Intrinsic Magnetic Fields of the Planets: Mercury to Neptune [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1994 **349**, 249-260
doi: 10.1098/rsta.1994.0129

Intrinsic magnetic fields of the planets: Mercury to Neptune

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In the past three decades, studies of the magnetic fields of Earth's Moon and all the planets, except for Pluto, have been conducted by spacecraft of the U.S.A. and of Venus and Mars by the former U.S.S.R. Among the terrestrial planets, only Mercury (Mariner 10: 1974 and 1975) is globally magnetized while the Moon and Venus are unmagnetized. The situation at Mars is still unclear, but if any global field exists, it is quite small. In 1979, Pioneer 11 discovered a magnetic field and radiation belt at Saturn, further elaborated on by Voyagers 1 (1980) and 2 (1981). Pioneers 10 (1974) and 11 (1975) and Voyagers 1 (1979) and 2 (1979) examined in detail the magnetic field of Jupiter, which had been inferred initially and studied remotely due to its non-thermal radio emissions in the late 1950s. Jupiter's magnetic field is much stronger than Earth's and distinctly non-dipolar close to the planet. Saturn has a much weaker field than Jupiter, and it is surprisingly axisymmetric (to degree $n = 3$) with respect to its rotation axis. The Voyager fly-bys of Uranus and Neptune in 1986 and 1989 discovered global magnetic fields and trapped energetic particle radiation belts. Both Uranus and Neptune display remarkably similar magnetic fields (quite different from Jupiter, Saturn and Earth). In an astrophysical sense, Uranus and Neptune are described as oblique rotators because of the large angular offset of their magnetic axes from their rotation axes (59° and 47°). Additionally, their magnetic 'centres' are displaced by substantial fractions of a planetary radius (0.31 R_{U} and 0.55 R_{N}). This paper summarizes our present knowledge of the quantitative characteristics of the magnetic fields of these planets.

1. Introduction

Among the many exciting results in the recent studies of our solar system by spacecraft have been the discovery and derivation of quantitative descriptions of the intrinsic magnetic fields of the planets Mercury, Jupiter, Saturn, Uranus and Neptune. The only plausible explanation for these planetary fields and the observed and well-documented terrestrial secular variation is that there is a coherent motion of an electrically conducting 'fluid' in their interiors. This leads to the generation of electrical currents and associated magnetic fields by a dynamo process (Stevenson 1983; Soward 1992). While the details of the physical properties of the interiors of the planets is relatively unknown, by comparison with Earth, there appears to be no obstacle to the assumption that all of the planets' global magnetic fields are generated within an electrically conducting core

Phil. Trans. R. Soc. Lond. A (1994) **349**, 249–260

Printed in Great Britain

TEX Paper

Table 1. *Summary of U.S. spacecraft, 1973–1993, which have discovered and investigated* in situ *the magnetic fields of the planets.* Discovery *encounters are in italic*

	Planet				
	Mercury	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)			2006/1+		

or shell region. However, a continuing challenge for theorists is the development of a comprehensive and adequate theory for solving the problem of how rapidly rotating, self-gravitating and highly condensed bodies throughout the universe generate their magnetic fields. Thus, dynamo theory remains one of the continuing challenges in astrophysics!

The U.S.A. has launched spacecraft to study the magnetic fields of all of the planets (see table 1). The former Soviet Union has launched spacecraft to only Mars, Venus and Earth's Moon. Mars' magnetism remains an enigma. The recent technical failures of both the Phobos 1 and 2 spacecraft of the U.S.S.R. in 1989 and the U.S.A. Mars Observer spacecraft in 1993 guarantee that this Martian mystery will continue, at least until the next century, unless the Russian Mars-94 and/or Mars-96 missions are successful. Studies of the magnetic field of Jupiter began with ground-based remote observations by radio astronomers in 1955. Analyses of long-term observations of these non-thermal microwave emissions, due to synchrotron radiation from energetic electrons trapped in the magnetic field of Jupiter, provided relatively good estimates of a dipole representation of the planetary field. But the situation for the other planets was not the same. There were no ground-based or spacecraft observations of non-thermal radio emissions. Nor were there any certifiable indications of possible auroral activity from ultraviolet observations. Some speculations were based upon very scanty data, which were not confirmed.

Figure 1 presents the electromagnetic spectra of the four giant planets: Jupiter, Saturn, Uranus and Neptune as measured by the Voyager 1 and 2 spacecraft. An extremely important result is that the rotation period of these planets has been accurately derived by studies of the temporal variations of these signals. The periods are presented in table 2, along with dipole magnetic field representations of all the planets. Since there are no visible surface features on Jupiter, Saturn, Uranus and Neptune, it is assumed that the 'radio' rotation period is that of the interior of the planet, where the global fields are generated. Knowledge of this rotation period has permitted more accurate estimates of the characteristics

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

planet	dipole moment ($\mathrm{G\ cm}^3$)	tilt and sense	dipole equal. field (nT)	stagnation point distance	rotation period (R_{p})
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	$< 2 \times 10^{22}$	–	< 60	1.2	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}	$-46.8°$	14 000	26	16.1^{h}

of the planetary interiors from the observed figures of the planets. Table 2 also indicates the upper limits to the Venetian, Martian and lunar magnetic fields that have been determined by orbiting and/or fly-by spacecraft. This paper shall confine itself to a discussion of the known characteristics of the magnetic fields of the five planets: Mercury, Jupiter, Saturn, Uranus and Neptune.

2. Global field and solar wind ramifications

The existence of a global magnetic field at a planet with sufficient strength to deflect the solar wind leads to several unique characteristics of the planetary environment. 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 charged particles. External to this cavity is a detached bow shock wave in the supersonic and super-Alfvénic solar wind flow. Finally, a magnetic 'tail' develops, which trails far behind the planet in the antisolar wind direction. The distance to the Sunward stagnation point of solar wind flow, measured in units of planetary radii, varies from a low value of 1.4 at Mercury to as great as 70 or more at Jupiter. This parameter and those describing the global field as a simple offset tilted dipole, are summarized in table 2.

The traditional method to quantitatively describe a planetary magnetic field is the development by Gauss, using spherical harmonic coefficients for magnetic multipoles. 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 is a dipole. Thus, a basic result of the solar wind interaction is that a bipolar magnetic tail develops in the aft-body region of solar wind flow. Within this magnetic tail is a field reversal region, referred to as a neutral sheet, which contains an embedded plasma whose origins are the atmosphere of the parent

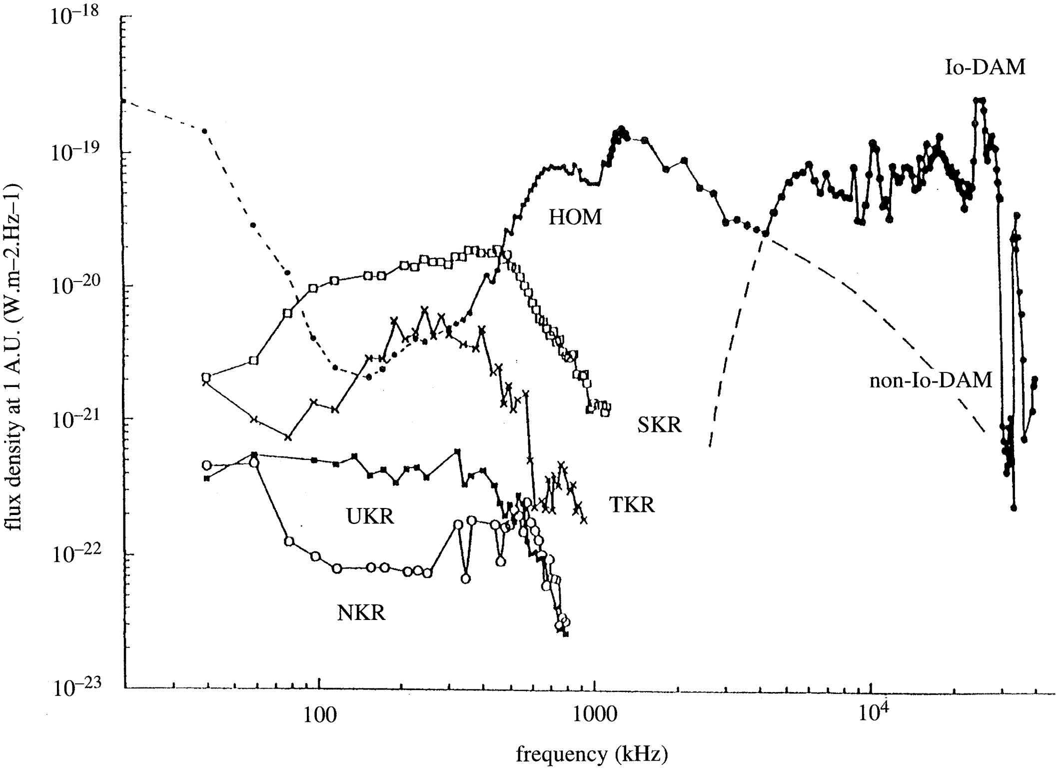

Figure 1. Non-thermal auroral radio emission spectra of the four giant planets Jupiter, Saturn, Uranus and Neptune, and Earth as determined by the Voyager 1 and 2 spacecraft.

planet, the naturally occurring moons, and the shock-modified solar wind. The strength of the magnetic field in the magnetic tails of the planets varies, depending upon the properties of the solar wind. The magnetic tail appears to be an important energy storage regime which participates importantly in the dynamics of planetary magnetospheres.

A unique feature of the magnetic tails of Uranus and Neptune is associated with the obliquity of the planetary rotation axes and the large angular offsets of the magnetic dipole axes from the rotation axes. At these planets, these two parameters combine so that a unique magnetic pole-on configuration of solar wind interaction occurs during portions of their heliocentric orbits. This means that as the planet rotates, the magnetic axis of the planetary dipole field becomes collinear with that of the solar wind velocity. This is theorized to lead to a magnetic tail configuration in which the plasma sheet becomes cylindrical in shape surrounding a unipolar flux tube.

This is in opposition to the case at Earth, where the plasma sheet develops as a transverse planar structure in the magnetic tail which separates the bipolar lobes or flux tubes of the magnetic tail. At Jupiter and Saturn, a bipolar magnetic tail and plasma sheet similarly develops. Important consequences of the solar wind interaction, trapped radiation belts and plasma sheets is that there are a number of electrical current systems external to the planet. The magnetic fields of these currents can have important contributions to the *in situ* measurements of the magnetic fields by fly-by or orbiting spacecraft.

Table 3. *Spherical harmonic coefficients or multipole parameters for Earth and the four giant planets: Jupiter, Saturn, Uranus and Neptune*

planet (radius in km)	Earth (6378)	Jupiter (71 372)	Saturn (60 330)	Uranus (25 600)	Neptune (24 765)
model	IGRF 85	O6	Z3	O3	O8
$g(1,0)$	−0.29877	4.24202	+0.21535	+0.11893	+0.09732
$g(1,1)$	−0.01903	−0.65929	0	+0.11579	+0.03220
$h(1,1)$	+0.05497	0.24116	0	−0.15685	−0.09889
$g(2,0)$	−0.02073	−0.02181	+0.01642	−0.06030	+0.07448
$g(2,1)$	+0.03045	−0.71106	0	−0.12587	+0.00664
$h(2,1)$	−0.02191	−0.40304	0	+0.06116	+0.11230
$g(2,2)$	+0.01691	0.48714	0	+0.00196	+0.04499
$h(2,2)$	−0.00309	0.07179	0	+0.04759	−0.00070
$h(3,0)$	+0.01300	0.07565	+0.02743	+0.02705	−0.06592
$g(3,1)$	−0.02208	−0.15493	0	+0.01188	+0.04098
$h(3,1)$	−0.00312	−0.38824	0	−0.07095	−0.03669
$g(3,2)$	+0.01244	0.19775	0	−0.04808	−0.03581
$h(3,2)$	+0.00284	0.34243	0	−0.01616	+0.01791
$g(3,3)$	+0.00835	−0.17958	0	−0.02412	+0.00484
$h(3,3)$	−0.00296	−0.22439	0	−0.02608	−0.00770
dipole moment	$0.304R_{\rm E}^3$ G	$4.28R_{\rm J}^3$ G	$0.215R_{\rm S}^3$ G	$0.228R_{\rm U}^3$ G	$0.142R_{\rm N}^3$ G
dipole tilt	+11.4°	−9.6°	−0.0°	−58.6°	−46.9°
OTD offset	$0.08R_{\rm E}$	$0.07R_{\rm J}$	$0.04R_{\rm S}$	$0.31R_{\rm U}$	$0.55R_{\rm N}$

3. Mercury

Only one spacecraft, the U.S.A.'s Mariner 10, has studied the planet Mercury. Launched in 1973, it used a gravity-assisted manoeuvre at Venus to encounter Mercury sequentially three times. This was due to a serendipitous exact integer relationship (1 to 2) between the heliocentric orbital periods of Mercury and Mariner 10. Successful encounters in March 1974 and again in March 1975 provided direct observational evidence for a global magnetic field at Mercury. The discovery of an intrinsic magnetic field was a great surprise, since there was neither any prior evidence of or speculation that there would be a planetary field of global extent. The surface of Mercury is similar to Earth's Moon with a rich history of impact bombardment recorded in its numerous craters.

The Mariner 10 magnetic field data set is a challenge for analysis, because of the significant contributions of electrical currents associated with the deflected solar wind flow (Ness 1979; Connerney & Ness 1987). The conclusion is that Mercury possesses an equivalent dipole moment with an equatorial field which is approximately 0.1% of Earth's and a dipole magnetic field axis tilted approximately 14° from the rotation axis, a value similar to Earth's 11.4° (see table 2).

There is no permanently trapped radiation belt at Mercury. This is due in large part to the very small size of its magnetosphere, relative to the planet itself. Thus, remote studies of the magnetic field at Mercury cannot be conducted by radio astronomers. There are, at present, no definitely planned missions to return to Mercury to elaborate more fully on its magnetic field.

Thermal models of Hermean evolution predict too thin a subcurie point shell of permanently magnetized material which would be sufficient to carry the requisite magnetization. Thus, the current view is that the Hermean field is due to an active dynamo in the interior.

4. Jupiter

Ground-based observations of Jupiter's non-thermal microwave radio emissions began with their discovery in 1955. They were eventually interpreted some years later as due to the presence of a global field at Jupiter and generated by the trapped and precipitating electrons in the radiation belt. Careful study of the polarization, frequency and time variable characteristics yielded reasonably good estimates of an equivalent dipolar magnetic field of Jupiter. Subsequent *in situ* spacecraft observations since 1974 have refined considerably our knowledge of not only the Jovian main magnetic field, but also the electrical currents throughout the Jovian magnetosphere which significantly distort the field.

The most recent quantitative model of the main magnetic field of Jupiter is that developed by Connerney (1993) and referred to as the GSFC-O6 model. The shorthand nomenclature uses an alphabetic character to specify the degree of the highest multipole term used while the numerical digit indicates the highest degree of the multipole term necessary in the analysis of the available spacecraft data. Thus, O6 means an octupolar representation based upon a sixth-degree (and order) analysis. The O6 model is based upon the 1975 observations by Pioneer 11 and the 1979 observations by the Voyagers 1 and 2 spacecraft. No evidence for any secular change in the main magnetic field of Jupiter (the dipole term) was deduced during the five year interval between Pioneer 11 in 1975 and the Voyager observations in 1979.

The most intense magnetic field of all of the planets exists at Jupiter. The maximum field in the northern hemisphere is 14 gauss, which is in good agreement with the maximum frequency of microwave radio emissions, 42 MHz. The equatorial fields range from 3.3 to 8 gauss. This variation in field intensity and lack of polar symmetry (10.4 gauss in the south) is due in large part to the presence of important higher-order multipole terms. The 'geometry' of the Jovian and terrestrial fields appears similar when appropriately normalized, primarily because of the similar tilt of their magnetic fields (9.6° and 11.4°). Figure 2 presents the O6 model and includes the footprint of the field line threading through the moon Io. It is known to be closely coupled to and responsible for the modulation of certain radio emissions from the parent planet.

A principal question for future studies of the Jovian magnetic field is whether or not there is any detectable secular variation. It is possible that the future Galileo orbiting spacecraft will be able to contribute to answering this question. However, due to the hazards of radiation damage associated with the intense radiation belts of Jupiter, after its first periapsis at 5.95 R_J, the periapsis will be raised to 15 R_J or more. It is not yet clear whether the 1992 encounter of Jupiter by the ESA–NASA spacecraft, Ulysses, will be able to contribute meaningfully to our knowledge of the secular change of the dipole moment of the planetary field since its periapsis was also at $\sim 6\ R_J$.

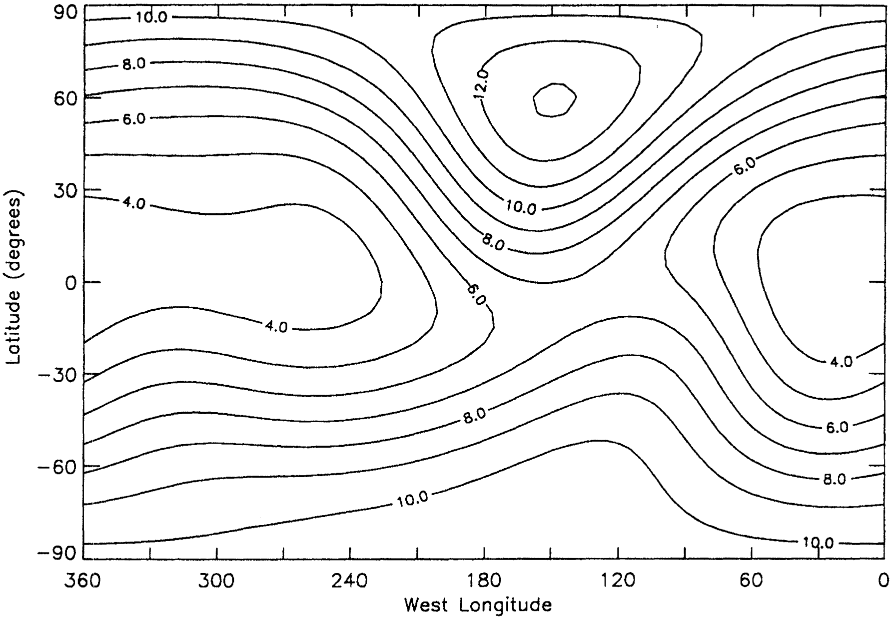

Figure 2. Isointensity of the Jovian magnetic field, O6, in a Mercator projection.

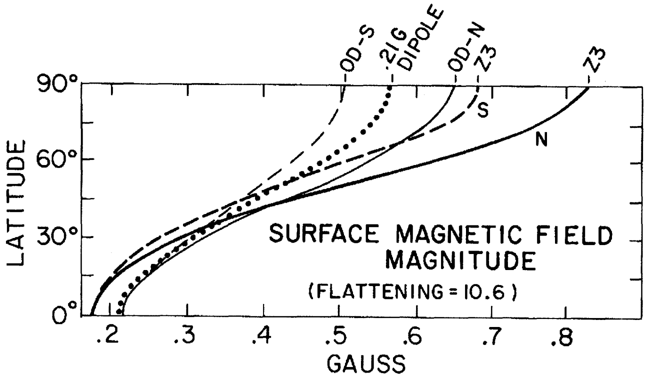

Figure 3. Latitude variation of the Saturnian magnetic field, Z3, for different models.

5. Saturn

Saturn possesses the most unusual magnetic field of all the planets. The magnetic field was discovered by Pioneer 11 in 1979 and confirmed and elaborated upon by the Voyagers 1 and 2 spacecraft in 1980 and 1981. Saturn's magnetic field appears to be symmetric with respect to the rotation axis (Connerney *et al.* 1982, 1983). The derived quantitative model of the magnetic field (Z3; see figure 3) includes only the axially symmetric dipole, quadrupole, and octupole terms (g_1°, g_2°, and g_3°).

This model permits comparison of observed radiation belt structure with that predicted on the basis of absorption by the naturally occurring moons. In their orbits, the moons behave like occulting disks and create 'holes' in the radiation belts. Their locations can be used to test global field models. The enigma of

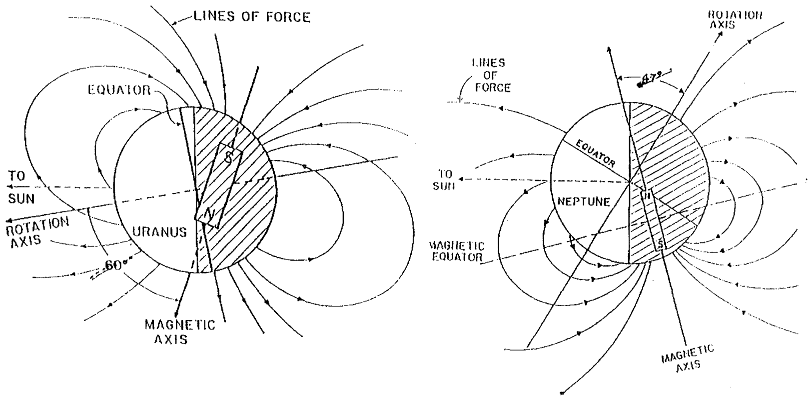

Figure 4. Cartoon of planetary magnetic field representations at Uranus and Neptune as spatially offset and tilted dipoles.

Saturn is that its auroral radio emissions are time varying with what is most assuredly the rotation period of the planet. Detailed examination of the source location of these modulated radio emissions implies that there is a region close to the rotation pole where these emissions are generated. This Saturnian kilometric radiation is evidence for the departure of the magnetic field in the polar region, close to the planet, from axial symmetry. Expectations are high that the ESA–NASA Cassini mission, scheduled for launch in 1996 and arrival at Saturn in 2002, may provide the necessary observational data to resolve the inconsistency of Saturn's periodic radio observations and, at present, its axially symmetric magnetic field description.

6. Uranus

The only measurements of the magnetic field and magnetosphere of Uranus were conducted by the discovery mission of Voyager 2 in January 1986 (Ness *et al.* 1991, and references therein). It was with considerable surprise that a global magnetic field was detected, as well as an associated and well-developed magnetosphere and radiation belt structure. This is because the planet Uranus is not exothermic, i.e., it does not radiate as much energy as it receives from the Sun. Thus, it was at first thought that there would not be a sufficiently strong internal energy source available to power any dynamo process.

But an even greater surprise at Uranus was that the magnetic dipole axis is offset from the rotation axis by 58.6°. It was speculated that this might be related to the large obliquity of the planet, 98.2°. But the observation of a similarly highly oblique magnetic field at Neptune, subsequently, meant that this hypothesis was not well founded (see figure 4). The combined obliquity and large tilt of the planetary magnetic field means that at times the magnetosphere configuration of Uranus will be periodically pole-on.

Another important feature of the magnetic field of Uranus is that its magnetic centre is spatially displaced by a significant amount from the centre of the planet. Equivalently, this means that there are very large higher-order multipole moments at Uranus (see table 3.)

At Jupiter and Saturn, the transit time for a fly-by spacecraft while within the magnetosphere is many times the rotation period of the parent planet. Thus, the

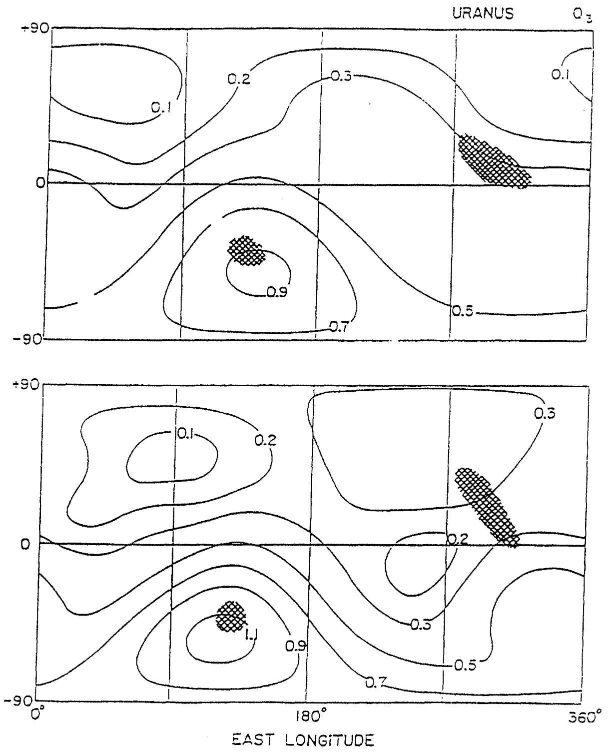

Figure 5. Isointensity maps (Mercator projections) of the Uranian Q3 and O3 model fields projected to the surface of the planet.

fly-by trajectories appear to spiral radially in and out providing wide radial and longitudinal ranges and, for certain trajectories, a wide latitude range. However, at Uranus, the fly-by was limited in longitude extent although it did have a wide latitude extent. These combine in the analysis procedures to restrict the ability to uniquely determine with confidence the higher-order multipole moments at Uranus. At present, the quantitative models for the Uranian field include dipole, quadrupole and, with less certainty, the octupole terms.

Figure 5 presents the O3 and Q3 representations of the Uranian field. It is seen that the field intensities, extrapolated to the surface of the planet, are similar as are the locations of the auroral zones for these two models.

Notice should be made that the auroral zones at Uranus are displaced far from the rotational polar regions of the planet. Indeed, one of the polar regions is essentially equatorial. Unfortunately, due to the geocentric bias toward scheduling UV searches for aurora at the rotational polar regions, in advance of the encounter, there are very sparse Voyager 2 observations of aurora at Uranus.

7. Neptune

Following the very surprising results at Uranus, it was with some confidence that a global magnetic field was expected to be detected at Neptune because this planet is exothermic (Curtis & Ness 1988). The bigger surprise of the 1989 encounter by Voyager 2 was that Neptune also possessed a global magnetic field for which the dipole magnetic axis is offset far from the rotation axis (46.8°)

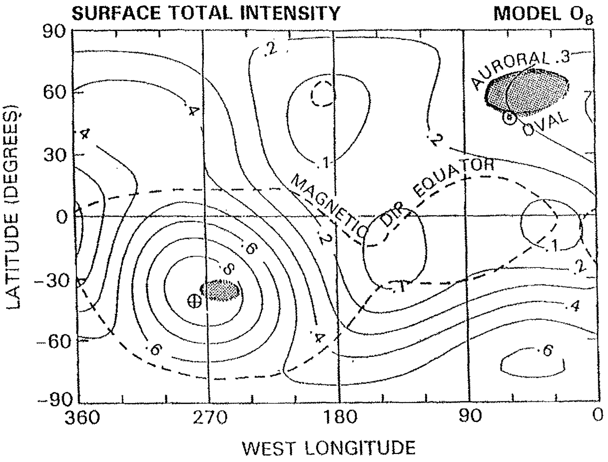

Figure 6. Isointensity map (Mercator projections) of the Neptunian O8 model field projected to the surface of the planet.

(Ness *et al.* 1989). Moreover, its magnetic centre is also displaced, but even more so, from the centre of the planet, than at Uranus (31% at Uranus and 55% at Neptune).

Figure 6 presents the O8 model of the Neptunian magnetic field, as well as the location of the theoretically computed auroral zones. Both Uranus and Neptune are remarkable in that the aurora are expected to occur far from the rotational polar regions. But, as at Uranus, Voyager 2 targeted its UV auroral observations for the rotational polar regions. Thus, very limited data were obtained on auroral phenomena.

Associated with a large angular tilt between the magnetic and rotation axes at Neptune, its magnetosphere will also periodically take on a pole-on configuration in its heliocentric orbit (Voigt & Ness 1990). Indeed, at the present epoch (1990s), during each planetary rotation, it passes from being Earth-like to pole-on because of the combination of its obliquity and magnetic axis angular offset.

The timing of the Neptune encounter was especially serendipitous in that although determined entirely by the post-Neptune Triton encounter, the spacecraft entered the magnetosphere when the polar cusp region of the solar wind interaction was pointed Sunward. This was a most fortuitous occurrence since this is the only pole-on magnetosphere configuration for which *in situ* observations are available.

8. Comparisons

Initial studies of the magnetic fields of all the planets, except for Pluto, are now complete after 30 years. Schulz & Paulikas (1990) have shown that the magnetic fields of the planets Earth, Jupiter, Uranus and Neptune demonstrate a unique equipartition of global magnetic energy, based upon the spectrum of the harmonic coefficients representing the internal magnetic fields. From this they have deduced that the magnetic field generating region has an effective normalized radius at Earth, Jupiter, Uranus and Neptune of 0.432, 0.756, 0.464, and 0.662. These values are tantalizingly close to those for the radii of the conducting regions developed independently on the basis of plausible physical models of composition, rotation rate and body figure. It will be most interesting to follow future developments of this concept and its refinement along with the investigations of the symmetry properties of the planets, as conducted by Raëdler & Ness (1990).

9. Summary and questions for future study

During the past three decades, exploration of the planets by transportable laboratories known as spacecraft has led to discoveries and knowledge of the quantitative characteristics of the magnetic fields of the planets: Mercury, Jupiter, Saturn, Uranus and Neptune. Except at Jupiter, all of these observations represented significant discoveries.

At certain epochs in their heliocentric motion, both Uranus and Neptune have very different configurations of their magnetospheres' magnetic tails. While the three planets Earth, Jupiter and Saturn possess stereotype magnetic tail structures with bipolar lobes separated by a transverse plasma sheet, Uranus and Neptune will possess pole-on configurations and cylindrical plasma sheets at certain epochs in their heliocentric orbits. This is certainly one of the most interesting future study areas in planetary magnetospheres.

Future studies also will be important in establishing the characteristics of any possible secular variation of intrinsic planetary magnetic fields. At Mercury, a close orbiting spacecraft is required in order to provide an opportunity to describe its magnetic field quantitatively, due to the large volume fraction of its magnetosphere occupied by the planet.

Departures of axial symmetry of the Saturnian magnetic field are obviously present but not yet quantitatively described. This is certainly a task for the future Cassini mission.

Finally, the enigmatic matter of any Martian magnetic field will someday be known and, if it is global, studied. At present, hopes for such data soon are growing slimmer as the end of the century approaches.

Nonetheless, the existence of this new body of experimental observations on the magnetic fields of self-gravitating, rapidly rotating and condensed objects in the solar system is certainly having an important impact on our knowledge of planetary interiors and our comparisons with other objects in the universe.

I appreciate the contributions to the research reported upon here by my colleagues at the NASA Goddard Space Flight Center, Mario H. Acuna, Kenneth W. Behannon, John E. P. Connerney, Ronald P. Lepping, and at the University of Köln, Fritz M. Neubauer.

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Discussion

S. K. RUNCORN. Is the striking difference between the magnetic fields of Uranus and Nepturne and those of other planets explained by the fact that in the latter we are dealing with dynamo action in a central core, whereas in the former field generation is likely to be occurring in a spherical shell of ammonia and water? Perhaps in such a relatively weakly conducting electrolyte, the magnetic Reynolds number exceeds the critical value for dynamo action only in one part of the shell. Then the large dipole offset is not just a mathematical way of representing higher harmonics but is physically meaningful. Also the dominant Coriolis term in the magnetohydrodynamic equation will depend on the vertical component of the planet's rotation. It is perhaps significant that the dipole axes are near the radial direction at the offset position, i.e. at the dynamo.

N. F. NESS. Yes, we agree with you and had suggested the same thesis immediately after our Neptune data analysis revealed it to possess a dipolar magnetic field both highly oblique and off centre. The concept of a shell dynamo, we believe, is now rather firmly established observationally and Professor Runcorn has made the good point that the axes of the magnetic dipoles at Uranus and Neptune are rather close to the local zenith/radial directions.

S. MILLER (*University College London, London, U.K.*). Given the rather odd nature of the magnetic field of Uranus and its peculiar alignment to the ecliptic, would Professor Ness expect particle precipitation to be confined to the circumpolar regions or could they be more diffusely precipitated? I ask this because we have recently obtained images showing rather diffuse H_3^+ emission.

N. F. NESS. We have studied the precipitation pattern using a simple offset tilted dipole model and note that particle drifts lead to rather broader and less sharply confined regions near the magnetic poles. Use of higher order magnetic field models will not eliminate this feature, due primarily to the combined effects of a tilted and spatially offset magnetic field.

Note added in proof (13 December 1994)

The USA has recently approved the Mars Global Surveyor Project with a November 1996 launch and a planned September 1997 capture in a polar, near-circular orbit like that of the failed Mars Observer. The scientific payload is a reduced MO set of instruments but does not include the MO magnetometer system. Thus, perhaps the enigma of any Martian magnetic field will be solved before the end of the century.