Multiple X-line Reconnection Observed in Mercury’s Magnetotail Driven by an Interplanetary Coronal Mass Ejection

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Abstract

How magnetic reconnection drives Mercury’s magnetospheric dynamics under extreme solar wind conditions is not well understood. Here we report MESSENGER observations of an active reconnection event in Mercury’s magnetotail driven by an interplanetary coronal mass ejection on 2011 November 23. The primary Hall magnetic field, sequential passage of X-lines with Hall field perturbations, and flux ropes (FRs) provide unambiguous evidence of multiple X-line reconnection in an unstable ion diffusion region. In addition, large FRs consisting of multiple successive small-scale FRs are ejected tailward at quasi-periodic intervals of ~1 minute, which is comparable to the Dungey cycle time. We propose that these large FRs are generated by the interaction and coalescence of multiple ion-scale FRs. This is distinct from the commonly accepted Earth-like substorm process where plasmoids are created by widely separated X-lines in the magnetotail. These observations suggest that during extreme solar wind conditions multiple X-line reconnection may dominate the tail reconnection process and control the global dynamics of Mercury’s magnetosphere.

Unified Astronomy Thesaurus concepts: Solar magnetic reconnection (1504); Mercury (planet) (1024); Space plasmas (1544); Planetary magnetosphere (997); Solar coronal mass ejections (310); Solar-planetary interactions (1472)

1. Introduction

Magnetic reconnection is a primary process that drives planetary magnetospheric dynamics. Mercury’s magnetosphere is one of the most extreme planetary environments in our solar system due to the intense solar wind driving in the inner heliosphere. Like Earth, reconnection at Mercury occurs at the dayside magnetopause, where the solar wind energy is transferred into the magnetosphere, and in the magnetotail current sheet, where some energy is released back to the solar wind. This drives the circulation of magnetic flux and plasma that constitutes the Dungey cycle (Dungey 1961). However, the timescale of Dungey cycle at Mercury is estimated to be 2–3 minutes (Imber & Slavin 2017), which is much shorter than ~1 hr at Earth (Baker et al. 1996).

Magnetic reconnection is expected to play a much more important role in driving Mercury’s magnetospheric activity than at Earth or other magnetized planets (e.g., Slavin et al. 2009). MESSENGER frequently observed lobe field loading and unloading in Mercury’s magnetotail (Slavin et al. 2010; Imber & Slavin 2017). It is believed that magnetic energy is stored in Mercury’s magnetotail and eventually released by tail reconnection; this drives global magnetospheric dynamics in a manner analogous to substorms at Earth (Baker et al. 1996; Hones 1977). One substorm-associated magnetotail phenomenon is the formation of a large-scale plasmoid between the near-Earth and the distant X-lines and the subsequent injection tailward into the solar wind (e.g., Slavin et al. 1989). As for Mercury, large plasmoids are occasionally observed in the near magnetotail (Zhong et al. 2019). Moreover, Zhong et al. (2018) reported the first observation of a rapidly evolving magnetic reconnection process in Mercury’s magnetotail. They showed that the tail energy was released rapidly and impulsively as repeated tailward ejections of the reconnection fronts and instantaneously in response to the enhanced solar wind driving. However, direct observations of active magnetic reconnection sites are rare. The pattern of reconnection driving the global dynamics of Mercury’s magnetosphere remains poorly understood.

On 2011 November 23, an interplanetary coronal mass ejection (ICME) impacted Mercury’s magnetosphere. As the ICME passed, the solar wind dynamic pressure was inferred to be ~51 nPa, which is 4 to 9 times greater than normal (Slavin et al. 2014). The dayside magnetospheric dynamics were analyzed by Slavin et al. (2014). Here we report observations of active reconnection sites in Mercury’s magnetotail under this extreme solar wind condition. We provide unambiguous evidence of multiple X-line reconnection in an unstable ion diffusion region. The observations suggest that the multiple X-line reconnection may dominate the reconnection process in Mercury’s highly compressed magnetotail. Hence, it may be responsible for the global dynamics of the magnetosphere. The pattern of the magnetic energy released into the solar wind is distinct from Earth-like substorms or the convection of plasmoids created by widely separated X-lines.
2. Observations

An overview of the MESSENGER observations of Mercury’s magnetotail crossing on 2011 November 23 is shown in Figure 1. The high-resolution (20 vectors s\(^{-1}\)) magnetic field data from the Magnetometer (MAG; Anderson et al. 2007) and ion plasma data from the Fast Imaging Plasma Spectrometer (FIPS; one energy scan per 10 s; Andrews et al. 2007) were used. Between 08:17:00 UT and 08:31:37 UT the spacecraft traveled from the magnetosheath into the magnetotail near the noon-midnight meridian and crossed the far downstream southern magnetopause multiple times. The mean location of the nightside magnetopause was \(\sim 0.4 R_M\) inward from the normal magnetopause (Zhong et al. 2015). At \(\sim 09:25:00\) UT, the spacecraft traversed the current sheet from the southern to the northern lobe. The strength of the lobe field reached \(\sim 100\) nT, which is \(\sim 100\%\) stronger than it was for the orbits before and after the ICME. The substorm-related tail loading and unloading were not obvious. Instead, the lobe magnetic field was relatively constant throughout the tail crossing. These indicate that Mercury’s magnetotail was highly compressed and under a driving force that remained approximately constant throughout the passage of the ICME.

A remarkable signature is the occurrence of a large number of flux ropes (FRs) and their associated TCRs. The FRs and TCRs are characterized by north-to-south reversals or perturbations in the \(B_Z\) component, coincident with enhancements of \(B_Y\) and \(B_{\text{\|\|}}\). The positive-to-negative polarities in \(B_Z\) are indicative of tailward-moving FR structures. Thirty-three FRs or TCRs with durations longer than 10 s and \(B_Z\) peak-to-peak amplitudes greater than 10 nT were identified between 08:58:00 UT and 09:34:00 UT as the spacecraft moved from \(X_{\text{MSM}} = -3.33\) to \(-2.24 R_M\) and \(Z_{\text{MSM}} = -1.11\) to 0.22 \(R_M\) (red arrows in Figure 1(d)). The mean duration of these FRs is 16.8 s and they occurred at \(\sim 1\) minute intervals. These long-duration FRs have rarely been seen in previous observations (e.g., DiBraccio et al. 2015; Smith et al. 2017).

A close-up view of the magnetic field data across the current sheet is shown in Figure 2. The magnetic field data were rotated to a local current sheet coordinate system, \(LMN\), determined by the minimum variance analysis of the magnetic field. Here, \(N\) is the current sheet normal, \(L\) is directed along the reconnecting component of the magnetic field, and \(M = N \times L\) points in the out-of-plane direction. This coordinate system is only slightly different from the MSM coordinate system: \(L = [0.998, -0.037, 0.050]\), \(M = [0.033, 0.996, 0.081]\), and \(N = [-0.053, -0.080, 0.995]\). During the main current sheet
crossing (09:22:40–09:26:40 UT), the negative-to-positive reversal in $B_L$ indicates a south–north crossing of the current sheet. The large perturbations of the Hall magnetic field and the formation of FRs suggest that the evolution of the reconnection was highly unstable. In the diffusion region there are clear negative-to-positive reversals of $B_N$ just before FRs FR4–8. This indicates that the spacecraft passed multiple tailward-moving X-lines, as denoted by the purple arrows in Figure 2(d). Before it crossed FR4–6, the spacecraft was immersed in the Hall region with positive $(B_M - B_g)$. The passage of the X-lines results in negative perturbations of the Hall magnetic field (blue arrows in Figure 2(c)). This can be interpreted as the passage of the southward and planetward quadrupole Hall magnetic field of the X-line, as shown by trajectory T1 in Figure 2(e). In contrast, before crossing FR 7–8, the spacecraft was immersed in the negative $(B_M - B_g)$ region tailward of the X-line. The observed positive perturbation of the Hall magnetic field just after the X-line passed indicates that the spacecraft encountered the northward and
planetward quadrupole Hall magnetic field of the X-line, as shown by trajectory T2 in Figure 2(e).

Following the X-lines are FRs. The presence of a strong core field suggests that they have a helical magnetic field topology. For the large FRs (FR4–8) observed near the current center, the maximum core field (black arrows in Figure 2(c)) exceeds 40% of the lobe magnetic field. This strong core field resulted from the compression of the guide field and Hall magnetic field, as well as the radial inward pinch of the FR due to the presence of the helical fields (Ma et al. 1994). Enhancements of the 1–10 keV thermal ion flux were observed within the FRs (green arrows above Figure 1(e)). This is consistent with the plasma density compression and pile-up between two X-lines (e.g., Chen et al. 2008; Liu et al. 2009). The ions would be accelerated along the core field due to force imbalance in the $M$ direction, which yields further increases in the core field (Ma et al. 1994). Moreover, the magnitude of $B_M$ in the center of the FR reached approximately 100% of $|B|$, suggesting that the FRs are approximately oriented in the $M$ direction, or parallel to the X-line. The FRs being parallel to the X-line, as well as the strong core field, further support the theory of multiple X-lines reconnection process (Lee & Fu 1985).

From high-resolution magnetic field data sampled at 20 s$^{-1}$, a large number of small-scale FRs with timescales of $\sim 1$ s can be identified. Close-up view of 1 minute interval data between FR3 and FR4 are shown in Figure 3(a). Eight short-duration FRs were identified by the positive-to-negative polarity in $B_N$ and coincident with the increase in $B_M$ and the peak in $|B|$. Negative perturbations of $(B_M - B_N)$ were also observed just before these short-duration FRs appeared, indicating the passage of the X-lines (T1 in Figure 2(e)). Based on assumed tailward propagation speed comparable to the local Alfvén speed, $\sim 1600$ km s$^{-1}$ from derived ion density (Figure 1(f)), the mean diameter of the short-duration FRs in the $L$ direction can be estimated to be $\sim 10$ $d_t$, where $d_t = c/\omega_{pi} \approx 160$ km is the ion inertial length. This indicates that these are ion-scale structures.

The ion-scale structures were also observed in the large FRs where they were identified from smoothed data. The close-up views of FR1 and FR5 are shown in Figures 3(b) and (c), respectively. Their whole bipolar $B_S$ (smoothed $B_N$) actually consisted of multiple successive short-duration bipolar variations. Each short-duration positive-to-negative reversal in $B_S$ is coincident with the sub-peak in $B_M$ and $|B|$. These are key observational features for the interaction and coalescence of FRs (e.g., Wang et al. 2015; Zhou et al. 2017) and confirmed by the simulations (e.g., Markidis et al. 2012), as illustrated in Figure 3(d). The spacecraft crossed FR1 away from the current sheet, and the observed short-duration $B_N$ bipolar are superimposed in the whole $B_N$ bipolar. The spacecraft crossed FR5 in the vicinity of the current sheet center, whereas more sequential reversals in $B_N$ were observed in the middle part of the large FR. These observations are consistent for the trajectories T1 and T2 of the tailward-moving merged large FRs relative to the spacecraft (Figure 3(d)). These suggest that the large FRs were likely formed repeatedly through the interaction and coalescence of many ion-scale FRs.

3. Summary and Discussion

The observations of the primary Hall magnetic field, sequential passage of X-lines with Hall field perturbations, and FRs provide unambiguous evidence of multiple X-line reconnection process in an unstable ion diffusion region. During extreme solar wind conditions, Mercury’s magnetotail forms a long, thin, and compressed current sheet. Assuming the current sheet is stable in the $N$ direction, the width of the diffusion region ($2\delta$) is estimated to be $2d_t$. When the half-length of the current sheet $L \gtrsim 1600$ km or $0.65 R_M$, the diffusion region becomes unstable due to tearing instability, and hence multiple X-lines appear in the diffusion region (Lee & Fu 1986). Consequently, a chain of FRs would form between neighboring X-lines, as shown in Figure 4(a). From theory (Fu & Lee 1986), the formation and convection of magnetic FRs should have a recurrence time $\tau \sim 10t_A/R$, where $t_A$ is the Alfvén transit time and $R$ is the normalized reconnection rate. We estimated that $t_A = \delta/v_A \sim 0.1$ s and the average $R = |B_N/B_M| \sim 0.1$. Thus, the theoretical timescale $\tau = 10$ s is consistent with the average interval observed between repeated ion-scale FRs.

These ion-scale FRs are expected to interact, coalesce, and grow into larger FRs until they are ejected tailward, as shown in Figure 4(b). These large FRs are estimated to be $\sim 2 R_M$ in the north–south direction and a few $R_M$ in the $L$ direction. Convection of such large FRs is expected to release a large amount of magnetic flux into the solar wind, which is supplemented by the dayside reconnection. The magnetic flux transport at the nightside and dayside is balanced in a quasi-steady state, as indicated by the observed quasi-steady lobe field. The time needed to cycle the magnetic flux in the tail
Earth-like substorm process or the formation of large-scale plasmoids created by widely separated X-lines in the magnetotail.

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