THE MAGNETIC FIELD OF MERCURY

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Abstract

The USA Mariner 10 spacecraft encountered Mercury three times in 1974-1975. The 1st and 3rd encounters provided detailed observations of a well developed, detached bow shock wave which results from the interaction of the solar wind. The planet possesses a global magnetic field, and modest magnetosphere, which deflects the solar wind. The field is approximately dipolar, with orientation in the same sense as Earth, tilted 12^{o} from the rotation axis. The magnetic moment, 5×10^{22} Gauss-cm^{3}, corresponds to an undistorted equatorial field intensity of 350γ, approximately 1% of Earth's. The origin of the field, while unequivocally intrinsic to the planet, is uncertain. It may be due to remanent magnetization acquired from an extinct dynamo or a primordial magnetic field or due to a presently active dynamo. Among these possibilities, the latter appears more plausible at present. In any case, the existence of the magnetic field provides very strong evidence of a mature, differentiated planetary interior with a large core, $R_c \approx 0.7R_M$, and a record of the history of planetary formation in the magnetization of the crustal rocks.

Introduction

One problem of fundamental cosmological interest is why massive, rotating astrophysical objects such as planets, our sun, stars and pulsars possess large scale and in the latter cases, extremely intense magnetic fields. During the last decade, the USA and USSR have conducted in situ spacecraft studies of the magnetic fields and interactions of the solar wind with the terrestrial planets, the moon and the giant planet Jupiter. Remote observations by spacecraft of non-thermal radio emissions from Saturn and Uranus suggest that they also possess magnetic fields and radiation belts like Earth and Jupiter. The new results include appreciable magnetization of lunar rocks as well as evidence of localized lunar fields but a negligible global field, as is also the case at Venus. Mars possibly possesses a global field according to USSR studies. Mercury possesses not only a global

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magnetic field but a modest magnetosphere and magnetic tail. It is the purpose of this paper to briefly review the recent magnetic field data obtained from the Mariner 10 spacecraft, the present state of our knowledge and its implications regarding the interior of Mercury.

Mariner-Venus-Mercury 1973: Mariner 10

The first gravity assist mission of the space age was the USA Mariner 10 mission launched on 3 November 1973 to initially flyby the planet Venus and then to flyby the planet Mercury 3 times. The unique celestial circumstance which permitted three encounters with the planet Mercury was the deflection on 5 February 1974 by Venus of the Mariner 10 spacecraft into a heliocentric orbit with the resulting orbital period of Mariner 10, 176 days, being twice the orbital period of Mercury, 88 days. Due to a limited supply of spacecraft expendables, no further encounters were achieved.

Figure 1 projects, on the ecliptic, the trajectory of the spacecraft and the orbits and positions of the planets Earth, Venus and Mercury at the moments of encounter. Also shown at the bottom is the trajectory during the first encounter on 29 March 1974, which was a darkside pass with a closest approach distance from the surface of 723 km. The second encounter on 21 September 1974 was targeted so as to optimize imaging coverage of the south polar regions and passed too far from Mercury (50,000 km) to provide data on its magnetic field and the interaction with the solar wind. The third encounter on 16 March 1975 was similar to the first, being a very close approach towards the darkside near the north polar region at a miss distance of 327 km.

Both the first and third encounter data from the solar wind electron spectrometer, charged particle telescope and magnetometer instruments provided useful and complimentary data regarding the nature of the Hermean magnetic field, its magnetosphere and the solar wind interaction. (See review by Ness, 1976).

The magnetometer instrumentation on Mariner 10 was unique in that it was the first flight of a dual-magnetometer system (Ness et al, 1971). The purpose of this method is to permit in-flight determination and elimination of the magnetic field contamination in the measurements due to the presence of the spacecraft itself. The configuration chosen for Mariner 10 placed two triaxial fluxgate magnetometers on a deployable, segmented boom so that the sensors were located 4.36 and 6.93 meters from the center of the spacecraft. The system operated successfully (Ness et al, 1974a) and clearly established the validity of the method on those spacecraft for which insufficient magnetic constraints had been exercised during the fabrication of the spacecraft to assure insignificant contamination for a single, boom mounted magnetometer. The method has been further studied by Neubauer and Schatten (1974) and Neubauer (1975).

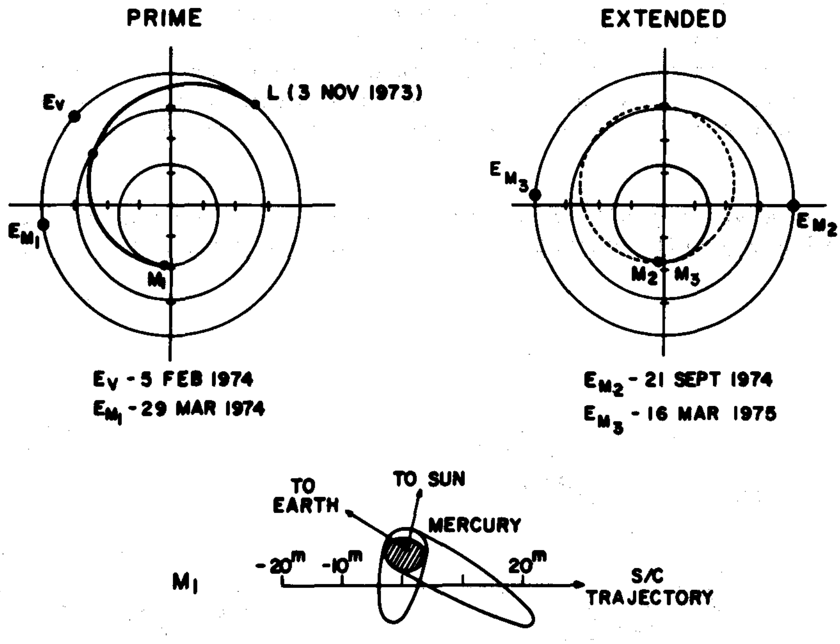

Figure 1. Trajectory of Mariner 10 Projected in Ecliptic

Magnetic Field Observations

The discovery of a modest magnetosphere surrounding the planet Mercury with a very well developed, detached bow shock wave in the solar wind flow was one of the most expected results of the first Mariner 10 flyby on 29 March 1974. In addition, intense fluxes of energetic particles were observed (Simpson et al, 1974), which, although not associated with any permanent radiation belts, were interpreted as being due to an acceleration process occurring in the magnetic tail-plasma sheet on the darkside of the planet.

These results were dramatically confirmed during the third encounter on 16 March 1975 and established unequivocally that the planet Mercury possesses a global, intrinsic magnetic field which is sufficiently strong to deflect the major fraction of solar wind plasma flow around the planet. The identification of the bow shock is easily accomplished by noting an abrupt increase in field magnitude and/or an increase in the level of fluctuations (Ness et al, 1974b).

The interaction with the solar wind should also be viewed as confining the planetary magnetic field to a region of space which is called the magnetosphere. Its boundary, the magnetopause, is well

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distinguished by an abrupt directional change in the magnetic field due to the electrical currents flowing within it and also by the termination of the higher level fluctuations previously detected as the bow shock was initially crossed. The region between the bow shock and the magnetopause is called the magnetosheath and can be thought of as a turbulent, thick, boundary layer separating the distorted planetary magnetic field, i.e. the magnetosphere, from the interplanetary medium.

The relative position of the bow shock and magnetopause surfaces observed along both encounter trajectories are summarized in Figure 2.

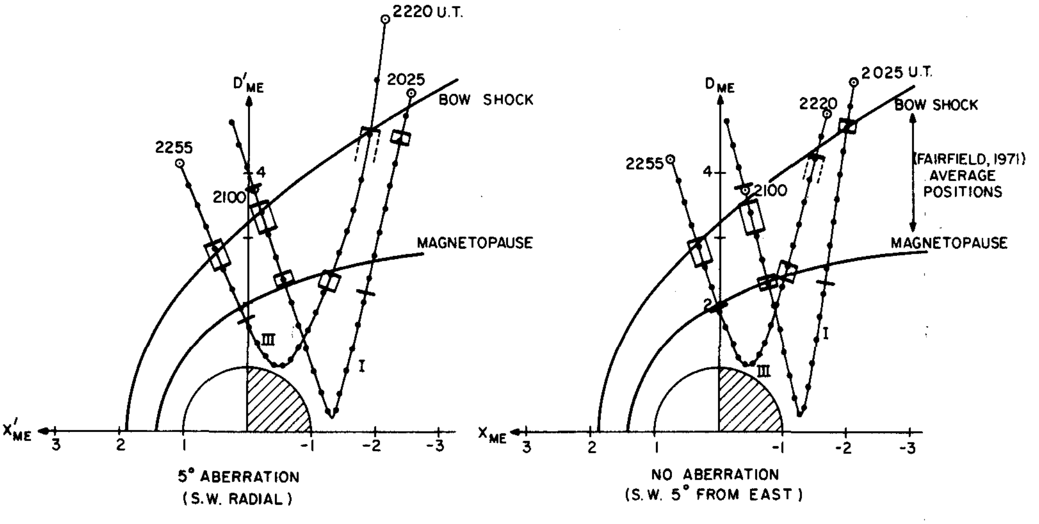

Figure 2. Trajectories of 1st and 3rd Mercury Encounters.

The coordinate system employed assumes cylindrical symmetry of both surfaces about the assumed direction of solar wind flow. In the left most portion of the figure, the flow is assumed radial from the sun and hence a 5^{o} aberration due to the heliocentric motion of Mercury and the approximately 600 km/sec velocity of the solar wind. The right hand portion shows the relative geometry with the flow direction deviated 5^{o} from the East, which leads to 0^{o} aberration. On occasion, the identification of a particular surface was ambiguous, due to multiple crossings being readily evident, and therefore a corresponding region along the trajectory has been indicated.

Included for comparison are surfaces obtained by scaling the results of Fairfield (1971) in his study of the terrestrial bow shock and magnetopause from an extensive suite of IMP observations. Comparison of the Hermean bow shock and magnetopause position with these

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curves leads to the following three conclusions:

1. The bow shock and magnetopause of Mercury are situated much closer to the planet Mercury than Earth. The planetocentric distance to the magnetopause at the stagnation point is approximately $1.45R_M$. This means that Mercury possesses a magnetosphere which is a factor 7.5 smaller than Earth's when normalized by the planetary radius.

2. Electron plasma density and velocity measurements outside the bow shock region yields an estimate of the solar wind momentum flux (Ogilvie et al, 1974; Hartle et al, 1975). This permits the computation of the equivalent dipole magnetic field deflecting the solar wind flow: a magnetic moment of Mercury of $3\text{x}10^{22}$Gauss-cm^3 = $4\text{x}10^{-4}$ Earth's.

3. The symmetry of the observed surfaces, relative to the comparison surfaces, is improved by assuming the solar wind flow was coming from the East by 5^o during both encounters.

Figure 3 presents the three orthogonal components of the magnetic field data observed during Mercury I encounter (Ness et al, 1975).

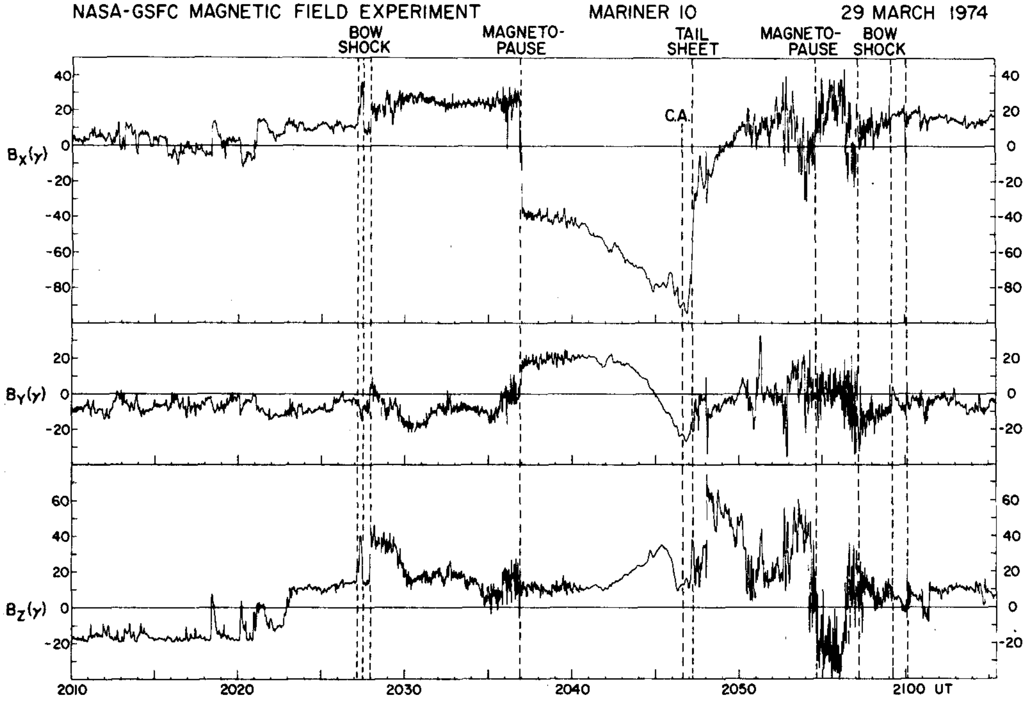

Figure 3. Magnetic Field Observations During First Encounter With Mercury.

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The bow shock is clearly identifiable with three traversals occurring between 2027-2028. The current sheet, which forms the magnetopause boundary, is clearly identified at 2037 by the sudden change in the B_X component, while the entrance to the field reversal-plasma sheet region is also readily identified at 2047.

While Mariner 10 was outbound from closest approach, the magnetosphere was very disturbed and intense bursts of energetic particles were observed. These data have been interpreted by Siscoe et al. (1975) as evidence of a substorm like disturbance in Mercury's magnetosphere. As is well known, such disturbances of the terrestrial magnetosphere occur when the Z-component of the interplanetary magnetic field is negative. Note in Figure 3 that the B_Z component was northward during entry to the magnetosphere but was southward during exit. The change in the interplanetary field direction alters the rate of transfer of energy from the solar wind to the Hermean magnetosphere and this leads to a release of the energy stored in the magnetic tail. This is reflected in the disturbances which are seen to occur between 2047 to 2055 in both the magnetic field as well as of the plasma within the magnetosphere, simultaneous with a sudden acceleration of charged particles.

No durably trapped radiation was detected but energetic electron bursts were reported as well as the presence simultaneously of protons (Simpson et al, 1974). There is some discussion concerning the spectrum of the electrons and whether or not protons were indeed present (Armstrong et al, 1975; Simpson, 1975; Christon et al, 1976; Hill et al, 1976). However, there is no dispute regarding the presence of transient bursts of high energy particles which must be associated with an acceleration process in the Hermean magnetosphere.

The above characteristic observations during Mercury I encounter were seen again during Mercury III encounter with some differences. Due to the higher, i.e. polar latitude, pass and the lower altitude, the maximum field intensity observed was 400γ, 4 times that of the Mercury I encounter value and more than 20 times that of the interplanetary field (Ness et al, 1976). However, only 1 burst of energetic particles was observed just after closest approach and no disturbance in the magnetosphere was noted.

Determining characteristics of the intrinsic planetary magnetic field are difficult due to the modest size of the Hermean magnetosphere. This is because even at closest approach to the planet, magnetic field observations are conducted in regions which are not far enough removed from the effects of the electrical currents flowing in the magnetic tail and magnetopause of the magnetosphere. It is necessary to take into account such external sources of magnetic field in the analyses. Furthermore, the quantity of data available is limited spatially to the trajectory so that an incomplete data set is obtained.

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The problem of determining planetary magnetic fields from spacecraft flyby trajectories has recently been studied by Ness and Thompson (1976). They discuss a methodology for optimizing the estimation of the intrinsic planetary field characteristics from a restricted data set. In the case of Mercury, the data from the third encounter yield an estimate of a magnetic moment of 5×10^{22} Gauss-cm^3 with the dipole axis tilted 12^o from the orbit plane normal. This value of magnetic moment is in good agreement with that derived by considerations of bow shock and magnetopause positions and scaling comparisons with the terrestrial magnetosphere and bow shock.

The observations and model data employed are shown in Figure 4. The goodness of fit is illustrated by the small discrepancy between the two.

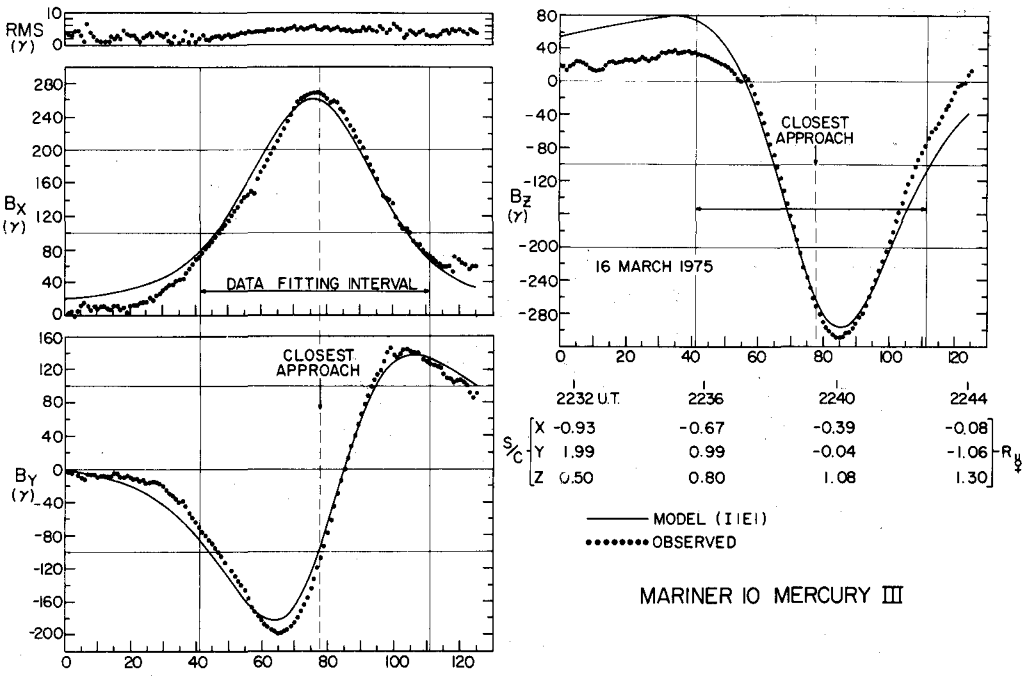

Figure 4. Magnetic Field Data and Model Comparison.

Orthogonal components of the magnetic field are presented as averages over 6 sec. and the RMS is included. Note that the major contribution to the RMS value is due to the spatial gradient of the magnetic field during the averaging interval.

Departures of the observed field from the theoretical model, which assumes a centered tilted dipole and a uniform external field, can be due to several reasons. Either the internal or the external magnetic

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field can be more complex than assumed in the model. However, the condition number for such analyses are too high to justify their use and so due to the intrinsic limitations of the trajectory, we are restricted to the simple model presented. It is also possible that the region of the magnetosphere probed is not free of electrical currents so that the assumption of a magnetic field derivable from a scalar potential is not correct. Furthermore, time variations may also contribute and in the analysis would masquerade as spatial variations.

The good comparison between theory and observations implies that the magnetic field of Mercury is well represented on a global scale as a simple, centered tilted dipole distorted by the solar wind. With this in mind a model magnetosphere has been constructed by Whang (1976) and is illustrated in Figure 5. His model is based upon a centered tilted dipole, an image dipole "upstream" and a cross-tail two dimensional current sheet on the night side. The dipole moment obtained

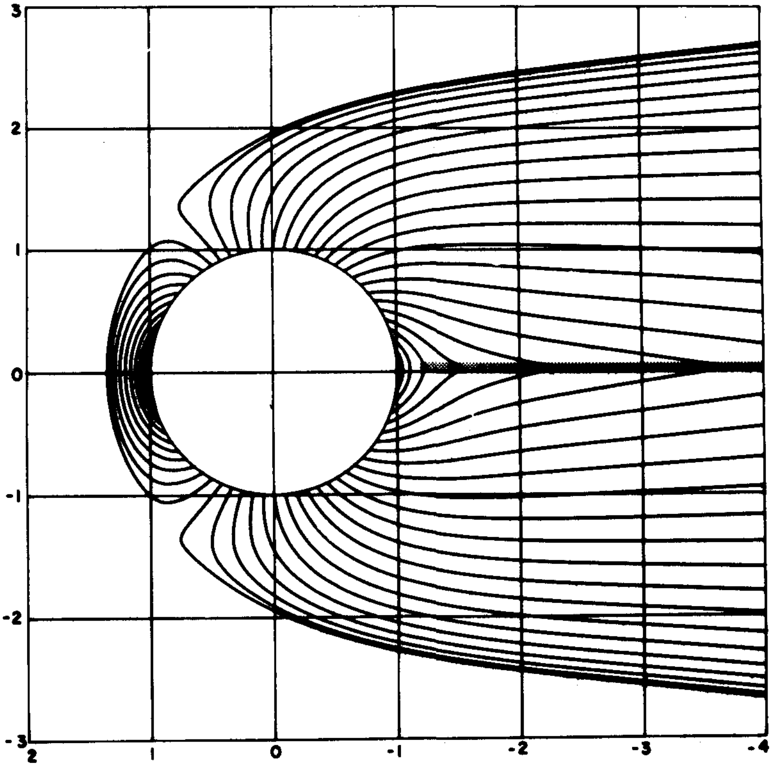

Figure 5. Noon-midnight Meridian Plane Projection of Field Lines.

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is 3.9×10^{22} Gauss cm^3 which corresponds to an undistorted equatorial field intensity of 266γ. This compares favorably with the 350γ value derivable from the spherical harmonic analysis previously discussed. Note in this figure how asymmetric the magnetosphere of the planet is, as indicated by the field line compression on the dayside and expansion on the nightside.

Origin of the Magnetic Field of Mercury

A fundamental question, which cannot be uniquelly answered, is what is the origin of this global, planetary magnetic field? The data do not support any theory which would invoke a complex induction process associated with the flow of the solar wind. The possible sources of the observed intrinsic magnetic field are:

1. Remanent magnetization after cooling and/or

2. A present day active internal dynamo such as on Earth (see the review by Gubbins, 1974).

Both sources depend upon the thermal history of the planetary interior and it is not possible to distinguish between the two mechanisms from the available magnetic field data. If definitive measurements of the planetary magnetic field were possible over an extended time period, then any secular changes, such as observed on Earth would be conclusive evidence for an active dynamo. The measurements between Mercury I and Mercury III are neither separated in time sufficiently far not sufficiently "complete" to permit use of the two different encounter data sets to attempt to answer this question.

Due to the high average density of the planet, 5.44 gm per cm^3, it is fairly certain that Mercury contains a large amount of iron and nickel, on the order of 60%. This is most probably concentrated in a large core (Sigfried and Solomon, 1974). If such a core were at low temperatures, below the Curie point, then a remanent magnetic field would be plausible. The problem then would be to determine the origin of the magnetizing field, if it were not primordial.

The possibility of a sufficiently cold interior seems rather remote in the light of studies on the thermal evolution of the terrestrial planets. Solomon (1976) has recently shown that an iron-nickel core most probably formed with a radius which is approximately 1600 km. Temperature profiles for two different cases, in which the core formed early or late, are shown in Figure 6.

Such a large core can clearly admit a planetary dynamo, if the appropriate combination of fluid motions and electrical properties exists. The apparently slow rotation of the planet is in fact not an impediment to the successful application of dynamo theory (Gubbins, 1974), since the important relevant physical parameters are

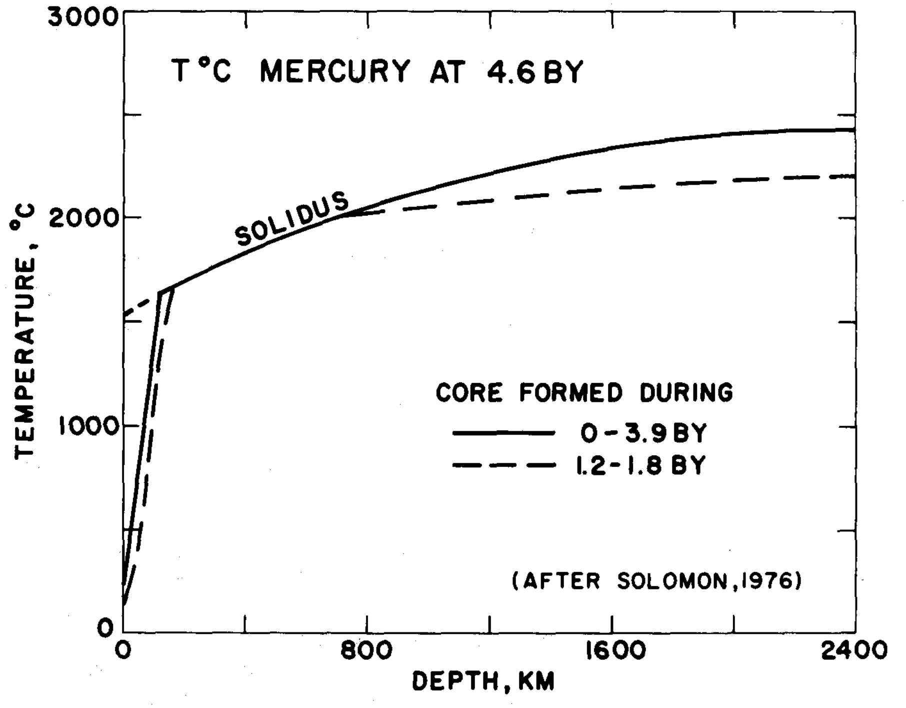

Figure 6. Thermal Profiles of Mercury, at Present.

differential rotation of the planetary interior and the magnetic Reynolds number. These critical physical parameters are much less well known than they are for Earth and our present knowledge cannot preclude an active dynamo in the interior as responsible for the observed global field.

Recently, an examination of the possibility of remanent magnetization as the source of the Hermean field has been conducted by Stephenson (1976). His model assumed a thin shell of material below the Curie point which had been magnetized by an internal source; either a dynamo or a primordial field. His study included two models, one in which the core was above the Curie point and one in which it was below. On the basis of recent thermal models, it seems most likely that the core is well above the Curie point.

For this case, Stephenson's model requires an ancient surface polar field of 5 to 10 Gauss using volume percentages of iron in the mantle rocks of 5% or greater. This is more than 100 times the values typical of lunar basalts. If the volume percentage of iron is reduced to that typical of lunar rocks then the polar field increases to about 2000 Gauss. This high value seems rather unreasonable and so on the basis of stephenson's results, remanent magnetization appears less likely to be the source unless the iron content of the Hermean mantle is abnormally high. Srnka (1976) has reported the results of a similar study of the ancient magnetizing field required. He reports a value of 16 Gauss required for a volume percentage of iron of about 3.0%. The thickness of the sub-Curie point mantle shell in these 2 studies was 240 km and 180 km respectively.

At the present time, it does not seem likely that Mercury's global magnetic field is the result of remanent magnetization. But there are a sufficient number of uncertainties in these models and this conclusion could be significantly modified. Of great importance is the magnetic permeability of the shell used by both Stephenson and Srnka. It is assumed to be unchanged as thermo-remanent magnetization is acquired. However, if the shell became ferromagnetic, the required magnitude of the ancient field could be substantially reduced.

Regardless of the origin of Mercury's magnetic field, it appears absolutely certain that its existence indicates the presence today of a differentiated, mature planetary interior as illustrated in Figure 7. Thus although Mercury, with its heavily crated surface, is very lunar-like, it also turns out to be quite Earth-like with its very well developed large core, and magnetic field. In all probability, the resolution of the origin must await future visits by spacecraft to the planet.

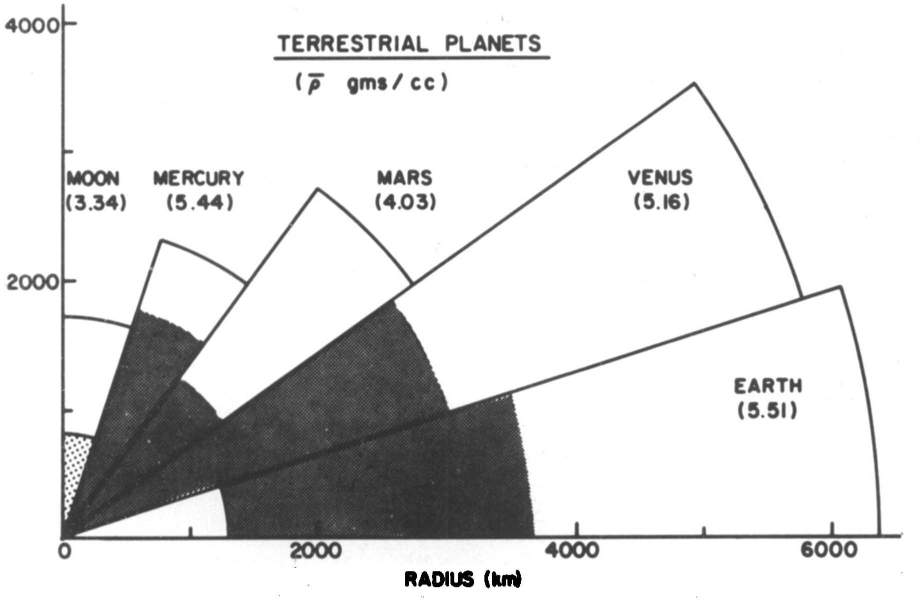

Figure 7. Comparison of Terrestrial Planetary Interiors.

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