Introduction

The field of planetary magnetism has advanced rapidly over the last four years. In fact it was not deemed necessary to review this subject in the last quadrennial report. This advance has resulted both from new data and from refined analyses of existing data files. New data have become available from Mariner 10 at Mercury, from Venera 9 and 10 orbiting Venus, and Pioneer spacecraft flying past Jupiter. No new missions carrying magnetometers to Mars or the moon have taken place during the last four years. However, new analyses of Mars 2, 3 and 5 and Apollo data has improved our understanding of the magnetic field of these two bodies.

Table I lists all space flights carrying planetary magnetism missions ending in December 1978, when the Pioneer Venus orbiter will reach Venus. In mid-1979 Voyager 1 and 2 will encounter Jupiter and then swing by on their way to Saturn. Pioneer 11, having swung by Jupiter in December 1974, is presently headed for a Saturn encounter in mid-1979.

Mercury

Mariner 10 made three encounters with Mercury. The first and third of these passed by the darkside of the planet and clearly detected a distorted planetary field. Preliminary analyses indicated a moment of from $3.2 \times 10^{22} \, G \, cm^3$ to $5 \times 10^{22} \, G \, cm^3$ (Ness et al., 1974a; 1975; 1976). More recently Whang (1977) and Jackson and Beard (1977) have taken into account boundary currents and tail currents and have revised the moment downward to $2.4 \times 10^{22}$. Russell (1978a) has derived a moment of $1.8 \times 2 \times 10^{22} \, G \, cm^3$ on the basis of average shocks and magnetopause positions in comparison with the terrestrial positions. Slavin and Holzer (1978) have criticized these later analyses on two grounds; first that tangential stress on Mercury's magnetopause may be more important than on earth, and second that the correct normal stresses are not used in the derivations of the moments. It is quite likely that the solar wind dynamic pressure was much higher than usual during the Mariner 10 encounters. Hence, the magnetic moment of Mercury may be as high as $6 \times 2 \times 10^{22} \, G \, cm^3$.

The source of the planetary field is most probably an internal dynamo. A magnetized crust has been postulated (Sharpe and Strangway, 1976; Stephenson, 1976). However, if the magnetizing field were external, there must have been an extremely high (\approx 10G) steady primordial interplanetary field, and, if it were internal, magnetic reversals would have limited the amount of crustal magnetization in any one direction so that a negligible dipole moment would have resulted (L.J. Straka, unpublished manuscript, 1978). There has been some concern about the fraction of the time the solar wind would spend on the surface of Mercury (Siscoe and Christopher, 1975). Hood and Schubert (1978) have pointed out that the highly electrically conducting interior of Mercury stiffens the magnetosphere against short-term changes in external pressure. Thus, only very long enduring increases in solar wind pressure, e.g., solar cycle variations, could push the magnetopause down to the planetary surface. Much remains to be understood about the planetary magnetic field of Mercury. Not only is the size of the dipole moment of interest, but higher moments as well. Only an orbiter which also samples the solar wind will be able to answer these questions. However, no such mission is presently being planned.

Venus

Initially, Venus was thought not to have a planetary magnetic field. Mariner 2 passed by Venus at 6.6 planetary radii (R$_{V}$) and saw nothing. Mariner 5 approached within 1.4 R$_{V}$ of the center of the optical shadow of the planet and 1.7 R$_{V}$ of the center of the planet. The experimenters chose not to rule out a planetary field, but concluded that it must be less than $8 \times 10^{22}$ Gauss-cm$^3$ (Bridge et al., 1969). Venera-4 measured the magnetic field at Venus down to 200 km altitude. Dolginov et al. (1969) compared their Venera-4 data with simultaneous Mariner 5 data in the solar wind and came to the conclusion that the planetary moment might even be less than $10^{22}$ G cm$^3$. Since then, these conclusions have been questioned. First, when allowance is made for the external current systems, the "planetary" field in the Venera-4 data does appear to increase with decreasing distance with an inverse cube law (Russell, 1976a). Secondly, Mariner 5 field data in the wake have the direction expected for tail field lines (Russell, 1976b). The maximum moment consistent with these data was estimated to be $6.5 \times 10^{22} \, G \, cm^3$.

The initial paper on the Venera 9 and 10 magnetic measurements reported consistency with the earlier interpretation of the Venera-4 data (Dolginov et al., 1976a). This interpretation was immediately criticized (Russell, 1976c) on the grounds that the Venera-9 data in the wake were very similar to terrestrial magnetotail data. Later, the Russian group divided on the interpretation of the data (Dolginov et al., 1977) in an interesting paper which includes a minority report by one of the authors (Yereshenko). Based on the behavior of the distant tail field, Dolginov et al. (1978) now support the existence of an intrinsic planetary moment.
of 2-3 x 10^{22} \text{ G cm}^3. Further, he claims the variable magnetic fields, seen near periapsis and interpreted as induction in the planetary ionosphere by Yeroshenko, are in fact spacecraft fields (Dolginov, unpublished manuscript, 1978). Further, the dayside ionosphere is too thin to contain all the flux observed in the tail. Thus, some of the flux must be rooted in the planet; not all can come from induction (B.E. Goldstein, personal communication, 1978). The Pioneer Venus orbiter, with its much lower periapsis of 150 km, should quickly settle this question. However, in the meantime, the sentiment at least in the Russian community seems to be on the side of Yeroshenko (cf. Breus, 1978). If Venus proves to have an intrinsic planetary magnetic field, a low altitude polar orbit would be necessary to completely map the planet since the Venus field is too weak to stand off the solar wind (Russell, 1977). Such a mission is being planned by NASA, but it is not clear whether this mission will include magnetic measurements.

Mars

The lines are more clearly drawn on Mars. Dolginov et al. (1973; 1976b) have consistently interpreted their Mars 2, 3 and 5 data in terms of a planetary magnetic field arising from a moment of 2.5 x 10^{22} \text{ G cm}^3. The only U.S. measurements of the magnetic field of Mars were made too far from the planet on the Mariner 4 flyby. Mariner 4 made only a grazing encounter with the bow shock (Smith, 1969), from which no conclusive evidence of the nature of the obstacle to the solar wind could be drawn. The Dolginov et al. interpretation has been questioned first by Wallis (1975), who questioned the identification of the bow shock by Dolginov et al. on the one hand on the dayside which was the cornerstone of their interpretation. This criticism of the Mars 3 data has been essentially repeated by Russell (1978b), who also points out that the field lines, identified by Dolginov et al. as magnetospheric, appear like they are magnetosheath field lines draped across the planet. Dolginov (1978a) objects to this criticism. Another major criticism of the interpretation of Dolginov et al. is that the Mars 5 data near the planetary wake do not behave in a terrestrial tail-like manner. Rather, again they appear to be solar wind magnetic fields draped over an ionospheric obstacle (Russell, 1978c). Again Dolginov (1978b) responds in his defense relying that the magnetic field in the Martian wake seems to be independent of the polarity of the solar wind magnetic field. However, this defense is invalid because it is not the radial component, from which polarity is defined, but rather the component transverse to the flow which controls induction. Therefore, it seems most probable that Mars does not have an active magnetic dynamo (Russell, 1978d). Dolginov (unpublished manuscript, 1976) does not concur with this conclusion.

Magnetic measurements at Mars have been completely neglected by the American space program since the Mariner 4 flight in 1965 despite a rather robust program of Martian investigations in other areas. As a result, we are less sure of the existence of a planetary field at Mars than we are of the other five innermost planets of the solar system (including Saturn). As with Venus, we need low altitude measurements from polar orbit, but it is also essential to monitor the solar wind. If a two spacecraft mission cannot be flown, the one spacecraft should be in eccentric orbit. The only present U.S. plans to make Martian magnetic measurements are on a 275 km flyby pass by the Galileo spacecraft on its way to Jupiter in 1982.

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 heli um magnetometer which measured a planetary magnetic field corresponding to a moment of 1.5 x 10^{20} \text{ G cm}^3 (Smith et al., 1974a,b,c). Pioneer 11 carried a high field fluxgate magnetometer (Acuña and Ness, 1975a) in addition to the vector heli um magnetometer. The fluxgate magnetometer was added late in the mission (but well before Pioneer 10 encountered Jupiter) in case the Jovian magnetic field was stronger than expected. This addition turned out to be quite unnecessary as the field measured by the vector helium magnetometer stayed on scale through peri jove. The existence of two directly competing instruments on the same spacecraft could be expected to lead to some controversy, especially when the raw data were in disagreement (Acuña and Ness, 1975b; Smith et al., 1975; Davis and Smith, 1976). Eventually, the two magnetometer groups compared their measurements with the pitch-angle distributions obtained by the energetic particle investigators on the same spacecraft and found that the vector helium data ordered the charged particle data well, whereas the fluxgate data did not (Acuña and Ness, 1976a). Recalibration of the fluxgate sensors using an in-flight calibration of the spacecraft analog-to-digital converter revealed a 10% sensitivity shift which resolved much of the difference between the two sets of raw data, and the final analyses of the two groups became much more similar (Acuña and Ness, 1976a,b; Smith et al., 1976). The final agreed dipole moment was 1.55 x 10^{20} \text{ G cm}^3 with dipole:quadrupole:octupole moment ratios of 1.00:0.25:0.20. This compares with a value of 1.00:0.14:0.10 for earth.

Very little more can be done with these data to aid in the derivation of the planetary multipole moments. New data are required, especially over the two polar regions. It is expected that the Voyager measurements will help but a little in this regard. The Galileo spacecraft presently scheduled to be injected into Jovian orbit in mid-1985 will also contribute little to the improvement of the determination of the planetary moment. Rather, Galileo will be able to probe the current systems external to the planet and investigate the magnetism of the Jovian satellites, in particular Ganymede and Callisto, by which the spacecraft will fly repeatedly. Significant improvements in the determination of the planetary moment await improvements in the radiation hardness of electronic components to enable spacecraft to make repeated close encoun-
The Moon

Although the moon has no detectable planetary dipole moment, it possesses a pervasive but variable crustal magnetization over the entire lunar surface whose origin still remains unknown. No new lunar missions have been undertaken in the last four years. The only mission planned, the Lunar Polar Orbiter, did not pass the budgetary approval process. Analysis has continued of both the returned lunar samples and the surface and orbital magnetic measurements. Important progress has been made, and although lunar magnetism remains an enigma, the nature of this enigma is becoming better defined. First, the returned lunar samples have a natural remanent magnetization imprinted by an external field whose magnitude was on the order of one Gauss (Stephenson et al., 1974, 1976; Cisowski et al., 1977). The strength of this ancient magnetizing field appears to have decreased with time (Stephenson et al., 1975). The measurements of lunar fields at the Apollo landing sites (see reviews by Fuller, 1974, and Dyal et al., 1974) have now been supplemented by detailed orbital mapping of limited regions of the lunar surface with direct measurements and other larger regions with indirect measurements. Direct measurements of the lunar surface field can be made over the whole moon when the moon is in the geomagnetic tail. However, the available data covers but a small fraction of the moon's surface (Russell et al., 1973a). Measurements can also be made in the lunar wake when the moon is in the solar wind, but this mapping is still in progress. The fraction of charged particles reflected by the lunar surface is also a measure of the surface field strengths and scale sizes. Color maps of these orbital measurements can be found in the frontispiece of the Fifth, Sixth, Seventh, and Eighth Lunar Science Conferences.

Orbital field measurements also put an upper limit on the present-day lunar dipole moment of $10^{19}$ G·cm$^3$ (Russell et al., 1975). Runcorn (1975a,b) has pointed out that the lack of a detectable moment and the presence of a magnetized crust is consistent with an ancient lunar dynamo. In Runcorn's model, lunar magnetic anomalies are associated with demagnetization by craters. However, lunar magnetic anomalies are not crater-associated as expected in this model (Weiss et al., 1977; Hood et al., 1978a). Lunar surface magnetization is not completely random. In the farside region studied to date, it is mainly east-west and radial (Hood et al., 1978b). It may be correlated with geologic age (Russell et al., 1977) or ejecta deposits (Hood et al., 1978a). It is interesting in this regard that the large magnetic anomalies are antipodal to major impact basins. There are some clear correlations with geologic features such as with the graben Rima Siriusalis (Anderson et al., 1977) and bright ray Reiner gamma (L.L. Hood, unpublished manuscript, 1978).

It is obvious from the data obtained from the Apollo missions that lunar geology and magnetism are correlated, but since the Apollo missions surveyed only the near equatorial regions, we cannot always determine which geologic property, e.g., age or chemistry, is responsible for the correlation. Further data is needed before significant progress can be made in this area.

The Outermost Planets

The only information we now have on the presence or absence of planetary magnetic fields of the outermost planets is derived from the detection of radio emissions. The earth and Jupiter are intense emitters of kilometric and decametric radiation, respectively. Saturn has been found to emit similar waves (Brown, 1975; Kaiser and Stone, 1975). Assuming the characteristic frequencies scale as the gyro-frequency, the spectra obtained from Saturn imply an equatorial surface field of about 1 Gauss, or a moment of $2 \times 10^{29}$ G·cm$^3$. Possible emissions from Uranus have also been detected, but their identification is much less certain because of their similarity to terrestrial emissions and the unfavorable separation of Uranus and the earth as viewed from the IMP-6 spacecraft which made the observations (Brown, 1976).

In September 1979 Pioneer 11 will reach Saturn, crossing the ring plane at 2.8 $R_S$, and having a closest approach of 1.4 $R_S$. Voyager 1 will arrive in November 1980, crossing the ring plane at 6.2 $R_S$, and having a closest approach of 3.0 $R_S$. Voyager 2 will arrive in August 1981, crossing the ring plane at 2.9 $R_S$, with a closest approach of 2.7 $R_S$. If both Voyager spacecraft are healthy upon reaching Saturn, current plans are to send Voyager 2 off to Uranus after the Saturn flyby.

Fig. 1. Bode's law of planetary magnetism. Magnetic moment normalized to terrestrial moment is plotted versus angular momentum normalized to terrestrial angular momentum. Symbols denote Mercury (M), Venus (V), Mars (M), Earth (E), Earth Moon system (E-M), Jupiter (J), and Saturn (S). The two estimates for Mars correspond to the original estimate by Dolginov et al. (1976b) and a recent re-evaluation (Russell, 1978c).
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\text{Planet} & \text{Mission} & \text{Date of Encounter} & \text{Trajectory/Orbit} \\
\hline
\text{Mercury} & \text{Mariner 10} & 3/29/74 & \text{Flyby at 700 km} \\
 & & 3/16/75 & \text{Flyby at 327 km} \\
\text{Venus} & \text{Mariner 2} & 12/14/62 & \text{Flyby at } 6.6 \text{ } R_V \\
 & \text{Venera 4} & 10/18/67 & \text{Entry probe} \\
 & \text{Mariner 5} & 10/19/67 & \text{Flyby at } 1.7 \text{ } R_V \\
 & \text{Venera 9} & 10/22/75 & \text{Orbit } 1.25 \text{ by } 19 \text{ } R_V \\
 & \text{Venera 10} & 10/25/75 & \text{Orbit } 1.25 \text{ by } 19 \text{ } R_V \\
 & \text{Pioneer Venus Orbiter} & 12/4/78 & \text{Orbit } 1.02 \text{ by } 12 \text{ } R_V \\
\text{Mars} & \text{Mariner 4} & 7/15/65 & \text{Flyby at } 3.9 \text{ } R_M \\
 & \text{Mars 2} & 11/27/71 & \text{Orbit } 1.3 \text{ by } 9 \text{ } R_M \\
 & \text{Mars 3} & 12/2/71 & \text{Orbit } 1.3 \text{ by } 63 \text{ } R_M \\
 & \text{Mars 5} & 2/13/74 & \text{Orbit } 1.5 \text{ by } 10 \text{ } R_M \\
\text{Jupiter} & \text{Pioneer 10} & 12/4/73 & \text{Flyby at } 2.9 \text{ } R_J \\
 & \text{Pioneer 11} & 12/3/74 & \text{Flyby at } 1.6 \text{ } R_J \\
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Concluding Remarks

Figure 1 shows the so-called magnetic Bode's law for the planets, a popular display for summarizing planetary moments (Kennel, 1973; Hill and Michel, 1975; Dessler, 1976; Siscoe, 1977; Russell, 1978). We note if Slavin and Holzer's (1978) re-evaluation of the moment of Mercury is correct, then the point labeled X on this figure should be raised to slightly above the dashed line. In any event, it is impossible to plot all the planetary moments on one straight line on this plot, even if we exclude Mars, which may not have an active dynamo at present. The two points for Mars serve to illustrate the problem with the Martian measurements. No magnetic data have been taken in a region which would settle the controversy once and for all, i.e., in the Martian wake. Magnetic measurements have been lacking in the otherwise ambitious American Mars program. The Russian orbiters have been at high altitudes, and have not provided data in the wake.

We have stressed measurements of the dipole moment in this review, for that is all the information we have about most of the planets. However, information about the source of the field is contained in the multipole moments (Elphic and Russell, 1978) and in the secular variations (Hide, 1978). Thus, we should continue our program of planetary exploration and refine our knowledge of the multipole moments even after we know the dipole moment quite well. In most cases this will require carrying magnetometers into low altitude polar orbit.

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