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Magnetospheres of the planets

D.B. MELROSE[*]

Department of Theoretical Physics, The Australian National University,
Canberra, Australia

The structures of the known and inferred planetary magnetospheres are compared, with emphasis on the terrestrial and Jovian magnetospheres. The formation of the Earth's and Jupiter's radiation belts is reviewed.

It is pointed out that rotational mass loss releases free energy. The inferred loss of $\approx 10^{29}$ ion s^{-1} from Jupiter implies an available internal energy source $\approx 3 \times 10^{20}$ erg s^{-1}. This is roughly equal to the rate energy is required to account for the 850K ionospheric emission. Rotational mass loss can also supply the energy required to accelerate the energetic particles emitted by Jupiter.

INTRODUCTION

A magnetosphere may be defined as a region around a magnetised condensed object where the motions of populations of charged particles are dominated by the magnetic field of the condensed object. The magnetospheres of the planets are of interest in themselves, and they are also of interest as natural laboratories for the study of various plasma processes. Examples of plasma processes which can be studied in the magnetospheres are magnetic reconnection, the acceleration and diffusion of fast particles, emission processes, and plasma instabilities. In this talk I shall review the qualitative structures of the known planetary magnetospheres and then discuss some specific problems relating to energy sources and to the acceleration of fast particles in the Jovian magnetosphere.

The structure of the terrestrial and Jovian magnetospheres are reviewed first and then the properties of the other planetary magnetospheres are reviewed briefly. Existing ideas on the formation of the Earth's radiation belts are reviewed in the following section. Finally, the role of rotation in the Jovian magnetosphere is discussed, and it is pointed out that rotational mass loss releases free energy which is available as the energy source for the particles accelerated by Jupiter; it is suggested that this energy is deposited in the ionosphere and is the internal energy source required to account for the excess (over the solar input) thermal emission from the Jovian ionosphere.

THE MAGNETOSPHERE OF THE EARTH

The terrestrial magnetosphere remains the definitive example of a magnetosphere. Recognition of its separate existence dates from the discovery of the radiation belts by Van Allen in 1958. Early interest in the magnetosphere concerned the interaction of the solar wind with the geomagnetic field. However, much of the effort in understanding the magnetosphere has been directed toward the thermal plasma: its origin, distribution, motions, plasma parameters, the spectra of waves it can support, and the interaction of these waves with particles. A description of the magnetosphere entails a description of the magnetic structure and the distributions of thermal plasma and of fast particles. Although the description here is for the Earth, many of the features apply to other planetary magnetospheres. Where "planet" is used below, the description applies to the Earth and at least one other planet.

Bow shock

In practice, the two features common to all planetary magnetospheres are a ***bow shock*** and a turbulent region downstream from it called a ***magnetosheath*** **(Fig.1).** Upstream the flow of the solar wind is super-Alfvénic (flow speed > Alfvén speed) relative to the planet, and across the bow shock the flow becomes sub-Alfvénic. The simplest possible theory for the location of the bow shock is to assume that the planetary magnetic field is dipolar, with surface field B_p ($= m_P/R_P^3$ where m_P is the magnetic moment and R_P is the radius of the planet), and that the shock occurs where the magnetic pressure equals the ram pressure P_P of the solar wind at the orbit of the planet. The stand-off distance r^* to the shock, in units of R_P, is then given by

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[*] Present address: School of Physics, University of Sydney, Sydney, N.S.W., Australia

$$r^* = \left[\frac{B_P^2}{8\pi P_p}\right]^{1/6} \tag{1}$$

The value r* is included in Table 1. The observed stand-off distance for the Earth has a typical value of r* = 11 (Fairfield 1971) and varies about this due to changes in the solar wind. The magnetospheres of Mercury and Mars are relatively much smaller (r* is $O(1)$), and that of Jupiter is much larger (r* is $O(10^2)$). Equation 1 is an over-simplification because it ignores the effects of plasma in the magnetosphere on the magnetic field near the magnetopause; these effects are substantial for Jupiter.

The inner boundary of the magnetosheath is called the *magnetopause.* Inside the magnetopause the magnetic field lines are connected to the planet. Inside the Earth's magnetopause the flow of plasma is convective rather than turbulent, and of lower density than in the magnetosheath.

The tail, the clefts and the mantle

The flow of the solar wind drags magnetic flux downstream from the planet to form a magnetospheric tail (Fig.1). The field lines in the tail are open in the sense that they have only one end tied to the planet. On the dayside of the planet there are two polar cusps or clefts (one per hemisphere) separating open and closed magnetic field lines. For the Earth, the clefts are filled with turbulent solar-wind plasma which flows in from the entry layer and can penetrate down to the ionosphere, defining the dayside auroral zones. Most of the plasma is reflected and then drawn back by the solar wind to form the plasma mantle, which is $\approx 1 R_E$ thick just inside the magnetopause along the tail.

The plasma sheet and substorms

The magnetic polarity is opposite in the northern and southern hemisphere in the tail, and there is a region of relatively dense (0.1–$1\,\mathrm{cm}^{-3}$) and hot ($\approx 1\,\mathrm{keV}$) plasma, called the plasma sheet separating the regions of opposite polarity. The plasma originates from the solar wind. The plasma sheet extends at least to the orbit of the moon at $60 R_E$. The inner edge of the plasma sheet is near the nightside cusp which separates the last closed field line and the first open field lines on the nightside. The ionosphere is accessible to the plasma in the sheet through the nightside cusp and down the field lines into the nightside auroral zone.

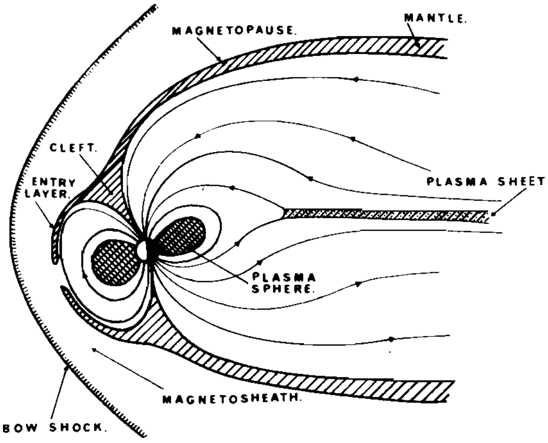

Fig.1 The important features of the terrestrial magnetosphere are illustrated on a schematic north–south cross-section.

Table 1 The properties of the planets are summarised following Siscoe (1978). The estimate of the equatorial magnetic fields for the outer planets is based on the magnetic Bode's law (Fig.6). The final column is based on Equation I.

	Solar distance (AU)	Radius R_P (10^3 km)	Spin period	Equatorial surface field	Angle (deg)	r*
Mercury	0.4	2.49	58.6d	350γ	−10	1.6
Venus	0.7	6.10	243d	.30γ(?)		1.1
Earth	1.0	0.37	24h	.31G	11.5	11
Mars	1.5	3.38	24.5h	65γ	<20	1.4
Jupiter	5.2	71.4	10h	4.1γ	10	50
Saturn	9.5	60.4	10h	1.0γ		40
Uranus	19.2	23.8	−24h	1.4γ		50
Neptune	30.0	22.2	−24h	1.3γ		50

Magnetic reconnection must occur in the neutral plane embedded in the plasma sheet. It is now widely accepted that the rate of reconnection is governed by external conditions rather than by local plasma conditions. This is contrary to the conventional assumption made in discussing reconnection in solar flares, for example in the reviews by Parker (1963) and Svestka (1976, Chap. 6). Dungey (1965) recognised the importance of the direction of the interplanetary magnetic field on reconnection (Fig.2). When the interplanetary field is northward, no reconnection occurs on the dayside, but when it is southward, reconnection occurs at a neutral point on the dayside, and magnetic flux is convected over to the tail by the solar wind. Reconnection must occur in the neutral plane at an average rate which allows the magnetic flux to be returned to the dayside.

Magnetic *substorms* are global instabilities which are triggered by an increase in the southward component of the interplanetary magnetic field (see the review by Russell & McPherron (1973)). The position and structure of the plasma sheet depend on the rate of reconnection. and when a rapid change in the external conditions occurs, the required changes can occur explosively. The most obvious consequence of

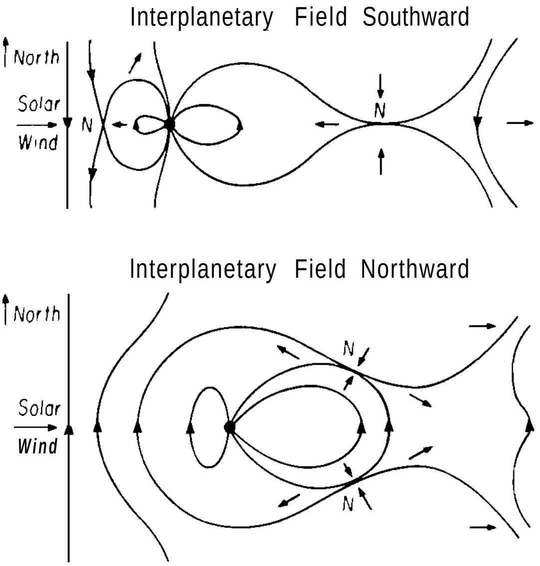

Fig.2 The neutral points in an idealised terrestrial magnetosphere field are illustrated following Dungey (1965).

this instability is a dumping of plasma from the inner region of the plasma sheet into the nightside aurora zones.

The plasmasphere

The innermost region of the magnetosphere is the plasmasphere. It extends to heights of $\approx 3R_E$ and is threaded by closed magnetic field lines which originate from low and middle magnetic latitudes. The plasma is cold ($\approx 1\,\mathrm{eV}$) and in diffusive equilibrium with the ionosphere from which it originates. The magnetic field is approximately potential and the plasma corotates with the solid Earth. The outer boundary of the plasmasphere is the plasmapause where the number density drops by a factor of ten or more.

The interconnected region between the plasmasphere and the other plasma regions defined above is called the plasma trough. The plasma in the trough originates from the solar wind and does not corotate. The radiation belts (see below) occur in the closed-field region of the plasma trough.

THE MAGNETOSPHERE OF JUPITER

The existence of a Jovian magnetosphere has been recognised since nonthermal radio emission at decimetric wavelength (DIM) was discovered by Sloanaker (1959). DIM was attributed to synchroton emission from electrons trapped in Jovian radiation belts (Drake & Hvatum 1959). Jupiter had also been recognised as a nonthermal source at decametric wavelengths (DAM) by Burke & Franklin (1955). The discovery of the effect of Io on DAM by Bigg (1964) stimulated early interest in the Jovian magnetosphere. Prior to the flyby of Jupiter by Pioneers 10 and 11 many of the properties of the Jovian magnetosphere had been predicted, and data obtained from the flybys showed that most of the qualitatively important effects had been anticipated. Perhaps the most surprising result is that Jupiter is a source of relativistic ($=10\,\mathrm{MeV}$) electrons and populates the whole solar cavity with these electrons.

Apart from its size (– 10 times the Earth on a relative scale and – 10^2 times on an absolute scale), there are two notable qualitative differences between the Jovian and terrestrial magnetospheres. First, rotation plays a much greater role in the Jovian magnetosphere. Corotation seems to occur throughout the magnetosphere (Van Allen 1976). Secondly, the only important sources of plasma are internal to Jupiter (the ionospheres of Jupiter and its satellites). Both these differences had been anticipated.

In describing the Jovian magnetosphere I follow Goertz (1976) in dividing it into three regions: the inner ($<10R_J$), intermediate ($?10R_J$, $\lesssim 30R_J$) and outer ($\gtrsim 30R_J$) magnetospheres.

The inner region

The inner region is qualitatively similar to the terrestrial magnetosphere, and its properties had been predicted quite well. The magnetic field is approximately potential. It is stronger than the terrestrial field (Table 1) and has significant quadrupolar and octupolar corrections similar to the terrestrial field. The dipole component is oriented opposite to the Earth's and at an angle of about 10° to the rotation axis. Detailed models of the magnetic field have been given by Smith *et al.* (1974a,b, 1976) and by Acuna & Ness (1976), and they are consistent with the field inferred from DAM and DIM (see Warwick (1970)).

Populations of trapped energetic particles are present. There is a general increase in particle fluxes with decreasing distance from Jupiter, but the increase is not uniform, giving a shell-like structure (Simpson & McKibben 1976). Some of these shells coincide with the orbits of the satellites, notably Io, and satellite effects analogous to those observed had been predicted (Mead & Hess 1973). The observed distribution of energetic electrons is compatible with the requirement that they produce DIM through their synchroton emission (Coroniti 1975). In particular the pitch-angle distribution of the electrons, and of energetic ions, strongly favours large values of sin α (a "pancake" distribution), as inferred from DIM (e.g., Roberts 1965). Inward radial diffusion is an important ingredient in the formation of both the Jovian

Table 2 The important satellites of the outer planets are listed, and the radii of their orbits and the radii of the satellites are given. The final column is the maximum electric potential across the satellite due to its relative motion through a corotating magnetosphere (after Mendis & Axford (1974) and Siscoe (1978)).

	Distance in R_P	Radius (10^3 km)	Rotational electric potential (kV)
Jupiter			
Io	6.0	1.8	408
Europa	9.6	1.6	155
Ganymede	16	2.6	100
Callisto	27	2.5	35
Saturn			
Titan	20	2.5	13
Neptune			
Tritan	14.3	2.0	8

and terrestrial radiation belts (see The formation of the Earth's radiation belts, below). However, inward radial diffusion from the solar wind cannot account for the Jovian radiation belts quantitatively. I shall return to this point in Rotation effects and acceleration in the Jovian magnetosphere.

The Jovian satellites (Table 2) are sinks for energetic particles which as they diffuse inwards collide with the satellites (Mead & Hess 1973). Io is also a source of energetic particles, notably 100 keV electrons (Hubbard et *al.* 1974, Fillius & McIlwain 1974a,b). Such energetic electrons are thought to produce DAM, although the details of the emission process remain uncertain (see, for example, Smith (1976)).

Io is also a source of thermal plasma, specifically sodium and hydrogen (Brown 1974, Judge & Carlson 1974, Smyth & McElroy 1977). The plasma in the Jovian magnetosphere probably originates either from photo-electrons emitted from the Jovian ionosphere (Ioannidis & Brice 1971, Swartz et *al.* 1975) or from Io.

The intermediate region

In the intermediate region the magnetic field deviates significantly from a potential field. The field lines become more radial and the outer parts lag behind the feet. These effects become more pronounced in the outer region.

The distinguishing feature of this region (Van Allen 1976) is that the trapped particles, particularly the lowest-energy electrons observable ($\approx$40 keV), have an equatorial pitch-angle distribution strongly favouring small sin α (a "dumbbell" distribution). The fluxes of energetic particles are not stationary, as in the inner magnetosphere, but are chaotic and time-dependent.

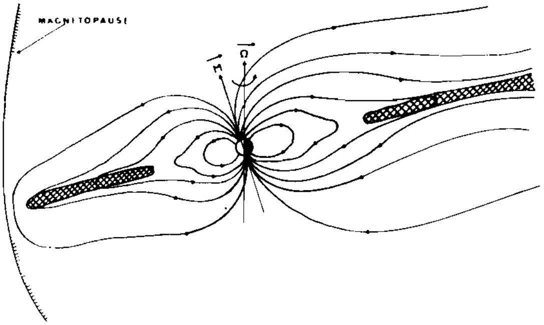

Fig.3 A north–south cross-section of the Jovian magnetodisc is illustrated.

The outer region

The outer region extends from $30R_J$ to the magnetopause. It does not include the tail, if there is one. Neither Pioneer 10 nor Pioneer 11 traversed the tail region.

The dominant feature of the outer region is rotation. The magnetic field lines are drawn out into a nearly radial direction and close across a thin magnetodisc (Fig.3). Smith et *al.* (1974a,b) and Hill et *al.* (1974) argued that the magnetodisc should be in the rotational equatorial plane, which is the position of minimum centrifugal potential energy. However, Goertz (1976b, 1978) pointed out that the grad$B$ force should not be neglected, and that it drives the plasma towards the plane of minimum B, i.e., the magnetic equatorial plane. Goertz also pointed out that the grad$B$ force dominates when the temperature exceeds the rotational energy, and that this condition is satisfied in the magnetodisc. Goertz (1978) has developed a model for the magnetodisc based partly on observational data and on an analytic model due to Goldstein (1976). The relevant parameters of the model are its thickness $\approx 2R_J$, temperature $= 10$ keV, number density $= 1\,\mathrm{cm}^{-3}$ at $30R_J$ to $10^{-2}\,\mathrm{cm}^{-3}$ at $80R_J$, and current $\approx$ 10-'Am-'.

The magnetic field in the magnetodisc is turbulent. A strong correlation, on a timescale of minutes, exists between the magnetic fluctuations and fluxes of $\approx$ MeV protons (Walker et *al.* 1978). The correlation is such that the net pressure remains roughly constant, i.e., larger fluxes correlate with weaker fields.

The other main feature of the outer region is the flux of escaping energetic particles. These show a 10 h periodicity which is interpreted as an emptying and refilling of the outer magnetosphere over one Jovian rotational period (Simpson & McKibben 1976). The escaping particles were detected prior to encounter with Jupiter, and may well fill the whole solar cavity (Teegarden et *al.* 1974). The origin and acceleration of these particles is discussed below (Rotational effects and acceleration of Jovian magnetosphere).

THE OTHER MAGNETOSPHERES

Mercury

Mercury has no significant atmosphere or ionosphere, and was not expected to have a significant intrinsic magnetic moment because of its slow rotation. Consequently it came as a surprise when the two encounters of Mariner 10 with Mercury showed that there is a well formed magnetosphere (Fig.4). The estimated surface magnetic field is 220γ ($1\gamma = 10^{-5}$G $= 10^{-9}$T) and the magnetopause is at $r^* = 1.6$, **i.e.,** about $0.6R_P$ above the surface of the planet (Ness *et al.* **1974a).** A plasma sheet was observed in the tail (Ogilvie *et al.* 1974). Variations in particle fluxes on a timescale ≈ 1 min fit scaled down versions of terrestrial substorms (Siscoe *et al.* 1975). Finally. unexpectedly high and transient fluxes of energetic (several hundred **keV)** electrons and protons were observed **(Simpson** *et al.* 1974).

The magnetospheres of Jupiter and Mercury can be regarded as opposite limiting cases when compared with the terrestrial magnetosphere. They are. respectively, giant and miniature, rapidly rotating and effectively non-rotating, and populated entirely from internal sources and entirely from the solar wind.

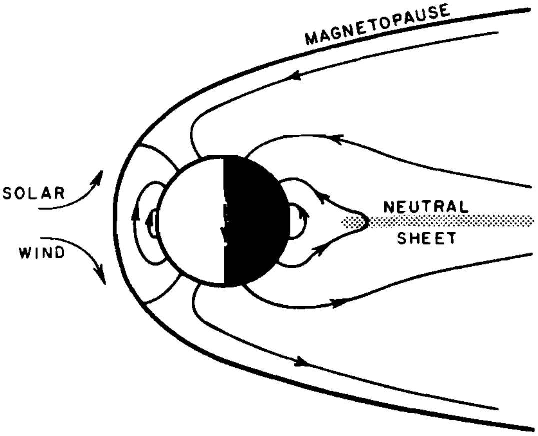

Fig.4 The magnetosphere of Mercury as illustrated by Roederer (1976).

Mars

From the encounters of Mars 2 and Mars 3 with the planet Mars it is known that the planet has a bowshock and a **magnetopause.** The data have been interpreted as implying a surface magnetic field of 60γ which would be sufficient to give $r^* = 1.4$, **i.e.,** a stand-off distance of the solar wind at a height of $0.4R_P$ (Dolginov *et al.* 1973, Gringauz *et al.* 1973). However, the data are also compatible with an induced magnetosphere (Cloutier & Daniell **1973), i.e.,** magnetic deflection of the solar wind due to currents induced in the Martian ionosphere. Rassbach *et al.* (1974) suggested that at times when it is intense the solar wind may penetrate to the Martian atmosphere **(Fig.5).**

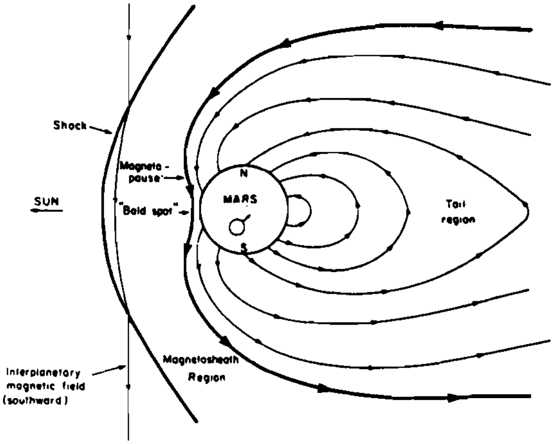

Fig.5 A possible configuration of the magnetosphere of Mars as envisaged by Rassbach et ***al.*** **(1974) and Hill & Michel (1975).**

One obvious difference between the magnetospheres of Mars and Mercury is that particle acceleration occurs only in the latter. Hill *et al.* (1978) have argued that this is because convection, which produces electric fields, cannot occur in the Martian magnetosphere because of the highly conducting ionosphere.

Venus

There is some controversy over the existence of an intrinsic magnetic moment for Venus (Bridge *et al.* 1974, Ness *et al.* **1974b,** Russell 1976, Ness 1976). Venus seems to have no **dayside** magnetosphere (Russell **1977a,b,** Ness **1976),** and whether or not the nightside region is called a magnetosphere is a matter of definition. A "wake" is a more appropriate name for the nightside region (Lepping & Behannon 1978).

Saturn, Uranus, and Neptune

It is **widely** believed **that** the outer planets have magnetospheres probably similar to the Jovian magnetosphere. The only direct evidence of the existence of a magnetosphere is for Saturn which is a source of radio emission at ≈ 1 MHz (Brown 1975); Uranus is perhaps also a radio source (Brown 1976). There is also an indication that Titan may be inside the magnetosphere of Saturn **(e.g.,** Siscoe 1978). Models for the magnetospheres are based on estimating the magnetic field through a postulated "magnetic Bode's Law" **(Fig.6,** Kennel 1973).

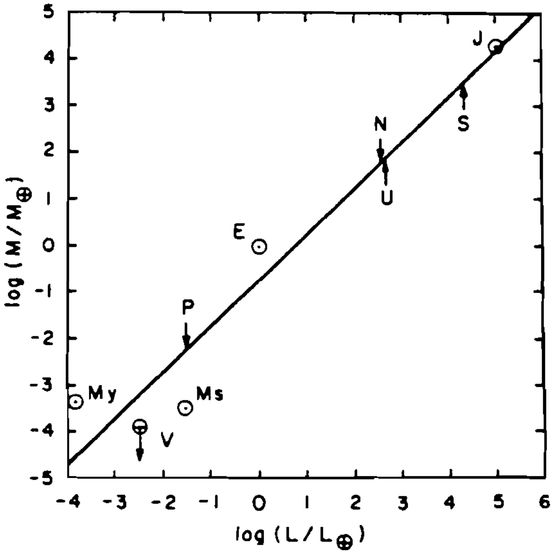

Fig.6 The "magnetic Bode's Law" is illustrated by a log-log plot of the planetary magnetic dipole moment versus planetary angular momentum in units of the terrestrial values. The positions of the planets for which data are available are illustrated by circles, and the arrows indicate the estimated magnetic moments for the other planets (Kennel 1973, Hill & Michel 1975).

The case of Uranus warrants comment. The spin axis of Uranus is nearly orthogonal to the orbital axis. Granted that the magnetic axis is expected to be roughly aligned with the rotation axis, over an orbital period of Uranus the angle between the magnetic axis and the flow velocity of the solar wind should cover the complete range. A pole-on configuration, which should occur regularly, would be an interesting variant of known magnetospheric structures (Siscoe 1971).

THE FORMATION OF THE EARTH'S RADIATION BELTS

As a preliminary to discussion of acceleration of fast particles in the Jovian magnetosphere, it is appropriate to summarise existing ideas on the formation of the Earth's radiation belts. The radiation belts consist of energetic particles trapped in closed magnetic field lines outside the plasmasphere. The formation of the radiation belts is understood qualitatively and semi-quantitatively: the particles originate from the solar wind, diffuse inwards gaining energy, and then are lost by precipitation into the atmosphere.

In more detail, the formation of radiation belts may be understood as follows. Once a particle enters the closed-field region from the tail its motion, in the absence of perturbations, may be described in terms of three periodicities: its spiralling motion about an individual field line, its bouncing motion along a field line, and its drift motion around the Earth. Corresponding to these three quasi-periodic motions are three adiabatic invariants denoted *M*, *J*, and ϕ respectively. For a particle with momentum p and an equatorial pitch angle a on an approximately dipolar field line which crosses the magnetic equator at a distance L, in units of R_P, one has

$$M \propto (p^2 \sin^2\alpha) L^3,$$
$$J \propto (p|\cos\alpha|) L,$$
$$\phi \propto L^{-1}. \qquad (2)$$

Fluctuations on a timescale comparable with any one of these periodicities cause the corresponding adiabatic invariant to change. If the distribution of particles is described as a function of *M*, *J*, and ϕ, then such fluctuations cause diffusion in *M*, *J*, or ϕ. Convective motions cause fluctuations which violate ϕ, and wave-particle resonances involving whistlers and electrons or ion-cyclotron waves and ions cause pitch-angle scattering which changes both *M* and J. (Bounce-resonance interactions can also occur but are not thought to be as important as the other two in the present context.) Diffusion in ϕ implies diffusion in L, **i.e.,** inward or outward diffusion. An inspection of the diffusion equation shows that the equilibrium condition has the number density of particles increasing more steeply with decreasing L than is the case for particles in the magnetosphere. Hence diffusion in L drives particles inwards. If *M* and J are conserved then, for a decrease in L, Equation 2 implies an increase in p and an increase in sin ***a***. Hence the energy of the particles increases as they diffuse inwards.

The final stage in the formation of the radiation belts is the loss of particles in the inner regions. This occurs through pitch-angle scattering. For electrons (the case of ions is similar) the pitch-angle distribution is an increasing function of sin ***a***, due primarily to presence of a loss cone, and such a distribution is unstable to the generation of whistlers. The growth rate for whistlers is proportional to the number density of energetic electrons and to the magnetic field strength, and hence increases rapidly with decreasing L. The main loss mechanism for whistlers is propagation out of the region where they are growing (Kennel & Petschek 1966). Effective growth occurs at the L–value where the growth rate exceeds the loss rate. Once this threshold is exceeded, the whistlers grow and then scatter the electrons into the loss cone thereby reducing the number of electrons and the effective growth rate. Thus the number density of electrons is maintained at the threshold value for effective growth of whistlers (Kennel & Petschek 1966).

The foregoing theory accounts for the features of the radiation belts semi-quantitatively, and although our detailed understanding of the microscopic processes involved may change, the overall picture is unlikely to change significantly.

ROTATIONAL EFFECTS AND ACCELERATION IN THE JOVIAN MAGNETOSPHERE

The effect of rotation in the Jovian magnetosphere is of particular interest to me, it having been the topic addressed in my first paper on astrophysics (Melrose 1967). Here I would like to present an old idea of mine (unpublished work, 1968) which may be relevant to the problem of how **Jupiter** accelerates the energetic particles of which it is such a copious source, and to why its ionosphere radiates more energy than it absorbs in solar radiation.

Rotational effects

First let me summarise the important points of my earlier investigation of rotational effects (Melrose 1967).

(1) The combined effects of gravity and rotation imply that the potential energy along a field line which extends beyond $2.2R_J$ is double humped (Fig.7). For field lines which extend far enough ($4.3R_J$) the potential energy near the **equatorial** plane is less than the value at the surface of the planet.

(2) Plasma which escapes from the magnetosphere is counter streaming (a dumbbell pitch-angle **distribution)** in the equatorial plane. Such distributions are unstable to the generation of waves which scatter the particles and cause them to diffuse in pitch-angle. As a **consequence plasma** becomes trapped **and** cannot return to the ionosphere.

(3) As the density builds up the distribution becomes unstable to interchange instabilities which transfer matter outwards. Eventually the magnetic stresses are incapable of **containing** the plasma which escapes from Jupiter's environment.

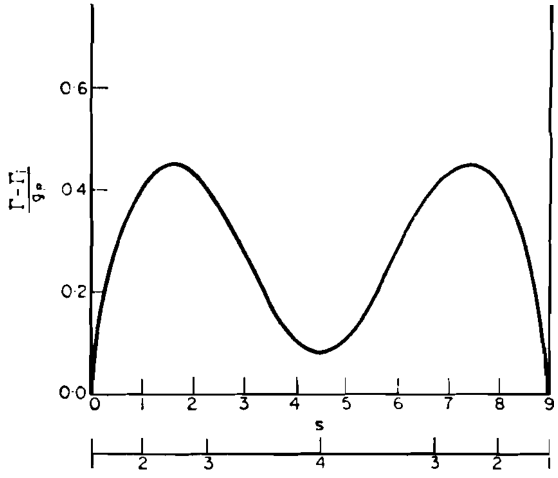

Fig.7 The potential ϕ along a magnetic field line is illustrated following Melrose (1967). The central minimum falls below zero for lines originating at magnetic latitudes greater than 61° (L = **4.3**).

These and related ideas have been developed and discussed by many other authors, **e.g. Gledhill** (1967). Carr & Gulkis **(1969), Mendis** & **Axford (1974),** Michel & Sturrock (1974) and Hill (1976).

Rotation as an energy source

Gold (1976) argued that rotation is the internal source of energy in the Jovian magnetosphere, but he did not discuss this point quantitatively. The idea which I developed in 1968 is based on the following simple result: if a rotating magnetosphere gains or loses corotating plasma at a distance R, then free energy is released in the magnetosphere at a rate

$$\dot{E} = \tfrac{1}{2}\,\dot{m}\,R^2\Omega^2 \qquad (3)$$

where $\dot{m}$ is the rate mass is gained or lost. (The derivation of Equation 3 is elementary and will be given elsewhere.) I envisaged plasma escaping from the ionosphere and then being thrown off the corotating magnetosphere at about $50R_J$. However, because I assumed a cool ionosphere **(10^3K ≈ 0.1eV)** an insignificant amount of plasma would escape across the potential barrier in **Fig.7** which has a height of 6–13eV.

The problem of an adequate source of plasma has since been partly overcome by appealing either to photo-electrons from the ionosphere (Ioannidis & Brice 1971, Swartz *et* al. 1975) or to plasma from **Io** (Brown 1974, Judge & Carlson 1974, Hill & Michel 1976, Smyth & **McElroy** 1977). Each source has been estimated as giving perhaps 10^{28} **ions** s^{-1} to the magnetosphere. Goertz (1978) has argued that the observed magnetic structure of the outer magnetosphere requires $= 10^{29}$ **ion** s^{-1} escaping from Jupiter. Assuming these ions escape with an orbital velocity corresponding to that at $50R_J$, the energy deposited in the magnetosphere is E $\approx 3 \times 10^{20}$ **erg** s^{-1}. The power going into fast particles is $\approx 10^{18}$ **erg** s^{-1} (Goertz 1978) and is only a small fraction of this.

The estimated total power available (3×10^{20} **erg** s^{-1}) is remarkably close to that required to account for the excess (over the solar input) power radiated from the Jovian topside ionosphere (Fjeldbo *et al.* 1976). **Hunten** & Dessler (1977) estimated that the high temperature observed requires an input of **0.25**–0.5 **erg** $cm^{-2}s^{-1}$ compared with a global-mean input from solar ionising radiation of **0.013 erg** $cm^{-2}s^{-1}$. The required power input, integrated over Jupiter is 1.5–3 $\times 10^{20}$ erg s^{-1}.

There are several further arguments for an internal source of plasma and of energy in the Jovian magnetosphere. More specifically, the arguments are that the fast particles in the Jovian magnetosphere originate internally and not, like the Earth's radiation belts, from the solar wind. The first argument is the absence of a correlation between DIM and the solar cycle (Komesaroff & McCulloch 1976, Klein 1976); if either the electrons or the energy were to come from the solar wind one would expect DIM to vary in some way with the solar cycle. The second argument is the inadequacy of the increase in energy through inward diffusion; to account for the synchroton-emitting electrons by inward diffusion conserving the first adiabatic invariant would require injection from the solar wind of electrons with energy $\sim$ 10 times the energy which such electrons are known to have (Coroniti 1975). One concludes that the energy supplied to the electrons and partly radiated in DIM is of Jovian origin.

Rotationally driven turbulence

The rotational energy released through throwing off plasma should be in the form of turbulent motions of various kinds in the outer magnetosphere. The reason is that the stresses are transferred to the outer magnetosphere by the magnetic field, and the magnetic field must be the vehicle which transfers most of the energy released back to the ionosphere. Only a small fraction of the energy available needs to be transferred to energetic particles to account for the escaping flux of fast particles and for the trapped synchrotron-emitting electrons.

Radial diffusion occurs much faster in the Jovian than in terrestrial magnetosphere, and this requires a source of turbulent motions internal to Jupiter: Brice & McDonough (1973) suggested ionospheric winds driven by winds in the neutral atmosphere, and Coroniti (1974) suggested solar-wind coupling to the polar cap. Rotation seems a plausible source for the required turbulent motions. Clearly it is adequate quantitatively, but a detailed model for throwing off plasma is needed before one can identify the details of the resulting turbulent motions.

Acceleration of fast particles

Acceleration will occur whenever a quasi-periodic energy-changing mechanism and a randomising process operate together. The randomising process then causes the changes in the distribution of particles to lag behind the quasi-periodic mechanism, and the driving force is damped. Specific mechanisms have been suggested for the Jovian magnetosphere by Sentman *et al.* (1975) and by Carbary *et al.* (1976). My interpretation of the general idea is as follows. In phase space (with the adiabatic invariants M, J, and ϕ as coordinates) the quasi-periodic process is in radial transport and consists of at least two steps: diffusion in ϕ, corresponding to inward radial diffusion, followed by diffusion in J due to a mechanism proposed by Nishida (1976). There is a weakness in this idea in that diffusive processes drive particles down a gradient in phase space, and hence cannot lead to a quasi-periodic motion in two dimensions. However, once a third dimension (the energy dimension effectively) is included, diffusion can drive particles down a spiral in phase space. A quasi-periodic variation in sin α and L then couples to a systemic increase in energy.

These ideas need to be developed further. Nevertheless, it does seem that free energy is available to drive turbulent motions and that a specific acceleration process is available to convert part of the turbulent energy into energetic particles.

QUESTIONS

Lecturer: D.B. MELROSE
Question asked by: I. LERCHE

Question: Mercury is so small that any intrinsic magnetic field would most likely have diffused away over the lifetime of the solar system, yet Mercury is observed to have a relatively strong ($\sim 350\gamma$) field. Would you care to explain how the field is maintained?

Response: As I said, the discovery of an intrinsic Hermean magnetic field was a surprise, and I do not know how one can account for it.

Lecturer: D.B. MELROSE
Question asked by: B. BUTI

Question: How about the interaction of high energy electrons, from the Jovian magnetosphere, with the interplanetary gases? Any beam-plasma instability?

Response: The energetic particles have been observed only outside the Jovian magnetosphere where they are diffusing through the solar wind. The details of how they escape are unknown, and there is no observational data relating to any streaming or beam-plasma instability associated with them.

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