RECENT ADVANCES IN PLANETARY MAGNETISM*

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Abstract. During the past decade, significant advances in the *in situ* measurements of planetary magnetic fields have been made. The U.S.A. and U.S.S.R. have conducted spacecraft investigations of all the planets, from innermost Mercury out to Jupiter. Unexpectedly, Mercury was found to possess a global magnetic field but neither the Moon nor Venus do. The results at Mars are incomplete but *if* a global field exists, it is clearly quite weak. The main magnetic field of Jupiter has been measured directly for the first time and confirms, as well as augments appreciably, the past 2 decades of ground-based radio astronomical studies which provided indirect evidence of the field. Progress in developing analytically complete models of the dynamo process suggests a possible common origin for Mercury, Earth and Jupiter.

1. Introduction

During the last decade, U.S.A. and U.S.S.R. spacecraft have conducted *in situ* studies of the magnetic fields of the terrestrial planets, the Moon and the giant planet Jupiter as well as the characteristics of their interaction with the magnetized solar wind. New and surprising results have included detection of appreciable magnetization of lunar rocks (Fuller, 1974) and evidence of localized lunar magnetic fields but no global field. A significant global field of Mercury and a magnetosphere have been detected (Ness *et al.*, 1975, 1976); while there is a possible global field of Mars (Dolginov *et al.*, 1976) but a negligible field at Venus (Dolginov *et al.*, 1969). Radio astronomical observations of non-thermal radio emissions from Saturn and Uranus by spacecraft (Brown, 1975; 1976,) suggest the existence of not only a planetary magnetic field but also a radiation belt like Earth and Jupiter. In addition, considerable progress has been made in theoretical studies of the dynamo mechanism for generation of such magnetic fields. While such a process is unquestionably responsible for the magnetic fields of Earth and Jupiter, the magnetic field of Mercury can also be explained on the basis of remanent magnetization of sub Curie point material in its outer most layers.

Of fundamental cosmological interest is why massive rotating astrophysical objects such as the planets, our Sun, stars and pulsars possess large scale, and in some cases, very intense magnetic fields. It is particularly fitting, therefore, that this article should appear in a volume honoring Hannes Alfvén on his 70th birthday. Alfvén's work in space plasma physics (summarized in part in Alfvén and Fälthammar, 1963) was conducted early in his career. More recently he and his colleagues have turned their attention to the problem of

* Paper dedicated to Professor Hannes Alfvén on the occasion of his 70th birthday, 30 May, 1978.

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the origin of the solar system (Alfvén and Arrhenius, 1976). Throughout all of Alfvén's investigations, the role of magnetic fields and their relationship to and interaction with celestial objects and plasmas has been a dominant theme. This brief review will summarize the highlights of our recent advances in studies of planetary magnetism.

The advent of the space era and its associated unique transportable "laboratories" for the *in situ* investigation of physical properties of the interplanetary medium and the characteristics of the planets has increased remarkably our quantitative knowledge of details on individual members of the solar system. Undoubtedly, the most significant results have come from visual photography of the surfaces of the planets, not only for its intrinsic value to scientists but also its impact on the average citizen. These data showed that there were periods in the history of formation of the surfaces of the terrestrial planets during which intense bombardment has occurred and whose cratering effects are brilliantly visible in the surfaces of Mercury, Moon and Mars. Even the satellites of Mars, Phobos and Deimos, have been observed to possess surfaces eroded and shaped by impacting projectiles. Direct observation of the surface of Venus from orbiting spacecraft is impossible because of the dense cloud cover but ground-based radar studies suggest the existence of large circular shaped features which are assumed to be due to impact craters.

MOON

The history of formation of the surfaces of the Moon and terrestrial planets and indeed the geological mapping of the different epochs is possible through a careful analysis of such photographs. The history of evolution of a planet is also recorded in the magnetic "memories" of the crystalline rocks. There is no measurable global magnetic field of the Moon, but this only sets an upper limit to its value of 1.3×10^{18} G cm^3 for the component perpendicular to the rotation axis. There is as yet no firm upper limit on the component parallel to the rotation axis (Russell *et al.*, 1974). On the other hand, the existence of local lunar magnetic fields up to 100's of gammas and the return of magnetized lunar samples (Fuller, 1974) requires an explanation. Sources of such magnetization range from internal to external sources. Both the Sun and impacting comets (Gold and Souter, 1976) have been invoked by some, while an internal dynamo is suggested by others to be the primary source of the magnetic field responsible for the existence of contemporary magnetized materials.

An interesting idea has been proposed (Runcorn, 1975) in which an extinct dynamo in the Moon magnetized the lunar crust and mantle but the external effects would be immeasurable due to a unique cancellation hypothesized to be characteristic of such a process. Subsequent disruption of the homogeneity of the crust by impacting projectiles permits a leakage of magnetic flux which is responsible for the local magnetic fields observed as well as explaining the magnetization of the existing samples.

However, the basic concept that a zero external field results from such a process has been successfully disputed on the basis of not being a physically plausible or possible course of evolution (Srnka, 1976). While there is no resolution of the source of magnetization, the correct understanding of lunar magnetization will offer a unique insight

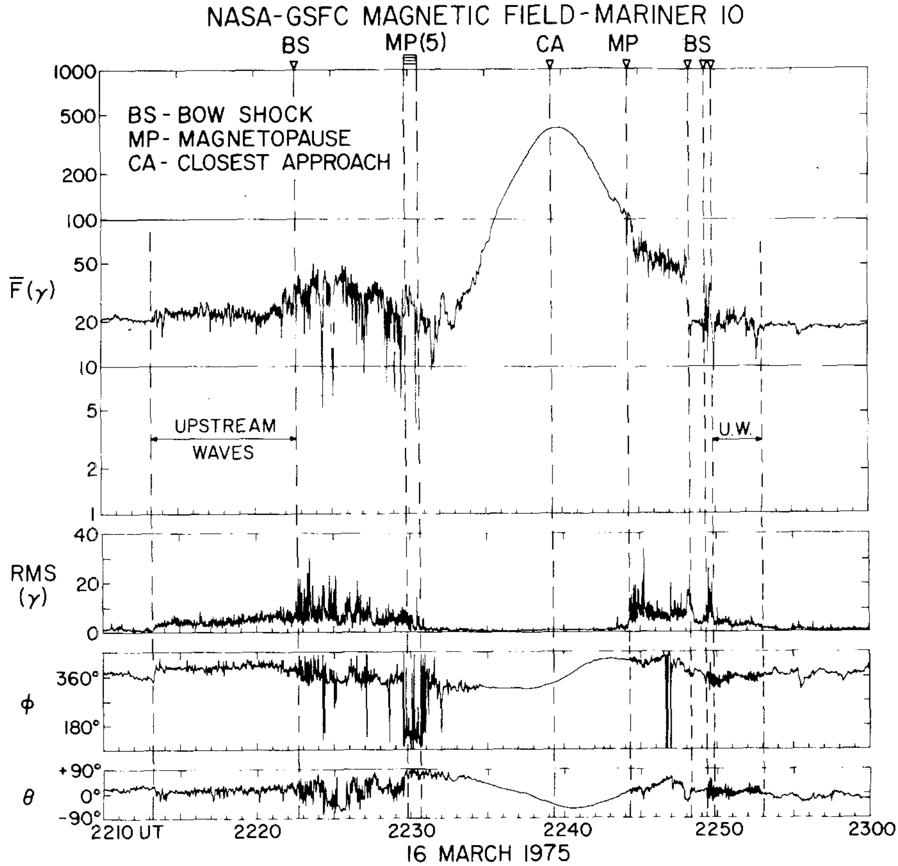

Fig. 1. Mariner 10 magnetic field data (F = field intensity, $1\gamma = 1$ nanotesla, RMS = Pythagorean mean of x, y, z root mean square deviations over 6 seconds, ϕ and θ = longitude and latitude of field vector in Mercury-Sun-orbit plane coordinates) (Ness *et al.*, 1976). ($\theta = 0, \phi = 0$ points towards Sun, $\theta = 0, \phi = 180°$ away).

into the evolution of the lunar interior. Data sets presently available are too limited in areal extent and accuracy to provide definitive answers and future lunar missions are required.

MERCURY

Certainly one of the more surprising discoveries of space investigations has been the detection of a global magnetic field at Mercury, with a surface intensity approximately 1% of Earth's (Ness *et al.*, 1975; 1976). Multiple flybys by the U.S.A. Mariner 10 spacecraft clearly revealed not only the existence of a planetary magnetic field but also the formation of a modest magnetosphere and magnetic tail due to the interaction of the solar wind. Data obtained by the NASA/GSFC magnetometer on the third encounter are shown in Figure 1. Clearly evident in the figure are the characteristic boundaries associated with solar wind interaction with the planets:

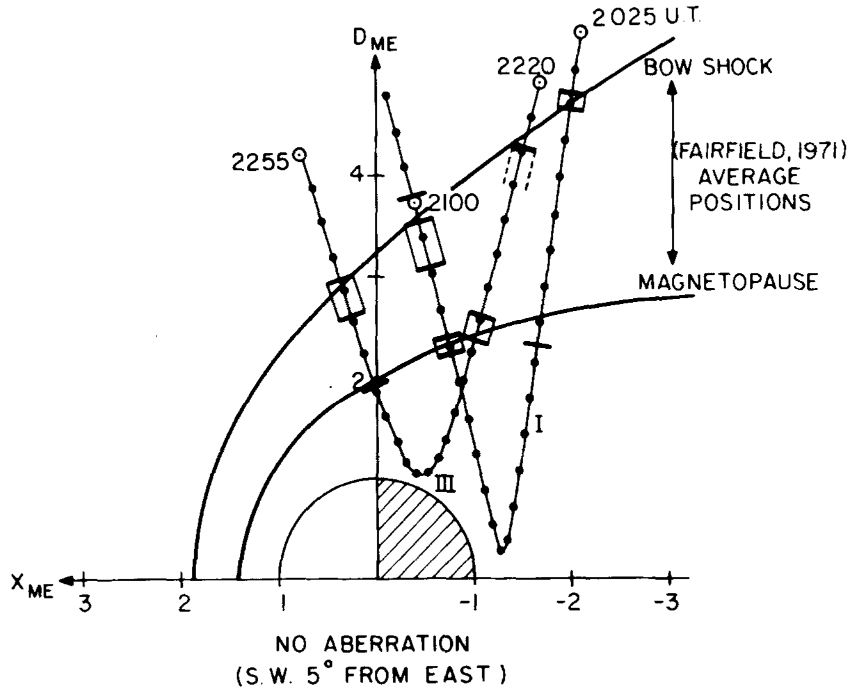

Fig. 2. Comparison of positions of bow shock and magnetopause observations at Mercury by Mariner 10 with average positions at Earth. Scaling assumes that Hermean magnetosphere is smaller than Earth's by a factor (6378 ÷ 2439) × (11 ÷ 1.45) = 20 (Ness *et al.*, 1976).

(1) the detached *bow shock wave*, which develops because of the super Alfvénic flow of solar plasma past the planet and

(2) the *magnetopause*, a current sheet, exists because the highly conducting plasma cannot penetrate into the planetary magnetic field. Our qualitative understanding and description of these two characteristic discontinuity surfaces surrounding a planet depends heavily upon basic work in studying the interrelationship of magnetic fields and plasmas conducted by Alfvén many years ago.

The region near closest approach in the Hermean magnetosphere shows a maximum field of 400γ, which was observed at 327 km from the surface of the planet. Quantitative analyses of these data using spherical harmonics lead to the result that the equivalent centered dipole moment of Mercury is tilted at an angle of $14 \pm 5°$ from the rotation axis, with a magnitude of $4.9 \pm 0.2 \times 10^{22}\,\mathrm{G\,cm^3}$. This value is roughly 0.04% of the Earth's moment but the substantially smaller radius of the planet Mercury, 2439 km, leads to an equivalent dipole equatorial field intensity of $336 \pm 12\gamma$.

The position of the detached bow shock and magnetopause crossings observed by Mariner 10 during its two direct penetrations of the magnetosphere of Mercury are shown in Figure 2. These are presented in a coordinate system assuming cylindrical asymmetry

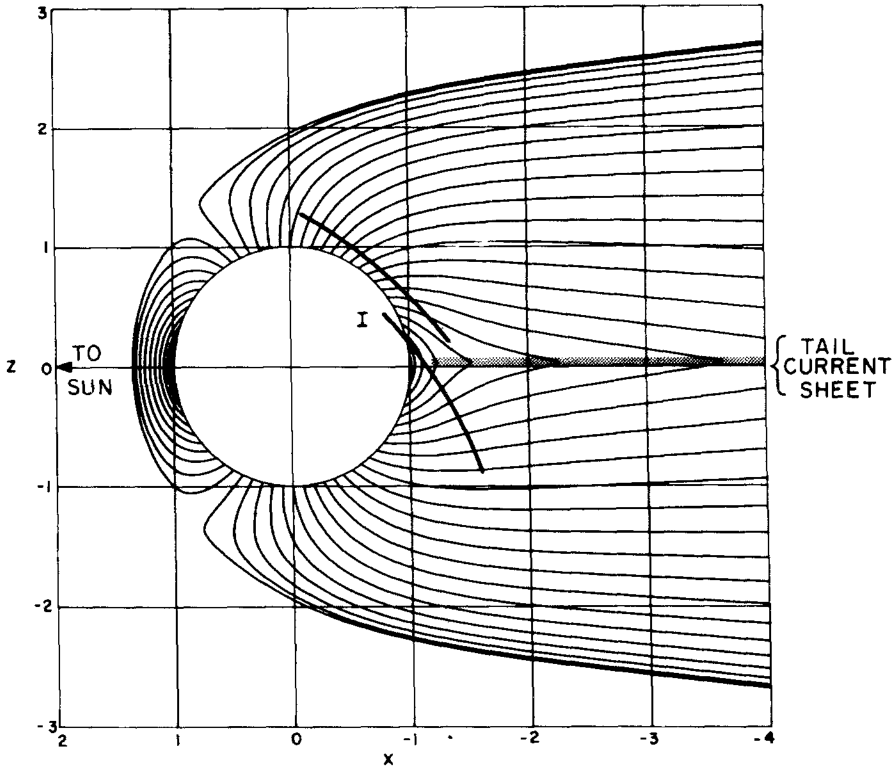

Fig. 3. Model magnetosphere of Mercury, showing field lines in the noon-midnight meridian plane with the Sun off to the left. (Whang and Ness, 1975).

about the direction of solar wind flow. While approximately radial from the Sun, this can vary by as much as ± 10–15°. For comparison, average positions of the bow shock and magnetopause observed at Earth are presented, scaled by a relationship such that the stagnation point distance of solar wind flow at the magnetopause of Mercury, $1.45 \pm 0.15 R_M$, is made equivalent to $11 R_E$, observed in the case of Earth. In this diagram, the comparisons of the observations at Mercury with those at Earth show excellent agreement, with the assumption that the solar wind flow was deviated by 5° to the East at the time of the observations.

In spite of the limited data available on direct observation of the magnetosphere of Mercury, it is possible to construct a mathematical model of the magnetic field based upon an analogy with similar models for solar wind interaction with the Earth's planetary field. The results of such a study are shown in Figure 3. The modest nature of the global field is vividly illustrated, with the planet Mercury occupying a very large fraction of the magnetosphere. In the case of Earth, with a stagnation point distance of $11 R_E$, the Earth occupies almost an insignificant fraction of the magnetosphere geometrically. The limited volume of space available in the Hermean magnetosphere and the strong day-night asymmetries in the available space preclude the existence of permanently trapped radiation belts such as found at Earth and Jupiter. This explains why no non-thermal radiation was observed from Mercury which could have presaged the detection of a planetary magnetic field, as done so successfully at Jupiter.

The implication of the existence of a planetary magnetic field at Mercury that is of greatest significance for the evolution of the solar system is that the planet possesses a highly differentiated interior (Ness, 1978). In fact, the core is amongst the largest, fractionally, of all the terrestrial planets, with a radius approximately 75% of the planet itself. Thus, although Mercury's surface is very Moon-like in its appearance, due to cratering impacts and the absence of a sensible atmosphere and other constituents to cause erosion, its interior is very much Earth-like. Whether or not the observed magnetic field is due to a presently active dynamo or remanent magnetization is unknown (Cassen, 1977; Ness *et al.*, 1976; Strangway, 1977). Arguments have been presented on both sides for the origin of the magnetic field. Regardless, it is certain that there exists within the surface rocks on Mercury a history of the evolution of the planet which, when measured, will contribute immensely to our general understanding of the origin of the solar system.

MARS AND VENUS

The U.S.S.R. has been particularly vigorous in its study of Mars and especially Venus. There have been both magnetometers and plasma instruments on almost all the spacecraft which they have launched. Well developed detached bow shock waves are observed surrounding and very close to both planets (see Figure 4). However, there have been no unequivocal identifications of either magnetosphere or magnetopause structures in the results reported to data. For Venus, a low value has been set for the upper limit to the global field, a moment of less than $1\text{–}6 \times 10^{22}\,\mathrm{G\,cm^3}$ (Dolginov *et al.*, 1969; Russell, 1976). This is sufficiently low that the magnetic field itself does not play an important role in the interaction of the planet with the solar wind. The ionosphere is the dominant reason for the deflection of the solar wind flow around the planet and the development of a detached bow shock wave (Gringauz *et al.*, 1976).

Studies at Mars have suggested the existence of a planetary field (Dolginov *et al.*, 1976), although the location of the data available has not been optimum for studying the clearly weak magnetic field which may exist at the planet. The U.S.S.R. results on the magnetic field suggest a value of 64γ for the equivalent dipole equatorial field value. Unlike Venus, this value is sufficiently large that the magnetic field would play an important role in the deflection of solar wind around the planet. Unfortunately, the quality and quantity, as well as the position of the data and the nature of the interaction is still uncertain as to whether or not there exists a substantial global magnetic field at Mars (Bogdanov and Vaisberg, 1975; Vaisberg *et al.*, 1976).

The data shown in Figure 4 illustrate how close the bow shock is at Venus to the surface of the planet, consistent with the absence of a global field. However, the results for Mars suggest that unless its ionosphere extends especially far, a magnetic field may well be present in order to deflect the solar wind flow.

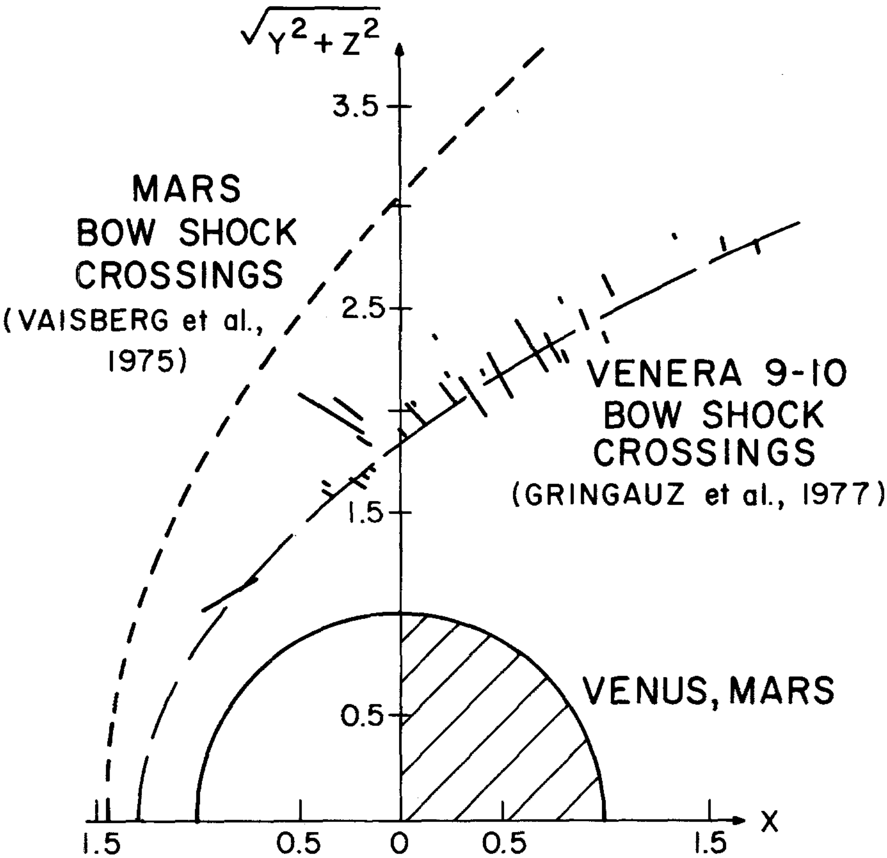

Fig. 4. Comparison of the location of the bow shocks observed at Mars and Venus by U.S.S.R. spacecraft. The scaling used is that in which the radii of the two planets are made equal. (Gringauz *et al.*, 1976).

JUPITER

Non-thermal radio emissions from the planet Jupiter have been studied for more than 2 decades and a prediction of a gigantic magnetic field, 1–10 G at the equator, made far in advance of direct measurements by the U.S.A. spacecraft Pioneers 10 and 11 in 1973 and 1974. Direct observations reveal a unique feature of the magnetosphere formed by solar wind interaction with the planet that was not generally anticipated. As illustrated in Figure 5, in which the size of the planet is not to scale, there exists a distortion of the outer magnetosphere of the planet which appears much as though its magnetic tail were wrapped around it in sharp contrast to the Earth's case, in which the tail extends in the anti solar wind flow direction. It is thought that this "magnetodisc" develops as a result of the rapid rotation of the planet, combined with its intense magnetic field and an ionospheric source of plasma.

The Pioneer 11 showed that another of the unique aspects of the magnetic field at

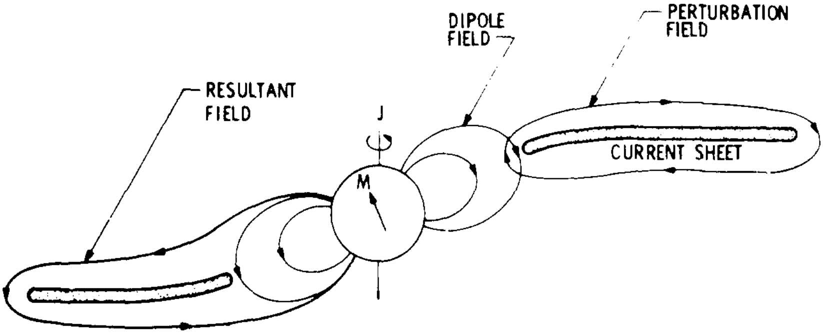

Fig. 5. Schematic diagram of the "magnetodisc" model of Jupiter's magnetosphere. Not drawn to scale, the current sheet extends from roughly 15–20R_J to 40–80R_J. (Smith *et al.*, 1976).

Jupiter is the presence of significant high order multipole terms. (Acuna and Ness, 1976; Smith *et al.*, 1976). While the data set is not complete to allow a comprehensive analysis, results indicate the existence of quadrupole and octupole terms, 24% and 21% of the dipole, that are considerably larger than those at Earth, 13% and 9%. These large values lead to a significant variation of the surface field intensity such that the maximum field is 14 G, in the North polar regions, while the minimum field is only 4 G. Figure 6 illustrates this variation on the surface of the planet and at a distance of $2R_J$ to contrast the effects of the large high order moments in the magnetic field. The surface values show a wide variation, by almost a factor of 4, while the values at $2R_J$ show a range of approximately 2, appropriate for a purely dipole internal field.

Another feature of the presence of high order, magnetic multipole moments is the distortion of the equatorial surface of minimum field intensity for charged particle trapping. This is illustrated in Figure 7 at several radial distances. From past ground-based radio wave observations, the rocking of the polarization ellipse was used to interpret the tilt of the magnetic dipole axis of Jupiter, relative to its rotation axis. The values obtained ranged from 8 to 12°. This figure illustrates why such a variability is to be expected, since different investigators using different frequencies would naturally be sensitive to different portions of the magnetosphere's trapped particles, whose emitted radiation is being observed. Thus, depending upon those values, an equivalent tilt angle over the range 8 to 12° is to be expected.

The planet Jupiter also possesses a large number of satellites, some of which are important with respect to their interaction with the plasma and trapped radiation belts. All the satellites are found to be good absorbers of energetic particles but Io, somewhat enigmatically, is also found to be a source of particles. Studies of the Pioneer data continue and future spacecraft missions, the two Voyager encounters in March and July of 1979, will continue our studies on this pulsar-like object within our own solar system. The beaming of decametric radiation and its modulation by Io still challenge the theorists but progress is presently being made and no doubt that understanding will contribute to the improvement in models of pulsar radiation.

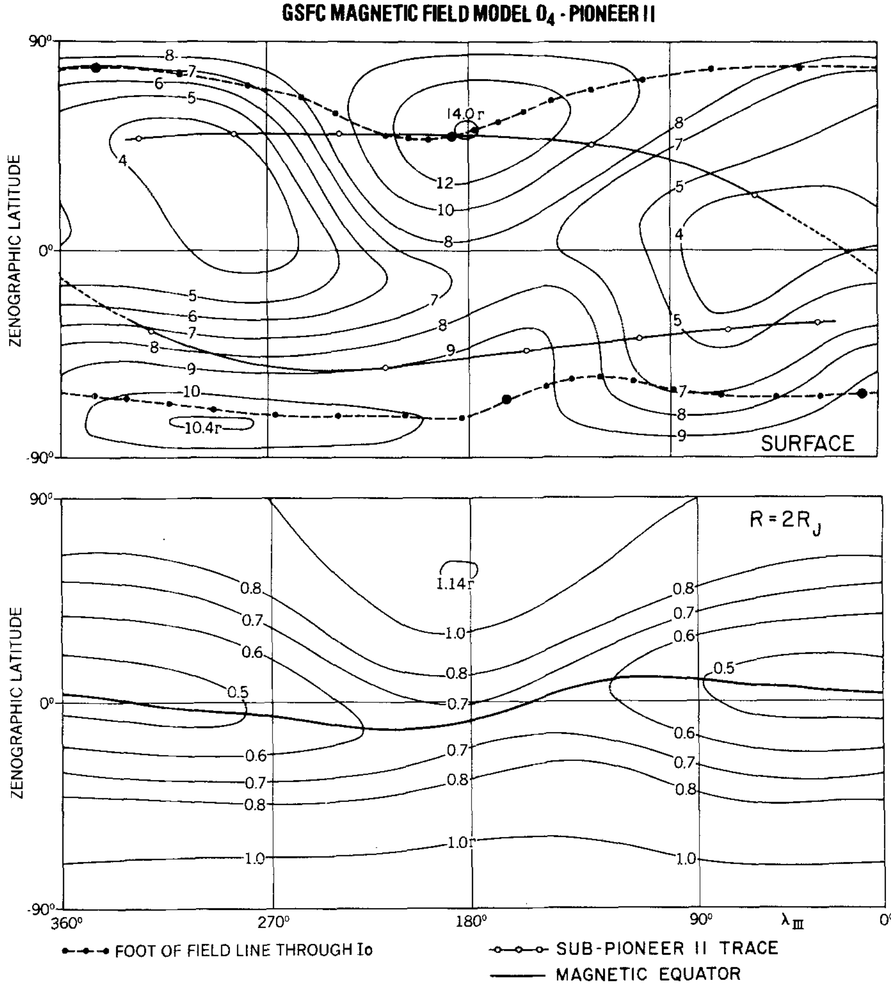

Fig. 6. Iso-intensity contour maps in Gauss of the magnetic field of Jupiter on the "surface" of the planet (assumes equatorial radius of 71,732 km and a flattening of 1/15.4) and at $2R_J$. (Acuna and Ness, 1976).

SATURN AND URANUS

Success observing non-thermal radio emission from the planets Saturn and Uranus has been quite limited and possible results obtained in a few observations by spacecraft (Brown, 1975; 1976). The value obtained by scaling the spectral characteristics from Saturn to Jupiter suggests an equivalent dipole equatorial field intensity of 0.5–1.0 G. In September 1979 the U.S.A. spacecraft Pioneer 11 will penetrate this magnetosphere and should yield precise information on the characteristics of not only the planetary field but also its magnetosphere. The Voyager spacecraft will also penetrate the Saturian magnetosphere, should one exist, in 1981. Finally, it is hoped that one of the Voyager spacecraft will encounter a Uranian magnetosphere in 1985.

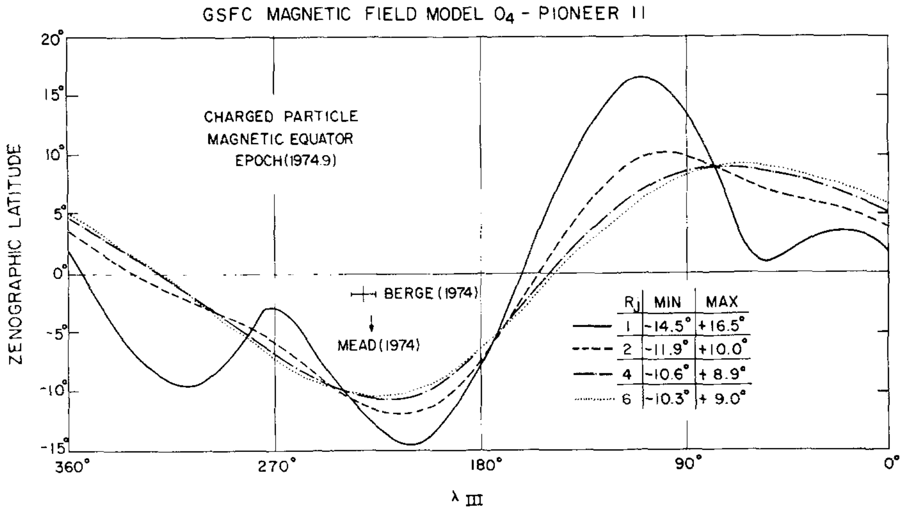

Fig. 7. Variation of the latitude of the charged particle equator (minimum |B|) at different radial distances. (Acuna and Ness, 1976).

2. Theoretical Studies

The basic processes generating planetary magnetic fields (Levy, 1976) are also applicable to a broad range of astrophysical objects from the Sun through to pulsars. Studies of magnetohydrodynamic dynamos have been conducted for sometime, with limited success due to the basic non-lineartiy of the problem which results from combining Maxwell's equations with the laws of incompressible fluid flow. However, this research has continued and present understanding of the kinds of fluid motions that efficiently generate magnetic fields has emerged. As in all non-linear problems, attempts have been made to linearize or approximate the description of the problem so as to permit the derivation of solutions.

Most recently Busse (1975) has introduced a particularly simple example of two-dimensional convection cells for which he can then solve the appropriately linearized equations. With application to planetary magnetic field generation, the geometry is illustrated in Figure 8. The axes of the convection cells are shown parallel to the rotation axis. Again, a linearization of the appropriate equations leads to some unique results. Since there is no large differential rotation, a strong toroidal magnetic field is not generated and hence the Lorenz forces remain small compared to the Coriolis forces. As opposed to much of the past work, then, it is found that the magnetic field at the core is not much larger than a simple extrapolation of the spheroidal field from the surface. Whether or not such a model is a valid representation of planetary magnetic field generation is uncertain. However, it offers several attractive features. Busse (1976) has shown how his model can be applied with moderate success to the magnetic field observations at Mercury, Earth and Jupiter.

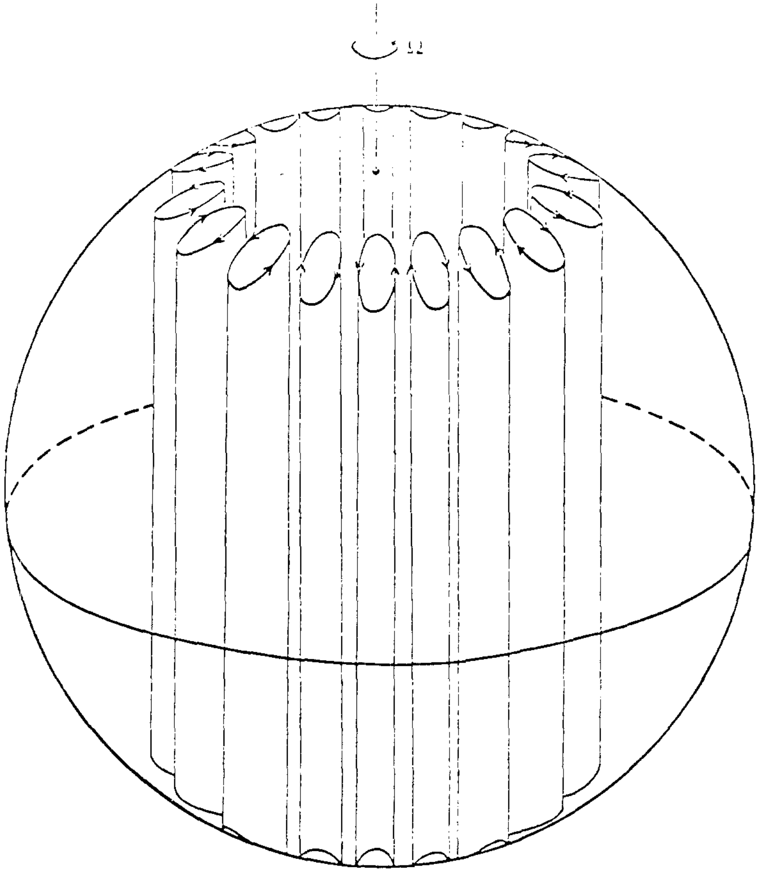

Fig. 8. Schematic diagram of convecting cells in planetary interior as elaborated by Busse (1975, 1976) to model the planetary dynamo mechanism.

Additional implications from the data thus far available on planetary magnetism show that such models must incorporate means for alternating the polarity of the field in order to be consistent with the observed field reversals detected for the terrestrial globe throughout its recent history.

3. Conclusions

The existence of abundant new and firm data, summarized in Table I, on the magnetic fields of the planets Mercury to Jupiter augment considerably the data base against which comparisons of theoretical models of planetary magnetic field generation can be made. The further study of the magnetic characteristics of Venus, Mars, Saturn and Uranus will provide a broad spectrum of planetary classes and scale sizes such that the data should unambiguously indicate a common origin, if such exists. On the other hand, perhaps such

TABLE I

Magnetic dipole moments of the planets

Planet	Moment (G cm^3)	Equatorial Field (γ)	Tilt	Polarity
Mercury	$4.9 \pm 0.2 \times 10^{22}$	336 ± 12	$14 \pm 5°$	+
Venus	< 1–6×10^{22}	< 4–30	?	?
Earth	8.1×10^{25}	31000	11.7°	+
Moon[a]	$< 1.3 \times 10^{18}$[a]	< 2[a]	?	?
Mars	$< 2.5 \times 10^{22}$	< 64	< 15–$20°$	– (?)
Jupiter	1.6×10^{30}	4–8×10^5	$9.6° \pm 0.2°$	–
Saturn	1×10^{29}	5×10^4	?	?
Uranus[b]	3×10^{27}	2×10^4	?	?

[a] Component ⊥ to equator. Unknown ∥ to rotation axis.
[b] Rotation axis nearly in ecliptic.

a goal of uniformitarianism is inappropriate. We may find that there is not a common origin of the present day magnetic fields of the planets, in that some of them may be due entirely to remanent magnetization, associated with the early history of their formation, and others due to primarily an active process in the interior today. The contributions of Hannes Alfvén and his colleagues over the years to the general study of cosmic magnetism and the origin of the solar system permeate much of present day research and will continue to do so in the future.

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