Electron-to-ion Bulk Speed Ratio as a Parameter Reflecting the Occurrence of Strong Electron-dominated Current Sheets in the Solar Wind

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Abstract

Current sheets (CSs) are preferred sites of magnetic reconnection and energy dissipation in astrophysical plasmas. Electric currents in them may be carried by both electrons and ions. In our prior theoretical studies of the CS formation in turbulent plasmas, we utilized fully kinetic and hybrid code simulations with ions considered as particles and electrons—as a massless fluid. We found that electron-dominated CSs in which electrons become the main carriers of the electric current and contributors to energy dissipation may form inside or nearby ion-dominated CSs. These structures represent a distinguished type of CSs and should not be mixed up with so-called electron-scale CSs. Current simulations show that such CSs are characterized by the electron-to-ion bulk speed ratio \( u_e/u_i \), with \( u_e \) and \( u_i \) being the electron and ion bulk speeds, respectively. Applying the \( u_e/u_i \) parameter to the solar wind data may allow locating the strongest electron-dominated CSs with an ordinary spacecraft resolution of 1–3 s. This study shows that, indeed, electron-dominated CSs observed during a period of quiet solar wind conditions at 1 au impact the surrounding plasma, which may be reflected in sharp changes of \( u_e/u_i \). Electron-dominated CSs are found to be localized in the vicinity of ion-dominated CSs identified via changes in the magnetic field and plasma parameters, displaying the same clustering. We conclude that \( u_e/u_i \) may be used as one of the key parameters for statistical studies of CSs in the solar wind and analyzing the role of electrons in them.

Unified Astronomy Thesaurus concepts: Heliosphere (711)

1. Introduction

Spacecraft routinely observe electric-current-carrying thin plasma layers, or current sheets (CSs), in collisionless space plasmas (e.g., Nakamura et al. 2006; Sundkvist et al. 2007; Greco et al. 2009; Pedesta 2017a; Azizabadi et al. 2021; Jain et al. 2021; Khabarova et al. 2021b). In the solar wind, CSs are formed at discontinuities that separate regions with differently directed magnetic fields (Syrovatskii 1971). Such discontinuities may represent a continuation of large-scale neutral lines of the solar origin, form at edges of various streams and flows, between magnetic islands, and result from magnetic reconnection, instabilities, and wave propagation (Khabarova et al. 2021a). CS structures are known to play a significant role in the development of turbulence and energy release in the form of heating or particle acceleration (Muñoz et al. 2014; Khabarova et al. 2015, 2016; Muñoz & Buechner 2018a; Lazarian et al. 2020; Jain et al. 2021; Azizabadi et al. 2021; Khabarova et al. 2021a; Pezzi et al. 2021b, 2022). They can contribute to an energy cascade when the magnetic energy is transported from larger to shorter scales until it is transferred to the kinetic energy of particles via magnetic reconnection and/or dissipation.

In collisionless plasmas, CSs may thin down to kinetic plasma scales, such as the inertial length or gyroradii of particles, whichever is reached earlier (Jain et al. 2021; Azizabadi et al. 2021). Then, kinetic instabilities would cause additional, small-scale turbulence, which directly dissipates energy or allows fast magnetic reconnection. This sequence of events is well known for large, long-lived CSs of the solar origin, such as the heliospheric CS (HCS). Dynamical processes occurring at the HCS create a wide cloud of secondary, smaller-scale CSs and other dynamically evolving coherent structures in its vicinity (see Khabarova et al. 2021a and references therein). The specifics of dissipation mechanisms, a threshold of microinstabilities, and an efficiency of the energy conversion depend on the structure and properties of CSs, in particular, on the kind of particles carrying the electric current, their possible anisotropic distribution, and other macro- and microscopic plasma parameters.

On the other hand, turbulence can create thin and short-lived CSs (e.g., Howes 2016) as found in numerous numerical simulations of dynamical processes in space turbulent plasmas (Maron & Goldreich 2001; Perri et al. 2012; Franci et al. 2015; Howes 2016; Pezzi et al. 2022). In the solar wind, this scenario is realized far from long-lived and large-scale CSs, in undisturbed plasma. CSs created by turbulence may merge and form larger and longer-lived structures if plasma is impacted by waves, instabilities, or flows.

In order to understand peculiarities of the CS formation, mainly macroscopic, fluid-type numerical simulations have been carried out (see, e.g., Biskamp & Welter 1989; Bárt et al. 2010, 2011). Based on the results of restricted electron-MHD...
The occurrence of CSs is known to determine the shape of the power spectrum of magnetic field variations in the solar wind. This interesting fact has been discovered by Li et al. (2011) and then recently confirmed by Borovsky & Burkholder (2020). Li et al. (2011) showed that the CS-abundant solar wind is characterized by the Kolmogorov-like power spectrum with the slope of $-1.7$, and the solar wind without CSs demonstrates Iroshnikov–Kraichnan scaling with the slope of $-1.5$. Borovsky & Burkholder (2020) performed an analysis of factors forming the shape of the spectrum and concluded that both purely topological characteristics of CSs and dynamical processes occurring in them and their vicinity impact the spectrum considerably.

Since a dissipation mechanism in and around CSs is not quite clear yet, their visual or automated identification in space and subsequent thorough statistical studies of their properties are crucial to understanding numerous processes associated with these plasma objects. Satellite observations in Earth’s magnetosphere, spacecraft observations in the solar wind, and theoretical investigations allowed the understanding of general properties of proton-current-dominated CSs with a width up to several proton gyroradii. As for electron, thinner currents, prior limitations of thin CS models and insufficiency of spatial/temporal resolution of observations gave only rough estimates of the thickness and the amplitude of the electron current peak (see Zelenyi et al. 2004, 2011, 2019; Malova et al. 2012, 2013, 2017 and references therein).

It must be stressed that the term “electron CS” sometimes used in the literature may be confusing because this mixes up electron-scale CSs with a width of several electron gyroradii and electron-dominated CSs of any origin in which the electric current is mostly carried by electrons. Sometimes this is the same since CSs in which electrons carry the current can be very thin. However, the term “electron-dominated CS” has a wider meaning because it does not impose a thickness limit on the particular CS. Theoretical estimations show that the width of electron currents in the solar wind CSs can be one to two ion gyroradii (Malova et al. 2017), and one may expect that very strong electron currents in electron-dominated CSs and the effects in plasma may even be wider (Pezzi et al. 2021a; Vasko et al. 2021). The current study considers not electron-scale CSs but electron-dominated CSs. We will show below that strong electron-dominated CSs can be as wide as ion CSs.

The appearance of modern instruments with a high resolution for the magnetic field has provided researchers an opportunity to investigate a new kind of CSs called super-thin CSs (STCSs) in magnetospheres. Such CSs have been observed in the course of new spacecraft missions such as MAVEN in the Martian magnetotail (Grigorenko et al. 2019). Recent studies confirm the existence of STCSs in the terrestrial magnetotail (Leonenko et al. 2021). A half-thickness of STCSs is about a few or less electron gyroradii; therefore, these current layers can be considered as electron-dominated very thin CSs. The Magnetospheric Multiscale (MMS) mission, with its electron-scale tetrahedron configuration, has been very useful in understanding properties of electron-scale STCSs in both Earth’s magnetopause and magnetotail (e.g., Phan et al. 2016; Dong et al. 2018; Leonenko et al. 2021).

Contrary to the magnetosphere, there have not been investigations of properties of CSs determined by the electron currents in the heliosphere so far. Studies of CSs in the solar wind are focused on ion CSs only. Various criteria are used for identifying proton- or ion-dominated CSs. Most commonly, significant rotation of the magnetic field vector (sometimes, from one direction to the opposite) and signatures of the crossing of a neutral line are employed to distinguish between ordinary discontinuities and CSs. These are primary signs of CS crossings. Additionally, observers analyze the behavior of plasma parameters, namely, the plasma beta ($\beta$) that usually sharply increases at strong ion CSs and the ratio of the Alfvén speed to the solar wind speed (which decreases at CSs). These are secondary signatures identifying ion-dominated CSs. An overview of both visual and automated methods of CS identification in the heliosphere can be found in Khabarova et al. (2021b).

An identification of thin current layers of electron scales based on data from most spacecraft operating in the solar wind is still complicated (e.g., Kellogg et al. 2003, 2006). The main reason for that is the insufficiency of the resolution of measurements. Spacecraft typically allow only measurements of plasma parameters and the magnetic field with a 1–3 s resolution, which is far larger than electron scales. The second reason is the absence of multiscale missions owing to which thin electron-scale CSs were discovered and studied in the terrestrial magnetotail (Sergeev et al. 1993; Runov et al. 2003, 2006). All measurements in the solar wind are single-spacecraft. The only mission that could help is MMS since a part of its orbit lies in the solar wind. However, MMS leaves the terrestrial magnetosphere and stays in the solar wind only for a short time, during which the burst mode is mostly switched off. This does not allow for performing comprehensive studies of thin electron-scale CSs in the solar wind.

Meanwhile, since strong electron-dominated CSs in the solar wind can be wider than electron-scale CSs, the task of finding them outside the terrestrial magnetosphere does not seem hopeless. Below, we will show an example of crossing of such a CS with MMS in the solar wind. If one knows specific features characterizing the occurrence of strong electron-dominated CSs in the solar wind, then it is possible to apply commonly accepted techniques for CS identification to recognition of electron-dominated CSs from the in situ data, using an ordinary spacecraft resolution of 1–3 s (Khabarova et al. 2021b). It also would be interesting and useful to find secondary or indirect signatures of strong electron-carried currents.

Theoretical studies and numerical simulations may help work out the problem. A theoretical approach in the frame of hybrid 1D or 2D models in which ions are considered with a quasi-adiabatic approach and the electron motion is treated as an MHD flow is known to be the best perspective in the description of such thin multilayered CSs (Zelenyi et al. 2004, 2011; Petrukovich et al. 2011; Malova et al. 2012, 2013). A comprehensive work (Zelenyi et al. 2020) has provided the basis of the theory of STCSs, and recent numerical simulations allowed finding the way to identify electron-dominated CSs via an analysis of spatial variations of plasma parameters (Azizabadi et al. 2021; Jain et al. 2021).

For a better understanding of the CS formation and their expected thinning down to kinetic scales, different kinds of
numerical simulations have been carried out utilizing a variety of different plasma models, such as hybrid codes that consider ions as particles and electrons as a fluid (Azizabadi et al. 2021; Jain et al. 2021). The latter investigation revealed, supported by theoretical estimates, an extra criterion that can be used for a better understanding of the structure of CSs in turbulent plasmas. This criterion is based on the finding that within thinning CSs the (shear) flow velocity of the current-carrying electrons in the direction parallel to the ambient magnetic field \( (|u_e|) \) should significantly exceed by a large amount the ion bulk flow velocity \( (|u_i|) \) in this direction. At the same time, the plasma density would vary only weakly (less than 10%) throughout the CSs. Thus, the ratio of electron to ion bulk flow velocities \( (|u_e|/|u_i|) \) should become very large at the strongest electron-dominated CSs in the solar wind.

Theoretical studies predict that ion- and electron-dominated CSs may be observed by a spacecraft in different ways. First, a thin electron-dominated CS can be embedded in the wider ion-dominated CS (Malova et al. 2017). Second, spatially separated electric currents in which electrons and ions are main carriers may form at reconnecting CSs, due to the effect of partial separation of charges (Zharkova & Khabarova 2012, 2015; Khabarova et al. 2020). In that case they may be observed with a high resolution as two closely located CSs dominated by electrons and ions, but in fact these are two parts of the same bifurcated CS with the currents spatially separated with respect to the main neutral plane. It is not clear whether closely lying ion- and electron-dominated CSs can be found from situ observations via variations in plasma parameters in this case. There are no predictions regarding formation of totally isolated (single) ion- or electron-dominated CSs in the solar wind either, and we know nothing about their possible survival time if such CSs form owing to some nonstationary processes. No one knows if they may live for the time period sufficient for their observation with spacecraft. Therefore, the existence of electron-dominated CSs raises a lot of questions, and it would be important to carry out a study that allowed for finding an approximate location of electron-dominated CSs using their known impact on plasma parameters.

The structure of the manuscript is as follows. We first carry out simulations that show formation of CSs in a turbulent plasma and describe the jump criterion of \( |u_e|/|u_i| \) within CSs from the theoretical point of view (see Sections 2 and 3, respectively). Then, we mimic a crossing of several simulated CSs with a virtual spacecraft to show that the corresponding sharp variations in \( |u_e|/|u_i| \) can potentially be spotted by a spacecraft in the solar wind with a typical resolution of 1–3 s (Section 3). In Section 4 we describe the observational approach to the problem of finding the impact of electron currents on the ambient plasma reflected in variations of plasma parameters. A supporting case study of the CS crossing in the solar wind with MMS follows the theoretical part. It is aimed at a preliminary estimation of the ability of the \( u_e/|u_i| \) parameter to recognize plasma structures associated with electron-dominated CSs. Then, we utilize the Wind spacecraft observations, identifying such magnetoplasma structures and comparing their found locations with those of ion-dominated CSs, using the method described by Khabarova et al. (2021b). Finding an approximate location of electron-dominated CSs may be very useful for future statistical studies of solar wind CSs in which electrons are the main current carriers. The conclusions of the investigation are drawn and discussed in Section 5.

2. Simulation Results

We carried out hybrid code simulations of a turbulent plasma in which we treated ions as particles and electrons as an inertialess fluid on a two-dimensional mesh spanning over an x-y plane. For this sake we utilized the PIC-hybrid code A.I.K.E.F. (Müller et al. 2011). We initialized the simulations with random-phased fluctuating magnetic fields and plasma velocities within a wavenumber range \( |k_x|, |k_y| \ll 0.2 \) (\( k_z = 0 \)). Here \( k_x \) and \( k_y \) are wavenumbers in the x- and y-directions, respectively, and \( \beta = 1/\omega_B^2 \), \( \omega_B = B_0/\sqrt{\mu_0 n_0 m_i} \), and \( \omega_i = eB_0/m_i \) are inertial length, Alfvén velocity, and cyclotron frequency of ions, respectively (\( \mu_0 \) is the vacuum magnetic permeability, \( e \) the electron charge, and \( m_i \) the proton mass). The fluctuations are imposed on an isotropic background plasma of uniform density \( n_0 \). All initialized modes have the same energy and an rms value \( B_{rms}/B_0 = 0.24 \), where \( B_0 \) is the uniform magnetic field applied perpendicular to the simulation plane. Electron and ion plasma beta are \( \beta_e = 2\mu_0 n_0 k_B T_e/B_0^2 = 0.5 \) and \( \beta_i = 2\mu_0 n_0 k_B T_i/B_0^2 = 0.5 \), with \( T_e \) and \( T_i \) being the electron and ion temperatures, respectively, and \( k_B \) the Boltzmann constant. The simulation box size \( 256d_i \times 256d_i \) is resolved by \( 512 \times 512 \) grid points with 500 macroparticles per cell. The time step was chosen to be \( \Delta t = 0.01 \omega_i^{-1} \). Periodic boundary conditions are applied in all directions.

In the course of the evolution of the initially long-wavelength magnetic and ion velocity fluctuations, CSs are formed by \( \omega_i t = 50 \) (Figure 1). These CSs later break up, developing shorter-wavelength turbulence (Daughton et al. 2011; Muñoz & Büchner 2018b; Dahlin et al. 2015), as shown at \( \omega_i t = 150 \) in Figure 1. Our hybrid code simulations revealed that within the CSs the parallel (to \( B_0 \)) electron bulk flow velocities became much larger than the parallel ion bulk velocities (Jain et al. 2021). The perpendicular (to \( B_0 \)) bulk velocities of electrons and ions, on the other hand, are of the same order but smaller than the parallel bulk velocity of electrons. Therefore, the net bulk speed of electrons is larger than that of ions.

In space observations, special care has to be taken to distinguish between parallel and perpendicular (to the magnetic field) velocity components. It is typically easier to get net velocity of particles in space observations. In order to interpret the observations, we examined the ratio \( u_e/|u_i| \) of the net bulk velocities \( u_e = |u_e| \) and \( u_i = |u_i| \) of the electrons and ions, respectively. As an example, Figure 2 depicts the isolines of \( u_e/|u_i| \) in the simulation plane at \( \omega_i t = 50 \) and \( \omega_i t = 150 \). It can be seen that the electron bulk speed \( u_e \) exceeds the ion bulk speed \( u_i \) by several times in ion-scale CSs. Moreover, the ratio \( u_e/|u_i| \) enhances as the turbulence evolves from \( \omega_i t = 50 \) to 150.

In order to detect a jump in \( u_e/|u_i| \) in time series measurements by spacecraft, it is more practical to look at the derivative of \( u_e/|u_i| \). Figure 3 shows the magnitude of the spatial gradient of \( u_e/|u_i| \) in the simulation plane. It is clear from Figures 2 and 3 that the value of \( |\nabla (u_e/|u_i|)| \) in CSs is better distinguished from its value outside CSs as compared to the values of \( u_e/|u_i| \).

Figure 4 shows the line-outs of \( u_e/|u_i|, |\nabla (u_e/|u_i|)|, \) and \( J \), along the normal of the three CSs (CS1, CS2, and CS3) highlighted in Figure 1. It can be seen that \( u_e/|u_i| \) takes a jump from its value of the order of unity outside CSs to a value at least several times larger in CSs. Note that the value of \( u_e/|u_i| \) inside CS sheets is not unique. It might be different for different CSs. Therefore, the actual value of \( u_e/|u_i| \) inside CSs is
Figure 1. Parallel current density $J_z$ at two moments of time: $\omega_{ci}t = 50$ (left column) and $\omega_{ci}t = 150$ (right column). Three CSs, numbered 1, 2, and 3, are highlighted at $\omega_{ci}t = 50$ by enclosing them in rectangles with dashed borders. The red line in each rectangle is the CS normal. Mean magnetic field is in the out-of-plane ($z$) direction as shown by arrows on the left.

Figure 2. Ratio $u_e/u_i$ of the magnitudes of the electron ($u_e = |u_e|$) to the ion bulk speeds ($u_i = |u_i|$) at two moments of time: $\omega_{ci}t = 50$ (left column) and $\omega_{ci}t = 150$ (right column). Rectangles with dashed border enclose the three CSs (CS1, CS2, and CS3) at $\omega_{ci}t = 50$.

Figure 3. Magnitude of the gradient of the ratio $u_e/u_i$ at two moments of time: $\omega_{ci}t = 50$ (left column) and $\omega_{ci}t = 150$ (right column). Rectangles with dashed border enclose the three CSs (CS1, CS2, and CS3) at $\omega_{ci}t = 50$. 
not as important as the jump in its value from outside to inside the sheets as far as the CS detection is concerned. This jump is characterized by $\nabla (u_e/u_i)$. Note that $\nabla (u_e/u_i)$ inside CSs is dominated by the gradient along the CS normal, which changes sign across the CS. A dip in the value of $\nabla (u_e/u_i)$ at the peak of $u_e/u_i$ in Figure 3 corresponds to this change of sign of $\nabla (u_e/u_i)$.

In Section 4, we will use the jump condition of $u_e/u_i$ to detect CSs in solar wind by applying the condition to the time series measurements made by the Wind spacecraft in quiet solar wind from 00:00 on 1998 February 13 to 12:00 on 1998 February 14 with a resolution of 3 s. For these observations (solar wind speed $V \sim 400$ km s$^{-1}$, density $\sim 10$ cm$^{-3}$), the spacecraft travels approximately 1200 km $\approx 16d_i$ during a 3 s measurement. Therefore, the time series measurements by the Wind spacecraft are effectively averaged over a distance of approximately 16$d_i$. We average the simulation values of $u_e$ and $u_i$ over a distance of 16$d_i$ along an assumed spacecraft trajectory passing the simulation plane at $y = -95.4d_i$ to find out if $\bar{u}_e/\bar{u}_i$ still jumps at CSs ($\bar{u}_e$ and $\bar{u}_i$ are the averaged values) or the jump is washed out by the averaging procedure. Figure 5 shows the assumed trajectory and line-outs of $\bar{u}_e/\bar{u}_i$ along the assumed spacecraft trajectory. Here $\bar{u}_e$ and $\bar{u}_i$ are the values of $u_e$ and $u_i$ averaged over a distance of 16$d_i$ at each point on the trajectory, respectively. Green vertical lines cross the trajectory at locations of CSs.

3. Theoretical Estimate of the Electron-to-ion Bulk Speed Ratio

For a quantitative comparison with observations it is appropriate to estimate the expected values of electron and ion bulk flow velocities. Theoretical estimates for the ratio of

\[
\frac{u_e}{u_i}\]

Figure 4. Line-outs of $u_e/u_i$, $\nabla (u_e/u_i)$, and $j_z$ across the three CSs (CS1, CS2, CS3) highlighted in Figure 1 at $\omega_c t = 50$.

Figure 5. Top: color-coded $j_z$ at $\omega_c t = 50$ in a subdomain ($y \in [-125, -75]$ on the vertical axis and $x \in [-128, 128]$ on the horizontal axis) of the $x$-$y$ simulation plane. The horizontal dashed line drawn at $y \approx -95.4$ in the top panel is an assumed spacecraft trajectory. Bottom: line-outs of $j_z$ and $\bar{u}_e/\bar{u}_i - 1$ along the assumed spacecraft trajectory. Here $\bar{u}_e$ and $\bar{u}_i$ are the values of $u_e$ and $u_i$ averaged over a distance of 16$d_i$ at each point on the trajectory, respectively. Green vertical lines cross the trajectory at locations of CSs.

the out-of-plane electron and ion bulk velocities, $|u_{el}|/|u_{iz}|$, was obtained approximating ion response as unmagnetized (Jain et al. 2021). Here we estimate theoretically the ratio of the total electron and ion bulk velocities, $u_e/u_i$, under the approximation of unmagnetized ions.

For CSs with thicknesses of the order of ion gyroradius $\rho_i = \sqrt{\beta} d_i$, ions can be approximated as unmagnetized while electrons are still tied to the magnetic field lines. Figure 6 shows line-outs across CSs CS1–CS3 of the turbulent magnetic field components perpendicular ($B_\perp$) and parallel ($B_z$) to the applied magnetic field $B_0$. The turbulent magnetic field near the CS center, where current density peaks, is an order of magnitude smaller than the applied magnetic field $|B_\perp|/B_0 \sim (B_z - B_0)/B_0 \sim 0.1$. Therefore, we take parallel and perpendicular directions inside CSs (approximately) with respect to the applied magnetic field $B_0 = B_0 \hat{z}$. We can then obtain ion bulk velocity $u_i$ from the ion’s momentum equation neglecting Lorentz force, parallel electron bulk velocity $u_{el}$ as $E \times B$ drift from Ohm’s law, and parallel electron bulk velocity $u_{el}$ from Ampere’s law:

$$\frac{\partial u_i}{\partial t} = \frac{eE}{m_i}$$

$$u_{el} = \frac{E_\parallel \times B}{B^2}$$

$$u_{el} = u_{iz} - \frac{\nabla \times B_z}{\mu_0 ne}.$$  

Electric and magnetic fields are related by Faraday’s law:

$$\nabla \times E = - \frac{\partial B}{\partial t}.$$  

Here $\nabla \equiv \hat{\partial}/\partial x + \hat{\partial}/\partial y + \hat{\partial}/\partial z$. In Equation (1), the convective derivative $(u_i \nabla u_i)$ is neglected compared to the time derivative inside CSs under the approximation $|u_i| \nabla u_i \sim u_{el}/v_{Ai} \sim 0.1 \ll 1$ (for $\partial / \partial t \sim v_{Ai}/L$ and $\nabla \sim L^{-1}$) as was demonstrated by simulations (Jain et al. 2021). Equations (1) and (2) give estimates as $u_{el} \sim LE_\parallel/d_B$, $u_{iz} \sim LE_z/d_B$, and $u_{el} \sim E_z B_0/B^2$.

Estimating $E_\parallel \sim E_{v_{Ai}}$ and $E_z \sim E_{B_0}/B^2$ from Faraday’s law, we get

$$u_{el} \sim v_{Ai} L B_\perp/d_B$$

$$u_{iz} \sim v_{Ai} L B_z/d_B$$

$$u_{el} \sim v_{Ai} B_0 B_z/B^2.$$  

Here $B_\perp = |B_\perp|$ and $B_z = B_z - B_0$ are turbulent magnetic field components. The first term $(|u_{el}| \sim v_{Ai} L B_\perp/d_B)$ on the right-hand side of Equation (3) can be neglected in comparison to the second term $(|\nabla \times B_\perp|/\mu_0 ne \sim v_{Ai} d_B L/B)$ for perpendicular spatial scales lengths $L \ll d_i$, giving

$$u_{el} \sim v_{Ai} d_B B_\parallel/L.$$  

The parallel and perpendicular components of electron and ion bulk velocities can now be compared inside CSs using Equations (5)–(8). Equations (5) and (7), $u_{el}/u_{iz} \sim (B_\parallel/B_0)(d_i/L)$. For unmagnetized ions ($L < \rho_i \sim d_i$) and $B_\parallel \sim B \sim B_0$, $u_{el}/u_{iz}$ is typically smaller than the results of the hybrid simulations (Jain et al. 2021). Inside CSs, the perpendicular ion bulk velocity is typically smaller than the perpendicular electron bulk velocity owing to the demagnetization of ions. From Equations (6) and (8), $u_{el}/u_{iz} \sim d_i^2/L^2 > 1$. Note that both the ratios $u_{el}/u_{iz}$ and $u_{el}/u_{iz}$ are greater than unity but $u_{el}/u_{iz}$ is consistent with the simulations (Jain et al. 2021). Using $B_\parallel \sim B$, $B_\perp \sim B$, and $d_i^2/L^2 \gg 1$, the ratio of the net electron and ion bulk velocities, $u_e = (u_{el}^2 + u_{iz}^2)^{1/2}$ and $u_i = (u_{el}^2 + u_{iz}^2)^{1/2}$, respectively, can be written as

$$u_e \sim \frac{d_i^2}{L^2} \frac{b_L}{b_i}$$

$$u_i \sim \frac{d_i^2}{L^2} \frac{b_L}{b_i}.$$  

The ratio $u_e/u_i$ is smaller than the ratio $u_{el}/u_{iz}$ by a factor of the order of unity, again consistent with the results of the hybrid simulations (Jain et al. 2021). With the CS thinning, therefore, the current in the sheet is confirmed to be increasingly carried by the electrons.

4. High- and Low-resolution Observations of Electron-dominated Current Sheets in the Solar Wind

As noted in the Introduction, in most cases one cannot directly observe electron-scale CSs in the solar wind, first of all because of the absence of the constellation-type spacecraft operating there. Finding the location of CSs of any type in the solar wind is always a matter of the analysis of several parameters that specifically vary at CS crossings, as shown in Khabarova et al. (2021a, 2021b). The second problem is that a resolution of measurements of the magnetic field in the solar wind is usually about 1 s, which corresponds to one to two proton gyro radii. This is satisfactory for identifying ordinary ion-scale CSs, but this makes impossible direct observations of much thinner electron-scale CSs. As for electron-dominated CSs in the solar wind, so far there have not been studies concerning their properties and identification.

Meanwhile, it is useful to know at least an approximate location of electron-dominated CSs because they may carry currents larger than those carried by ions (Podesta 2017b;
We will show that, despite the obstacles discussed above, one may consider indirect observational signatures of electron-dominated CSs to recognize them from the solar wind data. A case study below confirms that at least some electron-dominated CSs can be characterized by very intense current densities comparable by width with well-known ion-dominated CSs.

First, we show an example of the electron-dominated CS observed by MMS with an unprecedentedly high resolution (150 ms for ions and 30 ms for electrons), checking the hypothesis that its impact on plasma parameters is strong and spatially wide enough to be detected with far lower resolution. Second, we apply the \( u_e/u_i \) signature of electron-dominated CSs to the solar wind data on the electron and proton velocity at 1 au obtained from the Wind spacecraft. We compare locations of electron-dominated CSs found via sharp variations of \( u_e/u_i \) with locations of ion-dominated CSs identified with the method described by Khabarova et al. (2021b). We claim below that a jump in the \( u_e/u_i \) parameter can potentially point out a strong electron-dominated CS located somewhere within the region crossed by a spacecraft for 3 s (which is a typical temporal resolution of the solar wind spacecraft for the magnetic field).

4.1. Example of High-resolution Observations of the Electron Current Dominated over the Ion Current as Detected by MMS in the Solar Wind

In the previous, theoretical section we showed that a strong electron-dominated CS crossed by a spacecraft in the solar wind can potentially be spotted even with a rough 1–3 s resolution because of the impact of a strong electric current on the plasma. The latter can be visible via the \( u_e/u_i \) ratio increase. To illustrate the same effect with in situ spacecraft measurements, we use the MMS mission data since its resolution allows studying the fine structure of CSs of all types, including the thinnest electron-scale CSs (Burch et al. 2016; Leonenko et al. 2021). The highest-resolution data are available when the burst mode is triggered. One can find more information about the burst mode measurements in Argall et al. (2020). Burst mode plots and data can be accessed on the mission website: https://lasp.colorado.edu/mms/sdc/public.

Figure 7 shows MMS1 observations performed in the burst mode from 17:23:43 to 17:24:23 UT on 2017 December 15, when MMS was in the solar wind. This is an overview of observations for this period provided on the mission website https://lasp.colorado.edu/mms/sdc/public/data/sdc/burst/all_mms1_summ/2017/12/15/burst_all_mms1_summ_20171215_172343.png. Sharp variations in \( B_z \) and \( B_x \), interplanetary magnetic field (IMF) components crossing zero lines coincide with the corresponding variations and enhancements in the ion flux in the keV range and electron flux up to hundreds of eV. The amplitude of the electric field increases considerably, together with sharp changes in the drift velocity. Such plasma objects can be classified as bifurcated CSs. An example of these CSs is shown in Figure 1 (see the pairs of blue and red curves). Sometimes they are also treated as magnetic holes or crossings of elongated flux tubes with borders representing CSs if one considers possible counterparts in 3D. What is important for the particular study is that if one calculates the current density for ions and electrons, then it becomes clear that the ion current dominates at one side of the dip in the total magnetic field and the electron current exceeds the ion current at the other side. This can be seen in the top panel of Figure 8. The electron current density is shown in blue, and the red curve represents the ion current density. The time period during which the electron current dominates is highlighted by the yellow stripe. The corresponding increase of the \( u_e/u_i \) ratio is seen in the bottom panel of Figure 8. One can find that changes in the plasma parameter are clearly pronounced at the crossing of the electron-dominated CS; they are smoother and even wider than the corresponding changes in the electric current density in the top panel. The effect does not disappear under the 3 s averaging, which means that using ordinary data from spacecraft like Wind may help reveal strong electron-dominated CSs in the solar wind.

4.2. Locating Electron-dominated Current Sheets by Means of the Electron-to-Ion Bulk Speed Ratio from the Low-resolution Wind Spacecraft Data

We use below data from Wind, a spacecraft operating at 1 au in the solar wind, at the first Lagrangian point. It has a typical resolution in terms of plasma and magnetic field measurements in the solar wind, far lower than a data resolution of such magnetospheric missions as MMS or Cluster, but at the same time, this is one of the rare spacecraft that allows measuring the electron velocity. Solar Wind Experiment (SWE) Electron Data Sources are available at NASA’s Space Physics Data Facility (SPDF) website https://cdaweb.gsfc.nasa.gov/index.html. They allow finding the velocity of electrons (\( u_e \)) necessary for the study. We further use the ion (proton) velocity (\( u_i \)) obtained by the Wind spacecraft 3-D Plasma and Energetic Particle Investigation experiment (Wind 3DP; http://sprg.ssl.berkeley.edu/wind3dp). From these data we calculate the \( u_e/u_i \) ratio and find the total magnetic field \( B \). Additionally, we employ the solar wind key parameters to compile a list of ion CSs via the automated method that considers sharp variations in the total magnetic field, \( \beta \), and the ratio of Alfvén speed \( V_A \) to the solar wind speed \( V \) (Khabarova et al. 2021b). This is the basis of the three-parameter method, on which the IZMIRAN database of CSs has been built (see https://csdb.izmiran.ru/). Summarizing, the following Wind data from the SPDF website have been used:

- WI_H2_MFI—Wind Magnetic Fields Investigation, high-resolution definitive data (IMF);
- WI_PM_3DP—Ion moments (the velocity, the density, and the temperature of the solar wind protons);
- WI_EM_3DP—Electron Plasma moments (the electron velocity).

The \( u_e/u_i \) data have the 3 s resolution, and the three key parameters to identify the ion CS location via the method described in Khabarova et al. (2021b) are calculated with a 1 s cadence. The noise effects can be neglected after the procedure of setting the threshold for spotting only strong CSs (see below).

We have selected a very quiet solar wind period from 00:00 on 1998 February 13 to 12:00 on 1998 February 14, during which the near-Earth plasma was not affected by either interplanetary coronal mass ejections (ICMEs) or stream interaction regions (SIRs). One can see in the top three panels of Figure 9 that the \( B_z \) and \( B_y \) components of the IMF in the Geocentric Solar Ecliptic (GSE) coordinate system vary around zero, and the \( B_x \) component shows a slow transition from the negative to positive IMF sector, suggesting a crossing of the heliospheric plasma sheet (HPS). The HPS is a wide area filled with numerous CSs produced, on the one hand, by magnetic
reconnection and instabilities developing at the HCS embedded in the HPS and, on the other hand, by the same processes occurring at other strong and long-lived CSs representing an extension of former streamers expanding from the solar corona (Maiiewski et al. 2020). Because of this, the IMF components may vary around zero for hours, and the IMF does not immediately change its direction at the HCS within the HPS (Khabarova et al. 2021a).

As seen in the bottom two panels of Figure 9, the spacecraft is in the slow solar wind with the ordinary, not elevated solar wind density. The proton bulk speed is lower than 450 km s\(^{-1}\), and the proton density curve lies below the level of 10 particles cm\(^{-3}\). Therefore, the interval is ideal for the exploration of turbulence enhanced by products of magnetic reconnection at CSs within and in the vicinity of the HPS.

First, we create a list of ion CSs, following Khabarova et al. (2021b). At the next step we identify plasma structures presumably associated with electron-dominated CSs as predicted by the simulations discussed above. Such structures are supposed to be characterized by sharp variations in \(u_e/u_i\) and simultaneous variations in the IMF module \(B\). Therefore, we identify them by calculating derivatives of \(u_e/u_i\) and \(B\) and setting up the noise thresholds as discussed below. Then, we compare both rows to find similarities and differences.

Figure 10 shows variations of the IMF strength in the top panel, according to which one may approximately estimate

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**Figure 7.** Bifurcated CS formed by ion- and electron-dominated currents as observed by the MMS1 satellite in the solar wind. From top to bottom: total IMF and three IMF components in the GSE coordinate system, ion and electron energy flux spectrograms, ion and electron densities, ion velocity components, ion drift speed in the \(Z\)-direction, and electric field vector. Temporal resolution is 150 ms for ions and 30 ms for electrons.
how often and where the locations of the strongest ion-dominated CSs are crossed by the Wind spacecraft. Sharp dips in $B$ seen with a 1 s resolution correspond to crossings of neutral lines at CSs when at least one of the IMF components equals zero in the corresponding reference system. This is the simplest way to identify CSs by eye known among observers. Additionally, $\beta$ and $V_\perp/V$ variations are taken into account since statistics shows that the plasma beta jumps and the $V_\perp/V$ ratio falls at ion CSs. To make the changes more pronounced, derivatives of these parameters are taken to identify CSs as described in Khabarova et al. (2021b).

Ratio $u_e/u_i$ is below 1 in the bottom panel of Figure 10 despite the theory predictions of a $u_e/u_i$ jump above 1 at electron-dominated CSs (see above). This is a result of working with real observations and necessary data averaging. The point is that this parameter is always below 1 in the background plasma around such CSs. CSs in which electrons carry the main electric current are thin in comparison with the space surrounding them and included into averaging. Predictions show that the visible input of the current into the $u_e/u_i$ jump should last for about 1 s. The input of the parameter exceeding 1 into the 3 s averaged picture is low in the background of dominating $u_e/u_i$ values far below 1. Only the strongest electron-dominated CSs can be detected with the 3 s resolution and seen as sharp increases of the $u_e/u_i$ parameter in Figure 10.

The result of the identification of ion CSs via the three-parameter method is shown in the first panel of Figure 11 in the form of red bars. A value of 0 means no CS, and 1 corresponds to the presence of a CS identified with the application of the following thresholds that cut off the noise: $B' \leq -0.11$, $V_\perp/V \leq -0.005$, and $\beta \geq 0.75$. The thresholds are shown as red horizontal lines. Imposing the thresholds helps us neglect possible device noise and too weak CSs to be of interest. The other panels show variations in the parameters that help detect CSs with an automated method, running the corresponding code similar to that described in Khabarova et al. (2021b).

We have found that, analogous to the $V_\perp/V$ parameter used in Khabarova et al. (2021b), $u_e/u_i$ itself displays the location of CSs worse than its derivative (compare the corresponding panels in Figures 10 and 11). The second (green) panel in Figure 11 shows the location of electron CSs identified using the proposed $u_e/u_i$ parameter and $B'$. The corresponding noise-cutting threshold is $(u_e/u_i)' \geq 0.05$. The other panels show variations in the parameters that help detect CSs with an automated method, running a corresponding code similar to that described in Khabarova et al. (2021b). Although the exact location of ion CSs (red) and electron CSs (green) does not always coincide, both the red and green panels show clear clustering of CSs in the same places, and the strongest CSs, easily visible as the sharp $B$ decreases and the plasma beta jumps, are successfully identified via both $(u_e/u_i)'$ variations and the three-parameter method.

Some difference between the location of ion and electron CSs can be explained, first, by the fact that the $(u_e/u_i)'$ parameter often catches an inner thin CS with the current produced by elections, which is embedded in the wider “ion” CS. Purely technically, two methods having different accuracies always return a little different location of the corresponding structures. Second, the $(u_e/u_i)'$ parameter is supposed to be more sensitive to thin CSs born as a result of pure turbulence than to CSs produced by magnetic reconnection at strong large-scale CSs such as the HCS (see the Introduction).

Figure 11 shows that despite very similar clustering, electron CSs may be observed without any association with ion CSs, and vice versa. This is an interesting result because this may not only reflect a different sensitivity of different methods but also have a certain physical sense, allowing us to suggest that CSs of very different types can form under different conditions. However, a confirmation of this idea requires thorough investigations of properties of electron and ion CSs observed in the differently originated solar wind flows or streams.

Therefore, preliminary results support the idea that the electron-to-proton velocity ratio can be considered as one of the key parameters to detect electron-dominated CSs. Further studies will show details of how ion- and electron-dominated CSs are related and why they sometimes exist separately.
5. Conclusions and Discussion

This study suggests a way to identify the strongest electron-dominated CSs in the solar wind via an automated method that may be used for statistical purposes. Electron-dominated CSs are current layers of various origins in which the electron current exceeds the ion current. Electron-scale CSs are a subset of electron-dominated CSs that can also be of ion scales. The main idea is based on theoretical and observational findings that the most intense electron currents impact the plasma significantly and can be spotted in the solar wind at scales of thousands of kilometers.

No electron-dominated CSs have been observed in the solar wind before because it was supposed that they should have an electron-scale width unresolvable by spacecraft. This study shows the first example of a CS with the current driven by electrons as observed by the MMS mission in the solar wind, outside the magnetosphere and the foreshock area. It is found

Figure 9. A period of a quiet solar wind: from 00:00 on 1998 February 13 to 12:00 on 1998 February 14. From top to bottom: the three components of the IMF in the GSE coordinate system, the proton bulk speed ($u_p$), and the proton density ($p^+$) as observed by the Wind spacecraft.
that electron-dominated CSs can be much wider than expected before, and variations in the electron and ion speeds can reflect the occurrence of such CSs at scales up to several ion gyroradii.

Observations show that the impact of electron-dominated CSs on the surrounding plasma is significant. It can be seen in the vicinity of $+/−$ several CS widths with respect to the location.

Figure 10. Key parameters helping identify both electron- and ion-dominated CSs for the same period as shown in Figure 9. From top to bottom: the IMF strength $B$, $β$, $V_A/V_e$, and $u_e/u_i$. 

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of the particular CS. Further studies with the help of the MMS mission are needed to analyze key properties and stability characteristics of electron-dominated CSs in the solar wind.

Beginning with the first investigations of thin magnetospheric CSs based on the unique MMS data, it has been known that electrons may carry the strongest electric current in some

Figure 11. Location of ion- and electron-dominated CSs identified for the same period as shown in Figure 9. From top to bottom: location of ion-dominated CSs identified via the three-parameter method (Khabarova et al. 2021b; red lines) vs. the location of electron-dominated CSs found via $(u_e/u_i)^\beta$ and $B^\gamma$ (green lines), respectively. Module of derivatives of $B$, $V_A/V$, $\beta$, and $u_e/u_i$ shows the sharpest changes in the parameters at CS crossings.
CSs. In this case, electrons are significantly heated and move fast, while ions keep the average temperature and display almost no acceleration (Wang et al. 2018; Macek et al. 2019; Bandyopadhyay et al. 2021). Recent numerical simulations show that, indeed, electron-dominated CSs are associated with an increase of the electron-to-ion bulk speed ratio $u_e/u_i$ and with electrons becoming the main carriers of the electric current. Numerical studies of the CS formation in turbulent plasmas by fully kinetic and by hybrid code simulations (in which ions are considered as particles and electrons as a fluid) found that thin electron-scale CSs can be formed inside ion-scale thicker CSs (e.g., Malova et al. 2017; Azizabadi et al. 2021). Simulations done for the magnetospheric conditions suggest that electron-dominated CSs can also exist independently of ion CSs (see, e.g., Zelenyi et al. 2020 and references therein).

High-accuracy observations of magnetoplasma structures at the magnetopause and in the tail of the terrestrial magnetosphere, as well as in planetary magnetospheres, show that electron current layers are usually found at sites where CSs become significantly thinned and ready for reconnection, or when magnetic reconnection is already underway (Nakamura et al. 2006; Panov et al. 2006; Runov et al. 2008; Grigorenko et al. 2019; Zelenyi et al. 2020; Hubbert et al. 2021). The thickness of such electron-dominated CSs may be as small as a few gyroradii of thermal electrons (Leonenko et al. 2021). Most of them are embedded in wider ion CSs, but single electron CSs can be observed too (Wang et al. 2018; Bandyopadhyay et al. 2021). Although electron CSs possess very similar characteristics in different plasmas, their lifetime and stability characteristics are different (Zelenyi et al. 2008, 2010, 2019). It seems that electron CSs not associated with ion CSs are ubiquitous in the Martian magnetosphere but rather rare in Earth’s magnetotail.

Before this study, the following question has remained opened: is it possible to find signatures of electron-dominated CSs in the solar wind plasma? Existing methods of identifying CSs in the heliosphere are focused on ion-dominated CSs, mainly considering the magnetic field behavior and, rarely, the behavior of plasma parameters (Khabarova et al. 2021b). There have not been comprehensive studies of electron-dominated CSs in the solar wind, for many technical reasons. Their automated identification and statistical investigations have been thought impossible for a long time. Even finding an approximate location of electron CSs is a difficult task, and case studies employing magnetospheric missions in the solar wind for this aim are extremely rare (e.g., Mistry et al. 2015). Meanwhile, studying such CSs is especially important because simulations show that electron CSs most probably carry the largest electric currents in the solar wind (Podesta 2017b).

To solve this problem at least partially, we suggested to use indirect signatures of electron CSs based on the results of numerical simulations. In this study we applied the $u_e/u_i$ criterion of the existence of an electron-dominated CS visible even at ion scales to the solar wind at 1 au utilizing the Wind spacecraft data. We selected a quiet solar wind period within which numerous sharp variations of $u_e/u_i$ were observed, suggesting that the most pronounced changes of $(u_e/u_i)^2$ in a combination with those of $B'$ may point out an approximate location of strong electron CSs, as both theoretical predictions and in situ observations show.

Then, the location of electron CSs identified that way was compared with the location of ion CSs identified via the other method (Khabarova et al. 2021b). It was found that the structures presumably indicating electron-dominated CSs were mostly formed at or in the vicinity of ion-dominated CSs, showing the same clustering. An interesting point is that some of electron- and ion-dominated CSs were registered separately, without CSs of the other type found nearby.

Summarizing, we report important properties of CSs formed in the turbulent solar wind that are associated with electrons becoming the main current carriers. We conclude that, first, electron-dominated CSs in the solar wind can be of ion scales and, second, the electron-to-proton velocity ratio may be considered as the major parameter identifying strong CSs of this type and allowing an analysis of their properties in turbulent plasmas. Based on MMS observations and simulations, we suppose that only the strongest electron-dominated CSs can be identified in the solar wind via such a method from observations made with a 1–3 s resolution typical for most spacecraft.

The results testing the hypothesis of the importance of the $u_e/u_i$ ratio in pointing to electron CSs are preliminary because electron CSs may be identified with a high degree of certainty only using several parameters, analogous to ion CSs, and with a high resolution. Here we just discuss an important feature of the solar wind plasma that may be associated with thin CSs produced by electron currents. Future case studies employing data from the MMS mission will show what parameters are most important to find electron CS crossings and how to build a reliable method of electron CS identification to investigate their properties statistically. So far, the proposed $u_e/u_i$ method can be considered as potentially useful for studies of turbulence in the solar wind and probing CSs in space plasmas.

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References

Argall, M. R., Small, C. R., Piatt, S., et al. 2020, FrASS, 7, 54
Azizabadi, A., Jain, N., & Büchner, J. 2021, PhPl, 28, 052904
Bandopadhyay, R., Chasapis, A., Matthaeus, W. H., et al. 2021, PhPl, 28, 112305
Bárta, M., Büchner, J., & Karlický, M. 2010, AdSpR, 45, 10
Bárta, M., Büchner, J., Karlický, M., & Skála, J. 2011, ApJ, 737, 24
Biskamp, D., & Welter, H. 1989, PhFIB, 1, 1964
Borovsky, J. E. 2010, PhRvL, 105, 111302
Borovsky, J. E., & Burkeholder, B. L. 2020, JGRA, 125, e27307
Burch, J. L., Moore, T. E., Torbert, R. B., & Giles, B. L. 2016, SSRv, 199, 5
Dahlin, J. T., Drake, J. F., & Swisdak, M. 2015, PhPl, 22, 100704
Daughton, W., Roytershteyn, V., Karimabadi, H., et al. 2011, NatPh, 7, 539
Dong, X. C., Dunlop, M. W., Wang, T. Y., et al. 2018, JGRA, 123, 5464
Franci, L., Landi, S., Matteini, L., Verdini, A., & Hellinger, P. 2015, ApJ, 812, 21
Greco, A., Matthaeus, W. H., Servidio, S., Chuychai, P., & Dmitruk, P. 2009, ApJL, 691, L111
Grigorenko, E. E., Zelenyi, L. M., DiBraccio, G., et al. 2019, GeoRL, 46, 6214
Hubbert, M., Qi, Y., Russell, C. T., et al. 2021, GeoRL, 48, e91364
Jain, N., & Büchner, J. 2014a, PhPl, 21, 062116
Jain, N., & Büchner, J. 2014b, PhPl, 21, 072306
Jain, N., Büchner, J., Comisel, H., & Motschmann, U. 2021, ApJ, 919, 103
Kellogg, P. J., Bale, S. D., Mozer, F. S., Horbury, T. S., & Remo, H. 2006, ApJ, 645, 704
Kellogg, P. J., Garnett, D. A., Hospodarsky, G. B., et al. 2003, JGRA, 108, 1045
Khabarova, O., Malandraki, O., Malova, H., et al. 2021a, SSRv, 217, 38
Khabarova, O., Sagitov, T., Kislov, R., & Li, G. 2021b, JGRA, 126, e29099
Khabarova, O., Zank, G. P., Li, G., et al. 2015, ApJ, 808, 181
Khabarova, O. V., Zank, G. P., Li, G., et al. 2016, ApJL, 827, 12
Khabarova, O., Zharkova, V., Xia, Q., & Malandraki, O. E. 2020, ApJ, 894, L12
Lazarian, A., Eynik, G. L., Jafari, A., et al. 2020, PhPl, 27, 012305
Leonenko, M. V., Grigorenko, E. E., & Zelenyi, L. M. 2021a, Ge&Ae, 61, 688
Leonenko, M. V., Grigorenko, E. E., & Zelenyi, L. M. 2021b, JGRA, 126, 107004
Macek, W. M., Silveira, M. V. D., Sibeck, D. G., Giles, B. L., & Burch, J. L. 2019, ApJL, 885, L26
Maiewski, E. V., Malova, H. V., Kislov, R. A., et al. 2020, CoRe, 58, 411
Malova, H. V., Popov, V. Y., Delcourt, D. C., Petrukovich, A. A., & Zelenyi, L. M. 2013, JGRA, 118, 4308
Malova, H. V., Popov, V. Y., Grigorenko, E. E., et al. 2017, ApJ, 834, 34
Malova, H. V., Popov, V. Y., Mingalev, O. V., et al. 2012, JGRA, 117, A04212
Maron, J., & Goldreich, P. 2001, ApJ, 554, 1175
Matthaeus, W. H., Van, M., Servidio, S., et al. 2015, RSPTA, 373, 20140154
Mistry, R., Eastwood, J. P., Phan, T. D., & Hietala, H. 2015, GeoRL, 42, 10513
Muñoz, P. A., & Büchner, J. 2018a, ApJ, 864, 92
Muñoz, P. A., & Büchner, J. 2018b, PhRvE, 98, 043205
Muñoz, P. A., Kilian, P., & Büchner, J. 2014, PhPl, 21, 112106
Müller, J., Simon, S., Motschmann, U., et al. 2011, CoPhC, 182, 946
Nakamura, R., Baumjohann, W., Asano, Y., et al. 2006, JGRA, 111, A11206
Panov, E. V., Büchner, J., Fränz, M., et al. 2006, AdSpR, 37, 1363
Perri, S., Goldstein, M. L., Dorelli, J. C., & Sahraoui, F. 2012, PhRvL, 109, 191101
Petrukovich, A. A., Artemyev, A. V., Malova, H. V., et al. 2011, JGRA, 116, A0025
Pezzi, O., Blasi, P., & Matthaeus, W. H. 2022, ApJ, 928, 25
Pezzi, O., Liang, H., Juno, J. L., et al. 2021a, MNRAS, 505, 4857
Pezzi, O., Pecora, F., Le Roux, J., et al. 2021b, SSRv, 217, 39
Phan, T. D., Eastwood, J. P., Cassak, P. A., et al. 2016, GeoRL, 43, 6060
Podesta, J. J. 2017a, JGRA, 122, 2795
Podesta, J. J. 2017b, SoPh, 292, 61
Runov, A., Baumjohann, W., Nakamura, R., et al. 2008, JGRA, 113, A07S27
Runov, A., Nakamura, R., Baumjohann, W., et al. 2003, GeoRL, 30, 1579
Runov, A., Sergeev, V. A., Nakamura, R., et al. 2006, AnGeo, 24, 247
Sergeev, V. A., Mitchell, D. G., Russell, C. T., & Williams, D. J. 1993, JGR, 98, 17345
Syrovatski, S. I. 1971, JETP, 33, 933
Zelenyi, L., Artemiev, A., Malova, H., & Popov, V. 2008, IASTP, 70, 325
Zelenyi, L., Malova, H., Grigorenko, E., Popov, V., & Delcourt, D. 2019, PPCF, 61, 054002
Zelenyi, L., Artemiev, A. V., Malova, K. V., Petrukovich, A. A., & Nakamura, R. 2010, PhyU, 53, 933
Zelenyi, L. M., Artemeyev, A. V., Malova, H. V., & Petrukovich, A. A. 2011, FIPPh, 37, 118
Zelenyi, L. M., Malova, H. V., Artemeyev, A. V., Popov, V. Y., & Petrukovich, A. A. 2011, FIPPh, 37, 118
Zelenyi, L. M., Malova, H. V., Artemeyev, E. E., Popov, V. Y., & Dubinin, E. M. 2020, GeoRL, 47, e86422
Zelenyi, L. M., Malova, H. V., Popov, V. Y., Delcourt, D., & Sharma, A. S. 2004, NPGeo, 11, 579
Zharkova, V., & Khabarova, O. 2015, AnGeo, 33, 457
Zharkova, V. V., & Khabarova, O. V. 2012, ApJ, 752, 35