

INTERACTION OF SOLAR WIND WITH MERCURY AND ITS MAGNETIC FIELD

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INTRODUCTION

The first *in situ* measurements of the solar-wind interaction with the planet Mercury and its magnetic field were performed by the Mariner-10 spacecraft on March 29, 1974. The unexpected observation of a very well-developed, strong detached bow-shock wave was interpreted (Ness et al., 1974; 1975a, b) as being due to the existence of a modest magnetosphere-like region associated with an intrinsic magnetic field of the planet. Simultaneous measurements of the low-energy electron flux ($13.4 < E_e < 687$ eV) by Ogilvie et al. (1974) provided strong correlative evidence for this interpretation. In addition, intense bursts of higher-energy electrons ($E_e > 179$ keV) and protons ($E_p > 500$ keV) were reported by the charged particle telescope experiment (Simpson et al., 1974) as occurring in a region of space corresponding to the magnetosphere and magnetosheath following the closest approach to Mercury. The lack of evidence for any appreciable atmosphere or ionosphere suggests that the interaction is unlike that at Venus, where a substantial atmosphere-ionosphere is responsible for the deflection of the solar-wind flow and the development of the detached bow-shock wave.

The targeting strategy for the second encounter on September 21, 1974 was biased to provide optimum imaging coverage of the south polar regions. The spacecraft did not approach close enough to the planet to observe directly the magnetic field of the planet or the bow-shock wave associated with solar-wind interaction. The third and final encounter on March 16, 1975 provided additional observations of the magnetic field environment and solar-wind interaction with the planet Mercury and dramatically confirmed the earlier interpretations of an intrinsic planetary field (Ness et al., 1975b; Hartle et al., 1975b).

It is the purpose of this report to present a brief review of the magnetic field and solar-wind electron observations and to estimate the intrinsic magnetic field of the planet Mercury and the implications of such a field for the planetary interior.

OBSERVATIONS

The bow shock is well identified both by the abrupt increase in average field magnitude and by the increase in the fluctuating magnetic field, as measured by the RMS parameter. The magnetopause is well distinguished by the abrupt directional change in the magnetic field and also reflected in the abrupt termination of high-frequency fluctuations measured by the RMS parameter. As the solar wind is deflected around Mercury, the magnetic field is confined to a region of space similar to the terrestrial magnetosphere. Electrical currents which flow on the surface of the magnetosphere, that is, in the magnetopause, are responsible for the abrupt change in direction which is characteristically observed in the magnetic field as a spacecraft crosses this surface. In addition, the development of a magnetic tail and neutral sheet is associated with the interaction and leads to a system of electrical currents whose magnetic field can be described as having an origin associated with the tail of the magnetosphere.

Magnetic-field data from the first encounter are shown in figure 1. As the spacecraft approached the planet, the interplanetary field was approximately 20γ in magnitude but increased suddenly to 40γ between 20:27 and 20:28 as the bow shock was traversed. Indeed, three traversals of the bow shock are readily distinguished. Note that the RMS parameter, which is the Pythagorean mean of the component fluctuations of the magnetic field over a 1.2-s interval, also increases. Subsequently, the field decreases from 40γ to $\sim 30 \gamma$ when a sudden directional change in the magnetic field occurs at 20:37, which is identified as traversal of the magnetopause. It is seen that the fluctuations, as measured by the RMS parameter, abruptly terminate coincident with that boundary. These data are completely consistent with the characteristics of the terrestrial magnetosheath and its boundaries as observed by Earth-orbiting satellites.

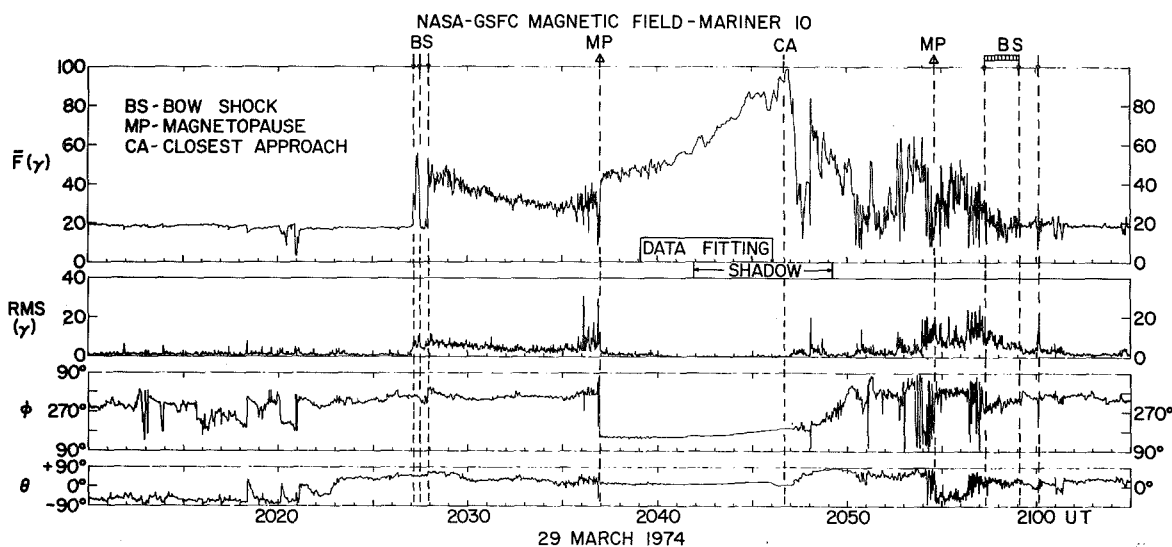


Figure 1. Magnetic-field measurements, presented in solar-ecliptic coordinates with θ = latitude and ϕ = longitude, obtained during first encounter with Mercury by Mariner-10.

As the spacecraft continues on its trajectory, the magnetic-field intensity rises while the direction changes slowly, but mainly it is directed away from the planet. The maximum field of 98 γ is measured just after closest approach (724 km) between 20:46 and 20:47. Subsequently, the field fluctuates very rapidly with large excursions in magnitude but with less significant variations in the direction. Identification of the outbound magnetopause and bow shock are difficult in this diagram because of the pulsating nature of the shock due to the interplanetary field direction being almost parallel to the bow-shock surface normal. By contrast, note the very sharp and distinctive bow shock observed inbound which is associated with the condition of a perpendicular shock.

Accompanying these magnetic-field data are simultaneous measurements of the solar-wind electrons, shown in figure 2. The identification of the boundaries of the magnetosheath, that is, the bow shock and the magnetopause, is simultaneous with those shown in figure 1.

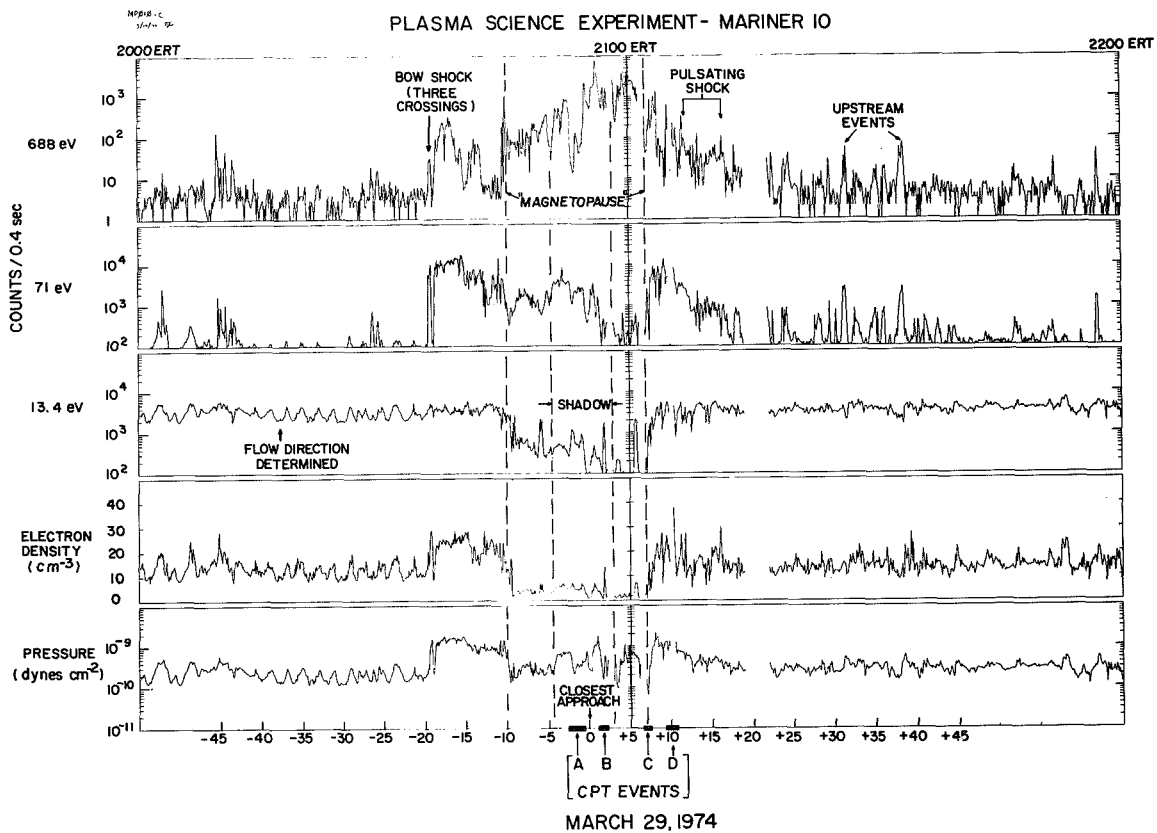


Figure 2. Solar-wind electron measurements simultaneous with the magnetic-field measurements in figure 1 (Ogilvie et al., 1974).

Characteristic changes in the electron spectrum and deduced equivalent fluid parameters, such as density and temperature, show excellent agreement with the overall model of the supersonic solar wind interacting with a large obstacle deflecting the solar wind. The rather disturbed conditions following closest approach on Mercury-I have been discussed by Siscoe et al. (1975) in the framework of a temporal variation of the magnetospheric structure due to the occurrence of a substorm associated with a southward interplanetary magnetic field.

The opportunity to confirm the observations of a strong solar-wind interaction with Mercury and the unique identification of a magnetic barrier as the obstacle to solar-wind flow occurred during the third encounter with the planet. Data from this encounter are shown in figures 3 and 4. Again, the bow-shock and magnetopause boundaries are well identified in both magnetic field and solar-wind electron data. The trajectory for the third encounter was selected to occur at a higher latitude than the near-equatorial pass of the first encounter with closest approach distance being only 327 km. These two parameters combine to provide a much more definitive sampling of the magnetic field of the planet in that the maximum field observed is 400 γ (see figure 3). The bow-shock characteristics, inbound and outbound, are the reverse of the Mercury-I encounter, due to the change in upstream interplanetary magnetic-field direction. This also provides an additional critical test of the nature of the obstacle to solar-wind flow. Were the magnetic field and magnetosphere created by a complex induction process, then its characteristics would be expected to change substantially between the two encounters. This is not the case since a very complementary set of magnetic-field and electron data (see figure 4) was obtained which provides unequivocal evidence for the existence of an intrinsic magnetic field of the planet. The trajectories of the Mariner-10 spacecraft for the two encounters are shown in figure 5. This figure illustrates that the first encounter was mainly an equatorial pass while the third encounter was a high-latitude, polar region pass.

ANALYSIS

The magnetic-field and solar-wind electron observations by Mariner-10 show a rather good correspondence to Earth's magnetosphere if the approximate scaling of sizes is taken into account. The stagnation point of solar-wind flow is inferred to be at ~ 1.5 Mercury radii, while for Earth, $11 R_E$. Thus, the planet Mercury occupies a very large fraction of the volume of the magnetosphere, and even when measurements are performed relatively close to the surface of the planet, the total magnetic field includes a substantial contribution due to the external sources. It is this fact, coupled with a very limited data set available in a restricted volume of the magnetosphere sampled by Mariner-10, which restricts our ability to analyze the data uniquely in terms of characteristics of an internal planetary magnetic field.

The approach used has been to assume internal sources described by an harmonic term of degree $n = 1$, which means a centered dipole whose tilt, phase, and magnitude are to be determined. A uniform external field is represented by the term corresponding to $n = 1$.

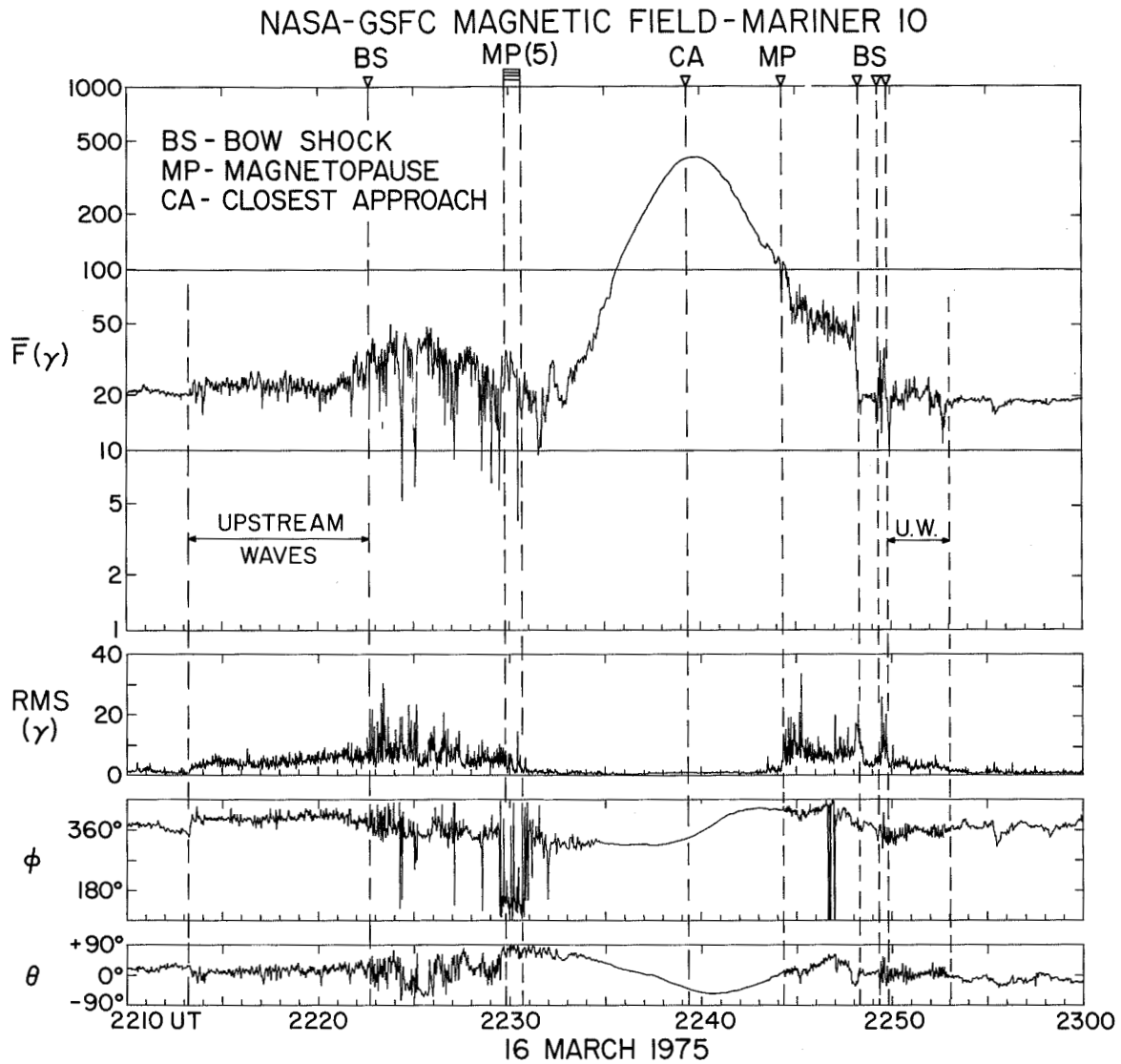


Figure 3. Magnetic-field measurements during third encounter with Mercury by Mariner-10.

A least-squares fit has been made to the data by a classical minimization process for the three orthogonal field components. The results obtained for the internal dipole coefficients are as follows:

	Mercury-I	Mercury-III
$g_1^0 =$	-344	-320
$g_1^1 =$	+ 16	- 41
$h_1^1 =$	- 59	+ 51

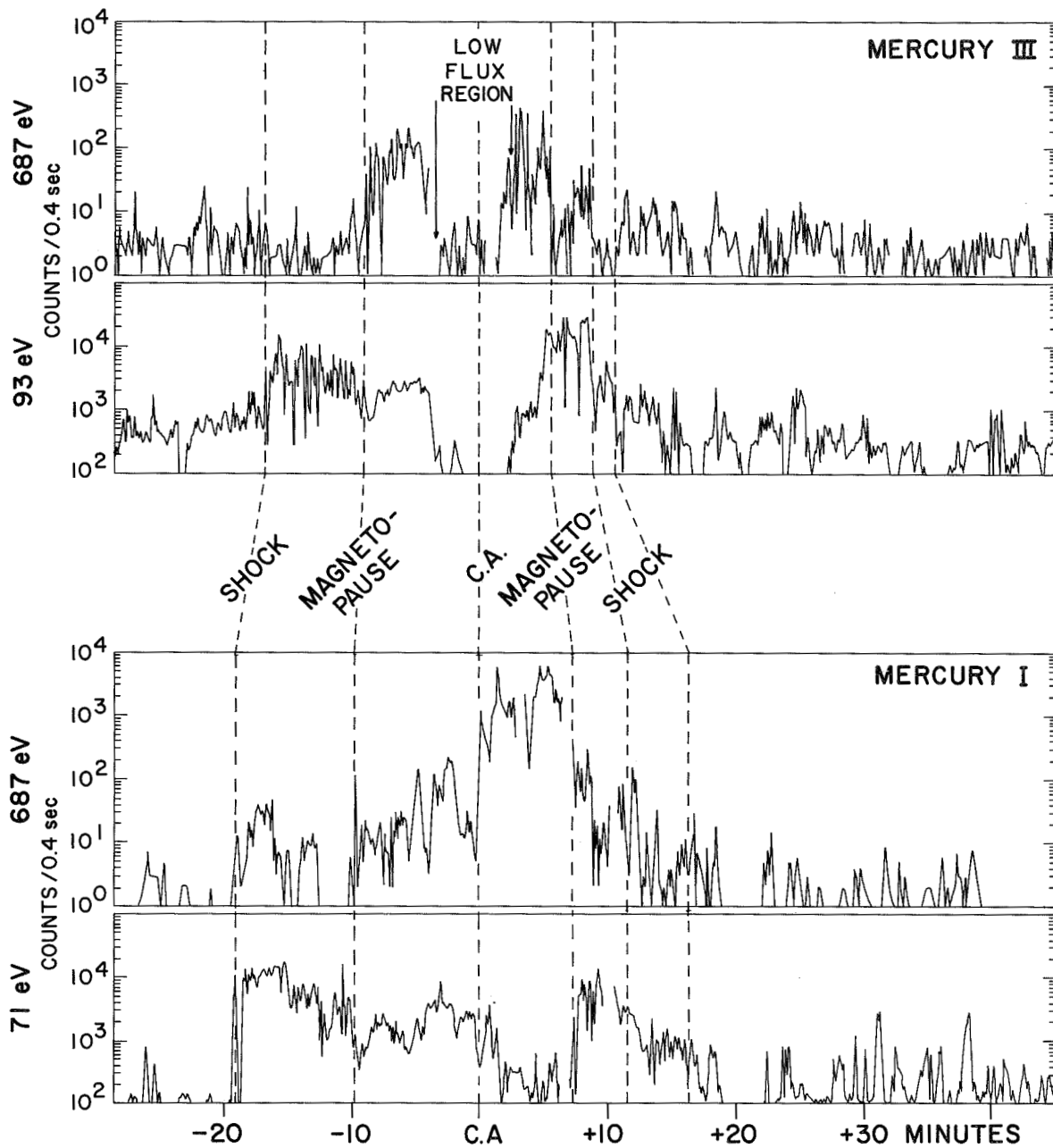


Figure 4. Solar-wind electron measurements at Mercury-I and -III encounters compared (note low flux region near CA) (Hartle et al., 1975b).

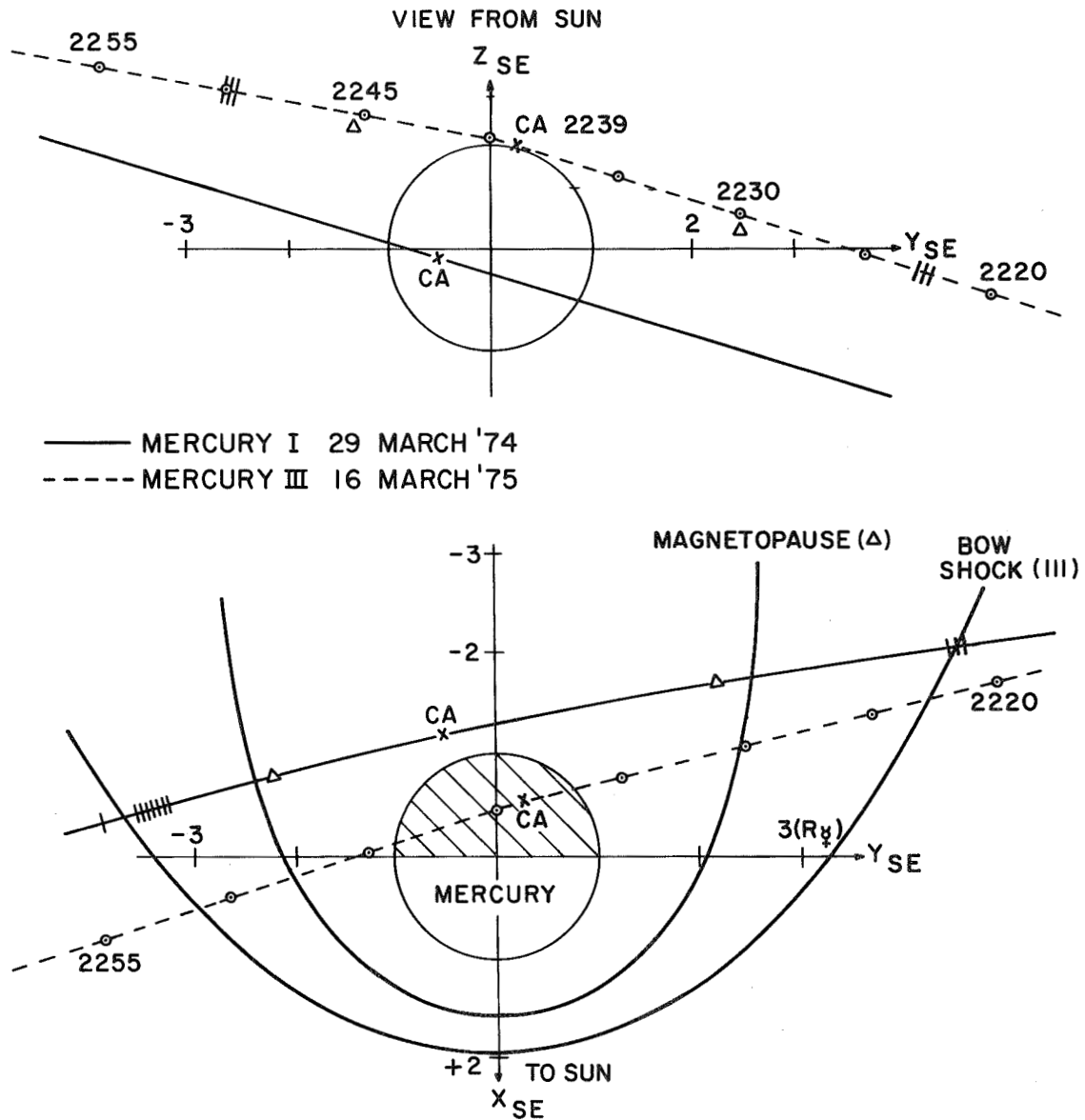


Figure 5. Trajectory of Mariner-10 during first and third encounters with identified positions of magnetopause and bow shock indicated accordingly. The theoretical shape of a scaled-down terrestrial magnetopause and bow shock are shown for $M_{\text{p}}/M_{\odot} = 7 \times 10^{-4}$.

From these harmonic coefficient sets, it is found that the intrinsic field of the planet is represented as due to a centered dipole of moment $4.7 \times 10^{22} \text{ G cm}^3$ oriented within 12° of the normal to the orbit plane. This moment compares very well with that deduced from the positions of the magnetopause and bow-shock boundaries and the inferred magnetic moment responsible for solar-wind deflection. Note that the sense of the dipole is the same as

Earth's. This dipole field corresponds to equatorial and polar-field strengths of 350γ and 700γ , respectively, which is about one percent of Earth's field.

One unique aspect of such a brief planetary flyby is that the encounter data provide an almost instantaneous snapshot of the entire solar-wind interaction region surrounding a planet. With this in mind, Fairfield and Behannon (1975) have analyzed the fluctuations of the magnetic field observed near the bow shock and in the magnetosheath. For Mercury-I inbound (see figure 6), the interplanetary magnetic field is perpendicular to the normal to the bow-shock surface and a sharply defined bow shock is observed. Upstream, right-hand circularly-polarized waves are observed which extend up to the Nyquist frequency of the experiment, 12.5 Hz. Outbound, the field is more parallel to the normal and this leads to a broad irregular region upstream from the shock in which left-hand circularly-polarized waves are observed but with a spectrum which cuts off sharply above 4 Hz.

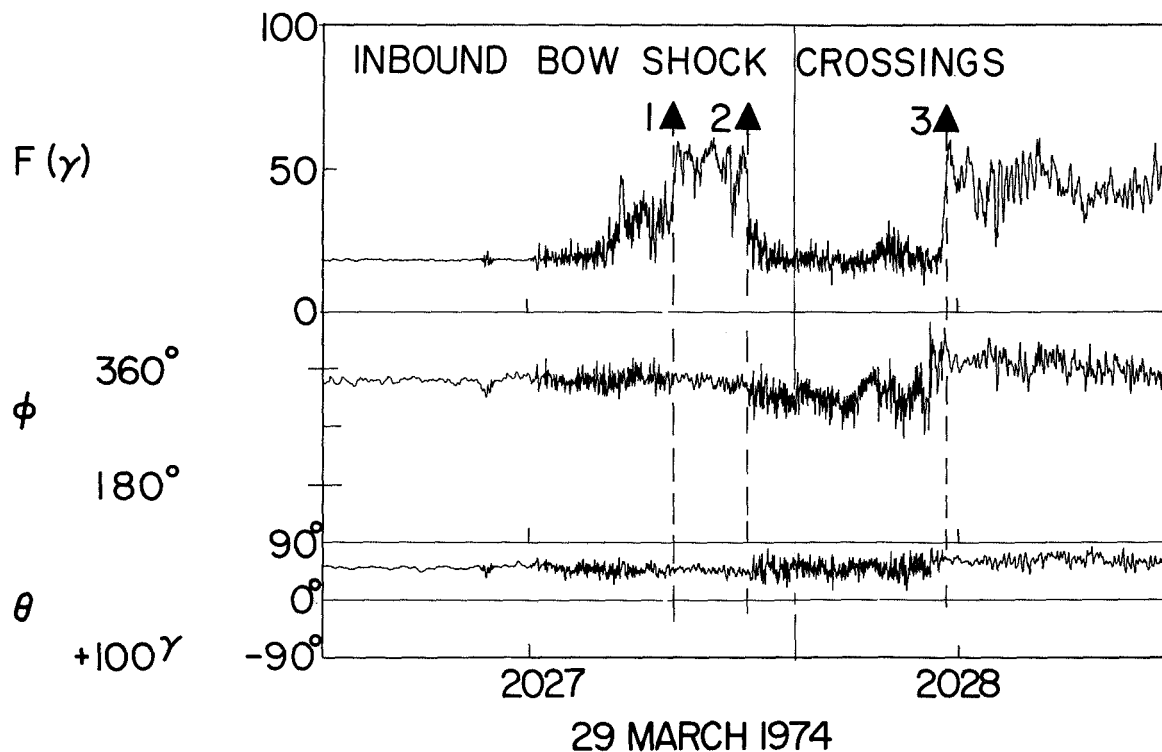


Figure 6. Detailed data (25 vector samples/s) during the three crossings of the bow shock at Mercury.

These observations can be easily explained in the framework of cold plasma dispersion theory for propagating whistler waves above the ion gyrofrequency. A large Doppler shift is associated with the convection of the waves past the spacecraft by the solar wind. Thus, depending upon the orientation of the magnetic field and the propagation direction, as well as

the phase and group velocities of the whistlers, it is possible to shift those which have propagated upstream to negative frequencies, that is, to change their polarization. All of the characteristics of the observed upstream waves can be explained in these terms. An interesting aspect of the magnetosheath wave observations has been the first identification of ion cyclotron waves downstream from the inbound perpendicular bow shock. While not yet reported present in the Earth's magnetosheath, it would be a surprise were they not present at certain times.

IMPLICATIONS

The existence of both a modest magnetic field of Mercury sufficient to deflect the solar wind and an imbedded neutral sheet leads to the conclusion that a magnetic tail of Mercury should exist. The optical properties of the Hermean surface are similar, in many respects, to those of the Moon. The lunar surface optical properties are influenced primarily by size, composition, and structure but also by ion bombardment by the solar wind. It is believed that the flux of solar-wind ions impacting the lunar surface leads to a darkening of surficial material.

The modest magnetosphere means that the major fraction of the solar wind is deflected around the planet. However, as Hartle et al. (1975a) have shown, only a small fraction of the incident solar wind entering the magnetosphere is necessary to explain the observed thin helium exosphere. That entry is most probably through the polar cap regions as well as the neutral sheet in the magnetic tail.

The orbit of Mercury is rather eccentric and the solar-wind intensity is known to vary with time. Siscoe and Christopher (1975) have considered these factors and concluded that, in spite of these variations, the modest magnetic field of Mercury is sufficiently strong that the solar wind should be deflected around the planet so that a detached bow-shock wave always exists. This conclusion is based upon present-day observations of the annual variation of solar-wind flux at 1 AU as measured by Earth-orbiting satellites. During the early formative stages of the solar system, however, it is possible that the solar-wind intensity was much higher so that the solar wind indeed impacted the surface of the planet.

A fundamental question which is not resolved is that of the origin of this global intrinsic planetary field. At the present time, it is not believed that the data support theories invoking a complex induction source mechanism due to the flow of the solar wind. The most plausible alternatives are:

1. A present-day active dynamo, or
2. Fossil magnetization due to an ancient dynamo or an enhanced interplanetary magnetic field during cooling.

Both depend upon the thermal state of the planetary interior, and it is not possible to distinguish between the two mechanisms from the magnetic data available. Due to the high average density of the planet, 5.44 g/cm^3 , it is fairly certain that a large amount of iron exists, on the order of 60 percent, which is probably concentrated in a large core. If such a

core were at low temperatures, below the Curie point, then a remanent magnetic field is quite plausible, although then the problem is to determine the origin of the magnetizing field if it was not primeval.

The possibility of a sufficiently cold core seems very remote in the light of studies on the thermal evolution of the terrestrial planets. Toksoz and Johnston (1975) have shown that, early in Mercury's history, a substantial iron nickel core formed with a radius of ~ 1600 km. Such a large core can probably support a planetary dynamo, if the appropriate combination of fluid motions and electrical properties exists. While the slow rotation of the planet may appear to be an impediment to the successful application of dynamo theory, the important physical parameters for a dynamo include dimensionless numbers for flattening, the differential rotation of the planetary interior, the magnetic Reynolds number, and other such quantities. Data at present are consistent with an active dynamo since, from a magnetohydrodynamic viewpoint, Mercury is rotating rapidly. Whether the dynamo is driven by precessional torques, as suggested by Dolginov,* or by thermal convection due to heat released by radioisotope decay, is not determinable from these data.

However, it is instructive to consider the magnitude of remanent magnetization required, in spite of the probable high near-surface temperatures. When a uniformly-magnetized thin spherical shell is assumed, the magnetization required is not much larger than the remanent magnetizations found in the returned lunar samples. With a lithospheric shell below the Curie point, whose thickness is 20 percent of the radius (488 km), the necessary magnetization is 3.1×10^{-4} emu/g. For a 10-percent thick shell (244 km), the value rises to 5.9×10^{-4} emu/g. This is well within the range of materials which may be expected to be present on the planet Mercury, since lunar surface materials yield magnetizations generally within an order of magnitude of 10^{-5} emu/g but at lower temperatures.

The existence of a magnetic field at Mercury indicates that an invaluable historical record of the formation of Mercury is available for study in the paleomagnetic data which shall be obtained at some future date by orbiter and lander spacecraft.

ACKNOWLEDGMENTS

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*See Sh. Sh. Dolginov's paper, "On Magnetic Dynamo Mechanism of the Planets," in this document.

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QUESTIONS

Ness/Gringauz: What is the maximum fractional fluctuation of the magnetic field near Mercury where ΔB represents the disturbed part of the observed magnetic field? What is the cool plasma sheet and hot plasma sheet in the Mercury magnetosphere? What is the accuracy of determination of the bulk plasma velocity from the electron data?

Ness: The largest relative perturbation is about 60 percent which occurs in the equatorial nightside cusp region of the Mercury-I encounter. I shall ask Dr. Bridge to comment on your second and third questions.

Bridge: The general spatial variations of plasma electrons observed during the first and third encounters of Mariner-10 with Mercury seem very similar to those observed in a comparable position in the magnetosphere of Earth. During the first encounter on the inbound pass, the spacecraft passed through the bow shock into a magnetosheath in which the average electron energy was about 100 eV. At the magnetopause boundary, the density dropped and the spacecraft entered into a region which seemed very similar to the cool, high-latitude plasma sheet of the Earth. Just before and after closest approach, the spacecraft is at a low magnetic latitude and the electrons are hotter, approximately 1 keV, as is typical of the low-latitude plasma sheet at Earth. Similar features were observed during the outbound pass of Mercury-I encounter. During the third encounter, the results were somewhat different but correspond well to the higher latitudes of the Mercury-III trajectory. The magnetosheath and cool plasma sheet were again seen clearly and, near the pole, there was a region of low-electron flux at all energy channels, which seems similar to the polar cap region at Earth. At Mercury, there is of course no inner convective zone which corresponds to the plasma sphere at Earth and the inner edge of the plasma sheet is very close to the planet.

The bulk plasma velocity derived from the solar-wind electron measurements is deduced to be accurate to within 30 percent.

Ness/Vaisberg: You have observed four crossings of the magnetopause at Mercury. Can you say something about the thickness of the magnetopause?

Ness: We have not yet attempted to estimate the magnetopause thickness, especially when it is in motion as evidenced by multiple crossings. A unique answer will not be possible but it appears to be quite thin, on the order of 100 km, based upon the two very abrupt crossings observed.

Ness/Troitskaya: Do you observe pulsations inside the magnetosphere of Mercury? What is their range of frequencies and is there some relation between them and the spectra of pulsations observed outside the bow shock? If a similarity of generation to the situation at Earth exists, there must also be a strong dependence of periods of pulsations outside the Mercurian bow shock and the value of the interplanetary magnetic field.

Ness: Yes, we do observe fluctuations within the magnetosphere of Mercury which appear like micropulsations. They are primarily low frequency, with periods of a few to several seconds, with an amplitude of a few to several gammas. But we have not yet analyzed them quantitatively in any detail nor attempted correlation with other relevant parameters. We shall keep your comments in mind.

Ness/Galeev: Could the diamagnetic effect of the solar-wind plasma injected into the cusp region of the Mercury magnetosphere modify the magnetosphere model which you have presented?

Ness: Yes, the magnetosphere model which was presented is based upon the use of an image dipole as representing the compression on the dayside of the magnetosphere. There are no other sources in the model except the neutral sheet current in the tail and hence injected solar-wind plasma would modify the idealized model mentioned.

Ness/Dolginov: In a preliminary result, you reported a large displacement of the dipole from the center of Mercury. What is the present understanding of this displacement? This is an important parameter in the kinetic models of the dynamo.

Ness: The result to which you refer was from a very preliminary analysis (published in *Science*, 185, pp. 151-160, 1974) which omitted consideration of any external sources of magnetic field. The final result for the first Mercury encounter was published in *J. Geophys. Res.*, 80, pp. 2708-2716, 1975, and assumed a centered dipole. The vector data set which we have available and the positions of the boundaries, that is, bow shock and magnetopause, are consistent physically with a small offset but are not sufficiently complete to estimate such an offset with high accuracy.

Ness/Spreiter: You compare your observations with the Rizzi theory for $M = 10$ and $M_A = 20$ saying that they are the only results available and that it would be better to use results for a lower M_A . Rizzi and I have published comparable results for $M = 10$ and $M_A = 2.5, 5, 10,$ and 20 in *Acta Aeronautica*, 1, pp. 15-35, 1974. Your comparison should be made with them. Also, the coefficient 1.07 that appears in the formula for the distance of the magnetosphere nose is based upon an outmoded Chapman-Ferraro pressure relationship $p = 2 m n V^2 \cos^2 \Psi$. This corresponds to specular reflection of solar-wind particles undeflected by passing through a bow-shock wave. Values of the order of one are much more appropriate than two for the coefficient. As discussed in my paper,* a combination of these considerations, with an improved magnetic field calculation of Choe et al. (1973) leads to a coefficient of about 1.20 rather than 1.07.

Ness: Thank you for pointing out the published paper based on Rizzi's 1971 thesis. The value of 1.20 you suggest is also very close to the 1.19 derived empirically by Fairfield (1971) in a comprehensive study of bow-shock and magnetopause positions.

I also want to point out that when a comparison of the position of observed bow shock and magnetopause are made with theory, the only parameter that can be determined is the ratio f^2/K (where f equals the ratio of stagnation point field to dipole field and K is as defined in your text). We cannot determine f or K separately. Also, since the solar-wind flow direction changes about the average direction by 5° to 10° , very detailed comparisons with bow-shock and magnetopause positions, such as occur in the case of very restricted data sets at Mercury and Venus, should take this into account.

Spreiter: I agree completely.

*See J. R. Spreiter's paper, "Magnetohydrodynamic and Gasdynamic Aspects of Solar-Wind Flow Around Terrestrial Planets: A Critical Review," in this document.