MESSENGER Observations of Rapid and Impulsive Magnetic Reconnection in Mercury’s Magnetotail

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Abstract

The nature of magnetic reconnection in planetary magnetospheres may differ between various planets. We report the first observations of a rapidly evolving magnetic reconnection process in Mercury’s magnetotail by the MESSENGER spacecraft. The reconnection process was initialized in the plasma sheet and then evolved into the lobe region during a ∼35 s period. The tailward reconnection fronts of primary and secondary flux ropes with clear Hall signatures and energetic electron bursts were observed. The reconnection timescale of a few seconds is substantially shorter than that of terrestrial magnetospheric plasmas. The normalized reconnection rate during a brief quasi-steady period is estimated to be ∼0.2 on average. The observations show the rapid and impulsive nature of the exceedingly driven reconnection in Mercury’s magnetospheric plasma that may be responsible for the much more dynamic magnetosphere of Mercury.

Key words: magnetic fields – magnetic reconnection – planets and satellites: terrestrial planets – plasmas – solar wind

1. Introduction

Magnetic reconnection is a fundamental process for converting magnetic energy into plasma energy and rearranging magnetic topology throughout the universe (Yamada et al. 2010). Observed frequently in the Earth’s magnetosphere, magnetic reconnection allows for global circulation of magnetic flux and plasma and controls large-scale dynamics (Dungey 1961; Vasyliunas 1975). Moreover, reconnection events have recently been reported in the magnetosphere of the outer planet Saturn (Arridge et al. 2015), as well as in the induced magnetosphere of Mars (e.g., Eastwood et al. 2008; Harada et al. 2017). Due to large differences in upstream solar wind conditions and internal planetary environments, the degree of a magnetosphere’s response to solar wind driving through magnetic reconnection can vary between planets (Jackman et al. 2014).

Mercury has a relatively weak magnetic field, with a planetary dipole moment about 3 orders of magnitude weaker than that of Earth (Anderson et al. 2011); on the other hand, as the innermost planet it experiences stronger solar wind forcing than Earth and other planets. Thus, the small and compressed nature of Mercury’s magnetosphere (Zhong et al. 2015a, 2015b) combined with the planet’s lack of atmosphere and ionosphere provides a unique plasma laboratory in the solar system. The greater interplanetary magnetic field magnitude and higher Alfvén speed in the inner solar system than that at Earth allows for magnetic reconnection to play a dominant role in Mercury’s magnetosphere (Slavin & Holzer 1979; DiBraccio et al. 2013). Recent MESSENGER observations of reconnection-related structures and phenomenon, including substorm-like activity (Slavin et al. 2010; Sun et al. 2015), dipolarization events or reconnection fronts (Sundberg et al. 2012; Sun et al. 2016), and the formation of magnetic flux ropes (Slavin et al. 2008, 2009, 2010; DiBraccio et al. 2015), show that these are similar to that at Earth but with very compressed timescales. With no direct onsite detection of reconnection sites, the nature of magnetic reconnection in Mercury remains unclear. Here we report the first detection of an active reconnection region by the MESSENGER spacecraft in Mercury’s magnetotail.

2. Observations and Analysis

The observations reported here were around 22:35:00 UT on 2012 May 12, when the MESSENGER spacecraft crossed the magnetotail current sheet at ∼2.0 RM (where RM is Mercury’s radius, 2440 km) down-tail of the center of the planet and ∼0.5 RM toward the dawnside as shown in Figure 1. An overview of high-resolution (20 vectors per second) magnetic field data from the Magnetometer (MAG; Anderson et al. 2007), ion flux data from the Fast Imaging Plasma Spectrometer (FIPS; Andrews et al. 2007), and energetic electron data from the Neutron Spectrometer (NS; Goldsten et al. 2007) are shown in Figure 2. FIPS had a large instantaneous field of view (FOV) of 1.4 π sr, though ∼0.25 π sr was blocked by the spacecraft and sunshade. NS detected energetic electrons indirectly by recording the bremsstrahlung photons produced by electrons with energies greater than 20–40 keV impinging on the instrument. The magnetic field data were analyzed in a local current sheet...
coordinate system, $LMN$, with $L$ along the reconnecting component of the magnetic field, $M$ along the guide field ($X$-line) direction, and $N$ along the direction normal to the overall current sheet. The $L$ direction was determined from the maximum variance of the magnetic field during the current sheet crossing. The eigenvalues from the variance analysis were $1361 \, \text{nT}^2$, $103 \, \text{nT}^2$ and $36 \, \text{nT}^2$. The large ratio of the maximum to intermediate eigenvalues suggests that the $L$ direction is well determined. But the $N$ direction may not be accurately obtained from variance analysis due to the insufficient separation between the last two eigenvalues. Thus, we used another method for the normally expected magnetotail configurations to determine the $N$ and $M$ direction, i.e., $N = L \times (z_{\text{MSM}} \times L)$ and $M = N \times L$. Relative to the aberrated Mercury Solar-Magnetospheric (MSM) coordinate system (see Figure 1 caption), $L = (0.95, 0.31, 0.02)$, $M = (-0.31, 0.95, 0.00)$, and $N = (-0.02, -0.01, 1.00)$.

The spacecraft began to move from the low-density lobe into the high-density plasma sheet around 22:33:00 UT, characterized by the decrease of the magnetic intensity $|B|$ (Figure 2(a)) and associated enhancement of the ion flux (Figure 2(c)). During the current sheet crossing, MESSENGER observed a sudden decrease in $B_N$ to large negative values around 22:34:37 UT. The negative $B_N$ indicates the spacecraft passing tailward of the X-line, and the negative-to-positive reversal in $B_L$ indicates a south–north crossing of the current sheet. The out-of-plane magnetic field component $B_M$ shows a significant bipolar feature, i.e., a positive $B_M$ (south to the neutral sheet, $B_L < 0$) followed by a negative $B_M$ (north to the neutral sheet, $B_L > 0$), with a peak amplitude ~66% of the asymptotic $B_L$ outside the current sheet. These magnetic field signatures suggest a crossing of the quadrupole Hall magnetic field structure tailward of the reconnection site (Sonnerup 1979). Such a quadrupole $B_M$ pattern is due to ion–electron decoupling (Sonnerup 1979) and is a key signature by which to identify active collisionless reconnection in the ion diffusion region (e.g., Nagai et al. 2001; Øiersen et al. 2001; Eastwood et al. 2010). The negative $B_N$ lasted about 35 s, in which the reconnection process developed into the lobe, evidenced by the ion flux being reduced to the lobe region levels. Around 22:35:12 UT the spacecraft moved away from the reconnected field line region into the inflow lobe region.

The rapid fluctuations of $B_N$ (Figure 2(g)) indicate that reconnection was active and in an unsteady state. From the observed features of $B_N$, we divided the reconnection crossing interval into five short periods: T1–T5, as shown in Figure 2(d)–(h). Schematic diagrams in Figure 3 show the evolution of magnetic structures corresponding to the five periods. Note that the MESSENGER was moving relatively slowly (order of ~1 km s$^{-1}$) compared to these reconnection structures that were sequentially observed while the spacecraft moved over them.

In T1, $B_N$ shows a sharp fall, or a sharp $|B_N|$ pileup, at ~22:34:42 UT, suggesting a tailward-moving reconnection front (e.g., Angelopoulos et al. 2013). Similar structure is also termed a “dipolarization front” in the case of the Earth for earthward-oriented jets and interpreted as signatures of transient or burst reconnection (e.g., Runov et al. 2009; Fu et al. 2013a). Associated with the reconnection front, an intensive burst of energetic electrons (Figure 2(h)) and a local $B_M$ dip (Figure 2(f)) were also observed. The local $B_M$ dip under the background Hall field suggests a strongly distorted quadrupolar structure, which was likely induced by current carried at the reconnection front by field-aligned energetic electrons in the ion diffusion region. Notably, a narrow $B_N$ spike, with a local $|B|$ dip and bipolar-like perturbations in $B_L$, was observed at ~22:34:42.6 UT, possibly a small-scale current filament formed due to a local instability. Similar fine-scaled structures were also observed at ~22:34:53.2 UT during T2 and ~22:34:56.8 UT during T3.

![Figure 1](image_url) Crossing of a magnetic reconnection region in the near-Mercury magnetotail by MESSENGER. The meridional (a) and equatorial (b) plane of the Mercury’s magnetosphere showing magnetic reconnection of the tail magnetic field lines (green curves). The blue lines show the trajectory of MESSENGER spacecraft through the current sheet crossing near the position of $(-2.0, -0.5, -0.1) R_M$ in aberrated Mercury Solar-Magnetospheric (MSM) coordinates. The MSM system is centered on Mercury’s offset internal dipole with the X-axis oriented sunward along the Sun–Mercury line, the Z-axis parallel to the planetary spin axis and positive in the northward direction, and the $Y$-axis completes the right-handed system. An aberration of 6.8° due to Mercury’s instantaneous orbital speed through the radial solar wind speed of 400 km s$^{-1}$ is assumed. The displacement of the planetary center relative to the $X$–$Z$ plane is because of the northward offset of the magnetic dipole by $\sim 0.2 R_M$ (Anderson et al. 2011). The dimensions of the magnetosphere in the two planes contain differences due to asymmetries in Mercury’s magnetopause geometry (Zhong et al. 2015a). The red arrows are the projections of the current sheet coordinate system (LMN) axes.
In T2, the spacecraft was located very close to the neutral sheet center and detected a magnetic flux rope at \(\sim 22:34:52\) UT. The positive-to-negative polarity of the \(B_N\) signature indicates that the flux rope was moving tailward away from the reconnection site. The formation of such magnetic flux ropes is a relatively common feature of diffusion regions in Earth’s magnetosphere (e.g., Wang et al. 2016).

In T3, there were two sequential tailward-moving reconnection fronts observed, at \(\sim 22:34:55\) UT and \(\sim 22:34:57\) UT. The two reconnection fronts are characterized by sudden decreases of \(B_N\) from background value about \(-7\) nT to \(-23\) nT and \(-18\) nT, respectively, in less than 1 s. These reconnection fronts formed inside of the ion diffusion region and represent a consequence of enhanced external driving during unsteady reconnection (Sitnov & Swisdak 2011; Fu et al. 2013a).

In T4, there were two sequential positive-to-negative bipolar signatures in \(B_N\) with each reversal coincident having a peak in \(|B|\), which was a feature of tailward-moving secondary flux ropes generated by secondary reconnection (Eastwood et al. 2016). During the first secondary flux-rope crossing, the positive-to-negative perturbation of \(B_M\) under the background Hall field (Figure 2(f)) was possibly a nested structure of...
Figure 3. Schematic of the rapidly evolving reconnection process in Mercury’s magnetotail. The evolution of magnetic structures in the ion diffusion region corresponds to the subintervals T1–T5 in Figure 2: a reconnection front (T1), the formation of a magnetic flux rope (T2), the formation of two sequential reconnection fronts (T3), the formation of two sequential flux ropes generated by secondary X-lines (T4), and highly time-varying reconnection (T5). The gray inflow arrows denote the period of enhanced external driving. The star in each panel shows the approximate location of the spacecraft relative to the current sheet. The blue dashed arrow shows the trajectory of the tailward-moving magnetic structure relative to the spacecraft consistent with the observations.
quadropoles of opposite polarities adjacent to the secondary reconnection site (Jain & Sharma 2015a, 2015b). The formation of new secondary X-lines (at beginning of T4) behind the reconnection front (T3) has been found in numerical simulations of strongly driven reconnection (Sitnov & Swisdak 2011). The increase of $B_t$ and $|\mathbf{B}|$ during T4, which even exceeded the lobe region values (Figures 2(d) and (e)), is consistent with an enhancement of the external driving (Slavin et al. 2010).

In T5, MESSENGER moved away from the neutral sheet center. The perturbations of $B_N$ and $B_t$ indicate that the reconnection process was highly unsteady.

The energetic electron bursts (Figure 2(h)) were also observed in the diffusion region. The peaks in the energetic electron count rate correspond to the first reconnection front and the related magnetic flux rope, suggesting electron acceleration by unsteady reconnection (Fu et al. 2013b). The lower flux of energetic electrons after T2 is probably due to reconnection of the lobe field that has a very low plasma density or is far away from the current sheet center. The energetic electrons enhanced at the end of T5 is probably due to the reconnection separatrix crossing when the spacecraft moved away from the diffusion region. The energetic electron bursts were observed previously in Mercury’s magnetosphere (e.g., Ho et al. 2011; Lawrence et al. 2015; Baker et al. 2016; Dewey et al. 2017). Nevertheless, how to accelerate electrons to such a high energy level within such a small magnetosphere remains a question. Observations of energetic electron bursts inside of the diffusion region presented above suggest that energetic electron acceleration at Mercury is directly linked to a local active reconnection process.

3. Discussion

The observations of repeated reconnection front structures, secondary flux-rope formation, and energetic particle bursts have provided evidence of the enhanced and impulsive nature of strongly driven reconnection. The durations of reconnection structures are very brief as observed by MESSENGER due to the short ion inertial lengths and high Alfvén speeds in Mercury’s magnetotail. For example, the reconnection front inside of the diffusion region were only on a timescale of ~1–3 s, while timescales of similar structures within ion diffusion regions observed at Earth were ~1 minute (Fu et al. 2013a). The reasons for the episodic nature of reconnection at Mercury on temporal scales of only 1–10 s are not known, but may provide insights into the durations of similar phenomena at the other planets.

Previous observations during MESSENGER’s third flyby had suggested a rapid magnetic flux transfer between the dayside magnetosphere and the tail on a ~2–3 minutes Dungey timescale (Slavin et al. 2010). In general, the normalized reconnection rate can be estimated by $R = B_N/B_{l0}$, where $B_{l0} \approx 40 \text{nT}$ is the lobe field strength in the inflow region (averaged from 22:35:20 to 22:36:20 UT). Taking the brief quasi-steady period T2, we find the average reconnection rate $R = 0.20 \pm 0.09$, demonstrating a very fast reconnection process. The magnetic flux transport rate can be estimated as $R \nu_B B_{l0} \approx 0.05 \text{MWb/s}/R_M$, where $\nu_B \approx 2500 \text{km s}^{-1}$ is the Alfvén velocity with the derived ion density $\sim 0.12 \text{cm}^{-3}$ in the inflow lobe region during 22:35:22–22:39:58 UT, assuming a thermalized Maxwell–Boltzmann ion distribution (Raines et al. 2011; Gershman et al. 2013). Giving the lower limit of the duration of reconnection (~35 s) and assuming the X-line length $\sim 1 R_M$, the magnetic flux transferred during this event was about 1.75 MWb, which corresponds to about 70% of the typical amount of the magnetic flux in the tail lobes (Imber & Slavin 2017). Such rapid recycling of the open flux implies that intense dayside reconnection (Slavin et al. 2009; DiBraccio et al. 2013) continuously feeds the magnetic flux into the tail and involves the control of the tail reconnection process globally. Future global simulations of reconnection in Mercury’s magnetosphere during intervals of strong solar wind forcing will further enhance our understanding of such intense reconnection-driven space weather events at Earth such as “sawtooth” substorms and major geomagnetic storms.

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