PLANETARY MAGNETOSPHERES: A COMPARATIVE VIEW

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INTRODUCTION

There are eight large bodies in the solar system about which definite statements regarding the existence or nonexistence of a magnetic field of internal origin can now be made. Of these bodies (Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, and the Earth's Moon), only Venus and the Moon have negligible surface magnetic fields. By negligible is meant that the magnetic fields are so weak that they do not sensibly perturb the local solar wind. The other bodies provide an interesting zoo of magnetic field configurations and attendant charged-particle behavior. Six of these bodies have magnetic fields, and two do not. Furthermore, of those which have magnetic fields, it appears that only that of Mars is ineffective in accelerating charged particles. At this point, general principles need to be formulated and theories should be proposed to explain:

- Why some of these bodies do, and some do not, have magnetic fields,
- Why there is such a specialized variety of particle acceleration phenomena, and
- Why the magnetosphere of Mars does not accelerate particles.

A MAGNETIC "BODE'S LAW"

It is known, both from observations of the secular variations of the Earth's magnetic field and from paleomagnetic records, that the Earth's magnetic field changes rapidly on a geological time scale. The general magnetic-field pattern of the Sun also changes rapidly. It is accepted that these two magnetic fields are continuously regenerated and modified by internal dynamo action. Not enough is known about the other magnetic-field configurations to state whether or not they originate by some similar active mechanism. However, one would presume that, if an internal conducting-fluid system is required, then Jupiter would have a magnetic field that would display similar secular variations.

Rotation rate, too, is regarded as important in dynamo theory. Dynamo theories generally require that, in addition to a fluid core, the body be spinning at some modest rate. Thus, while it is loosely understood why Venus does not have a magnetic field, the presence of a significant magnetosphere around Mercury is a genuine surprise. A list of what might have been expected on the basis of dynamo theory is given in table 1. Dynamo theory is

Table 1
Presatellite Expectations of Planetary Magnetic Field versus Experimental Findings

	Significant Spin	Expected to have Fluid Conducting Core (Before Flyby)	Predicted to Have Magnetic Field	Observed to Have Magnetic Field
Sun	Yes	Yes	Yes	Yes
Mercury	No	No	No	Yes
Venus	No	Yes	No	No
Earth	Yes	Yes		Yes
Mars	Yes	No (?)	No (?)	Yes
Jupiter	Yes	Yes	Yes	Yes
Saturn	Yes	Yes (?)	Yes (?)	Yes
Moon	No	No	No	No

apparently wrong in the case of Mercury and probably wrong in the case of Mars. One might say that being right six out of eight times is not bad. However, the classic test of a theory is its ability to predict. The fact that it is wrong two times out of eight means that either some new theory must be brought forth to explain these as special cases or else the basic theory is inadequate and needs to be either repaired or abandoned.

A hypothesis was put forth some time ago by Blackett (1947, 1949) to the effect that the magnetic moment of a rotating body was directly proportional to its angular momentum. In fact, he gave a quantitative relationship in which the magnetic moment was roughly equal to the square root of the gravitational constant times the angular momentum of the rotating body divided by the velocity of light. This is a sort of Bode's Law for magnetic moments in which an attempt is made to establish an empirical relationship without understanding the physical principles that govern it. While one might scoff at such doings, the results shown in figure 1 (from Hill and Michel, 1975) are impressive. For the bodies that have magnetic fields, Blackett's hypothesis seems to have a fair degree of validity. (The arrows for the four outermost planets in figure 1 indicate predictions. However, a recent data point for Saturn inferred from radio observations by Brown (1975) and Kaiser and Stone (1975) fits the predicted value.)

Brown (1967) was the first to point out that Blackett's hypothesis might hold for the planets although it fails in the case of the Sun. Since the Sun obviously has a different interior constitution from that of any of the planets, it is not surprising that the Sun should be treated as a special case. However, a proper theory of the magnetism of rotating bodies should carry within it a quantitative explanation of the discrepancies in the case of the Sun and those bodies that do not have magnetic fields. In this regard, see Dolginov* who proposes just this sort of general relationship.

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

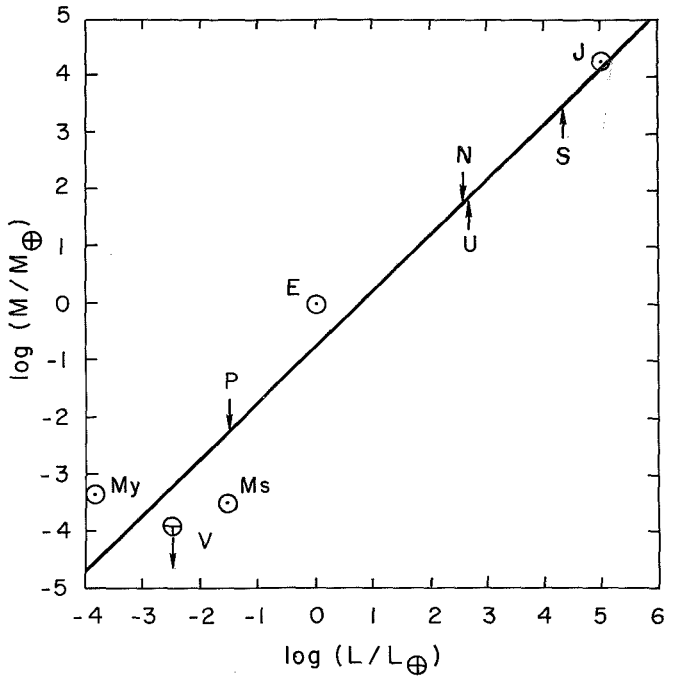

Figure 1. Log-log plot of planetary magnetic dipole moment versus planetary-spin angular momentum.

INTERACTION OF WEAK MAGNETOSPHERES WITH THE SOLAR WIND

Mercury and Mars may be considered to have weak magnetospheres. The standoff distance of the solar wind is expected to be less than one planetary radius above the surface at the subsolar point. Scaling from the case of the Earth leads to estimates of subsolar magnetopause distances of only about 0.3 to 0.7 planetary radii above the planetary surface. The relatively small size of these magnetospheres, compared to their parent planet, suggests some interesting differences in magnetospheric dynamics as compared to the Earth.

When magnetic merging between the interplanetary field and a planetary magnetic field is a factor, the size of the front portion of the magnetosphere can be significantly affected. Hill and Rassbach (1975) have shown that, for an extreme case in which there is no solar-wind induced distortion, the distance from the planetary center to the subsolar magnetopause can be closer to the Earth for a southward interplanetary field than for a northward interplanetary field by as much as 26 percent. This effect has been verified for the case of the Earth by Maezawa (1974), although the solar-wind flow reduces the above effect by more than a factor of two.

The reason for such a variation is clear if, as shown in figure 2, a dipole field embedded in a uniform interplanetary field, that is, (A) antiparallel to the dipole moment, or (B) parallel to the dipole moment is considered. The solution for case (A) may be obtained by inspection

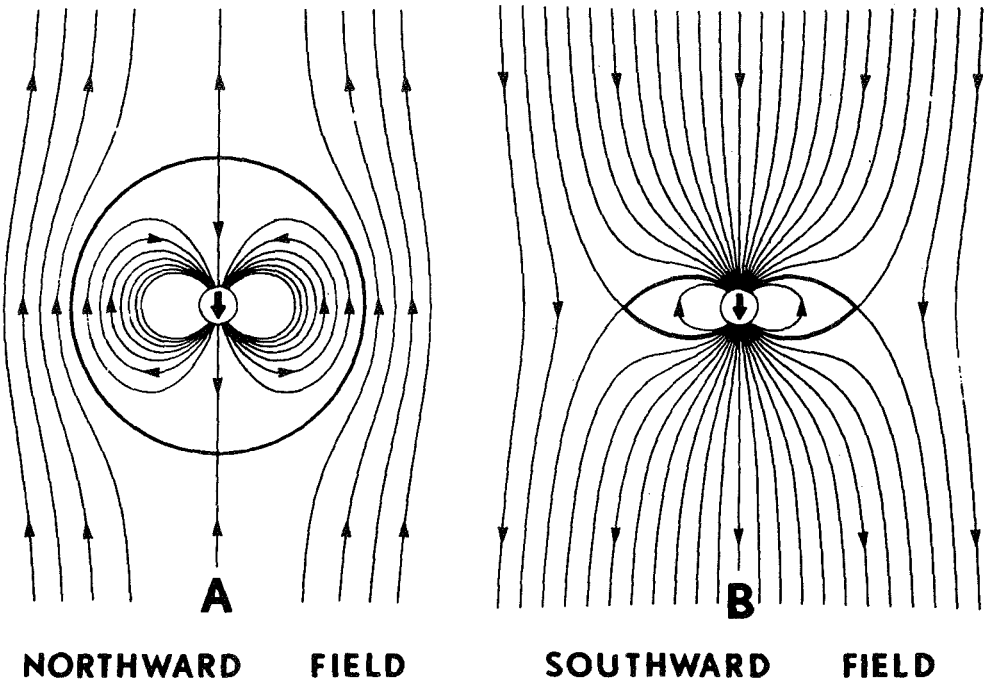

Figure 2. Magnetospheres that would result from the superposition of a planetary dipole and a northward (A) and southward (B) interplanetary magnetic field in the absence of a flowing plasma (Hill and Rassbach, 1975).

of the solution for the field produced by a perfectly-diamagnetic sphere inserted into a uniform magnetic field, which is a field-free cavity internal to the sphere and a superposed dipole plus uniform field outside. The strength of the dipole that is induced in the diamagnetic sphere is exactly that necessary to produce a polar field that will just cancel the external applied field at the North and South Poles. The equatorial field of such a dipole is one-half the polar field and is parallel to the external applied field. If this external-dipole field actually originates from a smaller dipole inside the larger sphere, then

$$\frac{B_0}{r_n^{\,3}} = \frac{B_i}{2}$$

where

B_0 = the magnetic field strength at the surface of the small dipole,

r_n = the distance to the large spherical surface for the case of the northward field as shown in figure 2, and

B_i = the strength of the unperturbed applied (or interplanetary) magnetic field.

Solving for r_n results in

$$r_n = \left[\frac{B_0}{B_i}\right]^{1/3} 2^{1/3}$$

For case (B), it is necessary to find the equatorial distance at which the magnetic field from the dipole exactly cancels the interplanetary field. Thus,

$$\frac{B_0}{r_s^3} = B_i$$

where r_s is the distance to this cancellation point for a southward-directed field.

Solving for r_s and taking the ratio r_n/r_s,

$$r_n = 1.26\ r_s$$

Because this pedagogical model does not allow for the distorting effect of solar-wind flow, it overestimates the influence of the orientation of the interplanetary field on the distance to the subsolar magnetopause. Fairfield (1971) has shown, and Maezawa (1974) has confirmed, that the Earth's magnetopause position does indeed show a variation that is consistent with the expectation of the above theory, but not as large. The magnetopause was observed to be approximately 10 percent closer to the Earth when the interplanetary field was southward as compared to the magnetopause distance for a northward-directed interplanetary field.

To the extent that magnetic merging is important, as much as a 26-percent variation in the magnetopause distance for Mars or Mercury, with changes in the interplanetary magnetic-field orientation, could be expected. As shown below, there are reasons to expect such a variation in the case of Mercury, but not for Mars. This difference probably explains why particles are accelerated within the magnetosphere of Mercury but not within the magnetosphere of Mars.

The solar-wind energy available to drive magnetospheric dynamical phenomena for Mercury and Mars is dramatically smaller than available for the Earth. The solar-wind energy flux striking the total cross section of the Earth's magnetosphere is approximately 5 TW (1 TW = 10^{12} W). In comparison, the magnetosphere of Mercury intercepts only 10^{-3} TW, and that of Mars slightly more than 10^{-4} TW. The Earth's magnetosphere absorbs approximately one percent of the solar-wind energy striking it, that is, the transfer of energy between the solar wind and the terrestrial magnetosphere has an efficiency of one percent. Thus, for a start, even if the coupling of solar-wind energy with the magnetospheres of Mercury and Mars were 100 percent efficient, their available energy would be less than that available to drive the terrestrial magnetosphere by factors of 10^2 or more. If some reasonable coupling efficiency is assumed, the available energy will be reduced by one or two orders of magnitude.

Satellite data have been interpreted by Dolginov et al. (1973) and Gringauz (1975) indicating that Mars has a magnetosphere. This paper will provisionally accept this claim and address the attendant problem as to why there are no energetic particles in the vicinity of Mars. Rassbach et al. (1974) have presented compelling arguments to the effect that the available energy from the solar wind to the Martian magnetosphere is not adequate to move the relatively-heavy Martian ionosphere so as to allow magnetospheric convection to occur. In essence, the Martian ionosphere shorts out both the interplanetary and convection $V \times B$ electric fields so that little magnetic merging occurs between the Martian magnetic field and the interplanetary magnetic field. It is not the magnetosheath plasma that inhibits the magnetic merging since, as shown by Zwan and Wolf (1975), the magnetosheath plasma is depleted in a thin layer adjacent to the magnetopause. Rather, the electric field is shorted out by the ionosphere.

Except for inner-belt protons that arise from the decay of cosmic-ray neutrons (Chaflin and White, 1973), nearly all of the energetic particle radiation in the Earth's magnetosphere is attributed to magnetic merging and magnetospheric convection. Since neither merging nor convection are apt to be important processes within the Martian magnetosphere, it is understood why energetic particles are not detected there as is the case for the Mercurian magnetosphere. It is interesting to recall that the absence of energetic particles in the vicinity of Mars had been earlier used as an argument against the existence of a Martian magnetosphere (for example, Van Allen et al., 1965).

Turning to Mercury, note that it is not surrounded by an ionosphere of any significance as far as inhibiting magnetospheric convection. In other words, magnetospheric convection can occur on Mercury without encountering any appreciable ionospheric drag. Therefore, magnetic merging at the nose of the Mercurian magnetosphere could take place at something near the local Alfvén speed, and the full solar-wind electric field could be impressed across the Mercurian magnetosphere. This potential can amount to more than 40 kV, and the magnetospheric convection speed can be significant—probably much faster than in the Earth's magnetosphere. This combination should lead to a very effective acceleration of particles, to perhaps relativistic energies within the magnetosphere of Mercury. Also, for Mercury, the magnetopause standoff distance varies with the orientation of the interplanetary magnetic field, becoming smaller with a southward-directed interplanetary field.

The above explanation, involving a conducting ionosphere combined with a relatively small area for collecting solar-wind energy, yields an acceptable solution to the problem of why the magnetosphere of Mars cannot accelerate particles and why the magnetosphere of Mercury, which lacks a sensible conducting ionosphere, accelerates particles with ease.

CONCLUSION

This interesting set of magnetospheres poses at least two broad sets of problems. One set of problems concerns the mechanism(s) by which the magnetospheric magnetic fields are generated. Hopefully, there will be one general theory that can explain them all, and at the same time, explain why Venus and the Moon do not have magnetospheres.

The other set of problems concerns the interesting range of magnetospheric phenomena that have been observed within the various planetary magnetospheres. These contain examples such as Mercury, which has a magnetosphere without a significant ionosphere; Mars, with a weak magnetosphere and dominant ionosphere; Jupiter, which apparently derives nearly all of the energy for magnetospheric phenomena from the planetary energy of rotation; and finally the Earth, which (supposedly) is understood so well. In addition, the Sun can exhibit magnetosphere-like behavior in the acceleration of particles in solar flares. The magnetosphere of Saturn is yet to be visited, although, according to Brown (1975) and Kaiser and Stone (1975), it is there and it accelerates particles. The presence of the rings of Saturn should have an interesting effect on any energetic particles in their vicinity. Finally, speculation about possible magnetospheres on Uranus, Neptune, and Pluto can be made.

ACKNOWLEDGMENT

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POSTSCRIPT

The latest issue of *J. Geophys. Res.* carries an interesting argument on the interpretation of the energetic particle data from the Mercury flyby. There is no doubt that energetic particles are accelerated in the vicinity of Mercury, but their spectra are in doubt. (Armstrong, T. P., S. M. Krimigis, and L. J. Lanzerotti, 1975, "A Reinterpretation of the Reported Energetic Particle Fluxes in the Vicinity of Mercury," *J. Geophys. Res.*, **80**, pp. 4015-4017, and Simpson, J. A., "Reply," *J. Geophys. Res.*, **80**, p. 4018.)

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QUESTIONS

Dessler/Bogdanov: There is one effect that is connected with the high conductivity of a Martian ionosphere. If the electric field ($E = V/C \times B$) of convection decreases, the velocity of the plasma also decreases. The magnetic field observed in the near-Martian space is approximately 20 γ and the potential drop across the Martian ionosphere is supposedly less than 100 V. The result is that the bulk velocity of the plasma drops to values less than 10 km per second and this may be one of the reasons for the observed plasma deceleration in the dayside plasma boundary layer.

Dessler: I agree. This must be the explanation.

Dessler/Vaisberg: Two features of the Mars-5 data may give some insight on the nature of the Martian tail region. First, the magnetometer revealed that the Z_{SE} component of the tail magnetic field is as large as the X_{SE} component of this magnetic field. Secondly, the shape of the retardation curves of the electron trap suggests that an alternative interpretation of the electron spectra is possible. That is, the flat part of the retardation curve may be explained by a directed flow of relatively-cold electrons. If the planet-directed electron current fills up a considerable part of the tail, the current density (4×10^{-9} amps/m^2) may generate a tail magnetic field of the proper direction with magnitude comparable to that measured by Dolginov et al. in the tail region (10 γ).