Contribution of Magnetic Reconnection Events to Energy Dissipation in Space Plasma Turbulence

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Abstract

By analyzing the magnetosheath measurements from the Magnetospheric Multiscale Spacecraft, we obtain statistical results for the contribution of magnetic reconnection (MR) events at electron scales to the energy dissipation of coherent structures in shocked turbulent plasmas. The partial variance of increments (PVI) method is employed to find coherent structures in the magnetic field data. We consider criteria to further identify MR events, such as reversal of magnetic field components, significant energy dissipation, and evident electron outflow velocity. Statistically, for most MR events, their PVI values are larger than those of other types of coherent structures, and their energy dissipations are also stronger. However, due to the relatively small number of MR events, their contribution to coherent structures’ energy dissipation is relatively trivial. If the dissipation of non-coherent structures is taken into account, MR’s contribution to energy dissipation would be even less. Hence, we suggest that MR events, though having strong dissipation locally, are not the major contributor to energy dissipation in the turbulent magnetosheath. After analyzing the features of non-MR current sheets, we propose that these are mainly coherent structures inherent to kinetic Alfven fluctuations.

Unified Astronomy Thesaurus concepts: Space plasmas (1544); Interplanetary turbulence (830); Alfven waves (23); Planetary magnetospheres (997)

1. Introduction

Compared with the upstream solar wind, plasmas in the magnetosheath have higher temperature, higher-density magnetic magnitude, and stronger turbulence. Strong magnetosheath turbulence, which results from the amplification of solar wind turbulence (Schwartz et al. 1996) and excitation of sheath plasma instability (Gary et al. 1993), is an ideal environment to observe various types of energy dissipation phenomena and understand the comprehensive framework of turbulence dissipation mechanisms. Coherent structures usually appear intermittently in turbulence. Turbulence intermittency has been widely studied in theory (Burlaga 1991; Marsch & Tu 1997), from simulations (Greco et al. 2008; Wan et al. 2016), and via observations (Marsch & Tu 1997; Osman et al. 2014; Chasapis et al. 2017). For example, tangential-discontinuity associated current sheets, which are a kind of coherent structure, can be strongly dissipated and hence heat local plasmas prominently (Wang et al. 2013). By contrast, the rotational-discontinuity associated current sheet does not contribute significantly to local plasma heating since it propagates through plasmas instead of co-traveling with the same patch of plasma over time (Wang et al. 2013; Zhang et al. 2015). How are the intermittent coherent structures of various kinds related to turbulence dissipation and plasma heating? It is desirable to understand various specific processes in the comprehensive scenario of turbulence energy dissipation by quantifying and comparing contributions from different turbulence dissipation mechanisms.

Turbulence dissipation mechanisms can be classified into dissipation of coherent structures and dissipation of waves. One class of coherent structure dissipation includes magnetic reconnection (MR) (Drake et al. 2003; Retinò et al. 2007; Shay et al. 2014; Fu et al. 2016; Wang et al. 2016; Ergun et al. 2020) and non-MR coherent structures (Alexandrova & Saur 2008; Wang et al. 2013, 2019; Wan et al. 2016; Chasapis et al. 2018a; Huang et al. 2018). Dissipation associated with waves includes resonance interactions between waves and particles, such as Landau resonance (Chen et al. 2019) and cyclotron resonance (Hollweg & Isenberg 2002; Isenberg & Vasquez 2019), and non-resonant random interactions between them (Chandran 2010; Chandran et al. 2013). Thanks to Magnetospheric Multiscale Spacecraft (MMS) measurements of current density and electric field with high cadence and high quality, the dissipation rate on scales (i.e., dissipation rate spectrum) can be derived. The dissipation rate spectra can measure the strength of wave–particle interaction and the partition of dissipated energy among different species along different directions (He et al. 2019, 2020).

There are various proxies to measure or approximate energy dissipation. Zenitani et al. (2011) proposed that the Joule-like heating term $j \cdot E'$ can represent the energy conversion from fields to particles. $j \cdot E'$ has been extended to distribution in the wavenumber domain for wave-like turbulence (He et al. 2019; Duan et al. 2020). The field–particle correlation method (Klein & Howes 2016; Ruan et al. 2016; Chen et al. 2019) can be used to find evidence of Landau resonance in the solar atmosphere and space plasmas. Combining theory and the particle-in-cell simulation, Yang et al. (2017) distinguished the energy transfer between thermal and kinetic energy of particles by investigating the pressure–strain interactions ($p\theta$ and Pi-D). Since then, there have been further simulations (Yang et al. 2017, 2019; Pezzi et al. 2019) and observational studies based on the Pi-D (Chasapis et al. 2018b; Zhong et al. 2019; Luo et al. 2020; Bandyopadhyay et al. 2020). The energy transfer across different scales can also be regarded as a proxy to quantify turbulence dissipation (Sorriso-Valvo et al. 2018, 2019). Other authors focused on the plasma kinetics related to the dissipation/energization effect, such as the non-Maxwellian distribution function (Greco et al. 2012), pressure anisotropy (Swisdak 2016), and entropy growth (Kaufmann &
3. Overview of Measurements by the MMS

To determine MR’s contribution to energy dissipation in space plasma turbulence, we analyze the MMS measurements in the magnetosheath. We use data of MMS1 in the time interval from 06:33:44 to 11:08:40 UT on 2015 October 25. As an example, the time series measured by the fast plasma instrument (Pollock et al. 2016), fluxgate magnetometer (Russell et al. 2016), and electric field double probe instrument (Torbert et al. 2016) of the MMS are shown in Figure 1. The magnetic field, velocity, and electric field contain strong fluctuations and sudden enhancements in intensity. The PVI index represents the strength of magnetic disturbance, and was introduced in detail in Section 2. We use \( j = e(n_j v_j - n_i v_i) \) to calculate the electric current density. The work done by the electric field on the plasma particle species \( (j \cdot E') \) is calculated in the plasma rest reference frame \( (E' = E_{GSE} + v \times B) \) to represent the energy conversion between fields and particles.

The result of applying the PVI method to magnetic field data (Figure 1(a)) is shown in Figure 1(b). By comparing the time series of magnetic field and PVI index, we can see that the stronger the magnetic field becomes, the larger the PVI index appears. In Figure 1(f), we show the time series of \( j \cdot E' \), which can be regarded as the dissipation rate of turbulence fields when \( j \cdot E' > 0 \) at the kinetic scale. It can be seen that the peaks of \( j \cdot E' \) do not always correspond to those of the PVI index. The concurrence between the peaks of \( j \cdot E' \) and PVI represents the dissipation caused by coherent structures. At other locations where evident signals of \( j \cdot E' \) are not associated with strong PVI, the dissipation may be contributed by vortex structures, which cannot be caught by the PVI method, or non-structure fluctuations such as waves.

Thanks to the high temporal resolution of measurements from the MMS satellites, we have the opportunity to study these disturbances and sharp peaks at electron scales. MR is one type of magnetic energy dissipation related to coherent structures. To statistically survey MR events, it would be convenient to first determine locations with concurrence of PVI and \( j \cdot E' \) peaks, and then diagnose the variable profiles carefully to identify the MR events. In addition, the contribution of different mechanisms to the total dissipation can be studied by classifying \( j \cdot E' \) into different types according to the disturbances of the magnetic field and the species’ bulk velocity.

4. Method of Identifying MR Events

After setting a certain PVI threshold level, which is adjustable, we can count the number of coherent structures with the PVI index greater than the threshold level and with significant dissipation rate. The coherent structures can be regarded as candidates for further identification of MR events. We perform a coordinate transformation to the magnetic field vectors and bulk velocity vectors of the coherent structures based on minimum variable analysis (MVA) of the magnetic field vectors. Magnetic field vectors in the new \( LMN \) coordinates have maximum, intermediate, and minimum variance in the \( L, M, \) and \( N \) directions. An encounter of a typical MR event is usually characterized by a depression of magnetic field strength (\( \delta |B| \)), a reversal in magnetic field component (\( B_L \)), a peak of particle species’ bulk velocity component (\( v_L \)), and an evident dissipation intensity (\( j \cdot E' \)).
the following, we will elaborate on how to identify MR events statistically as encountered by the spacecraft.

After obtaining the time series of the PVI index based on MMS magnetic field data, we employ three analysis steps to each PVI index peak. First, we investigate every PVI peak to judge whether it corresponds to a $j \cdot E'$ peak. When the time difference ($\delta t$) between the PVI peak and the $j \cdot E'$ peak is smaller than the time lag ($\tau$) of the PVI method, we consider them as concurrent. For events with concurrent PVI and $j \cdot E'$ peaks, we implement the MVA-based coordinate transformation to the data containing the peak of the PVI index to obtain the magnetic field and velocity in the $LMN$ coordinate system. Second, we calculate the relative difference of magnetic field strength between the PVI peak at the center and the two ambient sides, $(|B|_{\text{ambient}} - |B|_{\text{PVI,peak}})/|B|_{\text{ambient}}$. The ambient $|B|$ is assigned the value of the smaller $|B|$ of the two sides. If $(|B|_{\text{ambient}} - |B|_{\text{PVI,peak}})/|B|_{\text{ambient}} > 0.1$, we then mark it as a candidate MR event. Third, we check whether a reversal of $B_L$ occurs across the PVI index peak and whether there is a peak in the electron bulk velocity component $v_L$. If the observational data containing the PVI index peak time satisfy the preceding three steps, then an MR event can be determined. Since the MVA-based transformation depends on the time range, multiple time ranges are tested for the MVA transformation to improve the MR events’ recognition rate. Considering that the times of the PVI index peak, $j \cdot E'$ peaks, zero of $B_L$, and outflow velocity peak of an MR event do not usually accurately match each other, we allow them to have a small time deviation. In order to verify the feasibility of the identification method, we tested it using the catalog of MR events provided in Wilder et al. (2018), and concluded that the program successfully and automatically identified the MR events listed in the catalog. Therefore, the MR automatic identification method as introduced in this work is feasible, and the identified MR events as output are credible.

According to the preceding processes, we identify an MR event from MMS1 data (Figure 1). The time of MR occurs at about 11:07:46.60 on 2015 October 25, as shown in Figure 1(b). This MR was reported by Wilder et al. (2018). Our program can also identify other MR events that have not been reported before. Figure 2 shows an example of a newly identified MR event. By invoking the program, we survey the coherent structures and MR events based on MMS measurements from 06:33:44 to 11:08:40 on 2015 October 25. The result will be discussed in Section 5.

5. Analysis of Energy Dissipation Contributions

By integrating the dissipation intensity, $j \cdot E'$, related to MR events and comparing it with the dissipation intensity of coherent structures, the contribution of the reconnection events to the dissipation of the coherent structures can be determined. Table 1 lists the number of coherent structures with strong dissipation, the number of MR events, and the corresponding dissipation intensities under the condition of different PVI index thresholds. As can be seen from Table 1, with the increase of PVI index threshold, the number of coherent structures, the total dissipation intensity, the number of reconnection events, and the dissipation due to reconnection all decrease. From the data in Table 1, we illustrate the histograms of proportions in terms of number counts and dissipation intensity in Figure 3(a).

With the increase of the PVI index threshold, the number of coherent structures and MRs gradually decreases, while the proportions of the number count and dissipation intensity of MR events to their counterparts of coherent structures increase.

Figure 1. (a) Magnetic field vectors in the geocentric solar ecliptic (GSE) coordinates. (b) Partial variance of increments index series of the magnetic field. (c) Electron bulk velocity vectors in GSE coordinates. (d) Ion bulk velocity vectors in GSE coordinates. (e) Electric field vectors in the plasma reference reframe ($E' = E_{GSE} + v \times B$). (f) Energy conversion rate (which can be referred to as turbulence dissipation strength for turbulence study). (g) Position of the MMS1 spacecraft located in the magnetosheath. The bow shock (black dotted-dashed line) and magnetopause (black dashed line) are calculated by a 3D empirical model (Chao et al. 2002). (h) An example of magnetic reconnection selected by the automatic identification program developed in this work.

Table 1

| PVI Index Threshold | Number of Coherent Structures | Total Dissipation Intensity | Number of MR Events | Dissipation Due to MR |
|---------------------|-------------------------------|-----------------------------|---------------------|-----------------------|
| 0                   | 100                           | 500                         | 5                   | 20                    |
| 1                   | 90                            | 450                         | 4                   | 18                    |
| 2                   | 80                            | 400                         | 3                   | 16                    |
| 3                   | 70                            | 350                         | 2                   | 14                    |
| 4                   | 60                            | 300                         | 1                   | 12                    |

With the increase of PVI index threshold, the number of coherent structures and MRs gradually decreases, while the proportions of the number count and dissipation intensity of MR events to their counterparts of coherent structures increase.
This increasing trend indicates that coherent structures with a larger PVI index threshold are more likely to be associated with MR. When the PVI index threshold equals 3.5, the proportion of MR dissipation suddenly decreases, which may be due to the low number of MR events or to the appearance of other strong coherent structures.

From Figure 3(a), we know that the proportion of dissipation intensity contributed from the MR events to the dissipation of coherent structures did not exceed 15%. This suggests that MR events contribute a small proportion to the total energy dissipation of coherent structures rather than acting as the primary contributor. Taking the dissipation of non-structures into account, the contribution of MR events would become even smaller, say about 1%. Under the same PVI index threshold, the proportion of MR dissipation (blue bar) is higher than that of the number of MRs (black bar), indicating that the dissipation intensity per MR event is slightly higher than that per coherent structure. This suggests that it is easier for reconnection to achieve the dissipation of field energy locally than for other coherent structures. Despite this, due to the small MR number count in the magnetosheath, the contribution to the total field-energy dissipation from MR events is small.

In Figure 3(b), we plot a tree diagram to illustrate intuitively the contribution ratios of different dissipation mechanisms to the total field energy dissipation (the PVI index threshold is set to 1 for this plot). As shown in Figure 3(b), the MR contribution is about 5% to the dissipation of coherent structures. The contribution from MRs will be lower if we consider the dissipation of non-coherent structures, e.g., wave-like fluctuations. So magnetic reconnection may not be the dominant mechanism of field-energy dissipation in the magnetosheath turbulence, which may be dissipated through various co-existing mechanisms.

Besides the MR-related current sheets, we also find many non-MR current sheets in the Earth’s magnetosheath. The reversal of the magnetic field also characterizes these current sheets, but their difference from the MR current sheets is their lack of peak velocity. To investigate the nature of these current sheets, we calculate the correlation between electron bulk velocity and magnetic field in the LMN coordinate system (see Figure 4). In the L-direction, the peak of probability distribution of the correlation coefficient between \(v_{leL} \) and \(B_L \) \((CC(v_{leL}, B_L))\) is close to 1. This indicates that there is a velocity shear in the L-direction across the non-MR current sheets. The correlated velocity and magnetic shears make the non-MR current sheet propagate through the plasmas like waves rather than remain static relative to the plasmas. There exist no plasma inflows to drive magnetic fluxes converging toward the current sheets. Based on the correlation between velocity and magnetic field as well as the width scale of the current sheets, we proposed that the non-MR current sheets may be caused by nonlinear steepening of kinetic Alfvén waves. On the other hand, the peak around \(CC(v_{leL}, B_L) \sim 0\) indicates that a significant proportion of the current sheets may be related to non-wave-like structures, which have strong \(j \cdot E\) and PVI index. Hence, the non-MR current sheets are likely to have multiple possibilities for their origin.

### Table 1

| PVI' | Total Dissipation \(E_{\text{m}} \) \(\text{nW} \cdot \text{m}^{-3}\) (Proportion) | Total CS Number | MR Number (Proportion) |
|------|-------------------------------------------------|----------------|-------------------------|
| 1    | 202.0 10.8 (0.05)                                | 350            | 8 (0.02)                |
| 1.5  | 172.0 9.2 (0.05)                                 | 268            | 7 (0.03)                |
| 2    | 140.0 9.2 (0.07)                                 | 190            | 7 (0.04)                |
| 2.5  | 90.8 9.2 (0.10)                                  | 118            | 7 (0.06)                |
| 3    | 66.9 9.2 (0.14)                                  | 77             | 7 (0.09)                |
| 3.5  | 40.8 3.9 (0.10)                                  | 43             | 3 (0.07)                |
| 4    | 27.9 3.9 (0.14)                                  | 28             | 3 (0.11)                |

**Note.** PVI’ represents the PVI index threshold. CS stands for coherent structure. When considering the non-structures dissipation, the total energy dissipation is 856 nW s m\(^{-3}\).

### 6. Summary and Discussion

We carried out a statistical analysis of the contribution of MR to turbulence dissipation in the magnetosheath. We used the PVI method to identify coherent structures with strong magnetic disturbance, and used the MVA-based coordinate transformation to analyze the sub-time-interval of vector sequences surrounding each PVI index peak separately. We developed a program to identify MR automatically, which is proven to be feasible (see Figure 1(h) and Figure 2). To determine the reconnection events, we take into account the crucial features such as the reversal of magnetic field, decrease of magnetic magnitude, increase of electron velocity, and increase of dissipation intensity. Based on the thorough analysis of the identified MR events, coherent structures, as well as wave-like fluctuations, we draw the following conclusions.

1. With the increase of the PVI index threshold, the contribution from MR to coherent structures, in terms of number proportion and dissipation proportion, generally increases. A larger PVI index is more likely to be associated...
with an MR event, and this association is consistent with the simulation work of Servidio et al. (2011).

2. At different PVI index thresholds, the dissipation intensity of a single MR is slightly stronger. But due to the small proportion of MR (less than 15%), its contribution to the energy dissipation of coherent structures with strong dissipation is relatively trivial. When the dissipation of non-coherent-structure fluctuations is taken into account, the contribution of MR will be even smaller (1%). The suggestion that MRs may not be the dominant mechanism of turbulence dissipation in the magnetosheath is based on the observational data of our study, and needs more statistical analyses to confirm.

3. Besides MR, there are many non-MR current sheets in the magnetosheath. Electron bulk velocity and magnetic field of the non-MR current sheets in the $L$ direction of the $LMN$ coordinate system show a good correlation, with the correlation coefficient being close to 1. This $v - B$ correlation indicates that the non-MR current sheets may be related to the steepening of kinetic Alfvén waves. In addition, the peak in Figure 4(a), where the correlation coefficient is near zero, should be the contribution of the non-wave-like structures. Hence, the two peaks of the distribution in Figure 4(a) manifest the multiple nature of current sheets in the magnetosheath.

Observational results show that some strong $j \cdot E'$ peaks do not correspond to PVI peaks. One possible reason is that these strong $j \cdot E'$ peaks may occur at the non-coherent-structure locations, such as locally strong kinetic Alfvén waves. Note that the PVI method may fail to pick out some special coherent structures like vortexes, which have been reported in different space environments (Sundkvist et al. 2005; Alexandrova & Saur 2008; Roberts et al. 2016; Lion et al. 2016; Perrone et al. 2017; Wang et al. 2019). Therefore, the strong $j \cdot E'$ peaks without PVI peaks may be contributed from vortexes, which may alter the statistical value of the contribution from non-coherent-structures in Figure 3(b). Hence, the percentage (68%) of dissipation of non-coherent-structures in Figure 3(b) may include the contribution from vortex-like coherent structures. Nevertheless, our main conclusion, that magnetic reconnection may not be the most crucial dissipation mechanism of magnetosheath turbulence, is still valid. We suggest that more

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**Figure 3.** (a) Statistical results on magnetic reconnections (MRs) and coherent structures in terms of number ratio and dissipation contribution under different PVI thresholds. The left axis represents three types of ratios: the percentage of field-energy dissipations between MRs and coherent structures (blue bars), the ratio between reconnection events and coherent structures (black bars), and the ratio of dissipations between reconnection events and total fluctuations (red bars). The right axis is used to mark the number of MR events (solid black line). (b) Tree diagram representing the proportion of field-energy dissipation contributed from different mechanisms: dissipation of non-coherent structures (e.g., kinetic waves) and vortex- and wave-like coherent structures (68%), dissipation of non-MR coherent structures (31%), dissipation of MR events (1%).

**Figure 4.** Distribution of correlation coefficient (CC) between electron bulk velocity and magnetic field of non-MR current sheets in the $LMN$ coordinate system. (a) Distribution of $|CC(B_L, V_e)|$ with the maximum number located in $[0.9, 1.0]$; (b) distribution of $|CC(B_M, V_e)|$ with a roughly even distribution between $[0.1]$; (c) distribution of $|CC(B_N, V_e)|$ with the maximum number located in $[0.0, 0.1]$. 

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**NOTE:** Cs particularly refers to the coherent structures identified by the PVI method.

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important mechanisms than MR are needed to account for the energy dissipation in magnetosheath turbulence.

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References
Alexandrova, O., & Saur, J. 2008, GeoRL, 35, L15102
Bandyopadhyay, R., Matthaeus, W. H., Parashar, T. N., et al. 2020, PhRvL, 124, 255101
Burch, J., Moore, T., Torbert, R., & Giles, B. 2016a, SSRv, 199, 5
Burch, J., Torbert, R., Phan, T., et al. 2016b, Sci, 352, 6290
Burlaga, L. 1991, JGRA, 96, 5847
Chandran, B., Verscharen, D., Quataert, E., et al. 2013, ApJ, 776, 45
Chandran, B. D. 2010, ApJ, 720, 548
Chao, J., Wu, D., Lin, C.-H., et al. 2002, in COSPAR Colloq., Space Weather Study Using Multipoint Techniques, ed. L.-H. Lyu (Oxford: Pergamon Press), 127
Chasapis, A., Matthaeus, W., Parashar, T., et al. 2017, ApJ, 836, 247
Chasapis, A., Matthaeus, W., Parashar, T., et al. 2018a, ApJL, 856, L19
Chasapis, A., Yang, Y., Matthaeus, W., et al. 2018b, ApJ, 862, 32
Chen, C., Klein, K., & Howes, G. G. 2019, NatCo, 10, 740
Drake, J., Swisdak, M., Cattell, C., et al. 2003, Sci, 299, 873
Duan, D., He, J., Wu, H., & Verscharen, D. 2020, ApJ, 896, 47
Ergun, R., Ahmad, N., Kromyda, L., et al. 2020, ApJ, 898, 154
Fu, H., Cao, J., Vaivads, A., et al. 2016, JGRA, 121, 1263
Gary, S. P., Fuselier, S. A., & Anderson, B. J. 1993, JGRA, 98, 1481
Gosling, J. 2007, ApJL, 671, L73
Greco, A., Chuychai, P., Matthaeus, W., Servidio, S., & Dmitruk, P. 2008, GeoRL, 35, 19
Greco, A., Matthaeus, W., Servidio, S., Chuychai, P., & Dmitruk, P. 2009, ApJL, 691, L111
Greco, A., Valentinii, F., Servidio, S., & Matthaeus, W. 2012, PhRvE, 86, 066405
He, J., Duan, D., Wang, T., et al. 2019, ApJ, 880, 121
He, J., Zhu, X., Verscharen, D., et al. 2020, ApJ, 898, 43
Hollweg, J. V., & Isenberg, P. A. 2002, JGRA, 107, 1147
Huang, S., Sabraoui, F., Yuan, Z., et al. 2018, ApJ, 861, 29
Isenberg, P. A., & Vasquez, B. J. 2019, ApJ, 887, 63
Kaufmann, R. L., & Paterson, W. R. 2009, JGRA, 114, A00D04
Klein, K. G., & Howes, G. G. 2016, ApJL, 826, L30
Liang, H., Barbthuia, M. H., Cassak, P., et al. 2020, JIPh, 86, 825860502
Lion, S., Alexandrova, O., & Zaslavsky, A. 2016, ApJ, 824, 47
Luo, Q., He, J., Cui, J., et al. 2020, ApJL, 904, L16
Marsch, E., & Tu, C.-Y. 1997, NPGeo, 4, 101
Osman, K., Matthaeus, W., Gosling, J., et al. 2014, PhRvL, 112, 215002
Osman, K., Matthaeus, W., Hnat, B., & Chapman, S. 2012, PhRvL, 108, 261103
Perrone, D., Alexandrova, O., Roberts, O., et al. 2017, ApJ, 849, 49
Pezzi, O., Yang, Y., Valentini, F., et al. 2019, PhPl, 26, 072301
Phan, T., Eastwood, J. P., Shay, M., et al. 2018, Natur, 557, 202
Phan, T., Paschmann, G., Twitty, C., et al. 2007, GeoRL, 34, 14
Pollock, C., Moore, T., Jacques, A., et al. 2016, SSRv, 199, 331
Priest, E. 1986, in Plasma Penetration into Magnetospheres, ed. N. Kylais, J. Papamastorakis, & J. Ventura (Greece: Crete Univ. Press), 127
Retinò, A., Sundkvist, D., Vaivads, A., et al. 2007, NatPh, 3, 235
Roberts, O. W., Li, X., Alexandrova, O., & Li, B. 2016, JGRA, 121, 3870
Ruan, W., He, J., Zhang, L., et al. 2016, ApJ, 825, 58
Russell, C., Anderson, B., Baumjohann, W., et al. 2016, SSRv, 199, 189
Schwartz, S., Burgess, D., & Moses, J. 1996, AnGeo, 14, 1134
Servidio, S., Greco, A., Matthaeus, W., Osman, K., & Dmitruk, P. 2011, JGRA, 116, A09102
Shay, M., Haggerty, C., Phan, T., et al. 2014, PhPl, 21, 122902
Sorriso-Valvo, L., Carlone, F., Perri, S., et al. 2018, SoPh, 293, 10
Sorriso-Valvo, L., Catapano, F., Retinò, A., et al. 2019, PhRvL, 122, 035102
Sundkvist, D., Krasnoselskikh, V., Shukla, P. K., et al. 2005, Natur, 436, 825
Swisdak, M. 2016, GeoRL, 43, 43
Torbert, R., Russell, C., Magnes, W., et al. 2016, SSRv, 199, 105
Wan, M., Matthaeus, W., Roytershteyn, V., et al. 2016, PhPl, 23, 042307
Wang, R., Lu, Q., Nakamura, R., et al. 2016, NatPh, 12, 263
Wang, T., Alexandrova, O., Perrone, D., et al. 2019, ApJL, 871, L22
Wang, X., Tu, C., He, J., Marsch, E., & Wang, L. 2013, ApJL, 772, L14
Wildner, F., Ergun, R., Burch, J., et al. 2018, JGRA, 123, 6533
Yang, Y., Matthaeus, W., Parashar, T., et al. 2017, PhRvE, 95, 061201
Yang, Y., Wan, M., Matthaeus, W. H., et al. 2019, MNRAS, 482, 4913
Zenitani, S., Hesse, M., Klimas, A., & Kuznetsova, M. 2011, PhRvL, 106, 195003
Zhang, L., He, J., Tu, C., et al. 2015, ApJL, 804, L43
Zhong, Z., Deng, X., Zhou, M., et al. 2019, GeoRL, 46, 12693
Zhou, M., Berchem, J., Walker, R., et al. 2017, PhRvL, 119, 055101