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Disturbances in Mercury's magnetosphere: Are the Mariner 10 "substorms" simply driven?

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Abstract. In addition to providing the first in situ evidence of a magnetosphere at Mercury, the first flyby by Mariner 10 inspired reports of Earth-like substorms. While the small scales at Mercury should make the substorm timescale there much shorter than it is at the Earth, these early interpretations may have too readily assumed that the substorm requirement of an energy storage and release phase occurs. Instead, its size should make Mercury's magnetosphere especially prone to disturbances that are purely "driven" by the changing external boundary conditions on the magnetosphere imposed by the solar wind. These result simply from the magnetosphere's relatively unhindered reconfiguration in response to the varying interplanetary parameters, including the IMF southward component. In this paper we demonstrate that the "disturbed" structure observed outbound from closest approach during the first Mariner 10 flyby can alternately be explained as a consequence of a typical period of rotating IMF. We use an appropriately modified IMF-dependent terrestrial magnetosphere model scaled for Mercury, together with an assumed, reasonable IMF time series, to reproduce the magnetic field signature during the disturbed outbound pass segment. This result suggests that rapid restructuring of the small magnetosphere in response to changing local interplanetary conditions may dominate the magnetospheric dynamics at Mercury. Future Mercury magnetosphere missions should be instrumented to distinguish between this driven magnetospheric dynamism and any internal Earth-like substorm processes. These results also remind us that driven reconfigurations must always be considered in studies of transients in the terrestrial magnetosphere.

1. Introduction

When Mariner 10 first flew by Mercury's nightside, coming within 705 km of the surface in March 1974, it obtained magnetic field measurements (shown in Figures 1a and 1b) providing unambiguous evidence of a "miniature" Earth-like magnetosphere [*Ness et al.*, 1975]. A second flyby upstream added no additional magnetospheric data; however, a third at a closer nightside distance (327 km) at high latitude in March 1975 confirmed the presence of an internal field the order of ~7×10^{-4} times as strong as Earth's dipole.

Whang [1977] constructed a model of Mercury's magnetosphere based on the data from these two passes. They concluded that there were significant quadrupole and octupole contributions in the Hermean field, although later work [*Connerney and Ness*, 1988] showed that the measurements could be equally well explained using a pure dipole. Whang's method of analysis made assumptions regarding the "closed" nature of the Mercury magnetosphere as well as a consistent geometry during both passes. Indeed, the interval of poorest fit with the model coincided with the period of structured field observed on the outbound leg of the first pass (see Figures 1a and 1b), suggestive of dynamic behavior. This interval, which has since been interpreted as the Hermean analog of terrestrial magnetospheric substorms [e.g., *Siscoe et al.*, 1975; *Eraker and Simpson*, 1986; *Christon*, 1987], inspired the reanalysis described here.

Our understanding of magnetospheres has considerably improved since 1977, in part due to more complete and better observations and in part due to the development of three-dimensional numerical simulations of the solar wind interaction with a planetary dipole field. The terrestrial magnetosphere has been the natural focus of this attention because of both its accessibility and interest in our own "space weather." From the perspective of the present study, the key result from the terrestrial investigations is the confirmation that the basic configuration of the magnetosphere depends on the interplanetary magnetic field orientation (as suggested by Dungey as early as 1961). Thus it is interesting that in spite of this early realization, many analyses and interpretations still assume the "average" magnetosphere configuration prevails. Such has been the case at Mercury as well.

Recently, *Tsyganenko* [1996] developed a version of a data-based magnetospheric field model that depends on the interplanetary magnetic field (IMF) clock angle

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(arctan(B_{yimf}/B_{zimf})). This model produces magnetospheric field configurations that are generally consistent with those obtained in global MHD simulations [e.g., those of *Fedder et al.* 1995]. It also provides a relatively easily used tool for studying the configuration of magnetospheres under various interplanetary conditions. Since Mercury's magnetosphere to first order appears to resemble a scaled down version of the Earth's, and is moreover so small that it can establish a new configuration on the order of the nominal solar-wind transit time past it of ~1 min, we here examine the possibility that the above mentioned "dynamic" structure is a result of interplanetary field reorientations rather than an Earth-like substorm.

2. Description of the New Model

Tsyganenko [1996] describes the details of the data-based terrestrial magnetosphere model used here. The important addition to this model relative to Tsyganenko's earlier models, for the purpose of this application, is the inclusion of an "interconnection" field based on an assumed normal component distribution on the magnetopause. The adopted normal component distribution depends on the IMF clock angle, the distance from the subsolar point along the planet-Sun (X) axis, and the distance from the field line draped over the magnetopause that passes through the subsolar point. Data fits were used to determine the dependence of the strength of the interconnection field on the IMF clock angle. With the knowledge that the average interplanetary magnetic field during the Mariner 10 passes was ~20 nT, we can thus examine the extent to which an IMF-dependent magnetosphere model resembles the flyby results. However, several modifications are in order for this Mercury application. Because of Mercury's suspected lack of a stable trapping region for energetic particles and practically nonexistent ionosphere, the ring current and Birkeland current contributions were eliminated from the "modular" model. Moreover, because the in situ data from Mariner 10 are so sparse, as a first approximation an untilted pure dipole was adopted to represent

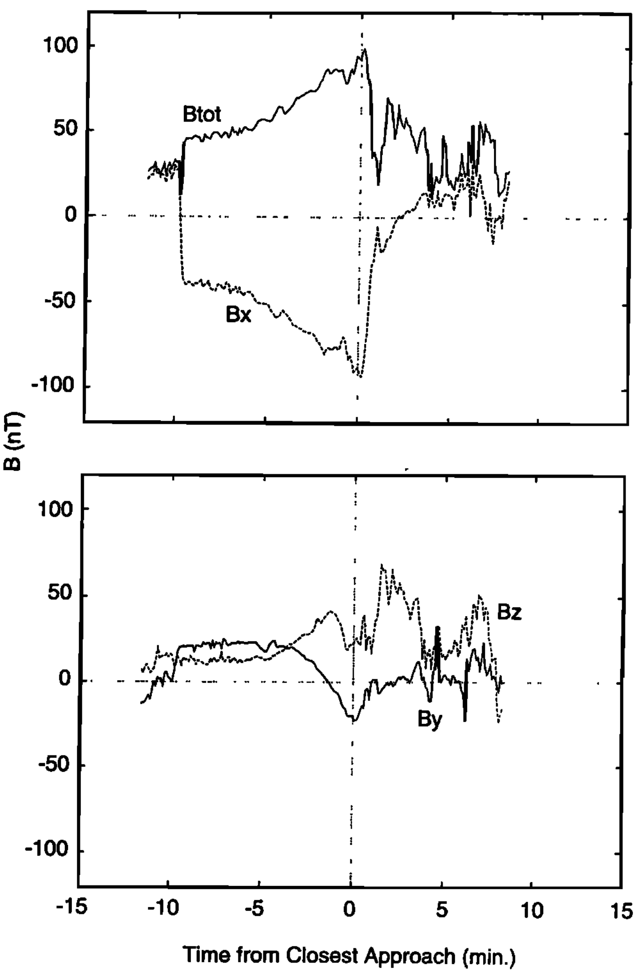

Figure 1a. Time series of magnetic field data from the first flyby of Mercury by Mariner 10 on March 29, 1974 [*Ness et al.*, 1975]. The coordinate system used is analogous to a GSE coordinate system for Earth, with x pointing toward the Sun, y opposite the direction of planetary orbital motion, and z upward from the Mercury orbital plane. Time is minutes from closest approach.

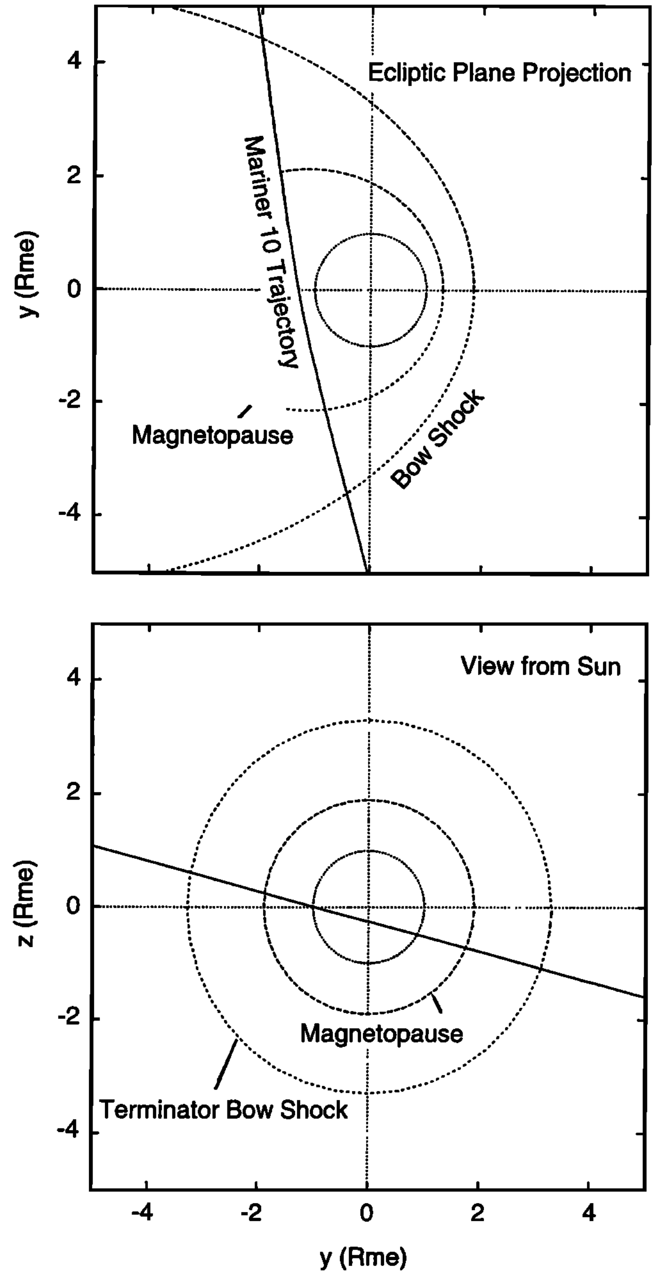

Figure 1b. Views of the Mariner 10 trajectory along which the field in Figure 1a was measured.

the internal field. Our initial comparisons with the data indicated that the model appears similar to the observations when the terrestrial magnetosphere field strength is multiplied by two and its scale is reduced by a factor of 7 (we note that *Ogilvie et al.* [1977] suggested a reduction factor ~8).

The IMF-dependent magnetosphere model helps us to visualize the range of configurations that the Mercury magnetosphere may take simply in response to a changing interplanetary field orientation. As illustrations, Figure 2 shows noon-midnight meridian field lines for zero IMF and for 20 nT northward and southward IMFs. Projections of 3-D magnetospheric field line configurations, for northward, southward and eastward IMFs, are shown in Figure 3. While the actual interplanetary field at Mercury's orbit is usually dominated by the X (planet-Sun axis) component, which is not included in the model used here (the IMF cone angle at 0.3-0.5 AU is ~20-25 deg), the magnetosphere field geometry is expected to be most sensitive to the IMF perpendicular component with which the intrinsic field merges on the dayside. It should also be recognized that the configurations in Figure 3 do not include the draped magnetosheath field that surrounds the magnetospheric field. Simulated "flights" through the magnetospheres illustrated in Figure 3 along the Mariner 10 first flyby trajectory produce the distinctive time series of the field components in Figure 4. These quite different-looking time series hint at the potential for a rotating IMF to produce apparent field "structure" during a flyby.

Figure 5 shows the typically variable local interplanetary field vector components (in the usual solar ecliptic coordinate system) measured outside of the Mercury bow shock on the day of the 1974 Mercury flyby. At a normal solar wind speed of 400 km/s it would take about 1 min for a particular solar wind element to pass by a magnetosphere about 10 Mercury radii (R_{me}~2439 km) long. This suggests that changes occurring on this timescale or longer may be considered to affect the near-Mercury magnetosphere configuration in a "quasi-steady" manner from the IMF control point of view. (The timescale for the terrestrial magnetosphere response, in contrast, is ~20 min. [e.g. *Bargatze et al.* 1985]. Thus we can surmise that the >1 min fluctuations in IMF direction seen in the interplanetary fields in Figure 5 are routinely reconfiguring the magnetosphere in a manner that should have been detectable during the ~20 min passes through Mercury's magnetosphere by Mariner 10.

Application of a time-varying magnetosphere configuration to the data from the first flyby of Mariner 10 requires that we assume some time history of the interplanetary field while Mariner 10 was within the Mercury magnetosphere. To obtain a first guess, we "flew" through the model along the spacecraft trajectory assuming zero IMF and subtracted the resulting model B_y and B_z components (those that determine the IMF clock angle) from the observed components as if simple superposition applied. Then we iteratively adjusted this inferred IMF time series, guided by the behaviors of the components in Figure 4, to obtain the result shown in Figure 6. The IMF time series that was required in the scaled magnetosphere model to obtain this result is shown in Figure 7, where we also show a sample of the local IMF

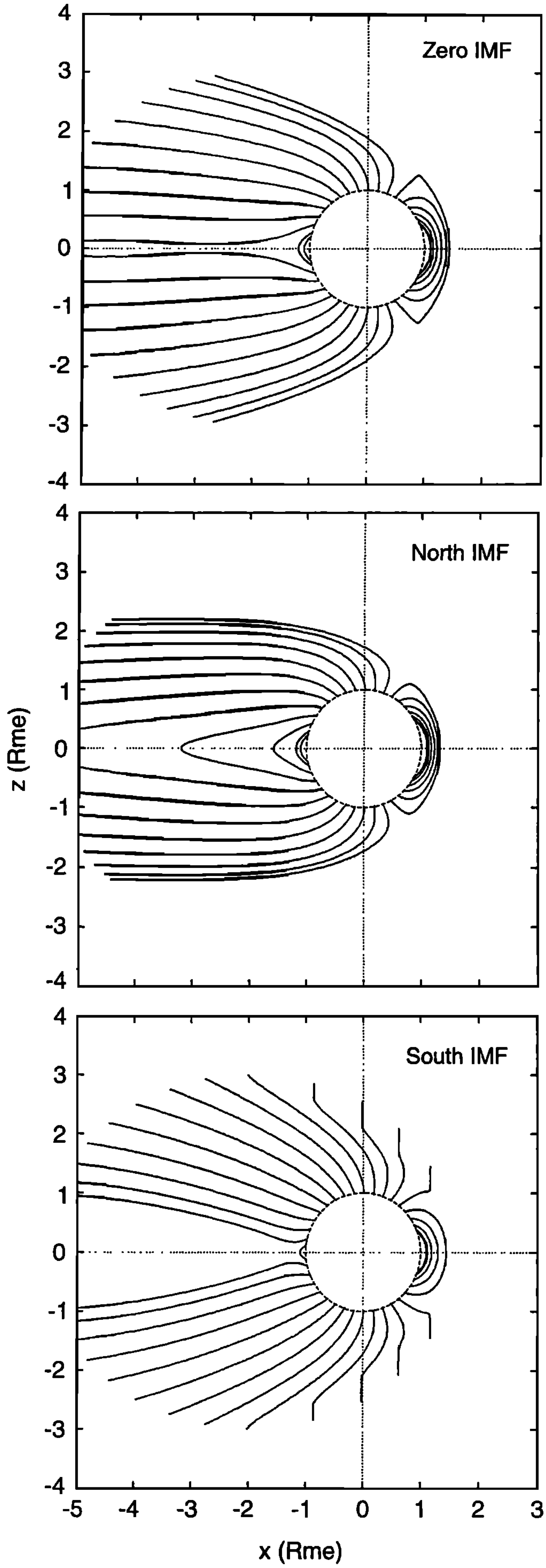

Figure 2. Configuration of field lines in the noon-midnight plane in our Mercury adaptation of the *Tsyganenko* [1996] model for (top) zero IMF and for (middle) 20 nT northward and (bottom) southward IMF.

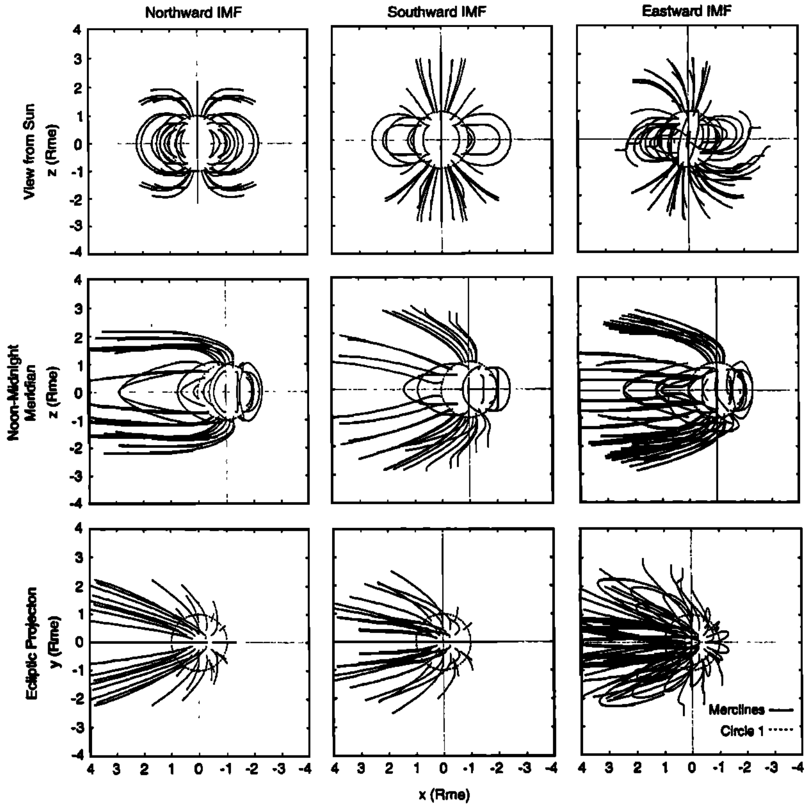

Figure 3. Orthogonal views of the three-dimensional field line structure of the Mercury magnetosphere model for three different (north, south and east) 20 nT IMF orientations.

(Figure 7a) with and without the inferred IMF inserted (Figure 7b). (This presentation is intended to illustrate that the inferred IMF is not atypical.) Our apparent success in Figure 6 at reproducing the trends in the observed field with a reasonable IMF time series suggests that what was observed outbound on Mariner 10 should be quite common at Mercury. Moreover, magnetospheric field variations of the magnitude observed are to be expected from IMF rotations and do not necessitate the

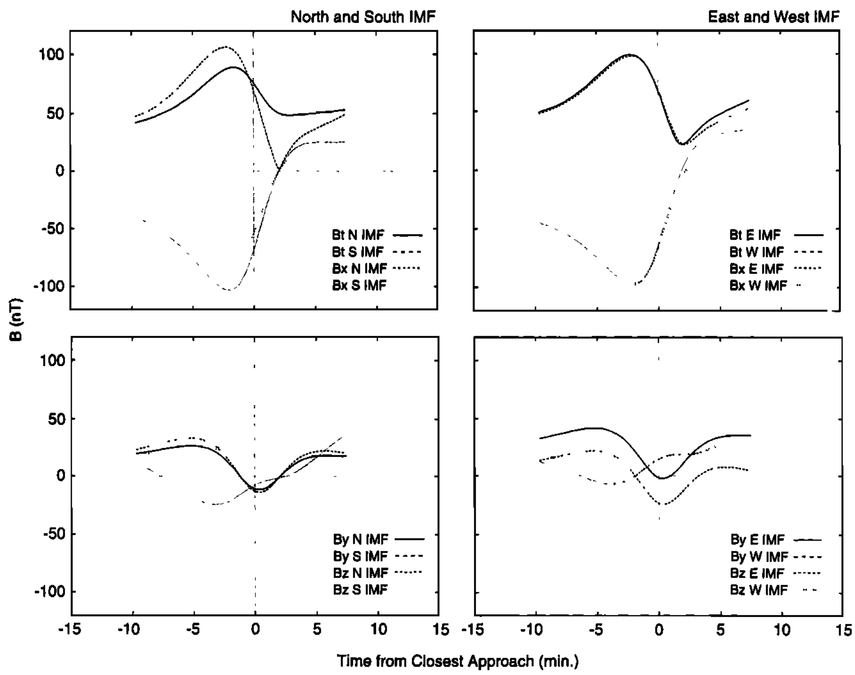

Figure 4. Simulated time series of magnetic field vector components along the Mariner 10 trajectory in Fig. 1b for different (20 nT) IMF orientations.

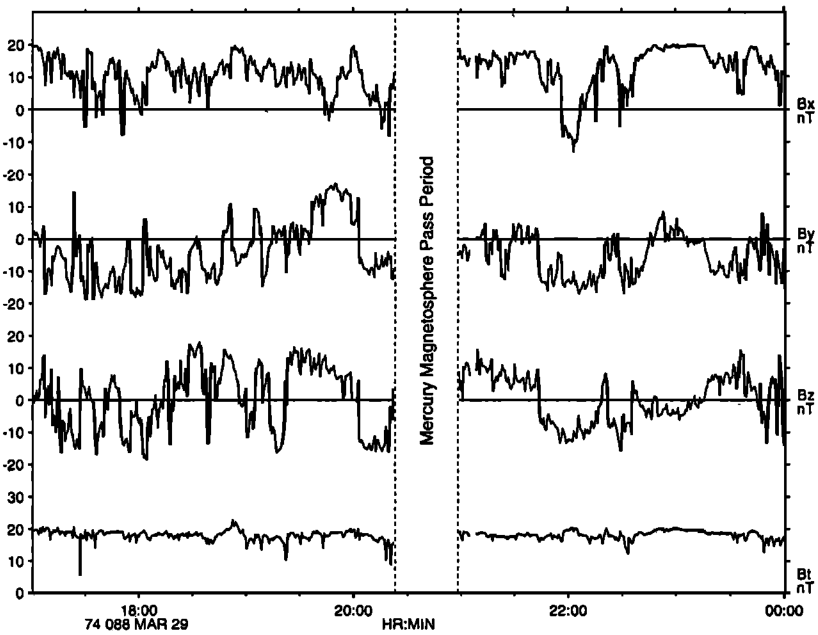

Figure 5. IMF variations observed on Mariner 10 around the time of the 1974 Mercury flyby.

operation of any special internal processes (e.g., substorm storage and release).

3. Substorm Electron Events?

One of the reasons for inferring that a substorm occurred during the first Mercury flyby was the appearance of transient energetic electron fluxes during the period of structured magnetospheric field [*Eraker and Simpson*, 1986]. However, a problem arising in interpreting these electron fluxes as internally generated was the small magnetosphere's inability to accelerate >30 keV electrons by substorm-like processes. *Baker et al.* [1986] and *Christon* [1989] offered alternative explanations such as injection of external (Jovian) electrons into the magnetosphere and observations of an energetic population associated with a magnetospheric plasma sheet akin to Earth's.

Our model allows us to examine the connections with the interplanetary populations as a function of time along the Mariner 10 trajectory since the open field line intersections can be determined. Figure 8 shows the time series of the electron data superposed on the Mariner 10 trajectory from *Christon* [1989] and our model field lines that map to the trajectory for the adopted first flyby IMF time series (in Figure 7b). The two field line "snapshots" shown are for both the time of the flyby and for ~20 s earlier (obtained by shifting the Figure 7b time series by that amount). The apparent freshly opening field lines in the tail

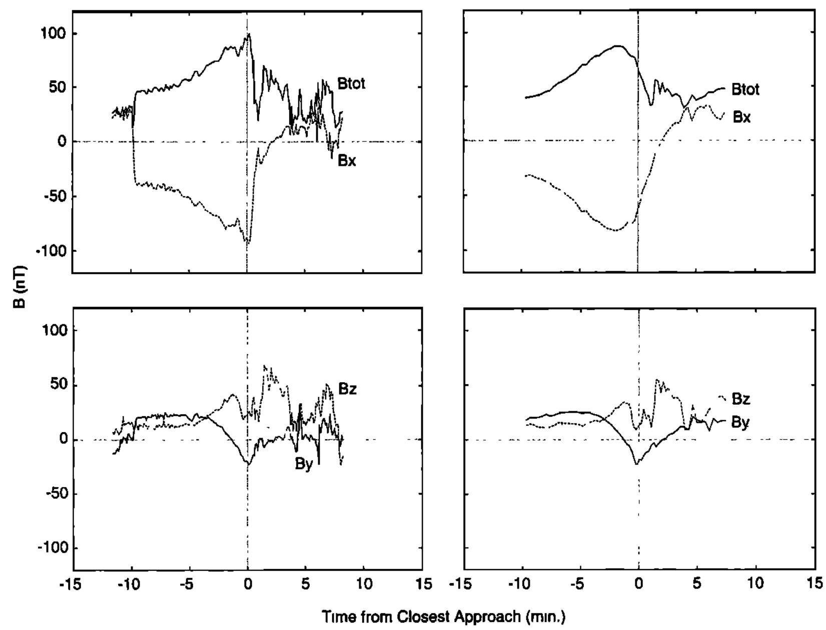

Figure 6. Comparison of a simulated time series produced by using the magnetosphere model with (right) varying IMF orientation (left) with the measurements from Mariner 10.

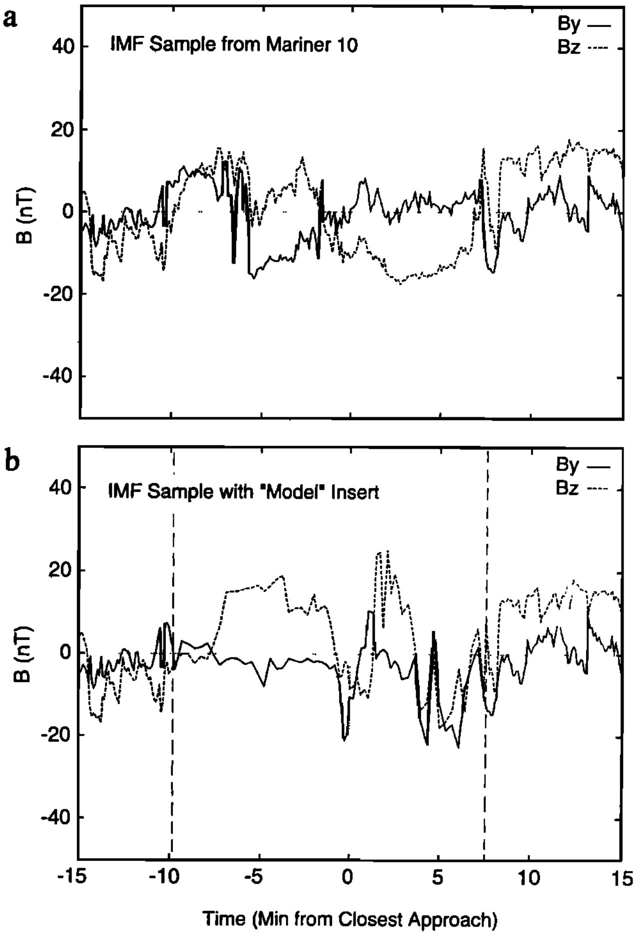

Figure 7. (a) Time series of B_y and B_z field components from a typical period of quiet solar wind and (b) assumed time series of IMF used to produce the field variations in the model in Figure 6. The adopted field (between the dashed lines) has been inserted into the time series above it to illustrate its unexceptional appearance.

coincide quite well with the "A" and "B" events. This finding is consistent with those analyses where it was concluded that the energetic electrons must be either external or magnetospheric boundary layer in origin (although it could be argued that they map to an X line in the tail).

An important conclusion that can be drawn from the above result is the value of measuring the solar wind electron heat flux on any future Mercury magnetospheric missions. Electron heat flux measurements could have been used to infer the relationship of the observed electron "events" to open field lines and in general to diagnose the magnetospheric configuration. While *Ogilvie et al.*'s [1977] instrument on Mariner 10 measured electrons in the heat flux energy range (>80 eV), it did not have the angular resolution necessary to separate the solar wind heat flux "beam" from the more general electron background. These heat flux measurements will be especially important on a single spacecraft mission with no upstream "monitor."

4. Possible Range of This Effect

The Mercury magnetosphere is expected to undergo average changes as Mercury moves from its aphelion at 0.47 AU to its perihelion at 0.31 AU. In response to the accompanying solar wind density (and hence dynamic pressure) change of a factor of ~2.3, the nominal subsolar magnetopause position should move from its inferred ~1.3 R_{me} Mariner 10 location to ~1.2 R_{me}. At the same time the magnetosphere will also be affected by the increased local interplanetary field strength, which changes from ~20 nT to over 45 nT on average at perihelion. Both the scale reduction and enhanced IMF should make the effects described here even more pronounced than those observed on Mariner 10.

The IMF variations in Figure 5 moreover represent "quiet" solar wind conditions. Given our findings, it is interesting to speculate what extreme configurations the Mercury magnetosphere might show in the face of unusually strong flows and fields such as those expected in passing coronal mass ejections (CMEs). The Helios 1/2 spacecraft orbited the Sun between 0.3 and 0.5 AU in 1975-1980, obtaining measurements of the interplanetary field and plasma during the rise to solar maximum 21 [e.g., *Mariani and Neubauer*, 1990]. A number of CMEs were observed on the Helios spacecraft, with fields as high as ~150 nT prevailing for hours. Yet these do not rival what might be expected based on some especially large CME fields (~80 nT) observed on Pioneer Venus Orbiter at 0.7 AU [*Luhmann et al.*, 1993]. Assumption of radial expansion alone would imply fields of up to ~435 nT occurred at the 0.3 AU distance of Mercury perihelion. These strong fields may have magnetospheric effects that exceed those of the associated enhanced dynamic pressures. Because the aforementioned interplanetary field strengths are so far above those allowed in the data-based magnetosphere model used here, we cannot hope to gain accurate insights from its use in these cases. However, such large IMF boundary conditions would provide an interesting exercise should a global MHD magnetosphere simulation for Mercury be attempted some day.

5. Concluding Remarks

The reanalysis of the first Mariner 10 flyby magnetospheric field measurements described here suggests that magnetic "structure" introduced by a changing magnetosphere configuration in the time-varying interplanetary magnetic field should be a regular feature of spacecraft observations. Interpretation of the data from Mercury must be sensitive to the possibility that much of what is seen is externally controlled, or driven. In this regard, it is notable that *Engle* [1997] recently argued that even the steady portions of the first and third Mariner 10 magnetosphere passes seem to require quite different solar wind dynamic pressures to explain their relative observed characteristics. This may be another case where IMF differences can provide an alternative (or additional) explanation. In addition, we are reminded that the strong southward interplanetary fields associated with CMEs have the potential to almost completely expose the planet's surface to the solar wind, a situation of potential importance for the atmosphere. Interestingly, the Mercury magnetosphere in a ~100 nT southward interplanetary field accompanying a moderately strong CME might very much resemble the recently detected, similarly scaled, Ganymede magnetosphere [*Kivelson et al.*, 1996] except that the solar wind flow is supermagnetosonic.

Mercury is a likely destination for a spacecraft mission carrying magnetospheric instruments during the next decade. Our current understanding of magnetospheres, especially from Earth observations and models, will be used to plan the best possible measurements. The above analysis adds support to concepts that

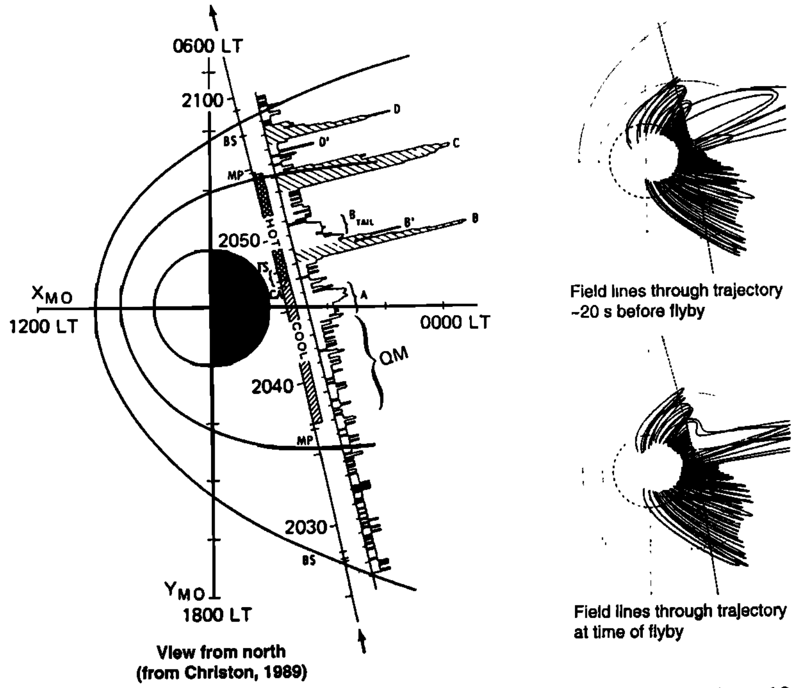

Figure 8. (left) Time series of energetic (>35 keV) electron fluxes measured on Mariner 10 as illustrated by *Christon* [1989]. (right) Ecliptic projection of model field lines that intersect the Mariner 10 trajectory calculated for (top) ~20 s before the flyby and (bottom) during the flyby using the IMF variation in Figure 7. Note that electron events A and B coincide with field lines that appear to be in the process of opening.

include trajectories and instrumentation addressing the interplanetary context. In particular, with a single spacecraft our ability to interpret what is observed inside of the small Hermean magnetosphere will depend critically on our ability to determine whether the spacecraft is on open or closed field lines.

Finally, these results increase our awareness of the nearly continuous "transients" that must also occur in the Earth's magnetosphere in response to changing interplanetary conditions. While both the larger size of the terrestrial magnetosphere and Earth's substantial ionospheric "load" moderate its responsiveness to external variations, here too one must consider in substorm studies and interpretations the role(s) that changing boundary conditions play. Mercury is the perfect natural experiment to help us appreciate those influences.

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