Second Neil Brice Memorial Symposium

# **"Magnetospheres of the Outer Planets"**

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# MAGNETIC FIELDS OF THE OUTER PLANETS

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With the recent Uranus encounters just concluded and the Neptune encounter scheduled to occur within the next few years, the magnetic reconnaisance of the solar system is drawing to a close. It is therefore appropriate to review what we have learned, what uses have been made of this new knowledge and to consider the major goals to be pursued by future missions. The outer planet measurements, combined with those of the terrestrial planets, have been used to advance the search for a fundamental relation between source strength, namely the magnetic dipole moment, and a few simple parameters characteristic of the planet or its core, such as density, radius and rotation period. Information regarding the higher order multipoles, limited principally to the quadrupole and octupole, have been used to estimate the radius of the fluid core or to infer the spectral distribution of the hydromagnetic turbulence within the core. Undoubtedly, a precise determination of the higher order moments will be advocated as a major scientific objective of the next generation of outer planet orbiters and an attempt should be made to investigate secular variations (such as changes in the magnitude of the dipole moment or in the location of the magnetic pole). The outer planets especially Jupiter and Saturn, probably represent our best and perhaps only, opportunity to extend the kinds of studies long associated with geomagnetism to the outer planets. Dynamo Hum.

# DISTRIBUTION OF PLASMA IN THE MAGNETOSPHERES OF JUPITER AND SATURN

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# A MAGNETOHYDRODYNAMIC SIMULATION OF THE INTERACTION OF THE SOLAR WIND WITH THE JOVIAN MAGNETOSPHERE

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We have modeled the interaction of the solar wind with a rapidly rotating magnetosphere by using a three dimensional time dependent magnetohydrodynamic simulation code. We have used two models for the azimuthal velocity. One in which corotation is enforced out to a critical radius and then decreases as 1/r and one in which the azimuthal velocity remains constant beyond the critical radius. The resulting magnetospheric configurations are similar to those inferred from Pioneer and Voyager observations at Jupiter. The magnetopause for the rapidly rotating magnetosphere is similar in shape to that of a magnetosphere where corotation is unimportant in the noon midnight meridian plane but is broader in the equatorial plane. Two large flow cells are found in the dayside magnetosphere which generate large scale field-aligned currents. The currents are away from the planet on the dusk side and towards Jupiter on the dawn side. Large scale away currents also occur in the early morning magnetosphere. These currents are generated by pressure gradients in the dawn side equatorial current sheet. In the equatorial plane, a large scale vortex forms in the plasma flow on the dawn side. Across this vortex the flow changes from the azimuthal direction to the tailward direction.

# PLASMA FLOW VELOCITIES IN THE MAGNETOSPHERE OF JUPITER

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We have completed a thorough analysis of some of the data obtained with the Plasma Science experiment during the Voyager 1 encounter with Jupiter. The spectra analyzed were obtained in the middle magnetosphere between 11 $R_J$ and 25 $R_J$ on the dayside of the planet. We used a model of the full response function of the instrument to do non-linear least squares fits to data obtained simultaneously with three of the four sensors of the experiment (the data from the fourth sensor acts as a check on the fits). From this analysis we have obtained the flow velocity of the plasma, as well as densities and temperatures of all of its major constituents. In some cases, using a more elaborate modeling scheme, we have also obtained limits on the thermal anisotropies (ratio of $T_\parallel$ to $T_\perp$). We have shown that the anisotropies are relatively small and do not siginificantly affect our results obtained under the assumption of isotropic distribution functions. We find that the plasma flow is primarily azimuthal and subcorotational, consistent with previous results. However, there is significant non-azimuthal flow as well. In a reference frame rotating with the local angular velocity of the plasma, there is a field aligned component of flow which varies up to 68 km $s^{-1}$. The field aligned flow is away from the magnetic equator between 13 and 25 $R_J$ and toward it between 11 and 13 $R_J$. There is also plasma flow perpendicular to the measured magnetic field which varies up to 30 km $s^{-1}$. This component is directed away from Jupiter between 15 and 25 $R_J$. Between 13 and 15 $R_J$ the perpendicular component is small and fluctuates. This complicated flow pattern is apparently related to both deviations of the magnetospheric configuration from azimuthal symmetry and time dependent changes in the magnetospheric structure. The logical source of both effects is the solar wind.

# PLASMA FLOW IN THE NIGHTSIDE MIDDLE MAGNETOSPHERE OF JUPITER

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Analysis of Voyager 1 and 2 magnetometer and plasma science data in the nightside middle magnetosphere of Jupiter (~9 $R_J$ to ~25 $R_J$) yields values for the mass outflow rate and azimuthal velocity of the plasma sheet plasma. These results are combined with previous work to demonstrate a model of convective flow in the plasma sheet that exhibits periodic superrotation on the night side.

# SOURCES OF RING CURRENT DENSITY WITHIN OUTER PLANET MAGNETOSPHERES

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The global configuration of a magnetosphere depends on the detailed balance of stresses between the fields and the resident particles. There have recently been revealed some surprises and some uncertainties concerning the sources of particle stress, and of the associated current densities, within the ring current regions of outer planet magnetospheres. At Jupiter, for instance, we have recently shown that planetward of ~ 20 $R_J$ the field stresses are balanced by the oft-invoked pressure gradients within the very hot (>20 keV) plasma component. Outside of 20 $R_J$, however, much more esoteric terms appear to be necessary involving pressure anisotropies or field-aligned flows. Additionally we have found that contrary to common expectations, Saturn rather than Jupiter is unique in having the co-rotation centrifugal stresses dominate over other sources of particle stress in some regions of the ring current spatial distributions. At Jupiter the need is clear for a serious rethinking about how the unique magnetodisc configuration is formed. In this talk we will address the issue of the sources of the ring current density within these magnetospheres, and we will include some results from the recent encounter of Uranus by Voyager 2.

# MAGNETOSPHERIC INTERCHANGE INSTABILITY

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The interchange instability is reviewed and instability conditions derived under a variety of circumstances. The introduction of field curvature is shown to have extremely important effects on the instability condition. We use a small perturbation approach for the instability analysis. Results are derived or rederived for plasmas of arbitrary beta, and straight and curved field geometry with and without significant gravitational or centrifugal body forces. The impoundment of the Io torus by the energetic ring current plasma is examined in the light of the stability conditions obtained. Recent criticism of the ring current impoundment hypothesis based on straight field line results is shown to be ill founded.

# PROBABLE HARMONIC CONTENT OF A REVERSING PLANETARY MAGNETIC FIELD

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The 60° inclination of Uranus' magnetic axis inferred from Voyager data supports the Siscoe-Saito (equatorial-dipole) model of a planetary magnetic reversal. Statistical arguments supported by terrestrial observation suggest that the Schmidt-normalized expansion coefficients $g_n^m$ and $h_n^m$ for $(n,m) \neq (1,0)$ are random variables belonging to one and the same "power" spectrum. This interpretation implies that the Siscoe-Saito model is more probable than any other and predicts a reasonable "core" radius, at least for the earth. The axial-dipole component $g_1^0$ in the present model consists of a systematically varying part and a randomly varying part, with the latter belonging to the same exponential spectrum as the $g_n^m$ and $h_n^m$ for $(n,m) \neq (1,0)$. Magnetic reversal corresponds to the condition $g_1^0 = 0$, but it would be highly improbable (under the random-variable interpretation) for $g_1^1$ and $h_1^1$ to vanish simultaneously with $g_1^0$. The implications for Uranus and other magnetized objects in the solar system are qualitatively similar, although the ratio of "core" radius to visual radius must vary from object to object.

# MAGPAC: A PLANNING PACKAGE FOR THE JOVIAN MAGNETOSPHERE

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MAGPAC has been developed over the past year in support of Galileo particles and fields investigators. It combines Jovian magnetic field and plasma models with satellite and spacecraft trajectories into one user-friendly menu-driven package. Using MAGPAC one can display proposed Galileo trajectories simultaneously with relevant magnetic and plasma features such as magnetic equator, satellite wakes, and plasma densities and temperatures. MAGPAC can therefore be used to help determine an optimal Galileo trajectory and later in interpretation of the field and plasma measurements.

Presently, the Magnetic Event File (MEF) program is under development. This program encompasses a database manager with a user-friendly interface to help the investigators to access and sort various magnetic events such as "magnetic equator crossings"; "closest approach to flux tube axis", etc.

We anticipate that the models and tools developed for MAGPAC can be modified to help in data analysis of many other flight projects such as Voyager and Pioneer Venus.

# THE SATURNIAN MAGNETIC FIELD

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We have included the magnetopause field as an intrinsic part of the dipole moment of a planetary dipole compressed by the solar wind. The contribution of the magnetopause is well understood and precisely calculable. To this we have added higher order intrinsic multipole moments and a parameterized disk of plasma current within the magnetosphere to obtain a good fit to Pioneer 11 and Voyager 1 and 2 data throughout the Saturnian magnetosphere.

# THE MAGNETIC FIELD OF URANUS: VOYAGER RESULTS

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During its encounter with the planet Uranus on January 24, 1986, the Voyager 2 spacecraft discovered a substantial magnetosphere and intrinsic planetary magnetic field. There are several unique features of the magnetic field which distinguish it from the other planets. Firstly, the angular offset between the magnetic axis of the dipole term and the rotation axis of the planet is very large, 60°. Secondly, when approximating the magnetic field by an offset tilted dipole, the spatial offset of the magnetic dipole from the center of the planet is quite large, approximately 0.3 $R_U$. Equivalently in a spherical harmonic representation there are significant higher order multipole moments required to adequately describe the magnetic field observations. Indeed, the magnitude of the quadrupole moment is almost equal to that of the dipole moment. The implications of this planetary magnetic field for the structure of the magnetosphere is significant. The dipole moment of 0.23 Gauss $R_U{}^3$ leads to an average subsolar point distance of the magnetosphere of 20 $R_U$. Thus, most of the moons of Uranus are imbedded deep within the magnetosphere and because of the large obliquity of the rotation axis and large angular offset of the magnetic dipole axis, these moons absorb and sweep out a complicated pattern in the structure of the radiation belts. Also, close to the planet the position of the magnetic poles and auroral zones are much closer to the equator than they are to the rotation poles. Finally, the entire magnetosphere and its well developed bipolar magnetic tail corotate with the planet around the planet-sun-line. This paper overviews these new results obtained and their implications.

# PLASMA OBSERVATIONS IN THE MAGNETOSPHERE OF URANUS

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R. S. Selesnick, J. D. Sullivan, R. E. Hartle, K. W. Ogilvie,
E. C. Sittler, Jr., F. Bagenal, R. S. Wolff, V. M. Vasyliunas,
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We describe the observations of the plasma within the magnetosphere of Uranus. These observations were made with the Plasma Science experiment on the Voyager 2 spacecraft during its encounter with Uranus in January, 1986. Uranus posesses an intrinsic magnetic field sufficient to stand off the solar wind and produce a substantial magnetosphere which contains the large moons and ring system of the planet. Within the magnetosphere proper, there is a low density plasma (on the order of 1 ion $cm^{-3}$) which is comprised principally of protons. The "core" of this plasma has a temperature of about 10 eV; there is also a complicated, non-Maxwellian component of the plasma distribution function which changes along the spacecraft trajectory. This component was also detected by the Plasma Science experiment and by the Low Energy Charged Particle and the Cosmic Ray experiments at much higher energies. The plasma is subsonic, and the temperature is larger than that expected for local ionization and pickup of neutral material. Although the non-Maxwellian part of the plasma extends to very high energies, the density is so low that the plasma $\beta$ is much less than unity, and the plasma flow is everywhere very sub-Alfvenic. The values of these parameters are consistent with the magnetometer observations of a vacuum magnetic field within the magnetosphere. These values are also consistent with the plasma flow being close to corotational. The plasma observations are not well organized by model magnetic L-shells; large day-night asymmetries are exhibited by both the ions and electrons. These asymmetries are probably related to solar wind driven convection which moves plasma sunward throughout the magnetosphere and results from the unique orientations of the spin and magnetic axes of Uranus with respect to the solar wind. High fluxes of electrons with energies of several keV made the spacecraft several hundred volts negative with respect to the surrounding plasma for three hours near closest approach to the planet. This potential accelerated positive ions into the plasma detectors and revealed that there was no substantial "hidden" thermal plasma population below the 10 volt

threshold of the instrument. There is no compelling evidence for a heavy ion component of the plasma. Such a component would be expected if sputtering of water ice from the surfaces of the Uranian moons were a dominant plasma source. Data from the Plasma Science experiment cannot be used to rule out the presence of alpha particles at the solar wind abundance and at temperature similar to those of the detected protons. However, the low helium to hydrogen ratio measured at > 0.5 MeV by the Low Energy Charged Particle experiment on Voyager argues against the solar wind being the dominant source of the magnetospheric plasma. The most likely source of the observed plasma appears to be ionization of Uranus' extended neutral hydrogen corona detected by the Ultraviolet Spectrometer experiment on Voyager 2, although a detailed analysis of this hypothesis is still to be carried out.

# LOW ENERGY ELECTRON PLASMA IN THE MAGNETOSPHERE OF URANUS

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During the Voyager 2 encounter with Uranus, the Plasma Science Experiment (PLS), which measures ions and electrons in the energy range from 10 eV to 6 keV, observed the plasma electrons within the Uranian magnetosphere. The spacecraft crossed the magnetopause and entered the Uranian magnetosphere about 18 $R_U$ from Uranus. In this outer region densities, $n_e \lesssim 10^{-3}$ $cm^{-3}$, were very low. A plasma torus containing cold ($\sim$10 eV) and hot ($\sim$500 eV) electron components with peak densities $\sim$ 1 cm was observed within L=7.8 inbound and L=18.3 outbound. Inside L=6.8 inbound and L=5.3, outbound with closest approach at L=4.75, the electrons became very cold ($T_e < 2$ eV). A definite inbound-outbound asymmetry in the electron density and temperature was observed; the electrons were of higher density and temperature during the outbound pass on the night side. We interpret this effect as an asymmetry in local time with fluxes at fixed L peaking near midnight local time, resulting from the close alignment of the Uranian spin axis in the anti-solar direction. Magnetospheric convection can be important with particle injection into the inner magnetosphere from the magnetotail where energization up to keV energies can occur. This local time asymmetry in keV electron fluxes may account for the observed asymmetry in the radio emissions from Uranus.

# SOLAR-WIND INTERACTION WITH THE MAGNETOSPHERE OF URANUS

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Voyager observations at Uranus have been interpreted as indicating the presence of a solar-wind driven magnetospheric convection system similar to that operating at Earth, but operating more efficiently at Uranus than at Earth. I will argue that this enhanced efficiency results from the bizarre geometrical arrangement whereby the spin axis lies essentially in the ecliptic plane, and points roughly toward the sun at present, while the magnetic dipole axis is tilted by a large angle (approximately 60 degrees) away from the spin axis. The magnetospheric magnetic field near the subsolar point thus rotates with the 17-hr planetary rotation period with respect to the interplanetary magnetic field, which tends to maintain a given direction (eastward or westward) for many rotation periods. If the convection electric field is provided by mapping of the solar-wind field along interconnected magnetic-field lines, as at Earth, then the convection electric field likewise varies with the planetary rotation period.

This rotational modulation of the convection electric field has two important consequences. One is the absense of a plasmapause separating open convection streamlines on the outside from closed rotational streamlines on the inside. The other consequence that shielding of the convection electric field by polarization of the ring current is effective only within about five planetary radii. The convection electric field therefore penetrates much closer to the planet than it would without the rotational modulation.

# THEORETICAL MODEL OF URANUS' BOW SHOCK*

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The Voyager II spacecraft measurements of the physical parameters of the Uranian bowshock[1,2], that is characterized by an Alfven-Mach number about 20, have motivated an attempt to construct a simple analytical model including some of the microscopic processes that should determine the observed shock structure. We have analyzed a relatively wide variety of one-dimensional equations and chosen among them one type that can reproduce the kind of plasma density spatial variations revealed by the experiments. We have disregarded, for the sake of simplicity, the important observation that the magnetic field direction changes significantly. The main processes included are an anomalous plasma resistivity associated with modes due to the electron streaming velocity to account for the ramp-up phase.

The following spatially oscillating structure is accounted for by the periodic onset of an electron current drive (acceleration) process due to plasma modes excited by the presence of an energetic ion population with transverse velocities to the direction of the solar wind.

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[1] H. S. Bridge et al., <u>Science</u>, <u>233</u>, 89 (1986).

[2] F. Bagenal et al., <u>EOS</u>, <u>67</u>, 333 (1986).

*Sponsored in part by the U. S. Department of Energy.

# MAGNETIC FIELD AND CURRENT STRUCTURES IN THE MAGNETOSPHERE OF URANUS

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We compare Voyager-2 magnetic field data with theoretical model calculations for the magnetosphere of Uranus. The Uranian magnetosphere is different from Earth's in at least three distinct ways. First, the planet's rotation axis is almost in the ecliptic plane, which lets the entire magnetosphere rotate with the spin period of the planet. It is not clear at this time whether the magnetosphere rotates like a solid body or generates twisted tail field lines due to some degree of differential rotation. Second, relative to a given IMF direction the magnetosphere changes periodically every 8.5 hrs. (the Uranian day is approximately 17 hrs) from an "open" to a "closed" configuration and back. In other words, the convection process is periodically interrupted by the planet's rotation; convection proceeds when the magnetosphere is "open" but stops when it is "closed." Third, there is no plasmapause in the Uranian magnetosphere. Thus plasma loaded magnetotail flux tubes convect closer to the planet than they do in Earth's magnetosphere. The magnetic field data seem to indicate that the magnetotail plasma sheet is indeed located closer to the planet in Uranus' magnetosphere than it is in Earth's.

The theoretical model that describes the Uranian magnetosphere is three-dimensional and satisfies the quasi-static MHD equilibrium equations in an approximate fashion. We use the plasma pressure distribution $P(\underline{x})$ to determine the magnetic field and current structures in the Uranian magnetosphere through the requirement of magnetohydrostatic force balance. Once the model $\underline{B}$-field agrees with the measured magnetic field data, the model can be used to determine the plasma Beta parameter, $\beta = 2\mu P/B^2$, in the plasma sheet. According to the information available at this time, we conclude that Beta is greater than unity in the plasma sheet ($\beta \gg 1$), which indicates that the Uranian magnetotail is plasma pressure dominated.

# THE MAGNETOTAIL OF URANUS

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Uranus has been shown from Voyager 2 observations to possess a fully-developed, bipolar magnetic tail with lobes separated by a plasma sheet and embedded current sheet. Over the $X_{SM}$ range 25 - 65 $R_U$, the intensity of the magnetic field in the tail lobes decreases as $|X_{SM}|^{-0.59\pm0.03}$. The plasma sheet has a thickness of $\sim$ 10 $R_U$ at the center of the tail and increases in thickness towards the flanks. The diamagnetic depressions in magnetic field strength within the plasma sheet are produced predominantly by the presence of protons and electrons of energies 10 eV - 6 keV. Except in possible transient events, the contributions of protons with energies $>$ 28 keV to the energy density is $\lesssim$ 1%. The cross-sectional shape of the current sheet is consistent with a parabola of the form $Z_{SM} = (-0.0076Y_{SM}^2 - 0.11Y_{SM} + 9.38)\ R_U$. The entire tail rotates through 360° about its central axis (~the planet-sun line) in response to the 17.24 hour rotation of the highly-tilted (60°) magnetic dipole of Uranus about the planet's sunward-pointing rotation axis. The tail is not entirely rigid in its response. Consequently, the magnetic field in the near-planet tail lobes exhibits a small amount of twist, of pitch $\alpha p = 5.5° \pm 3.0°$. The current sheet is twisted by a similar amount. These and other properties of the Uranian magnetotail will be discussed and compared with those of tails at Earth, Jupiter, and Saturn.

# ROTATIONALLY DRIVEN TRANSPORT: A RECAP

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Corotating with Jupiter, the Io torus feels a 1.2 g force on its 2 megaton mass acting to hurl it away from the planet. The magnetic field merely anchors the torus to a "vicious" ionosphere. To oppose 1.2 g with ionospheric drag, the torus must fly outward at nearly 2/3 of its corotation speed - which it does not do. Instead the torus is to a high degree self-balanced: the outward force on one side of the planet almost exactly counteracts the outward force on the other. Small departures from perfect symmetry allow the torus to drain away the roughly 1 ton of new plasma added each second. The drainage flow must entail intechange motions: mass depleted flux tubes move in to replace mass enriched tubes moving out. The resulting flow can be organized into a magnetosphere-scale steady or unsteady circulation or into small scale turbulent eddys. The convection and diffusion equations applying to the two scales of organization have been derived and solved for illustrative cases. That plasma fills the warm torus all around and field lines bend generally retrograde imply that plasma moves mainly outward at all longitudes-diagnostic of diffusive transport. In rotationally driven diffusion, the diffusion coefficient depends on the density gradient. The nonlinearity introduces negative feedback in responses to changes in time, and makes the torus stable. The scale size of the diffusive eddys is unknown. Linear analysis of the dynamical equations of a corotating plasma magnetically linked to a conducting ionosphere reveals three wave modes - one corresponding to the rotational instability driving diffusive transport. This mode is completly stabilized by the inner edge of the torus. Density inhomogeneities are required to activate the mode. The plasma ribbon discovered by Trauger provides the needed density inhomogeneity and sets a scale size for the eddys.

# EXTERNALLY DRIVEN TRANSPORT IN THE MAGNETOSPHERES OF THE OUTER PLANETS

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The relatively rapid rotation rates and sizes of the magnetospheres of the outer planets imply corotation speeds generally larger than any plausible plasma flow speeds associated with solar-wind-driven magnetospheric convection. The penetration of convective flow into the inner magnetosphere in the face of corotation is governed in part by the ratio of convection to corotation potentials but also depends on the angles between the planet's rotation axis, its magnetic dipole, and the solar wind flow direction. In particular, when the rotation axis is aligned with the solar wind flow, plasma transport by magnetospheric convection is not impeded in any direct way by corotation. Quantitative models of magnetospheric convection for various angles and their application to Uranus and other outer planets will be discussed.

# PLASMASPHERE IN ARBITRARILY ORIENTED MAGNETOSPHERES

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We investigate the formation of plasmaspheres in planetary magnetospheres with arbitrary orientations of the rotation and magnetic dipole axes. A traditional plasmasphere with closed orbits inside the plasmapause and open trajectories outside it only occurs for the limiting case of aligned rotation and dipole axes. A time variable plasmapause exists if the rotation axis is perpendicular to the solar wind flow direction. In any other case no definite plasmapause exists. Solar wind driven convection transports plasma throughout the magnetosphere with an effectiveness which increases as the orientation becomes further from one of the two limiting cases of strict plasmapause formation. Our analysis is applied to Earth and Uranus using the actual orientations of the rotation and dipole axes. Particle trajectories at Earth deviate only slightly from those obtained with traditional models. Uranus has no plasmasphere, and plasma convects sunwards throughout the inner magnetosphere.

# STEADY STATE PLASMA TRANSPORT IN A COROTATION-DOMINATED MAGNETOSPHERE

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We present a model for plasma transport in a rotation-dominated magnetosphere (e.g., Jupiter) containing an internal plasma source (e.g., Io). We make a distinction between magnetic flux tubes that are loaded with outward moving plasma and empty flux tubes that move in to compensate. In the outer region where full tubes are effectively isolated, their motion is described by a pair of coupled differential equations which have analytic solutions in the small velocity approximation. In a steady state, conservation of flux-tube plasma content requires that the average ratio of full to empty flux be a function of the radial outflow speed of the full tubes. Similar equations govern the motion in the inner region where full flux predominates and empty tubes are isolated. This raises the possiblility of net outward radial transport even when the radial gradient of average flux-tube content is positive. In the outer region where full flux tubes are isolated, the average steady-state flux shell content decreases outward as the inverse square of radial distance.

# THE RADIATION BELTS OF THE OUTER PLANETS

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# HOT PLASMA AND RADIATION ENVIRONMENT OF URANUS

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The Low Energy Charged Particle (LECP) Experiment onboard the Voyager 2 spacecraft measures ions and electrons in the ranges of 28 keV $\leqslant E_i \leqslant$ 150 MeV and 22 keV $\leqslant E_e \lesssim$, respectively. Angular distributions and energy spectra are obtained over most of this range with time resolution from 1.2 sec to 48 sec. Pulse-height analysis data enable discrimination of individual particle species at energies $\gtrsim$ 0.5 MeV/nucleon. Principal features of the LECP findings, include: (a) appearance of ions and electrons in the region upstream from Uranus, evidently escaping from the magnetosphere; (b) satellite absorption signatures which appear to be selective in energy and/or species; (c) Maxwellian energy spectra at low ($\lesssim$ 200 keV) energies with characteristic kT ~ 10-50 keV, and power-law tails at high ($\gtrsim$ 0.5 MeV) energies with $\gamma \sim 3$-10; (d) an ion population consisting almost exclusively of protons (H/He ratio $> 10^4$), at least at the higher ($\gtrsim$ 0.5 MeV/nuc) energies; (e) a plasma $\beta$ that has a maximum value ~ 0.01, i.e., much less than values of ~ 1 at Jupiter and Saturn. It would appear that the source of plasma may well be the hydrogen corona surrounding the planet, and that sputtering from planetary satellites is not a significant plasma source. The interaction of the proton population with the hydrogen corona should also produce energetic neutrals which would appear upstream from the planet.

# HIGH ENERGY PARTICLES AT URANUS: VOYAGER RESULTS

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The Cosmic Ray Experiment (CRS) onboard Voyager 2 discovered large fluxes of MeV charged particles trapped within the Uranian magnetosphere with the highest intensities found near closest approach to the planet. Outside the orbit of Miranda the MeV electron component was dominant and its radial intensity profile showed evidence for strong modulation by satellite sweeping, in contrast to Saturn where this effect was not as apparent. The inbound and outbound positions of the electron absorption signatures are considered in terms of the magnetospheric field geometry and the sweeping rates of the satellites along their orbits. Near and outward from the orbit of Umbriel the observed trapped radiation shows significant deviations from dipolar symmetry in magnetic longitude, indicating the effect of other magnetospheric field components. Comparison of inbound and outbound counting rates at different magnetic latitudes provides estimates of the MeV electrons' pitch angle distributions, which are radially variable but generally dominated by particles at large pitch angles. Estimates of the energy spectra for equatorially trapped electrons are used to calculate phase space densities for magnetic moments of order $10^4$ MeV/G. The positive radial gradients of these densities outside the orbit of Miranda are indicative of inward diffusion and acceleration from sources in the outer magnetosphere. The effects of internal sources (i.e., CRAND), satellite sweeping, and other loss processes require further consideration.

# PLANETARY ROTATION MODULATION OF JOVIAN ELECTRON SPECTRA IN THE MAGNETOSPHERE AND INTERPLANETARY MEDIUM

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The Pioneer 10 and Pioneer 11 encounters with Jupiter in December 1973 and December 1974, respectively, reveal that there were two different types of ~10 hour variations of the high energy electron spectra. One type, whose origin is due to the rotation of the inclined current sheet and trapped radiation, possesses a phase dependence which is a function of the azimuthal position of the spacecraft observations. The second type has a constant phase relative to the sun-Jupiter line and has the same phase both inside the magnetosphere and in the interplanetary medium. The phase of this 10 hour or 'clock' variation was preserved for over the 5 year period between Pioneer and Voyager encounters. We shall review the second type of 10 hour spectral variation and discuss recent evidence regarding its origin.

# THE RESPONSE OF ENERGETIC TRAPPED ELECTRONS TO A MODULATION OF IONOSPHERIC CONDUCTIVITY AT JUPITER

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~~A self-con~~sistent numerical model of the Jovian magnetodisc (Caudal, JGR, 91, 4201, 1986) has been used to compute the effect of the mechanism proposed by Goertz and Baker (JGR, 90, 6304, 1985) to ex~~plain the~~ 10-hour modulation of the spectral index of energetic electrons (>2 MeV) in the Jovian magnetosphere. According to this mechanism, the planetary rotation (with a period of 10 hours) leads to a modulation of the ionospheric Pedersen conductivity, which, in turn, modulates the magnetic configuration of the magnetosphere. The trapped electrons respond by a periodic shift of their energy spectrum. Due to the shape of the spectrum, this results in a modulation of the spectral index. The numerical model, once Pedersen conductivity variations have been taken into account, permits to confirm the presence of a significant modulation of the energy of trapped electrons in the middle magnetosphere, in accordance with observations. However, in the outer dayside magnetosphere (within 30 Jovian radii from the magnetopause, typically), the effect predicted by the model becomes small, and should also probably be hidden by modulations due to fluctuations of the solar wind. Thus, the efficiency of the proposed mechanism is confirmed in the middle magnetosphere, but some additional process (probably cross-L diffusion ?) has to be investigated to account for the spectral modulation of energetic electrons in the dayside outer magnetosphere too.

# COMPARISON OF ENERGETIC ION ABUNDANCES AT JUPITER, SATURN, AND URANUS

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The energetic ion composition in three outer planet magnetospheres (those of Jupiter, Saturn, and Uranus) has been measured at energies $\gtrsim$ 200 keV/nuc with the LEPT composition telescope subsystem of the LECP experiment on Voyager 1 and 2. Energetic ion composition is determined by the relative strengths of plasma sources and ion energization and loss processes. It is useful to compare composition at the outer planets to test our understanding of these processes. These comparisons can be used to determine which processes are common to these magnetospheres and which are not. For example, energetic molecular ions of hydrogen ($H_2^+$) have been observed in all three magnetospheres. $H_3^+$ was observed at Jupiter and Saturn. These must come from the planetary ionosphere. Hydrogen molecules in a magnetosphere have a finite lifetime due to photodissociation and dissociation due to impacts with ions, electrons, and neutral atoms. At Jupiter the $H_2^+$ lifetime is longer than at Saturn. These dissociation processes put an upper limit on the ion acceleration and residence time scales giving constraints to models. At Jupiter the energetic heavy ions (He and heavier) were both of solar wind and local origin (Io), while at Saturn only highly ionized solar wind ions could gain sufficient energy to be detected by the LEPT. Uranus is unique in that the only species besides protons to be identified was $H_2^+$. Its relative abundance was only $\sim$0.1%. The composition of the energetic ion population is found to be important in understanding a variety of magnetospheric problems.

# LOSSY RADIAL DIFFUSION IN THE INNER JOVIAN MAGNETOSPHERE

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We have numerically solved the time dependent radial diffusion equation for equatorically mirroring particles including losses due to absorption by moons, the ring, and synchrotron radiation. We also calculate the synchrotron emission at different wavelengths. Our calculations yield predictions for the variation of energetic electron fluxes with radial distance and DIM intensities. By comparing our results with available Pioneer 10, 11, and DIM observations we confirm the previous conclusions that additional losses due, e.g., to pitch angle scattering occur in the inner Jovian magnetosphere ($L < 6$). We also find that variation in the torus density which effects the fluxes of energetic particles at $L = 6$ should lead to observable variations in the DIM intensity.

# PARTICLE-WAVE INTERACTIONS IN SATURN'S MAGNETOSPHERE

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Several different plasma and wave features observed during the Voyager 1 and 2 fly-bys of Saturn suggest that the magnetosphere of the planet is quite dynamic. Understanding these phenomena is important in order to obtain an overall view of the dynamical processes which determine the structure of the magnetosphere. A particularly interesting event occured at ~9.25 Rs, just outside the orbit of Rhea, during the inbound Voyager 1 encounter. The angular distributions of the electrons (E>20 keV) measured by the Low Energy Charged Particle (LECP) experiment became isotropic in coincidence with the occurrence of brief bursts of plasma wave emissions at 5.62 kHz detected by the Plasma Wave Analyzer (PWA). At the same time, the plasma electrons measured by the Plasma Science (PLS) experiment in the keV-energy range were abruptly enhanced. No such occurrences were observed outbound at this radial distance. The particle-wave interaction process, possibly involving upper hybrid resonance emissions and/or chorus-related electrostatic bursts, were apparently spatially and temporally confined to this magnetosphere region through which Voyager 1 happened to pass. Details of the observations and interpretations in the context of wave-particle interactions will be presented.

# ACCELERATION MECHANISMS IN RAPIDLY ROTATING MAGNETOSPHERES

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A variety of charged particle acceleration mechanisms apparently operate in rapidly rotating magnetospheres. At Jupiter, energization mechanisms are required in the plasma torus, plasma sheet, and radiation belts to maintain torus emissions, UV and IR aurorae, and the planetary wind. A variety of mechanisms draw ultimately on the planetary rotation as the energy source; these include pickup, radial transport, and azimuthal drift in azimuthally asymmetric fields with localized pitch angle scattering. Important effects arise from first invariant violations due to wave-particle interactions and large field line curvature in the current sheet. These lead to efficient energization of ions and electrons.

# FROM THE IO TORUS TO THE PLASMA SHEET: PLASMA PROCESSES REVEALED BY VOYAGER

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While attention has previously been concentrated on either the Io torus or the plasma sheet, a current issue is the transport and evolution of plasma populations from one region to the other. Examination of PLS data reveals some evidence of the plasma processes occurring in this transition region. The extent of Europa's effect on the magnetospheric plasma is also discussed.

# APPLICATION OF CURRENT SHEET MAGNETIC FIELD MODELS TO PIONEER 11 CHARGED PARTICLE OBSERVATIONS IN JUPITER'S MAGNETOSPHERE: POSSIBLE SIGNATURES OF GANYMEDE AND CALLISTO

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Beyond about 10 $R_J$ from Jupiter, the configuration of magnetic field lines in Jupiter's magnetosphere is strongly affected by the presence of an equatorial current sheet. Using a Voyager 1 magnetic field model that explicitly includes the effects of this current sheet to describe the field line geometry we have re-examined observations of trapped protons and electrons made by Pioneer 11 at high latitudes in Jupiter's magnetosphere. We find that by use of the current sheet field model, some features in the charge particle time-intensity profiles that had previously been suggested to be effects of Ganymede appear more likely to be associated with Callisto, and some large and previously unexplained features, including one micro-signature-like feature, are alligned with regions in which evidence of the interaction of the trapped radiation with Ganymede and Callisto might be expected. Although many of the characteristics of these features (such as their magnitude, persistence, and similarity of appearance for protons and electrons) are difficult to explain, the close correspondence between their observed positions and the positions predicted by the field model suggests that they may be produced by the satellites. If this interpretation is correct, it argues that the configuration of the current sheet during the Pioneer 11 flyby in 1974 was very similar to that observed by Voyager 1 in 1979, and provides confirmation of the essential accuracy of the current sheet magnetic field model out to radii of about 30 $R_J$ from Jupiter. Explanation of the characteristics of the features sets interesting problems for future research on the dynamics and interactions of trapped particles with satellites in the outer regions of the jovian trapped radiation zone.

# THE INTERACTION OF TRAPPED PARTICLE POPULATIONS WITH THE NATURAL SATELLITES OF JUPITER AND SATURN

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Near-satellite observations by the Voyager 1 and 2 spacecraft during the Jupiter and Saturn encounters revealed localized depletions in the low-energy charged particle population. Such depletions may be caused by the absorption of these particles as they impact the neutral satellites imbedded in these magnetospheres. Various methods for calculating particle lifetimes due to satellite sweeping have been presented by a number of investigators [Mead and Hess, 1973; Hess et al., 1974; Mogro-Campero and Fillius, 1976; Thomsen, 1977; Thomsen and Van Allen, 1980; Bell and Armstrong, 1986]. These methods, however, have proven to be inadequate in explaining the observations [cf. Bell and Armstrong, 1985, 1986]. Such features are highly dependent not only on the satellite's position in the magnetic field at the time of interaction, but on the field line geometry, particle energy, and the timing of the spacecraft flyby. As a result, it is necessary to deconvolute the observations by following particles from the point of observation backward in time to the time of interaction. By this method it should prove possible to determine which (if any) of the currently used magnetic field models for Jupiter and Saturn is more useful in explaining the observations.

# A REANALYSIS OF VOYAGER 2 FIELD AND PARTICLE DATA NEAR GANYMEDE'S ORBIT

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Voyager 2 observed around a dozen plasma density voids in a region downstream of the Jovian satellite Ganymede which is located in the corotating magnetosphere of Jupiter. Large fluctuations in the intensities of LECP and high energy particles were also reported. Various explanations for these perturbations have been put forward, which include:

1. Absorption of particles and modulations of their energies by Ganymede,
2. Depletion of plasma in certain regions by ballooning mode instabilities, and
3. Modulations of field and particle intensities by ULF waves.

We have recently reanalyzed the PLS, LECP, and MAG high resolution data. A generally striking but not systematic correlation is seen between the thermal pressure of the particles (dominated by LECP particles) and plasma number densities. There is no correlation between the magnetic field perturbations and plasma properties, but the frequency contents of the magnetic and particle data are similar. In the light of our data analysis, we will reexamine the above hypotheses.

# AN UPPER LIMIT ON SHEPHERDING SATELLITES AT SATURN'S RING G

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A preliminary characterization of Saturn's Ring G has been obtained from its absorption signature in energetic proton intensity as observed with Pioneer 11 and by imaging and dust impact measurements with Voyagers 1 and 2. No associated, shepherding satellites have been detected optically. An independent upper limit on the sizes of any such satellites is inferred from the particle absorption signature. This upper limit on the sum of the cross-sections of one or more satellites is found by two different methods to lie in the range of 4 to 50 $km^2$.

# SPECULATIVE ESTIMATE OF A MAGNETIC MOMENT FOR IO

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If we accept Gold's hypothesis (Science, 206, 1071, 1979) that volcanoes on Io are, in part, controlled or influenced by the $10^6$ Ampere currents flowing to and from Io, and if we also accept the suggestion by Kivelson et al. (Science, 205, 491, 1979) that Io may have a sensible magnetic moment, we can estimate some properties of a magnetic moment for Io as follows:

(1) We note from the work of McEwen and Soderblom (Icarus, 55, 191, 1983) that volcanism on Io occurs largely within a band on each side of the equator. The two bands are nearly 60° apart, and their latitude varies smoothly and similarly with longitude.

(2) We assume the $10^6$ Ampere currents observed at Io enter and exit Io in or near an "auroral zone" that separates open from closed field lines. This boundary is determined by the merging of Io's magnetic field with Jupiter's. We further assume that volcanoes tend to form within this auroral zone.

(3) We adjust the strength and the tilt of Io's magnetic moment to obtain a best fit between the auroral zone and the location of the volcanoes.

One somehwat pleasing fit is obtained for a southward pointed dipole having a magnetic moment of $1.5 \times 10^4$ nT $R_I{}^3$ (i.e., an equatorial surface magnetic field of 0.15 Gauss) and having its magnetic north pole tilted 10° from the spin axis and displaced 0.1 $R_I$ southward. The motion of the Io torus plasma past Io generates a voltage of $2.5 \times 10^6$ volts across this Io magnetosphere, which, for the deduced magnetic moment, has a diameter of 6 $R_I$. Thus, as much as $2.5 \times 10^{12}$ Watts of electrical power is dissipated in the form of Joule heating at Io. Athough this power is small compared to the $4 \times 10^{13}$ Watts of thermal energy emitted from Io, it is larger than the $10^{11}$ Watts expended in the volcanic plumes.

The question remains as to whether volcanism on Io is in any way influenced by the electrical currents that are known to flow between the torus plasma and Io. If these currents do affect the location and behavior of the volcanoes, then the above analysis may give us a simple way to determine something of the magnetic moment of Io.

# THE INTERACTION BETWEEN IO AND THE PLASMA TORUS: EXCITATION OF ALFVEN WAVES

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The excitation of Alfven waves by Io has been proposed since around 1967. Observations by Voyager 1 in 1979 confirmed these expectations. We developed a three-dimensional self-consistent model of the interaction between Io and the plasma torus. Toroidal and poloidal fields were used for the calculation of the magnetic field in Io's vicinity. Euler potentials are introduced for the derivation of an elliptic differential equation for the electric potential. The far field distortions are built by Alfven wings. The model yields the electric fields, current densities and magnetic fields in the Alfven wings and in Io's vicinity. We will present results for different plasma conditions/Alfvenic Mach numbers.

# AN MHD SIMULATION OF IO'S INTERACTION WITH THE PLASMA TORUS

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We shall present preliminary results from a time-dependent, three-dimensional magnetohydrodynamic (MHD) simulation of the flow of the torus plasma past Io. In an MHD simulation, the plasma is modelled as a conducting fluid, and the partial differential equations for fluid flow are solved using finite difference methods. One advantage to this approach is that the equations are solved self-consistently.

Our initial simulations model Io as a finite conductor embedded in a sub-Alfvenic plasma flow. We shall compare the parameter regime and numerical technique for this effort with that of previously performed MHD simulations of the interaction of the solar wind with the earth's magnetic field, and we will discuss planned modifications of the code that will lead to a more realistic model.

# KINETIC EFFECTS OF IO'S ALFVEN WAVE

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We calculate for different scale heights of Io's ionosphere the perpendicular wave number spectrum of the Alfven wave excited by Io's motion through the magnetosphere of Jupiter. The collisionless damping of the wave as it propagates through the plasma torus is estimated assuming a realistic ion composition and realistic temperatures for the plasma torus. Outside the plasma torus the Alfven wave develops an appreciable parallel electric field which we estimate from our model calculation. We shall discuss consequences on the field-aligned acceleration of electrons by the Alfven wave.

# ALFVEN WAVE REFLECTIONS AND RADIO ARCS AT URANUS

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During the recent fly-by of Uranus, Voyager 2 received a few radio arcs resembling Jovian decametric arcs. Previously, multiple reflections of Alfven waves excited by Io appeared to successfully explain the Jovian arcs. In this paper a simplified model of the Uranus-Miranda system has been applied to attempt to explain the Uranian arcs similarly. Interestingly, the model predicts that multiple reflections of Alfven waves will occur only when Miranda is at extreme magnetic latitudes. When multiple reflections do occur, the periodicity of the arcs would be modulated by Miranda's magnetic latitude. The non-negligible motion of the spacecraft at the time of reception of the arcs complicates the correlation of the observed periodicity with the predicted periodicity. Nevertheless, the initial results correlate well.

# JUPITER MAGNETOSPHERE: THE MOVIE

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# 'NEW' PLASMA WAVE OBSERVATIONS FROM JUPITER

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Although the Voyager encounters of Jupiter occurred more than seven years ago and the Galileo mission is still several years off, a wealth of 'new' plasma wave observations have become available over the past few years. During the two Voyager encounters, over 12,000 wideband frames were obtained--almost 20 times more than were scheduled. Because of the Jupiter Data Analysis Program and an ever-increasing computational capability, most of these frames have now been Fourier analyzed. The temporal and spectral resolution of the wideband data are far superior to that of the spectrum analyzer data, hence, the numerous frames provide important new observations pertaining to a number of plasma wave phenomena and wave-particle interactions. The purpose of this paper is to present some of these 'new' observations in an effort to shed light on established problems and to perhaps identify a few new problems for study.

One phenomenon which appears repeatedly in the wideband data is broadband electrostatic noise. While we have presented a survey of the gross features of this low frequency noise, the high resolution observations show numerous examples of the emission in the middle and outer magnetosphere. In many cases the broadband noise is co-located with small scale gradients in the plasma density as determined by the low frequency cutoff of the trapped, nonthermal continuum radiation.

A large number of the new wideband frames provide information on the nonthermal continuum radiation including narrowband features and small time-scale brightness variations. The low-frequency cutoff of the radio emission is now available from a large number of time intervals providing quite accurate electron number densities over a large portion of the Jovian magnetosphere.

Additional measurements of electrostatic Bernstein waves will be shown which illustrate some of the fine scale features of these emissions which have not been studied heretofore in any great detail.

These are just a few examples of the observations made available by the wealth of wideband frames returned from Jupiter. It is hoped that these data will serve to stimulate further studies of the magnetospheric data sets provided by Voyager and perhaps will influence the direction of some of the Galileo studies.

# PLASMA WAVES IN THE MAGNETOSPHERE OF URANUS

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Radio emissions from Uranus were detected by the Voyager 2 plasma wave instrument about 5 days before closest approach at frequencies of 31.1 and 56.2 kHz. The bow shock was identified by an abrupt broadband burst of electrostatic turbulence about 10 hours before closest approach at a radial distance of 23.5 $R_U$. Once inside of the magnetosphere strong whistler-mode hiss and chorus emissions were observed at radial distances less than about 8 $R_U$, in the same region where the energetic particle instruments detected intense fluxes of energetic electrons. A variety of other plasma waves, such as $3f_c/2$ electron cyclotron waves, were also observed in this same region. At the ring plane crossing the plasma wave instrument detected a large number of impulsive events that are interpreted as impacts of micron-sized dust particles on the spacecraft. The maximum impact rate was about 20 to 30 impacts/sec, and the north-south thickness of the impact region was about 4,000 km.

# PLANETARY NONTHERMAL CONTINUUM: SOURCES AND ASSOCIATED RADIATIONS

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More than a decade of observations in the Earth's magnetosphere and the visits of Voyagers to Jupiter, Saturn and Uranus have shown the close similarity between the plasma waves and radio emissions at these planets suggesting that similar plasma processes are at work. A review of our present understanding of one of these radio emissions - nonthermal continuum - will be presented which will clearly show the value and importance of comparative radio planetology. In particular, there is strong evidence that the essential ingredients for the production of continuum are electrostatic upper hybrid waves in density gradients for the primary narrow band electromagnetic emissions, and the existence of a magnetospheric cavity for the trapping of these emissions to create the continuum. Those emissions which are at higher frequencies and which are not trapped in the cavity can be used to derive information on the positions and properties of their sources.

# NONTHERMAL CONTINUUM RADIATION IN THE JOVIAN MAGNETOTAIL

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Nonthermal continuum is observed at 1.2 kHz on Voyagers 1 and 2 within the Jovian magnetosphere. It is seen in the magnetospheric cavity on both the dayside and nightside, being most intense in the magnetotail lobes when Voyagers were above the plasma sheet. In these regions the radiation was distinctly left hand polarized when Voyagers were in the northern tail lobe and right hand polarized when in the southern tail lobe. The observations are considered within the context of other plasma waves reported to exist in the Jovian magnetosphere and of analogous emissions observed at Earth. Drawing in particular from our knowledge of continuum source regions within the terrestrial magnetosphere it is suggested that the most likely main source of the 1.2 kHz Jovian continuum is the morning/prenoon magnetopause. It is shown how the nonthermal continuum observed in the Jovian magnetotail can be utilized to extract information on the plasma sheet.

# PITCH ANGLE SCATTERING OF THE IONS AND RESULTANT AURORAL PRECIPITATION IN THE JOVIAN MAGNETOSPHERE

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The significance of the ion precipitation into the Jovian atmosphere for exciting auroral emissions is known through recent satellite EUV observations and X-ray observations. Temperature anisotropy of the hot ions attributed to the inward radial diffusion in the magnetosphere is regarded as a primary source of the unstable electromagnetic ion cyclotron waves which scatter the ions into the loss cone. Excitation of the unstable waves and subsequent pitch angle scattering of the ions ($H^+$, $O^+$, $S^+$, $S^{++}$ etc.) are studied with the use of a one-dimensional electromagnetic hybrid code. The presence of a large density change along a given magnetic field line is also an important factor to be taken into account. Detailed discussions will be given in the talk.

# PITCH-ANGLE DIFFUSION COEFFICIENTS FOR IONS IN THE IO PLASMA TORUS

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Whistler mode noise in the Io plasma torus can be converted to ion cyclotron waves at the local crossover frequency due to the presence of several ion species in the torus. Using whistler mode intensity measurements in the Jovian magnetosphere from Voyager I, bounce averaged diffusion coefficients have been calculated for protons, $O^{2+}$, $O^{+}$, and $S^{+}$ ions for energies ranging from 10 keV to 3 MeV if the whistler noise is converted to ion cyclotron waves. The coefficients were independently calculated for several cases: a) using the ambient concentrations and twice the ambient concentrations of the particle species, and b) assuming the converted waves remain as ion cyclotron waves and assuming conversion back to whistler mode waves at the $O^{2+}$ cyclotron frequency.

# PLASMA WAVES AT THE OUTER PLANETS: OUTSTANDING PROBLEMS OF THEORY AND INTERPRETATION

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The magnetospheres of Jupiter, Saturn, and now Uranus have exhibited a great variety of complex and interesting plasma wave and radio emissions. In many circumstances the waves have proven valuable as diagnostic probes of the plasma environment. In other cases they have played an active role in particle dynamics having a significant effect on the kinetic distributions of ions and electrons. Still, there remain many intriguing waves that have resisted attempts at a plausible explanation.

This paper will survey the field of plasma emissions and summarize those areas where problems of theory or interpretation exist. Many characteristic waves that have been observed regularly during the Voyager tour of planetary magnetospheres are reasonably well understood (at least in their rudimentary aspects) and will not be covered. Instead, emphasis will be placed on those emissions which are singular to particular planets or plasma configurations and where fundamental questions persist with regard to the identification of the mode, its source, or its generation mechanism. Where possible, tentative solutions will be presented along with suggested avenues for further investigation.

# A COMPARATIVE ANALYSIS OF SATURNIAN CHORUS

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The Voyager observations of Saturnian chorus are used as a basis for an analysis of Saturnian chorus in terms of various parameters relevant to the nonlinear cyclotron resonance interaction that is believed to be the interaction length and the threshold field intensity for phase trapping of the particles by the waves are derived for an inhomogeneous medium and are compared with the equivalent parameters for terrestrial and Jovian chorus. Estimates of particle precipitation fluxes that would be expected to be induced by the observed Saturnian chorus are provided and possible effects on the Saturnian ionosphere are discussed.

# Z-MODE RADIATION IN JUPITER'S MAGNETOSPHERE

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# BROADBAND JOVIAN KILOMETRIC RADIATION FROM THE IO PLASMA TORUS

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Broadband Jovian kilometric radiation was observed by Voyagers 1 and 2 to be beamed away from the zenomagnetic equatorial plane. Two theories were proposed for the equatorial shadow zone. One suggested that the Io plasma torus forms an obstacle to radiation produced on auroral field lines. The other theory proposed that the source is located on the outer flanks of the torus, the beaming being inherent to the emission mechanism. Results are presented which indicate that the latter is consistent with the observations and it would appear that the emission is produced by linear mode conversion of electrostatic upper hybrid to electromagnetic waves in plasma density gradients.

# SATURN KILOMETRIC RADIATION AND ION PICKUP FROM SATURN'S MOONS

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Newly born ions originating in the exospheres of the moons of Saturn represent a free energy source whose energy scales with the square of the relative velocity between the rotating Saturn magnetosphere plasma and the moons. We discuss the role of newly born ions in heating magnetosphere electrons and the subsequent interaction of this heated electron population with the centrifugal flute instability believed to be operative upon the dayside equatorial plasmasheet's outer boundary. The generation of Saturn kilometric radiation (SKR) from the combined effects of pick-up ion electron heating and the centrifugal flute instability is discussed. Solar wind control of SKR, in this scenario, is the consequence of solar wind distortion of the Saturn magnetosphere which sets up the necessary conditions for the centrifugal flute instability. The possibility of similar processes being operative in the generation of non-thermal radio emission from Jupiter, Uranus, and Neptune is considered.

# URANUS MAGNETOSPHERE: THE MOVIE

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# KILOMETER WAVE RADIO EMISSIONS FROM JUPITER AND SATURN: OUTSTANDING PROBLEMS

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Both forms of Jovian kilometric radiation, bKOM and nKOM, are closely related to the Io plasma torus. nKOM is certainly generated in the torus, and bKOM may be although this possibility has not yet been successfully verified by ray tracing. There is strong inducement to solve the source location problems of nKOM and bKOM because study of their long-term behavior provides an important synoptic method of monitoring the Io torus, perhaps even the Io volcanism. Saturn's kilometric radiation on the other hand is most likely emitted on high latitude field lines near the dayside auroral zones or from the magnetospheric cusps. However, the strong (100:1) rotation modulation of SKR has defied explanation because the usually accepted cause for this type of modulation, a tilted magnetic dipole field, does not exist at Saturn. Status of current research into these problem areas will be discussed along with some personal ideas for future research.

# EXTERNAL CONTROL OF PLANETARY RADIO EMISSION

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The various emission components of each of the known radio planets exhibit intensity fluctuations on time scales characteristic of their planetary rotation periods. Longer term fluctuations are also readily apparent in the data and in some case these are stronger than those due to the rotation effects. In the cases of earth and Saturn, the long-term fluctuations have been definitively attributed to the influence of the solar wind. At Jupiter, the high frequency emission is driven by the interaction of the magnetosphere with Io. The hectometer-wave Jovian emission is only weakly correlated with the solar wind, and the kilometer-wave emission, while manifesting extreme changes in intensity, is driven by some unknown process. Uranus radio waves exhibit long-term intensity fluctuations that are considerably smaller in magnitude than the rotation driven modulation, and it is not known if these fluctuations are solar wind related.

Despite the vastly different characteristics of the magnetospheres of each of these planets, the total output power level is a constant fraction of the solar wind input power at each planet. In order to understand the physics of the interactions that generate solar-wind driven radio emissions, much higher-time resolution observations need to be made.

# SOLAR WIND INFLUENCE ON NON-THERMAL PLANETARY RADIO EMISSION

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Extensive studies on the characteristics of planetary radio emissions yielded that the solar wind has a decisive effect on specific planetary radio components. Detailed investigations on the solar wind influence on planetary radio emissions have been performed at the "Terrestrial Kilometric Radiation" (TKR), at the "Decametric" (DAM) and "Hectometric" (HOM) Jovian radio emissions (independent from the Io satellite modulation), and finally at the "Saturn Kilometric Radiation"(SKR). The latter exhibited an exceedingly interesting behavior during periods in which Saturn was immersed in the distant Jovian magnetotail and therefore almost totally shielded off the solar wind. The very recent findings of the Uranus' radio emissions are not analyzed yet with respect to the solar wind influence, but due to the very dynamic behavior of the Uranus' magnetosphere it seems unlikely that the solar wind control is dominating.

# RADIO EMISSION FROM URANUS: VOYAGER RESULTS

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The principal emissions from Uranus were rotationally modulated at a sidereal clock period of 17.24 hours. They occurred essentially only below 100 kHz as seen on the dayside of the planet but extended as high as about 800 kHz on the nightside. The peaks of the emission generally associated with negative magnetic dipole tip presentation to the spacecraft and tended to be left-hand circularly polarized. They were a rather broadband continuum lying nominally in the extraordinary magnetoionic mode.

After closest approach, and between presentations of the negative dipole tip, there occurred impulsive narrow band bursts in patterns drifting mostly positively in frequency. These bursts exhibited the peculiar property of not decreasing in amplitude for several days after closest approach, but then abruptly dropped by at least 20 decibels, and perhaps disappeared completely. Before closest approach extremely intense, short-lived emissions occurred a number of times in the low frequencies also occupied by the continuum emissions.

The PRA instrument benefitted from one single 24-second frame of high-rate data in the frequency range 600 to 800 kHz at the time of closest approach. Other frames failed to reveal any Uranian emissions. But this single frame is rich in continuum emission modulated strongly at a quasi-period of about 30 milliseconds, and possibly also 3 milliseconds. On the nightside we saw strong modulation of the continuum emission from 50 to 500 kHz beginning very close to the time that Voyager crossed the magnetopause outbound. This modulation was broadband in that frequency range and quasi-periodic, with a period of about one minute.

In our preliminary interpretation we hypothesize a dayside lobe-shaped plasmasphere, lying within about L = 4, which blocks the propagation to Voyager of waves at higher frequencies than about 100 kHz. On the nightside these waves propagate freely, including through the magnetopause and bowshocks, but are focussed and defocussed by very large scale waves moving along those boundaries. The fast variations near closest approach would seem to indicate modulation associated with generating mechanisms in the exosphere of Uranus. The pattern of continuum-with-bite (near the times of negative dipole tip presentation) that occurs at high latitudes on the nightside may indicate that the emissions are beamed in rather narrow cones around lines of force near L = 4 on the nightside.

# STEREOSCOPIC DETERMINATION OF SATURN KILOMETRIC RADIATION BEAMING

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The correlation of simultaneous observations of Saturn Kilometric Radiation (SKR) made by the two Voyager spacecraft, at quasi-equal distances from before and behind the planet, shows that the instantaneous radiation pattern of SKR is narrow-beamed. This narrow instantaneous emission lobe is consistent with the thin conical sheet predicted by the Maser Synchrotron Instability process, at present the most promising mechanism for generating non-thermal planetary radio emissions. The orientation in space of this beam is constantly changing due to fluctuations of the magnetic field lines geometry and/or particle precipitations (probably induced by Solar wind pressure changes), statistically filling the large emission cone usually assumed to represent the SKR emission lobe in the literature. We suggest that the Terrestrial Kilometric Radiation might present the same beaming characteristics. This result should be taken into account for the determination of the source locations.

# PLANETARY RADIOEMISSIONS AND PROPAGATION EFFECTS

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Non thermal planetary radioemissions are thought to be produced by coherent plasma instabilities occurring in localized regions of the ionized planetary near environment. These emissions are characterized by: a dynamic spectrum highly structured both in time and frequency, with contrasted fringe-like patterns; a visibility, highly depending on the observing geometry.

We show that these properties may be often interpreted by focusing and diffraction by plasma lenses or mirrors, which are produced by large scale, isolated plasma structures or critical surfaces. We give orders of magnitude of the effects on both intensity and visibility, for the typical size scales, densities and radiofrequencies encountered in the giant planet magnetospheres.

Examples of focusing and diffraction phenomena actually observed in other contexts are displayed.

These effects could lead to reinterpret a lot of observational properties linked to power flux and directivity of the radiation, and put constraints on the actual size and structure of the jovian and saturnian radiosources.

In the case of the newly discovered radioemission from Uranus, preliminary estimations of such effects and possibly related observations are discussed.

# LOCALIZATION OF THE SOURCES OF THE JOVIAN DECAMETER RADIO EMISSION

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The sources of the jovian decameter radio emission are localized with the hypothesis that the high frequency limit of the emission corresponds to the surface gyrofrequency in the source region. Systematic measurements of the high frequency of the emissions recorded by the Voyager Planetary Radio Astronomy experiment, compared to the Pioneer magnetic field models, show that the sources of the Io-dependent emissions are, as expected, linked to Io. Well-defined peculiar features of the time-frequency dynamic spectra originate from the Io flux tube, in the north and south hemispheres. The main northern hemisphere emission occurs on magnetic field lines behind Io, which can be explained in the frame of the triggering of the emission by an Alfven wave pattern produced by Io movement in the jovian magnetic field. A similar study of the high frequency limit of the non-Io emissions gives indications about the properties of the energetic electrons responsible for the emission, and about the source location.

# RAY TRACING OF JOVIAN DAM RADIATION FROM SOUTHERN AND NORTHERN HEMISPHERE SOURCES: COMPARISON WITH VOYAGER OBSERVATIONS

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Because of a lack of readily usable information pertaining to the polarization of the Voyager 1 and 2 high frequency band data, a technique has been developed which aids the identification of Io-dependent decametric radiation originating from the southern hemisphere of Jupiter. This technique compares the results of model ray tracing calculations with the Planetary Radio Astronomy (PRA) observations. A large portion of the Voyager 1 and 2 PRA observations are sorted into bins ±3° wide centered on a specific Io central meridian longitude. When the data are plotted (as a frequency-longitude spectrogram) in this coordinate system, Io-dependent features can be identified and compared with ray tracing calculations performed in a model Jovian magnetosphere where it is assumed that the decametric emissions are generated in the RX mode from low altitude source regions along the instantaneous Io flux tube. Two different magnetic field models are used and the results are contrasted. In this study, we compare the observations for a constant sub-Io longitude of 260° with the corresponding model ray tracing. The results permit the identification of DAM spectral features from sources in both the northern and southern hemispheres.

# JUPITER'S DECAMETRIC SOURCE LOCATIONS

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Ray tracing calculations in a model Jovian magnetosphere permit certain features in the decametric emission recorded by the Voyager spacecraft to be identified with specific source locations in the north and south Io flux tube footprints and in the north and south auroral zones. The Voyager PRA experiment data, recast into a reference frame in which Io is fixed in Jovian Sys. III longitude, reveal (1) beaming of the radiation into thin sheets, (2) Io control in some longitude ranges, and (3) an Io-independent component of radiation.

Assuming the emission is launched from positions in the auroral zones (independent of Io position) and from the Io flux tube footprints, rays have been traced at frequencies slightly above the R-X mode cutoff. On the basis of correspondence of the ray tracing results with features in the reformatted Voyager data, a picture unfolds: The beaming of the radiation from four specific source locations (north and south auroral zones, north and south Io footprints) explains the geometry of the "traditional sources": A, B, C, and D seen by an observer located near Jupiter's equatorial plane. The two pairs of traditional sources, Io-B/Io-C and Io-A/Io-D correspond to the two pairs of intersections, in the observer's plane, of the hollow emission cones emanating from the north and south footprints of the Io flux tube. Ray tracing results are used to identify features in the Voyager data set and associate them with specific source positions.

# UV-AURORAL ORIGIN OF A COMPONENT OF JUPITER'S DECAMETRIC RADIATION

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We analyzed the simultaneous observations at 22 MHz of Jovian non-Io-A noise storms from Voyagers 1 and 2 and a ground-based observatory. We derived emission beam structures based on the data of five storms which were correlated at the two or three stations. The conical-sheet beam model was applied to the derived beam structures, and the emitting region of the radiation was inferred with the aid of the GSFC 04 magnetic field model. The result indicates that the emitting region lies above the UV auroral zone in the northern hemisphere of Jupiter, and in a limited longitude range which is consistent with that of the so-called active sector. There is considerable evidence that the UV aurora is caused by the precipitation of high energy heavy ions into Jupiter's ionosphere from the Io plasma torus. We therefore suggest that the decametric radiation is emitted by secondary electrons ejected from the top of the ionosphere as a result of the UV auroral particle precipitation.

# SOURCE FLARING: A NEW JOVIAN DECAMETRIC PHENOMENON

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An interferometric analysis of Jovian L-bursts on time scales of 100 msec has been initiated using the University of Florida 45-kilometer interferometer at 18 MHz. The most interesting of the results obtained so far is the detection of source "flaring"--the dynamic increase in apparent size of the Jovian emitting region that occurs within the duration of each of a certain type of L-bursts. Evidence is also presented which demonstrates the existence of two (or more) spatially discrete Jovian sources which radiate intermittently, only part of the time simultaneously. The implications of these results are considered.

# GENERATION MECHANISMS OF PLANETARY RADIO EMISSIONS

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The generation of electromagnetic radiations by direct and indirect mechanisms are discussed for a wide range of plasma parameters and for different forms of free energy sources. The theoretical results are compared with the radio emissions observed in the earth's auroral regions. Applications to radio emissions from Jupiter, Saturn, and Uranus are also suggested.

# LIMIT ON THE AMPLIFICATION BY THE CYCLOTRON MASER OF AN X-MODE WAVE

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A lot of attention has been paid in the recent years to the cyclotron maser instability which provides a likely explanation to nonthermal radio emissions from planets. Until now, the authors have investigated the stability in an homogeneous medium, an assumption which is far from reality since the size of the source, along the magnetic field, is comparable to the wave length. We will investigate, by a full wave calculation, the convective growth of an x-mode wave amplified by the cyclotron maser in an inhomogeneous medium. We will also discuss the respective roles played by trapping and inhomogeneity in determining the maximum amplitude reached; this level will be compared to those obtained from observations.

# EVIDENCE FOR LASING IN PLANETARY RADIO EMISSIONS

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The principal radio emission of planetary magnetospheres, as exemplified by the earth's AKR and Jupiter's DAM, are now widely attributed to energetic electrons and the Doppler-shifted cyclotron resonance instability of Ellis, Melrose, Wu, Lee and many others. A pertinent question, however, is whether that instability operates alone or in conjunction with ambient density irregularities to produce oscillating natural radio laser.[1] Recent radio observations of both the Earth and Jupiter, plus certain reinterpretations of older observations, would tend to favor the latter by showing a laser's coherence and beaming.

Coherence implies spectral discreteness, of the sort always found in the high resolution spectra of the AKR. The comparable feature at Jupiter would seem to be the well-known decametric S-bursts, for which lasing provides a long-needed alternative to discrete electron bunches as an explanation for their discreteness. In both cases, the observed spectra also often exhibit a regular fine structure which can be attributed to the expected longitudinal laser modes. The spectral spacing of that fine structure then indicates the laser length, or presumably the source thickness. The observed spacings imply that the individual radio lasers contributing to the AKR are about 25 km thick, whereas those at Jupiter are only about 5 km thick. The corresponding angular emission beamwidths, which are determined strictly by the laser length in wavelengths, should be about 10° and 3°, respectively. Although what organizes the beam directions isn't known, such three-degree beamwidths at Jupiter would readily account for the apparent sharpness of beaming which is observed. At the Earth, this beaming is presumably obscured by the broader beamwidth and the individual sources at different locations along the auroral oval being beaming in different directions. The beaming, however, shows itself indirectly in the statistical distributions of AKR amplitudes and it accounts for the wide range of amplitudes which are observed. At Jupiter in addition, the expected laser coherence also seems to show itself in the spectral bandsplitting recently discovered by Leblanc and Rubio. This splitting is attributable to wave refraction causing a caustic focus and producing interference comparable to that of grazing-incidence reflection. The final, and perhaps most striking evidence for lasing, is the remarkable external triggering of the emissions, now found at both planets, by incoming solar radio waves.[2] This triggering, which yields emissions long after the triggering stimulus has disappeared, would seem impossible without the self-excited oscillations which constitute lasing.

The radical new hypothesis that magnetospheric cyclotron radio emissions require lasing has profound implications: since oscillators always saturate, small-signals amplification no longer applies and the generation must be intrinsically nonlinear. The emitted power, moreover, should be independent of the wave gain (as long as the gain exceeds some oscillation threshold), and dependent instead upon the saturation process and the influx of free energy. In these and other aspects, lasing dominates in determining the observable properties to the point of supplanting the instability mechanism as the fundamental underlying physical process.

[1] J. Geophys. Res., 87, 8199, 1982.
[2] Geophys. Res. Lett., 8, 1091, 1981.

# BEAM STRUCTURE OF THE RADIO EMISSION FROM URANUS

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A beam model to account for the radio emission observed from Uranus over the range from 60 to 800 kHz is being developed. Major features of the observed modulation structure can be reproduced by the model, including the effects of occultations by the planet. Implications regarding the location and nature of the source are discussed.

# RADIO DETECTION OF URANIAN LIGHTNING BY VOYAGER 2

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Within distances of ~ 600 000 km from Uranus, the Planetary Radio Astronomy (PRA) experiment aboard Voyager 2 spacecraft detected intense impulsive (100 - 300 ms) bursts of broadband (~ 400 kHz to ~ 40 MHz) radio emission. This emission is very different from the Uranian magnetospheric radio component, also discovered during the recent Voyager-Uranus encounter. During the two previous Saturn encounters, in 1980 and 1981, the PRA experiments detected similar radio emissions, which have been interpreted as radio emissions associated with lightning activity in the atmosphere of the planet. By analogy with the Saturn Electrostatic Discharges (dubbed SED in the literature), we have adopted the term Uranian Electrostatic Discharges (UED) for these new radio bursts. We have determined the physical characteristics of UED (duration, polarization, power spectrum), and in the frame of their interpretation as lightning-associated radio bursts, we derive ionospheric peak electron densities over the Uranian day- and nightside hemispheres. The existence of lightning is an important parameter for further studies of the composition and dynamics of the atmosphere of Uranus.

# CORRELATIONS STUDIES BETWEEN SOLAR WIND PARAMETERS AND THE DECIMETRIC RADIO EMISSION FROM JUPITER

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Variations in the decimeter wavelength radio emission from Jupiter's magnetosphere are being investigated to search for possible correlations with various solar wind parameters. Both spectral analysis and correlation techniques are being used. The radio data used in this analysis span the time interval between 1973 and 1985 when Jupiter was observed at approximately weekly intervals using the NASA Deep Space Network antennas operating at 2295 MHz (13.1 cm). Solar wind data were obtained from various Earth orbiting satellites and from the Plasma Science Experiment (PLS) on Voyager 1 and Voyager 2. Results of the ongoing analysis will be presented.

# GROUND-BASED OBSERVATIONS OF THE IO TORUS

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# GROUND-BASED FABRY-PEROT OBSERVATIONS OF THE IO TORUS

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# THE STRUCTURE OF IO'S ATOMIC CORONA AND IMPLICATIONS FOR ATMOSPHERIC ESCAPE

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The escape of species from Io's atmosphere is studied using a steady state model of Io's thermal corona and its interaction with the Io plasma torus. The corona is assumed to be spherically symmetric with the radial density and compositional structure determined by the gas kinetic temperature, critical level radius, and mixing ratios of the component species, all free parameters in the model. Thermal and nonthermal escape processes are modeled and the results are compared with inferred torus and neutral cloud supply rates for O, S, Na and K. Scenarios are considered in which either S or O dominates the density structure of the corona. The spatial morphology of a calculated source of high velocity Na produced by charge exchange in the extended corona, when compared with the observed near-Io Na "jets" which have a spatial "width" of ~ 5 $R_{Io}$, requires an extended Na coronal component, consistent with the O dominated corona, a 1% critical level mixing ratio of Na, and a critical level radius 1.5 to 2.0 $R_{Io}$. Atmospheric sputtering is found to be the major escape mechanism for models in which the plasma flow reaches the critical level. However, such models produce total mass loading rates ~ 10 times larger than other inferred values suggesting that substantial plasma flow modification and deflection may occur in the corona at least one and possibly several scale heights above the critical level.

# UNDERSTANDING THE ESCAPE OF MATERIAL FROM IO AND ITS ROLE IN THE PLANETARY MAGNETOSPHERE

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The escape of material from Io and the manner in which this material interacts and fuels the planetary magnetosphere are studied. Highly-developed models for the Io neutral gas clouds of sodium, potassium, oxygen and sulfur are employed to analyze cloud brightness morphology data acquired by ground-based facilities and rocket flights. From analysis of the neutral-plasma interactions, we have estimated (1) the source rate of neutrals escaping the satellite, (2) the spatial character of the ion loading rate, the plasma mass loading rate, and ion energy input rate to the plasma torus, and (3) the source rate of fast neutrals tro the outer magnetosphere supplied by charge exchange in the plasma torus. These rates and their implications on the spatial structure of the torus will be discussed. The case for the presence of an east-west electric field in the planetary magnetosphere is strengthened by east-west asymmetries observed in the plasma torus (ultraviolet and optical ion emission lines) and in the Io sodium cloud (D-emission lines) that are shown to be anticorrelated. These east-west asymmetries and the possible time variability of this electric field will be discussed.

# CURRENT PROBLEMS IN THE IO PLASMA TORUS

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We discuss the current status of selected topics related to the energy supply, global structure, and local dynamics of the Io plasma torus. Questions bearing on these subjects include:

(i) Do spectroscopic observations indicate an "energy crisis" for the torus if ion pickup is the sole or dominant energy input mechanism?

(ii) What are the transport mechanisms by which neutrals and pickup ions escape Io, and how do the transport mechanisms affect the determinations of plasma composition and inferences of Io's interior composition and processes?

(iii) Are longitudinal asymmetries in EUV and n-Kom emissions evidence of permanent structural anomalies or global dynamical properties of the torus?

# DETECTION OF NEUTRAL ATOMIC CLOUD NEAR IO USING IUE

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An ultraviolet spectrum (1175-1985 Å) was obtained on 18-19 July 1986 with Io centered in the large aperture of the short wavelength spectrograph as Io moved in its orbit from a phase angle of 34° to 149° on the eastern (sunrise) side of Jupiter. The total integration time was 13.5 hours.

Emission lines of neutral sulfur and oxygen were positively detected near Io with a spatial extent along the slit close to that expected from the spatial resolution limit of the IUE (about 6 satellite radii). Emission lines from ionic species (SII, SIII, and SIV) were also present but filled the length (about 20 satellite radii) of the slit and, hence, were identified as resulting from the extended plasma torus.

# JOVIAN AURORAE: ION OR ELECTRON PRECIPITATION

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Voyager Ultraviolet Spectrometer (UVS) and International Ultraviolet Explorer (IUE) measurements have observed intense Lyman alpha and Lyman and Werner band emissions from the Jovian atmosphere at high latitudes which provide evidence for auroral precipitation at Jupiter. Although electrons between 10 and 30 keV with an energy flux of 10 ergs $cm^{-2}$ $s^{-1}$ will account for the measured UV emissions, both in situ Voyager energetic particle measurements and X-ray spectra from the Einstein observatory indicate that energetic oxygen and sulfur ions are responsible for the auroral emissions. To test this hypothesis we have modeled the energy loss and aeronomical consequences of oxygen ion precipitation. The results indicate that about 10 percent of the incident ion energy flux goes into electronic excitation of the precipitating ions which lead to observable UV emissions such as the 1304 angstrom line. We then used the IUE observatory to obtain high signal to noise spectra of the Jovian aurora in hopes of observing the oxygen and sulfur emissions. The results of this combined model and observational study of Jovian auroral processes will be presented.

# MOLECULAR AND ATOMIC HYDROGEN FROM TITAN IN THE OUTER KRONIAN MAGNETOSPHERE

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We have solved the rate equations for the species expected to be injected from Titan into the magnetosphere of Saturn. The source strengths for H and and $H_2$ taken from the published literature predict proton and $H_2^+$ densities significantly larger than those observed by the Voyager plasma experiment. It is found that the observed data can be reproduced by the model if both source strengths are reduced by about an order of magnitude. The reduced source strengths are sufficient to supply the observed neutral hydrogen cloud. The calculations were performed for two separate cases: one which the mass 28 ion seen in the Titan plume is $N_2^+$ and the other in which $H_2CN^+$ was assumed. The differences in the results were not sufficiently significant to provide a positive identification of the heavy ion. We point out possible sources for the apparent overestimates in the published source strengths.

# COUPLING OF THE ATMOSPHERE AND MAGNETOSPHERE: UVS OBSERVATIONS

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The magnetosphere of Uranus is connected with the atmosphere of the planet through several phenomena, including the aurora, the extended hydrogen corona, and possibly the electroglow. UV observations have identified auroral emissions that originate from a region of approximately 20° in diameter near the south (dark side) magnetic pole. Current investigations include a search for auroral emissions from the sunlit hemisphere. The search is hampered by the widely-distributed, bright electroglow emissions in the same wavelength region. Furthermore, the surface magnetic field strength is roughly 4 times more intense at the south magnetic pole than at the north, so the dayside aurora, if present, may differ in brightness and morphology from its counterpart on the dark side.

Neutral H from the exosphere extends well into the magnetosphere. A lower limit of 100 $cm^{-3}$ on the number denisty of the H corona at $R = 2.0\ R_U$ can be derived by extrapolating the thermal H density measured near $F = 28000$ km using the measured neutral temperature of 750 K. Resonance scattering from the thermal corona cannot account for the observed H Ly $\alpha$ brightness in the Uranian system. This suggests the presence of an additional source of H, another excitation mechanism, or both. The thermal corona may be augmented by fast H produced in the excitation of the electroglow. This H corona should serve as a source for magnetospheric ions.

# THE ELECTROGLOW PHENOMENON: JUPITER, SATURN, URANUS

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The sunlit atmospheres of the three outer planets Jupiter, Saturn and Uranus show photon emissions characteristic of electron excited hydrogen more or less uniformly distributed over the hemisphere. The phenomenon is distinctly separate from the precipitation processes producing auroral emission. Planet to planet electroglow/auroral relative energy deposition rates are uncorrelated. A simple solution based on direct excitation by solar photoelectrons is obviated by the large energy deposition rate required to account for observed EUV emission rates, the altitude distribution of the excitation, and the energy distribution of the electrons. The vertical distribution of emission intensity does not follow the scale height of the neutral atmosphere, but shows a substantially increasing density of exciting electrons relative to the neutral gas, with increasing altitude. The emissions extend through the exosphere on all three planets. There are planet to planet variations in the phenomenon, the most distinctive of which is a factor of ~ 10 lower mean energy of the exciting electrons at Uranus relative to Jupiter and Saturn. There is presently no plausible theory for the principal mechanism, which in the case of Uranus is responsible for heating the upper atmosphere to $T = 750$ K. The phenomenon will be reviewed with emphasis on Uranus, including a discussion of restrictions on theory.

# THE POST-VOYAGER SIGNIFICANCE OF IUE OBSERVATIONS OF URANUS

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Prior to the Voyager encounter, the IUE observations of bright H Ly $\alpha$ emission from Uranus which varied independently of the solar H Ly $\alpha$ flux were interpreted as evidence of auroral processes and therefore an active magnetosphere. Despite numerous predictions to the contrary, we now know that Uranus possesses an active magnetosphere with unique properties, and that H Ly $\alpha$ emission is produced by a combination of scattered sunlight, "electroglow," and polar aurora. The 4-year data base of the IUE observations can now be re-examined in terms of the potential contributions by these three processes and their variability with time. In particular, it will be argued that the continuous minimum level of emission observed by IUE is a combination of scattered sunlight and "electroglow," whereas the occasional highly variable emission above this level may be either polar aurora or "electroglow." Due to the offset of the magnetic dipole toward the dark hemisphere, the surface field strength is much lower and therefore the mirror point much lower at the sunlit polar than at the dark pole. This will allow more particles of lower energy to precipitate into the dayside atmosphere, which in turn will produce FUV emission with a much higher ratio of H Ly $\alpha$ to $H_2$ emissions than at the dark pole. Pending a good physical understanding of the process by which the "electroglow" is excited, it seems more plausible that a localized polar aurora would lead to a factor of two increase in 4 to 8 hours (as observed in the IUE data) than invoking a planet-wide brightening of the "electroglow."

# COMPARISON OF MODELLING RESULTS TO THE VOYAGER UVS URANUS OBSERVATIONS

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The Voyager/Uranus encounter provided several interesting results concerning the coupled atmosphere-ionosphere-magnetosphere system (e.g., an extended neutral hydrogen corona, relatively large ionospheric scale heights, structured ion density-altitude profiles and atmospheric emissions possibly resulting from thermal electrons as well as nightside aurora). These observations suggest significant electron-atmosphere interactions.

A one-dimensional theoretical model of the neutral atmosphere and ionosphere of Uranus has been used to interpret the Voyager 2 observations. The model solves the continuity and momentum equations for the major neutral species and the major and minor ionic species. Photoelectron and precipitating electron processes are incorporated using the two-stream approximation.

The estimated exospheric temperature used in the model reproduces the extended hydrogen corona which can be further enhanced by impact ionization of molecular hydrogen by soft electrons. Structure in the ion density-altitude profile can be produced by layers of minor species in the bottom-side of the ionosphere and by high altitude peaks which result from the impact ionization. The interactions of soft or thermal electrons (3-20 eV) with the ionosphere and neutral atmosphere are investigated in order to address possible mechanisms for the electroglow. The interactions of energetic electrons (~ 10 keV) are investigated as well to interpret the nightside auroral observations.)