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Planetary and lunar magnetism

In situ studies by spacecraft of the magnetic fields of Earth and all the planets except for Pluto began with the USSR's launch of Sputnik 3 in 1958. The study of the geomagnetic field by the USA followed with Vanguard 3 in 1959. Since then the US Explorer, Mariner, Pioneer, Voyager, Ulysses, and Galileo missions have surveyed all the planets from Mercury to Neptune as well as the Earth's Moon, the Galilean moons of Jupiter, and Saturn's largest moon, Titan. The USSR repeatedly studied Earth's Moon, Venus, and Mars with their Luna, Venera, Mars, and Phobos missions.

Mariner 10 discovered in 1974 and 1975 that Mercury was globally magnetized but with such a small intrinsic magnetic field that no durably trapped radiation belts were permanently associated with the magnetosphere, formed by the solar wind. Venus appears to be globally unmagnetized, according to results from Venera and Mariner spacecraft since 1961. The solar wind interaction with its atmosphere and ionosphere creates an induced magnetosphere, but devoid of any trapped radiation belts.

The magnetic field of the Moon has been studied by several spacecraft, especially Explorer 35 in 1968 (Ness 1969). Measurements on the lunar surface were conducted by the robotic rover Lunokhod in 1968 (Dolginov *et al*. 1975) and with the three Apollo Lunar Surface Experiments Packages (ALSEP) that were placed there during the Apollo program of the late 1960s and early 1970s (Dyal *et al*. 1972, 1974). The Apollo 15 and 16 missions each carried a sub-satellite which was launched into a 100 km altitude, low-latitude orbit. The data they gathered suggested the existence of magnetized crustal regions (Hood *et al*. 1981). More recent data provide much firmer evidence of localized regions of remanent crustal magnetization by the MAGER (MAGnetic field Electron Reflectometer) instrument on Lunar Prospector (Lin *et al*. 1998).

The latest detailed study of these lunar magnetized regions from Lunar Prospector data suggest a special geometrical relationship and correlation with impact craters which are antipodal in location to them (Halekas *et al*. 2001). The source of the magnetic field for these magnetized regions is unclear at present. They may indicate that there was an ancient lunar dynamo that had magnetized the lunar crust, or perhaps there is a magnetization process that occurs as a result of the high-velocity impacts which generate the observed craters. It is also possible that both processes are important.

In 1964 the US Mariner IV, and subsequently several Soviet Mars and Phobos probes, had placed upper limits on any global intrinsic Martian field, although the existence of a detached bow shock and magnetic tail were observed (Ness 1979a). Since achieving orbit in 1997, the US orbiter Mars Global Surveyor has finally clarified the long-standing enigma of the status of the Martian magnetic field with the discovery of localized intense remanent crustal magnetization but no significant global field (Acuña *et al*. 1999, Connerney *et al*. 1999).

Pioneers 10 (1974) and 11 (1975) and Voyagers 1 (1979) and 2 (1979) examined *in situ* the magnetic field and magnetosphere of Jupiter, which had been inferred from its non-thermal radio emissions, first detected in 1955. Jupiter's magnetic field is much stronger than Earth's and is distinctly non-dipolar close to the planet. More recently, the US Galileo and ESA Ulysses spacecraft have added to the database of *in situ* studies of the main field of Jupiter.

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Galileo has also studied the four Galilean moons during multiple close flybys, and results suggest that some of these moons possess an intrinsic or induced field.

In 1979 the US Pioneer 11 discovered a significant global magnetic field and trapped radiation belt at Saturn. This was studied in much more detail by Voyagers 1 and 2 in 1980 and 1981. Saturn was found to have a weaker field than Jupiter, and one that appears to be remarkably axisymmetric (to order and degree $n = 3$ in a spherical harmonic or multipole representation) about its rotation axis.

The Voyager 2 flybys of Uranus and Neptune in 1986 and 1989 discovered significant global magnetic fields and trapped energetic particle radiation belts. Both Uranus and Neptune display quite similar magnetic fields, but very different from those of Jupiter, Saturn, and Earth. As astrophysical objects, Uranus and Neptune are best described as oblique rotators because of the large angular offsets of their magnetic axes from their rotation axes (59° and 47°, respectively). Additionally, their *magnetic centers* are offset from their center of figure by substantial fractions of a planetary radius ($0.31R_U$ and $0.55R_N$, respectively).

This chapter summarizes our present knowledge of the quantitative characteristics of the magnetic fields of the planets and certain of their moons. An early review of space magnetometry by Ness (1970) summarized the first decade of *in situ* studies of the magnetic fields of Earth, Mars, Venus, and the Moon, discussed the technical problems of measuring weak interplanetary fields, and presented technical details of instrumentation. A more recent review of the author's role in space exploration has appeared (Ness 1996).

The dates of significant discoveries of planetary magnetic fields and the associated spacecraft are given in Table 1. An additional relevant mission parameter in these studies of solar wind interactions and the quantitative analysis of the intrinsic magnetic fields is the closest flyby or periapsis distance of the spacecraft trajectories relative to the center of the planet, in units of planetary radii.

GEOMAGNETISM AND PLANETARY DYNAMOS

The most plausible explanation for the origin of planetary magnetic fields, and the observed and well-documented terrestrial secular variation, is that there is a coherent regenerative dynamo motion of an electrically conducting fluid in a planet's interior. This motion is a result, most likely, of thermally driven convection. There are also suggestions that coupling of precessional torques, which arise in the differential motion between the cores and mantles of the planets, may drive this coherent motion. Finally, this coherent motion may also be driven by tidal forces associated with other celestial bodies in close proximity, for example Jovian tides in the Galilean moons, which display spin–orbit coupling as a result of tidal dissipation.

Study of the Earth's magnetic field has been under way ever since William Gilbert published his famous treatise, *De magnete*, in 1600. Geomagnetism is a well-established discipline with a long and distinguished history, but one that lies outside the scope of this chapter. Interested readers are referred to any of the many texts that address the many special problems of geomagnetism, such as Busse (1978), Campbell (1997), Backus *et al*. (1996), Jacobs (1994), Merrill *et al*. (1996), Stevenson (1983), and Soward (1992).

The internal motion in the Earth's electrically conducting core is regenerative in the sense that it leads to the maintenance of electrical currents and associated magnetic fields by the dynamo process. The observed secular variation of the geomagnetic field (Cain 1995) adds substantial support to this concept of dynamic fluid motion in the interior.

Table 1 Summary of US spacecraft, 1971–2004, which have discovered and investigated *in situ* the magnetic fields of the planets

	Year of encounter or orbit/periapsis in R_p					
	Mercury	Mars	Jupiter	Saturn	Uranus	Neptune
Mariner 10	•1974/1.30 1975/1.13					
Pioneer 10			1973/2.84			
Pioneer 11			1974/1.31	•1979/1.35		
Voyager 1			1979/4.88	1980/3.07		
Voyager 2			1979/10.1	1981/2.69	•1986/4.18	•1989/1.18
Ulysses			1992/6.3			
Galileo (orbiter)			1995+/6–15			
Cassini (orbiter)				[2004/1+]		
Mars Global Surveyor		•1997/1.03				

•Discovery encounter.

The history of the Earth's magnetic field is recorded in magnetized rocks and sediments, which bear magnetizable materials. The study of these ancient samples, which is the discipline of paleomagnetism, indicates that the geomagnetic field has reversed itself many times in the Earth's geological past (McElhinney 1973, Piper 1987). These reversals are dated through the study of the relative abundances of certain isotopes of the radioactive elements.

The physical properties of the interiors of the other planets can only be estimated, whereas the study of earthquake generated seismic signals provides accurate estimates of the structure and physical properties of Earth's interior. There appears to be no obstacle to the assumption that all planetary global magnetic fields are generated within electrically conducting core or shell regions. However, a continuing challenge is the development of a comprehensive and quantitative theory of how rapidly rotating, self-gravitating, and highly condensed bodies throughout the Universe generate their magnetic fields.

Dynamo theory remains one of the continuing basic challenges in theoretical planetary physics and astrophysics (Roberts 1995, Proctor and Gilbert 1996). Recent supercomputer simulations of the Earth's dynamo process that reveal intrinsic reversals have been reported by Glatzmaier and Roberts (1995, 1996) and Glatzmaier *et al*. (1999). Interesting laboratory experiments using molten sodium have recently been conducted which demonstrate the dynamo effect (Gailitis *et al*. 2000).

THE GEOMAGNETIC FIELD

Studies of the geomagnetic field prior to the space era were conducted on land and sea, sometimes with specially constructed sailing vessels such as the one used in the seventeenth century by Edmund Halley in an investigation of the deviation of the compass direction from true north in the Atlantic Ocean near South America. The major advance in studies of the geomagnetic field resulting from land and sea measurements occurred just as the space age began. This was the development of the theory of plate tectonics in the early 1960s. This was based upon paleomagnetic studies of crustal rocks and a vast database of total field measurements by instruments towed behind oceanographic research vessels.

Paleomagnetic results had shown that the geomagnetic field had reversed its polarity many times in the past. These reversals are features which mark the time of these events and were accurately dated from radioisotopes present in common rock-forming minerals. The oceanographic data were combined to demonstrate conclusively that ocean floors were spreading apart from central regions, called ridges, as a result of convection in the mantle driving the relative motion of the continents.

Thus, the oceanographic magnetic data were analogous to a tape recording since the hot upwelling molten material from the mantle preserved a memory of the status of the geomagnetic field as it cooled below its Curie point. The concept and the theory of *continental drift* was proposed in 1912 by the German meteorologist Alfred Wegener. He became Professor of Geophysics and Meteorology at the University of Graz, Austria, from 1924 to 1930, the year of his death. He had based his theory originally on the geometrical similarities of the coastlines of the South American and African continents, and matching geological formations on opposite sides of the South Atlantic. Wegener's ideas and theory of such moving continents were initially met with skepticism, which continued for a long time, with some geophysicists "proving" that such motion was physically impossible.

The first orbital flight of a magnetometer was aboard the Soviet satellite Sputnik 3 in 1958; this was followed by the US Vanguard 3 in 1959. It was not until 1979 that the USA dedicated a special mission to study the geomagnetic field, MAGSAT. This spacecraft carried both an ultra-precise triaxial fluxgate vector magnetometer and a cesium vapor total field unit to measure accurately the magnitude of the field. Use of these spacecraft data and standard ground station magnetic observatories allowed the development of models of the Earth's magnetic field up to degree and order 13 and beyond (McLeod 1996).

GLOBAL MAGNETIC FIELDS AND SOLAR WIND RAMIFICATIONS

The existence of a global planetary magnetic field with sufficient strength to deflect the solar wind leads to several unique features of the planetary environment (see the reviews by Stern and Ness 1982, Schulz 1995). The main feature is the formation of a magnetic cavity, or *magnetosphere*, from which undisturbed solar wind plasma is excluded and within which a distorted planetary field controls the motion of energetic charged particles – mostly electrons and protons, but some heavier ions too. Examples of the latter are found in the Jovian magnetosphere, which is populated with heavier ions such as S^{2+} and SO^{+} that originate in the SO_2 ejections from Io's active volcanoes. The neutral atoms become ionized by charge exchange with the co-rotating magnetosphere of Jupiter.

Outside this cavity a detached bow shock wave develops in the supersonic and super-Alfvénic solar wind flow. Finally, a *magnetotail* is formed which trails far behind the planet in the anti-solar-wind direction. The distance to the sunward stagnation point of solar wind flow, measured in units of planetary radii, varies from the low values of 1.2 at Mars (Vignes *et al*. 2000) and 1.4 at Mercury (Ness 1976) to as great as 70 or more at Jupiter. This parameter, and those describing the global field to lowest order and degree as a simple offset tilted dipole, are summarized in Table 2.

The traditional way of describing a planetary magnetic field quantitatively is based upon a method developed by Gauss. This uses spherical harmonic coefficients to represent magnetic multipoles. Modern methods of deriving planetary field representations from spacecraft data using generalized inversion techniques have been developed by Connerney (1981). The Gaussian coefficients for all of the planetary magnetic fields known to date are given in Table 3. The lowest-order magnetic field multipole moment ($n = 1$) is a dipole. Thus, a basic result of the solar wind interaction is that a bipolar magnetotail is developed. Within this magnetotail is a field reversal region, referred to as a plasma or neutral sheet, which contains an embedded plasma. The origin of this plasma is the atmosphere of the parent planet, any natural moons, and the shock-modified solar wind. The strength of the magnetic field in the magnetotails of planets depends primarily upon the properties of the solar wind. The magnetotail appears to be an important energy store, playing an important role in the overall dynamics of the magnetosphere. See Ness (1987) for a review of the discovery in 1964 and early space age studies of the Earth's magnetotail.

A unique feature of the magnetotails of Uranus and Neptune is the obliquity of their rotational axes combined with the large angular offsets of the magnetic axes from the rotational axes. This combination produces a unique magnetic pole-on interaction with the solar wind at certain periods during their orbits. As the planet rotates, the magnetic axis of the planetary dipole field becomes colinear with that of the solar wind velocity. This is theorized to lead to a magnetotail configuration in which the plasma sheet becomes cylindrical in shape, surrounding a unipolar flux tube (Voigt *et al*. 1987, Voigt and Ness 1990). This is the opposite of the case at Earth, where the plasma sheet develops as a transverse planar structure in the magnetotail, which separates the bipolar lobes or flux tubes of the magnetotail.

At Jupiter and Saturn a bipolar magnetotail and plasma sheet similarly develops. Important consequences of the solar wind interaction, trapped radiation belts, and plasma sheets are that there are a number of electrical current systems external to the planet. The magnetic fields of these currents have a significant influence on *in situ* measurements of the magnetic fields by flyby or orbiting spacecraft. These currents must be carefully considered and, if appropriate, explicitly modeled when attempts are made to extract accurate estimates of the intrinsic field of the planet.

MERCURY

Only one spacecraft, the US Mariner 10, has studied the planet Mercury. Launched in 1973, it used a gravity-assist maneuver at Venus to encounter Mercury. There were three encounters, due to a serendipitous exact-integer relationship between the heliocentric orbital periods of Mercury and Mariner 10. Successful encounters in March 1974 (Ness *et al*. 1974) and again in March 1975 provided direct observational evidence for a global magnetic field at Mercury (Ness 1978). The second one, in September 1974, was dedicated to imaging the surface and did not penetrate the magnetosphere or cross the magnetopause and detached bow shock wave.

Data from the magnetic field experiment on board Mariner 10 during the 1975 encounter are shown in Figure 1. The positions of the detached bow shock and magnetopause, scaled from Earth data, are shown superimposed on the plot of the magnetic field vectors projected on the plane of the spacecraft's orbit (Connerney and Ness 1988).

The discovery of an intrinsic magnetic field at Mercury was a great surprise, since there was neither any prior

Table 2 Summary of magnetic fields, solar wind sunward stagnation point, and rotation periods of the planets (Note: 1 G cm^3=10^{-3} A m^2; 1 nT=10^{-5} G=10^{-9} T)

Planet	Dipole moment (G cm^3)	Tilt and sense	Dipole equatorial field (nT)	Average stagnation point distance (R_p)	Rotation period
Mercury	5×10^{22}	+14°	330	1.4	58.7^d
Venus	$< 4 \times 10^{21}$	—	< 2	1.0+	-243^d
Earth	8.0×10^{25}	+11.7°	31 000	10.4	23.9^h
Moon	$< 1 \times 10^{19}$	—	< 0.2	none	
Mars	$< 2 \times 10^{20}$	—	< 0.5	1.29	24.6^h
Jupiter	1.6×10^{30}	−9.6°	428 000	65 ± 15	9.92^h
Saturn	4.7×10^{28}	−0.0°	21 200	20 ± 3	10.66^h
Uranus	3.8×10^{27}	−58.6°	23 000	20	17.24^h
Neptune	2.0×10^{27}	−46.9°	14 000	26	16.1^h

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