Mariner 10 observations of field-aligned currents at Mercury

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Abstract. The Mariner 10 observations firmly established the presence of a modest intrinsic magnetic field ($M \sim 300 \, nT \, R_M$) at Mercury and a magnetosphere with much the same structure as that found at the Earth. Due to the limited duration of the two passes through this small magnetosphere, about 1 h in total, the opportunities to learn about its dynamics were very limited. However, clear evidence of substorm activity was obtained in the form of intense energetic particle injections similar to those observed in the near-tail region at Earth. In this study the Mariner 10 magnetic field measurements taken during the two nightside flybys are re-examined for evidence of field-aligned currents (FACs). Given the very tenuous nature of the Hermean atmosphere and the high resistivity anticipated for its regolith, the FACs coupling the magnetosphere to the weak ionosphere and/or planetary surface might be expected to be low in intensity and short-lived. Surprisingly, compelling evidence is found for intense FACs following a substorm-type energetic particle injection observed during the first fly-by in 1974. The interplanetary magnetic field orientation observed several minutes later when Mariner 10 exited into the magnetosheath was southward and, thus, favorable for dayside reconnection which could power substorm processes. The implications of these FAC observations for the height integrated electrical conductivity at low altitudes, for the electrodynamics of this magnetosphere, and for the planning of a future Mercury mission are discussed. © 1997 Published by Elsevier Science Ltd. All rights reserved.

Introduction

One of the major discoveries made by NASA’s early planetary missions was the existence of a modest intrinsic magnetic field at Mercury with a dipole moment of about $300 \, nT \, R_M$ (see review by Connerney and Ness (1988)). This magnetic field is sufficient to stand-off the average solar wind at an altitude of about $1 \, R_M$ as depicted in Fig. 1 (see review by Russell et al. (1988)). For the purposes of comparison the diameter of the Earth is indicated at the bottom of the figure (i.e. $1 \, R_E = 6380 \, km$; $1 \, R_M = 2439 \, km$). Whether or not the solar wind is ever able to compress and/or erode the dayside magnetosphere to the point where solar wind ions could directly impact the surface remains a topic of considerable controversy (Siscoe and Christopher, 1975; Slavin and Holzer, 1979; Hood and Schubert, 1979; Suess and Goldstein, 1979; Goldstein et al., 1981).

Overall, the basic morphology of this small magnetosphere appears quite similar to that of the Earth. The magnetic field investigation observed clear bow shock and magnetopause boundaries along with the lobes of the tail and the cross-tail current layer (Ness et al., 1974, 1975, 1976). The colatitude of the polar cap was estimated on the basis of these measurements to be about $25^\circ$ as compared with a typical value of $16^\circ$ at Earth. The plasma investigation was hampered by a deployment failure which kept the ion portion of the instrument from making any useful measurements. However, the electron portion of the instrument recorded the bow shock, the low density, cool plasma in the high latitude magnetosphere and the hotter electrons in the plasma sheet (Ogilvie et al., 1974, 1977). As expected from the large fraction of the magnetosphere occupied by the planet, the cosmic ray experiment did not detect any trapped radiation belts at Mercury (Simpson et al., 1974). However, intense energetic particle events were observed in the tail during the first Mariner 10 encounter and, as will be discussed later, they have provided strong evidence for terrestrial-type substorm activity at this planet (Simpson et al., 1974; Siscoe et al., 1975).

In considering Fig. 1, and the analysis to follow, it is useful to note that a scaling in which $1 \, R_M$ at Mercury corresponds to $\sim 6 \, R_E$ at Earth produces good correspondence between the boundaries and magnetospheric...
regions at these two planets (Ogilvie et al., 1977). Hence, the $2R_M$ distance from the center of Mercury to the subsolar magnetopause maps to about $12R_E$ at the Earth which is, indeed, close to the average magnetopause nose distance. Similarly, the surface of Mercury would correspond roughly to geosynchronous distance within the Earth's magnetosphere and rule out the possibility of a plasmasphere or trapped radiation belts even if the planet possessed the sources and the rotation rate to create such a region (N.B. Mercury's rotational and orbital periods are 59 and 88 days, respectively). Finally, the observed near-tail diameter of 4–5$R_M$ scales to about 24–30$R_E$ which is close to the typical near-tail diameter at Earth.

In the sections to follow a concise review of the Mariner 10 observations will be presented as they apply to our primary purpose: the search for FACs electrodynamically linking Mercury's magnetosphere to its weak ionosphere or regolith. After presenting Mariner 10 magnetometer measurements which strongly suggest such FACs do sometimes exist in the near-tail tail of Mercury, we will discuss their implications for Mercury's plasma environment and for the dynamics of its magnetosphere.

**Mariner 10 encounters**

Following its launch on November 2, 1973 the Mariner 10 spacecraft had three close encounters with the planet Mercury on March 29, 1974, September 21, 1974, and March 16, 1975. All three fly-bys occurred at a heliocentric distance of 0.46 AU. This compares with perihelion and aphelion distances for Mercury of 0.31 and 0.47 AU, respectively. The spacecraft trajectories during the first and third encounters, which took it through Mercury's small magnetosphere, are displayed in Fig. 2 in Mercury centered solar ecliptic coordinates (adapted from Ness et al. 1976). In these "MF" coordinates the $X_{ME}$ axis is directed toward the Sun and the $Y_{ME}$ axis is in the plane of the ecliptic, perpendicular to $X_{ME}$ and directed oppositely from the direction of planetary orbital motion. The $Z_{ME}$ axis completes the right-handed orthogonal system and is positive toward the "north". The first encounter was planned to pass through the wake of the planet and survey its interaction with the solar wind. The closest approach to the surface of the planet during this passage was near 700 km and a peak magnetic field intensity of about 100 nT was observed (Ness et al., 1974). The second encounter was targeted well upstream of the planet to return images in full sunlight and did not intersect the magnetosphere. The third encounter was intended to achieve higher latitudes and lower altitudes in order to confirm the intrinsic nature of the magnetic field. This effort was successful with a closest approach altitude of only 327 km and a peak magnetic field intensity of about 400 nT (Ness et al., 1976).

A radial projection of the two Mariner 10 trajectories through the nightside magnetosphere onto the surface of this planet are shown in Fig. 3 (adapted from Lepping et al. 1979). As discussed by Ness et al. (1974, 1975) and Ogilvie et al. (1974, 1977), the first encounter saw the spacecraft traverse the near-tail starting in the south lobe of the tail, crossing the plasma sheet, and eventually exiting through the north lobe of the near-tail (see also Christon 1987). The third encounter, in contrast, took the spacecraft through the northern high latitude magnetosphere where it observed quiet magnetic fields and the "horns" of a cooler, quiet-time plasma sheet (Ness et al., 1976; Ogilvie et al., 1977).

Our re-examination of the Mariner 10 observations during the third encounter confirmed the quiescent condition of Mercury's magnetosphere during this interval reported by the original investigators (see review by Russell et al. 1988). The interplanetary magnetic field was directed northward both before and after the encounter (Ness et al., 1976). Hence, conditions were unfavorable for dayside reconnection and the input of large amounts of energy into the magnetosphere. No major energetic particle events were detected (Eraker and Simpson, 1986) and the passage through the horns of the plasma sheet revealed relatively cool plasma electrons characteristic of the quiet-
time plasma sheet at the Earth (Ogilvie et al., 1977). Despite a spacecraft trajectory which passed across the polar cap and "auroral oval" regions where kilovolt electron precipitation produce auroras at the Earth (see Fig. 3), we found no evidence for FAC signatures. Since FACs and magnetospheric convection, in general, decrease greatly in intensity or even disappear during extended intervals of northward IMF (e.g. Hoffman et al., 1988), it is not possible to infer whether the lack of FACs during the third encounter is associated with the northward IMF or
some other factor peculiar to Mercury. Accordingly, the Mariner 10 observations collected during this third encounter will not be considered further in this study.

Substorm observations

Figure 4 displays 1.2 s averages of the magnetic fields observed during the first Mariner 10 encounter in Mercury centered solar ecliptic coordinates. Vertical dashed lines mark the inbound and outbound magnetopause crossings as well as the point of closest approach to the planet. The tail-like nature of the magnetic field during the inbound passage is very evident with $B_y > B_x, B_z$. During the outbound passage the magnetic field variations are extremely dynamic. These large amplitude variations in the total field intensity have a number of different sources. The large dip in field intensity just after closest approach coincided with the spacecraft becoming immersed in a hot plasma sheet (Ogilvie et al., 1977). Hence, it is most probably diamagnetic in nature (see Christon, 1989).

Less than a minute after Mariner 10 entered the plasma sheet, i.e. the strong dip in magnetic field intensity beginning around 20:47 UT, there is a sharp increase in the $B_x$ field component. As displayed in Fig. 5, the initial sudden $B_x$ increase and subsequent quasi-periodic increases are nearly coincident with strong enhancements in the flux of $>35$ keV electrons observed by the cosmic ray telescopes (Simpson et al., 1974; Eraker and Simpson, 1986; Christon, 1987). This energetic particle signature, and several weaker events observed later in the outbound pass, were interpreted as evidence for substorm activity by a number of studies (Siscoe et al., 1975; Baker et al., 1986; Eraker and Simpson, 1986). The Christon et al. (1987) analysis of both the magnetic field and energetic particle signatures for this interval clearly showed that this event is qualitatively identical to commonly observed substorm "injections" at altitudes between geosynchronous orbit and the inner edge of the plasma sheet at the Earth. Such energetic particle and magnetic field signatures have been alternatively referred to as "dipole collapse" or "dipolarization" events (Heppner et al., 1967), "injection fronts" (Moore et al., 1981), or "current sheet disruption" events (Sauvaud, 1992) depending upon the theoretical interpretations of the various researchers. Attempts to understand the underlying physical processes causing this phenomenon are still at the cutting edge of magnetospheric physics today. What is important for our present study of Mercury's magnetosphere is that clear and readily identifiable substorm signatures were present between 20:48 and 20:49 UT during the outbound Mariner 10 passage of the first encounter.

The very short duration of the substorm signature in Fig. 5, about 1 min, as compared typically with 1 h at the Earth was first addressed by Siscoe et al. (1975). Although much remains to be understood concerning substorm processes, it is clear that they correspond to intervals of greatly enhanced magnetospheric convection which involves the dissipation of large amounts of stored magnetic energy from the tail lobes through the acceleration of energetic particles, the driving of intense FACs linking the tail and ionosphere and the generation of strong bulk flows and heating in the central plasma sheet. Siscoe et al. argued that the timescale of isolated substorms at the Earth is
determined by the time necessary for plasma to convect across the polar cap or, equivalently, from the outer boundary of the tail down to the mid-plane where reconnection can take place. They estimated, using typical solar wind and magnetotail parameters, that the time necessary to "cycle" all of the flux in the tail lobes at the Earth is about 1 h which is indeed comparable to a time span of a typical substorm. Relative to conditions at 1 AU, the larger solar wind dynamic and static pressures and enhanced interplanetary \(-V \times B\) electric field associated with the intense ambient IMF at 0.46 AU result in a much more rapid magnetic flux cycle time than that found in the tail of the Earth. The value calculated by Siscoe et al. was approximately 1 min, in close agreement with the duration of the energetic particle event in Fig. 5.

Hill et al. (1976) took these concepts a step further by pointing out the limiting effect that the conductive ionosphere is thought to have on magnetospheric convection (e.g. Coroniti and Kennel, 1973). This effect, usually referred to as "line-tying", occurs because ions convecting in response to the electric field which the magnetosphere attempts to impose on the ionosphere experience a net drag force as a result of collisions with thermospheric neutral species. These collisions effectively "short-out" part of the magnetospheric electric field. The greater the ionospheric conductivity, the lower the total electric potential which the solar wind can maintain across the magnetosphere. The lower the electrical conductivity in the polar cap region, the closer the potential drop across the magnetosphere can approach to the maximum possible which is just the width of the magnetosphere times the solar wind \(-V \times B\) electric field. At Mercury Hill et al. assumed that any ionosphere would be unimportant and suggested that the low conductivity of the regolith (about 0.1 mho based upon lunar sample analysis) would make line-tying negligible and the full solar wind imposed cross-magnetosphere potential drop would then contribute to the short magnetotail flux cycle times suggested by Siscoe et al. (1975). Detailed discussions of what is known regarding Mercury's tenuous neutral atmosphere/ionosphere and its implications for the magnetosphere are given in Potter and Morgan (1985), Cheng et al. (1987), Ip (1987), Hunten et al. (1988), and Killen and Morgan (1993).

**Field-aligned current observations**

Two minutes after the energetic particle injection event, the \(B_y\) component of the magnetic field went through a very pronounced bipolar variation with a full amplitude of about 60 nT. As shown in Fig. 4, this bipolar variation
in the $B_y$ i.e. approximately the east–west component, around 20:51 UT was the largest perturbation in this field component recorded during either of the Mariner 10 passes through Mercury's magnetosphere. At this time the spacecraft location in ME coordinates was approximately $(-0.95 \, R_M, -1.56 \, R_M, 0.23 \, R_M)$. As can be seen in Fig. 3, this $B_y$ signature occurred at a distance from the center of the planet of about $1.84 \, R_M$ and a local time of approximately 03:50 (i.e. 58° from the midnight meridian).

In the expanded scale view of Fig. 6, it can be seen that this $B_y$ signature was accompanied by only small variations in the $B_x$ and $B_z$ components. The background field at the time of this bipolar event was mostly in the $X_{ME}$-$Z_{ME}$ plane. The average $B_z$ around this event was about twice the magnitude of $B_x$ as would be expected for a pass through the near-tail region of the terrestrial-type magnetosphere at a distance approaching geosynchronous orbit at the Earth.

The 20:50:55–20:51:18 UT magnetic field signature in Fig. 6 is well known to the magnetospheric community and can be readily interpreted as being due to the spacecraft traversing a central quasi-planar current sheet in which the current flow is nearly aligned with the ambient magnetic field (e.g. Iijima and Potemra, 1976). Given the Mariner 10 trajectory in Fig. 2, the main gradient in $B_y$ from negative to positive is indicative of an upward FAC at the spacecraft. This upward current sheet is largely balanced by two smaller downward current sheets before and after as indicated by arrows in Fig. 6. The occurrence of multiple current sheets is particularly common on the nightside of the auroral oval during substorms (Iijima and Potemra, 1978).

What do these currents correspond to in the Earth's magnetosphere? Since the strong central current sheet was directed upward at the spacecraft and therefore downward into the planet's auroral zone at a point well east of midnight, it could be associated with the Region 1 currents which flow into the poleward edge of the auroral zone in the dawn hemisphere at the Earth (Iijima and Potemra, 1976). Alternatively, dawnside current down into the auroral zone could also be associated with the east-most leg of the substorm current wedge (McPherron et al., 1973). This latter interpretation is of interest because of the substorm energetic particle injection observed a couple of minutes earlier. However, experience at the Earth has shown that, especially in the near-tail, it is often difficult to uniquely associate a single current sheet event with a specific current system (e.g. Elphic et al., 1987). All of these "field-aligned" currents couple the magnetosphere to the ionosphere, or in the case of Mercury, perhaps also to the regolith.

Minimum variance analysis performed upon this field perturbation yielded a well determined normal direction to the main current sheet, $(-0.625, -0.364, 0.691)$, which corresponds to a direction within 30° of the $Z_{ME}$ axis consistent with the current sheets being quasi-aligned with
constant L-shells. The tilt of the current sheet normal is consistent with the FAC being observed on distorted, closed field lines north of the cross-tail current layer.

Under the assumption that the observed magnetic field perturbation is caused by an infinite current sheet, the sheet current density corresponding to a total field perturbation of 60 nT in Fig. 6 is about 50 mA m\(^{-2}\). If this current sheet were indeed quasi-aligned with a constant L-shell, and given the Mariner 10 trajectory, the average current intensity in the central current sheet would be approximately 0.7 \(\mu\)A m\(^{-2}\). This calculation assumes that the current layer was stationary during the very oblique crossing by Mariner 10. A more likely scenario is that some dynamic event caused the current sheet to move and precipitate a rapid crossing at the observed time. Still, both the sheet current intensity and current density inferred in this manner from the Mariner 10 observations lie within the range of values observed at ionospheric to near-tail altitudes (e.g., Iijima and Potemra, 1976; Elphic et al., 1987).

Although the current in the auroral oval generally varies as a function of local time, solar wind, and substorm conditions, it is of interest to estimate what the total current flowing into the auroral oval might be on this occasion. To make the estimate, we simply assume that the sheet current intensity extends along a circular path about the \(Z_{ME}\) axis with a constant value. The total current into the Mercurian equivalent of the Earth’s auroral oval is then just \(J_{T} = 2\pi R_{E} J_{E}\), where \(R_{E}\) is the distance of Mariner 10 from the normal to the ecliptic plane at the center of the planet (i.e., the \(Z_{ME}\) axis). Inserting the sheet current intensity yields \(1.4 \times 10^{6}\) A. This value for the total current lies within the 1–3 \(\times 10^{6}\) A range typically reported for the total Region 1 or 2 currents at the Earth (Iijima and Potemra, 1976).

Discussion

In recent years much attention has been devoted to improving our understanding the electrodynamics of the Earth’s coupled solar wind–magnetosphere–ionosphere system. For example, experimental studies have shown that for a given cross-polar cap potential, the greater the ionospheric conductivity, the larger the FACs which are driven between the ionosphere and magnetosphere (Fujii et al., 1981; Robinson, 1984). In this case the solar wind is regarded, by analogy to circuit theory, as acting over large-scale lengths as a “voltage source”. Thus, if the ionosphere were negligible and the electrical conductance appropriate for currents closing in the regolith at Mercury were only 0.1 mho, as suggested by Hill et al. (1976), then the FACs within Mercury’s magnetosphere would be expected to be much weaker than at Earth where height integrated conductances of 1–10 mhos are typical (e.g., Kamide et al., 1986). Thus, even when the stronger IMF and enhanced solar wind electric field at 0.5 AU are considered, the FACs at Mercury should be weaker by a factor of 2–50 with the larger differences occurring during substorms when precipitation at the Earth greatly enhances ionospheric conductivity. Accordingly, FACs at Mercury would be expected to be generally weaker and to disappear more readily as the IMF turns northward and the driving voltage applied ultimately via reconnection at the dayside magnetopause subsides.

For these reasons, the Mariner 10 observation of what appears to be a strong FAC signature in the near-tail following a substorm energetic particle injection and just prior to the spacecraft’s exit into a southward IMF is extremely interesting. Once additional measurements become available from a Mercury orbiter mission, it may be found that the total FAC estimated from this single Mariner 10 event, \(1.4 \times 10^{6}\) A, is excessive due to the errors inherent in our analysis of this event. However, it may also be the case that once the low altitude neutral atmosphere of Mercury is more fully explored, that sufficient charge carriers may exist in the ionosphere to allow for significant current closure at very low altitudes. For example, Cheng et al. (1987) have calculated a Pederson electrical conductance appropriate to the currents driven by the photo-ionization and the pick-up of sodium ions by magnetospheric convection in Mercury’s magnetosphere which is 2–3 times greater than the 0.1 mho previously suggested for the regolith below. Only comprehensive, low altitude in situ particles and fields measurements will resolve this issue.

Future Mercury orbiter missions

Mercury is of particular importance to the magnetospheric physics community because it is at once so similar to Earth’s magnetosphere and yet so different in key aspects (e.g., ionospheric conductance or the ratios of magnetospheric scale lengths to characteristic ion and electron gyro radii). Hence, Mercury may be an exceptional fertile testing ground for theories regarding critical processes in the Earth’s magnetosphere. For example, the very tenuous nature of its atmosphere should make internal plasma sources far less significant than at Earth or any other of the known magnetospheres. This fact should make Mercury ideal for quantitative modeling of how and to what degree solar wind plasma enters a terrestrial-type magnetosphere. Mercury’s location in the inner heliosphere also exposes this magnetosphere to solar wind conditions which are relatively rare at 1 AU. In particular, it has been suggested that the lower Alfvénic Mach numbers and more intense IMF at 0.3–0.5 AU will result in reconnection rates at the dayside magnetopause which are a factor of 3 greater than at the Earth. Again, measurements at Mercury could be pivotal to the testing of existing models of the reconnection and lead to dramatic advances in our understanding of this important magnetospheric process. Finally, and perhaps most importantly, observations from a Mercury orbiter may lead to great advances in our understanding and modeling capability with respect to magnetospheric substorms. With substorm durations of only about 1 min, it should be possible to gather definitive substorm statistics and observe complete substorms at a variety of locations throughout the magnetosphere without the motion of the spacecraft aliasing the in situ measurements as commonly happens at Earth where substorms typically last 1–2 h. Furthermore, many theories of substorms at the Earth
differ as to the critical role of “feedback” between conditions at high altitudes and the electrical conductivity in the ionosphere at the foot of the magnetospheric flux tubes which becomes greatly enhanced due to precipitating energetic electrons. At this point it appears doubtful, but not impossible, that some similar feedback mechanism is operating at Mercury with its very weak atmosphere. Additional examples of scientific questions of great interest to the magnetospheric community which would directly benefit from measurements at Mercury are described in Mercury Orbiter: Report of the Science Working Team (1991).

Summary

In this study we have re-examined the Mariner 10 magnetic field observations for evidence of FACs. No FAC signatures were detected during the third encounter despite its low periapsis and high latitude trajectory across Mercury’s polar cap. However, this negative result could be attributed to the northward IMF observed both before and after the magnetospheric passage without recourse to any factors intrinsic to Mercury. The reason is that FACs are known to weaken and largely disappear at Earth during extended intervals of northward $B_z$ as magnetospheric convection decreases in intensity. In contrast, examination of the first Mariner 10 encounter showed a clear example of a FAC sheet in the near tail with two weaker adjacent current sheets of lesser intensity and opposite polarity. Despite the weakness of any ionosphere and the expected resistive nature of the underlying regolith, the total current estimated from this single substorm-related FAC event, $1.4 \times 10^6$ A, is comparable to typical values for the terrestrial magnetosphere. This surprising result may be due to the inherent uncertainties associated with estimating total current from a single point measurement or it may reflect higher than anticipated substorm electric fields in this small magnetosphere and/or the existence of unexpected charge carriers and transport mechanisms at very low altitudes. However, what is clear is that the FACs identified in this study add yet one more item to the extensive list of features common to both magnetospheres.

To achieve closure on these and other issues related to Mercury’s magnetosphere an orbiter mission which is adequately instrumented to conduct the necessary particles and fields investigations will be required. For example, to complement the vector magnetometer, a vector electric field instrument is highly recommended. This would allow measurement of the Poynting flux of electromagnetic energy carried downward by FACs and waves (e.g. Gary et al., 1994) as well as the index of refraction, i.e. $E/DB$ ratio, so that FACs and Alfvén waves can be separated (e.g. Ishii et al., 1992). Furthermore, it would be highly desirable to carry instruments capable of investigating this planet’s tenuous atmosphere and its interactions with the magnetosphere.

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