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MESSENGER observations of flux ropes in Mercury's magnetotail

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ABSTRACT

We report an investigation of magnetic reconnection in Mercury's magnetotail conducted with MESSENGER Magnetometer and Fast Imaging Plasma Spectrometer measurements during seven "hot seasons" when the periapsis of the spacecraft orbit is on Mercury's dayside. Flux ropes are formed in the cross-tail current sheet by reconnection. We have analyzed 49 flux ropes observed between 1.7 R_M and 2.8 R_M (where R_M is Mercury's radius, or 2440 km) down the tail from the center of the planet, for which minimum variance analysis indicates that the spacecraft passed near the central axis of the structure. An average Alfvén speed of 465 km s^{-1} is measured in the plasma sheet surrounding these flux ropes. Under the assumption that the flux ropes moved at the local Alfvén speed, the mean duration of 0.74 ± 0.15 s determined for these structures implies a typical diameter of ~345 km, or ~0.14 R_M, which is comparable to a proton gyroradius in the plasma sheet of ~380 km. We successfully fit the magnetic signatures of 16 flux ropes to a force-free model. The mean radius and core field determined in this manner were ~450 km, or ~0.18 R_M, and ~40 nT, respectively. A superposed epoch analysis of the magnetic field during these events shows variations similar to those observed at Earth, including the presence of a post-plasmoid plasma sheet, filled with disconnected magnetic flux, but the timescales are 40 times shorter at Mercury. The results of this flux rope survey indicate that intense magnetic reconnection occurs frequently in the cross-tail current layer of this small but extremely dynamic magnetosphere.

1. Introduction

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft has provided continuous observations of Mercury's dynamic magnetosphere and local space environment since its insertion into orbit about the innermost planet on 18 March 2011. Prior to then, the only in situ measurements at Mercury were supplied by three flybys by the Mariner 10 spacecraft (Ness et al., 1974, 1975) and three flybys by MESSENGER (Anderson et al., 2008, 2010; Slavin et al., 2008, 2009, 2010; Zurbuchen et al., 2008; Raines et al., 2011). Mariner 10 measurements demonstrated that Mercury possesses a weak intrinsic magnetic field, a result later confirmed by MESSENGER observations indicating that the magnetic dipole moment is 195 ± 10 nT-R_M^3 (where R_M is Mercury's radius, or 2440 km) (Anderson et al., 2011). After MESSENGER's first Mercury year in orbit (1 Mercury year = 88 Earth days), Anderson et al. (2011) reported a northward offset of the nearly axially aligned dipole moment from the planet's center by ~20% of the planet's radius, or 484 ± 11 km. Mercury's magnetosphere, formed by the interaction between the solar wind and the intrinsic planetary magnetic field, is affected by Mercury's proximity to the Sun and the small moment of the internal field. This small magnetosphere nonetheless experiences many of the same processes as those at Earth.

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One of these processes is magnetic reconnection, a ubiquitous phenomenon in space plasmas responsible for the explosive transfer of electromagnetic energy from magnetic fields to charged particles in the plasma. During reconnection, sheared magnetic fields are able to merge at sites called X-lines, where ions and electrons become demagnetized to form diffusion regions (e.g., Shay et al., 1998; Hesse, 2006). In this manner, magnetic reconnection is responsible for many of the dynamic effects observed in Mercury's magnetosphere.

These reconnection-driven dynamics are responsible for the circulation of mass, momentum, and energy within Mercury's magnetosphere, through a process known as the Dungey cycle (Dungey, 1961). At Mercury, typical Dungey cycle times are ~2 min, which is approximately 30 times shorter than the ~1 h Dungey cycle time at Earth (Siscoe et al., 1975; Slavin et al., 2009, 2012a). The cycle begins with magnetic reconnection at Mercury's dayside magnetopause, which has been documented on the basis of magnetic field components normal to the boundary (DiBraccio et al., 2013) and helical structures known as flux transfer events (Slavin et al., 2012b; Imber et al., 2014). The Dungey cycle continues in the magnetotail, where dipolarization events are observed in the near tail as the currents weaken and the magnetic field relaxes (Sundberg et al., 2012). Tail reconnection has been observed in the form of extreme loading and unloading events, traveling compression regions (TCRs), and plasmoids (Slavin et al., 2009, 2010, 2012a). However, little is known about the characteristics of plasmoids at Mercury or their contribution to the Dungey cycle.

Plasmoids are known to have two different magnetic structures: magnetic loops and flux ropes. Flux ropes form as a result of magnetic reconnection occurring at multiple X-lines in the plasma sheet, where the oppositely directed fields in the north and south lobes meet at the cross-tail current sheet (Fig. 1a and b) (Hesse and Kivelson, 1998). The two tail lobes are sheared with respect to one another, as a result of stresses imposed at the magnetopause by dayside reconnection. This shear causes a component of the magnetic field in the east–west direction to be generated in the current sheet (Cowley, 1981) and, as a consequence, flux ropes possess a helical topology with a strong axial core field (Hughes and Sibeck, 1987). This structure is different from that of conventional magnetic loops, formed by closed planetary field lines that are pinched off via reconnection at a single X-line. Once created, the plasma-sheet flux ropes are ejected from the dominant reconnection X-line, the site with the highest outflow speed, either toward or away from the planet. As they move through the magnetotail, the fields in the lobes drape around the flux rope structure and become locally compressed. These compressions, or TCRs, can be used to remotely sense a passing flux rope if it is not directly encountered (Slavin et al., 1992, 1993). Both flux ropes and TCRs have been identified in a number of planetary magnetospheres from magnetic field measurements (e.g., Venus, Russell and Elphic, 1979; Saturn, Jackman et al., 2007, 2011, 2014; Jupiter, Vogt et al., 2010, 2014; Mars, Eastwood et al., 2012).

Hones (1977) was the first to document plasmoids from Interplanetary Monitoring Platform (IMP) 8 data acquired in Earth's magnetotail. Since the discovery of plasmoids, many studies have been performed to investigate their characteristics at Earth (Hones et al., 1984; Slavin et al., 1989, 1995; Moldwin and Hughes, 1992; Ieda et al., 1998; Nagai et al., 2000). For example, Ieda et al. (1998) surveyed Geotail particle and magnetic field data to select 824 tailward-traveling flux ropes at locations ranging from 16 R_E to 210 R_E down the tail from the center of the planet (where R_E is Earth's radius). The average duration of these events was 1.2–1.8 min. From Geotail measurements in the near-tail plasma sheet (14 R_E to 30 R_E away from the planet), Slavin et al. (2003a) identified 73 quasi-force-free flux rope events by selecting

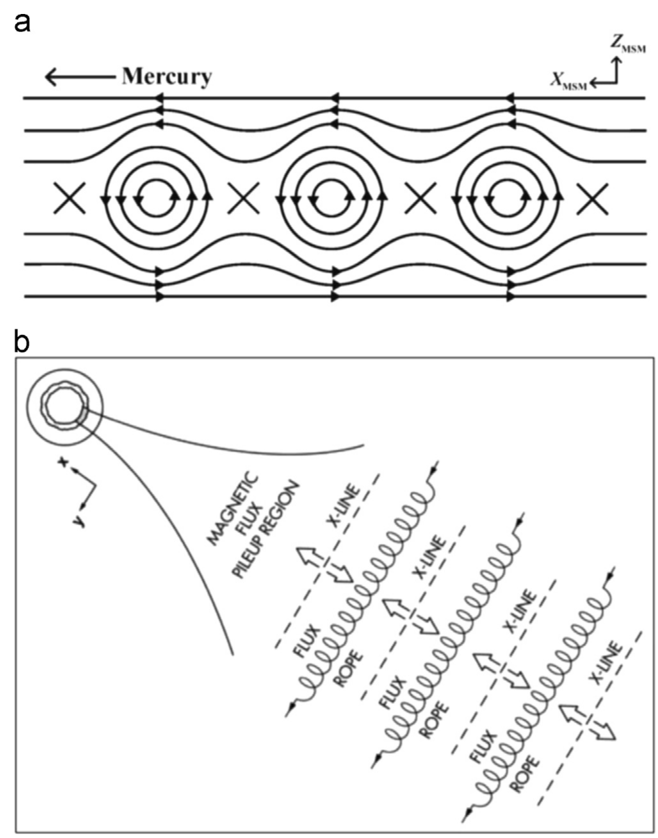

Fig. 1. Schematic views of flux ropes formed as a result of reconnection at multiple X-lines within the plasma sheet. (a) A side view of field lines in the *X*–*Z* plane. Mercury is located to the left, and the arrows indicate the opposing directions of the magnetic field within the north and south tail lobes. X-lines are marked by the × symbol. (b) Top-down view in the *X*–*Y* plane, adapted from Slavin et al. (2003a), illustrating the helical structure of flux ropes in the magnetotail.

events only when the internal magnetic field variations could be well fit by the Lepping et al. (1990) force-free model, which allowed the dimensions and core magnetic field intensity to be determined (see Section 4 in this paper and Lepping et al., 1990, 1995, 1996). A superposed epoch analysis revealed that the average duration of these events was ~28 s for 35 planetward-traveling flux ropes and ~32 s for 38 tailward-moving flux ropes (Slavin et al., 2003a). These results confirmed the Ieda et al. (1998) findings that flux ropes are small in size, a few R_E in diameter, and generated close to Earth. However, for the first time, Slavin et al. (2003a) observed near-equal numbers of planetward- and tailward-traveling flux ropes, a result that strongly argued for a formation mechanism involving simultaneous reconnection at multiple X-lines. These conclusions were later supported by flux rope and TCR investigations that made use of Cluster measurements (Slavin et al., 2003b, 2005; Eastwood et al., 2005). More recently, Imber et al. (2011) completed a statistical survey of 135 flux ropes and TCRs in the near-Earth tail using data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission. These results demonstrated a large dawn–dusk asymmetry, and many events were separated by only tens of seconds, indicating that reconnection was occurring simultaneously at multiple X-lines.

Only seven plasmoid events were encountered in Mercury's magnetotail during the MESSENGER flybys (Slavin et al., 2009, 2012a). These plasmoids appeared to have magnetic loop-like topologies with time durations of ~1–3 s, implying diameters of ~(0.2–0.6) R_M. In the post-plasmoid plasma sheet, the events had durations of ~4–5 s. Slavin et al. (2012a) suggested that a more