5

Mercury's magnetic field and internal constitution

5.1 A MERE THIRTY MINUTES

Mariner 10 first encountered Mercury's magnetosphere on 29 March, 1974 at 2037 UT as it approached Mercury. It was at a distance of 1.9 radii from the planet surface. Magnetic field and charged particle instrumentation made measurements for only short periods of the first and third flybys of the planet, but investigators were able to piece together a picture of the magnetic field environment at Mercury based on analogy with that of Earth's magnetic field and particle environment. However, because Mercury's atmosphere is very thin and the magnetosphere is very small, it probably lacks the *ionosphere* and trapped *radiation zones* of Earth's *magnetosphere*. Signals in the ~30 minutes of data (~17 minutes during the Mercury 1 equatorial pass and ~13 minutes during the Mercury 3 high-latitude pass) provide all we know about Mercury's magnetic field, magnetosphere, and particle environment.

5.1.1 A significant magnetic field discovered

The measured magnetic field is strong enough to present an obstacle to the solar wind, which streams towards Mercury in a manner similar to that which occurs at Earth. As the spacecraft approached the planet, it first encountered a sudden jump in the magnetic field associated with the *bow shock*. In addition, signals measured by the instruments indicated entry into and exit from a *magnetopause* surrounding a magnetospheric cavity. The magnetospheric cavity is estimated to be a factor of about 20 times smaller than the Earth's magnetic cavity and would fit in an Earth-sized sphere of about 12,000 kilometers in diameter. The magnetic polarity is the same as that of the Earth with respect to the direction of the angular momentum vector associated with the planet's rotation. The magnetometer experiment measured an increase in the magnetic field as the spacecraft approached the

Table 5.1. Third encounter magnetometer results.

	Time of observation Pacific Daylight Time (PDT) hr:min	
Event	Predicted	Actual
Cross bow shock	3:31 ± 02	3:31
Cross magnetopause	3:39 ± 01	3:39
Maximum field*	3:49 ± 01	3:49
Recross magnetopause	3:54 ± 01	3:56
Recross bow shock	3:58 ± 02	5:59

* Predicted field strength was 200–500 nT; actual strength was 400 nT.

planet. The *interplanetary magnetic field* (IMF) typically has a strength of about 6 nT (Tesla – units to measure magnetic intensity) at Earth and about 25 nT in the vicinity of Mercury, but at closest approach to Mercury the magnetic field strength reached 100 nT. If the rate of increase continued to the surface, Mercury would have a ground-level magnetic field of about 200 to 500 nT. Although this strength is only about 1 percent of Earth's field, it is adequate to deflect or stand off the solar wind and produce the bow shock observed by plasma and charged particle experiments. Table 5.1 compares the actual measurements to a first encounter predicted model used to infer the shape and strength of the magnetic field at Mercury.

5.1.2 Comparison to Earth's magnetic field

On Earth, the configuration of the magnetic field, the magnetosphere, and surrounding interplanetary medium are well-known from extensive ground and orbital spacecraft measurements. The Earth's field is believed to be generated by a dynamo and changes by up to 100 nT per year at the surface in some places. The geologic records show that it changes polarity every 500,000 years or so. We know from seismic data that the Earth has a fluid outer core and the heat flux of the interior has more than enough energy to support a dynamo. We use these facts to build a model for the same concepts on Mercury even though there is great uncertainty because of the scant amount of data. If we assume that our interpretation of the data is correct, and Mercury does indeed have a smaller, but similar magnetic field to that of Earth, then we can illustrate these concepts in Figure 5.1.

The solid body of Mercury fills a greater portion of its magnetosphere than does the Earth. The cusp regions, where the field lines intersect the surface of the planet are probably at lower latitudes on Mercury than on Earth, and the magnetosphere probably fluctuates more rapidly and more often than on Earth as a result of more perturbations from the solar wind – *flares*, *coronal mass ejections*, and other solar related phenomena.

The dynamic disturbances of particles and fields measured *downstream* from Mercury appeared similar to substorms in the Earth's *magnetotail* with its associated *plasma sheet* and *cross-tail currents*. A color illustration of Mercury's magnetosphere and its interaction with the solar wind is shown in Figure 5.2. (color plate section).

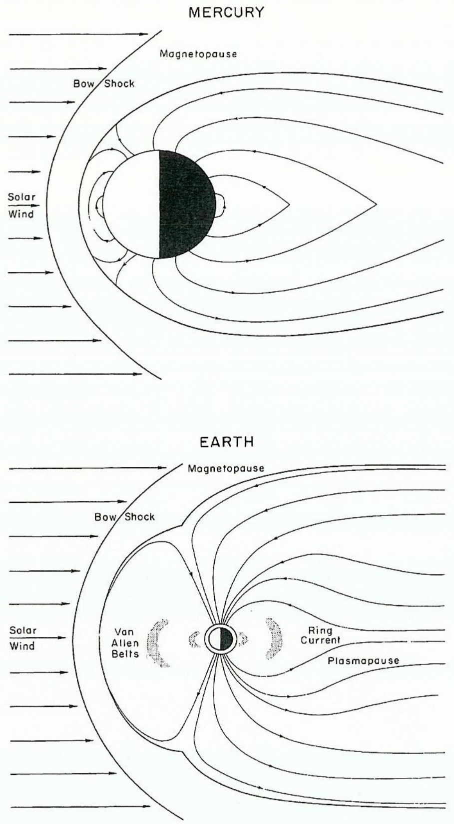

Figure 5.1. A comparison of models for the magnetic fields of Mercury and the Earth. Mercury's is assumed dipolar. Mercury fills a smaller portion of the magnetic cavity in the solar wind because its field is about 1% that of the Earth (from R. G. Strom, 1987).

5.1.3 Mercury's magnetic field could be remanent

It is possible that the interpretation of the *Mariner 10* particles and fields instruments was biased by comparison to the known field of the Earth. However, this does not seem likely as the evidence for the current interpretation following the three *Mariner 10* encounters was convincing. Nevertheless, it may turn out that Mercury's fields are largely *remanent fields* left in the crust from a much earlier period. We have good examples of such remanent fields in our Solar System on the Moon, Mars, and Earth.

5.2 REMANENT MAGNETIC FIELDS ON THE MOON

The remanent magnetic fields at the lunar surface have been a source of intense interest and debate since their discovery with instrumentation on the *Apollo* landers and orbiters during the 1960s and 1970s. Localized magnetic fields up to several tens of nT were found at orbital altitudes above the antipodes of the Imbrium and Crisium basins, and there fields are associated with bright albedo features scattered across the lunar surface. More recent observations from instruments on the *Lunar Prospector* spacecraft found some evidence for surface fields as high as 200 nT. Suggestions for their sources include: magnetized ejecta from deep impacts, crustal material shocked in the presence of an existing field (shock magnetization), or plasma cloud magnetic enhancement of surface regolith concomitant with large impacts. For the third hypothesis, the suggestion is that reduced Fe in the regolith is magnetized directly by the enhanced field of the impacting plasma.

Associated with some of the greatest magnetic anomalies are surface regions of considerably higher *albedo* than the surrounding soils. One of the best known examples of intense localized magnetic fields is Reiner Gamma in western Oceanus Procellarum shown in Figure 5.3. This region consists of a bright magnetic region surrounded by darker soils outside the magnetic region. It has been suggested that the magnetic fields in these regions have protected the surface from darkening by shielding soils from the solar wind and charged particle sputtering.

5.3 MARS' REMANENT MAGNETIC FIELDS

In 1998, the magnetometer/electron reflectometer (MAG/ER) experiment on *Mars Global Surveyor* (*MGS*) made a startling discovery of intrinsic intense magnetization mainly confined to the heavily cratered, ancient southern highlands. These remanent magnetic fields reach a maximum strength of ~220 nT at the *MGS* mapping altitude of 370–438 km. The fields are thought to be "frozen" into the rocks and are consistent with a reversing dynamo halted in an earlier period when they were generated in the deep interior. This was a surprising discovery because previous orbiters had not detected strong magnetic fields on or around Mars' surface. Previous studies of the upper atmosphere had not detected a "stand-off" region between the upper atmosphere of Mars and the solar wind. Some of these remanent fields are quite strong, about the strength of the magnetic field measured on Mercury. At Mars many orbits of MGS were able to map the magnetic regions fully and determine their strength and extent over the surface as shown in Figure 5.4.

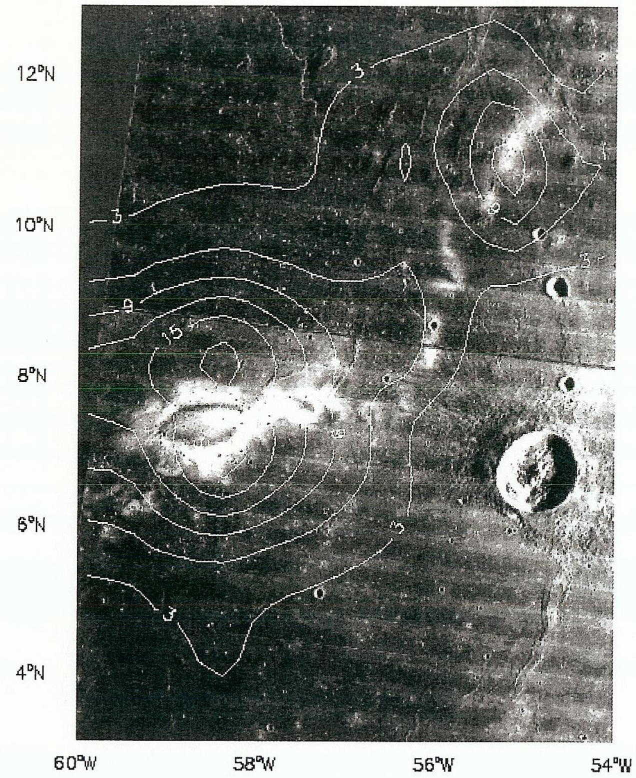

Figure 5.3. The remanent magnetic fields on the Moon were measured with the magnetometer and electron reflectometer on *Lunar Prospector*, an orbiter sent to the Moon in 1998. Contours of field strength in nT are plotted over an image of the Reiner Gamma region in western Oceanus Procellarum obtained by *Lunar Orbiter 4* in 1967. The 30-km-diameter crater Reiner is at the lower right (courtesy of Lon Hood, University of Arizona).

Mars has a highly oxidized surface, although at this time the exact details of the composition of the dust and rocky competent layers are not known. However, much of the planet is covered by basalt and its weathering products. Regions of hematite have also been discovered on the surface by identifying its spectral signatures in data from the Thermal Emission Spectrometer (TES) on the *MGS*. Thus, plausible material for the source of the strong remanent fields are titanomagnetite or

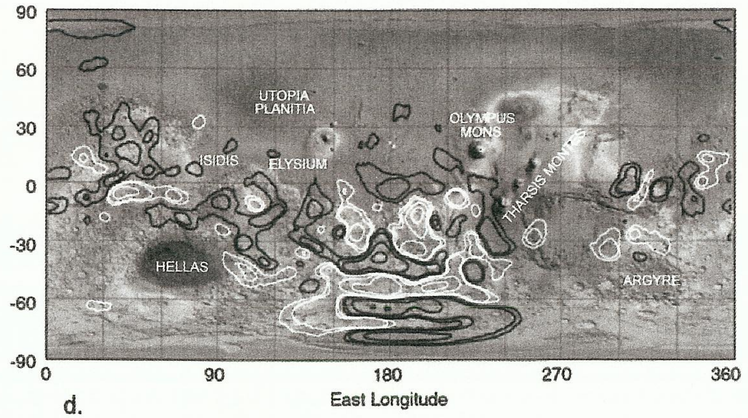

Figure 5.4. *Mars Global Surveyor* discovered magnetic fields in Mars' crustal materials. The strength of the radial magnetic fields vary from $B_r = -160$ to $+160$ nT. Contour lines on the map show the locations and strengths of the magnetic fields B from -10 to 200 nT, with black low and white high (courtesy of *Mars Global Surveyor* particles and fields scientific team).

titanohematite. Iron sulfides (pyrrhotite) have also been suggested as plausible remanence carriers in the deep crust of Mars. There are other possibilities but the exact composition remains unknown.

5.4 A NEW LOOK AT OLD DATA

Recent spacecraft exploration of Mars has resulted in new studies and insights regarding the remanent magnetic fields. One explanation for the distribution of the newly discovered remanent magnetic fields in the southern highlands is that impact shock demagnetization occurred during the very large Hellas and Argyre impacts. These impacts would have raised the temperature of the crust in and near the impact areas to values above the Curie point and demagnetized the rocks.

Now, because of the new discoveries on Mars, scientists are taking a new look at the *Mariner 10* data from both the particles and fields and magnetometer instruments. Some scientists are seriously examining the *Mariner 10* data to see if it too could be interpreted in terms of irregularly distributed strong remanent fields on Mercury's surface rather than the dipolar configuration that scientists debated when the data were originally interpreted in the 1970s. Knowing that their conclusions rested on a mere thirty minutes of data leaves considerable uncertainty in some researchers minds. If Mercury's magnetic field is remanent, then it will be the first dipolar remanent field ever discovered. Since there is no known way to take more measurements from Earth, it is crucial to go back to Mercury and measure its magnetic environment from orbit.

5.5 INTERIOR STRUCTURE AND CONSTITION

Our current understanding of planetary dipolar magnetic fields is that they are generated by electrical currents induced by dynamo action in a thermally convecting, differentially rotating, liquid metallic core. Most scientists believe such a mechanism causes the Earth's dipolar magnetic field. For a large planet like the Earth, it is not unlikely for a liquid core to remain even four billion years after planetary formation. Seismic data from many Earth-based seismograph networks confirm the existence of the liquid outer core and a solid inner core.

Mercury, however, is small compared to Earth. It seems likely that its core would have cooled and solidified during the past four billion years. Many theoretical studies have attempted to explain how a small planet like Mercury could keep a liquid outer core and generate the measured magnetic field. Some models which include light elements in the core like sulfur, oxygen, or silicon show that a liquid outer core at this time in geologic history is possible. But we are terribly hampered by lack of both chemical and dynamic data. Detailed knowledge of the elemental surface composition and of the gravitational moments of the planets are required before further modeling will be useful. Many more details relating to the interior structure and composition are discussed in Chapter 12.

5.5.1 What if there is an active dynamo?

If the magnetic field is a presently active dipole and Mercury presently has an outer fluid core, physical mechanisms must maintain high core temperatures up to the present time. Proposed means of facilitating this are: (1) provide more internal heat by enriching the core in the radioactive elements uranium and thorium; (2) retain the heat longer by reducing the thermal diffusivity of the mantle; or (3) add some light alloying element to lower the melting point of iron. The addition of a light alloying element is considered to be the most likely cause. Although oxygen is such an element, it is not sufficiently soluble in iron at Mercury's low internal pressures. Metallic silicon has been suggested, but sulfur is considered to be the most likely candidate. For a sulfur abundance in the core of less than 0.2%, the entire core should be solidified at the present time, and for an abundance of 7% the core should be entirely fluid at the present time. Therefore, if the outer core is presently molten and sulfur is the alloying agent, then Mercury probably contains between 0.2–7% sulfur in the core.

5.5.2 What if there isn't?

If the magnetic field is a remanent field it permits the possibility of a completely solid core at present. Thus the sulfur content could be less than 0.2%. For a sulfur content of 0.2%, the core takes almost the age of the Solar System (4.6 billion years) to solidify. With less it would solidify much faster, but it would still take well over a billion years to completely solidify because of its very large size. However, if Mercury's field is remanent then it requires a thick layer of abundant magnetic minerals (perhaps more than 30 km thick) which may be unrealistic from a geochemical and petrological standpoint.

5.5.3 Relevance of Mercury's surface composition to the magnetic field question

Magnetic minerals responsible for crustal magnetic remanence must contain iron in a form that can acquire and preserve magnetic fields. The ability of rocks and minerals to maintain magnetic fields over long time periods is called *remanence*. One of the more common minerals, and one that may be responsible for remanent fields on the Moon, is metallic iron. On Mars a possible candidate is titanohematite, a solid solution mineral of Fe_2O_3 and $FeTiO_3$. Titanomagnetite, a solid solution of two end-member minerals Fe_3O_4 and Fe_2TiO_4 is another possibility. A solid solution can exist with varying amounts of each of the two end member minerals comprising its makeup. Because the surface composition of Mercury appears to be low or devoid of FeO-bearing materials, oxidized iron-bearing silicates would have to be buried for the remanent field scenario to be possible if it were caused by remanence of titanomagnetite or titanohematite. Alternatively, with Mercury's other similarities to the Moon, it could be that the remanent fields, if they exist, would be associated with metallic iron.

However, another mineral that has remanence is pyrrhotite, Fe_7S_8. Iron sulfides have been postulated as possible components of Mercury's regolith as a possible source of sulfur in the atmosphere and deposits in high-latitude cold craters where the high coherent backscatter of radar signals has been observed. There will be much more about the high-latitude radar backscatter images and their possible causes in Chapter 7. Until measurements positively identify sulfur in some form on Mercury, all of these suggestions remain speculative.

5.6 SPACE WEATHER AND SPACE WEATHERING ON MERCURY

The Sun is constantly emitting particles, as well as light, into the Solar System. Ions, mostly protons, and electrons stream from the Sun and move throughout the Solar System dragging solar magnetic fields with them. The average geometry of these streaming fields is a spiral ever increasing in distance from the Sun. The particles emanating from the Sun make up the *solar wind*. The spiraling magnetic field (*Parker spiral*) is called the interplanetary magnetic field (IMF).

5.6.1 Space weather

Fluctuations and rapid changes in the "average state" of the solar wind and IMF are called *space weather*. At times of high solar activity, large flares leap out from the Sun carrying unusually large numbers of charged particles and distorting the normal positions of the magnetic field in the solar wind. Sometimes the x-ray and ultraviolet (UV) flux from the Sun increases drastically for short periods of time. The corona of the Sun may emit ejections of atoms and ions into the Solar System. Collectively,

these phenomena of rapid changes in sunlight, solar particles, and fields are called space weather. On Earth we are familiar with satellite-to-Earth communications being occasionally interrupted during periods of unusual *space weather*. On Mercury the effects of space weather are even stronger than on Earth because it is closer to the Sun and the intrinsic magnetic field of the planet is smaller than that of Earth.

An intrinsic magnetic field like that of the Earth can hold off the solar wind as shown in Figure 5.2. Although charged particles and fields can enter into the Earth's magnetic field near the magnetic poles, when they do, they encounter the Earth's atmosphere. Interaction of space weather and the Earth s upper atmosphere and ionosphere result in high-altitude chemical changes and auroral displays. Earth's surface is largely sheltered from the effects of protons, other ions, and fields from the Sun.

Ions traveling parallel to the magnetic field lines near Mercury may come from the Sun or from Mercury's surface or atmosphere. Most ions are H^+ or He^+, but we know that there are Na^+, K^+, and Ca^+ in the vicinity of Mercury because the neutral counterparts of these ions have been discovered in Mercury's exosphere (there will be more about this in Chapter 6). There may be S^+, OH^+, O^+, and other ions from *photoionization* of neutrals delivered to Mercury s atmosphere from volatilization of meteoritic and surface materials. These ions may be recycled by induced electric fields near Mercury and redirected toward Mercury's surface to be neutralized and stored in cool places, or, they may be swept away from the planet to join other ions in the IMF.

5.6.2 Space weathering

Space weathering is distinct from space weather. Space weathering is what happens to surfaces of asteroids, the Moon, and Mercury as they undergo modification from sunlight, meteoritic bombardment, charged particle sputtering, and assaults from a myriad of other physical processes in space.

Modeling of Mercury's magnetic field, based on *Mariner 10* data illustrated in Table 5.1. showed that Mercury s magnetosphere could push against, and hold off, the solar wind from Mercury's surface at low- and mid-latitudes. But because the field at Mercury is relatively small, and there is only a very thin atmosphere on Mercury, regions on Mercury's surface are subject to ion and electron bombardment. Also the surface is directly subjected to the effects of sunlight at all wavelengths because there is no thick attenuating atmosphere like on Earth or Venus to diminish short wavelength (extreme ultraviolet (EUV) and UV) light. Thus Mercury's surface undergoes space weathering. This will discussed in more detail in later chapters.

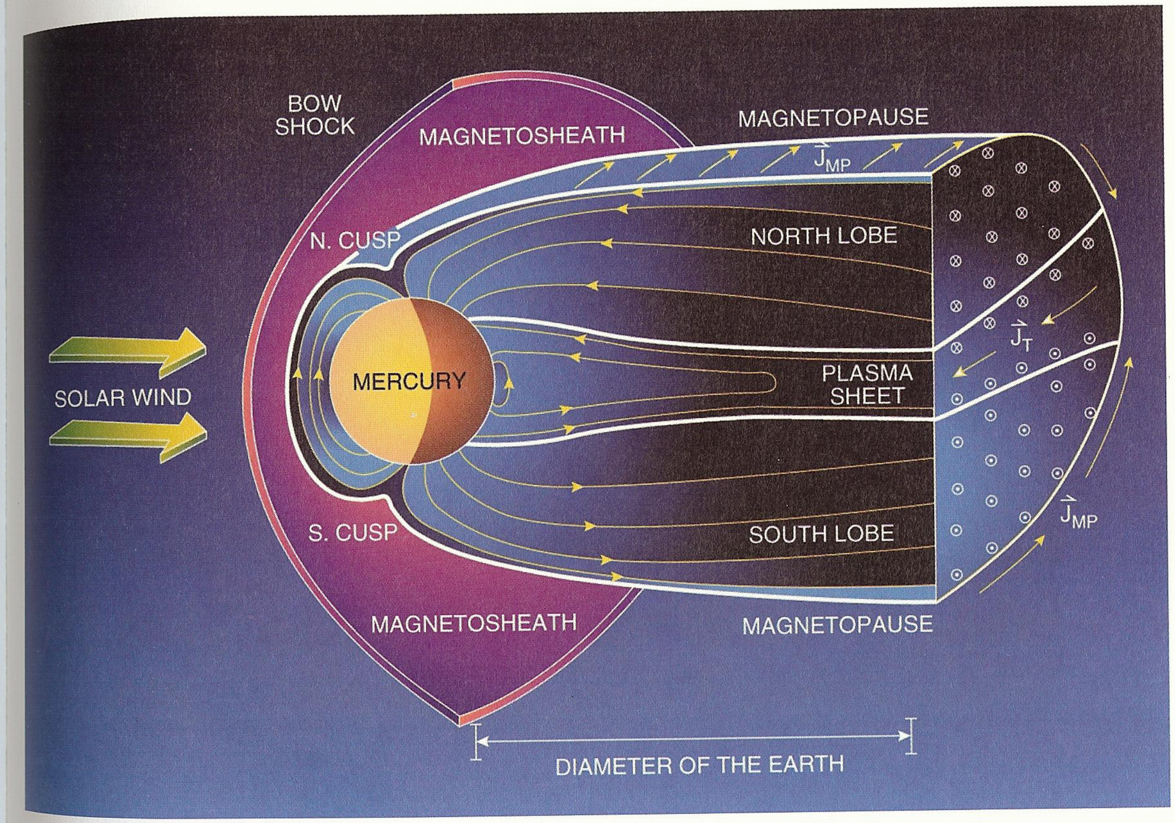

Figure 5.2. This concept of Mercury's magnetic field is based upon the *Mariner 10* data and subsequent modeling and analyses of those data. It is possible that this view will change with new observations made by particles and fields instrumentation on future missions to Mercury (courtesy of James Slavin, NASA Goddard Space Flight Center, Laboratory for Extraterrestrial Physics, Greenbelt, Maryland, USA).