

PLANETARY MAGNETIC FIELDS: SALIENT CHARACTERISTICS

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Abstract

Completion of the survey of the giant planets by Voyager 1 and 2 has revealed many new and quite surprising results regarding the existence and properties of the magnetic fields of Jupiter, Saturn, Uranus and Neptune when compared to Earth. The most striking observational finding is that both Uranus and Neptune have significant global fields whose magnetic axes and centers are offset appreciably from the planetary body rotation axes and centers. This leads to greatly distorted locations and shapes of the associated auroral zones at Uranus and Neptune, when compared to Earth, Jupiter or Saturn. Nonetheless, there are certain characteristics of all these magnetized planets which seem similar when studying their field symmetries. There also appears to be an equi-partition of magnetic energy among available degrees of freedom at each planet; which yields reasonable values for nominal core radii. Additionally, the structure of the magnetospheres and magnetic tails with embedded neutral sheets vary with time due to both planetary rotation and solar wind fluctuations. The absorption of the energetic trapped particles by naturally occurring moons and rings leads to significant changes in the details of the radiation belt structures. This paper overviews the quantitative properties of the magnetic fields of Earth and the four giant planets as their salient characteristics control auroral and radio emissions.

1 Introduction

One of the most impressive accomplishments of the exploration of our solar system has been the discovery and quantitative elaboration of the characteristics of the magnetic fields of the planets Mercury, Jupiter, Saturn, Uranus and Neptune. (It should be noted that the Jovian field had been studied remotely by radio astronomers since 1957, well before spacecraft in-situ investigations.) The only satisfying explanation for these planetary magnetic fields, and the terrestrial secular variation which has been observed, is based upon the concept of motion in the electrically conducting interior which generates electrical currents and associated magnetic fields by the dynamo process.

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At present, there appears to be no major challenge to the concept that all of the planets possess conducting cores or shells due to their composition and physical state. Earth possesses an iron core, while Jupiter and Saturn possess metallic hydrogen cores. Uranus and Neptune, most likely, possess conducting mantles or shells of ionic solutions of ammonia and water. However, due to the intrinsic difficulty in analytically solving the problem of rapidly rotating, self-gravitating, highly-condensed bodies throughout the universe, dynamo theory has not yet been developed to the stage at which it is possible to make exact predictions for the magnetic fields of such objects.

Spacecraft studies of the moon and Venus have demonstrated no detectable global planetary fields. The situation at Mars is unclear except that an upper limit indicating a relatively weak, if any, global magnetic field may exist. It should also be noted that there is no evidence of nonthermal radio emission associated with trapped radiation belt particles from Mercury or Mars as there is from the planets Earth, Jupiter, Saturn, Uranus and Neptune. Thus, this paper shall confine itself to a discussion of the salient characteristics of the magnetic fields of these five planets.

2 Ramifications and summary OTD representations

The presence of a planetary magnetic field of global extent with sufficient strength to deflect the solar wind leads to a number of significant characteristics. The principal one is the formation of a magnetic cavity and the development of a detached bow shock wave in the supersonic solar wind. The distance from the center of the planet to the stagnation point of solar wind flow, measured in units of planetary radii, varies from the small value of 1.4 at Mercury to as large as 70 at Jupiter. This parameter and others related to the simple representation of the global magnetic field as an offset tilted dipole, are summarized

SUMMARY OF PLANETARY MAGNETIC FIELDS

PLANET	DIPOLE MOMENT (G CM ³)	TILT AND SENSE	DIPOLE EQUA. FIELD (nT)	STAG. PT. DISTANCE (Rp)	RING CURRENT (10 ⁶ A)	R.C. FIELD (nT)	$\frac{F_{RC}}{F_D}$
MERCURY	5×10^{22}	+14°	330	1.4	----	----	----
VENUS	$< 4 \times 10^{21}$	---	< 2	1.0	----	----	----
EARTH	8.0×10^{25}	+ 11.7°	31,000	10.4	0.7	20	6
MOON	$< 1 \times 10^{19}$	---	< 0.2	none	----	----	----
MARS	$< 2 \times 10^{22}$	---	< 60	1.2	----	----	----
JUPITER	1.6×10^{30}	- 9.6°	428,000	65±15	300	200	5
SATURN	4.7×10^{28}	- 0.0°	21,200	20 + 3	10	10	5
URANUS	3.8×10^{27}	-58.6°	23,000	20	----	----	----
NEPTUNE	2.2×10^{27}	-46.9°	14,000	25±2	----	----	----

NOTE: $1 \text{ G CM}^3 = 10^{-3} \text{ AM}^2$, $1 \text{ nT} = 10^{-5} \text{ G} = 10^{-9} \text{ TESLA}$

$F_{RC}/F_D = \text{R.C. Field/dipole equatorial field (10}^{-4}\text{)}$

Since the lowest order magnetic field moment is that of a dipole, a bipolar magnetic tail develops in the aft-body portion of solar wind interaction region with the planet. Within this magnetic tail is a field reversal region, the neutral sheet, containing an embedded plasma. The strength of the magnetic field in the magnetic tail of the planets varies, depending upon the condition and direction of the solar wind plasma and its magnetic field. Indeed, magnetic energy is stored in the magnetic tail and then released at times of magnetic storms.

One unique feature of the magnetic tails of Uranus and Neptune are that the obliquity of the planetary rotation axes and the tilt of the magnetic axes from the rotation axes combine so that the unique pole-on configuration of solar wind interaction can occur. This means that, as the planet rotates, the magnetic axis of the planetary field becomes co-linear with that of the solar wind velocity. This should lead to a magnetic tail configuration in which the plasma sheet is cylindrical in shape, as opposed to being a transverse planar structure separating the bipolar lobes of the magnetic tail for more usual configurations which occur at all times for Earth, Jupiter and Saturn.

The trapping of energetic particles and plasmas in the planetary magnetic fields leads to the development of radiation belts which are reflective of both the energetics of the solar wind interaction process, as well as the composition of the atmospheres of the parent planet and its moons. Also important for the giant planets is the presence of naturally occurring satellites, i.e. moons and rings, which absorb the radiation belt particles and at the same time such absorption can lead to secondary emission and sputtering. The entire process is rather complicated, and this field of investigation has only begun to be explored since spacecraft made their first observations in-situ in the past twenty years.

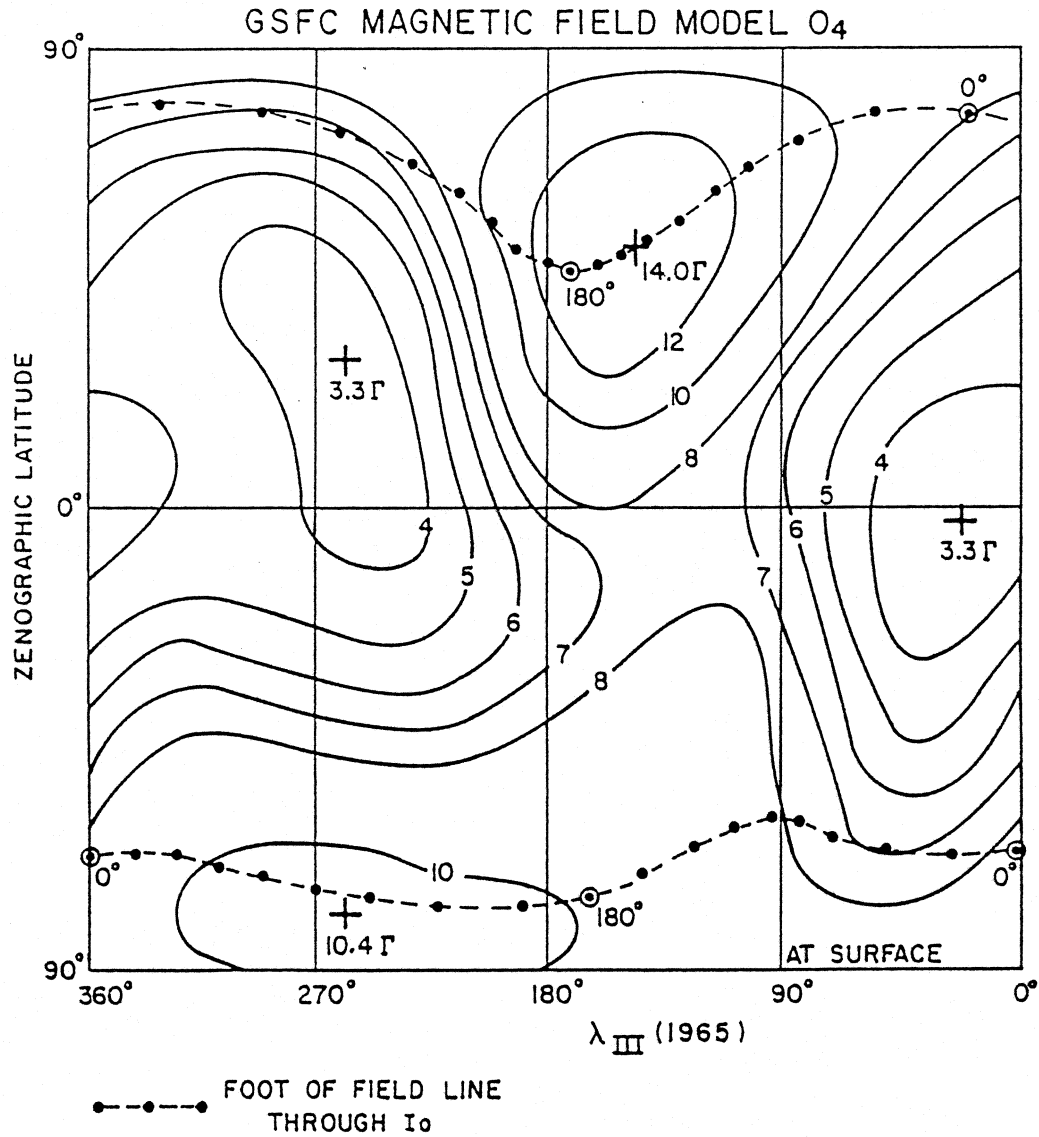
3 Jupiter

The presence of a planetary field at Jupiter was deduced more than 30 years ago from ground based observations of nonthermal radio emissions. By careful study of the polarization and frequency characteristics of these radio signals, the general characteristics of the main magnetic field of Jupiter were determined rather well. The subsequent in-situ spacecraft observations refined our knowledge of the Jovian magnetic field and magnetosphere considerably, but the pioneering ground based studies represent a remarkable achievement for remote sensing studies. Such an approach was subsequently used in studies of other more exotic objects in our universe such as quasars and pulsars.

The standard model for the main magnetic field of Jupiter is the GSFC O4 model, developed by Acuña and Ness [1976] on the basis of Pioneer 11 observations. Subsequent studies by the Voyager 1 and 2 spacecraft have confirmed these earlier results and also shown that there is, at present, no evidence for any secular change of the field of Jupiter during the 5-year interval between Pioneer 11 in 1974 and Voyager 1 and 2 observations in 1979.

Jupiter possesses the most intense magnetic field of all the planets, with a maximum surface field of 14 gauss in its northern hemisphere, a maximum field of 10.4 gauss in the

southern hemisphere, and equatorial fields ranging from 3.3 to 8 gauss. This variation in field and the lack of polar symmetry is due to the presence of higher order terms in the magnetic field spherical harmonic or magnetic multipole representation. The gaussian coefficients for all the planets are given in Table 2. Figure 1 presents the O4 model and includes the footprint of the field line threading through the unique moon Io. It is known to be closely coupled to the modulation of radio emissions from the parent planet. The quantitative results of analysis of spacecraft observations are completely consistent with the many years of accumulated ground based radio observations.



Planet (Radius in Km)	Earth (6378)	Jupiter (71,372)	Saturn (60,330)	Uranus (25,600)	Uranus (25,600)	Neptune (24,765)
Model	IGRF 85	04	23	Q3	Q3	08
$g(1,0)$	-0.29877	+4.2180	+0.21535	+0.11893	same	+0.09732
$g(1,1)$	-0.01903	-0.6640	0	+0.11579	same	+0.03220
$h(1,1)$	+0.05497	+0.264	0	-0.15685	same	-0.09889
$g(2,0)$	-0.02073	-0.203	+0.01642	-0.06030	same	+0.07448
$g(2,1)$	+0.03045	-0.735	0	-0.12587	same	+0.00664
$h(2,1)$	-0.02191	-0.469	0	+0.06116	same	+0.11230
$g(2,2)$	+0.01691	+0.513	0	+0.00196	same	+0.04499
$h(2,2)$	-0.00309	+0.088	0	+0.04759	same	-0.00070
$g(3,0)$	+0.01300	-0.233	+0.02743	0	+0.02705	-0.06592
$g(3,1)$	-0.02208	-0.076	0	0	+0.01188	+0.04098
$h(3,1)$	-0.00312	-0.580	0	0	-0.07095	-0.03669
$g(3,2)$	+0.01244	+0.168	0	0	-0.04808	-0.03581
$h(3,2)$	+0.00284	+0.487	0	0	-0.01616	+0.01791
$g(3,3)$	+0.00835	-0.231	0	0	-0.02412	+0.00484
$h(3,3)$	-0.00296	-0.294	0	0	-0.02608	-0.00770
DIPOLE MOMENT	0.304 IR_E^3	4.28 IR_J^3	0.215 IR_S^3	0.228 IR_U^3	same	0.142 IR_N^3
DIPOLE TILT	+11.4°	-9.6°	-0.0°	-58.6°	same	-46.9°
OTD OFFSET	0.08 R_E	0.07 R_J	0.04 R_S	0.31 R_U	same	0.55 R_N

Table 2: Spherical Harmonic Coefficients

rotating magnetosphere with the moon Io. It is hoped that in 1996 the USA Galileo spacecraft will contribute significantly to an evaluation of both the interaction of Io with the co-rotating magnetosphere of Jupiter, as well as studies of the auroral processes in the Jovian magnetosphere. The Galileo spacecraft, in its orbiting of the planet Jupiter, will have only one flyby at the Io orbit. Due to radiation hazards, its periapsis will be raised to 15 or more Jovian radii after the first orbit. The Jovian encounter in 1992 by the joint ESA–NASA spacecraft Ulysses will not be sufficiently close to the planet to add significantly to our knowledge of the higher order moments of the planetary field.

4 Saturn

Of all the planets possessing global magnetic fields, Saturn is at present both the most unique and enigmatic. Discovered by Pioneer 11 in 1979, and confirmed by Voyagers 1 and 2 in 1980 and 1981 with finer elaboration, Saturn's magnetic field has been found to be axially symmetric [Connerney et al., 1983]. A model (Z3) of the magnetic field has been developed including quadrupole and octupole terms. This model permits comparison of the observed radiation belt structure with that predicted on the basis of absorption by naturally occurring moons. The agreement validates the global magnetic field model.

However, the radio emissions from Saturn are unsteady and regularly modulated at the rotation period of the planet. This implies that there must be a loss of axial symmetry in the field configuration close to the planet. An unsuccessful attempt to incorporate certain characteristics of Saturnian kilometric radiation as evidence for Saturn's magnetic field anomaly has been presented by Galopeau et al. [1991]. The models developed by those authors fail to satisfy several basic requirements such as being inconsistent with the in-situ magnetic field observations available and assuming a priori that all emissions occur at the same altitude, i.e. at the surface of the planet. The latter assumption is quite unrealistic since it ignores atmospheric properties. Nonetheless, this indicates one approach to improve model magnetic fields through the introduction of other independent observational data which depend critically upon the structure of the magnetic field.

5 Uranus

The discovery and only measurements of the magnetic field and magnetosphere of Uranus were conducted by Voyager 2 in January 1986. Since the planet Uranus is not exothermic, i.e. it does not radiate as much energy as it receives from the sun, it was uncertain if there would be sufficient internal energy available to maintain a dynamo. Thus, it was with considerable surprise that a magnetic field was detected and a well-developed magnetosphere and radiation belt structure observed.

Because of the obliquity of the planet Uranus, 98.2° , and the phase in its heliocentric orbit, it was thought that the observation of any magnetic field and associated magnetosphere structure would closely resemble that of the pole-on configuration. The rotation axis at encounter was only 10° from the planet sun line. However, it was found that the magnetic

axis of Uranus is inclined by 58.6° from the rotation axis of the planet and so a pole-on configuration was not possible at this epoch. As discussed by Ness et al. [1992], the magnetosphere configuration of Uranus will periodically be pole-on in the future. An important feature of the magnetic field model of Uranus is that its magnetic center is offset a significant distance from the planetary center. This equivalently says that there are large higher order moments than the dipole.

The basic model for the Uranian magnetic field uses terms including only dipole and quadrupole, Q3 [Connerney et al., 1987]. However, in spite of uncertainties in the analysis procedure, octupole terms have been derived and are included in the O3 representation shown for comparison with Q3 in Figure 2. While there appear to be some differences in the location of the auroral zones and in the field intensities on the surface of the planet, the Q3 and O3 models demonstrate a close similarity. The importance of this comparison is to illustrate that by careful analysis of observational data obtained by other instruments on Voyager 2 or possibly from ground based observations, it may be possible to infer which of these two models more accurately reflects the true global magnetic field configuration.

At first thought, it might be considered that the structure of the radiation belt of Uranus would be useful in separating which of the two models is more accurate. Unfortunately, because of the large tilt of the magnetic axis of Uranus and the many moons and rings embedded deeply in its magnetosphere, there are considerable overlaps of the absorption characteristics of these naturally occurring moons and ring particles. Neither auroral observations nor radiation belt observations have yet been fully utilized to distinguish among these two models.

6 Neptune

Following the surprising results at Uranus, a global magnetic field was expected at Neptune since it is exothermic. However, the surprise of the 1989 encounter by Voyager 2 was that Neptune also possesses a global field with a magnetic axis tilted far from the rotation axis (46.8°) [Ness et al., 1989]. Additionally, its magnetic center is displaced even more from the center of the planet (30% at Uranus and 55% at Neptune). Figure 3 presents both the Q8 and O8 models of the Neptunian field. The purpose of this presentation is similar to that for the planet Uranus, namely, a comparison of low order magnetic field representations in an attempt to ascertain a commonality but separability of location of the auroral zones. Both Uranus and Neptune are remarkable in that the aurorae quite possibly occur near equatorial regions. Unfortunately, there are as yet no published results concerning the specific location of auroral observations by Voyager 2 at either Uranus or Neptune.

However, studies of nonthermal radio emissions of both planets have proceeded on the basis of a rich variety of sources. Principal interests began with variations associated with the rotation of the planets. Establishing the rotation period of these planets has been a primary goal in order to confirm our understanding of models of the planetary interior based upon mass distributions and body figure. Neptune, like Uranus, possesses a number of naturally occurring moons and rings located deep within its magnetosphere. Again,

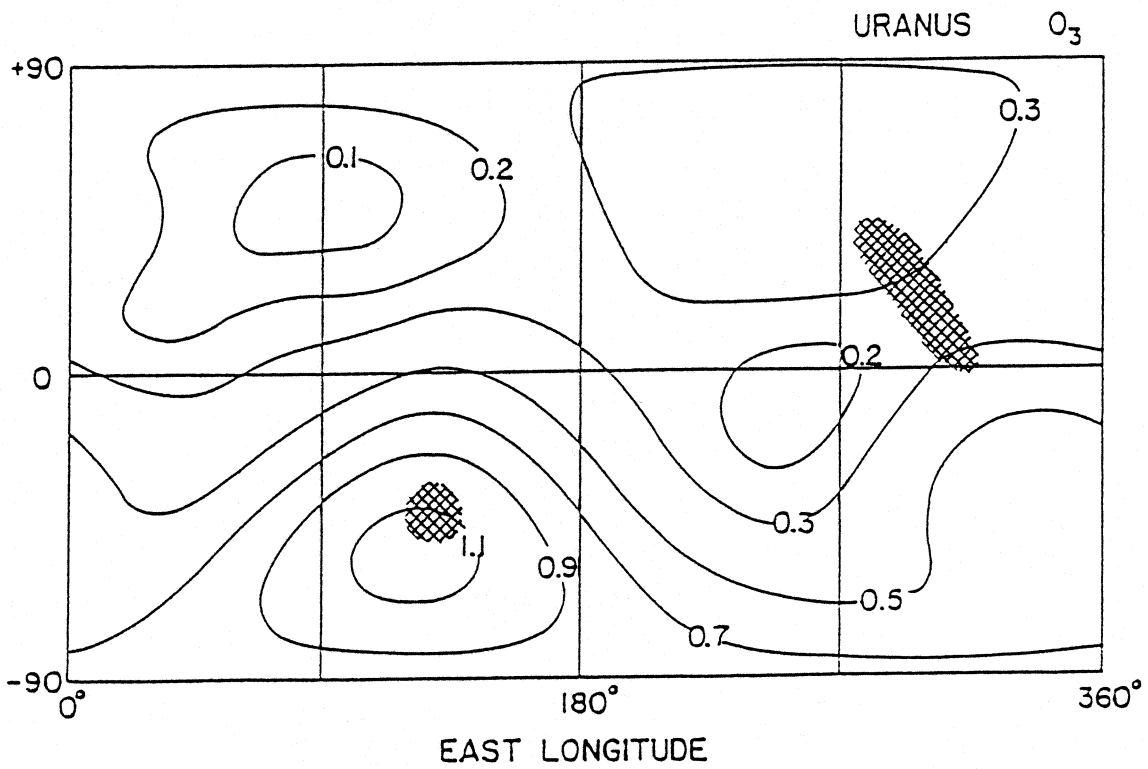
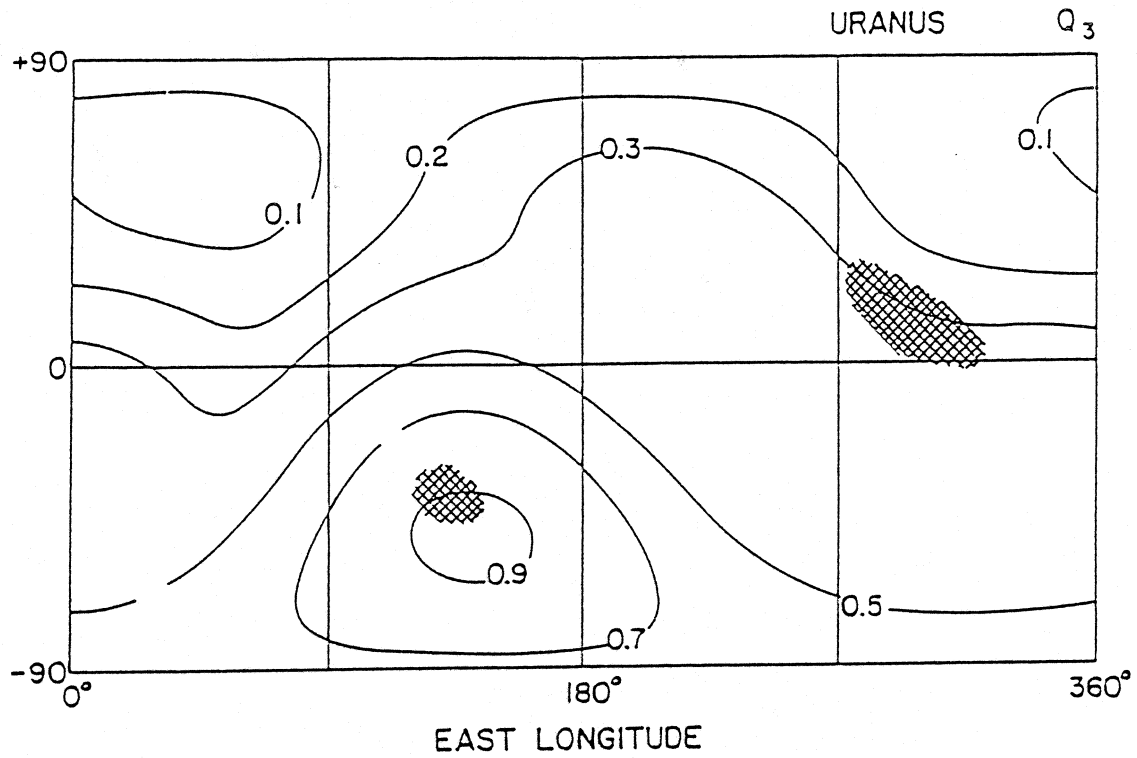


Figure 2: Isointensity mercator plots on surface of planet of Q_3 and O_3 models of Uranus' magnetic field. Cross hatched areas represent theoretical location of auroral and polar cap zones.

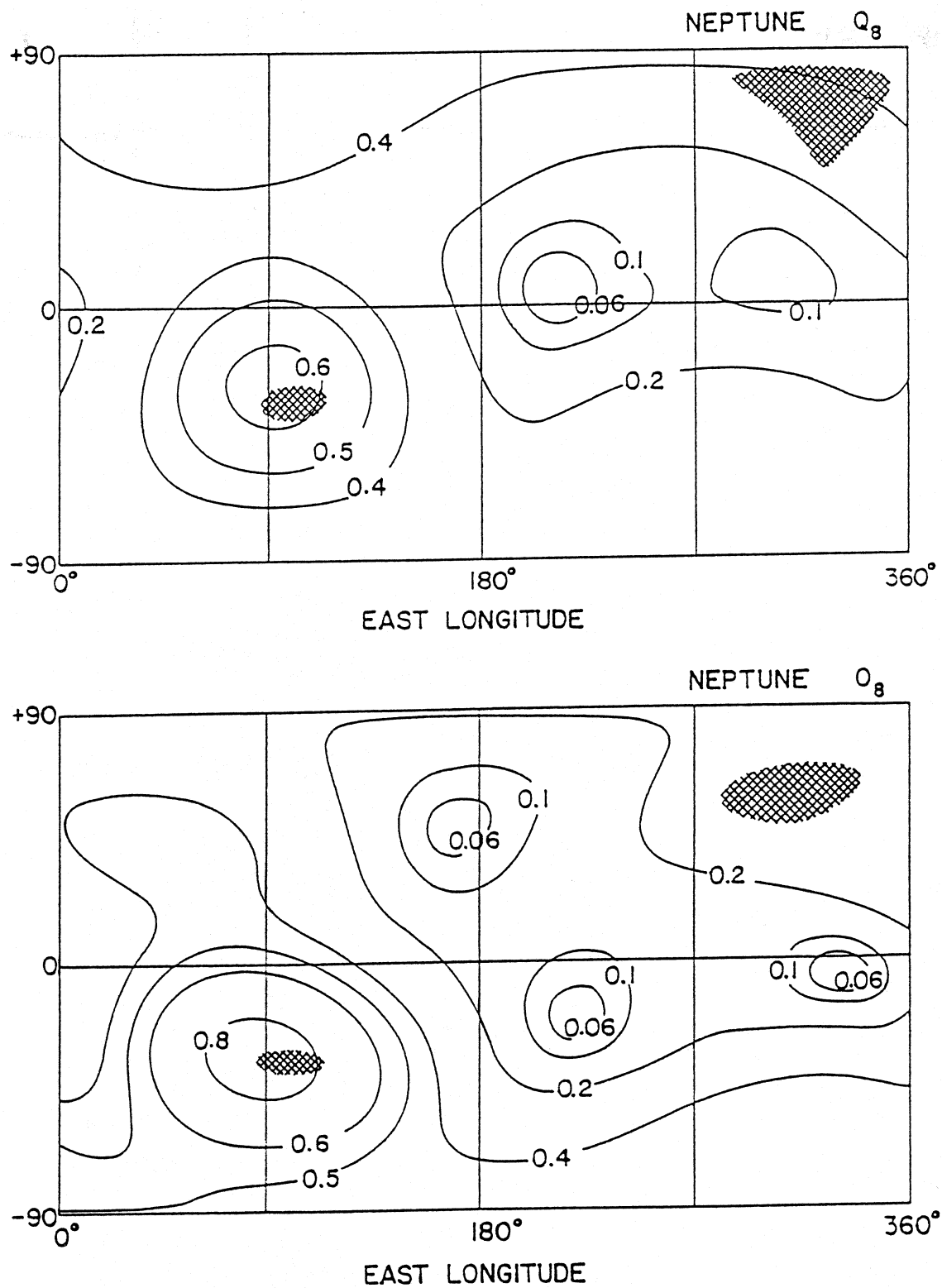


Figure 3: Isointensity plots in surface of planet of Q_8 and O_8 models of Neptune's magnetic field. Cross hatched areas represent theoretical location of auroral and polar cap zones.

because of the large inclination between the magnetic and rotation axes, the structure of the radiation belts includes many overlaps in absorption features associated with the individual moons and rings.

But the most surprising and satisfying result of the Voyager 2 encounter was the serendipitous occurrence of the pole-on magnetosphere configuration. This occurs once every rotation of the planet at this epoch in its heliocentric orbital motion [Voigt and Ness, 1990]. The timing of the Neptune encounter was determined entirely by the post-Neptune Triton encounter for which dual occultation of both solar and radio signals was desired. That the spacecraft encountered the polar cusp region of the solar wind interaction with the Neptunian magnetosphere was a fortuitous bonus, which is still talked about within the scientific community.

Since a pole-on configuration occurs, it also logically follows that the magnetic tail of Neptune should have contained a cylindrical plasma sheet. However, the spacecraft trajectory was such that after Neptune closest approach, V2 did not transit through the cylindrical plasma sheet. Nonetheless, the body of observations obtained by Voyager at Uranus and Neptune, when combined with those of Pioneer and Voyager at Jupiter and Saturn, has created a data base which magnetospheric scientists and radio astronomers shall be studying for the next decade. The purpose will be to unravel the rather complicated behavior of these naturally occurring plasma physics laboratories as our understanding improves step-by-step.

7 Comparisons

Study of the symmetry of magnetic fields of the planets has been presented by Raedler and Ness [1990]. They have shown that by appropriately choosing a special axis for each of the planets, the degree of symmetry of the magnetic fields of each of them is considerably enhanced when intercompared. Schulz and Paulikas [1990] and Schulz [1992] have shown that the magnetic fields of the planets demonstrate an equi-partition of global magnetic energy, based upon the spectrum of harmonic coefficients representing the internal fields. From this, they have deduced that the field generating magnetofluid medium region has an effective radius for Earth, Jupiter, Uranus and Neptune of 0.432, 0.756, 0.464, and 0.662. These values are tantalizingly close to plausible values developed independently on the basis of physical models of composition, rotation rate and body figure. It will be interesting to see the further development of this concept and its refinement along with the investigation of the symmetry properties.

Figure 4: (color plot, next page) Comparison of color coded isointensity plots of magnetic fields of Earth, Jupiter, Uranus and Neptune. Obvious similarities can be seen between Uranus (O3) and Neptune (O8). (Saturn is not included because its field is axially symmetric and so would appear as horizontal bands.)

8 Multiple Dipoles

In the attempt to determine implications of the external fields for the internal sources and characteristics of the dynamo process, one problem relates to the uniqueness theorem in potential theory. Some authors have proposed that a system of multiple dipoles better represents the multipole system centered at the planet. For example, Wang [1987] has assumed a 5 dipole model as representing the O4 model of the magnetic field of Jupiter developed by Acuña and Ness. The difficulty in this approach is that 3 of the subsidiary dipoles so derived possess moments which are larger than the original main dipole in the O4 model.

This emphasizes the nonuniqueness of potential theory in which even with unique vector measurements which completely specify the magnetic field external to a source region, nothing unique about the distribution of sources can be derived.

9 Major conclusions and questions raised

The size, configuration and dynamics of planetary magnetospheres are determined not only by the supersonic solar wind plasma, but also by the characteristics of the planetary global magnetic field. The internal structure of the planetary magnetospheres is controlled by the inclination of the magnetic axis relative to the rotation axis as well as the presence of embedded moons. All of the magnetized planets possess magnetic tails. At certain epochs in their heliocentric orbital motion, Uranus and Neptune are quite different from Earth, Jupiter and Saturn. The latter three planets possess the stereotype magnetic tail structure, bipolar lobes separated by a transverse plasma sheet. But Uranus and Neptune, on occasions, because of the pole-on configuration, possess cylindrical plasma sheets. This is one of the principal targets for future studies of planetary magnetospheres: The in-situ investigation of the pole-on magnetosphere configurations at Uranus and Neptune and their plasma sheet configuration and dynamics.

The moons and rings of all the giant planets interact in a very special way with their co-rotating magnetospheres. The moons and rings are both sources and sinks of gases, plasmas and energetic particles. The radiation belts of these planets are structured in a way which is determined critically by the magnetic axes inclinations and the location and characteristics of the rings and moons.

Io is uniquely coupled to the Jovian magnetosphere and ionosphere electrostatically. It is uncertain at present, and is clearly a topic for future studies, as to whether or not this interaction is the predominate force driving Jovian aurora, or whether the solar wind interaction with the Jovian magnetosphere is the primary energetic mechanism.

It is hoped that the future spacecraft missions to Mars, the USA Mars Observer in 1992 and the USSR Mars probes 1994, 1996 will finally resolve the continuing and problematic aspect of whether or not Mars possesses a global magnetic field. This new body of experimental observations on the magnetic fields of self-gravitating, rapidly rotating, condensed objects in the solar system will certainly have important ramifications for

other similar, but more exotic, objects in our universe. A comparison of magnetic fields is given in Figure 4.

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