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Flux Transfer Events at Mercury

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An examination of high-resolution Mariner 10 magnetic measurements in the vicinity of the Mercury magnetopause for the three available crossings at high resolution reveals the signatures of what have been called flux transfer events (FTE). These events occur both in the magnetosheath and in the magnetosphere. They last about 1 s and hence have a dimension of about 400 km, or about 5% of the width of the Mercury magnetosphere. This relative dimension is similar to that observed at earth, but the repetition rate is about an order of magnitude faster at Mercury. The net amount of flux transfer is much less than that at the earth. We estimate that less than 1% of the available solar wind potential drop is applied by FTE's to the magnetosphere of Mercury. Evidence for "steady state" reconnection is also observed which may apply a potential drop from 5 to 25 kV across the Mercury magnetopause. The magnetopause itself appears to be about 500 km thick. The shape of the magnetopause at the crossing locations can be approximated with a simple rotationally symmetric conic section with its focus at the center of the planet and an eccentricity of 0.8.

INTRODUCTION

There are four basic types of solar wind interactions with planetary bodies. The solar wind interacts with solid bodies, such as the moon, and is absorbed. It interacts with magnetospheres, such as the earth's magnetosphere, and is deflected. It interacts with planetary ionospheres, such as the ionosphere of Venus, and is also deflected. Finally, it interacts with neutral gases, such as those emitted by comets, which add mass to the solar wind and decelerate it. Within each of these classes of interaction there is a spectrum of possible behaviors, because the plasma conditions vary throughout the solar system, as do the parameters describing the obstacles. In the inner solar system the Mach number and beta of the solar wind should be low because the interplanetary magnetic field strength is relatively high [cf. *Russell et al.*, 1982]. Near Mercury, for example, the expected free stream magnetosonic Mach number is about 3, whereas at 1 AU it is about 5.5. Similarly, the expected ratio of thermal to magnetic pressure, or beta, is about 0.9 at Mercury and 1.8 at earth. Additionally, the behavior of the interaction may be affected by the nature of the obstacle. For example, both Mercury and the earth have intrinsic magnetospheres [cf. *Ness*, 1979*a*], but Mercury does not have a dynamically significant ionosphere, whereas the earth does. In the terrestrial magnetosphere, field-aligned currents flow which couple the plasmas in the outer magnetosphere to the ionosphere. The drag between the ionospheric plasma and the earth's neutral atmosphere provides the load in this electric circuit. Mercury cannot have such field-aligned current systems. Also, it has been postulated that the terrestrial ionosphere can provide electrons to neutralize any charge separation electric fields arising in the solar wind interaction with the magnetopause. This, in part, can explain why the magnetopause is so thick, although trapped energetic particles must also have some role [*Berchem and Russell*, 1982]. Mercury does not have such a reservoir of ionospheric electrons. In short, then, we might expect differences in the solar wind interactions with the earth and Mercury, and these differences might appear in the structure of the magnetopause.

Mercury has been visited by but one spacecraft, Mariner 10. There were three flyby passes, two past the nightside and one in front of the planet. The two nightside passes provided our crossings of the magnetopause as illustrated in Figure 1. Measurements were made with a flux gate magnetometer [*Ness et al.*, 1974] and a rearward looking, low-energy electron, electrostatic analyzer [*Ogilvie et al.*, 1974]. Ion data were not available because of an instrumental malfunction. The measurements of the magnetic field of Mercury have been reviewed by *Ness* [1979*a*, *b*]. Analysis of the magnetopause has concentrated on its location [cf. *Russell*, 1977; *Slavin and Holzer*, 1979]. We know of no publication contrasting the structure of this boundary at Mercury and the earth.

Because of the differences in the solar wind at 0.4 and 1.0 AU and because Mercury lacks a detectable ionosphere, it would appear to be profitable to examine the magnetopause of Mercury as recorded in the Mariner 10 magnetic field data. High-resolution data (0.04 s per sample) are available and were obtained for three of the crossings from the National Space Science Data Center. Data from a fourth crossing, the 1974 outbound crossing, have apparently been lost. In this paper we analyze these magnetic field data in the same manner as we have examined the terrestrial magnetopause [*Russell and Elphic*, 1978] and more recently the Jovian magnetopause [*Walker and Russell*, 1985].

OBSERVATIONS

The magnetometer data available from the data center consist of 0.04-s measurements in Mercury solar orbital (MSO) coordinates. Mercury solar orbital coordinates have X directed toward the sun, Z along Mercury's north orbital pole, and Y completing a right-handed set. We note that the initial results from Mariner 10 were given in Mercury solar ecliptic coordinates based on the earth's orbital plane. Since the aberration angle of the solar wind is ordered in Mercury solar orbital coordinates, we will use that system for quoting positions and normals throughout this paper. In order to study the nature of the magnetic variations, we use yet a third system. We rotate the measurements into boundary normal coordinates with the N direction outward along the (calculated) magnetopause normal, the L direction along the projection of the magnetospheric field, just inside the boundary, and

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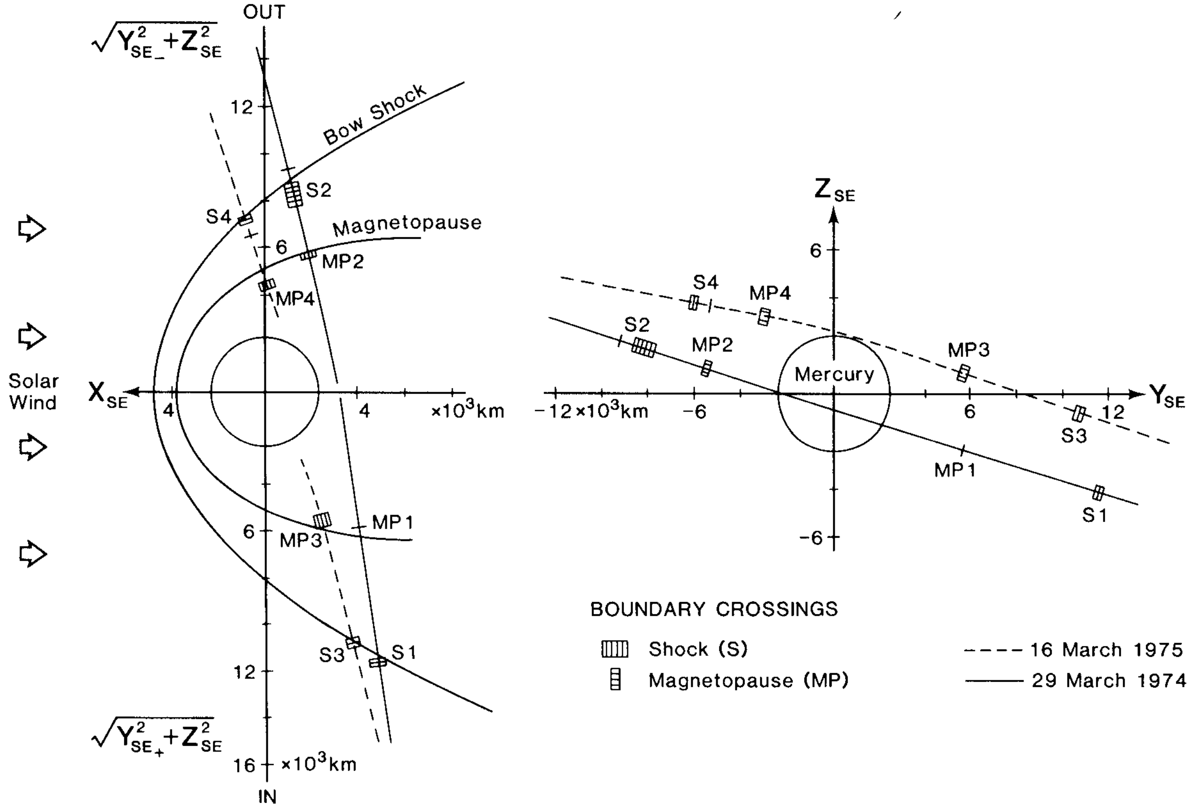

Fig. 1. Trajectories of Mariner 10 on its first and third Mercury flyby. The left-hand panel shows the trajectories in a solar cylindrical projection with inbound and outbound lags plotted separately at the bottom and the top of the panel. The right-hand panel shows the projection of the trajectories on the Mercury solar orbital Y-Z plane.

the M direction perpendicular to **N** and **L** pointing along the magnetopause toward dawn. In order to determine the direction of the normal, we calculate the average magnetic field during quiet intervals just outside and just inside the magnetopause. Then, assuming that at quiet times the magnetopause approximates a tangential discontinuity and that the instantaneous magnetopause normal is roughly along its average direction, we compute the normal to be along the vector cross product of the magnetospheric and magnetosheath fields. Below we present the results of performing these transformations on the available magnetopause crossings. We note that because the magnetospheric and magnetosheath fields are almost parallel in our last example, we have to modify somewhat the above approach.

March 29, 1974, Inbound

The magnetic field measurements across the first Mariner 10 magnetopause crossing are shown in Figure 2 in boundary normal coordinates. Table 1 lists the position of the spacecraft, the derived normals from our tangential discontinuity and minimum variance analysis, as well as a model which is a simple rotationally symmetric conic section with its focus at the center of Mercury. The eccentricity of the conic section has been chosen to be 0.8 to match the observed flaring angle, at this and the other two crossings to be discussed. The observed flaring angle is the angle between the observed normal and the vector perpendicular to the sun-Mercury line through the observation point as projected in the plane containing the sun-Mercury line and the point of observation. This geometric model is chosen to use the expected cylindrical symmetry of the boundary and to "average" the normals over this limited range of local times. It is not intended for use as a global model. The direction of the tangential discontinuity normal used in this analysis is (0.268, 0.793, −0.548) in Mercury orbital coordinates. This normal is consistent with a flaring angle of 15° in this solar-oriented coordinate system. In a solar-wind-oriented system the flaring angle would be about half this value. The normal projected in the Y-Z plane points 34° below the equatorial plane. If the magnetosphere were rotationally symmetric about the solar wind flow, we would expect this angle to be 22°. The minimum variance direction system is (0.223, 0.864, −0.451), which is 7° from our model normal. The average field strength along the minimum variance direction is directed outward, as one would expect for reconnection in the southern hemisphere, and is small, 1.9 nT, or 6% of the magnetic strength at the magnetopause. This smallness is consistent with the fact that the tangential discontinuity and rotational discontinuity normals are so close.

Prior to the crossing, on the left-hand side of Figure 2, the magnetic field has a negative B_L component and a positive B_M component. After the crossing the average magnetic field is along B_L (by definition). The normal component is zero on average, in both the magnetosheath and the magnetosphere. There are significant short-term fluctuations in the normal component. One of these occurs at 2036:52 and lasts for about 1 s. The fluctuation in the normal component goes first positive (pointing outward) and then negative. This fluctuation is accompanied by a magnetic field strength increase and a re-

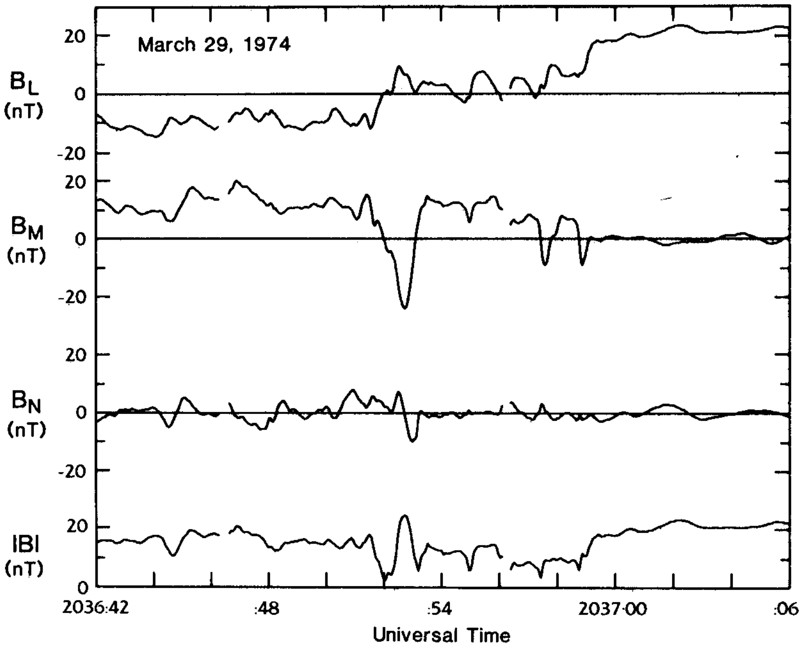

Fig. 2. Magnetic field measurements across first inbound magnetopause crossing, MP1, expressed in boundary normal coordinates. The temporal resolution of the data is 0.04 s.

versal of the B_M component to strongly negative. The B_L component begins to turn positive at this point, suggesting that the spacecraft is just beginning to cross the magnetopause.

Such behavior of the magnetic field has been reported at earth [*Russell and Elphic*, 1978] and interpreted as a flux transfer event (FTE), i.e., patchy or spatially and temporally varying reconnection. Such structures are deduced to consist of twisted tubes of magnetic field [*Paschmann et al.*, 1982; *Cowley*, 1982; *Saunders et al.*, 1984]. The orientation of the field in the center of this event is far from that either in the magnetosphere or the magnetosheath. This turning of the field away from the magnetospheric direction as evidenced by the large negative B_M component is similar to that seen at earth. A twist in the field is equivalent to a field-aligned current along the axis of a FTE. Since Mercury does not have an ionosphere, this current cannot close in the planetary ionosphere or through the planet if the surface is similar to that of the moon. Hence ionospheric closure cannot be a necessary condition for FTE formation.

There is only one crossing of the magnetopause here which would occur if the velocity of the magnetopause were comparable to or less than that of the spacecraft. If it were greater than that of the spacecraft and oscillating about its average position, there would be several crossings. However, this is only a statistical argument. In any one crossing the velocity could be arbitrarily large. If we assume that the velocity of the magnetopause is small in relation to that of the spacecraft and take the spacecraft velocity relative to Mercury (see Table 1) to be its velocity in the magnetopause frame, the 10 s required to cross the magnetopause, 2036:52–2037:02 UT, indicates that the magnetopause is about 100 km thick. On the other hand, the other two magnetopause crossings to be examined below both consist of multiple crossings. Hence it is possible that the magnetopause does move at velocities of about 50 km/s. If so, then the Mercury magnetopause has a thickness comparable to that of the earth of about 500 km.

Figure 3 shows data obtained 48 s earlier. At 2036:07 there is a positive-negative transient in B_N and a significant B_M perturbation away from either the magnetospheric or magnetosheath directions. In many respects this event is a dupli-

TABLE 1. Magnetopause Geometry

	Crossing		
	MP1	MP3	MP4
Date	March 29, 1974	March 16, 1975	March 16, 1975
Time, UT	2037	2229	2244
Location (MSO), km	(−4197, 5055, −2374)	(−2593, 6392, 339)	(80, −2420, 3460)
Model normal (MSO)	(0.208, 0.906, −0.369)	(0.373, 0.927, 0.044)	(0.653, −0.372, 0.660)
TD normal (MSO)	(0.268, 0.793, −0.548)	(0.287, 0.940, −0.182)	···
MV normal (MSO)	(0.223, 0.864, −0.451)	(0.369, 0.925, 0.086)	(0.612, −0.405, 0.679)
Angle N_M, N_{TO}, deg	12.6	13.9	···
Angle N_M, N_{MV}, deg	7.4	2.4	3.2
Velocity (MSO), km/s	(1.77, −9.90, 3.87)	(2.81, −9.65, 3.89)	(3.25, −10.08, 2.82)
V · N, km/s	−9.5	−9.0	8.3

TD, tangential discontinuity; MV, minimum variance.

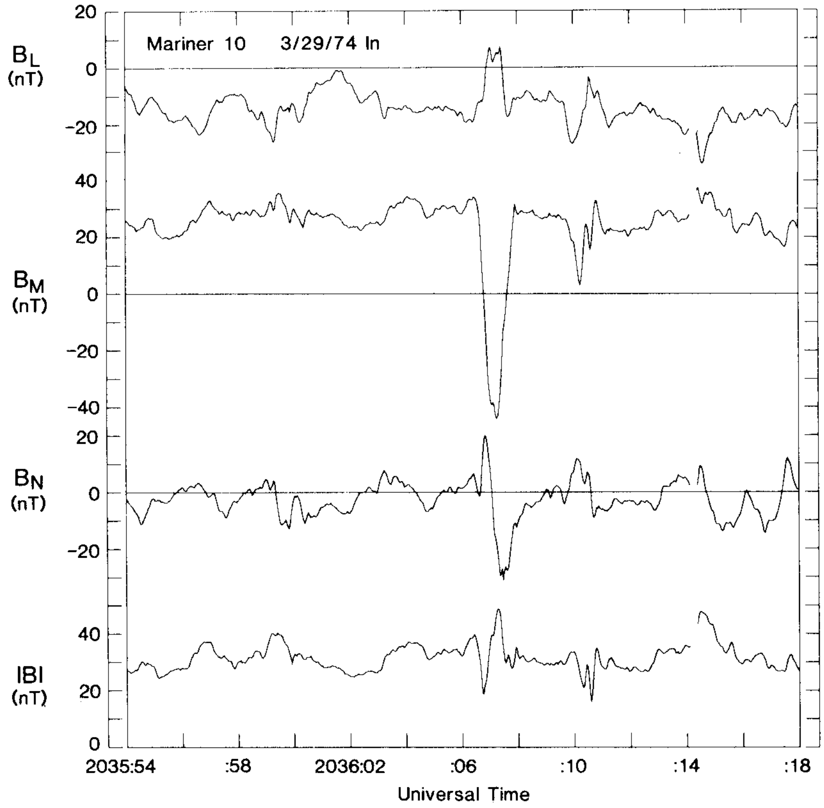

Fig. 3. Magnetic field measurements just external to the first inbound magnetopause crossing, MP1, expressed in boundary normal coordinates.

cate of the 2036:52 event except that it is not followed immediately by a magnetopause crossing. We note again the short, 1-s, duration of the event.

There is only one other event during this approach to the magnetopause, at 2036:21, that resembles an FTE. However, it is not as well developed as the events at 2036:07 and 2036:52. Prior to 2036:07 the magnetosheath shows much structure, but it does not resemble the signature seen for FTE's. In terrestrial records, flux transfer events are seen inside the magnetosphere [*Daly and Keppler*, 1982; *Rijnbeck et al.*, 1984] as well as outside. However, no obvious signatures were observed by Mariner 10 once inside the magnetosphere on this pass.

March 16, 1975, Inbound

The magnetic field measurements just in front of the second inbound magnetopause crossing are shown in Figure 4 in boundary normal coordinates. The normal direction MSO coordinates are (0.287, 0.940, −0.182). Thus the boundary is flaring at 16°, or slightly more than on the first pass, as would be expected from Figure 1. The normal points slightly southward, below the MSO equator by 10°. Although there is much variation in the B_N component, none of this variation resembles the classic signature of a flux transfer event, in which there is an enhancement in the field magnitude, a bipolar signature in B_N, and large B_M and B_L variations such as those seen in Figures 2 and 3. In fact, there appear to be no FTE signatures in the magnetosheath on this pass.

The magnetopause crossing takes place in Figure 4 from about 2229:15 to 2229:40. The gradual rotation of the field is masked somewhat by the large-amplitude fluctuations. However, it can be easily seen in low-pass-filtered data. Table 1 shows that the velocity of the spacecraft at this time is 9.0 km/s inward along the magnetopause normal. Thus the boundary is nominally about 225 km thick. However, since there is a partial return to the magnetosheath centered about 2230 (see Figure 5), we believe that the magnetopause was probably moving outward at least 9 km/s during the first crossing. Thus we believe the magnetopause was at least 500 km thick at this time, again consistent with terrestrial data.

The minimum variance magnetopause normal is also given in Table 1. It is only 2.4° away from our model normal. Its projection on the Y-Z plane is slightly upward, as one would expect according to the trajectory in contrast to the tangential discontinuity normal which points slightly downward. The average magnetic field component along the normal is 6 nT, or 30% of the total field strength at the magnetopause. The three eigenvalues corresponding to the maximum intermediate and minimum variance were 140, 28, and 3 $(nT)^2$ for our analysis of low-pass-filtered data with a 0.2-Hz corner frequency. The field inside the magnetosphere is directed antisunward, as would be expected in the southern hemisphere. The normal component across the magnetopause is directed outward, as would be expected for reconnection to the southern hemisphere.

Figure 5 shows the corresponding measurements just inside the magnetosphere. A magnetospheric flux transfer event is seen here at 2230:49. Apparently, FTE's were occurring on this day, but during the magnetosheath segment of the trajectory none were encountered. This is in contrast to the 1974 inbound pass during which magnetosheath FTE's occurred, but we observed no magnetospheric FTE's. The signature of

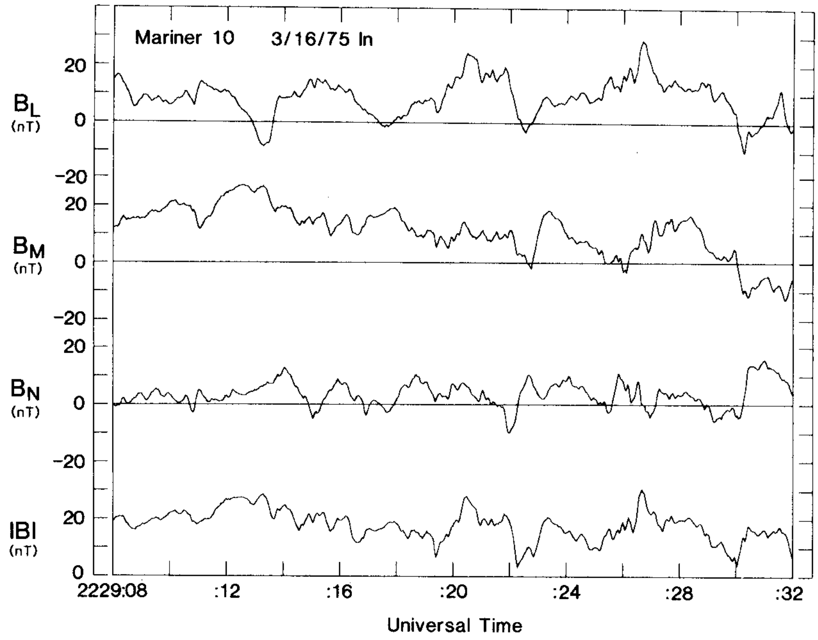

Fig. 4. Magnetic field measurements just outside the second inbound magnetopause, MP3, expressed in boundary normal coordinates.

this FTE is not unlike the previous magnetosheath FTE's or the FTE's seen at earth. There is the characteristic positive/negative signature in B_N and the twisting of the field away from the magnetospheric direction as shown in B_M.

March 16, 1975, Outbound

The final magnetopause crossing is shown in Figure 6. This crossing is at high latitudes. At this particular time and location the magnetosheath and magnetospheric fields were nearly parallel, although from the expected geometry of field line draping and the earlier and later observed IMF direction we would not expect them to be parallel at the subsolar point. Since the field in the magnetosheath and magnetosphere were nearly parallel, we could not use their cross product to determine the magnetopause normal. Instead, we chose to use the direction of minimum variance which proved successful in the other two crossings. The L direction was chosen to be along the magnetospheric field inside the magnetosphere perpendicular to the M direction. The resulting normal is along (0.612, −0.405, 0.679) in MSO coordinates. This corresponds to a flaring angle of 37° and a projected angle on the Y-Z plane of 59° above the MSO equator. This appears to be reasonable upon inspection of Figure 1 and is very close to our model normal. Figure 6 shows some interesting variations

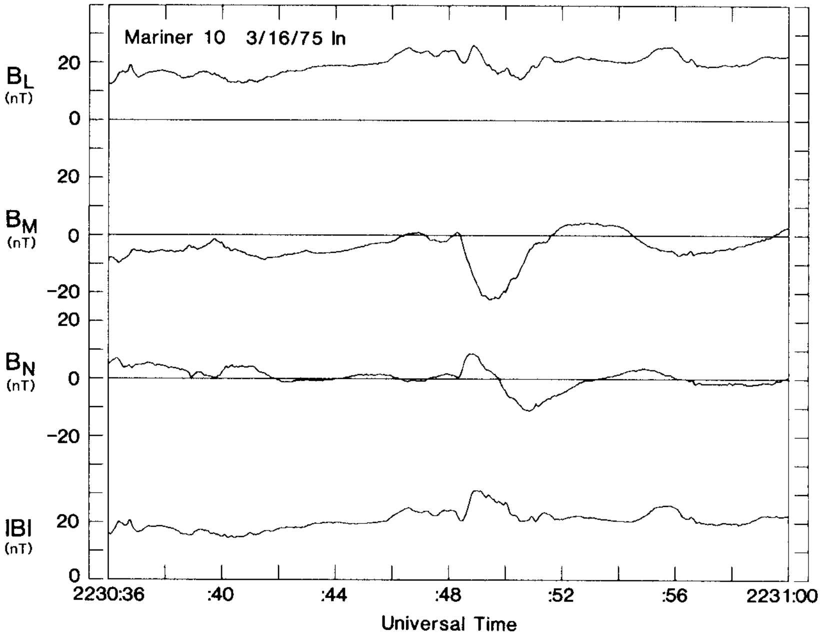

Fig. 5. Magnetic field measurements just inside the second inbound magnetopause, MP3, expressed in boundary normal coordinates.

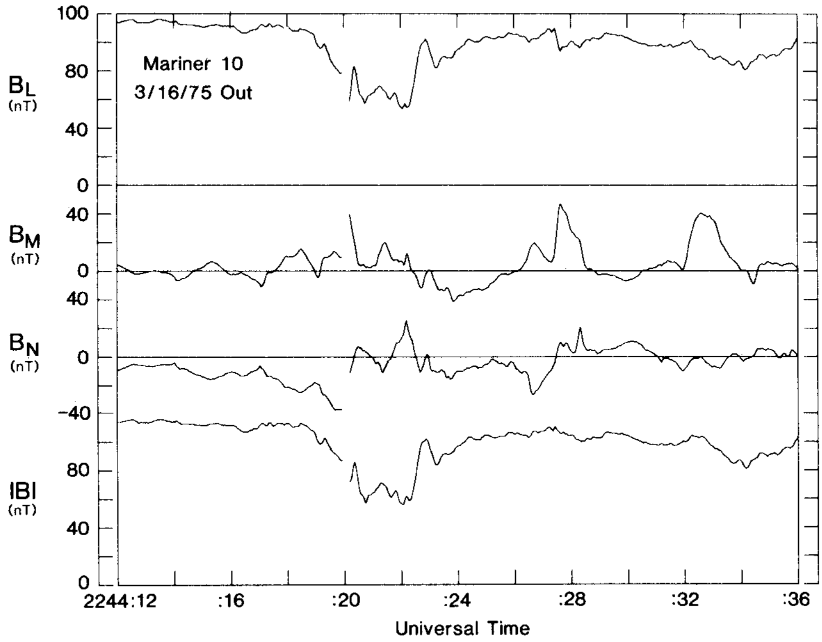

Fig. 6. Magnetic field measurements across the second outbound magnetopause, MP4, expressed in boundary normal coordinates.

in the magnetic field, but none of these appear to be classical flux transfer events. It is very hard to judge the beginning and end of the magnetopause crossing here, so we cannot infer the thickness. There also appears to be multiple partial crossings of the boundary. We note that the normal component of the field across the magnetopause is small, only 2% of the background field.

Figure 7 shows 24 s of data obtained 50 s later in the magnetosheath. The event at 2245:17 has a field strength enhancement, a positive/negative signature in the normal component, but only a slight twisting of the field in the *L-M* plane. This does appear to be another FTE. In short, then, we see FTE signatures either inside the magnetosphere or in the magnetosheath on all three passes.

DISCUSSION

The original observation of flux transfer events at the earth revealed them to be about 3 min long and to occur about every 15 min [*Russell and Elphic*, 1978]. Later more extensive studies showed that FTE's occurred more frequently on the average, about every 8 min, and could be much shorter [*Rijnbeck et al.*, 1984]. However, the shorter fluctuations tend not

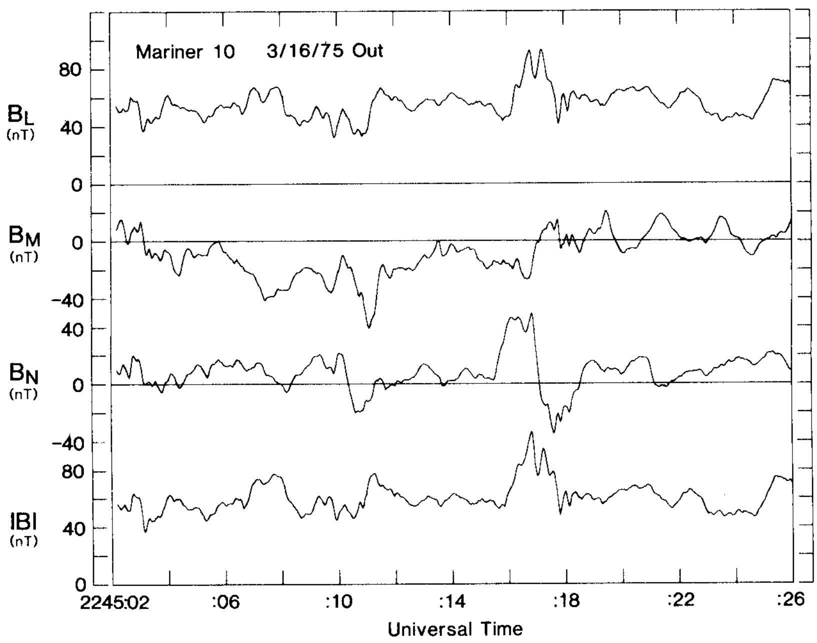

Fig. 7. Magnetic field measurements just outside the second outbound magnetopause, MP4, expressed in boundary normal coordinates.

to have clear a signature as the longer events, so that there is some debate as to whether all the smaller events should be classified as flux transfer events [*Berchem and Russell*, 1984]. The Mercury FTE's last about 1 s and reoccur about once a minute in the data studied. Around the time of this encounter the solar wind as flowing at about 600 km/s [*Slavin and Holzer*, 1979]. Thus in 1 s the magnetosheath plasma moves about 400 km. If a typical field strength inside a Mercury FTE is 40 nT and if the FTE is approximately circular in cross section as suggested by the size of the B_N fluctuations, then it contains about 5 kWb of magnetic flux in contrast to the approximately 25 MWb in a terrestrial FTE. The flux transfer rate is about 100 Wb/s, and this is responsible for the application of about 100 V across the magnetosphere in contrast to the perhaps 8–20 kV applied by FTE's at earth [*Russell and Elphic*, 1978; *Rijnbeck et al.*, 1984]. Since the magnetosphere of Mercury is 10^4 km across and the electric field in the solar wind at Mercury is about 8 mV/m, then the potential drop across the width of the magnetosphere is about 80 kV. Thus the FTE potential drop is less than 1% of the available potential drop from the solar wind.

While the dimensions of the Mercury FTE's are much smaller than their terrestrial counterparts, relatively they are not so small. The terminator distance of the Mercury magnetopause is about 5000 km, or 5% of the terrestrial distance. Mercury FTE's are about 400 km across, or about 6% of the typical 1 R_E scale size at earth [*Saunders et al.*, 1984]. Thus they are similar in relative dimensions to the terrestrial FTE.

The contrast between FTE's at Mercury, the earth, and Jupiter is also quite interesting. At Mercury and the earth, FTE's occur quite frequently and reach dimensions which are a significant fraction of the dimension of the magnetosphere. At Jupiter the FTE phenomenon is infrequent, and the size of an FTE is insignificant in comparison with the size of the Jovian magnetosphere [*Walker and Russell*, 1985]. Perhaps the difference in behavior is due to the difference in the solar wind Mach number in the inner and outer solar system. The terrestrial records should be examined for evidence of such control.

Flux transfer event occurrence has been shown to be controlled by the direction of the IMF [*Berchem and Russell*, 1984; *Rijnbeck et al.*, 1984]. We do not have a measurement of the direction of the interplanetary magnetic field when Mariner 10 was crossing the magnetopause on these days. If we assume that the magnetic field remained constant in direction during its magnetosheath passages, then the IMF orientation or the first pass would not have been expected to produce flux transfer events, for it was pointing northward by 63° above the equatorial plane. During the 1975 passage the field was pointing 19° above the equator in the Y-Z plane inbound and 33° below it outbound. The dominant characteristic of the field, however, was that it was strongly radially toward the sun.

In addition to the presence of flux transfer events, there was other evidence of reconnection. There was a rotation of the magnetic field at each crossing whose minimum variance direction was close to that of our model normal. Further, in our first two cases there was a significant normal component of the magnetic field across the boundary. If such components were present across the entire dayside hemisphere, there would be a 5 to 25-kV potential drop across the Mercury magnetopause. We note that the largest normal field was seen on the crossing for which we expect the field orientation to be most favorable for reconnection at the subsolar point. The quasi steady state reconnection appears to generate a much larger potential drop than might be associated with flux transfer events.

The 1974 outbound magnetopause crossing, for which no high time resolution data are available, is a candidate for even stronger reconnection. When the spacecraft entered the magnetosheath at 2055 UT, the magnetic field was strongly southward, as it had been earlier in the solar wind prior to 2025 UT. The fact that it was not southward immediately prior to the inbound bow shock crossing at 2027, nor immediately after the outbound shock at 2100, is consistent with the variability of the IMF seen on this day away from the encounter period. The disturbed period from 2047 UT to the magnetopause at 2055 UT has been interpreted as being due to a substorm [*Siscoe et al.*, 1975]. Since Mercury does not have an ionosphere and since the ionosphere plays a major role in substorm current systems, it is likely that a Mercury "substorm" is quite different than a terrestrial substorm. In fact, it may be most appropriate to consider the disturbed period on the 1974 outbound pass as a different magnetospheric "state" which occurs when the interplanetary magnetic field is southward.

The thickness of the magnetopause is not too unlike that of the terrestrial magnetopause. The presence of multiple and partial crossings indicates that the velocity of the magnetopause is greater than that of the spacecraft. The time required for crossing these boundaries, together with a velocity relative to the boundary about twice that of the spacecraft relative to Mercury, gives a magnetopause with a thickness of the order of 500 km. This implies that the magnetopause is more than one ion gyroradius thick. Such a thickness can be maintained by so-called "trapped particles" which gyrate on closed paths within the current layer and do not return to the magnetosheath. Finally, we were able to approximate the shape of the magnetopause adequately with a simple rotationally symmetric conic section with an eccentricity of 0.8. We do not expect this simple form to be applicable over the front of the Mercury magnetopause because it predicts a nose distance for the magnetopause, which is closer than that obtained given the measurement of the magnetic moment and the observed bow shock positions. In short, the Mercury magnetopause, despite its lack of an ionosphere, is much like the earth's magnetopause.

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