**MESSENGER** Observations of Giant Plasmoids in Mercury’s Magnetotail

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**Abstract**

Small-scale flux ropes, with estimated diameters of \(~500\) km and that pass over the **MESSENGER** spacecraft on timescales of seconds or less, are a common feature in Mercury’s magnetosphere. These magnetic structures, sometimes referred to as plasmoids, are believed to form as a result of rapid transient reconnection in the cross-tail current sheet at Mercury and the other planets. Here we report the occurrence of unusually large plasmoids in Mercury’s magnetotail observed, by the **MESSENGER** spacecraft. These plasmoids are remarkable for several reasons. Their spatial scales in the north–south direction exceed Mercury’s radius of 2440 km, and their time durations are comparable to or longer than the average Dungey cycle time of \(~200\) s. They also have a more loop-like magnetic structure than the more common helical-like flux rope topology. These new **MESSENGER** observations suggest that Mercury’s magnetosphere can dissipate large quantities of magnetic flux and energy not only through the formation of a large number of small flux ropes, but also occasionally by the formation and release of a single giant plasmoid.

**Unified Astronomy Thesaurus concepts:** Magnetic fields (994); Solar magnetic reconnection (1504); Plasma physics (2089); Space plasmas (1544); Planetary magnetosphere (997); Mercury (planet) (1024)

**1. Introduction**

Magnetic flux ropes are a common feature of magnetic reconnection in planetary magnetotails. They are important for two key reasons. First, they transport magnetic flux and plasma from the central plasma sheet both sunward toward the planet, to eventually replenish the dayside magnetosphere, and antisunward, to eventually merge with the solar wind. Second, they have been shown to accelerate and heat charged particles to high energies as they coalesce with other flux ropes and as they contract while relaxing toward lower-energy configurations. In two-dimensional models or simulations, flux ropes correspond to magnetic islands produced by multiple X-line reconnections (e.g., Lee & Fu 1985; Slavin et al. 2003; Zong et al. 2004; Eastwood et al. 2005) or small–scale secondary islands formed by microinstabilities within elongated electron current sheets near the primary reconnection site (e.g., Drake et al. 2006; Daughton et al. 2011). In the Earth’s magnetotail, plasmoids can be considered as a particular type of large-scale island that form between a near-Earth X-line and the last closed plasma sheet field line, whose farthest downtail point is notionally referred to as the distant X-line (e.g., Hones 1977; Slavin et al. 1985; Baker et al. 1996). The plasmoids, can be tens of Earth radii in diameter, and their formation and ejection are closely related to substorm activity (e.g., Slavin et al. 1989; Zong et al. 1997, 1998).

Mercury’s relatively weak intrinsic magnetic field (e.g., Anderson et al. 2011), combined with the strong solar wind forcing in the inner heliosphere, creates a miniature and highly dynamic planetary magnetosphere, with a size that is only \(~5\%\) of that of the Earth (e.g., Winslow et al. 2013; Zhong et al. 2015a, 2015b). The basic structure of Mercury’s magnetosphere is similar to that of the Earth, but the timescale of the large-scale magnetospheric convection cycle (Dungey cycle) was estimated to be much shorter, on average \(~3\) minutes (e.g., Slavin et al. 2010; Imber & Slavin 2017), comparing with \(~1\) hour at Earth (e.g., Baker et al. 1996). Previous **MESSENGER** observations have suggested that Mercury’s magnetosphere is populated with ion-scale flux rope structures only on timescales of seconds (e.g., Slavin et al. 2009; DiBraccio et al. 2015; Sun et al. 2016; Smith et al. 2017). Typical flux ropes in the plasma sheet had durations in **MESSENGER**’s frame of reference of about \(~\)1 s and, based on the assumption of sunward or tailward propagation speeds comparable to the local Alfvén speed \((\sim500\ \text{km}\ \text{s}^{-1})\), their mean diameters were only \(~300\) to \(~500\) km (DiBraccio et al. 2015; Smith et al. 2017). Zhong et al. (2018) reported the first observations of a rapidly evolving magnetic reconnection process in Mercury’s magnetotail that lasted for a period of \(~35\) s, during which small–scale flux ropes and reconnection fronts were produced repeatedly. These findings indicate that the release of mass and energy in Mercury’s magnetotail is rapid and intermittent.

Here we report the observation of two giant plasmoids with their durations comparable to the Dungey cycle time in Mercury’s magnetotail. We propose that these giant plasmoids form through reconnection at two widely separated sites in the cross-tail current sheet, in a manner analogous to the near-Earth neutral–line model of substorms (Hones 1977; Baker et al. 1996). The near-planet plasma sheet reconnection site is inferred to be very close to Mercury. Its reconnection rates are expected to be smaller than or comparable with the distant reconnection site because of the presence of heavy planetary ions in the near-planet plasma sheet, which sometimes allows the formation and ejection of these unusually large plasmoids.
2. **MESSENGER** Observations

Figures 1 and 2 show an overview of two large-scale plasmoids observed by **MESSENGER** during crossings of Mercury’s magnetotail in its orbits 506 and 3633, respectively. 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. FIPS had a large instantaneous field of view (FOV) of 1.4 $\pi$ sr, although $\sim$0.25 $\pi$ sr was blocked by the spacecraft and its sunshade. It can detect both solar wind ions (e.g., H$^+$, He$^{2+}$) and planetary heavy ions (e.g., Na$^+$-group and O$^+$-group ions). The data are presented in the aberrated Mercury solar magnetospheric (MSM) coordinate system, which is centered on Mercury’s internal dipole (offset to 0.2 $R_M$ north of to the planet’s center) 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 set (Anderson et al. 2011). The $x$- and $y$-axes have been rotated to account for the orbital motion of Mercury with respect to an average radial solar wind velocity of 400 km s$^{-1}$, producing the resultant $x$-axis approximately in the opposite direction of the solar wind flow in Mercury’s frame.

During **MESSENGER** orbit 506, the spacecraft crossed the plasma sheet south to north (21:18:12–21:32:09 UT), indicated by a change in $B_X$ from negative to positive. The plasma sheet was identified by the presence of hot plasma with high flux detected by FIPS, and the lobe region was identified primarily from the lack of ion flux. A large plasmoid was encountered while the spacecraft was traversing the northern lobe of the magnetotail, $\sim$2.2 to 1.9 $R_M$ downstream of Mercury. The plasmoid was identified by a large amplitude bipolar signature in the north–south component of the magnetic field ($B_Z$) from...
21:34:24 UT to 21:40:49 UT, lasting for ~6 minutes. The positive-to-negative polarity of the $B_Z$ signature suggests that the plasmoid structure was moving tailward. The plasmoid structure consists of an outer and an inner region, characterized by distinct boundaries encountered at 21:36:35 UT and 21:38:58 UT. The inner region was filled with hot and dense plasma sheet-like ions, including both solar wind H$^+$ and planetary heavy Na$^+$-group ions. The lack of a significant core field ($B_Y$ component) and the decrease of magnetic field strength ($|B|$) suggest a plasmoid with magnetic quasi-loop-like topologies rather than a helical flux rope structure (e.g., Slavin et al. 1989). In the outer region, the lack of ions and the presence of large negative $B_Y$ indicate that the lobe magnetic fields surrounding the closed loops were strongly distorted.

During MESSENGER orbit 3633, the spacecraft crossed the current sheet (07:31:30–07:43:40 UT) from the northern to the southern hemisphere. A plasmoid was detected while the spacecraft was traversing the southern lobe region of the magnetotail, ~2.3 to 2.5 $R_M$ downstream of Mercury. The duration of this plasmoid is also ~6 minutes, indicated by the large bipolar $B_Z$ signature from 07:44:25 UT to 07:50:20 UT.

The positive-to-negative polarity of the $B_Z$ component suggests that the plasmoid structure was also moving tailward. The magnetic and plasma properties of this plasmoid are very similar to the plasmoid observed in the northern hemisphere during orbit 506, including (1) clear boundaries of outer and inner regions (07:45:35 UT and 07:47:50 UT), (2) sheet-like plasma properties in the inner region, (3) decrease of magnetic field strength and a lack of significant core field, and (4) large $B_Y$ surrounding the inner region. All these features indicate a plasmoid composed of quasi-loop-like magnetic field and surrounded by distorted magnetic field structures. The distorted magnetic field was in an opposite direction to that of the former case, probably due to the observations in a different hemisphere.

3. Discussion

We have presented observations of giant plasmoids composed of quasi-loop-like magnetic fields in Mercury’s magnetotail. In contrast to the commonly detected ion-scale flux ropes, on a timescale of seconds, the durations of these two
plasmoids are comparable to a typical Dungey cycle time at Mercury, $\sim$3 minutes. Combining observations from the northern and southern hemispheres, we infer that the spatial scales of plasmoids in the north–south direction could exceed 1 $R_M$. We propose that these giant plasmoids were formed and trapped through large-scale reconnection at two well-separated sites, as shown in Figure 3. Analogous to the near-Earth neutral-line model of substorms (Hones 1977; Baker et al. 1996), plasmoids form when magnetic reconnection is initiated in a near-planet plasma sheet, where the disconnection of closed field lines is supplemented by the creation of new closed field lines at the distant X-line. The location of the near-Mercury neutral line can be inferred to be less than 1.7 $R_M$ and 2.3 $R_M$ downstream in orbits 506 and 3633, respectively. These locations are much closer to the planet than the previously estimated statistical location of $\sim 3$ $R_M$ (Poh et al. 2017). The long durations of these plasmoids suggest that the reconnection process can be continuous over a prolonged period of time in Mercury’s magnetotail. However, the temporal behavior of the near-planet reconnection may be unsteady, indicated by the presence of magnetic substructures. This is likely due to the formation of secondary reconnection X-lines, with lifetimes of seconds, embedded in the large plasmoids, as denoted in Figures 1(d) and 2(d).

The tailward ejection of these large plasmoids is expected when the reconnection rate at the X-line closest to Mercury exceeds that at the distant X-line. At this point, the giant plasmoid is surrounded by disconnected lobe magnetic field lines whose tailward $J \times B$ stress accelerates the structure down the tail. At Earth, the rate of reconnection of open lobe magnetic fields at the near-Earth site increases in a nonlinear, explosive manner due to high Alfvén speeds in the low plasma density lobe regions (e.g., Hesse et al. 1996). Quasi-stagnant plasmoids have occasionally been observed in the distant tail of the Earth during intervals of low geomagnetic activity (Nishida et al. 1986). At Mercury, the presence of high density plasma, rich in heavy ions (e.g., Na$^+$; Gershman et al. 2014), may reduce the near-planet Alfvén speed and reconnection rate until it transitions to reconnecting open lobe field lines. So long as the near-planet reconnection rate is smaller than or comparable to the distant reconnection site, the sunward $J \times B$ force of the open lobe magnetic fields being closed at the distant X-line is expected to keep the large plasmoid from being ejected.

The long-lived plasmoids reported here appear to be rare events in the MESSENGER data set. The likely reason is that MESSENGER crossed the central plasma sheet in a region planetward of the predicted average location of the near-Mercury X-line (Poh et al. 2017). Under these conditions, stagnant giant plasmoids are expected to form tailward of the region that is usually sampled by MESSENGER. The upcoming joint ESA-JAXA Bepi-Colombo mission will have two spacecraft orbiting Mercury, with aporphems of $\sim 2$ and $\sim 5$ $R_M$. In this manner the Bepi-Colombo spacecraft will enhance our understanding of how magnetic reconnection at multi-sites drives the global dynamics of Mercury’s magnetotail.

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**Figure 3.** Schematic of a giant plasmoid formed and trapped between two widely separated reconnection sites in Mercury’s magnetotail.