THE MAGNETOSPHERE OF MERCURY

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Mercury's intrinsic magnetic field is strong enough to stand off the solar wind well above the surface of the planet under usual solar wind conditions. Thus, it has a magnetopause and a bow shock which are quite similar to their terrestrial counterparts, albeit much smaller in linear dimension. However, the absence of any significant atmosphere or ionosphere alters the flow of current in the Mercurian magnetosphere from the patterns at the Earth and may affect the transfer of energy from the solar wind to the magnetospheric plasma. Thus, the magnetosphere of Mercury is unique in the solar system. In the limited data provided by Mariner 10, Mercury's magnetosphere strongly resembles a miniature terrestrial magnetosphere in which everything simply happens more quickly and repeats more often than in the terrestrial magnetosphere. Nonetheless, estimates of the power requirements for the observed particle acceleration event are somewhat higher than expected. Many of the ambiguities inherent in the interpretation of the Mariner 10 data can be resolved only by the acquisition of new in-situ observations.

1. INTRODUCTION

Mercury is of great interest to those studying planetary magnetospheres. Mercury has an intrinsic magnetic field, one which is strong enough to stand off the flowing solar wind plasma well above the surface of the planet. Thus, its interaction with the solar wind has similarities to the interactions of Earth,
Jupiter, Saturn and Uranus with the solar wind. However, Mercury is also different from these other planets in ways that are important for determining the properties of, and processes occurring in, a planetary magnetosphere. First, Mercury has the most rarefied atmosphere of any of the planets with known magnetospheres. Atmospheres are important to planetary magnetospheres because they provide the lower boundary of most magnetospheric systems. When neutral atmospheric atoms become ionized they are affected by the magnetic and electric fields in the planetary magnetosphere and they then, in turn, affect those electric and magnetic fields. In particular, the electrons and ions which result from atmospheric photoionization can carry electric current. At the Earth, Jupiter, Saturn and possibly Uranus, the electrical conductivity of the near surface region of ionization, known as the ionosphere, is high enough that significant currents flow parallel to the planetary surface. These currents are dynamically important in that they affect how ionized matter is transported throughout the planetary magnetosphere. At Mercury there is a dynamically insignificant ionosphere and the surface is expected to be highly insulating. Thus, the dynamics of the Mercurian magnetosphere should be different from the dynamics of the Earth’s magnetosphere. We cannot simply scale terrestrial processes to Mercury if the terrestrial process involves a strong ionospheric current.

Another important difference in the Mercurian magnetosphere is its size. The magnetic moment of Mercury is over 1000 times smaller than that of the Earth and the solar wind at Mercury is stronger than at 1 AU. The size of the magnetosphere is determined by the balance between the magnetic pressure of the planetary magnetic field and the dynamic pressure of the flowing solar wind plasma. Both pressures combine to give a magnetosphere whose linear dimensions are only 5% of those of the Earth. Since the solar wind moves at the same average speed at Mercury as at the Earth and other natural velocities of the plasma at the Earth and Mercury are similar, within a factor of two or three, events in the solar wind pass by the Mercurian magnetosphere in much shorter time than by the terrestrial magnetosphere. If some wave in the plasma flowing past Mercury is unstable and grows with time, it has a shorter time in which to grow at Mercury than it would near the Earth. As a result, the amplitudes of disturbances in the plasma at Mercury could be substantially different than at the Earth. Also, the high velocity of Alfvén waves at Mercury has led Slavin and Holzer (1979a) to propose that reconnection at Mercury may be more efficient than at the Earth.

Another important difference about Mercury is that the planet occupies a much larger fractional volume of its magnetosphere than the Earth, Jupiter, Saturn or Uranus occupy of their magnetospheres. The inner regions of the magnetospheres of these other four planets contain quite stable and, in some cases, quite intense radiation belts. However, the equivalent region in the Mercury magnetosphere is below the surface of the planet and so the stably trapped charged particle environment of Mercury is probably quite benign.
The above three differences do not exhaust the distinctive features found at Mercury. The fact that the interior of Mercury should become highly electrically conducting close to the surface may affect the compressibility of the magnetosphere. The solar wind density and temperature and the solar and galactic cosmic ray particle populations are somewhat different than at the Earth. This too may affect the nature of the interaction. Other differences may exist at Mercury that we do not yet appreciate, but, even in the absence of any other differences, we can be sure that Mercury presents us with sufficient contrasts that we can test our models of how magnetospheres work. Thus, those who are concerned with planetary magnetospheres are very interested in the magnetosphere of Mercury. Unfortunately, there is very little data with which to work.

In this review we will examine the available data and the possible implications of these data. We divide the review into two major sections, the solar wind interaction and the processes in the magnetosphere. Before treating these two major topics, we review the history of the investigation of the Mercury magnetosphere, the plasma and energetic particle environment in which Mercury is situated, and briefly the planetological properties of relevance to the magnetosphere.

History

The only spacecraft to have visited Mercury is Mariner 10, which was launched on 2 November 1973, and flew by Mercury on 29 March 1974, after a Venus swing by on 5 February 1974. Mariner 10 re-encountered Mercury on 21 September 1974 and 16 March 1975 after which it was no longer tracked. The first encounter (M I) passed the night side of the planet coming within 707 km of the surface at 2046:38 on 29 March 1974. The second encounter (M II) was a distant dayside flyby, coming within 50,000 km of Mercury at 2059:01 UT on 21 September. The third encounter (M III) was another close night-time flyby, coming within 327 km of the surface at 2239:23 on 16 March 1975. (These trajectories are discussed in more detail below; see Figs. 6 and 11.)

Mariner 10 was a three-axis stabilized spacecraft carrying three instruments which could contribute to the understanding of the magnetosphere. The first was a fluxgate magnetometer that had two ranges of ± 16 nT and ± 128 nT, each quantized to 10-bit accuracy for a digital window of 0.030 or 0.26 nT depending on range. The magnetometer could measure field strengths above 128 nT to a maximum of 3188 nT through the application of bias fields. During the first encounter the magnetic field stayed below 128 nT on each sensor (Ness et al. 1974a). On the third Mercury encounter the magnetic field reached 400 nT (Ness et al. 1975b). The fluxgate magnetometer included two redundant sets of triaxial sensors spaced 2.3 m apart on a 5.8 m boom. The difference in the readings of these two sets of sensors was used to put limits on
the contribution to the measured field from spacecraft sources (Ness et al. 1974b). The contribution to the measured field from the spacecraft was estimated to be $< 4$ nT (Ness et al. 1974a). The magnetic field was sampled at a rate of 25 vectors per second.

The plasma science instrument consisted of a sophisticated ion and electron analyzer observing the sunward direction and a less elaborate electron instrument observing in the antisunward direction (Ogilvie et al. 1977). These instruments were mounted on a motor-driven scan platform which could operate at a scan rate of either 1 or 4 deg s$^{-1}$. The former rate was used at Mercury. The sunward-facing detector did not function properly and never detected counts above the cosmic ray background. Thus, all conclusions about the nature of the low-energy plasma environment of Mercury come from the rear facing electron detector. The solar wind bulk speed could be determined from these data but only to about $\pm 50$ km s$^{-1}$. The instrument was a hemispherical electrostatic analyzer with 15 energy channels logarithmically spaced in energy between 13 and 715 eV. The instrument was stepped continuously through the 15 energy steps dwelling at each energy for 0.4 s and obtaining a complete energy spectrum in 6 s.

The third instrument was an energetic particle detector consisting of two telescopes, the Main Telescope (MT), and the Low Energy Telescope (LET) (Simpson et al. 1974; Eraker and Simpson 1986). The MT consisted of six detectors inside a plastic scintillator which was in anticoincidence with the telescope elements. The energy losses in 3 of the detectors (1, 2 and 5) were determined by 256-channel pulse-height analyzers. The LET was designed to measure low-energy protons and helium nuclei in the presence of a high intensity of low-energy electrons. For both telescopes the events accumulated for all particle range intervals were read out every 0.6 s together with the pulse height information. The telescopes were intended to measure electrons from 175 keV to 30 MeV and protons from 500 keV to 68 MeV. However, the detectors had some sensitivity to lower-energy particles when simultaneous deposition of energy by more than one particle piled up in the detector. Had instrumentation been carried by Mariner 10 to measure energies between the kilovolt range and the hundreds of kilovolt range, compensation could have been made for such pile-up effects. Since such instrumentation was not carried, there remains substantial ambiguity about the exact energy spectrum of the observed particles.

**Interplanetary Plasma Environment**

Mercury is unique in being both the closest planet to the Sun and, except for Pluto, having the most eccentric orbit (i.e., perihelion $= 0.31$ AU; aphelion $= 0.47$ AU). These two factors result in its magnetosphere being exposed to much denser and hotter solar wind plasma and more intense in-
TABLE I
Interplanetary Conditions*

<table>
<thead>
<tr>
<th>Planet</th>
<th>$R$ (AU)</th>
<th>$V_{SW}$ (km s$^{-1}$)</th>
<th>$N_P$ (cm$^{-3}$)</th>
<th>$B$ (nT)</th>
<th>$T_P$ ($10^4$K)</th>
<th>$T_E$ ($10^4$K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.31</td>
<td>430</td>
<td>73.</td>
<td>46</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>430</td>
<td>32.</td>
<td>21</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>430</td>
<td>14.</td>
<td>10</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Earth</td>
<td>1.0</td>
<td>430</td>
<td>7.0</td>
<td>6.0</td>
<td>8.0</td>
<td>15</td>
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<tr>
<td>Mars</td>
<td>1.5</td>
<td>430</td>
<td>3.1</td>
<td>3.4</td>
<td>6.1</td>
<td>13</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.2</td>
<td>430</td>
<td>0.26</td>
<td>0.83</td>
<td>2.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.6</td>
<td>430</td>
<td>0.076</td>
<td>0.44</td>
<td>1.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.1</td>
<td>430</td>
<td>0.019</td>
<td>0.22</td>
<td>1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.2</td>
<td>430</td>
<td>0.0077</td>
<td>0.14</td>
<td>0.82</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Scaling — $R^0$ $R^{-2}$ $(2R^{-2} + 2)^{1/2}/2R$ $R^{-2/3}$ $R^{-1/3}$

*Table adapted from Slavin and Holzer (1981).

...terplanetary magnetic fields than any of the other planetary magnetospheres. Table I lists the principal interplanetary plasma and magnetic field parameters, their radial scaling laws, and extrapolated values based on typical 1 AU measurements. It is at once apparent that not only are all of the parameters higher at Mercury, but the eccentricity of Mercury’s orbit produces very significant variations between perihelion and aphelion. One possible implication is that magnetospheric activity at Mercury may experience a strong semiannual variation.

Fortunately, the interplanetary environment between 0.31 and 0.47 AU has been well observed by the 1974-1980 Helios 1 and 2 missions (Musmann et al. 1977; Marsch et al. 1982). In Fig. 1 histograms of hourly averaged Helios 1 and 2 magnetic field magnitude, solar wind density, and velocity over the radial distances appropriate to Mercury have been compiled. The distributions are all quite broad, possibly as a result of both the 0.31 to 0.47 AU radial gradients and the solar cycle variations in these quantities over the years 1974 to 1980. The mean values all agree well with Table I and the factor of 4 to 9 increases in interplanetary magnetic field (IMF) magnitude and solar wind density over the 1 AU values are very evident.

The Helios observations may also be used to calculate derived parameters that play important roles in determining the nature of the solar wind-planet interaction. Collisionless shocks, for example, are classified in terms of the Mach number (the ratio of the velocity of the solar wind to the velocity of compressional waves), the ratio of plasma thermal to magnetic field pressure (usually referred to as the beta of the plasma), and the angle that the magnetic field makes to the local normal to the shock surface, $\theta_{BN}$ (Tid-
Fig. 1. Solar wind statistics derived from hourly averaged Helios 1 and Helios 2 observations obtained in the years 1974 to 1980 for the range of heliocentric distances corresponding to the orbit of Mercury (0.31 AU to 0.47 AU). Top panel shows histograms of field magnitude, middle panel shows density and bottom panel shows solar wind velocity. Means and standard deviations are indicated. (Data courtesy of NSSDC and Helios investigators.)
Fig. 2. Solar wind statistics derived from hourly averaged Helios 1 and Helios 2 observations for the orbit of Mercury for parameters expected to influence solar wind interaction with Mercury. Top panel shows Alfvén Mach number, middle panel shows ion beta and bottom panel shows angle between interplanetary magnetic field and shock normal at subsolar point.
man and Krall 1971; Greenstadt 1985). Furthermore, the nature of the bow shock determines the conditions in the magnetosheath including its width and shape, the amount of compression, the levels of turbulence, and the draping pattern of the magnetic field line (Russell 1985). Figure 2 shows that the Alfvénic Mach number and ion beta are much lower than is typical at the Earth and lower still than observed for the outer planets. So, too, should the magnetosonic, or compressional, Mach number and the total (electron plus ion) beta of the plasma be lower. These lower values for Mach number and beta will affect the nature of several of the processes occurring in the solar wind, but the median values at Mercury are within the range of values observed on occasion at 1 AU.

Energetic Charged Particle Environment

In addition to the highly variable solar wind plasma environment near Mercury, there are a number of other important sources of exogenic particle fluxes. These other particle populations include solar cosmic rays (SCR), galactic cosmic rays (GCR), Jovian electrons, and low-energy particles (~1 MeV) produced within the interplanetary medium. The energetic nuclei that pervade the inner solar system have a broad range of energies and compositions (see Table II). The nuclei of both the GCR and SCR components are primarily protons with a few percent alpha particles and about 1% heavy nuclei.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Energies (MeV nucleon$^{-1}$)</th>
<th>Mean Flux (particles cm$^{-2}$ s$^{-1}$)</th>
<th>Effective Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cosmic rays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protons and helium nuclei</td>
<td>5–100</td>
<td>~100</td>
<td>0–2</td>
</tr>
<tr>
<td>Iron group and heavier nuclei</td>
<td>1–50</td>
<td>~1</td>
<td>0–0.1</td>
</tr>
<tr>
<td>Galactic cosmic rays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protons and helium nuclei</td>
<td>100–3000</td>
<td>3</td>
<td>0–100</td>
</tr>
<tr>
<td>Iron group and heavier nuclei</td>
<td>~100</td>
<td>0.03</td>
<td>0–10</td>
</tr>
</tbody>
</table>

*Table taken from Reedy et al. 1983.
Galactic Cosmic Rays. The detailed spatial and temporal variations of the cosmic ray components at any point in the heliosphere are strongly controlled by the Sun's activity and the IMF. GCR particles probably originate in supernova remnants and/or the interstellar medium (Lingenfelter 1979) and subsequently are transported by various processes to the solar system. Observations near the Earth have clearly established that $< 1$ GeV n$^{-1}$ GCR particles are modulated by about a factor of 10 during the solar cycle, while for $E \geq 10$ GeV n$^{-1}$ the GCR ion population is not very strongly affected by solar variations (cf. Reedy et al. 1983 and references therein). As is evident from Table II, the GCR particles are highly penetrating, and they can represent a significant sputtering source for an airless planet like Mercury (McGrath et al. 1986). Clearly, owing to Mercury's weak intrinsic field, virtually all galactic cosmic rays will have essentially direct access to the entire planetary surface. Because of the stronger IMF and the greater proximity to the Sun, however, we would expect greater modulation of the GCR flux at Mercury's orbit during a given solar cycle. The surface layers of Mercury should have embedded within them a fascinating record of solar variability over the eons due to this GCR modulation effect.

Solar Cosmic Rays. Table II shows that SCR particle intensities are much higher than the GCR intensities, but the characteristic energies are much lower. Figure 3 (Castagnoli and Lal 1980; Reedy et al. 1983) shows the average solar proton spectrum as compared with the GCR proton flux for different degrees of solar-cycle modulation. As is clear from the figure, SCR proton fluxes tend, on average, to dominate the GCR fluxes below $\sim 500$ MeV. However, it should be kept in mind that just a few large solar flares produce most of the solar cosmic rays during any given solar cycle (Lal 1972). Calculations of the transport of solar particles predict that the integrated fluence of particles should obey an inverse square ($R^{-2}$) relationship, where $R$ is the distance from the Sun (Zwickl and Webber 1977). Thus, the average spectral character of SCR particles should be similar at Mercury and at 1 AU, but the absolute intensities would be factors of 4 to 9 higher at Mercury than at Earth. As with GCR particles, the SCR's will leave an important and distinctive historical record of solar activity in Mercury's surface.

Neugebauer et al. (1978) have tried to estimate the highest likely solar flare proton and electron fluxes as a function of heliocentric distance. The SCR component would likely be dominant under most circumstances. As shown by Neugebauer et al. (1978), one can estimate the average SCR electron flux fairly effectively based upon a knowledge of the SCR ion fluxes. Unlike the GCR and SCR nucleonic component, the solar electron fluxes will not produce much of a record in the Mercury surface layers (Reedy 1977), but solar electrons could be an important source population for the Mercurian magnetosphere as is the case for Jovian electrons discussed below.
Solar Neutrons. The estimation of the solar flare neutron flux and fluence near Mercury is difficult because a neutron flux of solar origin has not yet been unambiguously detected at 1 AU. This failure can be understood since all experimental attempts to identify a solar neutron flux have been made in Earth satellites or balloons, where two physical constraints make detection of solar neutrons very difficult (Neugebauer et al. 1978). First, the approximately 12 minute half-life of neutrons reduces greatly the flux of low-energy neutrons which could survive to 1 AU. Second, local neutron background generated in the spacecraft, mainly the cosmic radiation, has placed severe limits on the
Fig. 4. The dependence of the normalized solar neutral flux as a function of radial distance from the Sun for three neutron energies, 10 keV, 1 MeV, and 100 MeV. (Figure after Neugebauer et al. 1978.)
sensitivity for detection. Indeed, only upper limits on neutron fluxes have been reported (Lockwood et al. 1973; Kirsch 1973). Figure 4 (Neugebauer et al. 1978) illustrates the effect of the decay of neutrons of various energies as a function of radial distance. The measurement of this dependence has been proposed as a means to identify solar neutrons and to separate the solar from background neutron fluxes (Anglin et al. 1972). Two components of solar neutron fluxes are expected to be present in the heliosphere. First, a quasi-steady solar neutron production primarily from extended areas of solar activity (mainly 10 keV to 1 MeV neutrons). Second, an impulsive neutron production from solar flares associated with collisions between accelerated charged particles and the chromospheric and coronal material (mainly 1-100 MeV neutrons).

During large solar flares, the region near Mercury may be strongly illuminated with solar neutrons. A spacecraft near the planet could probably readily detect and characterize the solar neutron spectrum thereby learning a great deal about the mechanisms operative in solar flares. Moreover, the interaction of solar neutrons with the Mercurian surface could be detected remotely using neutron albedo fluxes and gamma ray sensor systems (Simpson et al. 1974), thereby giving a remote diagnostic technique for probing the Mercurian regolith from satellite altitudes.

**Jovian Electrons.** Jovian electrons, both at Jupiter and in the interplanetary medium near Earth, have a very hard spectrum that varies as a power law with energy (see, e.g., Mewaldt et al. 1976). This spectral character is sufficiently distinct from the much softer solar and magnetospheric electron spectra that it has been used as a spectral filter to separate Jovian electrons from other sources (Krimigis et al. 1975; Mewaldt et al. 1976; Chenette et al. 1977). A second Jovian electron characteristic is that such electrons in the interplanetary medium tend to consist of flux increases of several days duration which recur with 27 day periodicities (Teegarden et al. 1974; Mewalt et al. 1976). The Jovian electrons at 1 AU typically occur during the declining phase of solar wind streams and the 27 day periodicity of the Jovian electron increases was attributed by Conlon (1978) to the effects of recurrent, high-speed solar wind streams overtaking slower solar wind plasma. These form corotating interaction regions (CIR) in the heliosphere (see Fig. 5). A third feature of Jovian electrons at 1 AU is that the flux increases exhibit a long-term modulation of 13 months which is the synodic period of Jupiter as viewed from Earth (Chenette et al. 1977). Every 13 months, Earth and Jupiter are directly connected along the interplanetary magnetic field. Eraker and Simpson (1979) reported a broad range of synoptic data from Mariner 10 which showed that Jovian electron features persist in interplanetary space as close as 0.46 AU from the Sun. Their observations show the characteristically hard spectrum of the Jovian source; they show the modulation of the relativistic electron fluxes by CIR at the solar synodic period; the data also show
the long-term intensity modulation (7 month period) due to the synodic period of Jupiter as seen by Mariner 10. Figure 5 illustrates the orbit of Mercury and the likely relationship of Mercury’s magnetosphere to the Jovian electron transport. As revealed by the data of Eraker and Simpson (1979, 1986), the Mercury encounter (M 1) by Mariner 10 on 29 March 1974 occurred during the height of a Jovian electron increase in the interplanetary medium. Thus, it is very likely that Jovian electrons were enveloping the Mercury magnetosphere during this encounter. In analogy with the model developed for the Earth (Baker et al. 1979, 1986), it has been suggested that Jovian electrons could supply a spectrally hard electron population which would have a significant influence inside the magnetosphere of Mercury (Baker 1986).

**Planet**

Mercury is the smallest of the terrestrial planets with a radius of 2440 km, intermediate between the Earth’s Moon and Mars in size. It rotates more slowly than the Moon, rotating with a period of 59 days compared with the Moon’s 28 day period. It differs from the Moon in the sense that its axial rotational period is not synchronous with its orbital period. Rather it orbits the Sun every 88 days so that every two Mercurian years the same side of the planet faces the Sun. This slow rotation and close proximity to the Sun implies a very high dayside surface temperature (≥ 630 K). The night side, in long periods of darkness and with no appreciable atmosphere, is cold (95 ≤ T ≤ 130 K).

Our knowledge of the surface of Mercury comes primarily from the nearly 3000 photos taken by Mariner 10, having resolutions ranging from 1 to 3
km and covering about 40% of the surface of the planet. Consideration of all of the optical, thermal and radar-albedo information has led to the conclusion that many of the properties of the surface of Mercury are similar to that of the Moon (Chase et al. 1976; Hapke 1977). This suggests that the surface of Mercury consists of a fragmented layer similar in grain-size distribution to the lunar regolith. As we will discuss further below, there remain important questions about the electrical and thermal conductivities of such a regolith material.

Mercury is observed to have the highest mean (uncompressed) density of any planet (5.3 g cm$^{-3}$ versus 4.1 g cm$^{-3}$ for the Earth (at 10 kbar) (Ringwood 1979). This high average density is taken to imply a composition of 70% metallic-phase material and 30% silicate-phase material. As noted above, Mercury possesses an internal magnetic field. If this is due to a planetary dynamo, this requires a molten core (see, e.g. Ness 1979). Estimates place the core-mantle boundary temperatures below the melting point of FeNi, suggesting an admixture of lighter material such as O or S (Gault et al. 1977). Assuming a dynamo origin for the magnetic field (see, e.g., Stevenson et al. 1983), the dynamo region could be very close to the planetary surface. The internal magnetic field probably consists of both dipolar and higher-order components but the results of the Mariner 10 flyby and its very limited coverage of the planet leave an intrinsic ambiguity between the contribution of the dipole and higher-order moments (cf. the chapter by Connerney and Ness). The observed low field magnitude compared with the magnitude that could be reproduced by a dynamo, operating in a core of the size of that of Mercury, implies that the Mercury dynamo may not be self-sustaining and may involve thermoelectric currents (Stevenson 1987). Any remote observation of temporal variations of the magnetic field close to Mercury could also provide information about the electrical conductivity of the mantle.

The atmosphere of Mercury was found by Mariner 10 to consist of an exosphere (Broadfoot et al. 1974) of neutral He (600 cm$^{-3}$ surface density) and atomic hydrogen (8 cm$^{-3}$). Two principal candidates for producing the exospheric population are direct solar wind accretion on the surface and decay of thorium and uranium in the planetary crust. Recent, high-resolution spectral measurements of Mercury show emission in sodium D lines (Potter and Morgan 1985a). This suggests a substantial sodium population in Mercury’s atmosphere (Ip 1986), possibly due to photo-sputtering of the planetary surface (cf. Cheng et al. 1987). Potassium has also been discovered (Potter and Morgan 1986). Mariner results indicated only a modest ionosphere at Mercury with an upper-limit electron density of $10^3$ cm$^{-3}$. Direct observations in the polar cap reported by Ogilvie et al. (1977) showed electron densities of 0.1 cm$^{-3}$. At higher altitudes in Mercury’s magnetotail, the observed electron densities were commonly 1 cm$^{-3}$. All of the present evidence, therefore, suggests at most a very modest atmosphere and ionosphere at Mercury. This, in turn, would indicate that solar wind plasmas, and any solar energetic or
magnetospheric particle bursts, should be able to impact rather directly onto the planetary surface, except as they are stood off by the planetary magnetic field. Furthermore, magnetospheric processes should not be strongly affected by effects of the ionospheric conductivity at Mercury as they are at the Earth (see, e.g., Ogilvie et al. 1977; Hill et al. 1976). A major difference between the terrestrial and Mercurian magnetospheres should be in the sources for their plasma. At the Earth the solar wind is thought to be the dominant source (see, e.g., Hill 1974) but with a significant, and possibly very important ionospheric contribution (see, e.g., Baker et al. 1982). A major objective of magnetospheric studies at the Earth over the past two decades has been to separate quantitatively the two sources (see, e.g., Johnson 1983). The lack of a strong ionospheric source at Mercury may provide an opportunity for the study of how solar wind plasma enters a magnetosphere and is eventually precipitated onto the surface or lost down the tail. The plasma densities reported by Mariner 10 at high altitudes in the magnetosphere were higher than those observed at the Earth by a factor of about four, the ratio of the solar wind flux at 1 AU to 0.5 AU. This result was interpreted as confirming that the solar wind was the principal magnetospheric plasma source at Mercury as is observed at the Earth (Ogilvie et al. 1977).

II. SOLAR WIND INTERACTION

When the flowing solar wind plasma encounters a planetary magnetic field, it is deflected to either side of the planetary field and forms a magnetic cavity. The magnetic field exerts a pressure and the gradient in that pressure at the leading edge of the magnetic cavity exerts a force on the plasma. This force in turn stops the forward motion of the solar wind plasma and deflects it. This basic understanding of the formation of a magnetic cavity, or magnetosphere as it is called, allows us to calculate where the boundary of the magnetosphere lies and to first order the configuration of the magnetic field within the magnetosphere. We cannot calculate many of the properties of the thickness of this boundary, or magnetopause, nor the dynamics of the magnetosphere solely from the pressure balance since these other properties of the magnetosphere depend on other aspects of the interaction. However, knowledge of where the magnetopause is located for a particular solar wind dynamic pressure provides a good first order estimate of the strength of the planetary magnetic field, i.e., its intrinsic magnetic moment.

The magnetopause is also important because it is the site of energy transfer from the solar wind plasma to the magnetospheric plasma. What happens here determines how much energy eventually gets deposited on the planetary surface by the solar wind. We have no experience with a magnetopause not connected to an ionosphere except that gained at the four Mariner crossings of the Mercury magnetopause. We note that this energy deposition has been proposed to be a candidate for remote sensing with the VLA (Baker et al. 1986a).
In order that the solar wind be deflected by the planetary magnetic field, the solar wind must somehow sense the presence of the planetary obstacle. This information is transmitted upstream by a compressional wave, called a magnetosonic wave by plasma physicists. This magnetosonic wave is the analog of the usual sound wave in a collisional gas. The solar wind flows much faster than the speed of propagation of magnetosonic waves throughout all of the solar system except for a small region near the Sun. As a result, a standing bow shock wave is found upstream of each of the planets. This shock wave heats, slows and deflects the solar wind around the planetary obstacle. The Earth’s Moon does not have such a shock wave because it absorbs rather than deflects the solar wind. That Mercury does have a bow shock was the first indication of the presence of a planetary magnetic field. The location of a bow shock is an indication of how large an obstacle to the solar wind is present, but the location of the shock also depends on several properties of the plasma, such as Mach number, which are themselves variable. Hence, it is not as straightforward to deduce the strength of the planetary magnetic field from the shock position as it is from the magnetopause position.

Shocks themselves are interesting phenomena in space plasmas because the processes which act to heat and deflect the solar plasma can also accelerate particles to extremely high energies. The region upstream of a collisionless shock which is connected to the shock by interplanetary magnetic field lines is called the foreshock and is replete with many interesting energetic charged particle and plasma wave phenomena (cf. Russell and Hoppe 1983).

The three Mariner 10 passes each showed evidence for the presence of a planetary magnetosphere. The Mercury I and III passes detected the bow shock and magnetopause and directly sampled the nightside magnetosphere. Mercury II, despite being a dayside encounter 50,000 km upstream, also may have observed effects of the upstream particles and waves. In this section, we examine the observations of the upstream waves, the bow shock, the magnetopause and the structure of the nightside magnetosphere.

**Boundary Locations**

Both the plasma instrument and the magnetometer detected clear signs of a bow shock and a magnetopause on both the inbound and outbound portions of the Mercury I and III passes (Ogilvie et al. 1974; Ness et al. 1974a). The locations of these boundaries and the Mercury I and III trajectories are shown in Fig. 6. The magnetic field data from the Mercury I pass are shown in Fig. 7. The inbound bow shock is clearly defined by the sharp rise in field magnitude. There are multiple crossings of the boundary as it moves back and forth at velocities greater than that of this spacecraft. The behavior is not unlike that seen at the bow shock of other planets with magnetospheres. The diffuse nature of the outbound bow shock is associated with the fact that the interplanetary magnetic field was oriented at a small angle to the shock normal. This same behavior is observed at the Earth (cf. Russell 1985).
Fig. 6. Trajectories of Mariner 10 during the first and third Mercury flybys. Left-hand panel shows the projection on the ecliptic plane. Right-hand panel shows the view from the Sun.

Fig. 7. Mariner 10 magnetic field measurements during the 29 March 1974 Mercury I flyby. Top panel shows the magnetic field magnitude, the next panel down shows the standard deviation of the magnetic field overall the components, the next panel shows the ecliptic longitude of the field and the bottom panel shows the ecliptic latitude. BS: bow shock; MP: magnetopause; CA: closest approach.
The motion of Mercury in its orbit around the Sun causes an aberration of the otherwise nearly radial flow of plasma from the Sun. Correcting for this aberration in Fig. 8, we obtain the boundary crossing locations shown (Russell 1977). Extrapolating from these crossings to the subsolar region has large uncertainty because of the uncertainty in the shape of the boundary, the precise direction of the solar wind and the effects of flapping of the boundary. Nevertheless, if we do extrapolate, we obtain a subsolar magnetopause distance of $1.35 \pm 0.2 \ R_M$ and a subsolar shock standoff distance of $1.9 \pm 0.2 \ R_M$. These distances give a ratio of $1.41 \pm 0.3$ compared to 1.3 for the Earth. The value for this ratio should depend on the shape of the magnetosphere and the Mach number of the solar wind (Spreiter et al. 1966). The Mach number is lower on average at Mercury, and the larger ratio at Mercury than at the Earth is in accord with our expectations. However, the value is very uncertain. We can make no specific deductions about the shape of the magnetopause based on this ratio (in contrast to what was possible for Venus [Russell et al. 1985]) or from the shape of the bow shocks as has been done for other planets by Slavin and Holzer (1981).

The position of the subsolar magnetopause can be used to determine the magnitude of the intrinsic magnetic moment of the planet if the dynamic pressure of the solar wind is known and if the interior of the magnetosphere contains a low-beta plasma. If the thermal energy density of the plasma approaches that of the magnetic field, i.e., the beta = 1 condition, then some of
the pressure that holds off the solar wind is supplied by the plasma and the simple formula below does not apply.

If we take a magnetospheric shape factor appropriate for a gas dynamic interaction with a ratio of specific heats of $5/3$ and ignore plasma effects and tail current effects (Schield 1969), we obtain in SI units,

$$M = 6.1 \times 10^{-4} R_{sp}^3 (\rho V^2)^{1/2}.$$  

(1)

Here $R_{sp}$ is the subsolar magnetopause radius in m; $\rho$ is the density of the solar wind in kg m$^{-3}$; $V$ is the velocity of the solar wind in m s$^{-1}$ and $M$ is the magnetic moment in T m$^3$.

If we substitute the measured solar wind values from the electron instrument as reported by Slavin and Holzer (1979a), we obtain a moment of $1.5 \times 10^{12}$ T m$^3$. If we use their higher estimates of the pressure obtained by estimating the field strength at the subsolar point based on the observed strength at the terminator, we obtain a value of $2.7 \times 10^{12}$ T m$^3$. We note that if we use all the corrections proposed by Slavin and Holzer (1979a), we obtain a value of $6 \pm 2 \times 10^{12}$ T m$^3$. Estimating the moment in this way is thus uncertain by at least a factor of two. It has an advantage over inverting the direct observations of the magnetic field in that the position of the magnetopause is globally determined rather than due to local effects. Direct observations are available only from a limited portion of the planet and may not be truly representative of the entire planet (cf. Chapter by Connerney and Ness). On the other hand, our limited knowledge of the exact dynamic pressure of the solar wind during the encounters and the necessity of extrapolating from the terminator region makes this global method also uncertain.

The magnetosphere shields the planet from the effects of the solar wind both as a supplier of hydrogen and helium and as a scavenger of any outgassing and sputtering products. Siscoe and Christopher (1975) and later Goldstein et al. (1981) examined the statistics of location of the subsolar magnetopause of Mercury to determine how often the solar wind would strike the surface of Mercury. While both used slightly different assumptions about the strength of the magnetic moment, the properties of the solar wind and how much tangential stress was applied to the magnetosphere, they both concluded that the solar wind seldom strikes the surface of Mercury. Figure 9 shows probability curves for the standoff distance of the magnetopause for two different assumptions about flux transfer to the magnetotail by the tangential stress applied by the solar wind. The probability of the solar wind striking the surfaces of Mercury for a magnetic moment of $2.5 \times 10^{12}$ T m$^3$ varies from $6.1 \times 10^{-5}$ (aphelion with no tangential stress) to $6.6 \times 10^{-2}$ for perihelion with tangential stress.

Recently, D. Beard (personal communication, 1985) has advocated the use of the formula,

$$R/R_{sp} = 1 + 0.0851 \phi^2 + 0.0251 \phi^4$$  

(2)
Fig. 9. Panel (a) shows the distribution of the solar wind standoff distance for the case of Earth-like flux transfer. The heavy lines are for aphelion solar wind conditions; the thin lines are for perihelion conditions. The solid curves correspond to a magnetic moment of $2.5 \times 10^{12} \text{T m}^3$, the dashed curve to $3.5 \times 10^{12} \text{T m}^3$ and the dot-dash curve to $4.5 \times 10^{12} \text{T m}^3$. Panel (b) shows the same as panel (a) but with no flux transfer. (Figure after Goldstein et al. 1981.)

to extrapolate to the subsolar point where $\phi$ is the angle of the observations from the subsolar point measured in radians. When applied to the Mercury I and III magnetopause observations, this formula gives a smaller subsolar radius than used above, $1.2 \ R_M$. This value in turn is equivalent to a somewhat
smaller planetary moment and solar wind would impact the planetary surface more often.

Finally, two other more esoteric effects may affect the location of the magnetopause boundary. First, if the relative amount of magnetic flux in the tail to that in the magnetosphere is larger at Mercury than at the Earth, then the shape of the magnetopause will be different and the subsolar point will be closer to the planet for the same magnetic moment (Slavin and Holzer 1979a). The tangential drag on the magnetopause exerted by viscosity and by the phenomenon known as reconnection governs the amount of flux in the tail (cf. Russell and McPherron 1973). However, since there is little or no ionosphere at Mercury and since the ionosphere at the Earth plays a major role in modulating magnetic flux transport to and from the tail, it is difficult to assess by how much Mercury's tail differs from that of the Earth.

The second effect is the stiffening of magnetic field lines by the high electrical conductivity of the planetary core and mantle (Hood and Schubert 1979; Suess and Goldstein 1979). These highly conducting regions will oppose any forces that attempt to bend the field lines embedded in them until the currents set up in them decay. Thus, the core and mantle stiffen the field lines most against rapid solar wind variations and least against long-term variations. All these effects add uncertainty to estimates of how often the solar wind can directly impact the surface of Mercury.

Bow Shock and Upstream Waves

When the interplanetary magnetic field lies nearly parallel to the normal to the bow shock, the bow shock is locally very turbulent. Simultaneously, elsewhere on the bow shock where the interplanetary magnetic field lies at right angles to the bow shock normal, the shock is much more well defined. This situation was exemplified by both Mariner 10 shock encounters. Figure 7 shows a quiet magnetic field at the inbound shock crossings where the magnetic field was nearly orthogonal to the shock normal, and a very disturbed magnetic field at the outbound shock where the magnetic field lies almost parallel to the shock normal. On Mercury III, as illustrated in Fig. 10, the situation was reversed. The inbound shock was the quasi-parallel shock and the outbound was the quasi-perpendicular shock.

As mentioned in the introduction, the solar wind Mach number and beta of the solar wind at Mercury's orbit are on average lower than at the Earth. These parameters affect the structure of the shock, so that there will in general be less ion heating at Mercury than at the Earth (cf. Gosling and Robson 1985). The magnetic profile will at least for quasi-perpendicular shocks be more regular because the bow shock is weaker. On the other hand, the interplanetary magnetic field is oriented more radially out from the Sun at Mercury's orbit. Thus, there will be a more frequent occurrence of quasi-parallel bow shocks at Mercury than at the Earth.
Fig. 10. Mariner 10 magnetic field measurements during the Mercury III flyby. Panel (a) shows the magnetic field magnitude, panel (b) shows the standard deviation of the magnetic field over all three components. Panel (c) shows the ecliptic longitude of the magnetic field and panel (d) shows the ecliptic latitude. BS: bow shock; MP: magnetopause; CA: closest approach; UW: upstream wave. (Figure after Ness et al., 1975a.)

Figure 11 shows the magnetic field profile across the quasi-perpendicular inbound shock on Mercury I (Ness et al., 1974a). The structure and waves present are not unlike those seen at the Earth's bow shock (Fairfield and Behannon 1976). In front of the outbound quasi-parallel shock, waves were observed in the 5 to 10 s period range that were very similar to those seen at periods of 20 to 60 s at the Earth. Hoppe and Russell (1982) have shown that, in fact, these same waves seem to be present in front of the bow shocks of all the planets and that their wave frequencies are proportional to the interplanetary magnetic field at the planet.

Mariner 10 passed Mercury well upstream of the bow shock during the Mercury II encounter. Figure 12 shows the geometry of this passage and the measured magnetic field and plasma parameters. Panel (c) shows a number that is representative of the high-energy (∼600 eV) flux. Panel (l) shows the impact parameter of the field lines passing through the spacecraft. This parameter tells how close to the planet the field line comes. Some, but not all, of the strong peaks occur when the impact parameter is small, suggesting that Mariner 10 may have detected upstream electrons and associated magnetic disturbance 50,000 km upstream of Mercury.
Fig. 11. Mariner 10 magnetic field measurements at 0.04 s resolution across the bow shock on the inbound leg of the I pass. Panel (a) shows the field magnitude. Panels (b) and (c) show the ecliptic longitude and latitude and panels (d), (e) and (f) show the three solar ecliptic coordinates. (Figure after Ness et al. 1974a.)
Fig. 12. Panels (a) and (b) show the trajectory during the Mercury II encounter. An approximate bow shock is shown to illustrate the requirements for field line intersection with the bow shock. The panels below show low energy electron data obtained during this pass. In (c) is the sum of the highest-energy channel counting rates and in (d) the counting rate of the 13.4 eV channel. Below that is the magnetic field magnitude (e), the impact parameter (f) and its component on the Y solar ecliptic direction (g). (Figure after Ogilvie et al. 1977.)

Energetic electrons (E > 60 keV) and ions (E > 80 keV) almost 10^7 km from Mercury have been reported as probably coming from Mercury (Kirsch and Richter 1985). The enhancements in the direction coming from Mercury are small and close to the level of statistical significance. Kirsch and Richter (1985) attribute the putative energetic particles to substorms on Mercury
rather than bow shock acceleration. Their argument regarding the source of these particles is not convincing because they minimize the possible energization of the ions at the bow shock by using a 20 nT IMF in their calculation whereas, when discussing reconnection two paragraphs later, they maximize the energization by using an IMF that is twice as large. Since it is quite likely that, in fact, no particles were observed coming from Mercury, it seems moot to discuss the efficiency of the possible acceleration mechanisms.

In the same paper that discusses the upstream waves and bow shock, Fairfield and Behannon (1976) also examined the waves in the magnetosheath. Nothing unusual or particular about the Mercurian magnetosheath was observed. The low-energy electrons detected by the plasma analyzer were also quite typical of a planetary magnetosheath (Ogilvie et al. 1977), i.e., they were hotter than the solar wind and cooler than in the magnetosphere.

Structure of the Magnetopause

The magnetopause is the boundary between the flowing, shocked, solar wind plasma in the magnetosheath and the magnetic field and plasma of the magnetosphere. At the Earth, the plasma outside the magnetosphere is usually much more dense and cooler than that inside and the field strength is lower outside than inside. Since there is a change in the magnitude and the direction of the magnetic field at the magnetopause, a current flows at this boundary. The smallest thickness this boundary could have, under the assumption that no strong electric fields are present, is one proton gyroradius. This would occur if the current layer consisted only of particles that started in the magnetosheath and were turned around by the magnetospheric magnetic field and returned to the magnetosheath (cf. Willis 1971). However, this is not how the terrestrial magnetopause behaves (Berchem and Russell 1982). The magnetopause is many gyroradii thick because there is a population of so-called trapped ions that circulate in the boundary and do not return to the magnetosheath or the magnetosphere each orbit. It is of interest to determine if a magnetopause that is not connected to an ionosphere behaves in a similar way. Although it is somewhat difficult to make the measurement from a single spacecraft, the rough estimates that can be made from the Mariner 10 data indicate that the Mercury magnetopause is similar in thickness to that of the Earth (Russell and Walker 1985).

At the Earth, magnetic field lines are transported from the dayside magnetopause to the magnetotail by the process of reconnection (cf. Russell and McPherron 1973). This process may take place in a steady-state manner (cf. Sonnerup et al. 1981) or it may take place in a non-time stationary manner (Russell and Elphic 1979). It is very difficult to show that reconnection is taking place in a steady manner without 3-dimensional high-resolution plasma measurements. Mariner 10 was not so instrumented. On the other hand, the signature of non-steady or patchy reconnection at the Earth's magnetopause has a quite characteristic pattern at the Earth's magnetopause in the magnetic
field. To see this signature, it is best to display the measurements in a coordinate system that is oriented in the plane of the magnetopause. Figure 13 shows high-resolution magnetic field records taken just outside the first inbound magnetopause on the Mercury I pass and is displayed in "boundary-normal" coordinates (Russell and Walker 1985). The feature at 2036:06 which is strongest in the $B_M$ component looks very similar to the structures associated with terrestrial patchy reconnection and which have been called flux transfer events (FTEs). The strength of the magnetic signatures is similar to the terrestrial events but their durations are much shorter. The Mercurian flux transfer events are about 400 km across or about 6% of the size of a terrestrial event. Since the Mercurian magnetosphere is about 5% of the size of the terrestrial magnetosphere, the Mercurian events have the same relative scale as the terrestrial events. They also occurred more frequently, about once a minute at Mercury, compared with about once every 8 minutes on the Earth. Figure 14 shows an artist's conception of a series of flux transfer events connecting a planetary magnetosphere to the solar wind (Kuznetsova and Zeleny 1986).
The small scale sizes of these FTEs at Mercury have been interpreted to be due to the limited time for growth of the structures as they are blown back by the solar wind from the subsolar region (Kuznetsova and Zeleny 1986). One, therefore, might expect that at Jupiter the FTEs would grow to a much larger dimension. However, observations show that at Jupiter the FTEs are of similar size to those at the Earth. Kuznetsova and Zeleny (1986) hypothesize that there is an upper limit to the size of FTEs, and that they cannot grow to a size that exceeds by too many times the thickness of the magnetopause layer. At Mercury, then, the short transit time from the subsolar point limits the growth, and at Jupiter the magnetopause thickness limits the ultimate size.

We note that no evidence has been reported at the terrestrial magnetopause for smaller FTEs near the subsolar point. An alternate possibility is that FTEs grow at the subsolar point until they reach a certain size limited either by the size of the magnetosphere or by the thickness of the magnetopause, whichever provides the smaller upper limit.

**Magnetosphere and Magnetotail**

The crucial nightside and high-latitude portions of the magnetosphere were well sampled by Mariner 10, but the dayside magnetosphere was not probed directly. The dimensions of the dayside magnetosphere, however, were inferred from modeling and extrapolation of the magnetopause and bow shock surfaces (see, e.g., Ness et al. 1974a; Ogilvie et al. 1977; Russell 1977; Slavin and Holzer 1979a). Slavin and Holzer (1979a) obtained solar wind standoff distances of 0.3 to 1.1 R_{e} above the surface of the planet which were
dynamic-pressure-corrected. The variability was attributed to the effects of
dayside magnetic merging and magnetospheric dynamics as will be consid-
ered in later sections.

The fact that Mercury occupies a large fraction of its magnetosphere
significantly alters the expected structure of the magnetosphere. Figure 15
illustrates this in the noon-midnight meridian plane by superimposing a scaled
Mercury on the Earth’s magnetosphere. Simply because of size alone without
any other effects included, the features occurring in the inner magnetosphere,
the plasmasphere and the energetic radiation belts would all be absent. The
plasma sheet would almost touch the surface of the planet near midnight. The
polar cap field, consisting of field lines that entered the magnetotail, would
extend to much lower planetary latitudes on the night side. Figure 16 shows
the orthogonal view from the north. The solid lines with arrows now show the
motion of low-energy, or cold plasma, which drifts across magnetic field lines
that are all perpendicular to the page, because of the electric field applied to
the magnetosphere by the solar wind. The strength of this electric field is
proportional to the strength of the coupling between the solar wind and the
magnetosphere. There is also a component of the electric field due to the
rotation of the Earth and its highly conducting ionosphere. This rotation pro-
duces a set of closed streamlines in the inner magnetosphere of the Earth. On
these streamlines, plasma can circle the Earth essentially forever and build up
in density from sources in the ionosphere at low altitudes. This leads to the formation of the high-density, cold plasma region called the plasmasphere. Outside that region the plasma will be lost, convected out of the magnetosphere, through the magnetopause, at least whenever the coupling between the solar wind and the magnetosphere is strong.

Mercury rotates more slowly than the Earth; it does not have a substantial ionosphere and has very little ionospheric plasma with which to supply the magnetosphere. Thus, even if Mercury did not occupy much of its magnetosphere, we might expect it not to have a plasmasphere. Furthermore, the flow lines should be different from those sketched in Fig. 16; they should be much straighter than the terrestrial ones. Any cold or low-energy plasma that gets into the equatorial region should be swept out through the magnetopause. This should be an important loss process for the Mercurian atmosphere. Any ionized component will find itself swept out of the magnetosphere into the solar wind.

A simple way mentally to compare Mariner 10 observations with the same measurements at the Earth is to use a scaling where 1 $R_M$ equals 8 $R_E$. 
(Siscoe et al. 1975). Using such conversions, the MI encounter, had it taken place at Earth, would have corresponded to an entry into the magnetosphere at $X = -13 \text{ R}_\oplus$ and an exit at $X = -5 \text{ R}_\oplus$ with closest approach at $X = -8 \text{ R}_\oplus$, $Z = 3 \text{ R}_\oplus$, and the spacecraft would leave the magnetosphere at $X = 0.5 \text{ R}_\oplus$, $Z = 10 \text{ R}_\oplus$. While these scalings are only approximate and ignore the very different boundary conditions on these two magnetospheres (e.g., the conducting ionosphere at the Earth vs a poorly conducting regolith at Mercury), they do indicate that the Mariner 10 data set consists of primarily near-tail and high-latitude polar cap observations.

**Magnetic Field Observations.** Figure 17 (Ness et al. 1975b) displays an overview of the Mercury I (29 March 1974) magnetic field vectors projected on the plane perpendicular to the solar direction and on the ecliptic plane. This display complements the time series shown in Figs. 7 and 10. The corre-
sponding diagram for Mercury III (Ness et al. 1976) is not as instructive because the field is less tail-like at the low altitudes of the Mercury III pass. As expected on the basis of the scalings for a terrestrial-type magnetosphere, the region adjacent to the inbound M I magnetopause is the south lobe of the magnetotail. There follows a smooth monotonic increase in field magnitude to a peak field strength of 98 nT at closest approach (Ness et al. 1974b, 1975b). Shortly after closest approach, the field magnitude dropped and a strong current sheet was crossed which reversed the polarity of the X component of the magnetic field. The magnetic field decrease is believed to be diamagnetic and to correspond to the entry into a high-beta central plasma sheet analogous to the region separating the two lobes of the magnetotail at the Earth (Hartle et al. 1975; Ogilvie et al. 1977a). The structure of the current sheet is further investigated in Fig. 18 where the high-resolution (i.e., 25 vectors per second) magnetic field measurements have been subjected to a minimum variance

![Graphs of B1, B2, and B3 fields](image)

**Fig. 18.** High-resolution (0.04 s) magnetic field measurements across the current sheet during the M I pass in the minimum variance coordinate system. The minimum variance is along the B3 direction.
analysis (cf. Sonnerup and Cahill 1967). In the top panels the field is plotted in an orthogonal coordinate system where the maximum variation takes place along the B1 axis and the minimum is in the B3 direction. For a weak near-planet extension of the cross-tail current sheet, the minimum variance direction should be predominantly out of the magnetic meridian containing the dipole field. The analysis in Fig. 18 indicates that this is indeed the case with the minimum variance direction essentially antiparallel to the Mercury Solar Orbital (MSO) Y-axis. These results are consistent with the contention that it was the cross-tail current sheet which Mariner 10 crossed shortly after closest approach as opposed to a temporal variation.

The outbound M I magnetic field observations were very disturbed and characterized by large-amplitude fluctuations. Based on the measurements from all of the Mariner 10 instruments during this period and theoretical calculations, Siscoe et al. (1975) argued that Mercury’s magnetosphere is subject to frequent, short-duration, intense substorms which are directly analogous to the substorm phenomena observed in the Earth’s magnetosphere. The Mercury III high-latitude magnetic field observations in Fig. 10 are far quieter, especially quieter than those seen after closest approach in Fig. 7, with a very smooth rise and decline from the peak field magnitude of 400 nT at closest approach. This second encounter, with its very strong, well-ordered magnetic fields, proved definitively that Mercury possessed a significant intrinsic field which interacted with the solar wind to generate a magnetosphere. In terms of the modeling of the Mercury magnetic field, the two Mariner 10 encounters were highly complementary. The magnetic fields measured during Mercury I, because of its greater altitude, were predominantly due to the magnetospheric current systems driven by solar wind interaction (Ness et al. 1975a). While not as useful for the derivation of the intrinsic planetary magnetic field, the Mercury I observations did aid in the modeling of the magnetosphere (Whang 1977; Jackson and Beard 1977) and the subtraction of these large external fields from both the Mercury I and Mercurian III data sets. As treated in the Chapter by Connerney and Ness, the Mercury dipole moments inferred from the Mariner 10 observations vary from 6 to $2 \times 10^{22}$ G cm$^{-3}$ depending principally upon the magnitude of the higher-order moments included in the harmonic analyses (Ness 1979; Slavin and Holzer 1979b).

Figure 19 shows the magnetospheric field lines in the noon-midnight meridian. It is difficult to determine how long a planetary magnetotail extends even on a well-studied planet. Theoretically this depends on the viscosity of the solar wind and the merging efficiency. One recent estimate of the tail length gives a length of 15 to 60 RM and a polar cap radius of $22^\circ \pm 4^\circ$, assuming a merging efficiency of 0.1 to 0.2 (Macek and Grzedzielski 1986).

*Plasma Observations.* Counting rates for selected energy channels from the plasma electron experiment (Ogilvie et al. 1974, 1977) on the Mercury I and III passes through the magnetosphere are displayed in Fig. 20. At the
Fig. 19. Magnetic field lines and a realistic magnetopause and bow shock location for a model Mercurian field. (Figure after Jackson and Beard 1977.)

bow shock inbound and outbound for both passes, the electrons are hotter in the magnetosheath than in the solar wind. This can be seen as an increase in the flux at the lowest energy. The entrance into the magnetosphere for both encounters is marked by a rise in the high-energy flux and a drop of the low-energy fluxes. These electrons are similar to those seen in the plasma sheet
boundary layer at the Earth. No cold, dense plasmas indicative of ionospheric or plasmaspheric particles were encountered. This result is consistent with the $1R_M$ to $8R_\oplus$ scaling which would scale these terrestrial features to a location well below the surface of the planet. Most of the Mercury I and Mercury III trajectories placed the spacecraft in the vicinity of the midplane plasma sheet and its horn-like extension to lower altitudes. Figure 21 shows energy spectra obtained in the plasma sheet on the two passes. The plasma sheet densities at Mercury are higher than those measured at Earth by a factor of five which is close to the ratio of the solar wind density at 0.5 to 1 AU. This finding supports the hypothesis that the solar wind is their primary source (Ogilvie et al. 1977) in the absence of a significant ionosphere. The magnetospheric implications of the recent discovery of exospheric Na at Mercury (Potter and Morgan 1985a) will be considered in a later section.
Fig. 21. Three electron spectra obtained by the Mariner 10 electron spectrometer. Panel (a) shows a cool plasma sheet spectrum from M III. The high flux at low energies is due to photoelectrons. The shaded line is a scaled photoelectron spectrum from IMP-6. Panel (b) shows a cool plasma sheet spectrum from the M 1 encounter; panel (c) a hot plasma sheet spectrum from M I. (Figure after Ogilvie et al. 1977.)

In the case of the Mercury III passage at higher latitude, Fig. 20 indicates that the spacecraft penetrated a very low-flux region near closest approach. On the basis of the magnetic field observations (Ness et al. 1975a), this region should correspond to the low-altitude extension of the lobes of the magnetotail. These so-called polar cap regions at the Earth are populated by very low fluxes of solar wind electrons which enter the tail along open field lines which connect to the solar wind (see, e.g., Baker et al. 1986c and references therein). At Mercury the large size of the planet relative to the magnetosphere requires that the lobe magnetic fields intersect the surface over a larger area than at the Earth. Conservation of magnetic flux arguments by Ness et al. (1975a) indicate that the colatitude of the polar cap at Mercury is $\sim 22^\circ$, or nearly twice that observed at the Earth.

Figure 22 (Ogilvie et al. 1977) displays the principal plasma regions detected by Mariner 10. Straight lines mark the Mariner 10 trajectories and the magnetic equator based on the magnetic field modeling. The fact that the two passes were nearly parallel to the magnetic equator is consistent with the
near-continuous contact of the spacecraft with portions of the plasma sheet which lies near the magnetic equator at these altitudes. The one region not yet discussed is the hot plasma sheet segment of Mercury I which began around closest approach and extended through the rest of outbound passage. It is this region that was marked by the large magnetic fluctuations that Siscoe et al. (1975) interpreted as being temporal in nature and associated with substorm activity. During substorms at the Earth there is a large scale conversion of magnetic energy into charged particle heating and acceleration in the plasma sheet (Bame et al. 1967; Russell and McPherron 1973). This phenomenon is reproduced in Fig. 20 where the electron population shifts rapidly to higher energies. The peak electron energy was beyond the 690 eV upper threshold of the electron plasma detector, but it was estimated to be around 1 keV (Ogilvie et al 1977) as is typical for terrestrial substorms. This event will be discussed in more detail in the following section.
III. ENERGETIC PARTICLES AND MAGNETOSPHERIC DYNAMICS

As discussed in the introduction, Mariner 10 carried no instrumentation to measure energetic particles from about 1 to 100 keV. This is the energy range in which much of the energy flux in the terrestrial magnetosphere is observed. Furthermore, there were no Mariner 10 ion observations and most of the terrestrial energy flux is contained in the ions. Thus, it is difficult to make direct comparisons of the processes which energize the Mercurian and terrestrial plasmas. The major evidence for a substorm-like phenomenon at Mercury comes from the sudden entry into a region of hot electrons after closest approach on Mercury I, as discussed above, and the observations of energetic particle bursts with the charged particle telescopes. As mentioned earlier, the possibility of pileup of lower-energy particles to exceed the detectors' energy threshold, and our inability to use independent measurements to identify when this has occurred and make allowances, colors somewhat the interpretation of these energetic particle bursts.

Energetic Particle Bursts

The principal results on energetic particle bursts in Mercury's magnetosphere came from flyby M I on 29 March 1974. The upper half of Fig. 23 shows data from Eraker and Simpson (1986) for the period 2030 to 2100 UT. Panel (a) shows counting rates from a sensor designed to measure electrons with $E \geq 170$ keV, while panels (b) and (c) show concurrently measured plasma number density $n$ and electron temperature $T$. Panels (d), (e) and (f) show magnetic field data including field magnitude $B$, azimuth $\gamma$, and inclination $\Theta$. The field data are presented in a right-handed coordinate system in which $X$ is toward the Sun and $Z$ is perpendicular to Mercury's orbital plane.

Of note in Fig. 23 (upper half) is the fact that Mariner crossed the magnetopause (MP) at 2037 UT inbound, reached closest approach at 2046:40 UT, and subsequently crossed the magnetopause again at $\sim$2054:30 UT outbound. Several bow shock (BS) crossings were seen between 2057 and 2059 UT. Panel (a) shows several enhancements of the energetic electrons both in the magnetotail (events $A$, $B$, $B'$ and $C$) and in the magnetosheath (events $D$ and $D'$).

Siscoe et al. (1975) and Ogilvie et al. (1977) have shown that the energetic particle burst periods in Fig. 23 tended to be times of substorm-like behavior. According to these authors, Mariner 10 entered the near-tail below the plasma sheet, on the dusk side. The sheath field was northward on tail entry while the field inside the magnetopause was very tail-like and relatively quiet. As seen in Fig. 23, the magnetic field strength increased with time as the planet was approached and, as discussed above, the higher-energy plasma electrons decreased in intensity (see also Christon et al. 1986). Shortly after closest approach, the field strength decreased rapidly and the field inclination
increased markedly. This indicated a transition from a tail-like to a dipole-like field orientation. In the terrestrial case (Baker et al. 1984) this would be a clear signature of the onset of a substorm expansive phase. Between 2047 and 2054 UT there were several large changes in the magnetic field strength and these occurred in the same time period as did the large energetic particle bursts $B$, $B'$ and $C$. Even the particle burst $A$ prior to closest approach appears to have some (weak) magnetic field changes associated with it. The magnetic
field was strongly southward upon Mariner’s outbound exit from the magnetotail.

Siscoe et al. (1975) thus took special note of the fact that the IMF switched from northward to southward while Mariner was in the Mercurian magnetosphere. They suggest, in analogy with the Earth’s case, that this initiated strong sunward plasma sheet convection and, presumably, enhanced magnetotail energy storage. In this picture, when Mariner was about halfway through the tail, the southward IMF initiated a series of substorms. Siscoe et al. showed by scaling arguments that substorm time scales should be of order 1 to 2 minutes in Mercury’s case compared with 30 to 60 minutes in the terrestrial case (see, also, Slavin and Holzer 1979a). Hence, several substorms in a 20 minute period are not unreasonable for Mercury.

Eraker and Simpson (1986) developed this scenario further and suggested that the substorms in Mercury’s magnetotail resulted from magnetic reconnection (neutral line formation) in the range of 3 to 6 $R_M$ on the night side. They suggested, in close analogy with the Earth, that this substorm reconnection resulted in the impulsive acceleration of energetic particles and that this mechanism was the source of the bursts seen in panel (a) of Fig. 23. The magnetotail model envisaged by Eraker and Simpson and the likely region of particle acceleration is shown in the lower half of Fig. 23.

An important discovery of Simpson et al. (1974) and of Eraker and Simpson (1986) was that the energetic electron bursts detected by Mariner 10 were highly modulated with a period of 5 to 10 s. This is illustrated by the detailed field and energetic particle plot shown in Fig. 24. This exhibits high-resolution data for event C which commenced just prior to 2053 UT on 29 March 1974. Particularly striking features of this event were the rapid rise of flux by several orders of magnitude at the onset and the subsequent strong flux modulation at 6 to 8 s periods. The flux modulation was particularly strong during the decay phase of the event (i.e., from 2053:30 to 2054:15 UT).

Eraker and Simpson (1986) discussed an interpretation of the modulated energetic electron bursts as seen in Fig. 24 in terms of individual particle acceleration events of several seconds duration. Thus, each periodic increase in the events $B$, $B'$, $C$ and $D$, as shown in Fig. 23, upper half—see Eraker and Simpson 1986—was taken as a new episode of magnetic reconnection in Mercury’s magnetotail. Assuming the nominal response of the instrument to electrons and taking a minimum area for the size of the region of enhanced particle flux, they obtain an energy of $10^{10}$ J per 6 s burst. With a 1% efficiency for acceleration, the magnetosphere would have to supply energy at a rate of $10^{11}$ W to power the peak particle intensities. Assuming a maximum area for the region of enhanced particles, they obtain a peak power of $10^{13}$ W. Thus, of order $10^{11}$ to $10^{13}$ W of power would have to be extracted by Mercury’s magnetosphere from the solar wind to power each 6 s burst. This solar wind energy input rate is comparable to the solar wind energy transfer rate estimated for the terrestrial magnetosphere (Baker et al. 1984). Such a large
energy extraction rate for Mercury's magnetosphere would be surprising given that its cross-sectional area to the solar wind flow is ~700 times smaller than that of the Earth. It is also surprising that the tearing-mode instability would repeat that rapidly. Considerations that would lower the required energy would be if there were very significant electron pile up or a contribution of protons to the observed count rate or if the bursts observed were quite rare requiring a long period of energy accumulation before the energy could be released in these bursts.

In analogy with terrestrial substorm models, Baker et al. (1986a) assumed that, during a substorm on Mercury, a neutral line forms across a large fraction of the width of the tail at 3 to 6 R_M from the planet. A major effect of this neutral line would enhance greatly the sunward convection of plasma and magnetic flux in the plasma sheet (Siscoe et al. 1975), thereby rapidly returning flux to the dayside magnetosphere. In conjunction with neutral line flow
tion, there would be a strong planetward collapse of magnetic field lines which produces a much more dipole-like field region in the midnight sector, and a compression wave (Russell and McPherron 1973; Moore et al. 1981) which moves toward the planet at substorm onset, heating and accelerating plasma as it moves. Baker et al. (1986\n) hypothesized that energetic particles are impulsively accelerated in the magnetotail of Mercury and are then transported closer to the planet and injected on closed field lines. They then drift around the planet several times as a relatively coherent bunch (drift echoes) as is seen in the terrestrial case. Baker et al. calculated adiabatic drift times in reasonable accord with the 6 to 8 s periodicities seen in the recurrent bursts of the Mariner data. It is expected that, in each successive passage of the particle bunch through the dayside region, particles would be lost through the magnetopause; one would also expect that particles would be lost into the tail each time the bunch passed through the nightside region.

The event D (Fig. 23) seen in the magnetosheath would presumably correspond (in this model) to bursts of particles on draped sheath field lines lost through the magnetopause as the particle bunch passes around on the day side of the system. The broad overall decrease in the pulse peaks (decay of peak intensity) would be due to expected losses of particles from the system.

Baker et al. (1986\n) concluded that the available magnetic field, plasma, and energetic particle data support a model in which energetic particles are produced primarily near the tail reconnection region some 3 to 6 \( R_M \) from the planet. It is argued that for a brief period (a few seconds) there exist large (~500 keV) electric potentials near the tail neutral line due to an induced electric field. Quantitative estimates suggest that a region some 2 to 3 \( R_M \) wide must be involved in the inductive \( (\partial B/\partial t) \) process.

A variant on this model has been proposed by Christon et al. (1986). They note that as illustrated in Fig. 25 for event B there is a close correlation between the waves in the magnetic field and the fluctuations in the count rate during the decay phase of the burst. They propose that there are only two bursts during the B event, both of which have injection fronts at which the field and particles suddenly increase and following which the particles gradually decay. The analogous process on the Earth is called the multiple onset substorm. Christon et al. (1986) also attribute the bulk of the count rate of the energetic particle instrument to particles with energies above but in the neighborhood of 35 keV. Thus, their model and interpretation of the data requires lower overall voltage drops in the magnetosphere and a lower energy deposit in particle acceleration, placing fewer demands on the efficiency of energy extraction by the Mercurian magnetosphere from the solar wind than either of the other two models.

Relativistic Electron Events

The data taken by Mariner 10 in 1974 suggest two quite different kinds of energetic particle increases (see Fig. 23). The most evident difference between
the A and B events, for example, is the much higher peak counting rate in the B event (\(\sim 10^5 \text{ c s}^{-1}\)) compared to the peak of the A event (\(< 10 \text{ c s}^{-1}\)). In fact, the true B event count rate was really much higher than shown due to electronics saturation effects (see, e.g., Christon et al. 1979). The A event increased gradually toward a peak intensity and the entire event lasted for a period of over two minutes. In contrast, the B event lasted for only about 30 s at which time the B' increased occurred (Fig. 25). Furthermore, the B event exhibited a very fast rise time (\(\sim 1 \text{ to 2 s}\)) followed by a more gradual decay. This is reminiscent of fast rise-slow decay substorm events in the terrestrial magnetosphere (Baker et al. 1984) and is completely different from the A event.

A further distinction between the A and B events is in the magnetic field variations which occur in concert with the particle bursts. For event A there was a smooth, gradual increase (for the most part) of the field strength with no major fluctuations. Even in the detailed plots of the magnetic field components (Ness 1979; Christon et al. 1986), there were only modest breaks in the field traces associated with the A injection event. In contrast, the B event showed major changes in the field strength (Fig. 25) and overall field component configuration at the time of the event onset (Eraker and Simpson 1986; Christon et al. 1986). The field direction signatures at \(\sim 2048\) UT are consistent with the kind of field reconfiguration (return toward a dipolar state) which occurs at terrestrial substorm onset.
A final point of contrast between the A and B events is in the inferred electron energy spectrum. As shown by Eraker and Simpson (1986), the A event is well described by a power law spectrum \( \frac{\partial J}{\partial E} = k E^{-\gamma} \) with the spectral index \( 1.5 \leq \gamma \leq 2.0 \). On the other hand, the B event electron spectrum was found to be much softer and if a power law spectrum is again assumed, the B event requires \( \gamma \simeq 7 \).

In the case of the terrestrial magnetosphere, the source of relativistic electron populations at geostationary orbit (6.6 \( R_E \)) has been a continuing puzzle. The occurrence of distinctive relativistic electron bursts in the Mercurian system constitutes a surprising result within the framework of the generation mechanism of an Earth-like substorm. Baker et al. (1979, 1986a) have argued that Jovian electrons make a dominant contribution at higher energies in the Earth's outer magnetosphere. They suggested that the Jovian electron population enters the distant magnetotail and plasma sheet (where the fields are relatively weak) essentially unattenuated. The spectrally hard Jovian electron population then becomes part of the pre-existing plasma sheet population and begins to participate in the magnetospheric dynamical processes. This model suggests that Jovian electrons would be swept toward the Earth as part of the overall plasma sheet convection.

The model assumes that the electron's first adiabatic invariant \( (\mu \sim E/B) \) is conserved during the convection and injection process. Thus, as the electrons are transported from interplanetary space and the deep tail (where \( B \) is small) to the region of synchronous orbit (where \( B \) is large), there will be an increase of \( B \) by a factor of 20 to 50. Preservation of \( \mu \) and a spectrum extending down to of the order of 100 keV as \( E^{-1.5} \) suggests an increase of flux at a given energy by a factor of 100 or more due to this "adiabatic acceleration" effect. Even larger flux enhancements in the magnetosphere are possible if fluxes of Jovian electrons can be trapped and stored in the outer magnetosphere for many convective time scales. Throughout the magnetosphere, the Jovian electrons would dominate the magnetospheric population (at energies above hundreds of keV) since the Jovian spectrum is so much harder than the substorm-generated magnetospheric spectrum.

Baker (1986) has also advocated this model for Mercury to explain the A event. During normal, quiescent conditions, the Jovian population would probably dominate the Mercurian tail fluxes at most energies. During an episode of greatly enhanced tail convection (as when the IMF suddenly turns southward, for example), it would be expected that much of the tail electron flux would be swept strongly toward Mercury. Under such circumstances, there would be a large injection of Jovian electrons into the inner magnetosphere of Mercury. Thus, one would expect a burst-like increase of Jovian electrons for 1 to 2 minutes during periods of enhanced solar wind-magnetosphere coupling. As in the terrestrial analog, the Jovian electrons at Mercury are suggested to be a high-energy tracer population which has a distinctively hard-energy spectrum. This feature distinguishes the Jovian electrons in
clear way from solar or magnetospheric sources. Such a mechanism obviates the need for the magnetosphere of Mercury to produce highly relativistic, spectrally hard electron bursts by internal generation mechanisms.

In the case of Mercury, one has a very dynamic magnetosphere where it is highly unlikely that persistent, long-term particle trapping occurs (see, e.g., Ogilvie et al. 1977). Similarly, it seems unlikely that the magnetosphere of Mercury is stable on long enough time scales for substantial particle radial diffusion to occur (Hill et al. 1976). Furthermore, the planet fills a large fraction of the magnetospheric phase space so that trans-\(L\) diffusion at low altitude and high latitudes is impossible. All of these facts about Mercury argue against the kind of recirculation mechanism required by the internal generation model at the Earth. Yet, very high-energy electron bursts occur at Mercury, and this therefore suggests that the Jovian (external) source model is operative there.

Energy Input and Dissipation Rates

As a result of Mercury magnetosphere-solar wind interaction and the concomitant substorm-like processes, several possible remotely observable effects are expected (Baker et al. 1986b). First, because of magnetic interaction between the solar wind and Mercury’s outer magnetosphere, there may be “open” polar cusp and polar cap field lines onto which solar wind plasma may have relatively direct access. This inflow of solar wind plasma could potentially constitute a large incident particle kinetic energy flux if one considers the entire magnetospheric cross section as a collection area. Assuming a magnetospheric obstacle size of radius 3 \(R_M\) (1 \(R_M = 2440\) km) to the solar wind flow (see, e.g., Ness 1979), one has \(A_M = \pi R^2 \sim 2 \times 10^{18}\) cm\(^2\). Taking a solar wind speed of 300 to 800 km s\(^{-1}\) and a density of 20 to 50 cm\(^{-3}\) (Slavin and Holzer 1979b), the kinetic energy flux (\(pV^3\)) is estimated between 1 and 40 erg cm\(^{-2}\) s\(^{-1}\). Using the above area estimate, this gives \(10^{10}\) to \(10^{12}\) W of incident power, and even a small fraction of this intercepted power dumped onto the darkside polar caps could produce a substantial surface heating effect.

A more likely remotely observable effect at Mercury is the result of magnetospheric substorm energy dissipation. From examination of the available particle and field data, it is possible to estimate the solar wind electromagnetic energy extraction rate of the system and also the peak energy dissipation rates during explosive substorm onsets. Such estimates can be obtained based on scaling from the terrestrial case (Siscoe et al. 1975; Baker et al. 1986c) or they can be obtained directly from hot plasma and energetic particle observations made by Mariner 10 (see Eraker and Simpson 1986). Magnetospheric scaling arguments (Siscoe et al. 1975) suggest a solar wind energy input rate at Mercury of order \(10^9\) to \(10^{10}\) W. Even higher input rates (\(\sim 10^{11}\) W) might be required if certain substorm dissipation models apply (see, e.g., Eraker and Simpson 1986).
The amount of energy stored in the tail of Mercury and its rate of conversion into hot plasma has been estimated by several means. Siscoe et al. (1975) estimate substorm dissipation in the range \(10^{11}\) to \(10^{12}\) J; if this is dissipated on a time scale of \(\sim 10\) s, then as much as \(10^{11}\) W power is available. Alternative estimates of the substorm energy dissipation suggest \(10^{12}\) to \(10^{14}\) J of energy at a minimum during a substorm burst (Eraker and Simpson 1987, in preparation). Again using \(\sim 10\) s dissipation times, this suggests peak substorm powers of \(10^{11}\) to \(10^{13}\) W or more may be available. Since the body of Mercury fills so much of the magnetosphere, much of the hot plasma and energetic particle power (perhaps \(\geq 10^{12}\) W, during a major substorm burst) would be dumped directly onto the planetary surface.

A majority of the substorm-dissipated power should be confined to the band of magnetic flux tubes that map into the Mercury tail. This set of field lines which define the Mercury auroral zones is illustrated in Fig. 26. It is suggested that the precipitated hot plasma and energetic particles from substorms in this (primarily) nightside latitudinal band (from \(\sim 45^\circ\) to \(\sim 70^\circ\) lat) would constitute a large energy influx onto the cold regolith surface (Baker et al. 1986b). The total surface area of Mercury is \(\sim 8 \times 10^{17}\) cm\(^2\). If one assumes an auroral precipitation region of \(\sim 1/10\) the planetary surface and if one assumes a peak power of \(10^{14}\) W, on occasion, as much as \(\geq 1\) mW cm\(^{-2}\) may sometimes be incident on the \(\sim 110\) K surface.

The calculations of Baker et al. (1986b) suggest that appropriate ground-based infrared telescopes could provide useful information about the solar wind-Mercury interaction. They point out that the infrared data could allow nearly instantaneous assessment of magnetospheric reconfigurations and sequences of energy deposition. Radio observations, on the other hand, would provide time-averaged heating information relating to deeper layers

Fig. 26. Schematic illustration of acceleration of Jovian electrons and their eventual precipitation in a Mercurian auroral oval.
beneath the Mercury surface. Furthermore, by mapping the brightness temperature of the planet across the day-night terminator in two frequencies, one should be able to calibrate the electrical and thermal properties of the Mercurian regolith.

Baker et al. (1986b) therefore conclude that solar wind-magnetosphere interactions at Mercury should produce several effects which would in principle be observable from ground-based or near-Earth facilities: (1) there may be direct interaction of the solar wind with the surface of Mercury which could produce measurable heating effects; (2) substorm-like magnetotail processes within Mercury's magnetosphere may precipitate particles carrying in excess of $10^{12}$ W power into narrow latitudinal bands on the cold dark side of Mercury, producing surface-heated auroral zones; and (3) the presence of Jovian electrons within the inner Mercury magnetosphere may produce transient, very low-frequency synchrotron-emitting radiation belts. Thus, an observational program based on these ideas would hold great promise for providing remote information about the intrinsic properties of Mercury's magnetic field, about the planetary surface, about the dynamics of the Mercury magnetosphere, and about the interaction of this magnetosphere with the solar wind at ~0.4 AU. Such information has the possibility of greatly illuminating issues of general magnetospheric physics through comparative studies with the Earth, Jupiter, Saturn and other such systems. It would also permit a significant clarification of physical conditions near Mercury which would be crucial for proper definition of future Mercury-orbiting spacecraft that may be launched by NASA (Yen 1985) or other agencies.

OUTSTANDING PROBLEMS AND RECOMMENDATIONS

Based upon two magnetospheric passes by the Mariner 10 spacecraft, we have gained a superficial glimpse of the workings of Mercury's magnetosphere. We recognize many apparent similarities to the terrestrial system, but many questions remain. In future satellite missions to Mercury, it would be crucial to probe the dayside magnetosphere and magnetopause. Similarly, a Mercury probe should explore the deep magnetotail region ($r \approx 10 R_M$). Particularly valuable data could result from a highly elliptical, polar orbiting spacecraft.

A number of questions come to mind, based upon analogies with terrestrial magnetospheric analogs:

1. Are there permanent, or quasi-permanent, radiation belts near Mercury just above the planetary equator?
2. Is there anything equivalent to a geomagnetic storm on Mercury, including a major ring current development?
3. How does Mercury produce high fluxes of energetic particles during substorms and what implications does that have for the terrestrial magnetosphere?
4. How large (in latitude and longitude) are the auroral regions on Mercury, and what is the auroral energy dissipation rate?

5. What is the energy transfer rate into Mercury's magnetosphere from the solar wind? Is this process more efficient under the solar wind conditions prevalent at 0.4 AU?

6. How is the dayside reconnection process affected by the lower Alfvénic Mach number in the solar wind at Mercury?

7. How much magnetic flux is contained in the magnetotail? What is the size and shape of the magnetosphere?

8. How is global magnetospheric convection effected on Mercury without a substantial polar ionosphere?

9. Are plasmoids produced in the magnetotail during substorms as they are in the terrestrial case?

10. What are the true ion-to-electron flux ratios throughout the magnetosphere, both at quiet and at disturbed times? This question applies both at plasma and suprathermal energies.

11. What are the electron and ion energy spectra and angular distributions at all points in the magnetosphere, especially during substorms?

12. What plasma instabilities are associated with the larger loss cones present in the magnetosphere of Mercury?

13. How do the magnetospheric electric fields, both transverse and parallel to the magnetic field, affect the loss of the sodium atmosphere upon photoionization?

14. What is the plasma and energetic ion composition within the magnetosphere of Mercury, i.e., what are the ultimate plasma sources?

15. How does the magnetosphere of Mercury behave during intense solar flare bombardment? Where does this energetic flux hit the surface of the planet?

16. What is the role of particle and photon sputtering in producing an atmosphere and exosphere at Mercury and does such sputtering affect substorm dynamics?

17. How often and where does the solar wind hit the planetary surface?

18. What is the source of the observed MHD fluctuations in the magnetosphere? Are they caused by processes in the magnetosphere or in the solar wind?

19. What is the neutron flux from the Sun at quiet and disturbed times?

20. What are the dipole and higher-order moments of the planetary field? If rich in harmonic content, how does this affect the solar wind interaction and magnetospheric processes?

These and many other questions strongly suggest that a planetary orbiter mission for Mercury would be highly desirable. In fact, a pair of simple spacecraft near Mercury, one at low-altitude (polar) and the other in a highly elliptical orbit to monitor the deep tail or the upstream solar wind, would be
well suited to address these questions. Because of the high "metabolism rate" of Mercury's magnetosphere, a one-year mission at Mercury could provide a wealth of data on the magnetospheric dynamics, including a full range of substorm and (possible) storm activity.

Many questions about the intrinsic magnetic field properties and surface conductivities (thermal and electrical) remain crucial to understanding the workings of the inner magnetosphere. As discussed above, the remote radio and infrared observations suggested by Baker et al. (1986b) hold some potential for addressing several magnetospheric and surface questions until a spacecraft mission can be undertaken. Only an orbiter program, however, can fully resolve the magnetospheric structure and dynamics issues.

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