



## RESEARCH LETTER

10.1029/2018GL079181

### Key Points:

- Proton number densities are an order of magnitude higher, temperatures several times smaller, and  $\kappa$  values broader at Mercury than at Earth
- Protons become denser and cooler during the growth phase, and are depleted and heated after the substorm dipolarizations at both planets
- $\kappa$  changes are <20% at Earth, implying spectrum-preserving accelerations, and >60% at Mercury, implying spectrum-altering accelerations

### Supporting Information:

- Supporting Information S1

### Correspondence to:

W. J. Sun,  
wjsun@umich.edu

### Citation:

Sun, W. J., Slavin, J. A., Dewey, R. M., Raines, J. M., Fu, S. Y., Wei, Y., et al. (2018). A comparative study of the proton properties of magnetospheric substorms at Earth and Mercury in the near magnetotail. *Geophysical Research Letters*, 45, 7933–7941. <https://doi.org/10.1029/2018GL079181>

Received 12 JUN 2018

Accepted 25 JUL 2018

Accepted article online 2 AUG 2018

Published online 17 AUG 2018

## A Comparative Study of the Proton Properties of Magnetospheric Substorms at Earth and Mercury in the Near Magnetotail

W. J. Sun<sup>1,2,3,4</sup> , J. A. Slavin<sup>2</sup> , R. M. Dewey<sup>2</sup> , J. M. Raines<sup>2</sup> , S. Y. Fu<sup>3</sup> , Y. Wei<sup>1</sup> , T. Karlsson<sup>5</sup> , G. K. Poh<sup>2</sup> , X. Jia<sup>2</sup> , D. J. Gershman<sup>6</sup> , Q. G. Zong<sup>3</sup> , W. X. Wan<sup>1</sup> , Q. Q. Shi<sup>7</sup> , Z. Y. Pu<sup>3</sup> , and D. Zhao<sup>3</sup> 

<sup>1</sup>Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, <sup>2</sup>Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA, <sup>3</sup>School of Earth and Space Sciences, Peking University, Beijing, China, <sup>4</sup>Key Laboratory of Lunar and Deep Space Exploration, National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China, <sup>5</sup>Space and Plasma Physics, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden, <sup>6</sup>Geospace Physics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA, <sup>7</sup>Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, School of Space Science and Physics, Shandong University, Weihai, China

**Abstract** The variations of plasma sheet proton properties during magnetospheric substorms at Earth and Mercury are comparatively studied. This study utilizes kappa distributions to interpret proton properties at both planets. Proton number densities are found to be around an order of magnitude higher, temperatures several times smaller, and  $\kappa$  values broader at Mercury than at Earth. Protons become denser and cooler during the growth phase, and are depleted and heated after the dipolarizations in both magnetospheres. The changes of  $\kappa$  at Earth are generally small (<20%), indicating that spectrum-preserving processes, like adiabatic betatron acceleration, play an important role there, while variations of  $\kappa$  at Mercury are large (>60%), indicating the importance of spectrum-altering processes there, such as acceleration due to nonadiabatic cross-tail particle motions and wave-particle interactions. This comparative study reveals important intrinsic properties on the energization of protons in both magnetospheres.

**Plain Language Summary** Earth and Mercury are the only two planets possessing global intrinsic magnetic fields among the four inner planets, which are Mercury, Venus, Earth, and Mars, within the solar system. The interactions between the intrinsic magnetic fields and the continual flow of high-speed solar wind from the Sun form similar magnetospheres at the two planets, although the scale of the magnetosphere is much smaller at Mercury than at Earth. Magnetospheric substorms, a result of solar wind-magnetosphere coupling, occur in both magnetospheres. Comparative study of a similar process between different planets is meaningful as it can help us in understanding the specific process further as well as help us in understanding the intrinsic properties of the magnetospheres. This research paper characterizes the proton properties of magnetospheric substorms of both planets, revealing that different mechanisms control the behavior of protons during the magnetospheric substorms of the two planets.

## 1. Introduction

Earth and Mercury are the two planets characterized by existing global intrinsic magnetic fields among the four inner planets within the solar system. Therefore, their magnetospheres form in the interaction between the solar wind and the global intrinsic magnetic fields and are expected to behave similarly. The Earth's magnetosphere has been extensively sampled and investigated since the 1960s (e.g., Ness, 1965), while Mercury's magnetosphere was visited only by Mariner 10 (e.g., Ness et al., 1974) and MESSENGER (e.g., Solomon et al., 2007). Observations have revealed that Mercury's magnetosphere does share similar processes and structures with the Earth's magnetosphere (e.g., Slavin et al., 2010; Sun, Slavin, Fu, Raines, Sundberg, et al., 2015; Sun, Slavin, Fu, Raines, Zong, et al., 2015; Sun et al., 2016). Meanwhile, Mercury's magnetosphere has displayed many distinct properties (e.g., Gershman et al., 2014; Raines et al., 2015; Slavin et al., 2007, 2014).

The magnetospheric substorm is the fundamental response in both Mercury's and Earth's magnetospheres to solar wind driving. It is a process accompanied with global magnetospheric reconfiguration, including plasma sheet thinning and thickening, plasmoid ejections, and dipolarizations, and was observed to be

similar at the two planets (e.g., Baker et al., 1996; Hones, 1977; Slavin et al., 2010; Sun, Slavin, Fu, Raines, Sundberg, et al., 2015). But because the size of Mercury's magnetosphere is much smaller than the Earth's magnetosphere (e.g., Ness et al., 1974; Winslow et al., 2013), and the dayside magnetopause reconnection rate at Mercury is several times that at Earth (DiBraccio et al., 2013; Slavin et al., 2009), the duration of a magnetospheric substorm at Mercury (~2 to 3 min) is found to be tens of times shorter than at Earth (~2 to 3 hr; e.g., Imber & Slavin, 2017; Rostoker et al., 1980; Sun, Slavin, Fu, Raines, Zong, et al., 2015).

In the studies of plasmasheet ion variations during the substorm at Earth, the energization and heating of ions during the dipolarizations were well observed, which were proposed to be due to the betatron and Fermi accelerations as well as processes related to induce electric fields (e.g., Huang et al., 1992; Williams et al., 1990). However, ion variations during the substorm growth phase have different results, including density and temperature increased (Williams et al., 1990); density increased but temperature constant (Kistler et al., 2006; Nagai et al., 1997); density increased but temperature decreased (Artemyev et al., 2016; Sun, Fu, et al., 2017). The ion variations in the Earth's plasma sheet during the growth phase are not well understood and require further investigation.

Recently, MESSENGER observations have revealed the energization and heating of protons during Mercury's substorm dipolarizations (Dewey et al., 2017; Sun, Raines, et al., 2017). Since the time scale of substorm dipolarizations (~5 to 10 s) is comparable with the gyroperiod of protons in Mercury's magnetotail, the energization of protons is expected to be nonadiabatic (e.g., Delcourt et al., 2007, 2010; Ip, 1987; Sun, Raines, et al., 2017). However, systematic research on the variations of protons during magnetospheric substorms at Mercury remains lacking.

This study carries out a comparative study on the proton variations by employing kappa distribution to interpret the spectra during magnetospheric substorms at Mercury and Earth. Since magnetospheric substorms at the two planets not only share many similarities but also exhibit differences, it would be meaningful to comparatively study the plasma properties at the two planets during substorms. This comparative study on the proton variations reveals important intrinsic properties for the magnetospheres of both planets.

## 2. Observations

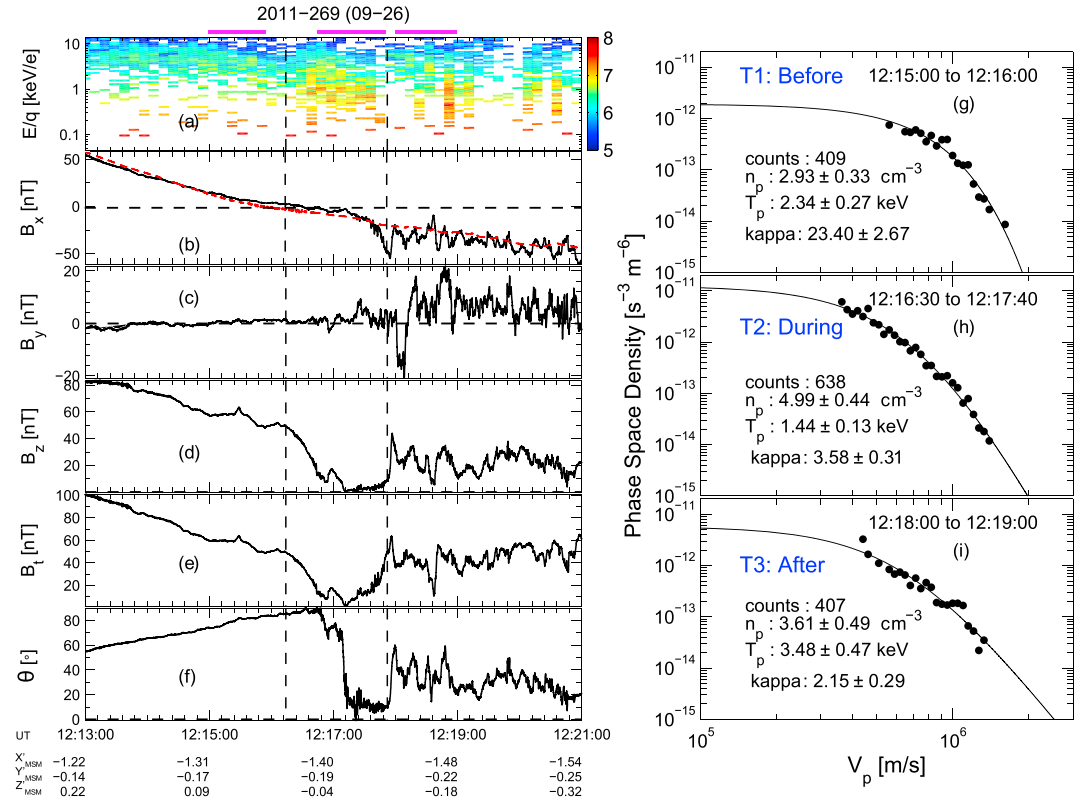
### 2.1. Instrumentations and Data Sources

This study focuses on events in the near planet tail regions, which are from  $-1.2 R_M$  to  $-1.8 R_M$  ( $1 R_M \sim 2,440$  km, a Mercury radius) at Mercury and from  $-7.5 R_E$  to  $-12 R_E$  ( $1 R_E \sim 6,371$  km, an Earth radius) at Earth. The regions of the two planets overlap considering a scaling factor of ~7–8 between the two planets (e.g., Siscoe et al., 1975). Observations at Mercury and Earth are provided by MESSENGER and THEMIS (from THD and THE; Angelopoulos, 2008), respectively. We utilize the measurements from the Magnetometer (MAG; Anderson et al., 2007) and the Fast Imaging Plasma Spectrometer (FIPS; Andrews et al., 2007) onboard MESSENGER, and the Fluxgate Magnetometer (FGM; Auster et al., 2008), the Electrostatic Analyzer (ESA; McFadden et al., 2008), and the Solid State Telescope (SST) onboard THEMIS. The MAG provides magnetic field measurements at a time resolution of 20 vectors per second. FIPS has an energy range from ~46 eV/q to 13.3 keV/q with an effective field of view of  $\sim 1.15 \pi$  sr, and a scan time of ~10 s. FIPS can distinguish different ion species through time-of-flight measurements. The FGM can provide magnetic field measurements with a time resolution of ~128 vectors per second, while the combined ion data from ESA and SST cover an energy range from ~5 eV to ~6 MeV over the full sky ( $4 \pi$  sr) and at spin-resolution (3 s). However, ESA and SST cannot distinguish the different ion species.

All quantities related to the Earth's magnetosphere are presented in geocentric solar magnetospheric (GSM) coordinates, where the x axis points toward the Sun, the z axis is the projection of the Earth's magnetic dipole axis (positive north) onto the plane perpendicular to the x axis, and the y axis completes the right-hand system. In Mercury's magnetosphere, we use the Mercury Solar Magnetospheric (MSM) coordinates (Anderson et al., 2011), which is defined similarly to the GSM.

### 2.2. Case Study at Mercury

On 26 September 2011 between 12:15 and 12:19 UT, MESSENGER observed a magnetospheric substorm. In this example, MESSENGER was located in the plasma sheet, as evidenced by the number of protons with energy greater than 1 keV shown in the proton spectrum (Figure 1a). The first vertical black dashed line



**Figure 1.** MESSENGER observations of a magnetospheric substorm at Mercury. (a) Energy spectrum for protons, in  $\log_{10}$  ( $\text{keV sr s cm}^{-2}$ ) $^{-1}$ . (b) Magnetic field  $X$  component,  $B_x$ . Dashed red line represents the  $B_x$  of the preceding plasma sheet crossing with no substorm signature. (c)  $B_y$ . (d)  $B_z$ . (e)  $B_t$ . (f) Magnetic elevation angle,  $\theta = \text{atan}(B_z/B_x)$ . (g) Averaged proton phase space density (PSD) from 12:15:00 to 12:16:00, prior to the substorm growth phase (T1: before). (h) Averaged proton PSD from 12:16:30 to 12:17:40, during the substorm growth phase (T2: during). (i) Averaged proton PSD from 12:18:00 to 12:19:00, after the substorm dipolarization (T3: after). Black lines in Figures 1g–1i are the kappa fitting results for the PSDs. The magenta marks above (a) indicate the durations for T1, T2, and T3, respectively.

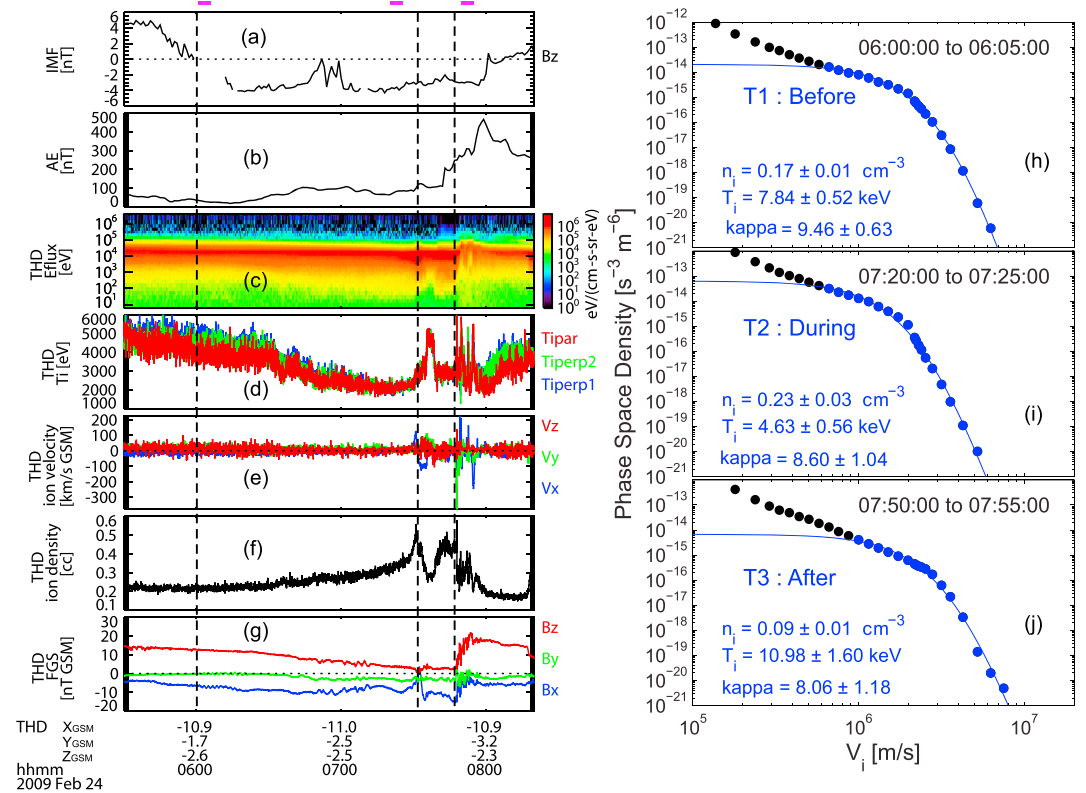
marks the beginning of the substorm growth phase ( $\sim 12:16:13$  UT) when  $B_z$  started to decrease notably (Figure 1d). The  $B_z$  decrease is a natural consequence of plasma sheet thinning.  $B_x$  was weak ( $\sim 0$  nT) starting at  $\sim 12:16:13$  UT, but became more negative and deviated from the dashed red line ( $B_x$  in the preceding no substorm plasma sheet crossing) near the second vertical dashed line (Figure 1b). Meanwhile, the magnetic field elevation angle ( $\theta$ ) decreased (Figure 1f). Both imply the stretch of magnetic field lines. These magnetic field variations are typical features for the substorm growth phase. This substorm growth phase ended at the time marked by the second vertical dashed line ( $\sim 12:17:50$  UT), when MESSENGER detected sharp increase in  $B_z$  (Figure 1d), that is, the dipolarization, followed by  $B_x$  decrease (Figure 1b) and  $B_y$  fluctuations (Figure 1c), which are the signatures of plasma sheet thickening and field-aligned current.

The averaged proton phase space densities (PSDs) before the substorm growth phase (Figure 1g; T1), during the substorm growth phase (Figure 1h; T2), and after the substorm dipolarization (Figure 1i; T3) are fitted with kappa distributions. Kappa distribution is constituted from a Maxwellian in low-energy portion and a power law in high-energy portion. The formula is a simple generalization of Maxwellian (e.g., Vasyliunas, 1968),

$$f_p^\kappa(v) = \frac{n_p}{2\pi(\kappa\omega_{\kappa p}^2)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)\Gamma(3/2)} \left(1 + \frac{v^2}{\kappa\omega_{\kappa p}^2}\right)^{-\kappa-1}$$

where  $v$  is the velocity of particles (proton in this study),  $n_p$  is the proton number density,  $\Gamma$  is the Gamma function,  $\omega_{\kappa p}$  is the thermal velocity, and the generalized temperature is

$$k_B T_p = \frac{\omega_{\kappa p}^2 \kappa m_p}{2\kappa - 3}$$



**Figure 2.** THD observations of a magnetospheric substorm at Earth. (a) IMF  $B_z$  from OMNI. (b) Auroral ejection index (AE). (c) Ion energy spectrum in differential energy flux. (d) Ion temperature. (e) Ion bulk velocity. (f) Ion density. (g)  $B_x$  (blue),  $B_y$  (green), and  $B_z$  (red). (h) Averaged ion PSD from 06:00 to 06:05 UT, at the beginning of substorm growth phase (T1). (i) Averaged ion PSD from 07:20 to 07:25 UT, near the end of substorm growth phase (T2). (j) Averaged ion PSD from 07:50 to 07:55 UT, after the substorm dipolarization (T3). Blue lines in Figures 2h–2j are the kappa fitting results for the main component PSDs shown in blue. The magenta marks above (a) indicate the durations for T1, T2, and T3, respectively.

where  $m_p$  is the proton mass and  $k_B$  is the Boltzmann constant. When  $\kappa \rightarrow \infty$ , this formula becomes the Maxwellian distribution. Kappa distributions provide  $n_p$ ,  $T_p$ , and  $\kappa$ . The index  $\kappa$  describes the slope of suprathermal particle tail ( $>1$  keV, in this study) in the distribution. In T1 (Figure 1g), the kappa distribution gives  $n_p \sim 2.93 \pm 0.33 \text{ cm}^{-3}$ ,  $T_p \sim 2.34 \pm 0.27 \text{ keV}$ , and  $\kappa \sim 23.4 \pm 2.67$ . The uncertainties were estimated in the least squares curve fit on the data. In T2 (Figure 1h), the distribution gives  $n_p \sim 4.99 \pm 0.44 \text{ cm}^{-3}$ ,  $T_p \sim 1.44 \pm 0.13 \text{ keV}$ , and  $\kappa \sim 3.58 \pm 0.31$ . Protons show clear density increase by  $\sim 70\%$ , temperature decrease by  $\sim -38\%$ , and  $\kappa$  decrease by  $\sim -85\%$  from T1 to T2. In T3 (Figure 1i), the distribution gives  $n_p \sim 3.61 \pm 0.49 \text{ cm}^{-3}$ ,  $T_p \sim 3.48 \pm 0.47 \text{ keV}$ , and  $\kappa \sim 2.15 \pm 0.29$ . Protons show number density decrease ( $\sim -28\%$ ), temperature increase ( $\sim 142\%$ ), and  $\kappa$  further decrease ( $\sim -40\%$ ) from T2 to T3.

### 2.3. Case Study at Earth

On 24 February 2009 between  $\sim 06:00$  and  $\sim 09:00$  UT, THD observed a magnetospheric substorm at Earth in the near-tail plasma sheet ( $\sim 11 R_E$ ). The start of the growth phase was at  $\sim 06:00$  UT, when a clear IMF southward turning was observed (Figure 2a, the first vertical dashed line). The second and third vertical dashed lines indicate two dipolarizations (Figures 2c–2g) corresponding to AE increase (Figure 2b). A smooth  $B_z$  decrease was observed in the growth phase (Figure 2g, between the first and second lines), indicating a plasma sheet thinning process. Ion density ( $n_i$ ; Figure 2f) and temperature ( $T_i$ ; Figure 2d) derived from onboard moments show an increase from  $\sim 0.2$  to  $\sim 0.55 \text{ cm}^{-3}$  and a decrease from  $\sim 4.5$  to  $\sim 2 \text{ keV}$ , respectively. Decreases in  $n_i$  and increases in  $T_i$  were observed after the two dipolarizations.

Ion distributions in the Earth's plasma sheet usually contain more than one component, with the main component being described by a kappa distribution (e.g., Christon et al., 1991; Haaland et al., 2010; Wing et al., 2005). The main component should be mostly composed of protons (e.g., Kistler et al., 2006) in the plasma

sheet. Figures 2h–2j show three averaged ion PSDs, which are taken at the beginning of substorm growth phase (Figure 2h; T1), prior to the first dipolarization (Figure 2i; T2), and after the second dipolarization (Figure 2j; T3). We fit the main components in the three distributions with kappa distribution. In T1, the kappa fitting gives  $n_i \sim 0.17 \pm 0.01 \text{ cm}^{-3}$ ,  $T_i \sim 7.84 \pm 0.52 \text{ keV}$ , and  $\kappa \sim 9.46 \pm 0.63$ . In T2, the values are  $n_i \sim 0.23 \pm 0.03 \text{ cm}^{-3}$ ,  $T_i \sim 4.63 \pm 0.56 \text{ keV}$ , and  $\kappa \sim 8.6 \pm 1.04$ . From T1 to T2, ions show clear density increase ( $\sim 35\%$ ) and temperature decrease ( $\sim -41\%$ ). The  $\kappa$  parameter shows a small decrease ( $\sim -9\%$ ), but the decrease is comparable with the uncertainties arising in the fitting ( $\sim 6.6\%$  for T1,  $\sim 12.1\%$  for T2). In T3 (Figure 2j), the fitting gives  $n_i \sim 0.09 \pm 0.01 \text{ cm}^{-3}$ ,  $T_i \sim 10.98 \pm 1.6 \text{ keV}$ , and  $\kappa \sim 8.06 \pm 1.18$ . Compared with the values in T2, ions show clear number density decrease ( $\sim -61\%$ ), temperature increase ( $\sim 137\%$ ), and a small decrease in  $\kappa$  ( $\sim -6\%$ ).

The above two cases have revealed that plasma sheet protons became denser and cooler during the substorm growth phase, and were depleted and heated after the substorm dipolarizations at both planets. The  $\kappa$  decreases were observed during the whole substorm periods, but with the relative changes of  $\kappa$  at Mercury ( $-85$  and  $-40\%$ ) much larger than that at Earth ( $-9$  and  $-6\%$ ).

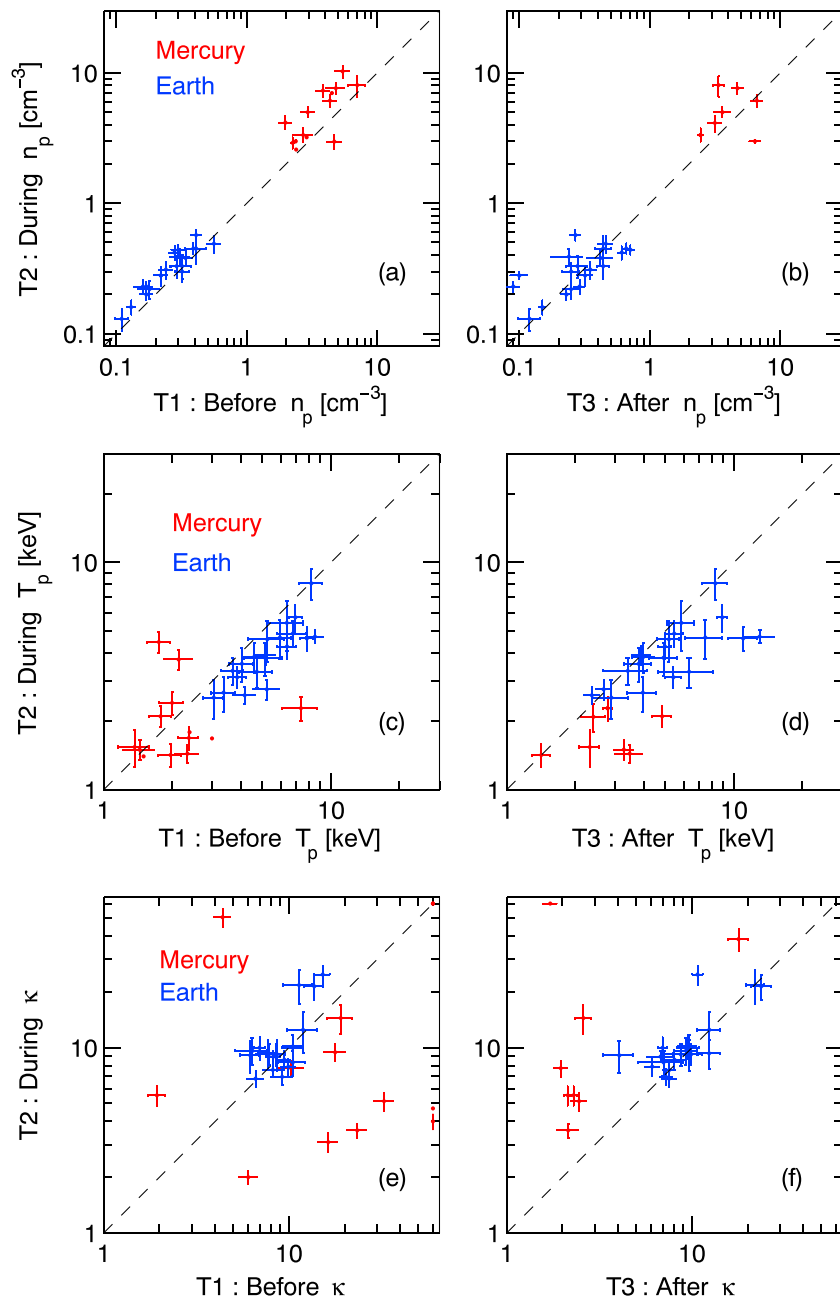
#### 2.4. Statistical Results and Comparative Study

This section performs a statistical study focusing on the proton variations during magnetospheric substorms at both planets. At Mercury, the magnetospheric substorm cases were selected based on the criteria from Sun, Slavin, Fu, Raines, Zong, et al. (2015). The cases should contain clear substorm growth and expansion phases features; that is, MESSENGER first observed a decrease in  $B_z$  and an almost constant or increased  $B_x$  ended by a sharp increase in  $B_z$  and followed by a decrease in  $B_x$  and fluctuations in  $B_y$ . Additionally, MESSENGER was required to be located in the plasma sheet. These selection criteria give 31 satisfied cases. The proton PSDs from FIPS were averaged over  $\sim 1$  min in T1, T2, and T3 for each case. In the fitting, we only select energy channels containing more than six counts, and at least ten channels meet this constraint, which ensures that each used energy channel contains enough counts and PSDs contain enough channels. This step is necessary since uncertainties in the plasma moments are reduced as the total counts became larger (Gershman et al., 2013). We obtain 14 qualified proton PSDs for T1, 16 for T2, and 8 for T3. At Earth, the selection criteria are similar to that of Sun, Fu, et al. (2017). The substorm growth phase started with a southward turning of IMF and ended with a substorm dipolarization in the near-Earth tail. Spacecraft should be located in the central plasma sheet during the period. We obtain 20 qualified substorm cases from THD and THE in 2008 and 2009.

The fitting results for T1, T2, and T3 at both planets are shown in Figure 3. The  $n_p$  (Figures 3a and 3b) in Mercury's plasma sheet are  $\sim 3$ – $10 \text{ cm}^{-3}$ , which are around an order of magnitude higher than the values in Earth's plasma sheet ( $\sim 0.1$ – $0.6 \text{ cm}^{-3}$ ). The  $T_p$  (Figures 3c and 3d) are generally several times lower at Mercury ( $\sim 1$ – $5 \text{ keV}$ ) than at Earth ( $\sim 3$ – $10 \text{ keV}$ ). The  $\kappa$  (Figures 3e and 3f) at Earth range mainly from  $\sim 5$  to  $\sim 20$ , while it has a broader range of values at Mercury, which is from  $\sim 2$  to  $\sim 60$ . The value 60 is the upper limit in our kappa fitting. At this limit the kappa distribution is nearly indistinguishable from a Maxwellian distribution (e.g., Pierrard & Lazar, 2010).

In Earth's plasma sheet,  $n_p$  increases from T1 to T2 (Figure 3a) in the majority of cases (18/20), while decreases (10/20) in half and increases (10/20) in the other half from T2 to T3 (Figure 3b). In Mercury's plasma sheet,  $n_p$  typically increases from T1 to T2 (13/14; Figure 3a) and decreases from T2 to T3 (6/8; Figure 3b). The average increase ratio of  $n_p$  ( $\Delta n_p/n_p$ ) from T1 to T2 at Mercury is  $0.41 \pm 0.091$ , which is comparable to the  $0.22 \pm 0.038$  at Earth. At Earth, the decrease in  $T_p$  from T1 to T2 is observed in all the cases (Figure 3c), and the increase in  $T_p$  from T2 to T3 is observed in most of the cases (17/20; Figure 3d). At Mercury from T1 to T2,  $T_p$  decreases in about half of the cases (8/14) and increases in the others, while  $T_p$  increases in all the cases (8/8) from T2 to T3. The average increase ratio of  $T_p$  from T2 to T3 at Mercury is  $0.36 \pm 0.21$ , which is also comparable to the  $0.14 \pm 0.047$  at Earth. However, changes in  $\kappa$  (Figures 3e and 3f) are less systematic. At Earth,  $\kappa$  remains similar from T1 to T2 and again from T2 to T3 (i.e., clustering around the dashed lines). At Mercury,  $\kappa$  often changes substantially (i.e., further away from the dashed lines) with changes that can be positive or negative from T1 to T2 but typically negative from T2 to T3.

Figure 4 shows the histograms of  $\Delta\kappa/\kappa$ , where  $\Delta\kappa$  are the  $\kappa$  changes from T1 to T2 (Figure 4a) or T2 to T3 (Figure 4b), and  $\kappa$  are the values in T1 (Figure 4a) or T2 (Figure 4b). In Figure 4a, blue bars (Earth cases) are

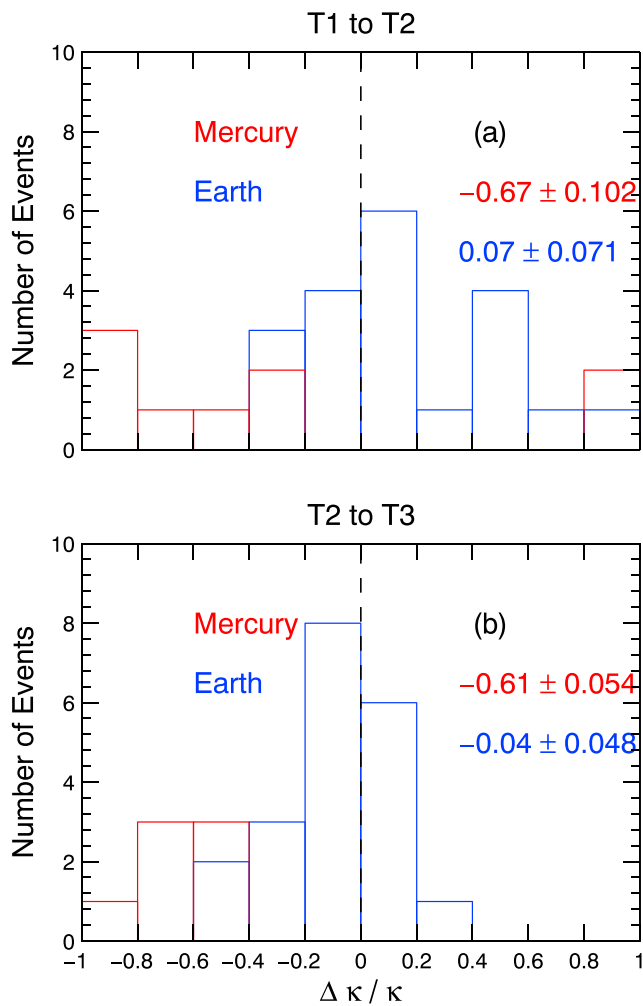


**Figure 3.** Distributions of proton densities ( $n_p$ ), temperatures ( $T_p$ ), and kappa values ( $\kappa$ ) during the magnetospheric substorms at both earth (blue) and mercury (red). (a)  $n_p$  at T1 and T2. (b)  $n_p$  at T2 and T3. (c)  $T_p$  at T1 and T2. (d)  $T_p$  at T2 and T3. (e)  $\kappa$  at T1 and T2. (f)  $\kappa$  at T2 and T3.

distributed near  $\sim 0$  with a mean value of  $0.07 \pm 0.071$ , while the red bars (Mercury cases) distribute mostly away from  $\sim 0$ , with the mean value of only negative bars of  $-0.67 \pm 0.102$ . In Figure 4b, blue and red bars distribute in a similar way to Figure 4a with the mean values of blue bars being  $-0.04 \pm 0.048$  and red bars  $-0.61 \pm 0.054$ . These statistical results on  $\kappa$  changes confirm the results in our case studies. The relative changes of  $\kappa$  of protons during the substorm at Mercury are larger than that at Earth.

### 3. Conclusion and Discussion

The variations of protons during magnetospheric substorms at Earth and Mercury are comparatively studied with the measurements from MESSENGER and THEMIS. This study utilizes kappa distributions to interpret



**Figure 4.** The distributions of the relative  $\kappa$  changes ( $\Delta\kappa/\kappa$ ). (a) The distribution of  $\Delta\kappa/\kappa$  from T1 to T2 and (b) from T2 to T3.

plasma sheet proton properties. It is found that  $n_p$  is about an order of magnitude higher in Mercury's plasma sheet ( $\sim 3\text{--}10\text{ cm}^{-3}$ ) than in Earth's ( $\sim 0.1\text{--}0.6\text{ cm}^{-3}$ ). The  $T_p$  is generally several times lower at Mercury ( $\sim 1\text{--}5\text{ keV}$ ) than at Earth ( $\sim 3\text{--}10\text{ keV}$ ). The  $\kappa$  at Earth mainly concentrates from  $\sim 5$  to  $\sim 20$ , while it has a broader range of values (from  $\sim 2$  to  $\sim 60$ ) at Mercury. In most cases, plasma sheet protons become denser and cooler during the substorm growth phase and are depleted and heated after the substorm dipolarizations at both planets. The changes of  $\kappa$  during the substorms at Earth are small ( $<20\%$ ), but are much larger at Mercury ( $>60\%$ ).

The small variations of  $\kappa$  during the magnetospheric substorm in Earth's plasma sheet indicate that spectrum-preserving processes, like betatron acceleration under the conservation of magnetic moment ( $\Delta W_{\perp} = W_{\perp} \Delta B/B$ , where  $W$  is the particle energy and  $B$  is the strength of magnetic field), play an important role. Charged particles at all energies would maintain relatively the same proportional energy and would not change the shape of high-energy tail under betatron acceleration (e.g., Christon et al., 1991). During the growth phase,  $B_z$  in the magnetic equatorial plane would decrease as a natural consequence of plasma sheet thinning, which suggested that protons would experience adiabatic betatron cooling and, therefore, result in  $T_p$  decrease. During the substorm dipolarization, the sharp  $B_z$  increase would cause strong betatron heating ( $T_p$  increase) for the protons.

At Mercury, the large variations of  $\kappa$  during the magnetospheric substorm indicate the importance of spectrum-altering processes, that is, energy-dependent energy increments. We propose two possible candidates for the spectrum-altering processes. One is the acceleration due to nonadiabatic cross-tail particle motion associated with thin current sheets (e.g., Ashour-Abdalla et al., 1990; Lyons & Speiser, 1982; Speiser, 1965). In Mercury's magnetotail, the field line radius of curvature in the equatorial plane is  $\sim 200\text{ km}$  on average (Rong et al., 2018). The 0.1-keV protons gyrating in a magnetic field of 10 nT would have a gyroradius of  $\sim 160\text{ km}$  comparable to the average radius of curvature.

On the other hand, the 1-keV protons could have a gyroradius of  $\sim 500\text{ km}$  comparable to the mean thickness of Mercury's tail current sheet ( $\sim 800\text{ km}$ ; Poh et al., 2017a). Thus, protons would predominantly move in the way of nonadiabatic cross-tail particle motion in Mercury's magnetotail. Lyons and Speiser (1982) showed that this cross-tail acceleration is sensitive to the ratio of the dawn-to-dusk electric field ( $E_y$ ) to the vertical  $B_z$ . The high  $E_y$  due to relatively high cross-tail potential (DiBraccio et al., 2015; Jasinski et al., 2017; Slavin et al., 2009, 2010) would result in strong cross-tail acceleration for protons at Mercury. The other possible candidate is wave-particle interactions (e.g., Catapano et al., 2017; Hasegawa et al., 1985; Shizgal, 2007). For the case in Figure 1, we do observe intense plasma waves with frequencies around the proton gyrofrequency, especially after the dipolarization in the wavelet spectrum of MAG data (see supporting information). This could be electromagnetic ion cyclotron (EMIC) waves, which were often observed in the Mercury's plasma sheet (Schriver et al., 2011). The accumulated pitch angle-energy distribution for protons shows loss cone feature suggesting possible mechanism for EMIC (see supporting information). Therefore, wave-particle interactions might also contribute to the changes of  $\kappa$  during the substorm at Mercury. It needs to note that this paragraph discusses two straightforward possibilities for the spectrum altering processes at Mercury. Other mechanisms could still play a role in the process.

There are several cases at Earth showing  $|\Delta\kappa/\kappa| > 0.4$  (Figure 4), indicating that spectrum-altering processes also exist in Earth's plasma sheet during magnetospheric substorms as proposed by previous studies (e.g., Christon et al., 1991; Huang et al., 1992). The magnetospheric substorm case at Earth shown in Figure 2 did contain plasma waves with frequency around the proton gyrofrequency during the dipolarization (see

supporting information). Since most of the cases at Mercury show  $|\Delta\kappa/\kappa| > 0.4$ , the spectrum-altering processes during the magnetospheric substorm at Earth might not be as intense as that at Mercury. This reveals that, during the magnetospheric substorms, protons could be well described by adiabatic betatron acceleration at Earth, while spectrum-altering acceleration processes dominate the behavior of protons at Mercury. We suggest that this different character of protons could closely relate to the distinct properties of the two magnetospheres. Most importantly, the scale of Mercury's magnetosphere is much smaller than that of Earth's magnetosphere (e.g., Siscoe et al., 1975; Winslow et al., 2013). The relatively thin plasma sheet and small radius of curvature of the magnetic field lines in Mercury's magnetotail (e.g., Poh et al., 2017a, 2017b; Rong et al., 2018) would make spectrum-altering processes important.

#### Acknowledgments

MESSENGER data used in this study were available from the Planetary Data System (PDS): <http://pds.jpl.nasa.gov>. The MESSENGER project is supported by the NASA Discovery Program under contracts NASW-00002 to the Carnegie Institution of Washington and NAS5-97271 to The Johns Hopkins University Applied Physics Laboratory. We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission (available at <http://themis.ssl.berkeley.edu/>). Specifically, D. Larson and R.P. Lin are acknowledged for the use of SST data; C. W. Carlson and J.P. McFadden for the use of ESA data; K.H. Glassmeier, U. Auster, and W. Baumjohann for the use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302. We also acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb service (OMNI data are downloaded from <http://omniweb.gsfc.nasa.gov/>) and World Data Center for Geomagnetism, Kyoto (AE, AL data; <http://wdc.kugi.kyoto-u.ac.jp/>). W.J.S. is funded by the National Postdoctoral Program for Innovative Talents (grant BX201600158) and China Postdoctoral Science Foundation (grant 2016M600124). This work is supported by the National Natural Science Foundation of China (grants 41704163, 41525016, 41474155, 41474139, 41661164034). Y.W. is supported by Thousand Young Talents Program of China. The contributions by one of the authors (J.A.S.) were supported by NASA's Heliophysics Supporting Research (NNX15AJ68G) and Living With a Star (NNX16AJ67G) programs. J. M.R. and D.J.G. were supported by NASA's Discovery Data Analysis Program (NNX16AJ05G). This work is also supported by the CAS Key Laboratory of Lunar and Deep Space Exploration through grant 2013DP173157. Wei-Jie Sun thanks Xuzhi Zhou (School of Earth and Space Sciences, Peking University) for the helpful discussions.

#### References

- Anderson, B. J., Acuña, M. H., Lohr, D. A., Scheifele, J., Raval, A., Korth, H., & Slavin, J. A. (2007). The magnetometer instrument on MESSENGER. *Space Science Reviews*, *131*(1–4), 417–450. <https://doi.org/10.1007/s11214-007-9246-7>
- Anderson, B. J., Johnson, C. L., Korth, H., Purucker, M. E., Winslow, R. M., Slavin, J. A., et al. (2011). The global magnetic field of mercury from MESSENGER orbital observations. *Science*, *333*(6051), 1859–1862. <https://doi.org/10.1126/science.1211001>
- Andrews, G., Zurbuchen, T. H., Mauk, B. H., Malcom, H., Fisk, L. A., Gloeckler, G., et al. (2007). The energetic particle and plasma spectrometer instrument on the MESSENGER spacecraft. *Space Science Reviews*, *131*(1–4), 523–556. <https://doi.org/10.1007/s11214-007-9272-5>
- Angelopoulos, V. (2008). The THEMIS mission. *Space Science Reviews*, *141*(1–4), 5–34. <https://doi.org/10.1007/s11214-008-9336-1>
- Artemyev, A. V., Angelopoulos, V., Runov, A., & Petrokovich, A. A. (2016). Properties of current sheet thinning at  $x \sim -10$  to  $-12 R_E$ . *Journal of Geophysical Research: Space Physics*, *121*, 6718–6731. <https://doi.org/10.1002/2016JA022779>
- Ashour-Abdalla, M., Berchem, J., Büchner, J., & Zelenyi, M. (1990). Chaotic scattering and acceleration of ions in the Earth's magnetotail. *Geophysical Research Letters*, *17*(13), 2317–2320. <https://doi.org/10.1029/GL017i013p02317>
- Auster, H. U., Glassmeier, K. H., Magnes, W., Aydogar, O., Baumjohann, W., Constantinescu, D., et al. (2008). The THEMIS fluxgate magnetometer. *Space Science Reviews*, *141*(1–4), 235–264. <https://doi.org/10.1007/s11214-008-9365-9>
- Baker, D. N., Pulkkinen, T. I., Angelopoulos, V., Baumjohann, W., & McPherron, R. L. (1996). Neutral line model of substorms: Past results and present view. *Journal of Geophysical Research*, *101*(A6), 12,975–13,010. <https://doi.org/10.1029/95JA03753>
- Catapano, F., Zimbardo, G., Perri, S., Greco, A., Delcourt, D., Retino, A., & Cohen, I. J. (2017). Charge proportional and weakly mass-dependent acceleration of different ion species in the Earth's magnetotail. *Geophysical Research Letters*, *44*, 10,108–10,115. <https://doi.org/10.1002/2017GL075092>
- Christon, S. P., Williams, D. J., Mitchell, D. G., Huang, C. Y., & Frank, L. A. (1991). Spectral characteristics of plasma sheet ion and electron populations during disturbed geomagnetic conditions. *Journal of Geophysical Research*, *96*(A1), 1–22. <https://doi.org/10.1029/90JA01633>
- Delcourt, D. C., Leblanc, F., Seki, K., Terada, N., Moore, T. E., & Fok, M. C. (2007). Ion energization during substorms at mercury. *Planetary and Space Science*, *55*(11), 1502–1508. <https://doi.org/10.1016/j.pss.2006.11.026>
- Delcourt, D. C., Moore, T. E., & Fok, M.-C. H. (2010). Ion dynamics during compression of Mercury's magnetosphere. *Annales de Geophysique*, *28*(8), 1467–1474. <https://doi.org/10.5194/angeo-28-1467-2010>
- Dewey, R. M., Slavin, J. A., Raines, J. M., Baker, D. N., & Lawrence, D. J. (2017). Energetic electron acceleration and injection during dipolarization events in Mercury's magnetotail. *Journal of Geophysical Research: Space Physics*, *122*, 12,170–12,188. <https://doi.org/10.1002/2017JA024617>
- DiBraccio, G. A., Slavin, J. A., Boardsen, S. A., Anderson, B. J., Korth, H., Zurbuchen, T. H., et al. (2013). MESSENGER observations of magnetopause structure and dynamics at mercury. *Journal of Geophysical Research: Space Physics*, *118*, 997–1008. <https://doi.org/10.1002/jgra.50123>
- DiBraccio, G. A., Slavin, J. A., Raines, J. M., Gershman, D. J., Tracy, P. J., Boardsen, S. A., et al. (2015). First observations of Mercury's plasma mantle by MESSENGER. *Geophysical Research Letters*, *42*, 9666–9675. <https://doi.org/10.1002/2015GL065805>
- Gershman, D. J., Slavin, J. A., Raines, J. M., Zurbuchen, T. H., Anderson, B. J., Korth, H., et al. (2013). Magnetic flux pileup and plasma depletion in Mercury's subsolar magnetosheath. *Journal of Geophysical Research: Space Physics*, *118*, 7181–7199. <https://doi.org/10.1002/2013JA019244>
- Gershman, D. J., Slavin, J. A., Raines, J. M., Zurbuchen, T. H., Anderson, B. J., Korth, H., et al. (2014). Ion kinetic properties in Mercury's pre-midnight plasma sheet. *Geophysical Research Letters*, *41*, 5740–5747. <https://doi.org/10.1002/2014GL060468>
- Haaland, S., Kronberg, E. A., Daly, P. W., Fränz, M., Degener, L., Georgescu, E., & Dandouras, I. (2010). Spectral characteristics of protons in the Earth's plasmashet: Statistical results from cluster CIS and RAPID. *Annales de Geophysique*, *28*(8), 1483–1498. <https://doi.org/10.5194/angeo-28-1483-2010>
- Hasegawa, A., Mima, K., & Duong-van, M. (1985). Plasma distribution function in a superthermal radiation field. *Physical Review Letters*, *54*(24), 2608–2610. <https://doi.org/10.1103/PhysRevLett.54.2608>
- Hones, E. W. Jr. (1977). Substorm processes in the magnetotail: Comments on 'on hot tenuous plasmas, fireballs, and boundary layers in the Earth's magnetotail' by L. A. Frank, K. L. Ackerson, and R. P. Lepping. *Journal of Geophysical Research*, *82*(35), 5633–5640. <https://doi.org/10.1029/JA082i035p05633>
- Huang, C. Y., Frank, L. A., Rostoker, G., Fennell, J., & Mitchell, D. G. (1992). Nonadiabatic heating of the central plasma sheet at substorm onset. *Journal of Geophysical Research*, *97*(A2), 1481–1495. <https://doi.org/10.1029/91JA02517>
- Imber, S. M., & Slavin, J. A. (2017). MESSENGER observations of magnetotail loading and unloading: Implications for substorms at Mercury. *Journal of Geophysical Research: Space Physics*, *122*, 11,402–11,412. <https://doi.org/10.1002/2017JA024332>
- Ip, W. H. (1987). Dynamics of electrons and heavy ions in Mercury's magnetosphere. *Icarus*, *71*(3), 441–447. [https://doi.org/10.1016/0019-1035\(87\)90039-X](https://doi.org/10.1016/0019-1035(87)90039-X)
- Jasinski, J. M., Slavin, J. A., Raines, J. M., & DiBraccio, G. A. (2017). Mercury's solar wind interaction as characterized by magnetospheric plasma mantle observations with MESSENGER. *Journal of Geophysical Research: Space Physics*, *122*, 12,153–12,169. <https://doi.org/10.1002/2017JA024594>



- Kistler, L. M., Mouikis, C. G., Cao, X., Frey, H., Klecker, B., Dandouras, I., et al. (2006). Ion composition and pressure changes in storm time and nonstorm substorms in the vicinity of the near-earth neutral line. *Journal of Geophysical Research*, *111*, A11222. <https://doi.org/10.1029/2006JA011939>
- Lyons, L. R., & Speiser, T. W. (1982). Evidence for current sheet acceleration in the geomagnetic tail. *Journal of Geophysical Research*, *87*(A4), 2276–2286. <https://doi.org/10.1029/JA087iA04p02276>
- McFadden, J. P., Carlson, C. W., Larson, D., Ludlam, M., Abiad, R., Elliott, B., et al. (2008). The THEMIS ESA plasma instrument and in-flight calibration. *Space Science Reviews*, *141*(1–4), 277–302. <https://doi.org/10.1007/s11214-008-9440-2>
- Nagai, T., Mukai, T., Yamamoto, T., Nishida, A., Kokubun, S., & Lepping, R. P. (1997). Plasma sheet pressure changes during the substorm growth phase. *Geophysical Research Letters*, *24*(8), 963–966. <https://doi.org/10.1029/97GL00374>
- Ness, N. F. (1965). The Earth's magnetic tail. *Journal of Geophysical Research*, *70*(13), 2989–3005. <https://doi.org/10.1029/JZ070i013p02989>
- Ness, N. F., Behannon, K. W., Lepping, R. P., Whang, Y. C., & Schatten, K. H. (1974). Magnetic field observations near mercury: Preliminary results from mariner 10. *Science*, *185*(4146), 151–160. <https://doi.org/10.1126/science.185.4146.151>
- Pierrard, V., & Lazar, M. (2010). Kappa distributions: Theory and applications in space plasmas. *Solar Physics*, *267*(1), 153–174. <https://doi.org/10.1007/s11207-010-9640-2>
- Poh, G., Slavin, J. A., Jia, X., Raines, J. M., Imber, S. M., Sun, W. J., et al. (2017a). Mercury's cross-tail current sheet: Structure, X-line location and stress balance. *Geophysical Research Letters*, *44*, 678–686. <https://doi.org/10.1002/2016GL071612>
- Poh, G., Slavin, J. A., Jia, X., Raines, J. M., Imber, S. M., Sun, W. J., et al. (2017b). Coupling between mercury and its nightside magnetosphere: Cross-tail current sheet asymmetry and substorm current wedge formation. *Journal of Geophysical Research: Space Physics*, *122*, 8419–8433. <https://doi.org/10.1002/2017JA024266>
- Raines, J. M., DiBraccio, G. A., Cassidy, T. A., Delcourt, D. C., Fujimoto, M., Jia, X., et al. (2015). Plasma sources in planetary magnetospheres: Mercury. *Space Science Reviews*, *192*(1–4), 91–144, 144. <https://doi.org/10.1007/s11214-015-0193-4>
- Rong, Z. J., Ding, Y., Slavin, J. A., Zhong, J., Poh, G., Sun, W. J., et al. (2018). The magnetic field structure of Mercury's magnetotail. *Journal of Geophysical Research: Space Physics*, *123*, 548–566. <https://doi.org/10.1002/2017JA024923>
- Rostoker, G., Akasofu, S.-I., Foster, J., Greenwald, R., Kamide, Y., Kawasaki, K., et al. (1980). Magnetospheric substorms—Definition and signatures. *Journal of Geophysical Research*, *85*(A4), 1663–1668. <https://doi.org/10.1029/JA085iA04p01663>
- Schríver, D., Trávníček, P. M., Anderson, B. J., Ashour-Abdalla, M., Baker, D. N., Benna, M., et al. (2011). Quasi-trapped ion and electron populations at mercury. *Geophysical Research Letters*, *38*, L23103. <https://doi.org/10.1029/2011GL049629>
- Shizgal, B. D. (2007). Suprathermal particle distributions in space physics: Kappa distributions and entropy. *Astrophysics and Space Science*, *312*(3–4), 227–237. <https://doi.org/10.1007/s10509-007-9679-1>
- Siscoe, G. L., Ness, N. F., & Yeates, C. M. (1975). Substorms on mercury? *Journal of Geophysical Research*, *80*(31), 4359–4363. <https://doi.org/10.1029/JA080i031p04359>
- Slavin, J. A., Acuña, M. H., Anderson, B. J., Baker, D. N., Benna, M., Board, S. A., et al. (2009). MESSENGER observations of magnetic reconnection in Mercury's magnetosphere. *Science*, *324*(5927), 606–610. <https://doi.org/10.1126/science.1172011>
- Slavin, J. A., Anderson, B. J., Baker, D. N., Benna, M., Board, S. A., Gloeckler, G., et al. (2010). MESSENGER observations of extreme loading and unloading of Mercury's magnetic tail. *Science*, *329*(5992), 665–668. <https://doi.org/10.1126/science.1188067>
- Slavin, J. A., DiBraccio, G. A., Gershman, D. J., Imber, S. M., Poh, G. K., Raines, J. M., et al. (2014). MESSENGER observations of Mercury's dayside magnetosphere under extreme solar wind conditions. *Journal of Geophysical Research: Space Physics*, *119*, 8087–8116. <https://doi.org/10.1002/2014JA020319>
- Slavin, J. A., Krimigis, S. M., Acuña, M. H., Anderson, B. J., Baker, D. N., Koehn, P. L., et al. (2007). MESSENGER: Exploring Mercury's magnetosphere. *Space Science Reviews*, *131*(1–4), 133–160. <https://doi.org/10.1007/s11214-007-9154-x>
- Solomon, S., McNutt, R. L. Jr., Gold, R. E., & Domingue, D. L. (2007). MESSENGER mission overview. *Space Science Reviews*, *131*(1–4), 3–39. <https://doi.org/10.1007/%20s11214-007-9247-6>
- Speiser, T. W. (1965). Particle trajectories in model current sheets: 1. Analytical solutions. *Journal of Geophysical Research*, *70*(17), 4219–4226. <https://doi.org/10.1029/JZ070i017p04219>
- Sun, W. J., Fu, S. Y., Slavin, J. A., Raines, J. M., Zong, Q. G., Poh, G. K., & Zurbuchen, T. H. (2016). Spatial distribution of Mercury's flux ropes and reconnection fronts: MESSENGER observations. *Journal of Geophysical Research: Space Physics*, *121*, 7590–7607. <https://doi.org/10.1002/2016JA022787>
- Sun, W. J., Fu, S. Y., Wei, Y., Yao, Z. H., Rong, Z. J., Zhou, X. Z., et al. (2017). Plasma sheet pressure variations in the near-earth magnetotail during substorm growth phase: THEMIS observations. *Journal of Geophysical Research: Space Physics*, *122*, 12,212–12,228. <https://doi.org/10.1002/2017JA024603>
- Sun, W. J., Raines, J. M., Fu, S. Y., Slavin, J. A., Wei, Y., Poh, G. K., et al. (2017). MESSENGER observations of the energization and heating of protons in the near-mercury magnetotail. *Geophysical Research Letters*, *44*, 8149–8158. <https://doi.org/10.1002/2017GL074276>
- Sun, W.-J., Slavin, J. A., Fu, S., Raines, J. M., Sundberg, T., Zong, Q.-G., et al. (2015). MESSENGER observations of Alfvénic and compressional waves during Mercury's substorms. *Geophysical Research Letters*, *42*, 6189–6198. <https://doi.org/10.1002/2015GL065452>
- Sun, W.-J., Slavin, J. A., Fu, S., Raines, J. M., Zong, Q. G., Imber, S. M., et al. (2015). MESSENGER observations of magnetospheric substorm activity in Mercury's near magnetotail. *Geophysical Research Letters*, *42*, 3692–3699. <https://doi.org/10.1002/2015GL064052>
- Vasyliunas, V. M. (1968). A survey of low-energy electrons in the evening sector of the magnetosphere with OGO 1 and OGO 3. *Journal of Geophysical Research*, *73*(9), 2839–2884. <https://doi.org/10.1029/JA073i009p02839>
- Williams, D. J., Mitchell, D. G., Huang, C. Y., Frank, L. A., & Russell, C. T. (1990). Particle acceleration during substorm growth and onset. *Geophysical Research Letters*, *17*(5), 587–590. <https://doi.org/10.1029/GL017i005p00587>
- Wing, S., Johnson, J. R., Newell, P. T., & Meng, C.-I. (2005). Dawn-dusk asymmetries, ion spectra, and sources in the northward interplanetary magnetic field plasma sheet. *Journal of Geophysical Research*, *110*, A08205. <https://doi.org/10.1029/2005JA011086>
- Winslow, R. M., Anderson, B. J., Johnson, C. L., Slavin, J. A., Korth, H., Purucker, M. E., et al. (2013). Mercury's magnetopause and bow shock from MESSENGER magnetometer observations. *Journal of Geophysical Research: Space Physics*, *118*, 2213–2227. <https://doi.org/10.1002/jgra.50237>