Adv. Space Res. Vol. 10, No. 1, (1)5–(1)13, 1990.
Printed in Great Britain.

0273–1177/90 $0.00 + .50

THERMAL PLASMA IN OUTER PLANET MAGNETOSPHERES

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ABSTRACT

The plasma environments of the outer planets are a study in contrasts. The magnetosphere of Jupiter is dominated by the prodigious plasma output of Io, with losses due to diffusion driven by mass loading. At Saturn, the small icy satellites are the major sources of plasma for the inner magnetosphere. The low mass loading rates there imply that the densities of the plasma tori are limited by dissociative recombination, rather than diffusive transport. At Uranus, the icy satellites are negligible plasma sources compared to the input from the extended neutral hydrogen cloud and the ionosphere. Convection driven by the solar wind penetrates deep into the inner magnetosphere because of the unique orientation of the rotation axis of Uranus. The expected magnetosphere of Neptune is similar to that of Saturn and Jupiter, with Triton, the ring arcs, and the planet as possible plasma sources. The Voyager 2 encounter with Neptune holds out the hope of a passage through a non-terrestrial auroral region, a unique event in planetary exploration.

OVERVIEW

In 1966, Gary Flandro, a graduate student doing pre-doctoral studies at the Jet Propulsion Laboratory, discovered a rare alignment of the outer planets that allows a spacecraft to use gravity assists to proceed from Jupiter to Saturn to Uranus and then to Neptune /1/. The alignment of the outer planets which makes this "Grand Tour" possible occurs only every 176 years, with the gravity assists making the total trip time to Neptune about 12 years (the unassisted flight time to Neptune would be about 40 years). The Voyager 2 spacecraft is now on the last leg of the Grand Tour, with closest approach to Neptune on August 24, 1989. In the present article, we review the results obtained by the Voyager Plasma Science Experiment (PLS) in the magnetospheres of Jupiter, Saturn, and Uranus, and then review our expectations for the encounter with Neptune. The PLS experiment /2/ consists of a set of four sensors which measure the properties of ions and electrons in the energy-per-charge range from 10V to 5950V. This energy range contains the dominant contribution to the number density of particles in these magnetospheres. However, the dominant contribution to the plasma pressure is at times above the PLS energy range, in the energy range of the Low Energy Charged Particle (LECP) experiment on the spacecraft /3/,/4/. We first give a brief overview and comparison of the magnetospheres, and then discuss topics of current research interest for each planet.

The magnetospheres of these three outer planets are alike in many ways. For example, the dominant flow pattern in their inner and middle magnetospheres is consistently in the sense of corotation with the planet. In other ways, they are very different, most dramatically in their plasma sources and source strengths. Table 1 compares some of the properties of the plasma at the various planets. There are a number of comments that should be made with regard to the entries in Table 1. The dominant plasma source at all of the planets except Uranus is thought to be the satellites, and this is reflected in the heavy-ion composition of the plasma in these magnetospheres. Jupiter is far and away the most massive of the magnetospheres, with the most prodigious plasma input, due to the presence of its active satellite, Io. The magnetospheres of Jupiter and Saturn are similar in many respects, but are distinctly different from that of Uranus. Most obviously, the planet is the source of the plasma at Uranus, instead of the satellites. Moreover, the plasma at Uranus is always subsonic with respect to corotation, whereas at Jupiter and Saturn it is transonic to highly supersonic. This is a consequence of the fact that transport at Uranus is dominated by sunward convection driven by the solar wind, giving rise to the short lifetime of plasma in the system and significant heating due to adiabatic compression by the sunward flow. The low Mach numbers at Uranus imply that the spatial distribution of plasma in the Uranian magnetosphere is very different than that at Jupiter and Saturn. Whereas at the later planets, plasma tends to be concentrated near the magnetic or centrifugal equator because the thermal speeds are smaller than or comparable to corotation speeds /5/, at Uranus the plasma is spread uniformly along

TABLE I. Thermal Plasma Properties

	Jupiter	Saturn	Uranus	Neptune[a]
Magnetopause	50-100 R_J[b]	20 R_S[b]	18 R_U[b]	10-50 R_N[b,c]
Sources	Io	Icy Moons, Titan	HI Cloud, Ionos.	Triton, Ionos.
Composition	H,O,S,Na,K	H,O,H_2O,N,OH,H_2	H	H,N,N_2,CH_n
Source Strength	$>10^{28}$ ion/s	10^{26} ion/s	10^{25} ion/s	10^{25} ion/s
Lifetimes	months - years	months	days	months
Content	10^{34} ions	10^{32} ions	10^{30} ions	10^{31} ions
MachNumbers[d]	1-20	1-5	0.2	1

[a]expected properties for encounter planning

[b]R_J = 70,398 km, R_S = 60,330 km, R_U = 25,400 km, R_N = 24,300 km

[c]assuming a surface field strength of 0.01-1G

[d]with respect to corotation speeds

the magnetic field lines because the plasma thermal speeds are so much greater than corotation speeds. In addition, there are features in the Uranian magnetosphere which are consequences of the deep penetration of solar-wind-driven convection into the Uranian magnetosphere, a penetration which does not occur at Jupiter and Saturn.

At Jupiter and Saturn, β values ($8\pi NkT/B^2$) can be comparable to or greater than 1, so that the magnetospheric magnetic field can be severely distorted by the presence of that plasma. In contrast, at Uranus, the consistently low values of β, both in the PLS and LECP energy range, implies that the Uranian magnetosphere is the best approximation to a "vacuum" magnetosphere that we have explored. Plasma transport at Jupiter is driven by instabilities associated with the high mass injection rates. At Saturn, with its lower mass injection rates, this is not an important process in the inner magnetosphere, although it may be important in the outer magnetosphere. Also, transport driven by atmospheric winds is important in the outer magnetosphere at Saturn. In the inner magnetosphere, dissociative recombination and charge exchange times are short compared to transport times, and transport is not a significant process for the thermal plasma. At Uranus, the transport is solar-wind-driven convection, leading to the short residence times. The situation at Neptune is thought to be similar to that at Saturn, with Triton replacing the icy moons and Titan as a plasma source. We now expand on these comments and discuss the current PLS research efforts at each of these planetary magnetospheres.

JUPITER

The low energy plasma environment at Jupiter has been previously reviewed /6/, and we discuss here only these topics which have been the subject of recent research. The original electron analysis at Jupiter was carried out by Scudder et al. /7/, and has recently been extended for the Io plasma torus region by Sittler and Strobel /8/. In all of the outer planet magnetospheres so far explored, the electrons exhibit both a thermal Maxwellian component and a suprathermal non-Maxwellian component. The electrons play a major role in the Io torus physics through the ionization of neutrals and ions by impact ionization, and thus detailed consideration of electron impact ionization rates is crucial to the understanding of the physics of these environments /8/. The original positive-ion PLS analysis at Jupiter (and Saturn as well) was based on a model for the sensor response appropriate for a supersonic plasma entering close to the normal of one of the four PLS sensors (the "finite aperature/infinite collector" approximation); the analysis was therefore limited to single sensor analysis in transonic flows and yielded no information on vector velocities (except in the cold Io plasma torus, due to the favorable geometry of the flow with respect to the main sensor normals there). The major advance in the Jovian and Saturnian ion analyses since the initial analyses has been the application of a much more sophisticated multi-sensor response code to a broad set of PLS data. This code has been developed at great effort and expense, but the results it provides on properties of plasma (particularly plasma velocity) are crucial to the understanding of the physical processes in these magnetospheres, and can be obtained in no other way. The multi-sensor analysis code was originally developed to analyze a handful of PLS spectra near the Io flux tube /9-12/, and in its initial form was slow and prohibitively expensive to use. It was made more efficient and extensively modified by one of the authors (RLM), and configured to analyze much larger amounts of data on a routine basis, in a variety of computing environments. The code as modified has subsequently been used to analyze PLS data at all of the outer planets thus far explored /13-19/. The use of this code has yielded new insights at every planet so far explored, but its use was particularly crucial in the analysis of data in the magnetosphere of Uranus /19/, where the plasma flow is oblique and subsonic throughout the magnetosphere, and where there is no region in which the simple approximation to the sensor response used in the first-cut analysis at Jupiter and Saturn is appropriate.

The use of the multi-sensor code in the inner magnetosphere of Jupiter, near the Io flux tube (IFT), was also crucial to the analysis of PLS data there, since the flow was highly oblique to all four PLS sensor normals in this time period. The plasma flow velocities near Io reflect the presence of the Alfvén wing generated by Io in its motion through the Io plasma torus at Jupiter /9/,/10/. The PLS velocity measurements show the direction of the ambient flow deviate first slightly toward and then strongly away from Jupiter (speeding up as it does so), as the ambient plasma moving with Jupiter flows around the plasma frozen to the IFT. The estimated current in the IFT is three million amperes, close to the maximum value expected theoretically. The energy flux in the Alfvén wing is about two billion kilowatts. This copious amount of energy pouring down along magnetic field lines toward Jupiter drives the decametric emission at the ends of the IFT, through processes that are complicated and not yet fully understood.

In the middle magnetosphere of Jupiter between 10 and 25 R_J, Sands and McNutt /14/ have applied the multi-sensor analysis to show that the plasma flows there tend to be azimuthal but sub-corotational, although there exists a substantial non-azimuthal component of the flow. The magnitude of this component can be as large as ~40% of the azimuthal component, with 20% a typical value. The non-azimuthal flow is mostly magnetic-field-aligned (although a cross-field component also exists) and directed away from the magnetic equator. The sense of these non-azimuthal flows is consistent with a model in which they are driven by solar wind compression of the dayside magnetosphere. These authors also concluded that there is no enhanced plasma outflow in the active sector, in contrast with the predictions of the corotating convection model of Hill et al. /20/. This model of plasma transport at Jupiter suggests that a depression of the surface magnetic field strength of Jupiter enhances radially outward plasma flow for a particular range of longitudes (the active sector). The PLS results suggest that the corotating convection model is not a major factor in the overall plasma transport in the Jovian magnetosphere, at least during the Voyager 1 encounter. In a related study, Richardson and McNutt /21/ have put an upper limit of 10% on changes in density between adjacent magnetic flux tubes in the inner Jovian magnetosphere. This limit rules out transport models which invoke inward motion of near empty flux tubes to replace outward-moving flux tubes carrying plasma from Io, in particular the models of Pontius et al. /22/ and Summers and Siscoe /23/. These observations and their interpretation have had a major impact on theoretical concepts regarding transport in the torus, since they have eliminated from consideration what had been the most commonly accepted models of this process.

In another area with implications for transport at Jupiter, McNutt et al. /13/ have re-examined the nature of the voids seen on Voyager 2 in the dayside middle magnetosphere and, on the basis of the velocities obtained from the multi-sensor analysis, concluded that these voids could not be associated with Ganymede, as originally thought /24/. Instead, these authors surmise that the voids are caused by a bubbling of the jovian magnetosphere due to a ballooning mode instability, and that this bubbling represents a different state of the magnetosphere as compared to one seen during the Voyager 1 passage. The difference between the two passes is ascribed to changing solar wind conditions upstream of Jupiter, with the ballooning mode instability triggered by a rapid increase in solar wind ram pressure during the Voyager 2 passage. Khurana et al. /25/, although agreeing that the voids are not associated with Ganymede, have subsequently pointed out that the PLS voids are accompanied by large enhancements of the flux of energetic ions and electrons in the LECP energy range, and argue that the voids are artifacts caused by the spacecraft charging negatively to values between a few kV and tens of kV. Such large negative voltages would cause the appearance of voids in the PLS measurements with no real decrease in ambient density. McNutt /26/, in an exhaustive review of all of the relevant data sets in this region, has concluded that the voids cannot be ascribed to charging effects alone. Although this area remains a subject of controversy, it is clear that something very unusual was occurring in this region of the middle magnetosphere of Jupiter during the Voyager 2 passage, and that it was very different from the state seen by Voyager 1 during its traversal of the region. A final resolution of the current controversy may have to await the arrival of the Galileo orbiter at Jupiter in 1995.

The multi-sensor analysis code is also being used to re-examine measurements made in the Io plasma torus. Increased attention has been focused on problems in the energetics in standard models of the plasma. Until recently, the energy balance and charge state of the torus was thought to be well understood, but Shemansky /27/ has revised the estimates of the cooling rates associated with SII, so that it is the dominant radiator of energy per ion in the torus, instead of SIII. The effect of such increased radiative efficiency of SII is dramatic, in that radiative cooling becomes so efficient that the electron temperature is maintained at a level too low to produce any significant density of SIII compared to SII, contrary to observation. Smith et al. /28/ have suggested that the resolution of this energy crisis is the inward radial diffusion of low-density, hot ions. It is thus of interest to know the phase space gradient of suprathermal ions in the PLS energy range between 300 V and 6 kV, since the inward diffusion of these ions may be important to the overall energy balance in the torus. This is a difficult problem to resolve from the PLS measurements in the torus, because of the complex nature of the plasma environment there, and because of a variety of instrumental effects which are negligible in the more benign environments outside of the torus. This is an area of continuing research.

Finally, Richardson /16/ has used the multi-sensor code to study the transonic ion distributions in the dayside magnetosheaths of Jupiter (and Saturn) and concluded that the ion distributions throughout the dayside sheath for all four encounters are well represented by two populations of protons, with comparable densities but with temperatures of 100 and 1000 eV. The bowshocks in this study were all supercritical (fast magnetosonic mach numbers in excess of 3), with post-shock β values ranging from 0.18 to 11. Although similar distributions are seen at Earth, the percentage of hotter protons is much higher at Jupiter and Saturn. Interestingly enough, such distributions are only occasionally seen at Uranus. The mechanism which produces these two temperature populations in the passage through the bowshock is thought to be related to ions reflected from the shock and then swept back across into the magnetosheath, in a manner analogous to the case at Earth /29/.

SATURN

Lazarus and McNutt /30/ and Sittler et al. /31/ carried out initial analysis of the PLS measurements at Saturn. Richardson /15/ subsequently applied the multi-sensor ion analysis technique to the Saturn ion data, and Richardson et al. /32/ have considered detailed models of satellite tori of the icy moons of Saturn (see also the review by Richardson /33/. The saturnian magnetosphere consists of an inner plasma sheet region where the density increases smoothly with radius and an outer mantle region where plasma densities and temperatures vary erratically. The boundary between these two regions occurs at L = 12 in the Voyager 2 pass and at L = 16 in the Voyager 1 pass. Analysis of the ion spectra show a composition consistent with the presence of H^+ and heavy ions with mass near 16, either water group ions (O^+, OH^+, H_2O^+) associated with the icy moons or nitrogen containing ions associated with Titan.

The source of the plasma in the inner magnetosphere is thought to be the icy moons Enceladus, Dione, Tethys, and Rhea. These inner satellites are embedded in a plasma environment in which they are continuously bombarded by energetic ions, corotating ions, and solar radiation, and this results in the injection of substantial amounts of neutral dissociation products of H_2O into the magnetosphere. The subsequent ionization of these neutrals provide the plasma sources for the inner magnetosphere. Richardson et al. /33/ find that the primary loss for plasma inside L = 8 is dissociative recombination (molecular ions) and charge exchange (atomic ions). Modeling of these source and loss processes in the inner magnetosphere gives equilibrium densities that are in good agreement with observations. Outside of L = 8, dissociative recombination is less important, and transport plays a major role in removing plasma. Outside the plasma sheet, the density peaks observed in the plasma mantle are thought to be blobs of plasma which become detached from the plasma sheet due to a centrifugally driven flute instability /34/. Voyager 1 also flew through Titan's wake, and an outflow of cold heavy ions was observed there /35/. The ions were prbably either N_2^+ or H_2CN^+, so that Titan is a significant plasma source in the outer magnetosphere of Saturn, perhaps contributing "plume" material which is wrapped around Saturn due to corotation /36/. Barbosa /37/ has also modeled a nitrogen plasma torus associated with Titan, and proposes that the saturnian aurora is excited by the ion and electron precipitation from this torus.

Broadfoot et al. /38/ observed a cloud of neutral H at Saturn which was originally interpreted as having escaped from Titan. Recently, this data has been reinterpreted in terms of a cloud of neutral H which escapes from Saturn's atmosphere and forms a dense cloud extending past Titan /39/,/40/. Richardson and Eviatar /41/ have argued that such an interpretation is inconsistent with the PLS data, since the presence of such a cloud in the inner magmagnetosphere would result in a much larger proton density than observed, and would remove all heavy ions from the magnetosphere via charge exchange. They thus propose that the neutral H cloud is associated with Titan as originally reported.

Finally, in an extension of the earlier analysis of Richardson /15/. Richardson and Eviatar /42/ have shown observationally that heavy ion distributions in the inner Saturnian magnetoare highly anisotropic, with the temperature perpendicular to the magnetic field greather than that parallel to the field. Calculations of coulomb time scales show that isotropization and energy diffusion time scales of water group ions are longer than the residence time of these ions, and that they therefore should be highly anisotropic and non-Maxwellian (the opposite is true for protons). Solutions of a steady-state kinetic equation for the distribution of perpendicular velocities for H_2O^+ picked up in Saturn's inner magnetosphere are also consistent with the observations (i.e., a broad peak in perpendicular velocity centered at about the corotation energy).

URANUS

The Voyager 2 encounter with Uranus in January of 1986 revealed a fully developed magnetosphere with a number of novel features. The most striking of these was the large 60° tilt of the magnetic dipole axis with respect to the rotation axis of the planet. In addition, the plasma environment at Uranus exhibited many unexpected properties /43/. These plasma features mark the Uranian magnetosphere as being intrinsically different from those of Jupiter and Saturn. Uranus is unique in the solar system in that its rotation axis lies nearly in its orbital plane. The orbital period of Uranus about the Sun is 84 years, and, in this particular epoch, the Uranian rotation axis lies close to the Sun-planet line. The pre-encounter expectations for the low energy plasma environment at Uranus were based on experience in the magnetospheres of Jupiter and Saturn. The classic calculation for the distance to the plasmapause /44/ for reasonable Uranian dipole moments and solar wind conditions at 20 AU yields a plasmapause distance which extends beyond the magnetopause on the dayside. Thus the magnetosphere of Uranus was predicted to be corotation-dominated, as at Jupiter and Saturn, instead of convection-dominated, as at Earth; that is, the plasma in the inner and middle magnetosphere would be corotating with the planet, and shielded from sunward flow driven by the solar wind. The major contributor to the plasma population was envisaged to be heavy ions produced by sputtering from the icy satellites, resulting in corotating plasma tori at Uranus similar to those seen at Saturn (i.e., consisting of the dissociation products H_2O), and with less important contributors being the ionosphere of the planet and the solar wind /45/,/46/. As at Jupiter and Saturn, it was expected that the thermal speed of the plasma in the PLS energy range would be comparable to or smaller than the local corotation speed--i.e., the plasma would be transonic or supersonic with respect to local corotation speeds. This situation is a natural result of local pick-up and radiative cooling of ions freshly ionized from neutrals. As a result, deep inside the inner magnetosphere the cold (with respect to corotational energies) plasma was expected to be confined reasonably closely to the magnetic or centrifugal equator (intermediate between the rotational and magnetic equators /5/), with a spatial distribution little influenced by the solar wind.

The reality of the plasma environment at Uranus was surprisingly different from these expectations. The plasma was found to consist of electrons and subsonic protons. There is no indication of the presence of heavier ions above threshold flux levels, and thus the Uranian moons do not appear to be a significant plasma source. Most surprisingly, the PLS data set exhibited prononounced day-night asymmetries deep in the inner magnetosphere. These asymmetries led to the realization /47/,/48/ that the near alignment of the solar wind velocity and the rotation axis, combined with the large angle between the magnetic dipole axis and the rotation axis, effectively decouples the corotation and convection electric fields at Uranus. As a result, a classic plasmasphere does not exist as such, and solar-wind-driven sunward convection penetrates deep into the magnetosphere. Plasma primarily corotates but also moves slowly sunward, so that the overall motion is along helical paths from the nightside to the dayside. This sunward motion is slow compared to corotation, but it sweeps out the magnetospheric plasma fast enough to prevent the formation of a dense plasmasphere. Estimates of the convection time scale are on the order of days, making the lifetime of plasma in the Uranian magnetosphere the shortest of the outer planets (cf. Table 1). A residence time of this order implies that heavy ion densities would never reach a level detectable by the PLS instrument /18/, so that the lack of detection of heavy ions is, with hindsight, not surprising .

The plasma electrons and ions at Uranus exhibit both a thermal component (with temperatures of tens of eV) and a hot component (with temperatures of a few keV). The thermal ion component is observed both inside and outside an L shell value near 5, whereas the hot ion and electron component is excluded from the region inside of that L shell. The source of the thermal component of the plasma is either the planetary ionosphere or the neutral hydrogen corona surrounding Uranus /49/, whereas the hot component is thought to be convected in from the magnetotail, with probably an ionospheric but possibly a solar wind source. There is a problem with the observed temperature of the warm component, in that local pick-up should produce ions with temperatures close to corotational energies, which are of order 1 eV or less in the regions of interest. Selesnick and McNutt /19/ propose that adiabatic compression resulting from sunward convection may explain the elevated temperature of ions picked up from the neutral hydrogen cloud. In this scenario, the neutral hydrogen source is continually ionized by electron impact ionization, and the resulting (cold) ions (which are initially tailward of their observation point) are then convected sunward and adiabatically heated to the energies observed by the PLS instrument. The model produces both the required heating of the ions and resultant energy spectra which agree qualitatively with those observed. Thus it is not implausible that the source of the warm ions is ionization of the neutral hydrogen cloud, although there are potential problems with the source strength.

The sharp inner edge observed at $L \approx 5.3$ inbound and $L \approx 4.8$ outbound suggests that the hot plasma trajectories were excluded from the planetward region. Such a "forbidden zone" is characteristic of particles drifting under a general dawn-dusk convection electric field combined with the azimuthal magnetic gradient and curvature drifts of particles with significant thermal energy /50/. The boundary of such a zone is called an Alfvén layer. Such zones have been studied in the context of the Earth's magnetosphere. Small energy dispersion at such boundaries (as is observed at Uranus) can be achieved by the inclusion of strong low-latitude shielding of the convection electric field at the inner edge due to the dynamics of hot plasma drifting in from the tail regions. The final quasi-steady location of the shielding boundary is determined by the flux tube content of the hot plasma and the ionospheric height-integrated Pedersen conductivity, Σ_P. McNutt et al. /18/ find that the observed location of the plasma edges at L = 5 is consistent with the flux tube content and estimated values of Σ_P at Uranus, although Mauk et al. /51/ have argued that this calculation does not include the pressure from the ions in the LECP energy range. Another problem with the shielding explanation for the plasma edges is that it requires a quasi-steady situation. Time variations in the externally applied convection electric field must be slow enough that the Alfvén layer has time to adjust to different positions. Sittler et al. /52/ estimate the shielding time to be on the order of 2 to 20 hours at Uranus, with the uncertainty associated with lack of knowledge of Σ_P. The time scale for variations in the convection electric field may be set by the rotation of the planet (with a period of 17.24 hours) because the planetary magnetic field changes its orientation with respect to the interplanetary magnetic field with that period, implying periodic enhancements of the dayside magnetic reconnection rate with resultant changes in the convection electric field. Therefore it is not clear whether the shielding time is short enough to maintain strong shielding and a thin boundary thickness. Thus, the sharpness of the plasma edges seen in the PLS data remains puzzling, although Selesnick /53/ has offered one possible explanation. It is important to remember that the Voyager 2 trajectory provided only a few hours of data from the inner Uranian magnetosphere, and this may not be representative of the important plasma dynamics at Uranus.

Uranus also possesses a well-developed magnetotail and plasma sheet similar in many respects to those of the Earth. Because of the near-alignment of the Uranian spin axis with the solar wind flow direction, the tail structure does not wobble up and down as at Earth or Jupiter, but instead rotates in space approximately about the sun-planet line. Even so, the actual dipole tilt angle in a rotating solar magnetospheric coordinate system varies only in the range from 22° to 38°. The values of this tilt are not unlike those of the Earth's, which never exceeds 35°. As Voigt et al. /54/ point out, it is the Earth-like tilt angles at Uranus which lead to the development of an Earth-like dipolar magnetic tail there, with lobes separated by a cross-tail current and plasma sheet /55/. The plasma edges discussed above could also be interpreted as the inner edges of the plasma sheet.

The bowshock observed inbound at Uranus is a high Mach number quasi-perpendicular shock and shows detailed structure in the transition region similar to that seen at the Earth /56/. Oubound there is evidence for periodic velocity decreases in the magnetosheath, at the planetary rotation period, and these may be signatures of magnetic reconnection /57/. The Uranian magnetosphere provides a unique opportunity to look for signatures of reconnection in the magnetosheath, because the orientation of the rotation axis allows Voyager 2 to sample sheath flow which passes over all magnetic latitudes. The cause of the velocity decreases is thought to be drag on the reconnected flux tubes which are coupled via Birkeland currents to the ionosphere. The outbound magnetosheath also has regions in which large plasma density and flow oscillations occur on a several minute time scale.

NEPTUNE

There is as yet no evidence for the existence of a magnetic field at Neptune, although since it is a sister planet to Uranus, there is every reason to expect that such a field will exist. Since the rotation axis of Neptune is inclined only 28.8° with respect to its orbital plane, the planetary magnetosphere is expected to be corotation dominated. If B is the equatorial surface field strength in gauss, the distance to the sub-solar magnetopause will be 51 $B^{1/3}R_N$ for reasonable extrapolations of solar wind parameters to 30 AU, following the scalings of Siscoe /58/. Other than the ionosphere of the planet, the most obvious plasma source for the magnetosphere is the large satellite Triton. Triton has a radius of 1750 km, with an uncertainty of 250 km, and is located 14.6 R_N from Neptune. A dipole moment for Neptune 0.25 that of Uranus is sufficient to put Triton well inside the magnetosphere at all orbital phases.

Conditions on Triton have lone been suspected as sufficient to support an atmosphere of heavy constituents, but the first detection of spectral absorption features did not occur until 1978 with the detection of methane /59/. Cruikshank et al. /60/ tentatively identify an absorption band at 2.16 μm as an indicator of the presence of molecular nitrogen. If this identification is correct it implies N_2 is present at high pressure in the gas phase or in a condensed state. In either case the resulting atmosphere will consist of N_2 and CH_4, with N_2 dominating by a factor of 1000:1 /61/.

Given that Triton has an atmosphere, Delitsky et al. /62/ have modeled the sputtering and subsequent molecular and atomic processes which should result in the formation of a plasma torus, and we quote some of their results. The two most likely atmospheres have either CH_4 as the only constituent or N_2 as the major constituent, depending upon whether the N_2 identification is valid. Neutrals are sputtered out of the atmosphere by energetic particles and by the corotating ions in the torus. The neutrals are ionized by solar radiation, electron impact, or charge exchange, and the ions subsequently removed by charge exchange, recombination, or transport processes. Informed guesses must obviously be made for quantities such as the transport rate, energetic particle flux, and electron temperature. For guidance as to the appropriate values to use, these authors have looked at measurements from Saturn, which is probably the planet most similar to Neptune. They also assumed an aligned dipole magnetic field with the size of the torus determined by Triton's excursion in L and latitude due to the inclination (158.5°) of its orbit. This results in a torus with a width of 4 R_N and a height of about 11 R_N. Cases were run for two transport rates and two energetic particle fluxes. Transport times of 10^7 s and 3.3×10^7 s were used, based on extrapolation of rates from near Rhea in Saturn's magnetosphere out to the orbital distance of Triton; energetic particle fluxes of 10^5 and $10^6 cm^{-3} s^{-1}$ were taken, comparable to fluxes observed at Saturn. The yields from both energetic particles and corotating ions were assumed to be 3; if the energetic ions are heavies as opposed to protons the yields would be higher. The electron temperature used was 50 eV; this number is also taken from Saturn measurements /31/, and in any case ionization rates are not extremely sensitive to electron temperature in this energy range. The model was started at time t=0 with no torus, and run until a steady state configuration was reached.

Very different results were found for the methane and nitrogen dominated atmospheres. If nitrogen is the dominant constituent, then the main species present will be N and N_2 and their ions. Ion densities range from 0.05 to 8 cm^{-3} depending on the transport rate and energetic particle flux used. Comparable amounts of N and N_2 were predicted, and should each be identified by the Voyager plasma experiment. If the atmosphere is primarily methane the plasma densities were lower, from 0.04 to 0.4 cm^{-3} for the different cases. This occurs because ionization of CH_4 gives molecular ions which are quickly lost via dissociative recombination. The only ion whose density is large enough to be detected by Voyager for all the transport rates and energetic particle fluxes used are protons, although for the higher density cases a peak at mass/charge 12-16 from the heavy ion products of CH_4 should also be detected. The densities given here are torus-averaged densities; densities near the equator will be higher than those near the torus boundaries by a factor which depends on the ion temperature and anisotropy. These results are based on numerous assumptions and should be treated as rough estimates. They do show that an ion torus should exist, and that its density will be large enough to be detected by the Voyager plasma experiment. The two major competing models of Triton's atmosphere give tori of very different composition, so plasma observations could provide an indirect verification of the composition of Triton's atmosphere.

One unique feature of the Voyager 2 encounter with Neptune is the high latitude and close approach distance of the encounter. Voyager will reach a latitude of 72°, with a closest approach distance of only 1.15 R_N, and the most exciting consequence of this is the possibility of a passage into the auroral zone at Neptune. Such an event would be unique in planetary exploration, as there has never before been a non-terrestrial auroral zone pass. However, simple scaling arguments /58/ predict that the cosine of the latitude of the equator edge of the polar cap varies as $\cos(87°)B^{-1/6}$ for reasonable extrapolations of solar wind properties, and therefore the polar cap proper may well be of limited extent at Neptune. The probability of an actual penetration into the auroral zone is small, especially considering the unknown tilt of the magnetic field. Even so, there are many high latitude phenomena which are of great interest (for example, field-aligned currents linking the planet with plasma tori, and precipitation of energetic ions at the inner edge of a ring current) which will very probably be observed.

SUMMARY

The Voyager mission has provided an opportunity to explore a variety of magnetospheres in situ. At Jupiter, we have been able to study a corotating magnetosphere dominated by the plasma input from one prodigious source, with almost every aspect of the physics there, from transport to energization to generation of the aurora, driven by that input. At Saturn, we again have a corotation dominated magnetosphere, but one where the environment is more benign because of the much lower mass input from the extended satellite sources. At Uranus, the most Earth-like of these magnetospheres because of the deep penetration of convective flows, we have had a chance to study solar-wind-driven convection in a uniquely different context than the terrestrial one, because of the orientation of the Uranian rotation axis at this epoch. At Neptune, we will have another opportunity to study a corotating magnetosphere with a satellite source, but with a very different configuration of that source. We also will have an opportunity to investigate the nature of the polar regions, with the possibility of comparative auroral studies. Neptune will undoubtedly provide us with many surprises which we cannot anticipate, adding one more regime to the varied and exotic plasma environments explored in this remarkable mission.

ACKNOWLEDGEMENTS

This work was supported under NASA contract number 957781 from the Jet Propulsion Laboratory to the Massachusetts Institute of Technology.

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