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Space Plasma Physics
Part 1: Basic Processes in the Solar System

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1 INTRODUCTION

Space Plasma Physics may be defined as the study of the physics of plasmas in space supported by direct, in-situ measurement. It is concerned primarily with the processes involved in the flow of matter and energy through the plasmas of the solar system. It is closely related to magnetospheric, ionospheric and cosmic-ray physics, solar physics, planetary physics, and astrophysics as well as some areas of laboratory plasma physics. Since different particle species, and even particles of different energy within a single species, behave very differently in the plasmas of the solar system, they cannot investigated using the amorphous-fluid approach of magnetohydrodynamics MHD. Consequently, magnetic fields will here be considered to have strength and direction only. The concept of moving field lines (useful as it may be where it can be justified) will be avoided.

The subject of space plasma physics, rich as it is with detailed, precision measurements, is still very much in its infancy as a sub discipline of plasma physics. This is partly because wave-particle interactions, although of acknowledged importance, are not yet fully appreciated for their key roles in promoting energy and particle transport in the predominantly collisionless plasmas of space. Much reliance is, in some quarters, placed instead on simple circuit theory, wholly appropriate to the analysis of systems with the mechanical constraints imposed by rigid conductors and electrodes, but of questionable validity in space plasmas.

Our approach will be be to review the basic processes and then to make a brief tour of the solar system to see them in action.

2 PHYSICS OF A MAGNETIZED PLANET

2.1 Charged-Particle Motion in a Magnetic field

We begin by considering the motion of a charged particle in the vicinity of a magnetized planet. We assume at first that the planet has no atmosphere and that its magnetic field is that of a dipole. Particles approaching the planet from great distances are deflected by the magnetic field $B \sim Mr^{-3}$, where M is the dipole moment and r is the radial distance from the centre of the dipole. Penetration as far as the planet's surface is possible readily from any direction only if the particle's ability to resist bending of its trajectory, ie momentum per unit charge, or **magnetic rigidity**, given (relativistically) by:

$$P = \frac{1}{Ze}\sqrt{E^2 + 2EE_0}$$

is $\gg \int \mathbf{B} \times d\mathbf{l}$, where dl is an element of the trajectory, Ze is the particle's charge, E its kinetic energy in eV, E_0 its rest energy in eV, and P the magnetic rigidity in Volts.

The Gyro-radius, r_L, is then given by:

$$r_L = 3.33\ P\ B^{-1}$$

where r_L is in metres, and B in nanoTeslas.

A proton approaching the Earth near the equatorial plane, where B is approximately perpendicular to the velocity v, requires $E \gg 10^{11}$eV to be immune from significant deflexion, and $E \sim 10^{10}$ eV to penetrate, with deflection, as far as the Earth's atmosphere. In the polar regions, penetration is easier, since particles can approach more nearly parallel to B. A planet's magnetic field thus serves as a energy or velocity filter to cosmic radiation (see Figure 1). Note that the constancy of phase-space (or velocity-space) density along a trajectory in such a dynamical system (**Liouville's theorem**) ensures that, since the process is also conservative in the planetary frame, particle densities and intensities remain unchanged. This means that trajectories are either **allowed** or not: there is no "funnelling" in the polar regions, and no "partial admission" anywhere else. Fine-scale intermixing of allowed and forbidden trajectories does, though, give rise to regions over which the average intensity is at an intermediate level.

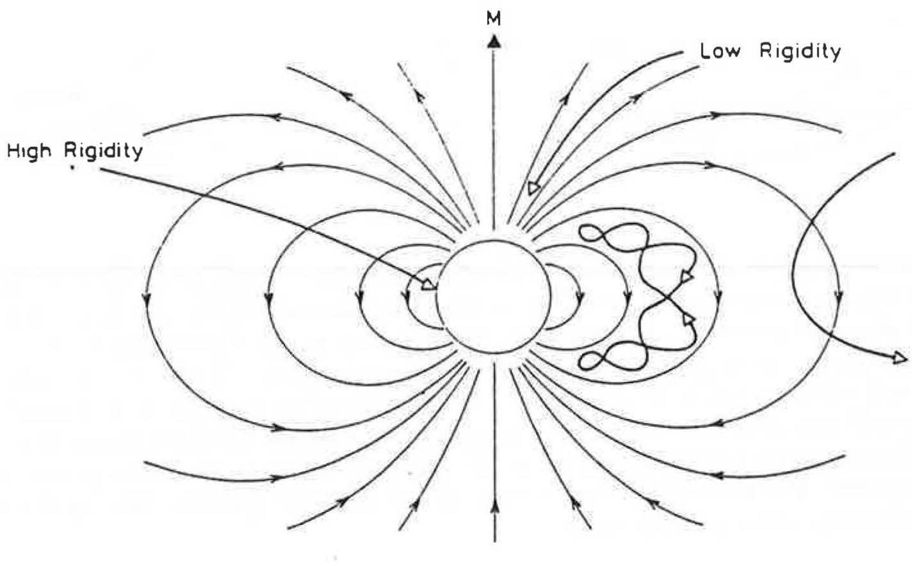

Figure 1. Model planet with dipole magnetic moment M, showing schematically particles of high magnetic rigidity gaining unrestricted access, and particles of low rigidity being repelled near the magnetic equator, gaining access in the polar regions, and executing trapped-particle motion.

By the same token that particles from outside can find it difficult to approach a magnetized planet, particles released from the planet, via for example photo emission, secondary emission, radio-active decay, or sputtering, finding themselves immersed in the planetary magnetic field, may be unable to escape. Such particles can become **trapped** in the magnetic field (see Figure 1). Under certain conditions, most readily fulfilled by lower-energy particles, **stable trapping** is possible. Stably trapped particles undergo simultaneously three types of motion (see Figure 2), each of which is characterised by an **adiabatic invariant**. There are three types of motion. The first is gyration perpendicular to B which.

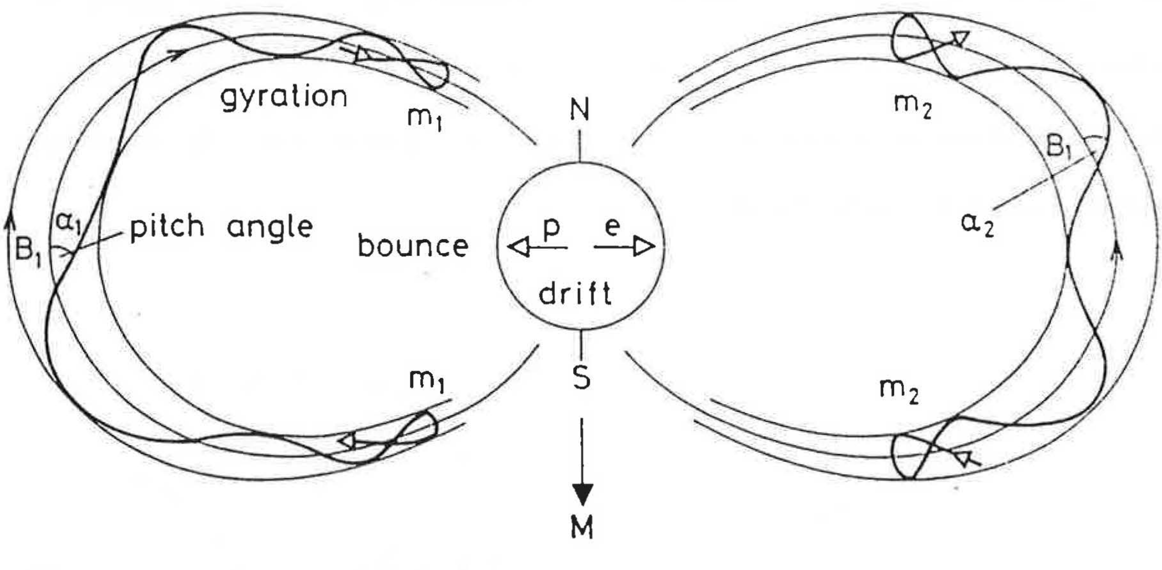

Figure 2. Illustration of the three basic modes of Motion — gyration, bounce and drift — of magnetically trapped particles. motion is shown for a planet which, like the Earth, has a southward-directed magnetic moment. For electrons, the sense of gyration is clockwise when seen looking downwards on the north geographic pole, and drift is eastwards. These are, of course, reversed for protons and other positively charged particles. Particles of pitch angle α_1 at a location where the magnetic field strength is B_1, will mirror at points m_1 lying on a surface where $B = B_1/\sin^2\alpha$ For particles having larger pitch angle, eg α_2, at the same field strength, the mirror points, m_2 are further from the planet. The locus of resultant motion of each particle's **guiding centre** of gyration defines an approximately torroidal **drift shell**.

as long as temporal changes in B are slow relative to the gyro-period of the particle and spatial changes occur gradually over many gyro-radii, preserves the magnetic moment, or

first adiabatic invariant:

$$\mu = \frac{E_\perp}{|B|}$$

where $E_\perp$ is the kinetic energy associated with gyro-motion, ie $\frac{1}{2}m(v \sin\alpha)^2$, where m is the mass, v the (magnitude of) velocity, and α the angle between v and B, known as the **pitch angle**. Note that, if there is no acceleration (ie no change in magnitude of v), the constancy of μ ensures that

$$\frac{\sin^2\alpha}{B} = constant$$

. The effect of this on a particle moving towards a region of enhanced magnetic field is to increase the pitch angle to, and beyond 90^0, thus reversing the motion parallel to B at a mirror point. The increase of pitch angle, representing an exchange of energy between parallel and perpendicular motion is equivalent to the repulsion of a bar magnet by a magnetic-field gradient. The situation is analogous to the motion of a variable length pendulum which preserves the ratio of the energy of oscillatory motion to the (variable) frequency.

The second mode of motion is that of bouncing or reflexion between **mirror points**. Provided that field changes are slow compared to the bounce period, the line integral of the parallel-to-B component of momentum, the **second adiabatic invariant**, is conserved. During this bounce motion, all particles repeatedly cross and re-cross the magnetic equator. The third type of motion is a drifting in longitude; which, again, if no sudden changes in magnitude or direction are encountered, conserves the magnetic flux through the drift shell. This is the **third adiabatic invariant**. Positive ions and electrons drift in opposite directions, setting up a diamagnetic **ring current**. This ring current has the effect of reducing the magnetic field inside the drift shell, and consequently, increasing it outside, thus distorting the intrinsic dipole nature of the field. The ratio of plasma pressure to magnetic pressure, β, may rise to values significantly greater than of unity. At this stage, the charged particles begin to control the magnetic field configuration rather than be subject to it. A point is reached when the magnetic field is completely governed by particle flow.

2.2 VELOCITY DISTRIBUTIONS

The most physically meaningful way of recording plasma particle populations is in terms of their **velocity space density** $f(v)$, where $f(v)$ = number per unit volume per unit element of velocity space, ie

$$f(v) = \frac{number}{dxdydzdv_x dv_y dv_z} \tag{1}$$

This quantity, according to Liouville's theorem, is conserved in a conservative, Hamiltonian system. Note, though, that it is not conserved in a dissipative interaction, such as one involving the equivalent of positive or negative friction. As a step in the standard proof of Liouville's theorem it is shown that

$$df/dt + f div_c v + f div_v a + 0$$

where a is the acceleration, div_c is the divergence in configuration space, and div_v is the divergence in velocity space. In a Hamiltonian system, each term of the divergencies cancels its opposite number (in fact, in most common systems, both divergencies are independently zero also), leading to Liouville's theorem:

$$df/dt = 0$$

Velocity-dependent acceleration, due, for example, to resonance or viscosity violates the above assumptions, and introduces changes in velocity-space density. The tendency of all particles to reach a common terminal velocity in falling through a viscous medium is a familiar case in point.

The usual constancy of velocity-space density, or the closely related **phase-space density** in which the velocity increments of equation (1) are replaced by momentum elements, serves as a useful tracer in transport and acceleration phenomena. Velocity space density, in general a function of speed and direction, may be quoted as a function of velocity or of kinetic energy in a specified direction. Where symmetry allows, eg when a distribution is gyrotropic, the full velocity-space distribution may be given in terms of contours of velocity-space density in $v_{\|B}$, $v_{\perp B}$ space.

It is important to note that measurements obtained from particle detectors are frequently expressed in terms of **intensity** or **directional flux** $j(E)$, where $j(E)$ is number per unit energy per unit area per unit time per unit solid angle. In the non-relativistic approximation

$$j(E) \propto Ef(E)$$

The function $j(E)$ is known as the **energy spectrum**. Note that a spectrum with a positive slope does not necessarily imply that there is also a positive slope in $f(E)$, and consequently in$f(v)$. Note also that measurements are sometimes given in terms of the count rate $c(E)$ of an electrostatic analyser, where

$$c(E) \propto E^2 f(E)$$

Even sharp peaks in $c(E)$ may not represent peaks or positive slopes in $f(E)$ or $f(v)$. It is vital, therefore, when examining, particle data to ascertain exactly which mode of presentation is being used.

2.3 Lines of force

Recall that a line of force — a concept much used in space plasma physics in representing magnetic fields — is a curve whose tangent gives the direction of the field at any point, and whose density is a measure of the field strength. In a mathematical sense a line of force clearly has continuity. It may be considered to be continuous in a physical sense, too, under circumstances where the field is suitably stable and where it effectively guides particle motion, eg in the inner region of the Earth's radiation belt. The concept needs to be considered very carefully, though, in situations where the field is variable or where, for any reason, particles of different species or different energy within a single species follow significantly different paths. Continuity between inner and outer parts of a planetary magnetosphere may for such reasons be a somewhat questionable concept. In the present context we suggest that lines of force are considered to represent local conditions only.

Imagine that the magnetized planet has, at a given instant, fully laden zones of trapped radiation ie having all possible trajectories being represented, but with low enough intensities not to distort the field unduly. Particles with magnetic moments too small for the particles to be magnetically mirrored will reach the atmosphere or surface and be lost by ionization. Secondary particles may be emitted as a result. A **loss cone** of directions will consequently be established in the trapped population. The half-angle of the loss cone at a point wherethe field strength is B is given by

$$\sin^2 \alpha = B/B_0$$

where B_0 is the field strength at the top of the atmosphere, or other absorbing surface.

2.4 Perturbation of Motion

Perturbations due to gyro-resonance with plasma waves can cause **pitch-angle scattering** resulting in **diffusion** into the loss cone and thence **precipitation** into the atmosphere (if the planet has one), or onto the planet's surface, to create, via ionization and excitation, one form of aurora, the **diffuse aurora**. The process is very effective in the Earth's radiation zones, though it is still not fully and quantitatively understood. **Doppler-shifted gyro-resonance** between electrons and **whistler-mode** electromagnetic waves is thought to play a key role in this process. Here, the waves, which propagate at frequencies below the electron gyro-frequency, are raised to the gyro-frequency in the frame of reference of an electron travelling in the opposite direction. Resonant interaction then leads to scattering in pitch angle and minor changes in energy.

Another form of perturbation, which may accompany pitch-angle scattering, is an acceleration directed parallel to B. This also lowers mirror points and causes aurora. The consequential enhancement of energy flux results at the Earth in the bright, highly structured and often spectacular **discrete aurora**. The process appears to be one of the most fundamental processes enacted within collisionless plasmas. There are two main theories to account for it (1) acceleration through **static, or quasi-static, potential differences**, which, as we shall see, is highly questionable on fundamental grounds, and (2) acceleration by **resonance with lower-hybrid waves**, which offers, in this author's oppinion, a promising explanation of the phenomenon. This issue, central to the understanding of space plasma physics, will be discussed in more detail in section 4.3.

Resonant interaction with a time-dependent electric field can produce acceleration together with a drift towards the planet, or a retardation with an outward drift, depending on the phase relation. This **radial diffusion** is sometimes confusingly described in terms of **Fermi acceleration** due to approaching mirror points, or adiabatic compression due to the reduction in volume of magnetic flux tubes in which particles find themselves. But this can be misleading, since the mirror points, although seen to approach from a reference frame moving with the particle, are stationary in the planetary frame in which energization is being considered.

2.5 Force-free Motion

Angular rotation of the planet introduces complications. If the magnetic and rotational axes are aligned, and if the planet is not a conductor and has no conducting ionosphere, there is no effect. However, if currents can flow in the planet or its frictionally-driven co-rotating atmosphere or ionosphere, the $\mathbf{v} \times \mathbf{B}$ force arising from motion at velocity $\mathbf{v}$ in the magnetic field $\mathbf{B}$ will cause charge to separate until the electric field, $\mathcal{E}$, of the space charge balances the magnetic force (see Figure 3).

At this stage

$$\mathcal{E} = -\mathbf{v} \times \mathbf{B} \qquad ()$$

(In MHD, where there are no particles or charges, this same relation is considered arise from motion of magnetic-field lines.) Once this balance is established, particles of the conducting planet or its ionosphere will be able to rotate with the planet **force-free**. Such co-rotation will naturally be maintained out to distances where a collision-effected viscous drag provides the necessary torque.

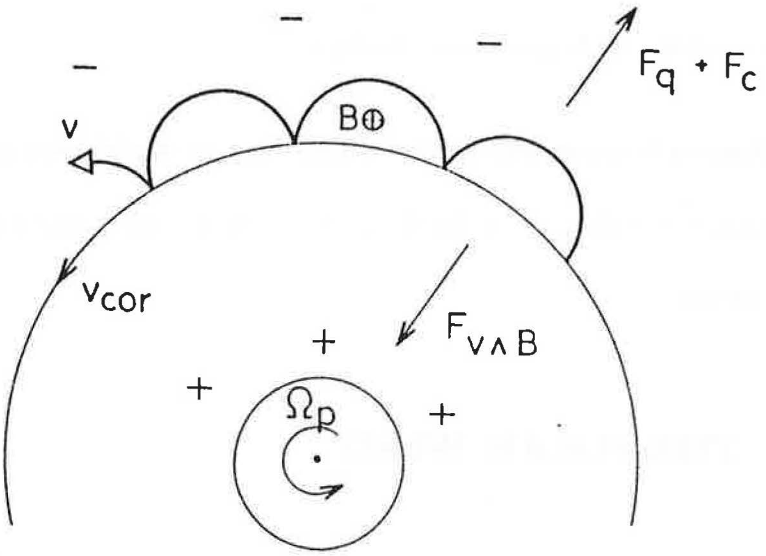

Figure 3. Force-free motion, illustrated for co-rotation in the equatorial plane of a planet with an extensive neutral atmosphere rotating at an angular velocity Ω_p. Motion given to charged particles by friction with the atmosphere will lead to deflection by the magnetic field (via the force $F_{\mathbf{v}\times\mathbf{B}}$) — electrons outward, and positively charged particles inward. The charge separation this produces builds up until the consequent, opposing electrostatic force F_q, combined with the centripetal force F_c, balances $F_{\mathbf{v}\times\mathbf{B}}$ to allow force-free co-rotation. A freshly introduced charged particle, or one which for some other reason does not co-rotate initially, will experience at first just F_q and will be accelerated radially. The motion thus introduced brings $F_{\mathbf{v}\times\mathbf{B}}$ into play, resulting in the cycloidal motion illustrated. The average azimuthal velocity equates to the co-rotational azimuthal velocity $\mathbf{v}_c$. Wave-particle interactions will serve to subsume such freshly introduced particles into the general co-rotation. Similar considerations apply to the propagation of the solar wind through interplanetary space, to the introduction of foreign material into the solar wind, and to convection of plasmas within magnetospheres.

However, co-rotation can prevail beyond the atmosphere if currents flow along magnetic field lines to ensure that they are electrostatic equi-potentials (this in fact is one of the tenets of magnetohydrodynamics), but it is unclear just how well this holds in practice. To the extent that it does hold, it implies that the magnetic field fills the role of an extended ionosphere. Co-rotation is believed to be impossible at distances beyond that at which the co-rotation velocity is greater than the Alfvén speed.

2.6 Limit of Planetary Control

A distance is eventually reached where, due to diminishing magnetic field, the planet's surroundings take control. In the solar system it is the **solar wind** that sets the boundary conditions.

3 THE SOLAR WIND

The solar wind is the expanding solar corona. It is a plasma of electrons and protons, with an admixture of helium and other solar constituents, streaming continuously and in a highly gusty fashion at speeds of 200-1000 km/s into the volume of space which includes the planets of the solar system, known as the **heliosphere**.

3.1 Protons and other ions

The protons and other ions form well-defined radial beams in velocity space. To a first order, they may be considered as drifting Maxwellians, with the magnitude of the drift velocity being much greater than the thermal speed. The energy density of the solar wind is, beyond a few solar radii, considerably greater than that of the solar magnetic field, so the regime is one in which the particles control and shape the field. They are able to overwhelm the solar magnetic fields and, effectively, extend the solar fields into space. Due to the **27-day rotation** of the sun, the radially-flowing solar wind sets up a pattern of magnetic field, known as the **garden-hose** or **Parker** spiral (see Figure 4).

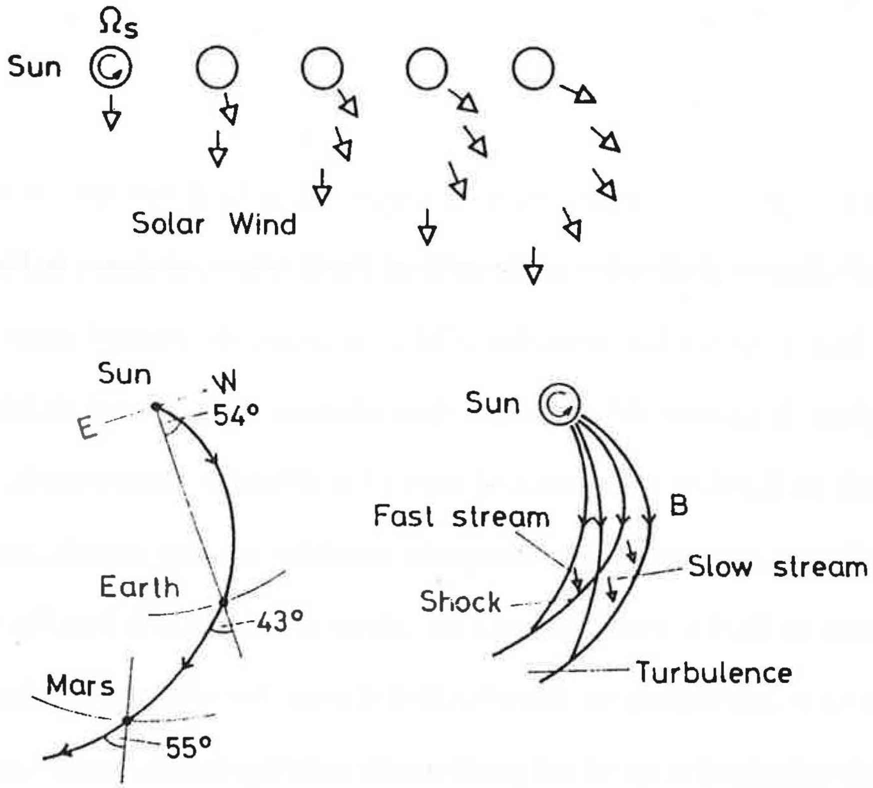

Figure 4. The solar wind and the interplanetary magnetic field. The top part of the figure shows how the locus of elements of solar wind emanating from a given location on the sun, rotating with angular velocity Ω_s forms a spiral pattern in the ecliptic plane. Due to the high electrical conductivity of the plasma, a magnetic field that is radial at the point of emission is drawn out into the same **garden-hose**, or **Parker** spiral, as illustrated in the lower parts of the figure. For a typical solar wind speed of 430 km/s, the interplanetary magnetic field is inclined to the radial direction by 43^0 at the Earth, and 55^0 at Mars. Under these conditions, both planets are magnetically conjugate to a region, seen from the planet to be towards the west limb of the sun. Variable solar-wind speeds lead (lower right) to gross departures from this picture, and to both shocks and turbulence.

The reason for this may be seen very simply if we assume that plasma flow and the magnetic field direction at the sun are purely radial, and that, due to the high conductivity, currents are readily induced to counter any influences attempting to change magnetic flux in any element of the plasma. Straightforward geometrical projection shows that the inclination, θ, of the magnetic vector at a radial distance r, much greater than the solar radius, is given by

$$tan\ \theta = \frac{r\ \Omega_S}{v_{SW}}$$

where ω is the solar angular rotation rate of 2.7×10^{-6} rad/s, and v_{SW}, the solar-wind speed. The pattern is (though this is rarely pointed out) very sensitive to these assumptions.

Even slight ($\sim 1^0$) departures from radial flow or field direction at the sun project into gross changes of direction at the orbit of Earth, where, as shown in Figure 4, the nominal inclination to the Earth-sun line is 43^0. At Mars, the nominal inclination is 55^0, and at Jupiter, it becomes 80^0. Since the time taken for average-speed (430 km/s) solar wind to reach the Earth at 1 astronomical unit (1.5×10^8 km) is approximately 4 days, or some 54^0 of the solar rotation period, **energetic particles** or **solar cosmic rays** released in **solar flares** are for this reason more readily able to reach the Earth from flares occurring towards the west (as seen from the Earth) limb of the sun. The solar wind continues to flow outward, with undiminished speed and geometrically reducing density, to meet, and eventually merge with, interstellar plasma and fields at the **heliopause**.

3.2 Electrons

The electron velocity distribution differs greatly from that of the ions. The solar wind is, therefore, not characterizable as a simple flowing plasma. This is because elecrton velocities are very much greater than the drift velocity. Electron drifts at the ion flow speed are almost insignificant. Solar-wind electrons have an approximately isotropic velocity distribution, occasionally showing a slight imbalance between opposite senses of flow parallel to the interplanetary field, about which direction the distribution is symmetric, or **gyrotropic**.

The electron velocity distribution, in common with the distribution of cosmic radiation, is very close to a power law. A power law, being self-similar on all scales, has no characteristic energy and, therefore, no meaningful temperature. For this reason concepts based on moments of the distribution function, including Debye lengths, must be treated with great care. This is an area of plasma physics requiring much more attention.

3.3 Current sheets

The necessity for the divergence of B to be zero ensures that there are regions of both polarities, one from the northern and one from the southern hemisphere of the sun. The current sheet dividing these lies generally in the region of the ecliptic, but has a wavy structure, often likened to a ballerina's skirt. Rotation of the sun introduces **sector boundary** crossings typically four times every 27 days. These crossings also introduce discontinuities in solar-wind properties.

The nature and behaviour of the solar wind out of the ecliptic plane can today only be inferred from remote sensing methods. However, the Ulysses space probe is now well on its journey of exploration which has taken it past Jupiter in February 1992 where it has swung out of the ecliptic to pass over the southern solar pole in 1994, and the northern pole in 1995.

3.4 Irregularities

Irregularities in solar wind flow density and speed give rise to interplanetary shocks, turbulence and 27-day (solar-rotation) effects in the interactions with the planets to be discussed below. **Solar flares** , with their production of solar cosmic rays or high-energy solar particles and enhanced solar-wind density, also represent major perturbations.

3.5 Ion Pick-up

Consider more closely the motion of ions and electrons forming the solar wind. Ions flow at an angle to B everywhere except, as assumed earlier, within the corona itself, so they experience a bending force. This is balanced, exactly as in the co-rotation effect discussed above, by a self-consistent space-charge field to allow the ions to flow effectively force-free at an angle to B. The space charge necessary to create the required density gradient is very weak, and the solar wind is still to all intents and purposes, electrically neutral. It is a common misconception that the electrons need to flow with the ions to preserve this neutrality. Man-for-man marking is obviously unnecessary. Neither do the electrons need to flow at the same speed to avoid setting up currents. In fact the electron behaviour is totally different to that of the ions, being governed by almost (but not quite) isotropic velocity distributions.

The space-charge field manifests itself very clearly in a phenomenon known as **ion pick-up**. An ion freshly formed in the solar wind, as the result of photo-ionization of planetary, cometary or material, experiences initially no magnetic force but it is subject to the space-charge field created by the solar wind. It is therefore accelerated parallel to the electric field. This motion introduces a bending force. The combined effect is to cause the ions to follow cycloidal paths in the direction of the solar wind, their mean speed being equal to that of the solar wind but ranging each cycle from zero to as much as double this value if the magnetic field is normal to the flow. This is a form of collisionless friction. Instabilities and other causes of scattering serve gradually to subsume the injected ions into the solar wind. Naturally, the energy for the ion acceleration is drawn from the solar wind which is locally loaded and slowed down.

3.6 Interaction with planets

When elements of the solar wind confront the obstacles formed by the magnetic fields of planets having magnetic fields, currents are induced to resist a change in magnetic flux, thus neutralizing the planetary field within the solar wind, and enhancing it nearer to the planet. Eventually a point is reached, in the approach towards the planet, where the density and energy of the solar wind are no longer able to generate enough current to overcome the increasing magnetic field, and the solar wind is forced to divert and begin to flow around the impenetrable obstacle. The process may be considered as a collisionless pressure balance, reached at the point where the combined pressures of the plasma and magnetic field are equal on the two sides of a boundary layer. The boundary layer which continues along the flanks of the magnetosphere is known as the **magnetopause**. The distance fro the centre of the planet to the furthest point upstream, or the "nose" of the magnetosphere is known as the **stand-off** distance. If the planet does not have a magnetic field, interaction is directly with the gravitationally unrestrained **exosphere**, the atmosphere, or the surface itself. In practice, the situation is more complicated than this because the solar wind is **supersonic** and **super-Alfvénic**, so a standing **bow shock** forms upstream. The shock serves the function of slowing and randomizing the flow sufficiently to allow flow around the obstacle. In this process, both the ions and electrons gain thermal energy, as discussed in detail in Part II.

A comet-shaped wake or **magnetotail** is generally created to form a downstream extension of the planet's magnetosphere. The exact nature of the interaction between the solar wind and the magnetosphere taking place across the **magnetopause boundary layer** serving to match one plasma to the other is still very much a mystery. It is clear that matter, momentum and energy are transmitted across the boundary layer in both directions — the planet **loading** the solar wind with planetary material, and the solar wind driving dynamical processes in the planet's magnetosphere. Plasma within the magnetotail is subject, through wave/particle interactions, to an effective viscosity applied across the magnetopause boundary layer. This sets up a circulation, or **convection**, of plasma within the magnetosphere which may or may not be along closed trajectories. The situation is again analogous to that in the solar wind itself — a space charge is set up whose electric field balances the magnetic force to allow force-free drift. Particles not initially drifting with their fellows will, as in the solar wind and in the co-rotation phenomenon, be picked up and eventually subsumed into the general flow. Closer to the planet co-rotation can become dominant.

A specific process that is considered by some workers to play a role in the transfer of matter an momentum across the boundary layer is that of **magnetic reconnexion**, originally thought of as a steady-state phenomenon, but increasingly seen as a transient, localized process known as a **flux transfer event**. This is an MHD concept in which interplanetary magnetic lines of force become joined to their planetary counterparts, allowing free flow of plasma particles from one regime to the other. The well established fact that the energy from the solar wind seems more readily transmitted to the Earth's magnetosphere when the interplanetary magnetic field has a southward component, and thus allows the joining to take place more readily, lends some support to this interpretation. Ion acceleration in the magnetopause is also often explained in these terms. However, there are problems with both the steady state and transient pictures. Unlike **magnetic annihilation**, in which magnetic energy is released and converted into particle kinetic energy, the steady-state reconnexion picture has a quasi-static magnetic field, which being unchanging can release no energy. The notion of the breaking and re-joining of magnetic lines of force is an issue whose physical foundations need much more attention, especially since the "X-type" neutral point, a major characteristic of "reconnexion" can be produced very simply using two attracting magnetic dipoles. Some recent studies of the terrestrial boundary layer indicate, in any case, that the layer is one of gradual transition from magnetosheath to magnetosphere properties in all quantities, more suggestive of a diffusion-controlled intermixing than of boundary rupture.

With the above processes in mind, let us tour the solar system to observe them in action. The tour cannot be comprehensive — space does not permit that —- but it will, I hope, reveal that, though governed by a relatively small set of physical processes, the interactions at different planets have their own distinct character, and will perhaps whet the appetite for further, detailed study of the infinitely fascinating natural plasma laboratories of planetary magnetospheres and outer atmospheres, where comparison serves as a substitute for the control that can be exercised in a laboratory experiment.

4 MAGNETOSPHERES OF THE PLANETS

4.1 Mercury

Basic Information

Mean distance from sun	5.8×10^7 *km*
Mean planetary radius, R_{Me}	2439 *km*
Magnetic moment	$5.1 \times 10^{12}\ Tm^3$
Inclination of magnetic axis	10^0
Upstream distance of bow shock	$\sim 2\ R_{Me}$
Stand − off distance	$\sim 1.6\ R_{Me}$
Visited by	*Mariner* 10 (1974, 1975)
	Orbiter proposed

Note that the spacecraft listed in this and subsequent tables are only those capable of plasma measurements.

Magnetosphere

The proximity of Mercury to the sun and the relative weakness of its magnetic field lead to a magnetosphere which is largely filled by the planet itself, the stand-off distance being typically only $\sim 1.6R_{Me}$ (see Fig 5). It is clear from this figure that the scope for stable radiation belts is rather limited. Nevertheless, there are trapped particles (H, He, O, Na and K, and of course electrons) and a definite tail. Sodium atoms are sputtered from the dayside of the planet primarily by by solar ultra-violet radiation and, to a smaller extent, by direct solar wind impact. These atoms become ionized, again by solar UV, either within the planet's magnetic environment where they are the source of the planet's predominantly heavy-ion magnetosphere, or within the solar wind where they are "picked up" and eventually subsumed. The slower atoms are drawn back to the surface where they may cause further sputtering. As depicted in Figure 5, the nightside of the magnetosphere is considerably distended through the diamagnetic effect of the plasma it contains.

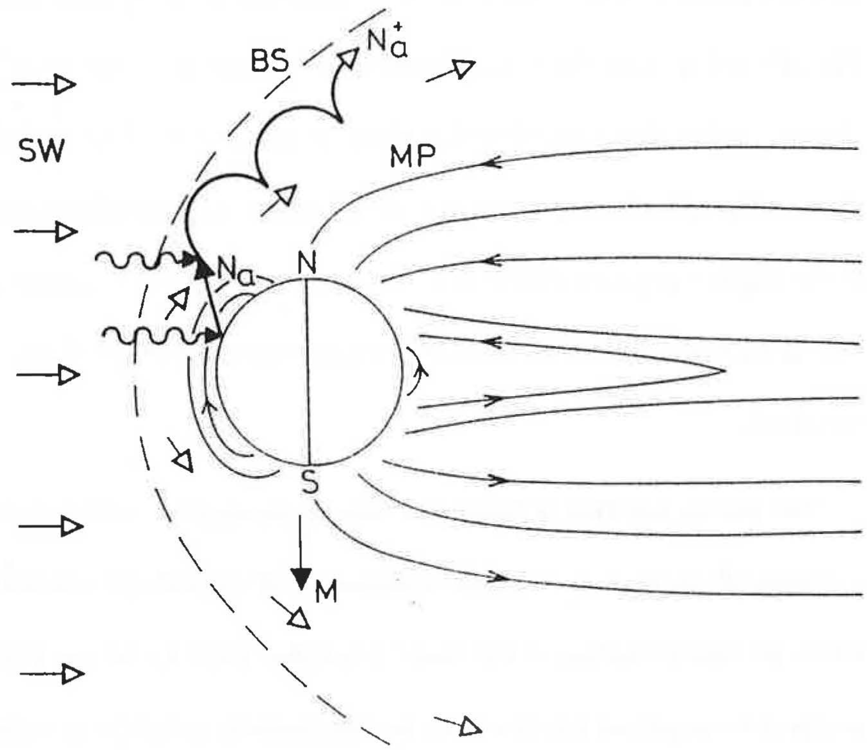

Figure 5. The magnetosphere of Mercury, perpendicular to the ecliptic and in the noon-midnight plane. The planet itself occupies much of the magnetosphere, leaving little opportunity for the the orderly motion depicted in figure 2. The obstacle presented by the magnetosphere and by the loading of the solar wind by sodium released from the surface generate a bow shock, *BS*.

There appear to be rapid changes in the particle fluxes and in the configuration of the magnetic field, similar in many respects to the **substorms** known at Earth (Section 4.3) even though Mercury has little or no atmosphere or ionosphere and its surface is a poor conductor. These facts seem to prove that an ionosphere is not essential to the substorm phenomenon as had previously been thought from studies at the Earth. Oxygen and potasium from the planet, and protons and helium ions from the solar wind are also found in the radiation zones. The exact manner of entry of the solar wind to the Hermean[1] magnetosphere is, as at Earth and the other planets, still very much a mystery.

In common with its counterparts at the other planets, the Hermean magnetosphere presents an obstacle to solar wind flow, causing a standing **bow shock** to form upstream. The effect of the bow shock is to broaden the velocity spectrum of solar wind ions, ie heating the ions and randomizing their directions, as required for them to find their way around the planet. The effect is greatest at the "nose" of the magnetosphere, and gradually diminishes as the impact parameter increases. An augmentation of the magnetic-field strength at the bow shock causes some ions to be reflected upstream a number of times before they penetrate the shock.

The piecing together of fragments from an incomplete survey, such as that resulting from a spacecraft encounter, is highly reminiscent of archeology, another form of endeavour in which an understanding of the basic principles helps to bridge gaps in information. The perspective so gained may,however, be very limited, as has been realized from the restricted view of the terrestrial magnetosphere to be gained from the **'fly-by'** of Galileo in December 1990, en route to Jupiter via **gravitationally-assisted** encounters with both Venus and Earth.

[1] A tour of the planets provides an excellent incentive for a revision of Greek as well as Roman mythology.

4.2 Venus

Basic Information

Mean distance from sun	1.1×10^8 *km*
Mean planetary radius, R_V	6161 *km*
Magnetic moment	$\rightarrow 0$
Upstream distance of bow shock	$\sim 1.4\ R_V$
Stand – off distance	*inapplicable*
Visited by (fly – by)	*Mariner* 2 1962
	Galileo(1990)
	and many others
Orbital missions	*Veneras* 9 *and* 10 (1975)
	Pioneer Venus (1978 – 1991)

Solar-wind interaction

Venus has little or no intrinsic magnetic field, so the solar wind interacts directly with the ionosphere and atmosphere. A rich spectrum of neutral particles (C, N, O and their compounds) released by these interactions from the atmosphere become ionized by solar radiation, and are consequently picked up and swept downstream to form an irregular comet-like tail which contains also a corpuscular umbra and penumbra, threaded by the interplanetary (solar-wind) magnetic field, as shown in Figure 6. The field, distorted by the need (in view of the high conductivity) to preserve continuity of magnetic flux linkage between plasma elements, appears to become "draped" around the planet. This draping is also a characteristic of the solar-wind interaction with comets (Section 5) which, like Venus, have extensive exospheres.

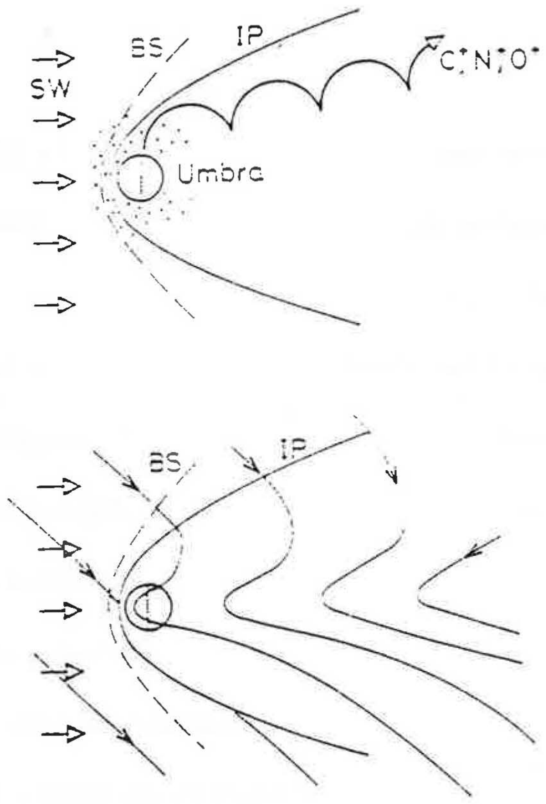

Figure 6. Solar-wind interaction with Venus. The upper part of the figure, symmetric about the planet-sun line, shows the solar-wind interacting directly with the atmosphere, to create a bow shock *BS* and an ionopause *IP*. The lower part of the figure shows, in the ecliptic plane, the local distortion of the solar-wind magnetic field, sometimes described as "draping", a phenomenon also associated with Mars and with comets.

Since Venus and the surrounding ions represent an obstacle to solar-wind flow, the planet gives rise to a bow shock and a magnetosheath or **ionosheath** of retarded and heated solar wind. Again, a similar situation prevails at comets where the solar wind is slowed by the loading caused by injected cometary material. A particularly revealing observation made by Galileo in 1990 was of the presence of very energetic ions outside the bow shock and streaming away from Venus. Since there are no radiation zones able to serve as a source for these particles, as is believed to be a contributory factor at other planets, it is clear that planetary bow shocks are effective accelerators of charged particles. The mechanism.

though, still remains obscure. A mechanism termed **Shock-drift acceleration** has been proposed; but, since it appears to draw on a static magnetic field and on the solar-wind electric field, which we have seen to be of space-charge origin, and therefore conservative, this process must be highly questionable. Wave / particle interactions with the elctrostatic turbulence always associated with bow shocks seems a much more likely explanation (see Part II).

4.3 Earth

Basic Information

Mean distance from sun	1.5×10^8 *km*
Mean planetary radius, R_E	6370 *km*
Rotation period	24 *hrs*
Magnetic moment	$-7.9 \times 10^{15}\ Tm^3$
Inclination of magnetic axis	11^0
Upstream distance of bow shock	$\sim 15\ R_E$
Stand − off distance	$\sim 10\ R_E$

Note that, unlike most of the other planets, Earth has a negative, southward directed, magnetic moment.

Magnetosphere

Far more is known, for obvious reasons, about Earth than about the other planets. Its ionosphere and magnetosphere have been explored using radio waves, high-altitude balloons, sounding rockets, and near-Earth, geosynchronous, and eccentric-orbit satellites. Photography and even the unaided visual observations of the aurora have also played a important roles.

The stand-off distance (see Figure 7) is large enough to allow the formation of a well developed and permanent radiation zone (named **the Van Allen belts** after their discoverer).

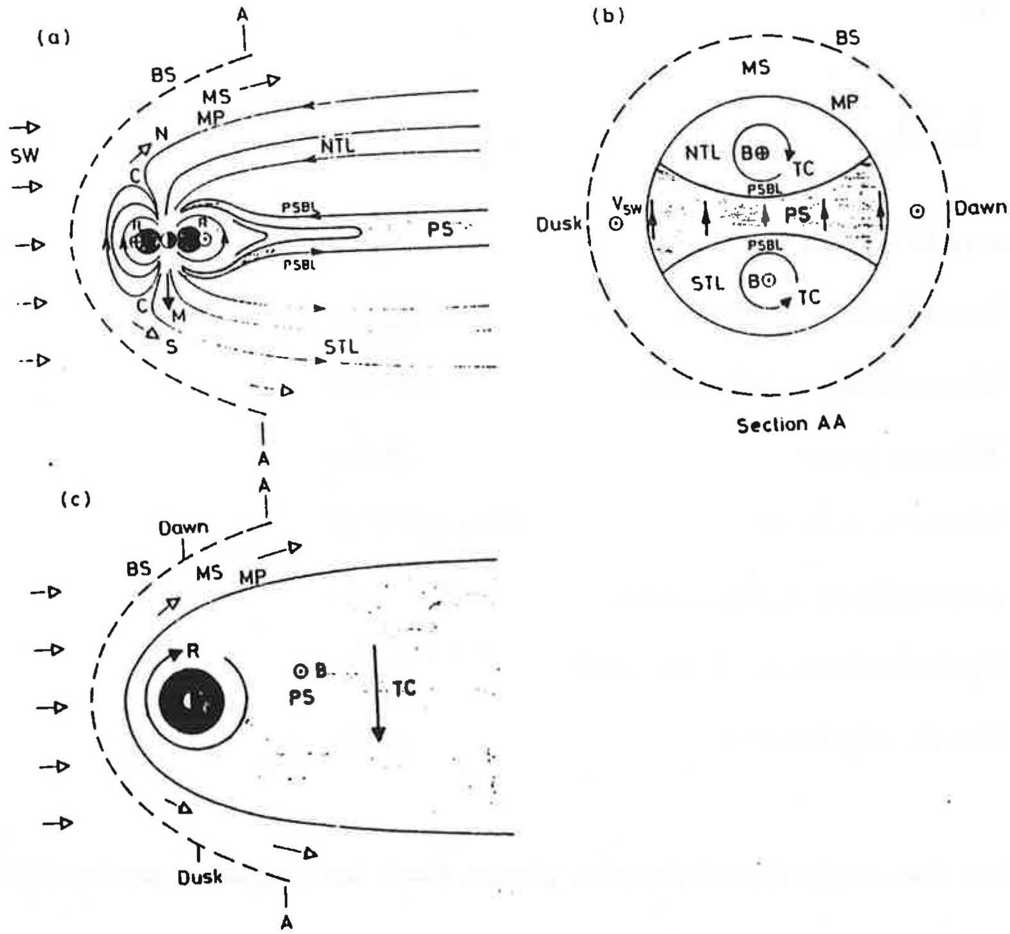

Figure 7. The magnetosphere of Earth. Part (a) is in the noon-midnight plane perpendicular to the ecliptic, (b) is the dawn-dusk plane perpendicular to the ecliptic, and (c) lies in the ecliptic plane. (b) is a cross section of (a), and (c), along *AA*. In order to avoid complication, the magnetosphere is drawn with the dipole tilt out of the plane of the paper. *BS* is the bow shock and *MS*, the magnetosheath. *MP*, is the magnetopause boundary layer and *NTL* and *STL*, the northern and southern lobes of the magnetotail. *PS* is the plasma sheet (lightly shaded), and *PSBL* is its (outer) boundary layer. *R* represents the ring current resulting from drift of particles in the radiation zone (see Figure 2), and *TC* the northern and southern elements of the tail-lobe current. The heavily shaded area is the plasmasphere. *C* is the Cusp, thought to permit ready access (as in Figure 1) to solar wind from the magnetosheath.

The innermost part of the magnetosphere, effectively an extension of the ionosphere, and approximately coinciding with the inner part of the radiation zone, is the **plasmasphere**. The plasmasphere is composed of particles of $\sim eV$ energies and is generally understood to be co-rotating with the Earth and its atmosphere. Next is the **plasmasheet** of $\sim keV$ particles forming a giant, distorted plasma torus around the Earth. It is dynamic in nature, in response to sudden changes, known as **substorms**, in the ring current of higher energy particles making up the radiation belt which co-exists with the relatively low-energy plasmasphere and plasmasheet. The exact nature of substorms is not fully understood, but it is clear that they cause the inflated magnetosphere to return at intervals (several times a day) to a more-nearly dipole configuration. It is still unknown whether these substorms are direct responses to changes in the solar wind, and in particular to the linking of solar and terrestrial magnetic fields through steady-state reconnexion and/or flux-transfer events, or whether there is an important element of spontaneous release of stored energy. The plasmasheet carries the solenoidal currents supporting the towards-Earth and away-from-Earth, northern and southern, lobes of the **magnetotail** magnetic field. It is widely believed that **field-aligned currents** into the ionosphere, and their closure through the ionosphere are essential elements of the substorm. However, the substorm-like changes at Mercury (Section 4.1), which are thought to be unable to support such currents, have raised serious doubts over this.

North and south of the plasmasheet lie the northern and southern **tail lobes** composed of low density plasma, mostly an outflow from the polar ionosphere. The magnetic field is stronger here than in the plasmasheet. The dawn-dusk flanks of the plasmasheet continue to the magnetopause boundary layer separating it from the magnetosheath. This topology is not evident in a noon-midnight projection. **Kelvin-Helmholtz instabilities** between the magnetosheath and the plasmasheet are thought to be projected along the magnetic field as **absolute instabilities** to result ultimately in the large-scale folds in the aurora and in ionospheric characteristics. The **plasmasheet boundary layer** forms at the boundary between the hot and dense plasmasheet and the relatively cool, diffuse plasma of the tail lobes. This naturally active region appears to be the seat of the more active and intense forms of the aurora such as the curtain-like **auroral arcs**.

There is much discussion at present over the nature of the magnetopause boundary layer, and in particular over whether it effects a smooth, diffusion-like transition, or whether it undergoes steady-state or sporadic rupture. Some measurements have been interpreted in terms of sporadic reconnexion in the equatorial midnight region at distances of 20 R_E, or so, with the formation of break-away clouds of plasma known as **plasmoids**. However it should be noted that isolated measurements from a single spacecraft, or even from two or more, cannot give a unique confirmation of the overall configuration. The electric-current system supporting the 2-d MHD concept of a plasmoid has still to be proposed. **Temporal/spatial ambiguity** is a real problem in such matters, and needs multi-point measurements before it can be resolved. The European Space Agency's Cluster mission, due for launch in 1995, will employ four spacecraft in close formation in the latest attempt to cope with this major difficulty.

Bow Shock

Moving further away from Earth we encounter the bow shock at typically $\sim 15 R_E$. The shock which serves to slow and heat solar wind ions also has the effect of accelerating some ions and electrons electrons (see also Section 4.3). The shock is a region of intense wave activity, the free energy for which derives from the solar wind. Solar-wind electrons, having velocities generally much greater than the ions, are able to cross the shock in either direction. Wave/particle interactions produce a bulge in the velocity distribution which this author interprets as a resonance with lower-hybrid electrostatic waves. There are also explanations in terms of the shock-drift acceleration, discussed in 4.2, and in terms of an electrostatic potential difference existing across the shock. We feel that the latter can be discounted on grounds of inconsistency with the existence of a low-energy tail to the distribution, and indeed on the same grounds of the former, namely that a localized, static (relative to transit time), electrostatic field is conservative. We shall return to this crucial question of particle energization processes in several other connexions. The rate and extent of change at the shock vary with with position along the shock surface and on the angle between the solar-wind magnetic field and the shock normal. Effects are greater and sharper where these directions are more nearly perpendicular, ie at a **quasi-perpendicular shock**. **Quasi-parallel shocks** are generally more gradual and diffuse. The shock, like the magnetopause, is highly variable in position, over many Earth radii, in response to variations in the solar wind.

Upstream from the shock are found electrons which have penetrated from downstream and ions which have been reflected at the shock. These "impurities" in the solar wind give rise to upstream wave activity. There is still no evidence, though, for the electron beams so confidently thought to be responsible for electron plasma oscillations in the upstream solar wind. There is further discussion of the bow shock in Part II.

Sources of plasma for the Earth's magnetosphere are from the atmosphere/ionosphere in the polar regions (the **"ion fountain"**), cosmic-ray albedo in which emitted neutrons decay into protons, electrons and neutrinos, and from the solar wind via the magnetopause and cusp regions. There is still much discussion over relative importance of these different sources. The terrestrial magnetosphere contains a rich variety of components, including doubly-ionized helium, almost certainly of solar origin, and oxygen ions of the full range of charge states, firmly indicative of a terrestrial source.

Precipitation and Aurora

Precipitation from the radiation belts arises from a number of causes. One is the straightforward result of a local weakness in the geomagnetic field near the south east coast of South America known as the **South Atlantic anomaly**. Here, particles that would mirror and remained trapped at other longitudes penetrate into the atmosphere without encountering a field strong enough to effect mirroring. Another cause of precipitation is pitch-angle scattering from otherwise stable orbits by gyro-resonance with em radiation, eg whistler-mode noise. It is interesting to note that, since whistler waves have frequencies below the electron gyro frequency, resonance is possible only through the upward shift in frequency produced by the Doppler effect between electrons and waves travelling in opposite directions. This leads to a diffuse, sometimes patchy and pulsating form of aurora, the underlying causes of which are still only partially understood. Diffuse aurora frequently contains pulsating patches. It is clear from a velocity dispersion between electrons of different energies — the faster ones arriving earlier — that the pulsations arise close to the equatorial crossing point of the tubes of force exhibiting the pulsations. This is not unexpected since this is the region where smaller deflections are required to drive electrons into the loss cone. The origin of the pulsations, typically of a period of several seconds, is still a complete mystery.

At the poleward edge of the diffuse aurora, which now seems well established as the "magnetic footprint" of the **plasmasheet boundary layer**, is found the structured or **discrete** aurora. It is clear that the electrons responsible for this are accelerated parallel to the magnetic field as they precipitate into the atmosphere. The acceleration occurs between the altitudes of 1000 and 10,000 km, and typically produces an electron velocity distribution with a peak in the region 5- 10 keV. The cause will be found in most articles on the subject to be a static (relative to the electron transit time of $\leq 1s$) electric field, possibly in the form of many (tens of thousands) of **electrostatic double layers**. However this "explanation" unaccountably overlooks the fact that electric fields due to space charge (large scale time variations can be ruled out) are conservative, and are therefore incapable of producing any net effect. Note the similarity with acceleration at the bow-shock. It will be found that models based on this interpretation all contain a major flaw, such as electrostatic equipotentials that are not closed surfaces. We have advanced and developed over recent years an possible explanation in which the acceleration is caused by electrostatic waves (of the lower-hybrid mode) whose phase velocity is comparable to that of the precipitating electrons. The electrons are able to "surf ride" on these waves, drawing energy from them in a process known as **Landau damping**. The process envisaged is an electrostatic equivalent of Fermi's model of magnetic reflexion from moving gas clouds put forward to account for the acceleration of cosmic rays. The motion of the electrostatic barrier in the former case, and the magnetic barrier in the latter, is essential for energy transfer. Consider the kinematic of a simple 2-body interaction. It is readily shown that one of the bodies can gain energy from a second body only in a reference frame in which the second has kinetic energy, ie in a frame in which the donor is moving. It can readily be shown, moreover, that the momentum of the donor has to be greater and oppositely directed to that of the recipient. In short, energy may be gained by a body only in a frame of reference in which, along the net direction of interaction, the center of mass of the system moves towards the body. The terrestrial auroral zone is an exceedingly complex plasma physics laboratory, exhibiting a wide range of processes whose relationships and cause-and-effect hierarchy have yet to be established. In addition to the precipitation of electrons and ions, with and without acceleration, there is also an upward streaming of both species of particle (sometimes simultaneously), and variously magnetic-field-aligned and perpendicular acceleration. There is also a full spectrum of electromagnet and electrostatic wave activity.

4.4 Mars

Basic Information

Mean distance from sun	2.3×10^8 *km*
Mean planetary radius, R_{Ma}	3332 *km*
Magnetic moment	$\rightarrow 0$
Upstream distance of bow shock	$\sim 1.5\ R_{Ma}$
Stand − off distance	*inapplicable*
Visited by	*Mariner* 4 (1965)
	Phobos (1989)

Solar-wind Interaction

Mars has no measurable intrinsic magnetic field. Interaction with the solar wind is, therefore, basically similar to that of Venus. Ionized hydrogen, oxygen and carbon dioxide from the atmosphere are picked up by the solar wind to create comet-like tail (Figure 8).

Near the centre of the tail there is a plasma regime characterized by anti-sunward streaming oxygen ions reminiscent of terrestrial auroral ion beams. This removal of material represents, on cosmic time scales, a significant erosion of the Martian atmosphere.

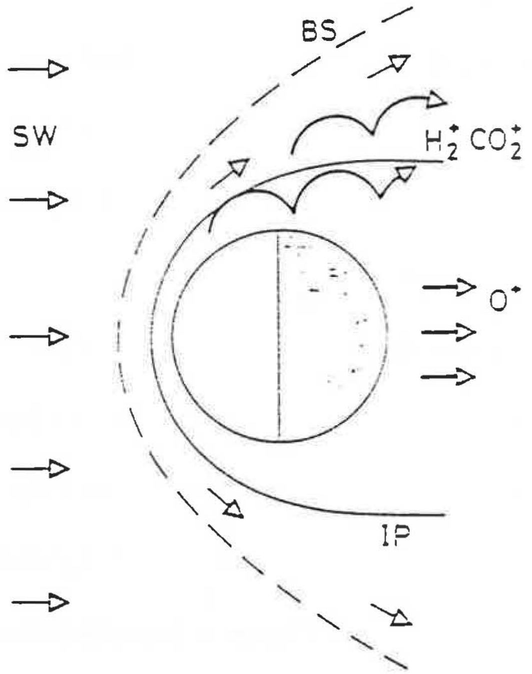

Figure 8. Solar-wind interaction with Mars showing, in a figure symmetric about the planer-sun line, the pick-up and erosion of ionospheric material.

The loading of the solar wind by the implanted ions introduces a bow shock with the now familiar retardation and thermalization of solar wind protons, strong wave activity and resonant acceleration of electrons again attributable, possibly, to lower-hybrid-wave turbulence.

4.5 Jupiter

Basic Information

Mean distance from sun	$7.8 \times 10^8\ km$
Mean planetary radius, R_J	$70000\ km$
Rotation period	$10\ hrs$
Magnetic moment	$1.4 \times 10^{20}\ Tm^3$
Inclination ofmagnetic axis	10^0
Upstream distance of bow shock	$\geq 100\ R_J$
Stand – off distance	$60 - 90\ R_J$
Visited by	*Pioneer* 10 (1973)
	Pioneer 11 (1974)
	Voyagers 1 *and* 2(1979)
	Ulysses (1992)
	Galileo (*due* 1996)

Magnetosphere

Jupiter's huge magnetic moment combined with the reduction in solar-wind pressure at the planet's considerable distance from the sun allow Jupiter, most fittingly, to dominate its environment out to distances of $100R_J$ or more. The ordered, dipolar magnetic field close to the planet gives rise to well-defined, high intensity radiation zones within $\sim 20R_J$. Proton acquire energies in excess of 10 MeV, and bi-directional streams of electrons are found up to severals tens of keV. Currents flowing within the magnetosphere exceed 10^9 Amperes. Jupiter is a strong source of radio emission at all frequencies up to several megahertz.

Jupiter's many moons serve as both sources and sinks for the radiation belt particles. In fact, a new moon was actually discovered from the channel it carved in the radiation. Precipitation, as at the Earth, produces aurora in Jupiter's atmosphere, and there is synchrotron emission from gyrating trapped electrons. The moon Io is of special interest since it is highly volatile through volcanic action, and generates its own plasma torus of sulphur and oxygen ions around the planet. There is also a dynamo action resulting from its motion through the magnetic field, leading to voltages of $\sim 400kV$ and a power of $\sim 10^{13}W$. Note here that the constraints set by the moon's physical structure and by the dynamics of its orbital motion serve the role of equivalent constraints in an engineered dynamo. This is unlike the situation sometimes envisaged for MHD dynamos, where the constraints vital to the functioning are often unspecified.

Much of the magnetosphere consists (see Figure 9) of a co-rotating **plasmadisk or magnetodisk** into which fresh ions from planetary and lunar sources are picked up in just the same way as ions are subsumed into the solar wind. Close to the planet the "disc" lies perpendicular to the magnetic axis, while at great distances centripetal forces tend to align it perpendicular to the rotation axis. Co-rotation continues out to distances $\sim 50R_J$ where the velocity reaches the Alfvén speed, when the coupling necessary to the process can no longer be maintained. This giant obstacle generates, of course, a well-developed bow shock. Particles accelerated within the magnetosphere escape from the polar regions into the solar wind, electrons being detectable even near the Earth, making Jupiter something of a rival to the sun itself. Precipitation from the ring current and other plasma regions produces aurora.

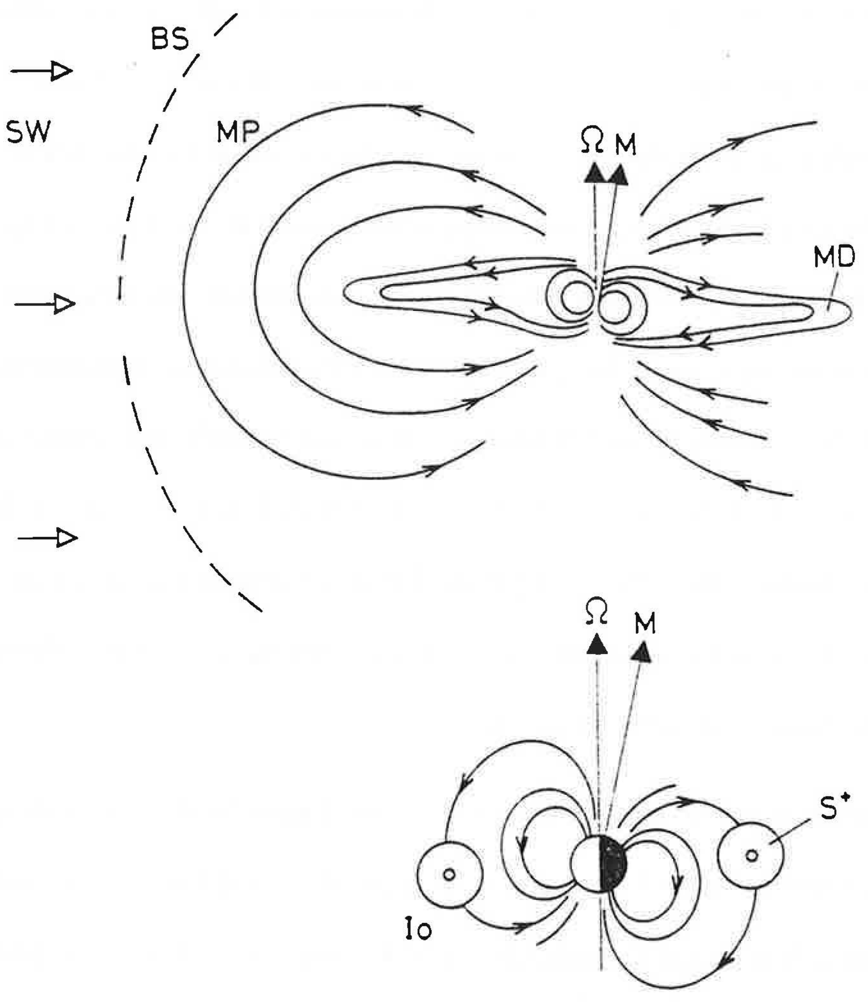

Figure 9. The magnetosphere of Jupiter, showing (shaded in upper figure) the co-rotating magneto-disk, MD, and the Io plasma torus (shaded in lower figure). The increased spacing of solar-wind arrows in this and subsequent figures reflects the reducing density of the solar wind with distance from the sun.

4.6 Saturn

Basic Information

Mean distance from sun	$1.4 \times 10^9\ km$
Mean planetary radius, R_S	$60000\ km$
Rotation period	11 *hrs*
Magnetic moment	$4.8 \times 10^{18}\ Tm^3$
Inclination of magnetic axis	1^0
Upstream distance of bow shock	$40 - 100\ R_S$
Stand − off distance	$20 - 40\ R_S$
Visited by	*Pioneer* 11 (1979)
	Voyager 1 (1980)
	Voyager 2 (1981)
	Cassini (*projected* 2004)

Magnetosphere

Saturn, in complete contrast to Jupiter majestic dynamism [2], has an extremely well-ordered magnetosphere (see Figure 10). The orderliness is due to the magnetic moment being almost precisely aligned with the axis of rotation, to the many moons lying in the equatorial plane, and to the strong and extensive fields being more than a match for the weakening solar wind at Saturn's great distance from the sun. Cosmic rays are almost totally excluded. Plasma co-rotates with the planet out to some $15R_S$, and there is a ring current composed of H^+ and He^+ from the ionosphere, O^+ from the icy satellites and rings,

[2] Holst's orchestral suite 'The Planets' captures this difference perfectly.

and N^+ from Titan through the pick-up process.

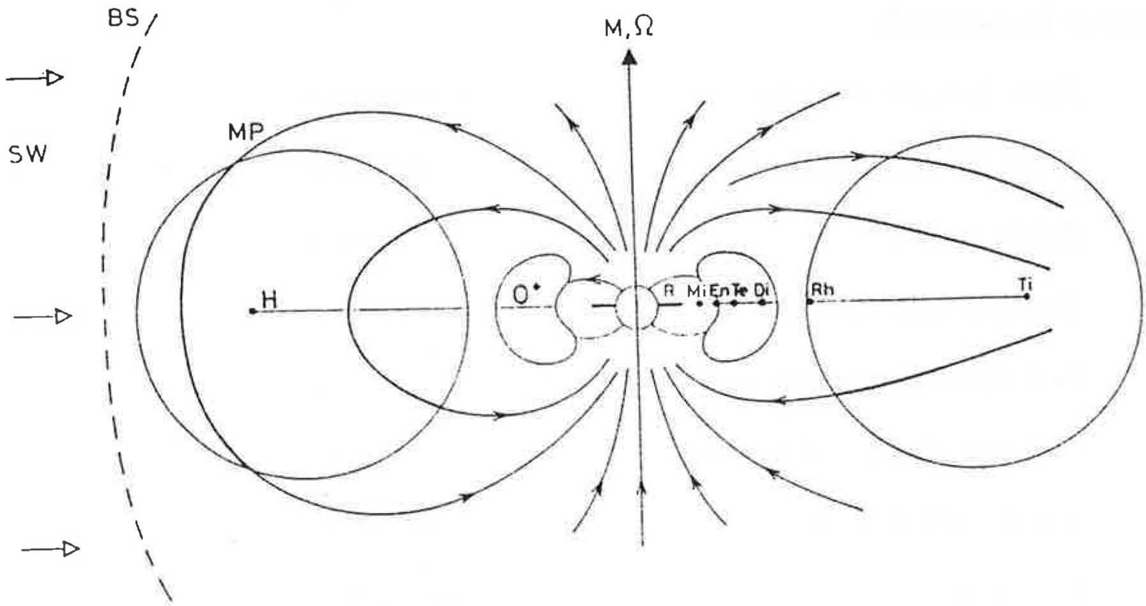

Figure 10. The magnetosphere of Saturn, showing the hydrogen torus surrounding the orbit of Titan, *Ti*, and the oxygen-ion torus associated with Dione, *Di*, and Tethys, *Te*. Positions of the rings, *Ri*, Mimas, *Mi*, Enceladus, *En*, and Rhea, *Rh*, are also shown.

Hydrogen atoms continuously emitted from Titan, but unable to escape from Saturn's gravity form a giant neutral torus centering on Titan's orbit. The inner magnetosphere, within $3R_S$ is devoid of radiation due to absorbtion by the rings. The many moons carve neat channels in the radiation zones, and in some instances (Dione and Tethys, for example) sputtered O^+ creates a rich plasma torus. Precipitation from the radiation zones produces visible aurora. As with the other planets, there is a plasmasheet, extended on the nightside of the planet, composed of ions of both planetary and solar-wind origin.

The magnetosphere contains an important and significant new plasma component — highly charged **dust grains**, ranging in size from microns to moons, the rings being the prime example. It is now recognised that an admixture of electrically charged dust can introduce new properties into a plasma, primarily as a result of the collective behaviour of large numbers of electrons surrounding charged dust grains which act in some sense like nuclei of giant quasi-atoms.

Saturn's calm and dignified magnetosphere is perhaps the closest to our original straightforward magnetized planet, and as such provides an ideal laboratory for investigating basic magnetospheric processes such as energization and radial diffusion. A new mission, Cassini, is currently being proposed to explore further, early in the next century, this intriguing corner of the solar system.

4.7 Uranus

Basic Information

Mean distance from sun	$2.9 \times 10^9\ km$
Mean planetary radius, R_U	$25000\ km$
Rotation period	$17\ hrs$
Magnetic moment	$3.6 \times 10^{17}\ Tm^3$
Inclination of magnetic axis	60^0
Upstream distance of bow shock	$\sim 20\ R_U$
Stand$_o$ff distance	$\sim 18\ R_U$
Visited by	*Voyager* 2 (1986)

Uranus produced a great surprise. Since the planet's axis of rotation was known to be directed, for the Voyager 2 encounter, almost directly towards the sun, and the magnetic axes of planets are generally relatively close to their rotation axes, it was confidently expected that Uranus would uniquely allow almost direct entry of the solar wind into the polar atmosphere, as in the case of the low-rigidity particles at high magnetic latitudes in Figure 1. This assumption went the way of many pure assumptions —- it was totally wrong! The magnetic axis was found to be inclined at an angle of some 60^0 (see Figure 11)[3]. Ambitions to photograph the auroral zones with cameras directed towards the rotation axes were thus completely thwarted. The transmission time of radio signals prevented any "real-time" adjustment.

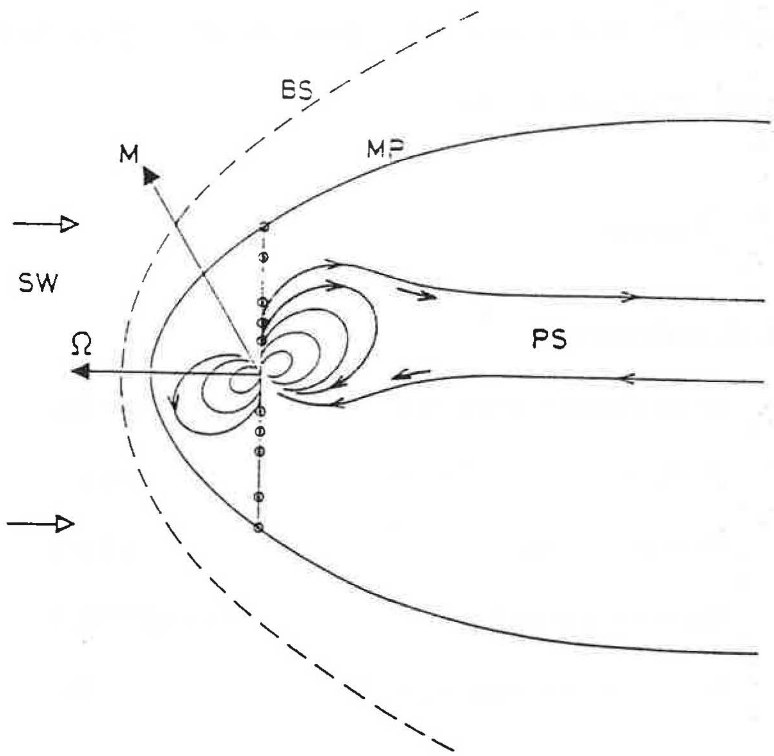

Figure 11. The magnetosphere of Uranus, in the perpendicular-to-ecliptic noon-midnight plane, showing the unexpectedly large tilt of the magnetic axis. The disruptive effect on the radiation zone of the many moons, whose crossing points of the plane are indicated, can readily be appreciated.

[3]'The Planets' makes a creditable attempt at portraying this maverick, good humoured deception, too.

Despite the massive wobble of the magnetosphere, Uranus does contain an inner zone of trapped radiation which exhibits the characteristic loss-cone angular distribution. There are, though, huge losses to the planet's moons since, in contrast to the conditions at Saturn, they sweep out large volumes of the magnetic environment. The tail region is almost devoid of charged particles. Ion streams, though, are found in the plasma sheet boundary layer just as they are at Earth, and, as at Earth, there are major re-configurations of the magnetic field. A feature, until very recently thought to be unique to Uranus, and due to the rotation axis being directed towards the sun, is a twisting of the magnetotail during substorms. However, a similar twisting has now been seen from Galileo in its recent journey along the Terrestrial magnetotail. A different explanation is, therefore, needed, providing yet another example of the value of comparative magnetospheric studies.

4.8 Neptune

Basic Information

Mean distance from sun	4.4×10^9 *km*
Mean planetary radius, R_N	$\sim$ 20000*km*
Rotation period	*uncertain*
Magnetic moment	$\sim 2 \times 10^{17}$ Tm^3
Inclination ofmagnetic axis	57^0
Upstream distance of bow shock	~ 35 R_N
Stand – off distance	*unknown*
Visited by	*Voyager* 2 (1989)

Neptune, not to be outdone, produced an even greater surprise. While the axis of rotation was directed at the usual large angle to the ecliptic plane, the magnetic axis was discovered to be inclined at such a large angle that, at the time of the encounter, it lay pointing towards the sun, as had been expected for Uranus! The field is highly complex and highly asymmetric (Figure 12).

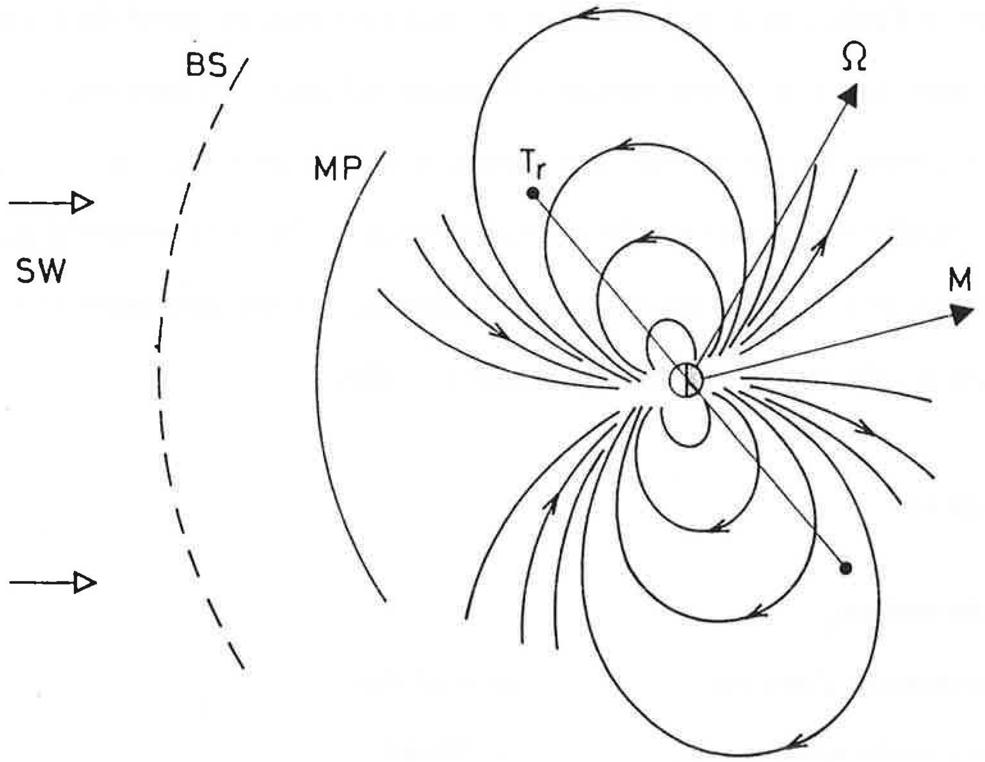

Figure 12. The magnetosphere of Neptune, in the perpendicular-to-ecliptic noon-midnight plane, showing how the large tilt of the significantly offset magnetic axis permits easy access to the solar wind (as with low-rigidity particles at high latitudes in Figure 1). The sweeping effect of Triton, *Tr*, will be readily apparent.

There is, though, a radiation belt inside the Triton orbit, and there is widespread aurora. Sources of plasma are the solar wind (as would be expected from the ready access), the atmosphere, sputtering from the moons, and heavy ions from Triton. The plasma density in the outer magnetosphere is too low to distort the field appreciably from its intrinsic value. Neptune's magnetosphere is generally considered to be the least active of the set, being controlled primarily by the planet's rotation, rather than by the variable solar wind.

4.9 Pluto

Pluto has not yet been explored, and for reasons of logistics cannot be this century. Predictions are invited!

5 Comets

Comets investigated to date are:

Halley	1986; *Giotto, Suisei, Sakigake* *and Vega's* 1 *and* 2 (1986)
Giacobini – Zinner	*ICE* (1986)
Grigg Skjellerup	*Giotto* (1992)

Erosion of the surface of comets by solar electro-magnetic and corpuscular radiation produces, especially close to the Sun, an envelope of atoms, molecules and dust particles. The neutral component is driven anti-sunwards by radiation pressure to form a **gas tail**, and the ionized component is picked up by the solar wind to form a **plasma tail** very reminiscent of planetary magnetospheres. The gas tail is generally curved due to aberration resulting from azimuthal motion of the comet, while the plasma tail is relatively straight and radial due to the high velocity of the picked up ions.

The loaded solar wind is much reduced in speed near the comet, causing a bow shock to form and various boundaries to develop. The loading at distances as great as 10^6 km introduces turbulence into the flow. Despite its small physical size ($\sim$ 10 km in the case of Halley), or rather because of its weak gravitational and magnetic fields, a comet has an influence on the solar wind almost as extensive as those of the giant planets.

6 Conclusions

Space plasma physics is a relatively young branch of Physics, which has until recently, in common with other areas of plasma physics, developed separately from companion areas. It is possibly for this reason that it is currently dominated by an observational approach and a tendency to base interpretation on initial impressions drawn largely from experience gained in media far less versatile and complicated than turbulent plasmas. As a result, understanding of the extraordinarily detailed and consistent measurements cannot yet be claimed to be very deep. A new era, though, can be anticipated, in which an understanding of the complex phenomena outlined above, and many more that can be expected to arise, will develop in parallel with that of the microphysics of plasmas in the laboratory leading ultimately a full appreciation of the workings of the most common state of known physical matter.

7 References

For the basics of the subject I recommend **Roederer J. G., 'Dynamics of Geomagnetically Trapped Radiation', Springer New York 1970** and **Handbook of Geophysics and the Space Environment, ed. A S Jursa, Air Force Geophysics Laboratory. Boston Mass, 1985.** For the latest information and for tracing the stages of development, papers within and cited in the following journals will be found helpful — **Journal of Geophysical Research A (Space Science), Planetary and Space Science, Annales Geophysicae, and Space Science Reviews, The Space Science Newsletter of the European Space Agency, Paris, and EOS, Transactions of the American Geophysical Union, Washington DC.** A useful compendium of references appears in **Contributions in Solar-Planetary Relationships, US National Report 1987-1990, American Geophysical Union 1991.**

In perusing the wealth of literature on Space Plasma Science, the reader is urged to exercise his or her critical facilities to the full, questioning in particular each adopted premise, assumption and simplification.