Planetary Magnetism

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PLANETARY MAGNETISM

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ABSTRACT

Several reviews of planetary magnetism have recently appeared. Instead of duplicating the material included therein, we concentrate on a discussion of the latest results in this area especially those results that have appeared since the earlier reviews were written.

INTRODUCTION

A planetary magnetic field can be represented mathematically by a series of multipole moments which vary with time. Information about the source of the field in the planetary interior is contained in the strength of the planetary moment, the relative strength of the observed multipole moments and the size of the secular variations. Mercury, Earth, Jupiter and Saturn all have significant intrinsic magnetic fields but only the latter three have been measured with sufficient accuracy to provide useful constraints on interior properties.

We have recently written both a quadrennial report of planetary magnetism covering the last four years progress (1975-1978) [1] and also a full length review of the subject [2]. Since planetary magnetism is subject to on-going studies, new results have appeared since these reviews but we do not feel it is necessary to repeat all the material in the above reviews. Rather we choose to summarize briefly earlier results and concentrate on the most recent research.

MERCURY

Mariner 10 made three encounters with Mercury. The first and third passes went through the darkside of the planet and detected a distended planetary field. Preliminary analyses indicated a moment which ranged from 3.2×10^{22}G. cm^3 to 5×10^{22}G. cm^3 [3,4,5]. More recently Whang [6] and Jackson and Beard [7] have taken into account boundary and tail currents and revised the moment to 2.4×10^{22} G. cm^3. If the solar wind conditions were average then the moment of Mercury as derived from the magnetopause and bow shock positions would be $1.8 \pm 0.2 \times 10^{22}$ Gauss-cm^3 [8]. Slavin and Holzer [9] have criticized these analyses on two grounds. They point out that the tangential stress on Mercury's magnetopause may be more important than on Earth and that the solar wind pressure was probably higher than reported. They feel that the magnetic moment of Mercury may be as high as $6 \pm 2 \times 10^{22}$G. cm^3.

It is very difficult to explain the intrinsic field of Mercury. A magnetized crust has been postulated [10,11]. However, if the magnetizing field were external, there must have been an extremely large steady primordial magnetizing field of about 10 Oe and if internal, reversals of the planetary dynamo would have limited the amount of crustal magnetization in any one direction resulting in a negligible dipole moment [12]. Since Mercury is small it should have cooled more rapidly than the earth stopping its internal dynamo. Nevertheless, Mercury's magnetic moment is close to that predicted for a planetary dynamo of Mercury's size and spin rate [13]. Much work remains to be done on the magnetic field of Mercury, but there will be little progress until more measurements are available.

VENUS

Early missions to Venus either flew by the planet or stopped making measurements in the upper ionosphere and therefore did not provide sufficient data to either measure the intrinsic field or provide a low upper limit to the moment [14,15]. While there were some suggestions that a weak intrinsic field existed [16] it was clearly too weak a field to stand off the solar wind flow. The Venera 9 and 10 orbit data did little to settle the controversy [17,18] but did lower the upper limit to 2×10^{22} Gauss-cm^3.

Pioneer Venus orbiter data are now available for over one year's operation. The Pioneer Venus data have advantages over previous measurements in that the spacecraft gets closer to the planetary surface and in that there is almost complete telemetry coverage. The magnetic field behind Venus can be strong, but it is irregular and changes from orbit to orbit [19]. Using over 120 orbits of data in the center of the solar wind wake behind Venus, an upper limit of 3×10^{21} Gauss-cm^3 has been obtained [20].

Venus rotates only slightly slower than Mercury and is only slightly smaller than the earth. Thus almost any scaling law for planetary dynamos will give a sizable magnetic moment for Venus. Busse [21] predicts a magnetic moment of 1.6×10^{23} Gauss-cm^3 over 50 times that observed. Obviously the interior of Venus is not convecting sufficiently strongly to drive a self-sustaining dynamo. Stevenson [22] has postulated that the energy source for the earth's dynamo is the freezing of the core but that Venus' core will not freeze to provide a similar energy source because of a lower central pressure.

THE MOON

Early attempts to detect a lunar magnetic field failed [23,24,25]. The Explorer 35 lunar orbiting spacecraft provided the first evidence of lunar magnetization. Although there was no detectable moment above 6×10^{20} Gauss-cm^3 [26], deflections of the solar wind above the terminators suggested that the lunar surface was magnetized [27]. Later Apollo subsatellite data measured both the lunar magnetic field and the limb compressions and confirmed the earlier hypothesis [28]. The surface measurements and the returned lunar samples also showed clearly the moon was magnetized [29,30]. One controversial but stimulating result is that the intensity of the ancient magnetizing field decreased from about 1 Oe at about 4×10^9 years ago to less than 0.1 Oe at about 3.3×10^9 years ago [31]. The present day lunar magnetic moment as determined by the Apollo subsatellites is less than 10^{19} Gauss-cm^3 [32].

There is much controversy over possible sources for lunar magnetism. One school proposes that there was an ancient lunar dynamo but that this dynamo stopped [33]; another prefers a cometary impact origin [34] to explain enigmas such as Reiner Gamma [35]. Most recently D.J. Stevenson has proposed an ancient dynamo in an asymmetric accumulation of liquid iron alloy to explain both the offset of the center of mass of the moon from its center of figure and lunar paleomagnetism [36]. Part of the reason for continuing controversy on the source of lunar magnetism is the incompleteness of the map of lunar magnetism as it presently exists. A low altitude polar orbiting magnetic survey is much needed.

MARS

The magnetism of Mars is also a controversial subject but here the disagreement is not over how the source operates'but whether there is an intrinsic field. The controversy over the interpretation of the original data has recently been debated [37,38,39,40]. New evidence in the form of a series of measurements in the Martian wake have been reported [41]. These latter data show that the field in the wake regions has differing polarities on successive orbits. This indicates that the dipole moment lies near the magnetic equator if it exists. An alternative explanation for this observation is a Venus-like "induced" field which changed on successive orbits of the satellite because external conditions changed. Another argument in favor of a planetary moment involves the pressure balance in the dayside ionosphere of Mars [42]. The thermal pressure of the ionosphere of Venus is sufficient to stand off the dynamic pressure of the solar wind. If the thermal pressure of the Mars ionosphere is not sufficient then there must be an additional component of the pressure. An intrinsic field could provide such pressure. However, Intriligator and Smith [42] do not scale the Venus ionosphere to Mars in a consistent manner. If they had the requirement for an additional component of the ionospheric pressure would have been negligible.

As with Mercury and the Moon a complete magnetic survey from low altitude polar orbit is needed at Mars although no such mission is presently planned. Thus, we will have to depend on the presently existing data sets for some time to come. A complete compendium of Mars 3 and 5 magnetometer data has been prepared [43] Mars 2 data also exist but do not have a known orientation. If these data are taken to be due to an intrinsic field, they suggest at most a moment of 2×10^{22} Gauss-cm^3, much less than would be expected from Busse's dynamo scaling law [13].

JUPITER

Pioneer 10 flew by Jupiter at an altitude of 2.9 Jovian radii (R_J) on 12/4/73 and Pioneer 11 at 1.6 R_J on 12/3/74. Pioneer 10 carried a vector helium magnetometer which measured a planetary magnetic field corresponding to a moment of 1.5×10^{30} Gauss-cm^3 [44]. In addition to the vector helium magnetometer Pioneer 11 carried a high field fluxgate magnetometer [45]. The fluxgate magnetometer was added late in the mission in case the Jovian field was stronger than expected but this addition turned out to be quite unnecessary. The data from these two instruments were in basic disagreement. The two magnetometer groups eventually compared their measurements with the pitch-angle distributions obtained by the energetic particle experimenters on the same spacecraft and found that the vector helium data ordered the particle data well but that the fluxgate data did not [46]. Recalibration of the analog-to-digital converter resolved much of the difference between the two sets of raw data and the final analyses of the two groups became much more similar [47,48]. The final agreed dipole moment was 1.55×10^{30} Gauss-cm^3 with a dipole quadrupole octupole ratio of 1.00:0.25:0.20 compared with 1.00:0.14:0.10 for the earth.

Although the data were now in better agreement there were still some major differences in the inverted field models and these differences became quite significant in the higher multipole moments [2]. These differences led Mullen and coworkers to attempt more sophisticated analyses [49]. They found solutions with much lower residuals which were therefore an "improvement" over the original models but still concluded that all the models were equally valid. The problem with the Pioneer 10 and 11 data is that there is poor longitudinal and latitudinal coverage close to the planet. In fact, Mullen et al. recommend not attempting to invert moments higher than quadrupole. They also find no evidence for secular variation.

Estimates of the possible strengths of the dynamo driven magnetic moments of the Galilean satellites have been made using Busse's scaling law [50]. They range from 2 x 10^{23} Gauss-cm^3 for Io to 1 x 10^{22} Gauss-cm^3 for Callisto. The discovery of volcanism on Io has led credence to the possibility of a molten conducting core in this satellite but volcanism does not necessarily imply such a core. Kivelson et al. [51] have suggested that available evidence from ionospheric configuration and energetic particle behavior are consistent with a moment of 6.5 x 10^{22} Gauss-cm^3. Recent Voyager measurements in the Io flux tube are also consistent with such an intrinsic moment [52].

Again progress in understanding the Jovian intrinsic magnetic field requires a low altitude polar orbiter. However, not only is this difficult energetically, but the radiation belt poses a serious radiation hazard to the electronic components that are used in present day spacecraft. The Galileo mission scheduled for 1986 includes an orbiter which will make close flyby's of all four Galilean satellites. These data should resolve the question of the existence of any intrinsic fields of the Galilean satellites.

SATURN

On September 1, 1979, Pioneer 11 reached Saturn crossing the ring plane at 2.8 Saturn radii (R_S) and passing 1.4 R_S from the center of the planet. The magnetic moment was found to be much less then expected, 4.7 x 10^{28} Gauss-cm^3 corresponding to an equatorial surface field of 0.22 G [53]. If we use Busse's scaling law and extrapolate from the Jovian field we deduce that the radius of the conducting core of Saturn must be about 42% of the radius of the Jovian core or about 23,000 km [2]. If one repeats the multipole moment ratio scaling of Elphic and Russell [54] one finds that such a small core would produce an magnetic field that was much more dipolar than the earth's with a dipole: quadrupole: octopole ratio of 1.00:0.12:0.05. Smith et al. [53] find an even smaller dipole to quadrupole ratio, 1.0:0.08. The smallness of the conducting core has been hypothesized to be due to helium rain in the outer core of Saturn depleting the outer core of helium and reducing its conductivity [55]. The major surprise of the magnetic measurements was neither the smallness of Saturn's magnetic moment nor the "purity" of its dipole moment. Rather the major surprise was that the angle between the dipole axis and the rotation axis of the planet was close to zero [53]. While the alignment of the dipole axis with the spin axis simplifies the analysis of the motions of the radiation belt particles it has an unfortunate impact on the measurement of the rotation rate of the planetary interior. Fortunately, there is enough asymmetry that, while impossible from field and particle data, radio data can be used. A period of 10h 39.9m has been found [56].

Voyager 1 will arrive at Saturn in November 1980 and Voyager 2 in August 1981, passing within 3.0 and 2.7 R_S of the planet respectively. These trajectories will not be much help in improving models of Saturn's magnetic field. However, Voyager 1 will pass within 4000 km of the surface of the planet-sized moon Titan and will possibly be able to probe its magnetic field.

CONCLUSIONS

While we have learned much about planetary magnetism in the last decade, there is still much to be done. It is to be expected that we know little about possible intrinsic fields at Uranus, Neptune and Pluto but our present state of ignorance of Mars is scandalous. Finally, even though we have determined dipole moments for Mercury, Jupiter and Saturn and shown that the lunar surface is magnetized, there is still much to do on these bodies. If we are truly going to use the magnetic field to infer interior properties we need good measures of the multipole harmonics in the field which in turn requires low altitude polar orbits. The only such mission even in the planning stages is a lunar polar orbiter.

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