Mercury: Magnetosphere

Among the major discoveries made by the MARINER 10 mission to the inner planets was the existence of an intrinsic magnetic field at Mercury with a dipole moment of ~ 300 nT R_M^3. This magnetic field is sufficient to stand off the solar wind at an altitude of about 1 R_M (i.e. ~2439 km). Hence, Mercury possesses a 'magnetosphere' from which the solar wind plasma is largely excluded and within which the motion of charged particles is controlled by the planetary magnetic field. Despite its small size relative to the magnetospheres of the other planets (see PLANETARY MAGNETOSPHERES), a Mercury orbiter mission is a high priority for the space physics community. The primary reason for this great interest is that Mercury, unlike all the other planets visited thus far, lacks a significant atmosphere; only a vestigial exosphere is present (MERCURY). This results in a unique situation where the magnetosphere interacts directly with the outer layer of the planetary crust (i.e. the regolith). At all of the other planets the topmost regions of their atmospheres become ionized by solar radiation to form ionospheres. These planetary ionospheres then couple to electrodynamically to their magnetospheres or, in the case of the weakly magnetized Venus and Mars, directly to the solar wind. This magnetosphere–ionosphere coupling is mediated largely through field-aligned currents (FACs) flowing along the magnetic field lines linking the magnetosphere and the high-latitude ionosphere. Mercury is unique in that it is expected that FACs will be very short lived due to the low electrical conductivity of the regolith.

Furthermore, at the Earth it has been shown that the outflow of neutral atmospheric species to great altitudes is an important source of magnetospheric plasma (following ionization) whose composition may influence subsequent magnetotail dynamics. However, the dominant source of plasma for most of the terrestrial magnetosphere is the 'leakage' of solar wind across the magnetopause and more direct entry through the northern and southern cusps. Although Mariner 10 did not return plasma composition measurements, the Hermean magnetosphere should be ideal for measuring the manner and rate of solar wind plasma entry due to the lack of strong internal atmospheric sources. Finally, the solar wind conditions experienced by Mercury as it orbits the Sun at 0.31 to 0.47 AU are quite different from those typically encountered by the Earth. This may allow for new understanding of the external factors affecting the transfer of mass, momentum and energy from the solar wind to planetary magnetospheres. This article provides a brief overview of what is now known about Mercury's magnetosphere and why it is a priority target for future planetary missions.

Mariner 10 encounters

Following its launch on 2 November 1973, the Mariner 10 spacecraft executed three close encounters with the planet Mercury on 29 March 1974, 21 September 1974, and 16 March 1975. The first encounter was targeted
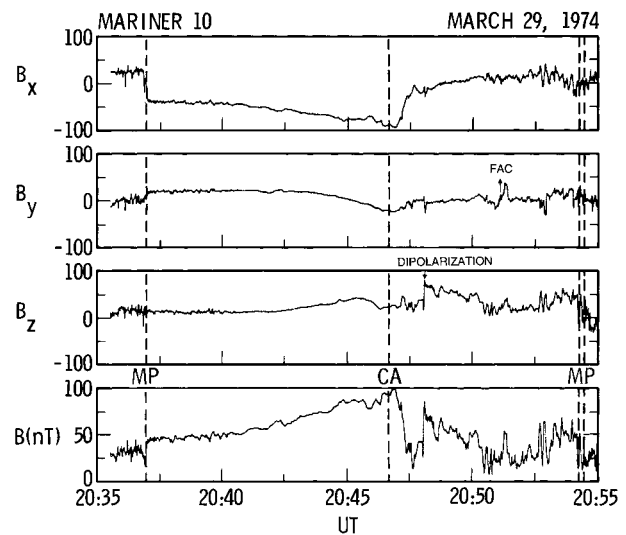

Figure 1. The Mariner 10 magnetic field observations (1.2 s averages) taken during the first encounter are displayed in Mercury centered solar ecliptic coordinates. In this system the X_{ME} axis is directed toward the Sun and the Y_{ME} axis is in the plane of the ecliptic, perpendicular to X_{ME} and 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. Magnetopause, dipolarization and field-aligned current signatures in the observations are labeled. (From Slavin *et al* (1997).)

to pass through the wake of the planet in order to determine its interaction with the solar wind. The closest approach to the surface of the planet occurred over the post-midnight equatorial region at an altitude of about 700 km. Figure 1 displays 1.2 s averages of the magnetic fields observed during the first Mariner 10 encounter in Mercury-centered solar ecliptic coordinates. The intensity of the magnetic field observed by Mariner 10 peaked near closest approach at just under 100 nT. This maximum is due to the increased contribution from the planetary magnetic field which varies as the inverse third power of the distance from the planet. The second encounter passed well upstream of the planet to return dayside images and did not allow observations of 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 near local midnight at ~68° N latitude and a peak measured magnetic field intensity of ~400 nT.

Magnetospheric structure

Both of Mariner 10's magnetospheric traversals began and ended with the magnetic field and plasma investigations observing clear magnetopause boundaries (see MAGNETOSPHERE OF EARTH: MAGNETOPAUSE). The magnetopause is the current layer formed by the interaction between the solar wind plasma and a planetary magnetic field. The magnetopause current layer confines most of the magnetic flux
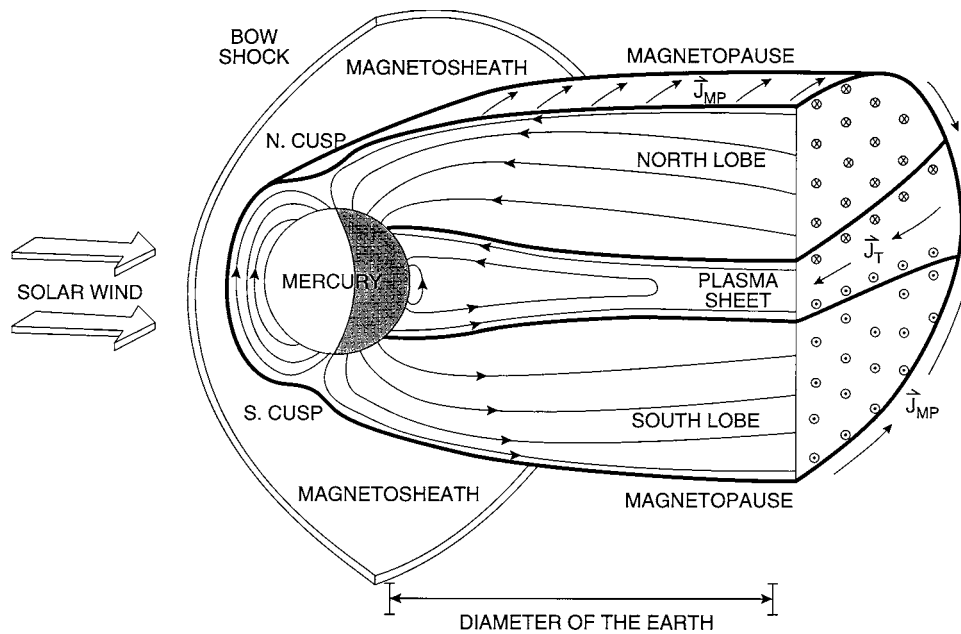
Figure 2. A schematic view of Mercury's magnetosphere as glimpsed by Mariner 10 with its primary regions, some representative magnetic field lines, and the tail current system labelled. Note that the regions typically occupied by radiation belts and the plasmasphere at the Earth are taken up by the planet in this miniature magnetosphere.

tubes rooted in the planet to the magnetospheric cavity. Vertical broken lines in figure 1 mark the inbound and outbound magnetopause crossings as well as the point of closest approach (CA) to the planet. Across the magnetopause current layer the magnetic field rotates in direction to its magnetospheric orientation and increases in magnitude until it is in equilibrium with the external solar wind pressure. The entry of Mariner 10 into the near-tail (see MAGNETOSPHERE OF EARTH: GEOMAGNETIC TAIL) of this magnetosphere is apparent in the tail-like nature of the magnetic field with $B_x \gg B_y$, B_z just inside the magnetopause during the first inbound passage.

Analysis of the Hermean magnetopause using the data sets collected by Mariner 10 has revealed some differences from what is usually observed at Earth. For example, the higher solar wind plasma density at 0.3–0.5 AU produces solar wind ram pressure that are about four to ten times greater than at the Earth. This results in higher magnetopause current densities and stronger magnetic fields inside the magnetopause at Mercury than are observed elsewhere in the solar system. The low altitude of the dayside magnetopause at Mercury has provoked much interest as to whether this boundary ever intersects the planetary surface and exposes it to direct impingement by the solar wind. Simple compression of the magnetopause by solar pressure enhancements would probably cause this to happen if it were not for the induction currents which are expected to be driven deep within the planet to oppose such changes in the magnetic field. However, this induction effect will, at times, be countered by the 'erosion' of magnetic flux tubes

by reconnection (see MAGNETIC RECONNECTION) at the dayside magnetopause. The net result of dayside reconnection is to remove flux tubes from the dayside magnetosphere, where they participate in standing-off the solar wind, and transport them into the magnetotail. In addition, it has been suggested that the reconnection rate at Mercury may be enhanced by the low Alfvén Mach numbers in the solar wind at 0.3 to 0.5 AU. Ultimately, the balance between these competing effects, induction and erosion, will rest in the actual nature of the electrical conductivity profiles in the planetary interior and the efficiency of the magnetic reconnection at the magnetopause.

During the outbound portion of the first Mariner 10 encounter the magnetic field variations were extremely dynamic. These large-amplitude variations in the field intensity and direction have a number of sources. The large dip in magnetic field strength just after closest approach coincided with the spacecraft becoming immersed in a hot plasma sheet (see MAGNETOSPHERE OF EARTH: PLASMA SHEET). These observations are consistent with the spacecraft abruptly transitioning from the magnetic field pressure-dominated lobes to the plasma pressure-dominated plasma sheet. In addition, there are large-amplitude variations in the B_y field component in figure 1 around 20:51 UT. This magnetic field signature is well known to magnetospheric scientists and can be readily interpreted as being due to the spacecraft traversing several quasi-planar field-aligned current sheets. Given the Mariner 10 trajectory, the main gradient in B_y from negative to positive is indicative of an upward FAC being traversed by the spacecraft. This

upward current sheet is largely balanced by two less intense downward current sheets seen just before and after the central upward current sheet. At Earth the occurrence of such multiple current sheets is particularly common over the nightside auroral oval during geomagnetically disturbed intervals. These currents are the primary means by which the magnetosphere transmits energy and momentum to the ionosphere, or in the case of Mercury, the regolith. Given the expectation of a highly electrically resistive regolith at Mercury, field-aligned currents will probably be very short lived and hence, only transient features of the Hermean magnetosphere.

Based on the Mariner 10 measurements, and terrestrial-style extrapolation, figure 2 depicts our present image of Mercury's magnetosphere; included are the primary regions, sample magnetic field lines, and the tail current system. Concerning the physical dimensions of this small magnetosphere, it was noted by the original flight investigators that a scaling in which $1R_M$ at Mercury corresponds to $\sim 6R_E$ at Earth produces good correspondence between the boundaries and regions at these two planets. Hence, the $\sim 2R_M$ distance from the center of Mercury to the subsolar magnetopause maps to about $12R_E$ at the Earth which is, indeed, similar to the average terrestrial magnetopause nose distance of 10–$11R_E$. More importantly, the surface of Mercury would correspond roughly to geosynchronous distance within Earth's magnetosphere. This scaling rules out the possibility of a plasmasphere even if the planet possessed the atmospheric plasma source and the rotation rate to create such a region. (Mercury's rotational and orbital periods are 59 and 88 days, respectively.) Trapped radiation belts such as are found in the terrestrial magnetosphere at distances of 2–$4R_E$, are also impossible. Finally, the observed near-tail diameter of 4–$5R_M$ scales to about 24–$30R_E$ which is somewhat less than the typical near-tail diameter at Earth of 30–$40R_E$. The reason for this discrepancy in this Earth-based scaling is the higher ratio of static to dynamic pressure in the solar wind at Mercury's orbit. The higher static solar wind pressures reduce the diameter of the tail relative to the subsolar magnetopause radius which is determined largely by the dynamic or 'ram' pressure.

Magnetospheric substorms

A *substorm* is a magnetosphere-wide disturbance which involves the conversion of large amounts of electromagnetic energy, either drawn directly from the solar wind or first stored in magnetic fields of the tail lobes, into plasma sheet heating, high-speed bulk plasma flows, energetic particle acceleration, and field-aligned currents which transfer energy to the planetary ionosphere, or at Mercury, to the regolith (see MAGNETOSPHERE OF EARTH: SUBSTORMS). The energy conversion mechanism is magnetic reconnection between the oppositely directed magnetic fields of the tail lobes in much the same manner as is thought to occur in solar flares. The understanding of the reconnection process and how it is influenced by both local plasma conditions in the tail

and electrodynamic coupling to the rest of the magnetosphere and the ionosphere, or regolith at Mercury, is one of the overarching objectives of magnetospheric physics research.

Less than 1 min after Mariner 10 entered the plasma sheet during the first encounter, i.e. beginning around 20:48 UT, it detected a sharp increase in the B_z field component. As displayed in figure 3, the initial sudden B_z increase and subsequent quasi-periodic increases are all coincident with strong enhancements in the flux of >35 keV electrons observed by the Mariner 10 cosmic ray telescopes. This energetic particle signature, and several weaker events observed later in the same pass, have been widely interpreted as evidence for substorm activity. Analyses of the energetic particle and magnetic field signatures for this interval have led to the conclusion that this Mariner 10 event is qualitatively identical to the substorm energetic particle injections and magnetic field dipolarizations observed at altitudes between geosynchronous orbit and the inner edge of the plasma sheet at the Earth. However, there are issues surrounding how a magnetosphere with such small dimensions compared with the relevant charged particle Larmor radii can be such a copious source of energetic particles. More complete energetic particle measurements to be returned by future missions to this planet may yield important clues to how the most energetic charged particles are accelerated in the tails of planetary magnetospheres.

The very short duration of the substorm signatures at Mercury, about 1 min as compared with 1–2 h at the Earth, is also of fundamental interest. Although much remains to be understood concerning substorm processes, it is clear that they correspond to intervals of greatly enhanced magnetospheric convection which leads to the dissipation of large amounts of magnetic energy drawn from the tail lobes. It has been argued that the temporal scale of isolated substorms at the Earth is determined by the time necessary for plasma to convect across the polar cap or, equivalently, from the magnetopause down to the plasma sheet where reconnection can take place. It has been 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, indeed, close to the typical duration of a substorm, i.e. ~ 1–2 h.

For Mercury, corresponding convection time constants of a few minutes have been calculated in agreement with the Mariner 10 measurements. The brevity of the convection time constant at Mercury is due largely to the small tail radius and relatively intense $-\mathbf{V} \times \mathbf{B}$ electric fields present in the solar wind at 0.3 to 0.5 AU. Furthermore, it must be noted that at Earth the dawn-to-dusk magnetospheric electric field is typically only 10–20 per cent of the total electric potential drop available from the solar wind. However, for Mercury it has been argued that the electric potential drop across the magnetosphere should more closely approach the maximum available potential drop
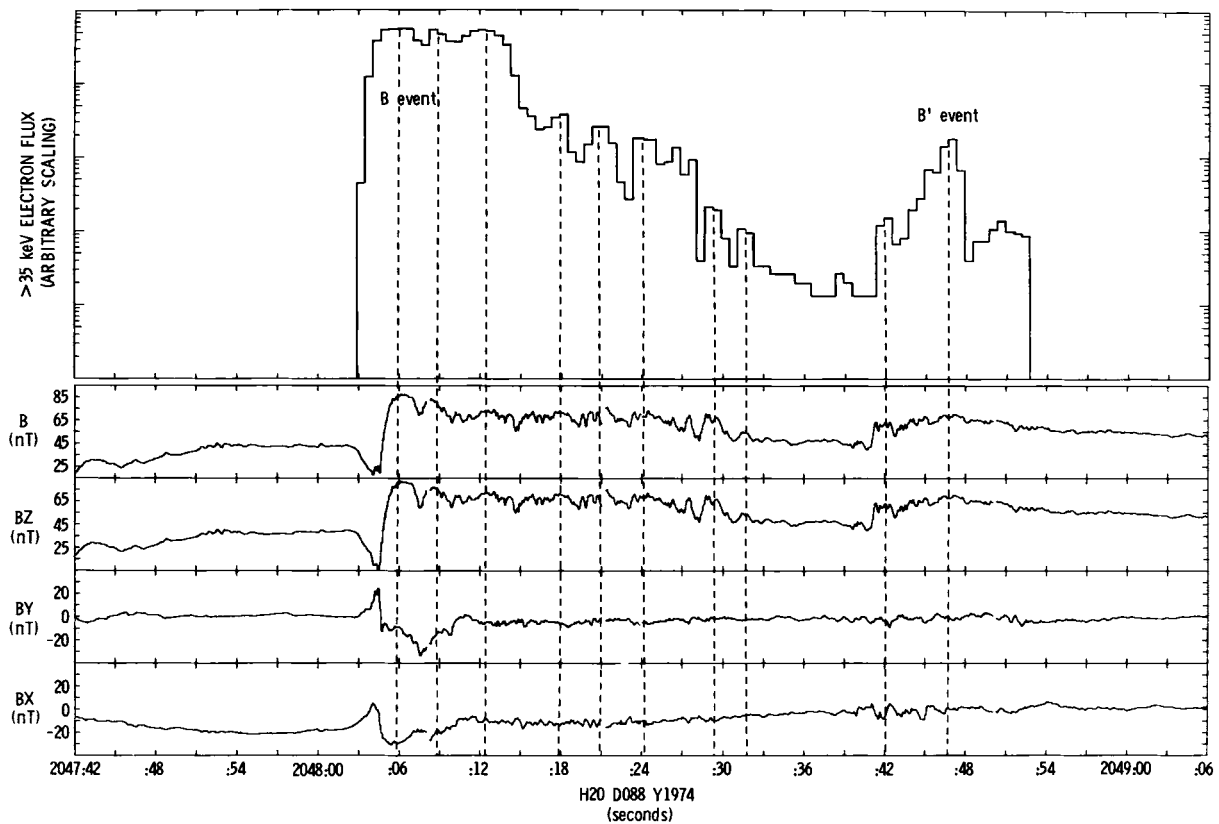
Figure 3. Highest sample rate measurements of the Mariner 10 energetic electron (>35 keV) flux (0.6 s resolution) and magnetic field (0.04 s resolution) are displayed for the substorm dipolarization event observed during the first encounter. (From Christon *et al* (1987).)

than is possible at other planets. The reason is that conducting ionospheres at the other planets act to 'short-out' a portion of this electric field that the solar wind is attempting to impose across the magnetosphere and, therefore, limit the intensity of the internal magnetospheric electric field. Hence, a determination of the factors responsible for the short substorm time scale at Mercury may be very important for our general understanding of electric fields and convection in all planetary magnetospheres.

Summary

From the preceding discussion, it can be seen that Mercury's miniature magnetosphere offers a unique testing ground for theories regarding many important processes. In particular, the very tenuous nature of its atmosphere implies that internal plasma sources are far less significant than at Earth or any of the other known magnetospheres. This fact should make Mercury ideal for quantitative modeling of how and to what degree solar wind plasma enters terrestrial-type magnetospheres. Mercury's relative proximity to the Sun 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 stronger interplanetary magnetic fields at 0.3 to 0.5 AU will result

in higher dayside reconnection rates and more intense large-scale magnetospheric electric fields than at the Earth. Hence, measurements at Mercury could also be pivotal to the testing of existing models of reconnection and electrodynamic coupling between the various regions of the magnetosphere. Observations from a future Mercury orbiter mission should also lead to great improvement in our understanding and modeling capability with respect to magnetospheric substorms. With durations at Mercury of only about 1 min, it should be possible to observe huge numbers of complete substorms at a variety of different locations throughout the magnetosphere in a relatively short time. Such a data set would be especially beneficial in the testing of substorm theories with respect to the role of electrodynamic 'feed-back' between the region at the foot of the magnetospheric flux tubes and convection in the magnetotail. Indeed, this small magnetosphere may offer our only opportunity to observe electrodynamic coupling in the asymptotic limit of a magnetosphere rooted in a relatively non-conducting planetary regolith.

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