Influence of the Heliospheric Current Sheet on the Evolution of Solar Wind Turbulence

Chen Shi, Marco Velli, Anna Tenerani, Victor Réville, and Franco Rappazzo

Abstract

The effects of the heliospheric current sheet (HCS) on the evolution of Alfvénic turbulence in the solar wind are studied using MHD simulations incorporating the expanding-box model. The simulations show that, near the HCS, the Alfvénicity of the turbulence decreases as manifested by lower normalized cross-helicity and larger excess of magnetic energy. The numerical results are supported by a superposed-epoch analysis using OMNI data, which shows that the normalized cross-helicity decreases inside the plasma sheet surrounding HCS, and the excess of magnetic energy is significantly enhanced at the center of HCS. Our simulation results indicate that the decrease of Alfvénicity around the HCS is due to the weakening of radial magnetic field and the effects of the transverse gradient in the background magnetic field. The magnetic energy excess in the turbulence may be a result of the loss of Alfvénic correlation between velocity and magnetic field and the faster decay of transverse kinetic energy with respect to magnetic energy in a spherically expanding solar wind.

Unified Astronomy Thesaurus concepts: Interplanetary turbulence (830); Magnetohydrodynamical simulations (1966); Solar wind (1534)

1. Introduction

Turbulence is a pervasive phenomenon in fluids and plasmas and has been observed to be a major feature of the solar wind. It is thought to be one of the main processes leading to solar wind heating (e.g., Kiyani et al. 2015) and contributing to its acceleration from the solar corona (e.g., Belcher 1971; Leer et al. 1982), while also affecting the acceleration and transport of energetic particles. Thus, understanding the origin and evolution of solar wind turbulence is crucial for fully understanding the heliosphere as a whole.

Coleman (1968), using Mariner 2 data, showed that the power spectra of fluctuations in the solar wind have power-law scaling relations, indicating a well-developed turbulence. Belcher & Davis (1971) found that these fluctuations are mainly outward-propagating Alfvén waves, with nearly incompressible plasma density and magnetic field. An important question is how the Alfvénic turbulence, or Alfvénic turbulence, evolves radially. In the 1970s, Wentzel–Kramers–Brillouin (WKB) (e.g., Alazraki & Couturier 1971; Belcher 1971; Hollweg 1974) theory of the radial evolution of the Alfvén wave amplitude was developed. Following these early works, non-WKB (e.g., Heinemann & Olbert 1980; Barkhudarov 1991; Velli 1993) theory shows that linear coupling between the outwards- and inward-propagating Alfvén waves leads to frequency-dependent reflection of the waves. Magnetohydrodynamic (MHD) models were developed to account for the evolution of the turbulence spectra and other parameters such as the wave energy densities (e.g., Tu et al. 1984; Zhou & Matthaeus 1990; Zank et al. 1996).

Elsässer variables $z^\pm = u \pm b$, where $u$ and $b$ are velocity and magnetic field expressed in Alfvén speed, i.e., $b = \hat{b}/\sqrt{4\pi \rho}$ with $\hat{b}$ and $\rho$ being the magnetic field and plasma density, are convenient in describing the Alfvénic fluctuations, as they represent the inward- and outward-propagating Alfvén waves, respectively. Two quantities have been used as important diagnostics of the Alfvénic turbulence, namely the normalized cross-helicity ($\sigma_z$), defined as

$$\sigma_z = \frac{|z^-|^2 - |z^+|^2}{|z^-|^2 + |z^+|^2},$$

and the normalized residual energy ($\sigma_r$), defined as

$$\sigma_r = \frac{|u|^2 - |b|^2}{|u|^2 + |b|^2}.$$

Here, $\sigma_z$ measures the relative amount of outward and inward wave energies and $\sigma_r$ measures the relative amount of kinetic and magnetic energies. A large number of works were conducted with regard to the radial evolution of these two quantities in the solar wind (e.g., Roberts et al. 1987; Bavassano et al. 1998; Bruno et al. 2007; Chen et al. 2020; Shi et al. 2021), but two outstanding problems remain unresolved. First, the normalized cross-helicity decreases with radial distance to the Sun, and second, a prevailing negative value of residual energy is observed. It is known that, in a homogeneous medium with a uniform background magnetic field, the Alfvénic turbulence evolves toward a status in which only one wave population survives, i.e., $\sigma_z = \pm 1$. This is the so-called “dynamic alignment” (Dobrowolny et al. 1980). In contrast to the theory, in the solar wind, the dominance of the outward Alfvén wave is gradually weakened during the radial propagation, as manifested by the decrease of $|\sigma_z|$. Besides, in a purely Alfvénic system, the kinetic and magnetic energies should be exactly equipartitioned, i.e., $\sigma_z = 0$, while in the solar wind, a magnetic energy excess is typically observed even at distances very close to the Sun, below 30 solar radii (Chen et al. 2020; McManus et al. 2020; Shi et al. 2021).
Figure 1. Evolution of the longitudinal profiles of background fields from a 1D run without any waves. Left column is the initial status at $30\, R_s$, middle column is at $121.59\, R_s$, and right column is around 1 au. Top row: density (blue) and temperature (orange). Middle row: radial speed (blue) in the expanding-box frame and longitudinal speed (orange). Bottom row: radial component (blue), out-of-plane component (orange), and magnitude (black) of the magnetic field. The quantities are normalized (see the text). The green shade shows the compression region, and the vertical dashed line marks the polarity reversal of the magnetic field.

One possible mechanism that resolves these paradoxes is the large-scale velocity shear in the solar wind. Coleman (1968) proposed that the differential streaming generates Alfvén waves at long wavelengths. These newly generated waves do not have a preferential propagating direction, and thus the initial dominance of the outward wave gradually declines. This shear-driven decrease of cross-helicity was confirmed by numerical simulations (Roberts et al. 1992; Shi et al. 2020). Velocity shear is widely adopted in turbulence models as a source for the wave energies, and is able to reproduce the observed decrease of $\sigma_c$ in the models. On the contrary, there has been no satisfactory solar wind turbulence model that leads to negative residual energy so far. For example, in the model by Zank et al. (2017), the source term for the residual energy is attributed to the stream shear, but whether this term causes growth or decay of the residual energy is arbitrary. The heliospheric current sheet (HCS) is a good candidate that may influence the evolution of Alfvénic turbulence. It is shown by both simulations and in situ observations that, in the proximity of the HCS, the Alfvénicity of the turbulence decreases in general (e.g., Goldstein & Roberts 1999; Chen et al. 2021). However, how the HCS modifies the dynamic evolution of $\sigma_c$ and $\sigma_r$ in the spherically expanding solar wind is still unclear.

In this study, we carry out two-dimensional MHD simulations using the expanding-box model (EBM). Large-scale solar wind structures, including the fast–slow stream interaction regions (SIRs) and the HCS, are constructed and evolve self-consistently in the simulations. We investigate how properties of the Alfvénic turbulence evolve radially and how SIRs and HCS modify its evolution. A superposed-epoch analysis of HCS crossings at 1 au is carried out using the OMNI data set, and the turbulence properties near the HCS are examined. The paper is organized as follows. In Section 2, we present the setup of the MHD simulations and the numerical results. In Section 3, we present the superposed-epoch analysis of the HCS crossings observed at 1 au. We then discuss our results in Section 4 and conclude in Section 5.

2. Expanding-box Model Simulation

2.1. Numerical Method and 1D Test Run

The code we use for simulations is a 2D pseudo-spectral MHD code used by Shi et al. (2020) to study the interaction between SIRs and turbulence. The EBM module is implemented so that the radial expansion effect of the solar wind is taken into account (Grappin et al. 1993; Grappin & Velli 1996). The expansion effect is not negligible in the solar wind, because it induces inhomogeneity of the background streams, which leads to the reflection of the Alfvén waves (e.g., Heinemann & Olbert 1980) and anisotropic evolution of velocity and magnetic fields in the radial and transverse directions (e.g., Dong et al. 2014). The EBM has also been employed to reproduce the “magnetic switchbacks” observed in the young solar wind (Squire et al. 2020). In our code, a finite spiral angle of magnetic field and stream interface is allowed so that compression and rarefaction regions are constructed. A detailed description of the numerical method can be found in Shi et al. (2020).

We carried out four simulations with two free parameters, namely whether a nonzero spiral angle is set and whether the expansion effect is included. Here, we mainly present results from the run with both a nonzero spiral angle and the expansion effect, i.e., the most realistic run. The parameters for the initial setup are chosen according to solar wind observations as described below. The simulation starts from $R_0 = 30\, R_s$ and ends at $R = 270.9\, R_s$, where $R_s$ is the solar radius. The initial spiral angle is $\alpha = 8.1$ so that the angle becomes $45^\circ$ at 1 au. The size of the simulation domain is $L_{x'} \times L_{y'} = 10 R_s \times 2 \pi R_s$, where $(x', y')$ is the corotating coordinate system, i.e., $x'$ is parallel to the background magnetic field and $y'$ is the quasi-longitudinal direction (Shi et al. 2020). $L_{y'} = 2 \pi R_s$ means that the domain is a full circle in the ecliptic plane. The initial background fields as functions of the quasi-longitudinal direction $y'$ are plotted in the left column of Figure 1 with normalized units. The quantities for normalization are: $\bar{n} = 200 \, \text{cm}^{-3}$, $\bar{B} = 250 \, \text{nT}$, $L = R_s$. 
\( \nabla \cdot B = 0 \). The number of grid points is \( n_x \times n_y = 2048 \times 8192 \) (we note that the simulation domain size is \( 10 R_s \times 60 \pi R_s \)) so that the smallest wavelength that is resolved is \( \lambda = 2 \Delta x' \approx 0.01 R_s \), corresponding to a wave period \( T \approx \lambda / U_0 \approx 15 \) s, which is approximately two magnitudes larger than the ion gyroscale and ion inertial scale. But we note that, in the MHD simulations, there are no intrinsic gyroscales and inertial scales—or in other words, these kinetic scale lengths are zero in MHD.

We process the simulation data using the same method as described in Shi et al. (2020). At each time—or equivalently, each radial distance to the Sun—we first calculate the \( x' \)-averaged fields, i.e., the background fields. Then we remove the background fields to get the wave fields. We only analyze wave components that are perpendicular to the \( x-y \) plane background magnetic field \( B_0 = B_0(y') \hat{e}_x \). We note here that, in the \( x-y \) plane, the background magnetic field is always aligned with \( \hat{e}_x \), as the \( x' \)-axis rotates away from the radial direction as the solar wind expands (Shi et al. 2020). The perturbed Elsässer variables are defined by

\[
    z_{out} = u_1 - \mathrm{sign}(B_0) \frac{b_1}{\sqrt{\rho}}, \quad z_{in} = u_1 + \mathrm{sign}(B_0) \frac{b_1}{\sqrt{\rho}}. \tag{3}
\]

We then apply a Fourier transform along \( x' \) to \( u_1, b_1/\sqrt{\rho}, z_{out}, \) and \( z_{in} \). As there are 2048 grid points along \( x' \), 1024 wave modes are resolved with wave numbers \( k_{\perp} = (1, 2, \cdots, 1024)/L_{\perp'} \), i.e., mode \( m \) corresponds to \( k_{\perp} = m/L_{\perp} \). We divide all the wave modes into 10 wavenumber bands, which are logarithmically spaced, i.e., band \( i \) contains modes \([2^{i-1}, 2^i)\), or wavelengths between \( L_{\perp'}/2^{i-1} \) and \( L_{\perp'}/2^i \). We then calculate \( \sigma_{x'}(y') \) and \( \sigma_{y'}(y') \) for each wavenumber band and also for integration of all wave modes.

In Figure 2, we present the \( y' - R(t) \) profiles color-coded with \( \sigma_{x'} \) (top row) and \( \sigma_{y'} \) (bottom row) for all wave modes (left column) and for band 03 (right column), which corresponds to a wavelength of \( \lambda \in [2.5 R_s, 1.25 R_s] \), or roughly to a wave period of \( T \in [38, 75] \) minutes. The figure is produced by piling up the \( y' \) profiles of \( \sigma_{x',y'} \) at different moments—or equivalently, different radial locations \( R(t) \). In the top left panel, we use dashed lines to mark the boundaries of fast streams, as defined above the \( y' \) profile at which the background radial speed equals 650 km s\(^{-1}\), and we use dashed black lines to mark the boundaries of slow streams, defined below the \( y' \) profile at which the background radial speed equals 400 km s\(^{-1}\). The two current sheets are located in the center of the slow streams, around \( y' \approx 0.5 L_{\perp'} \) and \( y' \approx L_{\perp'} \). We first inspect the left column of Figure 2, which shows \( \sigma_{x'} \) and \( \sigma_{y'} \) calculated using wave energies integrated over all wavenumbers. As already discussed by Shi et al. (2020), in regions with nearly uniform background fields, i.e., inside fast
streams and inside slow streams far from the current sheets, \( \sigma_c \) remains almost constant throughout the evolution, indicating that the Alfvénicity remains high in these regions. In the velocity-shear regions (regions between the black and white lines), \( \sigma_c \) declines with radial distance. In particular, in the compression region (around \( y' = (0.35 - 0.4)L_y \) and \( y' = (0.85 - 0.9)L_y \)), \( \sigma_c \) drops below 0 beyond 200\( R_s \). Shi et al. (2020) showed that, in shear regions, the damping of the outward Alfvén wave is significantly faster than the inward Alfvén wave, leading to the decrease in \( \sigma_c \). Except for near the current sheets, which will be discussed in detail later, \( \sigma_r \) oscillates around zero in all regions, indicating that the Alfvénicity of the waves is well-conserved for the long-wavelength modes (we note that the integrated wave energies are dominated by the modes of largest scales). The oscillation in \( \sigma_r \) is caused by periodic correlation and decorrelation between the outward and inward waves. From the left column of Figure 2, we also see that the evolution of Alfvén waves is significantly modified by the current sheets. In the neighborhood of the current sheets, \( \sigma_c \) decreases quite fast and \( \sigma_r \) evolves toward negative values. In the left panel of Figure 3, we plot the radial evolution of \( \sigma_c \) and \( \sigma_r \) in a band of width \( 2a_s \) around the current sheet initialized at \( y' = 0.5L_y \). Here, \( \sigma_c \) starts from a high value, i.e., 0.92, determined by the initial condition, drops to around 0.2 within 100\( R_s \), and then remains stable. The value of \( \sigma_r \) starts at exactly zero, rises slightly at the beginning due to the increase of kinetic energy caused by the magnetic pressure gradient at the current sheet as discussed in Section 2.1, and then starts to drop continuously, reaching a value of \(-0.3\) at 1 au. For comparison, we plot the time evolution of \( \sigma_c \) and \( \sigma_r \) from the run without expansion in the right panel of Figure 3. Evolution of \( \sigma_c \) does not show much difference between the two runs, while \( \sigma_r \) remains around zero in the run without expansion, indicating that the expansion effect is important to the decrease of \( \sigma_c \), around the current sheet, which will be discussed in more detail in Section 4.

In the right column of Figure 2, we show the \( y' - R(t) \) profiles of \( \sigma_c \) and \( \sigma_r \) for wave band 03. Compared with the left column, the drop of \( \sigma_c \) in velocity-shear regions is much more significant and the \( \sigma_c \)-drop regions around the current sheets are wider. For \( \sigma_r \), the most prominent feature is that, inside the compression regions, \( \sigma_r \) evolves toward \( +1 \), i.e., kinetic energy becomes dominant in these regions, indicating that the large-scale velocity shear and compression facilitate the transfer of kinetic energy toward small scales.

In Figure 4, we show the \( \chi \) spectra, i.e., the parallel spectra, of various fields calculated at the moment \( R(t) = 217.9R_s \). From left to right, columns are spectra averaged in \( y' \) bands of width \( 2a_s \) inside the fast stream, current sheet, and compression region, respectively. The top row shows the spectra of outward (blue) and inward (orange) Elsässer variables. The middle row shows the spectra of kinetic (blue) and magnetic (orange) perturbations. We multiply these spectra by \( k_y^2 \), as the “critical balance” model (Goldreich & Sridhar 1995) predicts a parallel spectrum \( E \propto k_y^{-2} \). We can see from Figure 4 that, in general, these spectra are steeper than the prediction of the critical balance model.
balance model except for inside the fast stream. This is because the shears in magnetic field and velocity turn the wavevector from quasi-parallel to quasi-perpendicular and gradually enlarge the perpendicular wavenumber, which speeds up the dissipation of the wave energies (Shi et al. 2020). The bottom row shows the spectra of $\sigma_c$ and $\sigma_r$ calculated from the spectra shown in the top and middle rows. Inside the fast stream, $\sigma_r$ is close to unity and $\sigma_c$ is close to zero for most modes, except for close to the numerical dissipation range, meaning that the waves maintain a high Alfvénicity over a large span of wavenumbers. Around the current sheet, $\sigma_c$ decreases to nearly zero for all wavenumbers. The value of $\sigma_r$ is negative for most of the wavenumbers, except for an intermediate range ($1 < k_r R_s < 3$) where it is around zero. In the compression region, $\sigma_c$ is overall smaller than the initial condition 0.92, but the curve of $\sigma_r$ shows a decrease with $k_r$ at small wavenumbers and rises again. The value of $\sigma_r$ is around zero for small wavenumbers, and it shows a significant increase with $k_r$, reaching its maximum value at the same $k_r$ where $\sigma_c$ reaches its local minimum. This indicates that, in the compression region, the large-scale stream structure generates small-scale fluctuations that are dominated by kinetic energy, as observed in previous simulations (e.g., Roberts et al. 1992). The newly generated fluctuations weaken the dominance of the outward Alfvén waves, consistent with the scenario proposed by Coleman (1968). We note that, for large wavenumbers ($k_r R_s \gtrsim 5$) the spectra are significantly modulated by the explicit numerical filter applied to the simulation, thus spectral breaks can be seen at large wavenumbers.

We do not present the perpendicular power spectra, for the following reasons. First, as the simulation coordinate system is non-Cartesian, there is no axis perpendicular to $B_0$. The $\gamma'$-axis is perpendicular to $B_0$ initially, but the angle between $\gamma'$ and $B_0$ gradually increases (Shi et al. 2020). Second, because of the elongated simulation domain along $\gamma'$, and also due to the spherical expansion, the resolution in $\gamma'$ is much lower than that in $x'$. Besides, as we would like to focus on certain longitudinal regions, e.g., around the HCS, instead of the whole $\gamma'$ range, the number of data points is limited. Because of the above reasons, it is difficult to produce physically meaningful perpendicular spectra.

In Figure 5, we plot the $\gamma'$ profiles of the normalized density fluctuation $\delta \rho / \rho$ (blue) and the square of the Mach number $(\delta u / C_s)^2$ (orange) in the simulation at moment $R(t) = 217.91 R_s$. Here, $\delta \rho$ and $\delta u$ are the root-mean-squares of density and velocity calculated long $x'$. $C_s$ is the speed of sound. Yellow and green shades mark the fast and slow streams, respectively. The vertical dashed lines are the locations of the current sheets. The normalized density fluctuation is overall small, mostly below 0.2, similar to the solar wind observation (e.g., Shi et al. 2021). In the compression region and near the current sheet, e.g., from $\Phi = 0.7 - 1.1$, $\delta \rho / \rho$ is highly correlated with $(\delta u / C_s)^2$, implying a large compressive component in the velocity fluctuations in these regions.

### 3. Superposed-epoch Analysis of HCS at 1 au

Although works have been carried out with regard to turbulence properties around SIRs (e.g., Borovsky & Denton 2010), literature on how HCS affects the solar wind turbulence is still incomplete. To validate our simulation results, we carry out a superposed-epoch analysis of HCS crossings at 1 au and study how the properties of turbulence change near HCS.

#### 3.1. Selection and Structure of HCS

For the current study, we use the OMNI data set, which contains magnetic field and plasma data from multiple spacecraft, including ACE and WIND (King & Papitashvili 2005). The time resolution of the data is 1 minute, sufficient for the study of MHD turbulence. We analyze data during two 4 yr periods: 2000–2003, which is around the solar maximum of solar cycle 23, and 2007–2010, which is around the solar minimum between solar cycles 23 and 24, as shown by the shaded regions in Figure 6, which plots monthly sunspot numbers.

The procedure to select HCS crossings can be stated as follows. We first calculate the one-day average of $B_{x,GSE}$, which is equivalent to the opposite of the radial component of the solar wind magnetic field. Next, we find days when its polarity changes, and we require that the polarities before and after each polarity-reversal day are maintained for at least 4...
days. Then we inspect the 1 minute data to determine the exact polarity reversal times. We identify 48 events for the solar maximum and 45 events for the solar minimum. A list of the HCS crossings is shown in Table 1.

A superposed-epoch analysis of the HCS structure is shown in Figure 7. From top to bottom, the rows show the GSE $B_x$, GSE $B_y$, voltage, GSE $V_y$, proton density, and proton temperature, respectively. The left column is the solar maximum and right column is the solar minimum. In each panel, gray curves are individual events and the blue curve is the median value of all events. In the top two rows, we also plot medians of the magnetic field strength in black curves. We have reversed the time series of certain events such that $B_x$ is always changing from negative to positive. The timescale for HCS crossings is on average 1–2 hr, and the HCS is embedded in much thicker (1–2 days) plasma sheets with enhanced proton density and lower proton temperature. The magnetic field strength is quite constant across the HCS, implying a force-free structure. By comparing the left and right columns of Figure 7, we see that

Figure 4. The $x'$ spectra of various fields at $R(t) = 217.9R_s$ inside the fast stream (left column), the current sheet (middle column), and the compression region (right column). The spectra are averaged in a $y'$ band of width $2\Delta y$, inside each region. Top row: spectra of the outward (blue) and inward (orange) Alfvén waves (Elssasser variables). Middle row: spectra of the kinetic (blue) and magnetic (orange) perturbations. Bottom row: spectra of $\sigma_t$ (blue) and $\sigma_r$ (orange) calculated from the spectra in top and middle rows.

Figure 5. Longitude profiles of the normalized density fluctuation $\rho/\rho$ (blue) and the square of the Mach number $(du/C_s)^2$ (orange) in the simulation at moment $R(t) = 217.91R_s$. $\delta \rho$ and $\delta u$ are the root-mean-squares of density and velocity calculated along $x'$. $C_s$ is the speed of sound. Yellow and green shades mark the fast and slow streams, respectively. The vertical dashed lines are the locations of the current sheets.

Figure 6. Monthly sunspot numbers from 1995 to 2015. The two shaded regions mark the two time periods used for OMNI data analysis and correspond to the solar maximum (2000–2003) and solar minimum (2007–2010), respectively.
the strength of magnetic field is larger during the solar maximum than the solar minimum. Another thing to notice is that there is a negative GSE $V_y$ at the HCS, i.e., the plasma flow is rotating in the same direction with the solar rotation. The reason might be that HCS is usually embedded in slow solar wind ahead of the compression region and pushed along the longitudinal direction in accordance with solar rotation (Siscoe 1972; Eselevich & Filippov 1988).

### 3.2. Turbulence Properties near HCS

We then analyze turbulence properties near the HCS. We use a running time window of width 128 minutes. Any time window with a data gap ratio larger than 20% is not considered. Inside each time window, we first apply linear interpolation to velocity, magnetic field, and proton density, to fill the data gaps. Then we calculate Elsässer variables after determining the polarity of radial magnetic field by averaging $B_x$ in the time window. Finally, we apply a Fourier transform to these fields. Following a method similar to the process applied to simulation data in the prior section, we divide the frequency into six bands such that band $i$ contains wave modes $[2^{i-1}, 2^i)$, e.g., wave band 6 contains waves whose periods are between $128/2^5 = 4$ minutes and $128/2^6 = 2$ minutes. We calculate $\sigma_c$ and $\sigma_r$ for each wave band by integrating wave energies in each band. In addition, we fit the power spectra and get the spectral slopes for velocity, magnetic field, and the outward and inward Elsässer variables.

| #  | Year | Month | Day  | Hour | Minute |
|----|------|-------|------|------|--------|
| 01 | 2000 | 01    | 10   | 00   | 30     |
| 02 | 2000 | 02    | 05   | 17   | 50     |
| 03 | 2000 | 02    | 31   | 19   | 40     |
| 04 | 2000 | 08    | 27   | 17   | 33     |
| 05 | 2000 | 09    | 24   | 15   | 50     |
| 06 | 2000 | 10    | 14   | 18   | 04     |
| 07 | 2000 | 11    | 23   | 19   | 33     |
| 08 | 2000 | 12    | 16   | 21   | 03     |
| 09 | 2000 | 12    | 22   | 21   | 23     |
| 10 | 2001 | 01    | 10   | 21   | 03     |
| 11 | 2001 | 02    | 14   | 07   | 17     |
| 12 | 2001 | 03    | 12   | 14   | 55     |
| 13 | 2001 | 04    | 22   | 00   | 23     |
| 14 | 2001 | 05    | 06   | 10   | 40     |
| 15 | 2001 | 05    | 17   | 21   | 32     |
| 16 | 2001 | 06    | 29   | 06   | 21     |
| 17 | 2001 | 07    | 10   | 16   | 30     |
| 18 | 2001 | 07    | 24   | 15   | 05     |
| 19 | 2001 | 11    | 16   | 11   | 28     |
| 20 | 2002 | 02    | 04   | 21   | 21     |
| 21 | 2002 | 03    | 03   | 22   | 49     |
| 22 | 2002 | 05    | 06   | 09   | 55     |
| 23 | 2002 | 06    | 02   | 02   | 40     |
| 24 | 2002 | 06    | 16   | 06   | 08     |
| 25 | 2002 | 06    | 25   | 16   | 37     |
| 26 | 2002 | 09    | 03   | 06   | 46     |
| 27 | 2002 | 09    | 27   | 05   | 29     |
| 28 | 2002 | 10    | 23   | 17   | 02     |
| 29 | 2002 | 11    | 10   | 02   | 57     |
| 30 | 2002 | 12    | 06   | 11   | 21     |
| 31 | 2002 | 12    | 19   | 07   | 41     |
| 32 | 2003 | 01    | 17   | 14   | 08     |
| 33 | 2003 | 02    | 12   | 22   | 54     |
| 34 | 2003 | 02    | 26   | 19   | 48     |
| 35 | 2003 | 03    | 11   | 17   | 18     |
| 36 | 2003 | 03    | 26   | 09   | 40     |
| 37 | 2003 | 04    | 08   | 02   | 34     |
| 38 | 2003 | 04    | 20   | 19   | 07     |
| 39 | 2003 | 05    | 04   | 16   | 00     |
| 40 | 2003 | 05    | 18   | 16   | 23     |
| 41 | 2003 | 06    | 26   | 12   | 30     |
| 42 | 2003 | 07    | 11   | 15   | 25     |
| 43 | 2003 | 07    | 26   | 12   | 01     |
| 44 | 2003 | 08    | 04   | 06   | 52     |
| 45 | 2003 | 09    | 01   | 06   | 13     |
| 46 | 2003 | 10    | 13   | 09   | 27     |
| 47 | 2003 | 12    | 05   | 01   | 26     |
| 48 | 2003 | 12    | 19   | 19   | 50     |

The Astrophysical Journal, 928:93 (11pp), 2022 March 20 Shi et al.
Figure 7. Superposed-epoch analysis of the HCS crossings. Epoch 0 is the moment of crossing. From top to bottom, the rows show $B_x$ and $B_y$ in GSE coordinates, $V_r$, GSE $V_y$, proton density, and proton temperature, respectively. Left column is solar maximum and right column is solar minimum. In each panel, the gray lines are individual events and the blue line is the median value. In the top two rows, the black curves are the medians of $|B|$. 

Figure 8. Superposed-epoch analysis of $\sigma_c$ (top row) and $\sigma_r$ (bottom row) near HCS. Left column is solar maximum and right column is solar minimum. In each panel, dark to light colors are wave bands 1–6, respectively, i.e., from low to high frequencies.
In Figure 8, we show superposed-epoch analysis of $\sigma_c$ (top row) and $\sigma_r$ (bottom row). The left column is the solar maximum and the right column is the solar minimum. Colors represent different wave bands such that dark to light colors are bands 1–6. We see that, in general, $\sigma_c$ decreases with frequency while $\sigma_r$ increases with frequency. The top left panel shows that, in a time window of ±1 day, approximately the width of the plasma sheet, $\sigma_c$ drops as we approach the center of HCS. In a narrow window of width comparable to the thickness of HCS, i.e., 1–2 hr, $\sigma_c$ drops significantly because the outward and inward waves mix with each other. The bottom left panel of Figure 8 shows a slight decrease of $\sigma_r$ inside the plasma sheet while a large drop of $\sigma_r$ is observed near HCS. During the solar minimum (right column of Figure 8), the above results qualitatively hold, but both $\sigma_c$ and $\sigma_r$ are lower compared with the solar maximum.

In Figure 9, we show the superposed-epoch analysis of various spectral slopes. Again, the left and right columns are the solar maximum and solar minimum, respectively. In the top row, the blue and orange curves are the spectral slopes of the velocity and magnetic field. In the bottom row, the blue and orange curves are the spectral slopes of the outward and inward Elsässer variables. In each panel, the two horizontal dashed lines mark the values 3/2 and 5/3 for reference. The shaded bands show the standard deviations of different curves.

In Figure 10, we plot the superposed-epoch analysis of the normalized density fluctuation $\delta \rho / \rho$ (blue) and the square of the velocity fluctuation Mach number $(\delta u / C_s)^2$ (orange). During solar minimum, the two quantities are highly correlated, whereas during solar maximum, they are correlated only close to the HCS. We note that, in our simulation (top left panel of Figure 4), a flatter $z_{\text{in}}$ spectrum compared with the $z_{\text{out}}$ spectrum is also observed. At the center of HCS, the inward and outward Elsässer variables have the same slope as expected because the two wave populations are not well-separated near the polarity-reversal time.

In Figure 10, we plot the superposed-epoch analysis of the normalized density fluctuation $\delta \rho / \rho$ (blue) and the square of the velocity fluctuation Mach number $(\delta u / C_s)^2$ (orange). During solar minimum, the two quantities are highly correlated, whereas during solar maximum, they are correlated only close to the HCS. We note that, in our simulation (top left panel of Figure 4), a flatter $z_{\text{in}}$ spectrum compared with the $z_{\text{out}}$ spectrum is also observed. At the center of HCS, the inward and outward Elsässer variables have the same slope as expected because the two wave populations are not well-separated near the polarity-reversal time.

In Figure 10, we plot the superposed-epoch analysis of the normalized density fluctuation $\delta \rho / \rho$ (blue) and the square of the velocity fluctuation Mach number $(\delta u / C_s)^2$ (orange). During solar minimum, the two quantities are highly correlated, whereas during solar maximum, they are correlated only close to the HCS. We note that, in our simulation (top left panel of Figure 4), a flatter $z_{\text{in}}$ spectrum compared with the $z_{\text{out}}$ spectrum is also observed. At the center of HCS, the inward and outward Elsässer variables have the same slope as expected because the two wave populations are not well-separated near the polarity-reversal time.

In Figure 10, we plot the superposed-epoch analysis of the normalized density fluctuation $\delta \rho / \rho$ (blue) and the square of the velocity fluctuation Mach number $(\delta u / C_s)^2$ (orange). During solar minimum, the two quantities are highly correlated, whereas during solar maximum, they are correlated only close to the HCS. We note that, in our simulation (top left panel of Figure 4), a flatter $z_{\text{in}}$ spectrum compared with the $z_{\text{out}}$ spectrum is also observed. At the center of HCS, the inward and outward Elsässer variables have the same slope as expected because the two wave populations are not well-separated near the polarity-reversal time.
ejec(es) bunch(es) of flux ropes from the tip of helmet streamers (Réville et al. 2020).

4. Discussion

We compare the simulation results from Section 2 and the superposed-epoch analysis from Section 3. In the simulation, $\sigma_c$ drops in a wide longitudinal range around the current sheet (Figure 2), which is also observed at 1 au (Figure 8). Similarly, in both simulation and observation, $\sigma_r$ drops in the neighborhood of HCS. Grappin et al. (1991) analyzed four months of Helios 1 data and found that, within the neutral sheet, the turbulence properties are close to the “standard,” or fully developed, MHD turbulence, rather than Alfvénic turbulence. Standard MHD turbulence is characterized by balanced outward/inward Elsässer energies and an excess of magnetic energy, consistent with our results. In this scenario, the background magnetic field dissipates the residual energy (the so-called “Alfvén effect”), which is a correlation between the two Elsässer variables generated by intrinsic nonlinear interaction. In other words, the Alfvén effect is essentially the dissipation of two colliding (correlated) counter-propagating Alfvén wave packets as first described by Kraichnan (1965), and hence it is determined by the background magnetic field strength along the wave propagation direction. Thus, the absolute value of the residual energy, regardless of its sign, is larger inside current sheets where the Alfvén effect is weaker. Grappin et al. (1991) explained the balance between outward/inward Elsässer energies at small scales by the fact that the injected energy at large scales due to velocity shear is balanced in $z_{in}$ and $z_{out}$. This interpretation, however, cannot explain the decrease in $\sigma_c$ around the current sheet in our simulation, because there is no such energy source near the current sheet in the simulation. Instead, the decrease of $\sigma_c$ around the HCS in the simulation is likely to be a result of the shear of background magnetic field that deforms the wave fronts and facilitates the dissipation of wave energies, similar to the velocity-shear effect. In addition, Grappin et al. (1991) does not answer the question of why the residual energy is negative instead of positive in the current sheets. Here, we propose a mechanism related to the expansion effect of the solar wind. Near the HCS, the weak background magnetic field allows fluctuations to evolve freely so they are dominated by the spherical expansion effect, which leads to $u_\perp, b_\perp \sim 1/R$, and $\rho \sim 1/R^2$, and consequently, $b_\perp/\sqrt{\rho} \sim 1$. Hence, as the radial distance increases, the transverse magnetic field fluctuation (in Alfvén speed) becomes larger than the transverse velocity fluctuation, leading to a negative $\sigma_r$. This mechanism is supported by Figure 3, which shows that without expansion, no net residual energy is produced. Meanwhile, Figure 3 also shows that the decrease of $\sigma_r$ cannot be explained by expansion effect and must be caused by processes related to the shear of the background magnetic field.

We note that our simulation cannot explain why, in the solar wind, $\sigma_r$ is generally negative even far from HCS, as can be seen from Figure 8. Recent studies using Parker Solar Probe data show that $\sigma_r$ is already negative at below 30 solar radii while $\sigma_c$ is increasingly high as the satellite moves closer to the Sun (Chen et al. 2020; Shi et al. 2021). Our results show that the presence of a current sheet indeed leads to a dominance of magnetic energy, but it also results in a decrease in $\sigma_c$. Thus, the observed ($\sigma_c \approx 0, \sigma_r \approx -1$) population of the solar wind fluctuations (e.g., D’Amico & Bruno 2015) is possibly Alfvénic turbulence evolved under the influence of current sheets, while the prevailing ($\sigma_c \lesssim 1, \sigma_r \approx -0.2$) population may be generated in the very young solar wind, with other processes taking effect, or it may be a natural result of the evolution of Alfvénic turbulence (e.g., Boldyrev et al. 2012).

Last, we would like to comment that the statistical study of Alfvénic turbulence properties near SIRs by Borovsky & Denton (2010) shows results quite different from our simulations. Their Figure 11 and Figure 16 show that, at the fast/slow stream interface, the magnetic energy dominance is enhanced, i.e., $\sigma_r$ decreases, and the Elsässer ratio $|z_{out}|/|z_{in}|$ increases, contradicting our simulation results showing that $\sigma_r$ declines and $\sigma_c$ increases at SIRs (Figure 2). The reason for this contradiction is unknown and requires further study.

5. Conclusion

In this study, we carry out two-dimensional MHD simulations, using EBM, and a superposed-epoch analysis, using OMNI data, to study the turbulence properties in the solar wind with a focus on the heliospheric current sheet. The simulation results show that both the normalized cross helicity $\sigma_c$ and normalized residual energy $\sigma_r$ drop in the neighborhood of HCS (Figure 2). The observation at 1 au shows that $\sigma_c$ and $\sigma_r$ decrease sharply at the center of HCS, on a timescale of 1–2 hr, which is the scale of the HCS crossings (Figure 8). The observation also shows that $\sigma_r$ starts to drop gradually in a much wider time range $\Delta t > \pm 1$ day, inside the plasma sheet bounding the HCS. The power spectra, calculated over frequency range $f \in [128^{-1}, 2^{-1}]$ minute$^{-1}$ using OMNI data, of velocity, magnetic field, outward and inward Elsässer variables steepen near the HCS (Figure 9), and steeper parallel power spectra near the HCS are also observed in the simulations (Figure 4), implying a stronger energy cascade of the turbulence. Last, both the simulation (Figure 5) and the satellite observation (Figure 10) show that, around the HCS, the density fluctuation $\delta \rho/\rho$ is highly correlated with the square
of the velocity fluctuation Mach number \( (\delta u/C_s)^2 \), implying a significant compressive component in the velocity fluctuations near the HCS (Grappin et al. 1991).

Our results confirm that current sheets significantly influence the evolution of solar wind turbulence in a way that differs from the velocity shear as discussed by Shi et al. (2020). They may explain the low cross-helicity and magnetic-energy-dominated population of fluctuations in the solar wind, but the origin of the prevailing high cross-helicity and slightly magnetic-energy-dominated fluctuations requires other mechanisms that play important roles close to the Sun, or at the source region of the Alfvénic fluctuations. Inspection of the Parker Solar Probe data is necessary to fully understand these mechanisms.

The OMNI data were obtained from the GSFC/SPDF OMNIWeb interface at https://omniweb.gsfc.nasa.gov. This work used the Extreme Science and Engineering Discovery Environment (XSEDE) EXPANSE at SDSC through allocation No. TG-AST200031, which is supported by National Science Foundation grant number ACI-1548562 (Towns et al. 2014). The work was supported by NASA HERMES DRIVE Science Center grant No. 80NSSC20K0604, which is supported by National Science Environment work used the Extreme Science and Engineering Discovery Dynamics (Berlin: Springer), 143.

Dong, Y., Verdini, A., & Grappin, R. 2014, ApJ, 793, 118
Escelevich, V., & Filippov, M. 1988, P&SS, 36, 105
Goldreich, P., & Sridhar, S. 1995, ApJ, 438, 763
Goldstein, M. L., & Roberts, D. A. 1999, PhPl, 6, 4154
Grappin, R., & Velli, M. 1996, JGRA, 101, 425
Grappin, R., Velli, M., & Mangeney, A. 1991, Annales Geophysicae, Vol. 9 (Paris: Gauthier-Villars), 416
Grappin, R., Velli, M., & Mangeney, A. 1993, PrRvL, 70, 2190
Heinemann, M., & Olbert, S. 1980, JGRA, 85, 1311
Hellinger, P., Matteini, L., Štverák, Š., Trávníček, P. M., & Marsch, E. 2011, JGRA, 116, A09105
Hollweg, J. V. 1974, JGR, 79, 1539
Hunter, J. D. 2007, CSE, 9, 90
King, J., & Papitashvili, N. 2005, JGRA, 110, A02104
Kiyani, K. H., Osman, K. T., & Chapman, S. C. 2015, RSPTA, 373, 2041
Kraichnan, R. H. 1965, The Physics of Fluids, 8, 1385
Leer, E., Holzer, T. E., & Flå, T. 1982, SSRv, 33, 161
McManus, M. D., Bowen, T. A., Mallet, A., et al. 2020, ApJS, 246, 67
Réville, V., Velli, M., Rouillard, A. P., et al. 2020, ApJL, 895, L20
Roberts, D. A., Goldstein, M. L., Klein, L. W., & Matthaeus, W. H. 1987, JGR, 92, 12023
Roberts, D. A., Goldstein, M. L., Matthaeus, W. H., & Ghosh, S. 1992, JGR, 97, 17115
Shi, C., Velli, M., Tenerani, A., Rappazzo, F., & Réville, V. 2020, ApJ, 888, 68
Shi, C., Velli, M., Panasenco, O., et al. 2021, Astro & Astrophysics, 650, A21
Siscoe, G. 1972, JGR, 77, 27
Smith, E. J. 2001, JGRA, 106, 15819
Squire, J., Chandran, B. D., & Meyrand, R. 2020, ApJL, 891, L2
Towns, J., Cockerill, T., Dahan, M., et al. 2014, UCE, 16, 62
Tu, C. Y., Pu, Z. Y., & Wei, F. S. 1984, JGR, 89, 9695
Velli, M. 1993, A&A, 270, 304
Zank, G., Adhikari, L., Hunana, P., et al. 2017, ApJ, 835, 147
Zank, G. P., Matthaeus, W. H., & Smith, C. W. 1996, JGR, 101, 17093
Zhou, Y., & Matthaeus, W. H. 1990, JGR, 95, 14881

\[ \text{References} \]

Alazzraki, G., & Couturier, P. 1971, A&A, 13, 380
Belcher, J. 1971, ApJ, 168, 509
Belcher, J. W., & Davis, Leverett J. 1971, JGR, 76, 3534
Boldyrev, S., Perez, J. C., & Zhdankin, V. 2012, in PHYSICS OF THE HELIOSPHERE: A 10 YEAR RETROSPECTIVE: AIP Conf. Proc. 1436 (Melville, NY: AIP)
Borovsky, J. E., & Denton, M. H. 2010, JGRA, 115, A10
Bruno, R., D’Amicis, R., Bavassano, B., Carbone, V., & Sorriso-Valvo, L. 2007, Ann. Geophys, 25, 1913
Chen, C., Bale, S., Bonnell, J., et al. 2020, ApJS, 246, 53
Chen, C., Chandran, B., Woodham, L., et al. 2021, A&A, 650, L3
Coleman, P. J., J. 1968, ApJ, 153, 371
D’Amicis, R., & Bruno, R. 2015, ApJ, 805, 84
Dobrowolny, M., Mangeney, A., & Veli, P. 1980, in Solar and Interplanetary Dynamics (Berlin: Springer), 143

\[ \text{Appendix} \]

List of Heliospheric Current Sheet Crossings Identified Using OMNI Data

The full list of the HCS crossings is shown in Table 1.

ORCID iDs

Chen Shi (时晨) @ https://orcid.org/0000-0002-2582-7085
Marco Velli @ https://orcid.org/0000-0002-2381-3106
Anna Tenerani @ https://orcid.org/0000-0003-2880-6084
Victor Réville @ https://orcid.org/0000-0002-2916-3837
Franco Rappazzo @ https://orcid.org/0000-0001-9030-0418