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Planetary magnetospheres

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RESUMEN

La serie de naves espaciales Pionero, Marinero y Viajero nos ha dado a conocer una impresionante variedad de magnetosferas planetarias. Debido a su cercanía, la magnetosfera terrestre es la que mejor entendemos. El viento solar provee parte del plasma y, aún más importante, provee la energía que da lugar a una amplia variedad de fenómenos que se observan en la magnetosfera de la Tierra. En el caso terrestre, la principal fuente de plasma magnetosférico es la ionosfera. A diferencia, el plasma de la magnetosfera de Júpiter se deriva principalmente de los gases volcánicos que escapan de su satélite Io (y en segundo término de la ionosfera joviana), y la energía para la magnetosfera de Júpiter se extrae de la energía cinética de la rotación del planeta. Debido a esto, el viento solar no es una fuente importante de plasma o energía para Júpiter. La magnetosfera de Júpiter muestra complejos patrones de comportamiento. Por ejemplo, en general, los fenómenos magnetosféricos en Júpiter no son axialmente simétricos. La gran mayoría de éstos se organizan de tal manera que ocurren alrededor de una sola longitud ~160° conocida como "el sector activo". Las diferencias y semejanzas en lo que ha resultado ser todo un zoológico de magnetosferas, ponen a prueba nuestro entendimiento de los procesos magnetosféricos y nos llevan a desarrollar nuevos y más generales principios en la física magnetosférica. La magnetosfera de Júpiter, al ser la más dinámica y la que tiene menos en común con otras magnetosferas del sistema solar, es quizá la más interesante de esta variedad para realizar estudios comparativos.

PALABRAS CLAVE: magnetosferas, Júpiter, interacción con el viento solar.

ABSTRACT

The Pioneer, Mariner and Voyager spacecraft have presented us with a bewildering variety of planetary magnetospheres. The Earth's magnetosphere, because of its proximity, is the best understood. The solar wind supplies some plasma and, most important, the power to drive the wide range of phenomena observed in the Earth's magnetosphere. For Earth, the ionosphere is the primary source of magnetospheric plasma. In contrast, the plasma in Jupiter's magnetosphere is largely derived from volcanic gases that escape from its satellite Io (and secondarily from the Jovian ionosphere), and the power for Jupiter's magnetosphere is supplied by the kinetic energy of Jupiter's spin. Thus, the solar wind is not an important source of plasma or energy for Jupiter. Jupiter's magnetosphere demonstrates complex patterns of behavior. For example, Jovian magnetospheric phenomena are, in general, not axially symmetric. Nearly all are organized so that they occur within a single ~160° range of longitude known as "the active sector". Differences and similarities in what has turned out to be a virtual zoo of magnetospheres test our basic understanding of magnetospheric processes and lead us to develop new, more general principles of magnetospheric physics. Jupiter's magnetosphere, being the most dynamic and having the least in common with other solar system magnetospheres, is perhaps the most interesting of the variety now available for comparative study.

KEY WORDS: magnetospheres, Jupiter, solar wind interaction.

INTRODUCTION

Although the basic idea of a magnetosphere (defined by Gold, 1959, as the space surrounding a planet in which its magnetic field exerts a dominant influence on the motion of charged particles) is one of long standing, (e.g., Birkeland, 1896; Hoyle, 1956), it was not until direct confirmation by spacecraft that the idea was widely accepted by the scientific community. The Earth's magnetosphere is the best explored and, therefore, the best understood. It is often treated as a standard against which magnetospheres of other planets are compared and explained. Yet, magnetospheres differ from one another, often in basic ways, so that such comparisons are often awkward and sometimes misleading.

Of the nine planets, eight have been visited by spacecraft, so we can speak with assurance about whether or not they have a magnetosphere. Direct measurements have shown that six planets have magnetospheres in the sense defined by Gold, and two do not. Although Pluto probably does not have a magnetosphere because of its small size, it has not yet been visited by a spacecraft, so final judgement on the existence of a magnetosphere must be withheld.

The six magnetospheres that we have explored thus far do not fit any single pattern. They do, of course, have in common a magnetic field of internal origin that in its outer regions is distorted into a comet-like shape by the solar wind, an auroral display, and trapped radiation belt, even if weak or transient. I should mention here Venus and (apparently) Mars, which do not have measurable planetary magnetic moments (Russell and Vaisberg, 1983; Yeroshenko *et al.*, 1990), but they do have solar-wind magnetic field draped around their respective ionospheres to form an induced magnetosphere (Cloutier *et al.*, 1983). The reader is referred to the recent work of Pérez de Tejada, 1986a, 1986b and 1987 and references therein, and Pérez de Tejada *et al.*, 1985, for discussions of our understanding of these interesting objects. The balance of this review will focus on the planets that are known to have internal magnetic fields of sufficient strength to form a magnetosphere in the solar wind, namely, Mercury, Earth, Jupiter, Saturn, Uranus and Neptune.

SOLAR-WIND POWER

A common feature of all magnetospheres is the delivery of power from the solar wind into the magnetosphere to drive a variety of magnetospheric phenomena. The average solar-wind speed v (430 km/sec) is nearly independent of heliocentric distance S, but the solar-wind mass density falls roughly as $1/S^2$, so both the solar-wind ram pressure ρv^2 and the power flux (energy density times velocity) $0.5\rho v^3$ fall as $1/S^2$ with heliocentric distance. The solar wind power impinging on a magnetosphere is $\rho v^3 \pi r_m^2$ where r_m, the radius of the magnetosphere, is determined by a balance between solar-wind ram pressure and the internal pressure of the magnetosphere. With the exception of Jupiter, the pressure, within a small, adjustable factor, balances the magnetic pressure just inside the magnetosphere

$$\frac{B^2}{2\mu_0} = \frac{B_0^2}{2\mu_0 (r_m/r_p)^6} = \rho v^2 = \frac{\rho_0 v^2}{S^2} \quad (1)$$

where B_o is the surface (or cloud-top) equatorial field strength, r_p is the radius of the planet, ρ_o is the solar-wind mass density at 1 AU, and S is the heliocentric distance in AU. We solve (1) for r_m and write the solar-wind power intercepted by a magnetosphere as

$$P = \pi r_m^2 \frac{\rho_o v^3}{S^2} = \pi r_p^2 \left[\frac{B_o^2 \rho_o^2 v^7}{2\mu_o S^4}\right]^{1/3} \quad (2)$$

Jupiter's magnetosphere is larger than inferred by eq(1) by about a factor of two because it alone among planetary magnetospheres contains plasma that fills its magnetosphere to the bursting point. With the exception of Mercury and Jupiter (again), the only important variables in eq(2) are the size of the planet r_p and the heliocentric distance S; Earth, Saturn, Uranus and Neptune all have values of B_o of about 2 - 3 x 10^{-5} Tesla. The value of B_o for Mercury is considerably weaker (3 x 10^{-7} T), and for Jupiter, considerably stronger (4 x 10^{-4} T). The power intercepted by the six known planetary magnetospheres is shown in Fig. 1. The power these planets expend in magnetospheric activity is a few percent of the impinging solar-wind power. This relationship to solar-wind power is something of an accident in the case of Jupiter's magnetosphere, for, as we will see when examining the workings of its magnetosphere, it draws power from the kinetic energy of the spinning motion of Jupiter itself.

A VARIETY OF MAGNETOSPHERES

In the following brief tour, we will contrast the working of the various magnetospheres with the Earth's,

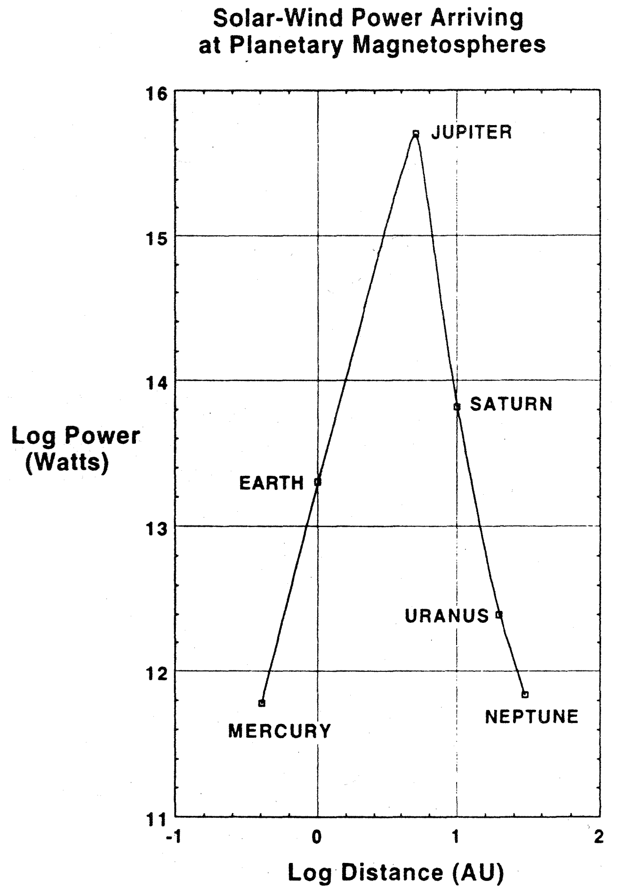

Fig. 1.

not that Earth's magnetosphere is in any way ordinary, but rather because we are so familiar with it.

Mercury. The speed of magnetospheric convection within the Earth's magnetosphere is regulated by the drag force of the conducting ionosphere, which is electrically connected to the magnetosphere through field-aligned Birkeland currents. Mercury does not have a magnetospherically significant ionosphere, and if the depth integrated conductivity of its surface is less than about 20 mhos, which is undoubtedly the case for Mercury's surface of dry rock, convection within Mercury's magnetosphere can proceed at speeds nearly that of the solar wind (Hill *et al.*, 1976). Thus, while magnetospheric convection can generate cross-tail potentials ~150 kV in the Earth's magnetosphere, cross-tail potentials ≥2500 kV are expected in Mercury's magnetosphere - and this is in spite of its tail diameter being 1/15th that of the Earth. The electric field strength in the Earth's tail is ~1 mV/m, while it is as much as 250 mV/m in Mercury's tail.That's a remarkable 1/4 Volt per meter!There is experimental evidence of such dynamic behavior as reviewed by Connerney and Ness, (1988) and Russell *et al.* (1988). Most recently, there has been a report of the detection of an auroral-like phenomenon in the tenuous sodium atmosphere of Mercury (Potter and Morgan, 1990).

Earth. In this review, the Earth's magnetosphere and its phenomenology are used as a "standard candle" against which other magnetospheres are compared. See the reviews by Fälthammar, Roederer, Gomberoff and González (this proceedings) for details and documentation.

Jupiter. The magnetosphere of Jupiter is in some ways the most interesting because it is so large, so powerful and so different from the Earth's magnetosphere. The Earth's magnetosphere, complete with its plasmasphere and Van Allen radiation belt, would fit inside the planet Jupiter - its magnetospheric tail is over 3,000 R_E = 0.15 AU across. If it were visible, as seen from Earth, it would extend four times the diameter of the full Moon. After the Sun, Jupiter's magnetosphere is the brightest radio source in the sky. Jupiter's magnetosphere utilizes about 250 times the power that is required to drive the Earth's magnetosphere. Jupiter is a powerful particle accelerator, for example, it is the source of cosmic-ray electrons with energies less than about 30 MeV that are detected at Earth. Finally, while particles for the Earth's magnetosphere come from the Earth's ionosphere, with some contribution from the solar wind, the predominant source of plasma (measured by mass) is its innermost large satellite Io. The supply from Io is so large (~10^3 kg/sec) that the magnetosphere bulges from plasma pressure on the sunward side and plasma flows antisunward down the tail, which is opposite to the direction of plasma flow in the Earth's magnetosphere. Because this review is limited in scope of coverage, I will concentrate on the effects of the injection of plasma from Io into the magnetosphere.

Power is supplied to Jupiter's magnetosphere by slowing its planetary spin. Even though as much as 10^{14} Watts are needed for its magnetosphere, Jupiter is so heavy and spins so fast (rotation period 10 hours), the slowing of the planet is negligible, even over geologic time scales. There are two ways to draw power from planetary spin. One is to extract energy from the outflowing plasma from Io (Dessler, 1980; Eviatar and Siscoe, 1980). Gas from Io is ionized near Io's orbital distance to form a torus of plasma consisting of sulfur and oxygen ions as well as ionic compounds of sulfur and oxygen. As the plasma moves away from Jupiter, the spinning magnetosphere attempts to keep the plasma corotating with the planet. The plasma, in effect, falls downhill in Jupiter's centrifugal potential.

$$P_t = \frac{dM}{dt} \int_{L_i}^{L_o} \Omega^2 r \, dr = \frac{dM}{dt} \times \frac{\Omega^2 (L_o^2 - L_i^2)}{2} R_j^2 \qquad (3)$$

where P_t is the power extracted by the outflow of torus plasma, dM/dt is the mass injection rate from Io, Ω is the angular velocity of the magnetosphere, L_i is the initial distance for the plasma (i.e., Io's distance of 6 R_J), and L_o ~20 R_J is the Hill distance at which effective enforcement of corotation ceases (Hill, 1979). The other way to extract power from planetary spin is to have the spinning polar cap act as a Faraday disc dynamo working against the solar wind, which in this case should be regarded as a load rather than a generator (Isbell *et al.*, 1984). With either mechanism, approximately 10^{14} W can be extracted from planetary spin to provide power to the magnetosphere.

The outflow of plasma down the tail creates a cross-tail electric field. Because Jupiter's magnetic moment is oriented opposite to the Earth's, the electric field is directed dawn to dusk as is Earth's. The electric field is of sufficient magnitude to cause a noticeable difference in the two ends (ansae) of the Io plasma torus. A decade ago, a persistent dawn-dusk asymmetry was found in the Io plasma torus by Sandel and Broadfoot (1982). The time-averaged brigthness distribution of the torus is fixed in local time (LT) with the maximum brightness occurring near 1900 LT and a minimum near 0700 LT. This brightness asymmetry was explained independently by Ip and Goertz (1983) and Barbosa and Kivelson (1983) in terms of a cross-tail electric field that is oriented dawn-to-dusk. This electric field causes the dusk ansa of the torus to drift closer to Jupiter and become brighter because the brightness of the torus is an exponential function of electron temperature, and electrons in the torus are heated by adiabatic compression as they move inward. It is argued that the dawn ansa is correspondingly dimmer because its electrons are cooled as they are moved outward by the cross-tail electric field. Sandel and Dessler (1988) presented experimental evidence showing that the action of the electric field on the torus is not uniform but, instead (as seen by Voyager 2 inbound) is concentrated on the receding ansa. Sandel and Dessler (1988) concluded that plasma flow down the tail is not uniformly distributed across the tail but, instead, is limited to the dusk flank, as anticipated by Vasyliunas (1983). Thus, while changes in the radial distance of the approaching ansa of the plasma torus are relatively slight, the motion of the receding ansa of the torus is striking (Fig. 2). An obvious way to explain this result is to call for an appropriate modulation of the electric field that is the cause of the asymmetry; the modulation of the electric field affecting the receding ansa is significant and the modulation affecting the approaching ansa is slight. So far, no spacecraft has entered the dusk side of Jupiter's magnetospheric tail to check on this asymmetric, time-varying flow. It is possible that this strange flow pattern may be detected by the Ulysses spacecraft, which will fly by Jupiter in February 1992. A complete survey of the dusk magnetosphere will be made by the Galileo spacecraft by the end of 1998 (if its high-gain antenna can be unfurled).

Saturn. The magnetosphere of Saturn is in some ways rather bland. The planetary magnetic field is largely a dipole oriented parallel the planet's spin axis, and the magnetosphere is not highly active. There are unremarkable northern and southern aurorae (Sandel *et al.*, 1982). However, on closer inspection, Saturn's magnetosphere has some superlative aspects. The rings of Saturn, consisting in large part of water-ice, act as both a radiation belt absorber and a radiation belt source; energetic particles diffus-

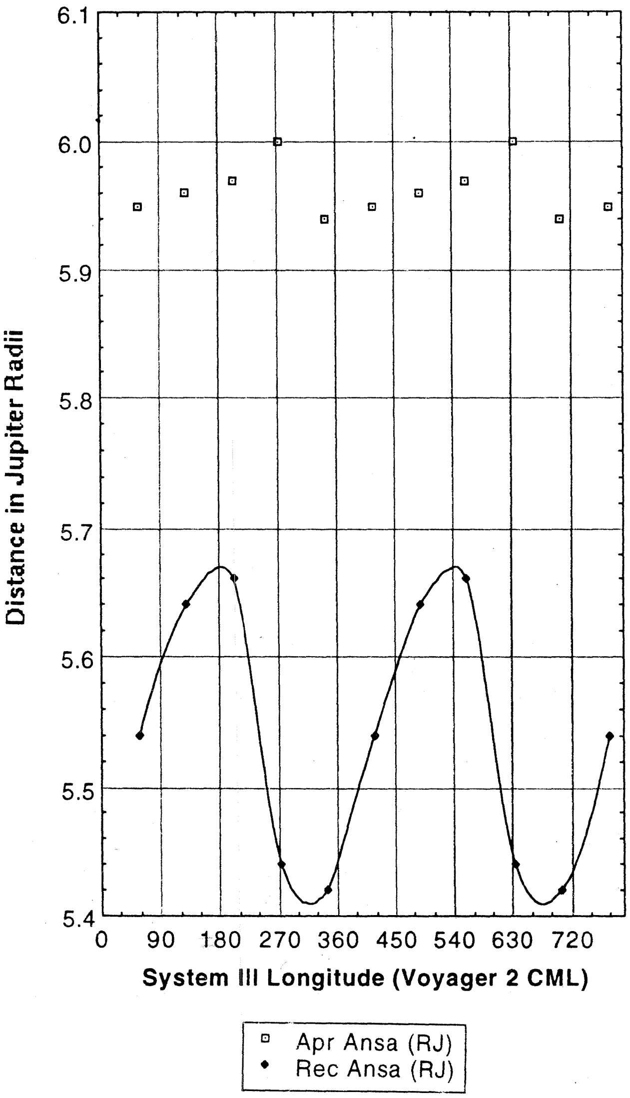

Fig. 2. Distance of Io torus ansae from dipole axis.

ing radially are absorbed when they reach the outer edge of Saturn's rings. Above the ring plane, one finds the most radiation-free region of space yet encountered. Yet, this zone is not entirely free of radiation; cosmic rays can enter relatively freely and cause nuclear disintegrations of oxygen nuclei contained in the ring ice. One of the common products of such nuclear events are energetic neutrons, some of which subsequently decay within the magnetosphere to produce durably trapped energetic protons and electrons. This process is often referred to as CRAND (Cosmic Ray Albedo Neutron Decay). It appears that Saturn provides us with a magnetosphere having an almost pure CRAND source (Schardt, 1983; Van Allen *et al.*, 1980). A puzzling aspect is that although the magnetic field is measured to be purely dipolar, it must contain some limited magnetic anomalies to account for the spin modulation of its radio emissions (Kaiser and Desch, 1982) and energetic particles (Carbary and Krimigis, 1982).

Perhaps the most mysterious aspect of Saturn is the magnetospheric connection to the spokes that form within the rings. While the magnetospheric connection with the spokes is not fully demonstrated, they have been shown to have two periods of formation that coincide with the periods of Saturn Kilometric Radiation (SKR) and Saturn Electromagnetic Disturbances (SED) (Porco and Danielson, 1984). The coincidence of the periods suggests that there is a magnetospheric connection (Porco and Danielson, 1982), but no accepted theory explaining such a connection has yet been put forth.

Uranus. Uranus was expected to be unusual because at the time of the Voyager flyby, its spin axis was pointed almost directly at the Sun. This orientation causes the magnetosphere of Uranus to be more tightly coupled to the solar wind than any other magnetosphere (Richardson *et al.*, 1988). They point out that the electric field of the solar wind, to the extent that it penetrates into the Uranian magnetosphere, is always in the direction to cause an antisunward drift and the spin of the planet, being nearly anti-parallel to the solar wind, cannot create a plasmasphere, no matter how rapid the planetary spin (Vasyliunas, 1986).

Uranus was the first of two planets found to have their magnetic moments oriented at a large angle to its spin axis (Connerney *et al.*, 1987). Before Voyager's Uranus flyby, all of the planets that had been examined up to then had their dipole oriented within 10° of their spin axis. If we were to change the Earth's magnetic configuration to appear as Uranus' it would be necessary to turn Earth so the north geographic pole was pointed nearly directly at the Sun and turn the magnetic dipole so its north pole passed through Tahiti.

Neptune. The Voyager spacecraft, in order to pass close to the satellite Triton, flew over the north pole of Neptune, passing within about 0.2 R_N of the cloud tops. Again, what was found was a complex magnetic field tilted at a large angle to the planetary spin axis (Connerney *et al.*, 1991). As can be inferred from Eq (2) and seen in Fig. 1, the solar-wind power at Neptune's magnetosphere is less than 10^{12} W. If only 1 or 2% is available for magnetospheric processes, the power level is only 10^{10}W, which is not enough to drive a magnetosphere with much vigor. An auroral display on Neptune was marginally detectable (Sandel *et al.*, 1990). One of the most intriguing aspects of Neptune's magnetosphere is its rapid change of aspect in which it is alternately oriented so the magnetic dipole points into the solar wind, giving the solar wind direct access to the polar cusp, and then, just 8 hours later, oriented in an Earth-like configuration with the solar wind impinging on the magnetic equator (Voigt and Ness, 1990).

The possibility has been raised that the magnetosphere of Neptune is driven by internal plasma flow that extracts energy from the kinetic energy of planetary spin (such as for Jupiter, eq (3)) (Broadfoot *et al.*, 1989). In the case of Neptune the plasma would come from the satellite Triton, and the gas in the torus would be largely nitrogen ions. Indeed, direct measurements show the plasma in the magnetosphere consists mainly of nitrogen ions (by mass) (Richardson and McNutt, 1990). Only ~1 kg/sec of nitrogen would be necessary to supply two plasma arcs that could power the weak level of observed magnetospheric activity (Hill and Dessler, 1990). However, the atmosphere of Triton is so cold that the means for getting even this much nitrogen out of its atmosphere and into the magnetosphere is unknown.

CONCLUSIONS

The six known magnetospheres in our solar system provide a rich variety of phenomena and mechanisms. As we learn how to generalize our understanding, we can expect to be able to extend magnetospheric physics into the farthest reaches of the universe where, for the foreseeable future, all information will be obtained by remote sensing. The *in situ* exploration of the planets by spacecraft has illustrated clearly how limited is our ability to determine the truth using only remote sensing data. Perhaps the best example is the series of papers published in *Geophysical Research Letters* in response to a challenge (Dessler, 1987) to demonstrate that in this first encounter with Neptune we had learned enough from the previous planetary encounters that we could confidently predict what Voyager would find when it got there. The results were humbling.

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