_{vb} > 0.95$ with the amplitude of $z^+$ as high as 60 km s$^{-1}$ and that of $z^-$ just above the observational uncertainty. We also find a region with high value of $C'_{vb}$ and moderate minus value of $\sigma_r$, in which the fluctuations are magnetic dominated with the Alfvén-velocity fluctuation amplitude reaching 60 km s$^{-1}$, $z^+ \sim 60$ km s$^{-1}$, and $z^- \sim 30$ km s$^{-1}$. These fluctuations are considered to be a result of MVAS. Outside this structure region, the amplitude of $z^-$ is close to the observational uncertainty. We also provide an empirical relations between the velocity fluctuation amplitude and $C'_{vb}$ and the deduced empirical amplitudes of magnetic field and Elsässer variables match the observational results. The empirical relations will be useful for theoretical and numerical studies related to solar wind fluctuations.

Compared to the observational results at 1 au observed by the WIND spacecraft, the amplitude distributions are similar in the data domain. MVAS already exist in the near-Sun region. Moreover, we report the following new features: (1) there is a

Figure 6. Upper panels: amplitude of $\delta v_A$ (left) and $\delta v$ (right) in the $C'_{vb}-\sigma_r$ plane obtained from the empirical relations. Lower panels: amplitude of $z^+$ (left) and $z^-$ (right) in the $C'_{vb}-\sigma_r$ plane obtained from the empirical relations.
domain in the $C_{vb} - \sigma_r$ plane for Alfvénic fluctuations with $C_{vb} > 0.95$ and $\sigma_r \sim 0$ in the near-Sun region, while this domain almost disappears at 1 au; (2) there is no interval with $C_{vb} < 0$ while they exist at 1 au; (3) the number of the distribution is zero in most pixels between 0.1 and 0.3 au, while it is more than 4 in most pixels at 1 au in the region $C_{vb} < 0.55$ and $\sigma_r < 0$. These similarities and differences provide clues to the evolution of solar wind fluctuations. We infer that the Alfvénic fluctuations with $C_{vb} > 0.95$ are generated in the near-Sun region and dissipate during the propagation. We think that MVASs are generated inside the near-Sun region and may be convected to 1 au. It is found that 25% of the switchback intervals are possible MVASs (Wu et al. 2021). However, we do not discuss the relationship between switchbacks and MVAS here and the nature of MVAS awaits further study. The fluctuations with inward sense do not appear in the near-Sun region, which indicates that the fluctuations with inward sense observed at 1 au may be created during the solar wind expansion.

However, we emphasize that the results should be interpreted with caution because of the limited data sets. The upper panels of Figure 7 show the distributions of radial distance $r$ (left), time (middle), and $V_0$ (right) for the pixel with $0.85 < C_{vb}' < 0.9$ and $-0.1 < \sigma_r < -0.05$, which has the most samples in the $C_{vb}' - \sigma_r$ plane. The radial distances, time, and $V_0$ cover over a wide range for this single pixel. We also present the distributions in the $r$-time plane for all the 3938 intervals we analyzed in the lower panels of Figure 7. The color represents the values of $C_{vb}'$ (left), $\sigma_r$ (middle), and $V_0$ (right), respectively. It is clear that the three parameters ($C_{vb}'$, $\sigma_r$, and $V_0$) vary with $r$ and time. We neglect the radial evolution of the fluctuations and take the samples as a whole group from 0.1–0.3 au in this study to enhance the statistics. These clues for the radial evolution inside from 0.1–0.3 au should be further tested using smaller radial distance ranges from future data. PSP in the first six orbits observed some slow solar winds that are not typical and come from the equatorial and midlatitude coronal holes (Bale et al. 2019; Badman et al. 2020; Huang et al. 2020). This may explain the absence of MFDT and the dominance of Alfvénic fluctuations. We also note that there are a few intervals with $\sigma_r$ close to 1, which suggests a dominance of velocity fluctuations over magnetic fluctuations. These kinds of fluctuations need to be further investigated.

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