THE MAGNETOSPHERE OF URANUS

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I. THE NATURE OF PLANETARY MAGNETOSPHERES

The magnetosphere of a planet, as the name implies, is the region surrounding the planet in which the planetary magnetic field plays a dominant role in determining the behaviour of the medium(1). The inner boundary of a magnetosphere is the surface of the planet if it has no significant atmosphere (as in the case of Mercury), or the lower ionosphere in the case of planets with atmospheres. The outer boundary, usually termed the "magnetopause", is shaped by stresses exerted by the solar wind, being blunt on the upstream side, with normal stresses playing a dominant role, and extending in a comet-like "magnetotail" on the downstream side away from the Sun largely as a result of the action of shear stresses. The characteristic size of a magnetosphere, namely the distance L_m (in planetary radii) to the subsolar point is determined approximately by balancing solar wind ram pressure and the magnetic pressure:

$$nmV_s^2 = C\, B_o^2/2\pi L_m^6 \qquad (1)$$

where n is the ion number density and V_s the speed of the solar wind, m is the average ion mass, B_o the (dipole) field strength at the surface of the planet and C is a constant of order unity.

In general, the magnetic pressure in a magnetosphere is much greater than that of the plasma contained and hence the magnetic field configuration is approximately that of a potential field with the given boundary conditions. There are exceptions, however, such as in the case of Jupiter, where the pressure of magnetospheric plasma and rotational stresses play a very important role in determining the magnetic field configuration. These additional stresses

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produce distributed currents within the magnetosphere, equivalent, for example, to an equatorial disk current distribution for the case of rotational stresses. The plasma pressure must always be dominant in the strong current sheets which appear in the magnetotail separating regions of out-going and in-going magnetic flux.

In all cases planetary magnetospheres are sufficiently large obstacles in the supersonic solar wind that bow shock waves must occur on the upstream side ahead of the magnetosphere. The chief function of the shock wave is to reduce the solar wind to subsonic speeds so that the flow may take account of the presence of the magnetosphere and flow around it. The shock wave itself, being collisionless, produces plasma wave turbulence, plasma heating and, in suitable circumstances, acceleration of particles to energies very much greater than that of the incident solar wind ions (i.e. >> 1 keV/nucleon)[(2)].

The interplanetary magnetic field carried by the solar wind plays an important role in the interaction with the magnetosphere in that it can reconnect with the magnetospheric field at the magnetopause and so change the topology and linkage of field lines (defined in the usual way by the plasma "frozen" to them). This has the effect of converting "closed" magnetic field lines (i.e. connected at each end to the planet itself) into "open" field lines (connected to the planet at only one end and leading into the interplanetary medium). Energetic particles can be trapped in closed regions of the magnetosphere, forming radiation belts for example, while open magnetic field lines permit the free access of particles of external origin and the free escape of magnetospheric particles[(3-5)].

Open magnetic field lines must eventually reconnect with each other to form closed field lines once again. This process, which takes place in the magnetotail, is likely to be the most important one for producing hot plasma and energetic particles which can subsequently be injected into the closed inner magnetosphere[(6)]. The upstream and downstream reconnection processes are in balance only on the average so that the ratio of closed to open magnetic flux can vary with time. Furthermore, there are reasons to believe that re-

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connection occurring in the magnetotail can be spontaneously and sporadically enhanced producing the phenomenon which is usually called a magnetospheric "substorm" and which has very close similarities to the solar flare phenomenon[7,8]. Magnetospheric "storms" are the consequence of major changes in the solar wind flow associated with solar disturbances such as flares and these are inevitably accompanied by strong substorm activity, at least in the case of the Earth.

As a direct consequence of reconnection a component of the magnetic field normal to the magnetopause (B_n) exists as well as a tangential component (B_t). Furthermore, the plasma at the magnetopause moves so that the Maxwell shear stress $B_n B_t/4\pi$ produces an energy exchange at a rate

$$W = \frac{1}{4\pi} \int_A B_n B_t V_t dA \tag{2}$$

where V_t is the plasma speed and the integration is carried out over the magnetopause surface (A). On the forward side of the magnetopause the sense of the stress is such that the magnetic field energizes the plasma at a rate

$$W_{m1} = \frac{1}{4\pi} \int_A (V_t B_n) B_t dA = \frac{1}{4\pi} \int_A E_m B_t dA \sim \frac{1}{8} \phi B_m L_m \tag{3}$$

where E_m is the electric field and B_m the magnetic field at the magnetopause, and ϕ the corresponding potential drop. On the tailward side of the magnetopause the external solar wind plasma works against the Maxwell shear stress and so builds up the magnetic energy stored in the magnetotail at a rate

$$W_{m2} = \frac{1}{4\pi} \int_A VB_t (B_n dA) \sim \frac{1}{4\pi} VB_t F \tag{4}$$

where F is the total open magnetic flux and B_t the field strength in the magnetotail. Note that B_t is determined (at large distances from the planet) by the pressure of the external interplanetary medium (excluding the ram pressure) and hence $B_t \sim B_m/M$, where M is the solar wind Mach number ($M \sim 10$ everywhere). Finally, as a conse-

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quence of reconnection occurring at the 'neutral' sheet in the magnetotail the average rate of conversion of magnetic to plasma energy is

$$W_t = \frac{1}{4\pi}\int_A B_t^2 V_n dA \sim \frac{B_t^2 V_n A_t}{4\pi} \sim \frac{\phi B_t L_t}{4\pi} \qquad (5)$$

where A_t is the area of the neutral sheet under consideration, L_t its length and V_n is the plasma speed towards the sheet.

II. ELECTRIC FIELDS IN MAGNETOSPHERES

An essential feature of magnetospheres which has an important bearing on the behaviour of the plasma and energetic particles they contain, is that large scale electric fields exist[(9)]. There are corresponding motions of the plasma such that in general the "frozen field" condition $\underline{E}+\underline{V}\times\underline{B} \sim 0$ is satisfied (except in restricted regions with strong electric currents flowing parallel to the field lines where a significant $E_{\parallel}$ can arise). These hydromagnetic motions of the plasma within a magnetosphere are generally called "convection" in the sense that one imagines the magnetospheric magnetic field lines to be moving and carrying the plasma along with them. The motions may be quasi-steady such as those induced by planetary rotation, atmospheric tides and the average solar wind/magnetopause interaction, or unsteady, such as those induced by variations in solar wind conditions, substorms and low frequency Alfvén and magnetoacoustic waves.

The convection electric fields provide a means for accelerating and decelerating the magnetospheric plasma and energetic particles as well as transporting plasma into and out of the magnetosphere. The energization can be regarded as an adiabatic effect associated with changes in the volume of magnetic flux tubes as they move radially and change shape. In the case of quasi-steady convection the energy changes are limited by the potential differences associated with the electric field pattern (typically ∿ 10% of the external potential difference). In the case of time-varying and random convection, however, there is no such constraint because the electric field is not steady and a few particles will always be able to move from regions of low magnetic field strength to regions of high magnetic

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field strength ("radial diffusion") with a corresponding increase of energy[10].

It is important to note that convective motions are to some extent controlled by the pressure gradients of the magnetospheric plasma and energetic particles as well as by the driving mechanisms mentioned above[11]. The pressure gradients can be regarded as making their presence felt as a result of particle drifts associated with inhomogeneities of the plasma and magnetic field which tend to set up space charge distributions and therefore additional electric fields. This effect can be partly but not completely neutralized by currents flowing to and from the ionosphere along magnetic field lines which in turn may cause parallel electric fields to arise if the density of the plasma required to carry the current is sufficiently low. The parallel electric fields accelerate particles into and out of the ionosphere, thus giving rise to auroral effects when the particles strike the upper atmosphere and possibly introducing new particles of ionospheric origin into the outer magnetosphere[12].

Electric fields are of particular importance in the vicinity of regions where magnetic field line reconnection takes place (loosely described as "neutral" or "X" points). Such electric fields may become transiently and locally very large in cases where the reconnection is sporadic and short-lived. The speed of reconnection (and therefore the electric field and voltage drop available) is limited only by the Alfvén speed (V_A) in the medium so that large transient voltage drops ($\sim V_A B L_m$) are possible as long as the magnetic field configuration is favourably configured for reconnection to occur, as seems to be the case during substorms. In the Earth's magnetosphere, for example, it is apparently possible for voltage drops of the order of $\sim$ 1 MV to exist in the magnetotail for times of the order of $\sim 10\text{–}10^2$ sec[13], which is very much larger than the voltage drops associated with other forms of convection (e.g. rotation $\sim$ 88 kV, solar wind driven convection $\sim$ 50-200 kV, tidally driven convection $\sim$ 30-50 kV). The voltage drops associated with reconnection are especially interesting because it is always possible for a few particles to move a considerable distance along the neutral line, consequently being rapidly accelerated to comparatively high energies.

III. SOURCES OF PLASMA AND ENERGETIC PARTICLES IN MAGNETOSPHERES

The chief sources of plasma in planetary magnetospheres are the solar wind and ionospheres of the planet and any satellites contained in its magnetosphere. In addition, magnetospheres are usually pervaded by a neutral component consisting of the exosphere of the planet (comprised largely of hydrogen), the exospheres of satellites, sputtered products from satellite surfaces and dust and the neutral interstellar medium (which penetrates to within 4 AU of the Sun in the case of hydrogen and 0.5 AU in the case of helium[14]). In addition, there are albedo neutrons and mesons produced as a result of the interaction between high energy cosmic rays and the planetary and satellite atmospheres and/or surfaces and also planetary rings.

Neutron decay can be an important source of energetic protons and electrons in regions of the magnetosphere close to the planet. However, the fluxes of neutrons are very low and it is necessary that the life times of the trapped particles be very long ($\sim$ years) in order to maintain a substantial radiation belt. The relevant loss mechanisms are charge exchange with the neutral background (in the case of protons) and pitch angle scattering followed by loss into the atmosphere of the planet. The latter may be the result of collisions with background plasma and neutral gas and plasma wave scattering due to waves injected from below (lightning flashes or man-made disturbances) or induced by plasma instabilities in the magnetosphere itself. A further important loss mechanism is absorption by planetary dust rings and satellites; this is of particular interest in regions where the energetic particle population is long-lived, since in such cases, the absorption lanes produced by satellites, for example, must be sharply defined.

Planetary ionospheres are a possible source of plasma, especially protons which tend to dominate at high altitudes and for which gravitational binding is least effective. In general, if magnetospheric convection and reconnection with the interplanetary magnetic field permits the plasma to escape into space, the upper ionosphere should flow continually away from the planet in the form of a "polar wind"[15] driven by electron heat conduction or hydromagnetic wave pressure gradients. In regions of the magnetosphere where escape into space is not possible, the plasma pressure will build up until an approximate hydrostatic equilibrium is achieved between the upper magnetosphere and upper ionosphere. A region where such an equilibrium has been achieved is called a "plasmasphere" and its boundary ("plasmapause") is defined by the outermost closed flow line of the convection pattern (at least in the steady state).[16]

Satellite ionospheres can be a copious source of plasma in cases where the satellites have sufficiently dense atmospheres to produce an ionosphere (e.g. Io and Titan). In such cases gravity does not play an important role and the plasma tends to be carried away by the convecting planetary magnetic field lines provided these are not captured by the satellite and/or are not so much distorted that they become disconnected from the planetary magnetic field. Since gravity is not as important as in the case of the planetary ionosphere it is to be expected that heavier ions than protons can be injected into the magnetosphere in this way (e.g. S, O, and SO_2 ions in the case of Io[17]). The existence of a satellite magnetic field of internal origin can protect its ionosphere from such stripping of plasma by the planetary magnetosphere if it is sufficiently strong to produce a region of closed magnetic field lines.

Neutral gas may also escape from satellites either by evaporation of their atmospheres or sputtering from their surfaces. Escaping particles with low energies remain trapped in orbit around the planet forming a neutral gas torus (H in the case of Titan and Na, K and SO_2 products in the case of Io)[18]. Neutral gas tori are also sources of plasma following collisional photo-ionization and also act as a loss mechanism for magnetospheric ions as a result of charge exchange. The process of ion mass pick-up involved when satellite upper atmosphere and torus atoms and molecules become ionized is interesting in that the new ions are accelerated to energies $T_{\perp}$ =

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$\frac{1}{2} mV_r^2$, where V_r is the convection speed relative to the satellite or neutral gas cloud. Furthermore, a pick-up electric current I is induced such that

$$V_r \dot{M} = I B L_n \tag{6}$$

where $\dot{M}$ is the total mass ionization rate and L_n is the characteristic dimension of the neutral gas cloud or atmosphere[19]. The current distorts the magnetic field pattern and must close through the planetary ionosphere allowing some possibility for the generation of radio wave emissions and parallel electric fields with associated particle acceleration[20].

It is in principle possible for plasma particles originating from the planet and satellites to be accelerated to high energies by interacting stochastically with plasma wave turbulence[10]. This is not a very efficient process in general, however, because there are no very powerful external sources of plasma turbulence and the waves are not always confined within the magnetosphere. The most effective acceleration mechanism for such particles is likely to be reconnection occurring on stretched-out field lines in the magnetotail followed by convection and/or diffusive transport back into the inner magnetosphere. In such a scheme there are no difficulties with the total energy requirement since the magnetic energy stored in the magnetotail can be tapped and this is in turn drawn from the solar wind and possibly in some cases from the rotational energy of the planet. Direct acceleration from ionospheres is possible as a result of the occurrence of parallel electric fields and if accompanied by energetic particle precipitation these may result in rather peculiar ions being introduced into the magnetospheric energetic particle population (e.g. H_2^+ and H_3^+ in the case of Jupiter and Saturn[21]).

The solar wind must always be considered as a possible source of plasma for a planetary magnetosphere. The mechanisms of entry include drift and diffusion across the magnetopause and flow along open field lines produced by reconnection between the interplanetary magnetospheric magnetic fields. Final capture of solar wind plasma on

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open field lines occurs only after reconnection occurs in the tail forming closed field lines which can convect the plasma into the inner magnetosphere. Since the plasma on open magnetotail field lines, whether of solar wind or planetary origin, tends to stream away from the Sun it is necessary for efficient capture of solar wind plasma that tail reconnection takes place at large distances from the planet. In the case of the Earth's magnetosphere, where plasma of internal origin does not play an important role in determining the dynamics of the situation, the capture efficiency (ε) for solar wind plasma is of the order of 10^{-3}-10^{-4} (22). Clearly, the solar wind plasma has a special signature in that the relative abundances of elements and isotopes correspond to those of the solar corona and the ionization state is that of a plasma with an electron temperature of the order of 1.5×10^{6}K. Thus one expects to find in addition to protons, ions such as He^{+2} and O^{+6}, whereas particles of internal origin have "non-solar" elemental abundances and tend to be singly ionized unless the magnetospheric plasma is sufficiently dense and hot as to permit ionization by electron impact to higher levels.

The interstellar gas is a further possible source of magnetospheric particles, which is important provided it can be ionized with sufficiently high efficiency. The ratio of the interstellar and solar wind sources is given approximately by

$$\alpha N_n L_m / 3\varepsilon\Phi_{sw} \tag{7}$$

where α is the ionization rate, N_n the density of the interstellar medium, L_m the characteristic size of the magnetosphere and Φ_{sw} the solar wind flux. If photo-ionization of the interstellar hydrogen is the dominant ionization process then both α and Φ_{sw} scale similarly with distance from the Sun and, in particular, $\alpha \sim 1.5\times10^{-7}$/sec and $\Phi_{sw} \sim 2\times10^{8}/\text{cm}^2\,\text{sec}$ at 1 AU. Taking $N_n \sim 10^{-1}/\text{cm}^3$ and $\varepsilon \sim 10^{-4}$, we see that the interstellar source is not likely to be important unless $L_m \gtrsim 10^{12}$cm, which is much larger than found for any magnetosphere observed to date.

IV. COMPARISON OF MAGNETOSPHERES

To date, magnetospheres have been found around the Earth, Mercury, Jupiter and Saturn (in order of discovery). Venus appears to have no significant magnetic field of internal origin, as do the comets, hence the description of a magnetosphere given above is not useful. Nevertheless, the term is sometimes applied to the region of strong magnetic field captured by the ionosphere from the interplanetary medium in such cases. It seems possible that a very weak magnetic field of internal origin exists in the case of Mars and hence one may consider that this planet has a genuine magnetosphere, at least transiently, but it is very much on the border line.

The Earth's magnetosphere has by now been rather thoroughly explored by a large number of spacecraft, although by no means everything is well understood. The strength of the Earth's magnetic dipole (0.3 gauss at the equator) is such that the characteristic dimension of the magnetosphere on the upstream side is typically $\sim 10\ R_e$ (Earth radii), although variations from $\sim 5\ R_e$ to $12\ R_e$ are possible. Rotation and atmospheric tidal effects play a relatively minor role and most of the energy input is provided by the solar wind. From (4) we deduce that, with $B_t \sim 10$-20 gauss, about 1% of the incident solar wind energy flux (10^{20}-10^{21} ergs/sec) goes into forming the magnetotail (i.e. 10^{18}-10^{19} ergs/sec) and about 10% of this ultimately appears in the inner magnetosphere in the form of energetic particles, some of which are lost into the atmosphere producing aurorae. The total energy stored in the magnetosphere is $\sim 10^{20}$-10^{22} ergs and the average dissipation rate about 10^{17}-10^{18} ergs/sec[(23)]. Most of the energetic particles in the magnetosphere appear to originate in the solar wind[(24)] but a substantial component (10% or more) of ionospheric origin is sometimes observed[(25)]. The contribution from atmospheric neutron albedo is very small. Since the Moon's orbit crosses only the distant magnetotail it has no significant influence on the magnetosphere, although interesting absorption effects can be seen in its immediate vicinity[(26)]. The inner boundary of solar wind induced convection lies usually in the range 3-6 R_e, depending on magnetic activity, and within this region a rather dense plasmasphere is formed (densities 10^2-$10^3\ cm^{-3}$ at the plasmapause)

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comprised largely of H^+ together with smaller amounts of He^+ and O^+ ions(27).

The undistorted equatorial field intensity of Mercury appears to be of the order of 260 gammas(27), which yields a minimum radius of the magnetopause of the order of 1.5 R_m. On the basis of terrestrial values, one might expect an energy influx of $\sim 10^{16}-10^{17}$ ergs/sec to the magnetotail and $\sim 10^{15}-10^{16}$ ergs/sec to the inner magnetosphere, with a solar wind particle injection rate of $10^{22}-10^{23}$/sec. Despite the relatively small size of the magnetosphere the low plasma density and relatively high magnetic field strength ($\sim$ 50-100 gammas) in the magnetotail allow large transient electric fields to develop and accordingly particles are observed to be accelerated to quite high energies(28). In view of the fact that the planet itself occupies a large part of the magnetosphere by volume, most of the particles trapped by the solar wind are presumably absorbed directly on the surface which should produce a continuous flux of sputtered ions and neutral atoms which may be observable spectroscopically(29). Mercury has no significant atmosphere or ionosphere and hence magnetospheric convection is impeded only by plasma pressure effects.

The magnetosphere of Jupiter is characterized by its very large size (4 gauss equatorial surface field and $\sim$ 50-100 R_J minimum radius), and the presence of the satellite Io in the inner magnetosphere. Io has a thin atmosphere associated with venting of gases such as SO_2 and an ionosphere which contributes a large flux of ions to the magnetosphere ($\sim 10^{28}$/sec)(17,30). The mass pickup current, according to equation (4), is $\sim 10^6$ amps and the corresponding energy dissipation $\sim 10^{19}$ ergs/sec. As a consequence of the rapid rotation of the planet, which dominates the convection, the centrifugal stresses are sufficient to distort the configuration of magnetospheric field lines into a disc-like structure which extends into the magnetotail forming a plasma sheet superficially similar to that of the Earth(31). There is a distinction, however, in that at Jupiter the plasma in this sheet is largely of internal magnetospheric origin and escapes down the tail whereas in the Earth's magnetosheath the plasma tends to be pre-dominantly of solar wind origin and is brought from the tail into the inner magnetosphere.

There is evidence for the presence of particles of solar wind origin at higher energies in the Jovian magnetosphere and also, surprisingly enough, particles of ionospheric origin (notably H_2^+ and H_3^+), presumably being extracted from the planetary ionosphere in some form of auroral process[21]. The total energy flux involved in these processes is $\sim 10^{22}$ ergs/sec with the rotational energy of the planet being probably the most important source. The particle injection rate is of the order of 10^{28}/sec with Io, the planetary ionosphere and the solar wind being of rather comparable importance[32]. Presumably the effects of rotation drive an unstable convection pattern[33-35] giving rise to radial diffusion of energetic particles. The latter may be given a significant boost in energy as a result of reconnection taking place in the magnetotail.

The Saturnian magnetosphere is rather more similar to that of the Earth than of Jupiter, despite its rapid rotation rate. The chief reasons for this are that the Saturnian magnetic field is relatively weak ($\sim$ 0.2 gauss at the equator)[36] and there is no strong source of plasma within the magnetosphere comparable to Io. The satellite Titan, which has a dense atmosphere and ionosphere, has an important effect on the outer magnetosphere as it produces in particular a neutral hydrogen torus which provides an upper limit to the lifetime of protons of $\sim 10^7$ sec[37]. The energetic particles in the magnetosphere appear to be largely of solar wind origin apart from a component comprised of molecular hydrogen ions which must originate in the ionospheres of Titan or Saturn itself[38]. There is evidence for a satellite source of plasma since large numbers of oxygen ions are present in the inner magnetosphere where there are several moderate sized satellites with icy surfaces[39]. By analogy with the terrestrial magnetosphere the solar wind energy input to the Saturnian magnetosphere is of the order of 10^{19}-10^{20} ergs/sec. The presence of the rings and a number of small satellites close to the planet is, however, of some interest since cosmic ray interactions producing neutron albedo and mesons appear to be the dominant source of the more energetic particles and the absorption lanes produced by satellites are very sharply defined indicating that there is little if any radial diffusion[40-42] in the inner magnetosphere.

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V. PROSPECTS FOR URANUS

At present the literature devoted to the magnetosphere of Uranus is very sparse indeed, consisting of a report of a possible observation of radio emissions from the planet[43], a number of discussions contained in proposals for the ill-fated MJU mission[44,45] and a few papers speculating on the possible nature and magnetic topology of the Uranian magnetosphere[46-48].

It is generally agreed that since in all other cases so far observed, the magnetic dipole axis and the axis of rotation of the planet are approximately parallel this should also be the case at Uranus. Since at the present time the axis of rotation is pointing almost directly at the Sun this implies that the Uranian magnetosphere is unusual in that the dipole axis is roughly parallel rather than roughly perpendicular to the direction of the solar wind flow. Furthermore, one polar region is constantly sunlit and thus has a permanent ionosphere with an electron density typically of the order of $10^4 cm^{-3}$, whereas the other pole is in darkness and any ionosphere that may exist can only be due to magnetospheric particle precipitation and a very weak contribution from galactic radiation. The rate of rotation of Uranus is somewhat longer than that of Jupiter and Saturn and it is also noteworthy that, although five small (probably icy) satellites and particulate rings are present, there is no obvious strong source of plasma and neutral gas such as Io and Titan.

The radius of Uranus is only half that of Saturn and its rate of rotation also slower, however, the angular momentum of the planet is comparable to that of both Saturn and Jupiter. In view of our ignorance of the internal structures of the planets and the lack of a quantitative magnetic dynamo theory it is not reasonable to do anything more than guess that the surface field of Uranus might lie in the range $B_o \sim 0.1$-1.0 gauss. Accordingly, the minimum radius of the magnetosphere, for average solar wind conditions at the orbit of Uranus, is given approximately by

$$L_u \sim 35\, B_o^{1/3} \sim 25\text{-}50\ R_u \qquad (8)$$

with $B_m \sim 5$ gammas. A magnetosphere of this size would usually en-

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close the entire Uranian satellite system but as the satellites are so small and probably lacking all but the most tenuous of atmospheres, one does not expect them to produce any significant magnetospheric effects other than acting as absorbers for energetic particles and plasma and possibly as a source of sputtered neutrals, which would probably be dominated by the products of water ice.

The bow shock standing ahead of the Uranian magnetosphere should accelerate particles to suprathermal energies as observed at the Earth and Jupiter. However, since the interplanetary magnetic field is on the average almost perpendicular to the solar wind direction at this distance from the Sun, it is not expected that the acceleration should be very efficient for particles originating in the solar wind. Suprathermal particles of interplanetary and solar origin should, however, be accelerated by the single reflection mechanism, but probably not very effectively by diffusive (multiple) reflection since the time scales available are relatively short[(49)].

It is to be expected that, as in the case of Saturn, the Uranian magnetosphere is not an especially active one and the radiation belts should not be very intense. The solar wind energy flux incident on the Uranian magnetosphere should be of the order of 2-8x 10^{19} ergs/sec under normal conditions, increasing by perhaps a factor 10 during disturbances. The rate at which energy is injected into the magnetosphere in this way is therefore probably of the order of 2-8x10^{17-18} ergs/sec, which is somewhat less than that found at the Earth, for example. The corresponding particle injection rate is of the order of 10^{25}-10^{26}/sec.

The most interesting aspect of the Uranian magnetosphere concerns the nature of its interaction with the solar wind, in view of the fact that it is unusual in being pole-on to the flow. As a consequence of the normal stresses exerted by the solar wind plasma and magnetic field it is to be expected that a distinct funnel is formed on the upstream side of the magnetosphere. The funnel should be deflected to one side as a result of reconnection between the planetary magnetic field and the interplanetary magnetic field, which on the average should lie in the ecliptic plane and be approximately perpendicular to the Sun-planet line. As a consequence of reconnection solar wind particles should be able to penetrate easily into the region near the pole on the sunward side of the planet causing some additional airglow in this region.

Freshly opened magnetic field lines must, in the usual manner, be stretched out and add to the two halves of the magnetotail. The open field lines contained in the magnetotail should consist of a roughly circular bundle emanating from the magnetic pole on the dark side of the planet, separated by a thin plasma sheet from a more crescent-shaped bundle of field lines with the opposite field direction. The latter bundle may also be displaced out of the ecliptic plane in the sense of planetary rotation by an amount dependent on the balance of stresses exerted by the ionosphere at the foot of the bundle and by the solar wind on the interplanetary side. The magnetic field strength in the magnetotail should be of the order of 0.5 gamma for average solar wind conditions.

The plasma sheet separating the two regions of oppositely directed magnetic fields in the magnetotail must map into a closed curve in the polar regions on the dark side of the planet. This curve should mark the high "latitude" edge of the auroral zone on the dark side. The auroral zone may not extend more than a few degrees in latitude because the total electric potential drop available from planetary rotation may be of the order of 10^{6-7}V whereas the solar wind induced convection (assumed to be about 1/10 of the interplanetary potential drop across the magnetosphere) is only of the order of $5x10^{4}$V. As a consequence, the magnetosphere could in principle contain a very large plasmasphere extending almost to the magnetopause. Since all moderately high latitude magnetic field lines have one end connected to a fully sunlit ionosphere a weak polar wind of protons and electrons should be sufficient to provide the necessary plasma if the escape time is long. It is conceivable that the distribution of plasma in the plasmasphere is thus dominated by rotational instability as in the case of Jupiter, but whatever the cause of radial diffusion it is likely to be relatively slow so that neutralization by the satellites could be a significant loss mechanism as well as escape along opened field lines into the magnetotail(34).

In such a quiescent magnetosphere one would expect the low

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energy plasma to be dominated by protons of ionospheric origin and possibly ions such as O^+ sputtered from the surfaces of the satellites and rings. The more energetic particles in the outer magnetosphere could be comprised of accelerated plasmaspheric ions, some molecular hydrogen ions as found at Jupiter and Saturn and ions of solar wind origin. The most energetic particles are likely to be the result of interactions between cosmic rays and the satellites, rings and atmosphere of the planet but there may also be a contribution from temporarily trapped particles of interplanetary or solar flare origin. As a consequence, much of the Uranian magnetosphere should be rather similar to the inner parts of the Saturnian magnetosphere and relatively stable in comparison with the magnetospheres of the Earth and Jupiter.

VI. CONCLUSIONS

On the basis of the above arguments and guesswork, it appears that the Uranian magnetosphere should be characterized by long time scales in the inner regions and hence sharply-defined satellite and ring absorption lanes and relatively low energetic particle intensities. Nevertheless, considerable activity may occur in the outermost parts of the magnetosphere and the magnetotail and a weak auroral zone may be detectable near the equator on the dark side of the planet. The topology of the magnetic field must have some peculiarities, notably the dayside funnel and the magnetotail with its plasmasheet cutting on the average across the ecliptic plane.

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