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JUPITER AND IO: A BINARY MAGNETOSHERE

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ABSTRACT

The magnetosphere of Jupiter and Io has recently been traversed by two Voyager spacecraft. Since the earlier Pioneers were not equipped to measure spatially and spectrally resolved photon emissions from the Io torus and Jovian aurora, the dominant plasma components in the magnetosphere, or plasma waves and radio emissions, the Voyagers have provided qualitatively new information that is still not fully digested. This review outlines qualitatively the physical picture emerging from ongoing data analysis and theoretical interpretation. We discuss observations of the Io torus EUV emmissions and Jupiter's aurora, emphasizing the difficulty of accounting energetically for their luminosity. We next turn to Jupiter's middle magnetosphere, concentrating on the observations of corotating ions, their ambiguities, and their implications. We then return to the classical question of Jupiter's interaction with the solar wind, as manifested by its magnetic tail. Finally, guided by terrestrial magnetospheric experience, we attempt to construct a unifying conceptual picture which, though uncertain, falls within the latitude afforded by the current state of data reduction.

1. INTRODUCTION

For almost two decades before the initial traversal of Jupiter's magnetosphere by the Pioneer 10 spacecraft, the vast system surrounding the planet was intensively studied using astronomical techniques and theoretical inferences based on comparisons with measurements in the terrestrial magnetosphere. During the early days of exploration of the earth's magnetosphere, observations of decimeter emissions from Jupiter (Drake and Havatum, 1959) were interpreted in terms of synchrotron radiation from energetic electrons trapped in a magnetic field considerably stronger than earth's. The presence of relativistic electrons suggested that Jupiter was immersed in the solar wind. Since the wind pressure at 5.2 AU is extrapolated to be only 3.7% of the value at 1 AU, the Jupiter magnetosphere had to be huge in comparison with that of earth (Carr and Gulkis, 1969; Scarf, 1969).

The analyses of the decimeter waves also suggested that the intense decametric radio bursts from Jupiter (Burke and Franklin, 1955) were probably associated with local phenomena that developed at relatively low altitudes, perhaps in the ionosphere where where the local field strength is high. With the discovery of the Io modulation effect on the decametric emmisions (Bigg, 1964), the concept of strong ionosphere-magnetosphere coupling at Jupiter gained acceptance, and early theories suggested that strong field-aligned currents would link Io and Jupiter (Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969).

The combination of a large dipolar magnetic field and a very high planetary rotation rate also indicated that Jupiter's magnetosphere would have properties very very different from those found at earth. Centrifugal forces would have to dominate the plasma beyond a few Jupiter radii (Ellis, 1968; Melrose, 1967; Gledhill, 1967; Piddington, 1967; Brice and Ioannidis, 1970), and even before the Pioneer encounters, these theoretical concepts implied that Jupiter's plasma environment would have characteristics associated with models of rapidly rotating stellar objects such as pulsars. The groundbased observations clearly showed that charged particles are accelerated, since cosmic rays from Jupiter (Pizzella and Venditti, 1973) as well as radio emissions were detectable from earth with intensity modulations correlated with Jupiter's rotation rate.

The Io radio modulation effect also directed the attention of ground-based observers to the region around the Io orbit, and in 1973 Brown detected faint emissions from a neutral sodium cloud near Io (Brown, 1974; see also Mekler and Eviatar, 1974). This observation introduced the idea that the innermost Galilean satellite had some kind of loosely bound atmosphere in which the gas atoms continuously escape to form a gigantic toroidal cloud enveloping the orbit. The sodium cloud discovery also led to the initial proposals that Io would contribute plasma to Jupiter's magnetosphere (Hill and Michel, 1976).

The Pioneer 10 and 11 encounters in 1973 and 1974 revolutionized our knowledge of Jupiter, and they also marked the onset of a new era in plasma astrophysics. As stated in Solar System Space Physics in the 1980's: A Research Strategy (U.S. National Academy of Sciences, 1980), Jupiter's magnetosphere became "... the only object in the cosmos for which inferences drawn from remote astronomical observation have been compared with direct in situ measurements of its neutral atom, plasma and magnetic field environment."

These pre-Voyager comparisons provided a great advance in our knowledge of Jupiter's magnetic field configuration and energetic trapped particle population. Moreover, between the Pioneer encounters, ground-based observers detected sulfur in the region around Io (Kupo et al., 1976), and the concept of Io as a source of heavy ions received increasing attention. However, since the Pioneer spacecraft were not instrumented to measure detailed characteristics of low energy charged particles or emission lines from magnetospheric ions, the inferences concerning the ground-based information related to Io and its effects on the magnetosphere did not make direct contact with Pioneer data. Since these initial outer planet probes had no instruments to measure plasma waves or radio emissions, other important areas of plasma astrophysics were also not directly addressed by Pioneer.

In 1979 and 1980, Voyager 1 and 2 provided definitive new in situ information that resolved many of the important outstanding questions related to the dynamics of Jupiter's magnetosphere and the nature of the Io interaction. The comprehensive Voyager payload included a high resolution ultraviolet spectrometer capable of mapping the Jovian aurora and detecting emissions from excited magnetospheric ions, a complement of receivers designed to measure local plasma waves and radio emissions over the range 10 Hz to 40 MHz and instruments to measure the distributions and the composition of plasma and suprathermal ions.

As Voyager 1 approached Jupiter, the ultraviolet spectrometer observed EUV sulfur and oxygen line emissions from a dense hot toroidal cloud located near Io's orbit (Broadfoot et al., 1979). The subsequent passage across the Io orbit confirmed the existence of this torus as well as the fact that ions of sulfur and oxygen, rather than sodium were the important constituents of the gas cloud. Thus, the EUV data and the other local measurements allowed us to evaluate the earlier ground-based optical observations and to select one set as being more significant than the other. Voyager imaging (Morabito et al., 1979) also verified the prediction by Peale et al. (1979) that Io would have volcanic activity, and the Io images generally explained why this satellite should be such a strong source of neutral and ionized gas.

Although many of the individual Voyager measurements, such as the EUV, may be related to earlier incomplete ground-based or Pioneer measurements or a subset of earlier theoretical predictions, the total impact of the Voyager encounter must be assessed in terms of the new knowledge about the overall strength of the Jupiter-Io interactions. Voyager showed that the plasma of Io origin is found throughout the magnetosphere and that this plasma is of such great dynamical significance that, in a very real sense, we must regard Jupiter and Io as a genuine binary system. That is, we find that without Io and its torus, the Jovian magnetosphere would have completely different characteristics and dynamics, while the effect of the large corotating Jovian field back on the Io system dominates the state of Io's extended atmosphere. Thus, from an astrophysical point of view, the Jupiter-Io system represents an accessible binary MHD object, as well as an example of a large-scale rigid rotator and a source of energetic particles and radio emissions. The torus itself also has characteristics similar to those associated with planetry nebulae (emission of both low and mid excitation forbidden spectral lines). Thus concepts and techniques applied to many problems of contemporary astrophysical interest arise in our study of Jupiter's magneosphere, and a review of the in situ measurements holds the promise of enriching our knowledge of astrophysical processes.

In order to discuss the organization of this review, we start with a schematic diagram (Figure 1) designed to summarize our present understanding of the binary magnetosphere in simplified fashion. We have sketched in three dimensions one quadrant of the portion of Jupiter's magnetosphere thus far studied by spacecraft. The solar wind is decelerated by the bow shock standing upstream, and the pressure of the magnetic field and plasma

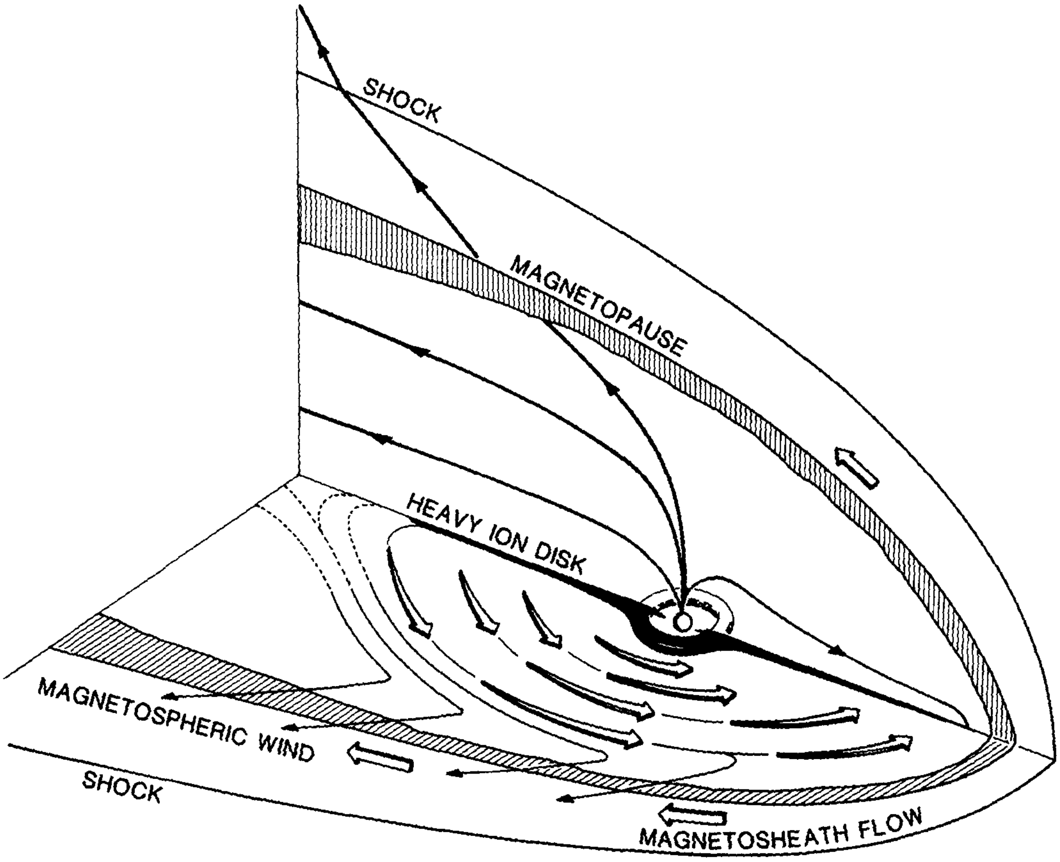

Figure 1. A sketch of the Jupiter-Io binary magnetosphere. Io is obscured within a heavy ion plasma torus of volcanic origin, which merges into a centrifugally confined heavy ion disk in the middle magnetosphere. The horizontal plane emphasizes the plasma flow pattern. Near Jupiter the flow is in the corotation direction; in the outer magnetosphere, the flow deviates from corotation, and plasma escapes through the wind. The vertical plane emphasizes the magnetic field structure. On the dayside, the field is stretched into a thin magnetic disk; on the nightside, reconnection of the Jovian and interplanetary fields produces a long magnetic tail.

within the magnetosphere constrains the shock heated plasma to flow around the obstacle in the magnetosheath. The magnetosheath extends from the shock boundary inward to the magnetopause, which represents the outer limit of Jovian magneic field and plasma. The position of the magnetopause depends on the variable balance of external and internal pressures. It has been observed between 50 and 100 Jovian radii (R_J) upstream of Jupiter. Dissipative processes, such as magnetic field reconnection, couple magnetosheath energy and momentum energy and momentum across the magnetopause and stretch the magnetic field into a long tail that extends far downstream from Jupiter. We have sketched in the vertical plane two field lines that extend into the tail and one that crosses the magnetopause to represent these processes.

As noted above, Io is a source of heavy ion plasma which is transported both radially inward and outward from Io. Within the inner magnetosphere, which we describe in Section 2, the interactions between Io, its plasma torus, and Jupiter lead to intense EUV emissions from the torus and auroral light emissions from Jupiter's atmosphere. Plasma of Io and Jovian origin is transported into the middle and outer magnetosphere, which we describe in Section 3. There, Jupiter's rotation magnetically spins up and centrifugally confines the plasma into a thin magnetized disk that has two components — a cold heavy one with much of the mass, and a hot($\sim$30 kev) ion component that has much of the pressure and whose origin is presently uncertain. This plasma is slowly transported radially outward, and the hot ion component has been observed to escape the magnetosphere altogether as a wind flowing downstream. There is a boundary layer about 10 R_J thick next to the magnetopause (hatched) where solar wind stresses modify the radical transport. The Voyager discovery of the magnetic tail is discussed in Section 4. Earth analogy suggests that if there is a magnetic tail, there ought also to be a flow from the tail towards Jupiter's nightside. For this reason, we have shown with dotted lines some of the magnetospheric wind streamlines emanating from the tail.

Some interpretations of the Voyager data are ambiguous at present, and, in any case, the data reduction is at any early stage. Uncertainties and questions still outnumber answers. We therefore chose to discuss those Voyager measurements where there seems to be general agreement and, moreover, to let theoretical prejudice guide us through the ambiguities in our present understanding. However, even at this early stage it is clear that the Juipter-Io system is of great importance as a cosmical entity in which many important processes of plasma astrophysics can be studied by direct means.

2. THE IO PLASMA TORUS

Prior to the Voyager 1 encounter, ground-based spectroscopists had observed line emission from neutral sodium and potassium (Brown, 1974; Mekler and Eviatar, 1974) and ionized sulfur (Kupo, Mekler, and Eviatar, 1976) which was spatially distributed in a torus near the orbit of Io. The emission intensities were temporally variable with Na and S II being anti-correlated. A conventional nebular analysis yielded estimates of the electron density from ~ 500 to ~ 5000 cm^{-3}, and electron temperatures at 5 to 10 ev. Although these estimates are uncertain, to maintain the inferred heavy ion plasma against losses would require a relatively high rate of mass addition to the torus and would imply a significant inertial loading of the torus magnetic field lines.

When it was still 1 AU from Jupiter, the Voyager 1 EUV experiment began to detect bright emission lines at 685 and 833 Å. Subsequent spatially resolved observations of these high excitation lines revealed a torus of hot plasma which began near Io and extended radially outward for several R_J. Later, during the close approach, the Voyager 1 Plasma Science experiment found that the cool plasma responsible for the low excitation lines seen from earth was located inside the inner edge of the hot torus. Spatially resolved scans of the Jovian disk in the EUV revealed another surprise: high latitude auroral emissions whose total luminosity, 10 to 100 times greater than earth's, strains the energy budget of the binary magnetosphere.

Auroral photon emissions at earth, and presumably also at Jupiter, have an energy source which is the precipitation of moderate to high energy electrons and protons. The precipitating particles are sustained by large scale hydromagnetic interaction between the terrestrial ionosphere and magnetosphere, in which plasma stresses are communicated via magnetic field-aligned currents. At Jupiter, the Io modulated decametric radio emissions have long been interpreted as due to a field-aligned current system linking Jupiter's ionosphere with Io; the $\underline{V} \mathrm{x} \underline{B}$ potential across Io drives current-carrying electron beams which radiate near the ionospheric foot of Io's field line.

The Voyager discoveries of the hot, heavy ion torus and Jovian auroral luminosity suggest that significant hydromagnetic coupling between Jupiter's ionosphere and magnetosphere is not limited to the Io magnetic flux tube. The ionization of heavy molecules injected by intermittent ionic vulcanism and venting inertially loads the magnetosphere. In order to accelerate the newly created ions to the corotation velocity, field-aligned currents must flow from Jupiter to communicate the necessary torque. As the heavy ion plasma diffuses radially outward from the torus into the middle magnetosphere, the continued enforcement of corotation requires ever larger torques. Hence, hydromagnetic field-aligned currents and, by analogy with earth, auroral particle acceleration and precipitation, should occur throughout the inner and middle Jovian magnetosphere.

In this section we review the Voyager torus observations, starting with the EUV and plasma measurements. We then discuss selected plasma wave and energetic particle data which may be related to the auroral precipitation. We briefly mention the discovery of decametric arcs by the planetary radio astronomy experiment and discuss a recent theoretical model which emphasizes the large scale influence of the Io-induced field-aligned current interaction. Finally, we summarize the problems of energetics posed by the torus and auroral observations.

EUV Emissions

The Voyager EUV spectrometers are sensitive in the wavelength range 500 Å < λ < 1700 Å and can be commanded to have variable slit orientations (Broadfoot et al., 1981). A graphic display of the Jovian and torus emissions is shown in Figure 2, taken from Sandel et al. (1979). Data acquired over several days were combined to produce an image of EUV intensity vs wavelength and radial distance, measured in the rotational equatorial plane. The spectrograph's slit is oriented perpendicular to the equatorial plane, and the spatial resolution is 0.5 R_J.

The intensity peak, which is centered on Jupiter, contains both resonance scattered solar Lyman α and Jovian auroral Ly α emission; the actual Ly α peak is 30 times the interstellar Ly α level, rather than the 2.5 shown. The auroral emission is concentrated at high Jovigraphic latitudes, and its peak intensity (60 kR [R = Rayleigh]) exceeds that of the planetary disk ($\leq$ 20 kR), although the disk dominates the total luminosity. The Jupiter-centered emission between 900 Å and 1130 Å is auroral excited Lyman and Werner bands of H_2 which have a brightness of 80 kR. The total auroral flux density is 2 ergs/cm^2-sec, which, if excited by electron impact ionization, would require an electron precipitation energy flux of 70 ergs/cm^2-sec. The auroral emission, which has a latitudinal width of about 6000 km, may be located at the ionospheric footprints of magnetic field

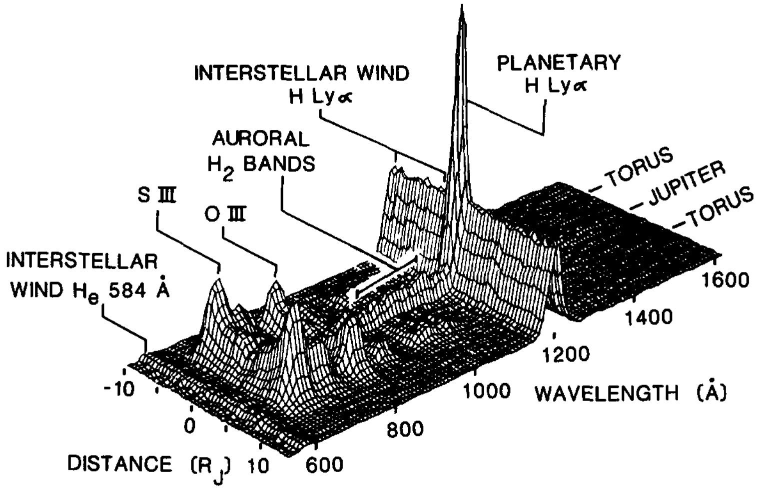

Figure 2. A spatially and spectrally resolved image of Jupiter and the Io plasma torus obtained by the Extreme Ultraviolet Spectrometer (after Sandel *et al.*, 1979). Data acquired over several days were combined to produce a one-dimensional picture. Auroral emissions are contained in the planetary hydrogen Lyman α peak and the Lyman-Werner molecular hydrogen bands; the planetary Ly α intensity is actually 30 times larger than the interstellar level, rather than the 2.5 ratio shown. The limb-brightened S 111 and O 111 emissions are radiated by the Io plasma torus.

lines which thread the hot Io plasma torus (Broadfoot *et al.*, 1979; 1981); however, the low polar viewing angle and the continued development of tail magnetic field models (Ness, *et al.*, 1979; Connerney, *et al.*, 1981) may combine to modify this conclusion. Broadfoot *et al.* (1981) estimate that the total power required to sustain the auroral luminosity is $1.2x10^{13}$ watts, probably in the form of particle precipitation.

The dominant EUV emissions from the Io torus are the strong multiplets of S III (at 700 Å, 683 Å, and 680 Å) and the blend near 833 Å of S III (at 825 Å), S 1V (at 836 Å) and O III (at 834 Å). The limb brightened image of Figure 2 can be modeled by an azimuthally symmetric torus with a major radius of 5.9 + 0.3 R_J and a minor radius of 1 + 0.3 R_J which is symmetric about the rotational equator. The total radiated power from the torus, estimated as $3x10^{12}$ watts, must be continuously supplied since the radiative cooling time is only about 20 hours.

The most abundant ions in the hot torus are sulfur and oxygen, and protons are a negligible constituent. Except for the low abundances of hydrogen and helium, the plasma conditions in the hot Io torus resemble those in high excitation planetary nebulae and H 11 regions. By incorporating radial diffusion losses into the conventional nebular analysis, Shemansky (1980) has shown that the observed excitation states within a given ionic species are consistent with LTE collisional ionization equilibrium for an electron temperature $T_e \approx 8x10^{4}$[a] K. However, the intra-species populations (e.g., S III and S IV) show evidence of disequilibrium and indicate the presence of a secondary non-LTE electron distribution with less than 1% of the plasma density and a temperature $T_e > 10^{6\circ}$ K. Although the excited state relaxation time is short, the total ion recombination times can be comparable to the radial diffusion loss times, thus affecting the relative populations of sub-species. By modeling this S II to S III density ratio, Shemansky (1980) estimated the radial diffusion time scale as 100 days at L = 6, which is comparable to the diffusion rates attained from energetic particle spatial profiles (Goertz and Thomsen, 1979).

The source of plasma for the Io torus is undoubtedly neutral SO_2, which is a major constituent of the Io atmosphere (Pearl et al., 1979) and surface (Fanale et al., 1979). although the details of how SO_2 is dissociated and ionized are uncertain, Shemansky (1980) argues that the majority of the dissociation products are neutrals which are then collisionally ionized by electron impact in the hot torus. If the oxygen and sulfur

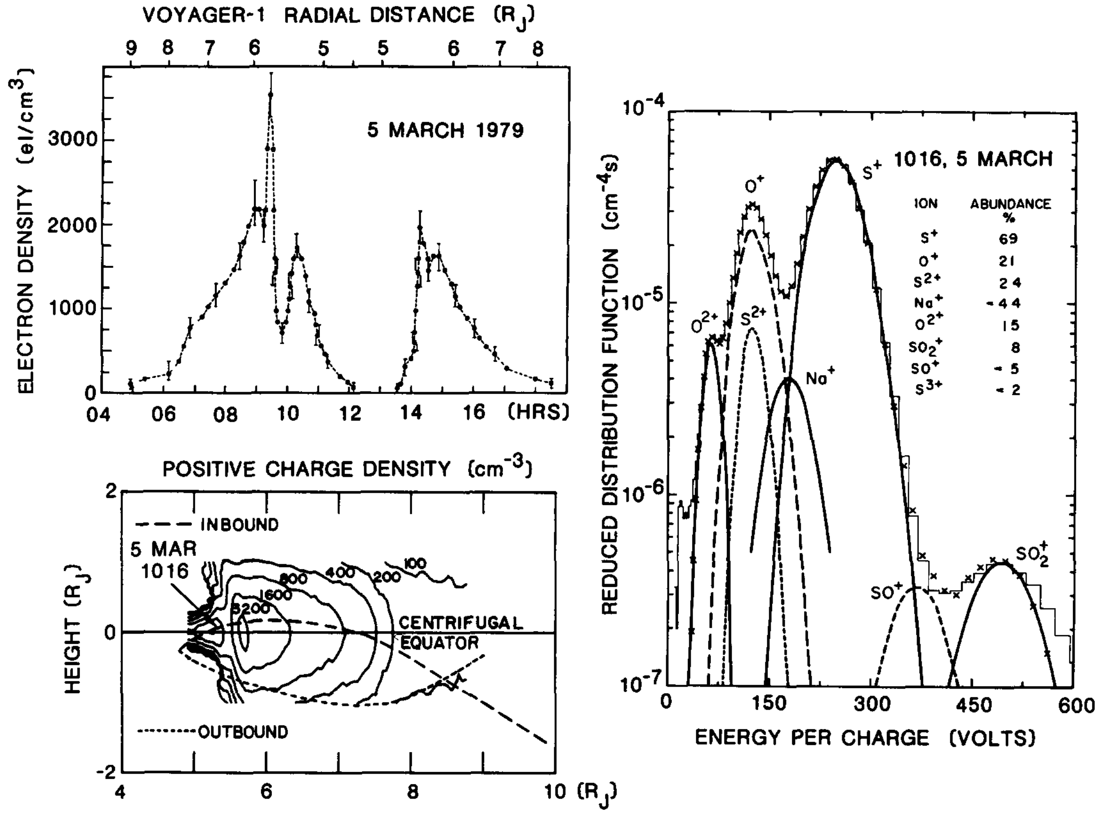

Figure 3. Electron density and heavy ion measurements in the Io plasma torus. The top left-hand panel shows the spatial profile of the local electron density obtained from the Planetary Radio Astronomy experiment by determining the electron plasma and upper hybrid frequencies (after Birmingham et al., 1981). The right-hand panel shows the heavy ion distribution functions measured by the Plasma Science Instrument at 5.3 R_J near the center of the cold inner plasma torus (after Bagenal and Sullivan, 1981). The curved lines are Maxwell fits to the data. The lower left-hand panel displays a contour map of the heavy ion density in a meridional plane (after Bagenal and Sullivan, 1981). The measured local ion density was extrapolated along magnetic field lines using a theoretical model.

neutrals enter the hot torus with velocities near or below the Io escape velocity, strong EUV emissions from O I, O II, and S II should be detected in the vicinity of Io. However, Broadfoot et al. (1979) found no detectable EUV enhancement when the spectrometer slit contained Io in the field of view. If the ionization of S and O occurs near Io, Shemansky (1980) finds that the absence of Io EUV emission implies an upper limit to the Io source strength of 10^{27} ions/sec. However, if the neutral atoms leave Io with velocities which greatly exceed the Io, but are less than the Jupiter, escape velocity, the neutrals could be ionized over a larger portion of the hot torus; in this case, the total Io source could exceed 10^{27} ions/sec.

In Situ Plasma Observations

The Voyager spacecraft carried two instruments — the Planetary Radio Astronomy [PRA] (Warwick et al., 1979a) and the Plasma Science [PLS] (Bridge et al., 1979a) experiments — which provided local measurements of the total torus electron density (PRA, PLS) and the ion distribution function (PLS). Figure 3 shows a collage of measurements from these two experiments; they are in broad agreement with the quantitative nebular analysis of the EUV emissions.

Within the high density torus, the electon plasma (f_p) and upper hybrid (f_{UHR}) frequencies are in the frequency range of the PRA experiment. By observing the cut-offs at f_p and f_{UHR}, Birmingham et al. (1981) constructed the spatial profile of the total electron density for the Voyager 1 traversal of the Io torus (upper left, Figure 3). Inside 7.5 R_J, the electron density increases rapidly to above $10^3/cm^3$, and reaches a sharp peak of $3200/cm^3$ at 5.7 R_J, just inside the orbit of Io (5.95 R_J). The secondary peak at 5.3 R_J occurs in the center of the cool Io torus. Within the hot torus, a negative spacecraft charge has, so far, prevented a confirming measurement of the electron density by the PLS experiment; in the cool torus, the electron temperature is below the PLS threshold (Scudder et al., 1981).

The PLS experiment consists of four Faraday cups which measure the energy per charge (E/Q) of positive ions in the range 10 ev to 5.95 kev. In the cool torus region near 5.3 R_J, the ion temperature, $T_i \sim 10^{40}$ K, is sufficiently low that the ion energy is primarily determined by the corotation speed. Here, the PLS instrument essentially operates as a mass-per charge (A/Z) detector, and the ion species and abundances can be determined for

$A/Z \gtrsim 8$ (Bagenal and Sullivan, 1981). In the cool torus, the species resolved distribution (right side, Figure 3) shows that ionized oxygen and sulfur are two most abundant ions. If the density of ions with $A/Z < 8$ is negligible, the total ion density agrees with the electron density obtained by the PRA experiment.

In the hot ion torus (outside 5.5 R_J), the ion temperature, $T_i \sim 5\text{x}10^{5\circ}$ K, is sufficiently high that the PLS cannot directly determine the ionic masses, since the E/Q peaks are not well-resolved. Bagenal and Sullivan (1981) fit the PLS measurements with distributions which modeled the ion composition, temperature, and bulk motion (corotation flow). Although model dependent, the inferred composition of the hot torus appears to be dominated by oxygen and sulfur, in broad agreement with the EUV observations.

Bagenal and Sullivan (1981) have used the local ion measurements as the input to a global model of the Io torus (lower left, Figure 3). The ion distribution is extrapolated along the magnetic field by a model which assumes isothermal and centrifugal equilibrium and includes the ambipolar potential required by charge neutrality with electrons. The cool torus inside 5.5 R_J is confined to the centrifugal equator with a scale height of 0.2 R_J. The NA I (Brown, 1974) and S II (Kupo et al., 1976) line emission observed from the ground originate in the cool torus. Outside 5.5 R_J, the ion temperature rises rapidly from $10^{4\circ}$ K to $5\text{x}10^{5\circ}$ K, and the plasma scale height increases to about 1 R_J. From the model, the total number of ions on a magnetic flux tube is inferred to peak at 5.7 R_J and to decrease monotonically radially inward and outward from 5.7 R_J; hence, the observed spatial profile is consistent with radial diffusion and/or convection of plasma away from a source located near Io (Richardson et al., 1980; Richardson and Siscoe, 1981). The outward transport of torus heavy ions should increase the inertial drag on the corotating magnetic field lines. Bagenal and Sullivan (1981) suggest that at 8.6 R_J, the plasma flow velocity may be only 90% of the corotation value, so that departures from strict corotation may begin deep in the Jovian magnetosphere (Hill, 1979).

Plasma Waves in the Io Torus

The Pioneer 10 and 11 instrument complement was designed to study energetic particles, electrons above 15 to 60 kev, and protons above 100 kev. The Pioneer measurements and their theoretical interpretation have been extensively reviewed (see articles in Gehrels, 1976; Kennel and Coroniti, 1977; Goertz and Thomsen, 1979), so that the radiation belts need only be briefly mentioned here.

Energetic particles are transported into the radiation belts from the middle and outer magnetosphere by radial diffusion driven by atmospheric neutral winds (Brice and McDonough, 1973; Coroniti, 1974), flux tube interchange convection (Siscoe and Chen, 1977) and/or large scale convection cells (Hill, et al., 1981). The adiabatic compression of the particle fluxes should be limited by the excitation of plasma wave instabilities which reduce the flux by pitch-angle scattering into the atmospheric precipitation loss-cone (Coroniti, 1974, 1975). Theoretical calculations of the energetic electron losses by electromagnetic whistler mode turbulence appeared to be broadly consistent with the Pioneer observations (Barbosa and Coroniti, 1976; Goertz and Thomsen, 1979). However, the absence on the Pioneer spacecraft of a plasma wave detector and an instrument to measure the cold plasma density, which determines the wave index of refraction, rendered the radiation belt interpretations incomplete and uncertain.

As with the EUV and PLS investigations, the Voyager Plasma Wave (PWS) and Planetary Radio Astronomy (PRA) instruments provided a new view of Jupiter's magnetosphere and plasma interactions (Scarf et al., 1979a; Gurnett et al., 1979b; Warwick et al., 1979a). Here, we will emphasize only those plasma wave observations which impact the problem of the Jovian aurorae and Io torus dynamics. The top panel of Figure 4 shows a PWS dynamic frequency-time spectrum from 50 Hz to 12 kHz obtained by the Voyager wideband telemetry system. The f-t diagram reveals two intense plasma wave emissions (dark shading) observed when Voyager 1 was inbound at 8 R_J near the outer edge of the torus. At low frequencies between 50 and 1.5. kHz, Scarf et al. (1979b) identified the continuous emission as whistler mode hiss and showed that these waves were present throughout the inner magnetosphere. The whistler frequency is far below the electron cyclotron frequency ($f_c \approx$ 22 kHz at this time), so that cyclotron resonant interactions occur only with energetic electrons in the range 0.1 to 1.0 mev. By scattering the trapped electrons into the atmospheric loss-cone, the observed whistler hiss could precipitate an energy flux of 5-10 ergs/cm^2-sec in 0.1 to 1.0 mev electrons (Scarf et al., 1979b; Thorne and Tsurutani, 1979), which would substantially contribute to the 70 ergs/ cm^2-sec required to sustain the Jovian aurora.

In Figure 4, a second whistler mode emission occurs between 9 and 10 kHz, just below one-half the electron cyclotron frequency. The impulsive nature and characteristic rising frequency structure are virtually identical to similar emissions in the earth's magnetosphere which are called "chorus." From an analysis of the frequency bandwidth and propagation properties of whistlers, Coroniti et al., (1980) concluded that the Jovian chorus was unstably generated by an anisotropic distribution of non-thermal electrons with a density 1% of the total electron density and a mean energy of 1 kev. The presence of this non-thermal electron distribution was confirmed by Scudder et al. (1981) and by the nebular analysis of the EUV emissions (Broadfoot et al., 1981). The chorus-induced precipitation of these non-thermal electrons deposits about 10-20 ergs/cm^{2}-sec into the Jovian ionosphere, again contributing substantially to the auroral luminosity.

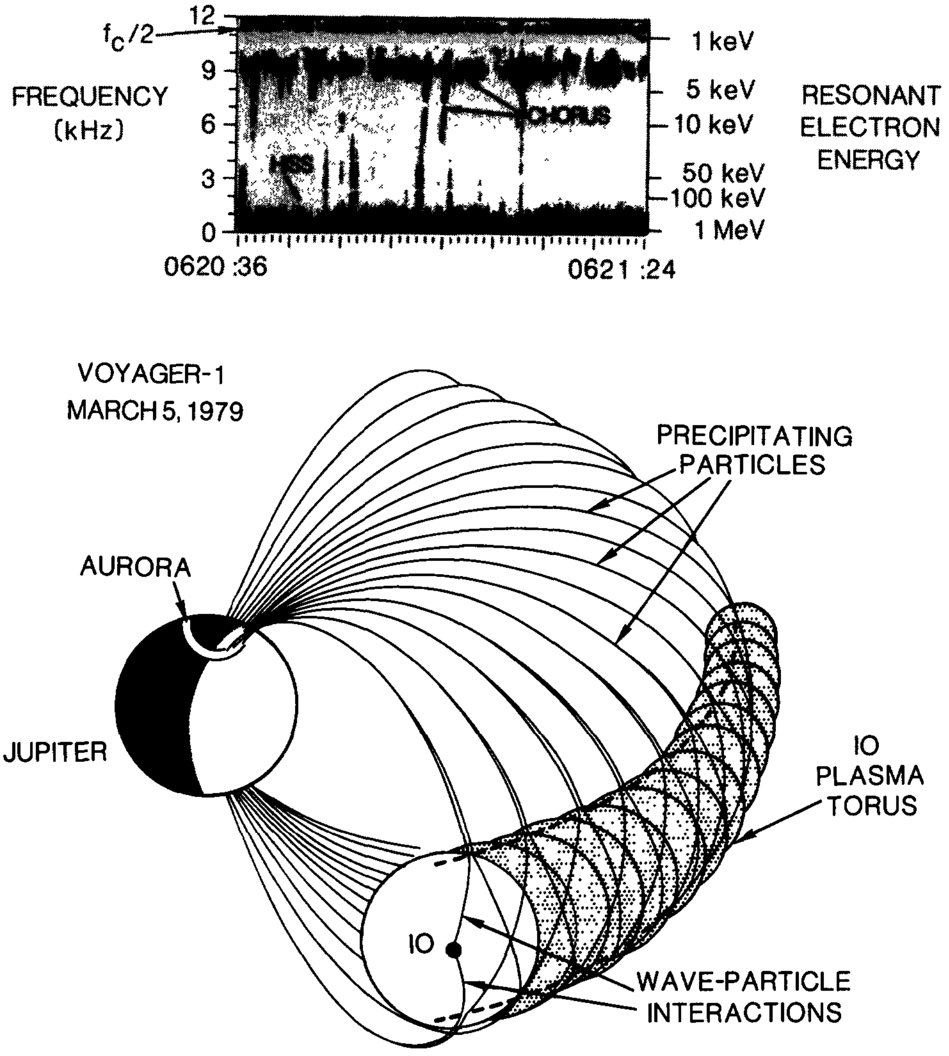

Figure 4. Whistler mode wave-particle interactions in the Io torus. The top panel shows a wideband frequency-time diagram obtained by the Plasma Wave instrument; shading indicates the intensity of the emissions. In addition to frequency, the vertical axis is labeled with the electron parallel energy which would be in cyclotron resonance with parallel progagating whistlers. Low frequency (< 1.5 KHz) hiss interacts with energetic (> 100 Kev) electrons, and chorus is resonant with medium energy (1-5 Kev) electrons. The lower panel schematically illustrates the scattering of trapped radiation belt particles into the atmospheric loss-cone, and their precipitation into the Jovian ionosphere. At least part of the EUV Jovian auroral luminosity occurs on field lines which are connected to the Io torus.

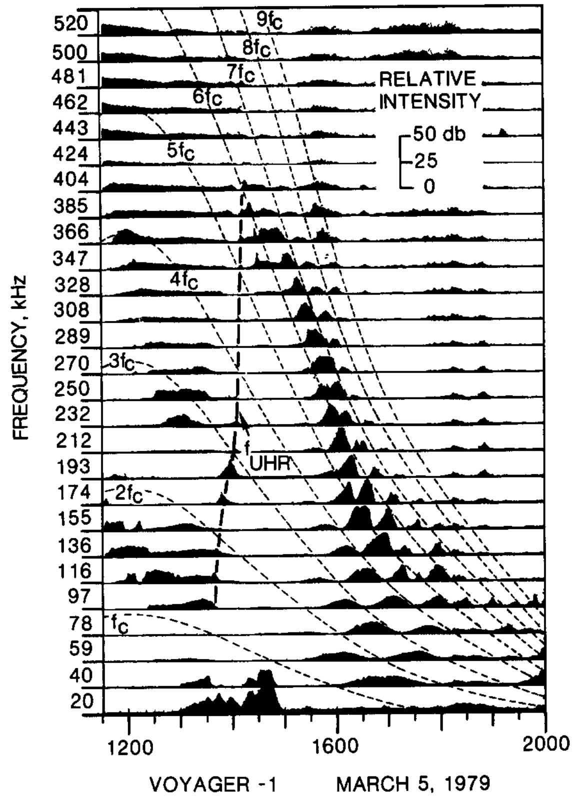

Figure 5. The Planetary Radio Astronomy 20 to 520 KHZ observations on the outbound Voyager 1 pass through the Io torus (adapted from Birmingham et al., 1981). The heavy dashed line is the upper hybrid frequency, which essentially follows the increasing electron density as Voyager penetrates the torus. The lightly dashed lines are the electron cyclotron frequency harmonics as determined by the magnetometer experiment. Electrostatic electron cyclotron harmonic waves occur near odd half-harmonics of f_c.

In addition to whistlers, the terrestrial auroral magnetosphere contains electrostatic plasma waves which are excited at roughly odd half harmonics of the electron cyclotron frequency $[(n+1/2)f_c]$ (Kennel et al., 1970). These modes resonantly scatter and precipitate moderate energy (1-10 kev) electrons, which produce the diffuse auroral luminosity (Ashour-Abdalla and Kennel, 1978a). In addition, nonlinear resonant and non-resonant interactions with these waves may rapidly heat the cold electron population which escapes from the auroral ionosphere.

Jovian electron cyclotron harmonic waves were discovered [see Kurth et al. (1980b)] on the inbound Voyager 1 crossing of the magnetic equator near 8 R_J, just outside the torus. Within the torus, the (n+1/2) f_c modes are in the PRA frequency range; a continuous display of these emissions is shown in Figure 5 (Birmingham et al., 1981). The lightly-dashed lines show the variation of the electron cyclotron harmonics as Voyager 1 passed outbound through the torus; note the rapid increase in the upper hybrid frequency (f_{UHR}) as Voyager penetrated into the dense torus. Inside the torus, quasi-continuous emissions were detected between the cyclotron harmonics up to n = 8. From a numerical analysis of the linear dispersion relation, Birmingham et al. (1981) suggest that the $(n+1/2)f_c$ waves are unstably generated by a loss-cone anisotropy of a small fractional density of hot (~ kev) electrons immersed in a dense cold (~10-20 ev) electron background. The instability free energy source is the same as that proposed to explain the terrestrial $(n+1/2)f_c$ emissions, but the ratio of hot to cold electron densities is reversed.

The Voyager observations of whistler mode hiss and chorus, and of the $(n+1/2)f_c$ electron cyclotron waves, indicate that the wave phenomenology of the Io torus is strikingly similar to the earth's auroral magnetosphere, thus strengthening the hypothesis that electron precipitation from the torus is a source of the Jovian aurorae. However, the radiation belts at Jupiter, as at earth, contain substantial fluxes of energetic ions which could significantly contribute to the overall torus energy budget and dynamics. Energetic proton (> 0.5 mev) detectors on Pioneer 10 and 11 reported a rapid spatial decrease in the proton phase space density between 10 and 5 R_J (Filius et al., 1976; Thomsen et al., 1977). The bottom panel of Figure 6 shows the ion phase space density measured on the inbound pass of Voyager 1 through the torus (Armstrong et al., 1981). The phase space density was constructed from differential flux measurements by the energetic particle experiment (Krimigis et al., 1979a; 1981) in the energy range 0.5 to 4.0 mev and corresponds to a constant value of the first (magnetic moment) adiabatic invariant of 70 mev/Gauss. Between 7.5 R_J and 6.0 R_J, the heart of the Io torus, the ion phase space density decreases by a factor of 10^3. Since inward radial diffusion transport without losses conserves the phase space density, the Voyager observations imply that a severe loss of energetic ions occurs within the plasma torus. Goertz (1980) has estimated that if the energetic ions (> 0.5 mev) are lost by precipitation, the total power delivered to the Jovian atmosphere as ion precipitation heat flux could be as large as 3.6×10^{13} watts, a power level comparable to the auroral luminosity.

If the ion phase space losses are due to precipitation, which mode of plasma wave turbulence is responsible for scattering the ions into the loss-cone? One possibility, as yet unsubstantiated, is electromagnetic ion cyclotron waves, the ion wave analog of electron whistlers. A second possibility is contained in the top two panels of Figure 6, which show the the output of the digital frequency channels (100 Hz to 56 kHz) and a wideband f-t spectrogram obtained at 6.2 R_J near the maximum gradient in the ion phase space density. Below 2 kHz, the emissions are whistler mode hiss; the emission the emission near 10 kHz in the digital data from 0600 to 0170 is the whistler chorus (Figure 5). Between 2 and 12 kHz, the f-t diagram shows a broadband, impulsive emission which exhibits very little frequency dispersion. In the digital data, these impulsive signals (10 kHz and below) become strong just after 0700 and terminate abruptly just inside 6 R_J where the ion phase space losses cease and Voyager enters the cold plasma torus.

In a study of 0.5 to 2.0 mev ions, Lanzerotti et al. (1981b) found that the ion pitch-angle distribution was moderately anisotropic and peaked at 90° during the interval of strong phase space losses. The anisotropy decreased, and the distribution approached isotropy near 6 R_J. The spatial coincidence of the ion phase space losses, the anisotropic pitch-angle distribution, and the impulsive 2-12 kHz wave emissions suggest that these wave modes might be responsible for the ion precipitation losses. Scarf et al. (1981a) have tentatively identified the impulsive emissions as a type of electrostatic ion acoustic wave which is destabilized by an anisotropic ion loss-cone distribution. Although the ion plasma frequency is only ~ 1-2 kHz in the torus, the observed frequency spectrum could extend to above 10 kHz due to the corotation Doppler shift of the short wavelength ion waves.

In summary, wave-particle interactions within the Io torus can scatter moderate to high energy electrons and ions into the Jovian atmosphere (Figure 4, bottom). Although the calculations are somewhat uncertain, the total precipitation energy flux seems to be comparable to the power required to excite the Jovian aurora.

Jovian Decametric Radiation

Ground-based radio astronomy observations established that the Jovian decametric radiation often consisted of narrowband emissions with upward and downward frequency drifts and that the emission probability between 20 MHz and 39.5 mHz was controlled by the orbital phase of Io. With a much greater sensitivity and frequency range than ground radio telescopes, the Voyager PRA instrument has provided a far more comprehensive survey of the decametric phenomena (Warwick et al., 1979a; Boischot et al., 1981), discovered a Jovian hectometric emission (Kaiser et al., 1979) below 1.3 mHz, and co-discovered a Jovian kilometric emission below 100 kHz (Scarf et al., 1979a; Warwick et al., 1979a; Kurth et al., 1980a; Desch and Kaiser, 1981).

Figure 7 shows a PRA f-t diagram for nine hours of decametric observations obtained when Voyager 2 was outbound at 87 R_J. The strong decametric radiation starting at 0515 occurs at an Io phase of 90^0 CML, which is the highest probability location for the source B Io-controlled emission. The Voyager PRA measurements reveal that the decametric radiation consists almost entirely of arcs — discrete narrowband emissions with rising and falling frequency-time structure. At a given frequency, the decametric arcs are typically separated by three to six minutes. Below 12 mHz, the arcs are detected at all Jovigraphic longitudes, with as many as 100 individual arcs observed during a single Jupiter rotation. Warwick et al.(1979a) argue that the repetitive arc patterns imply a geometric control, so that each arc consists of conically beamed radiation over a continuous freqency range. The arc radiation is generated at various frequencies along a single magnetic flux tube and is detected when the emission cone intercepts the observer.

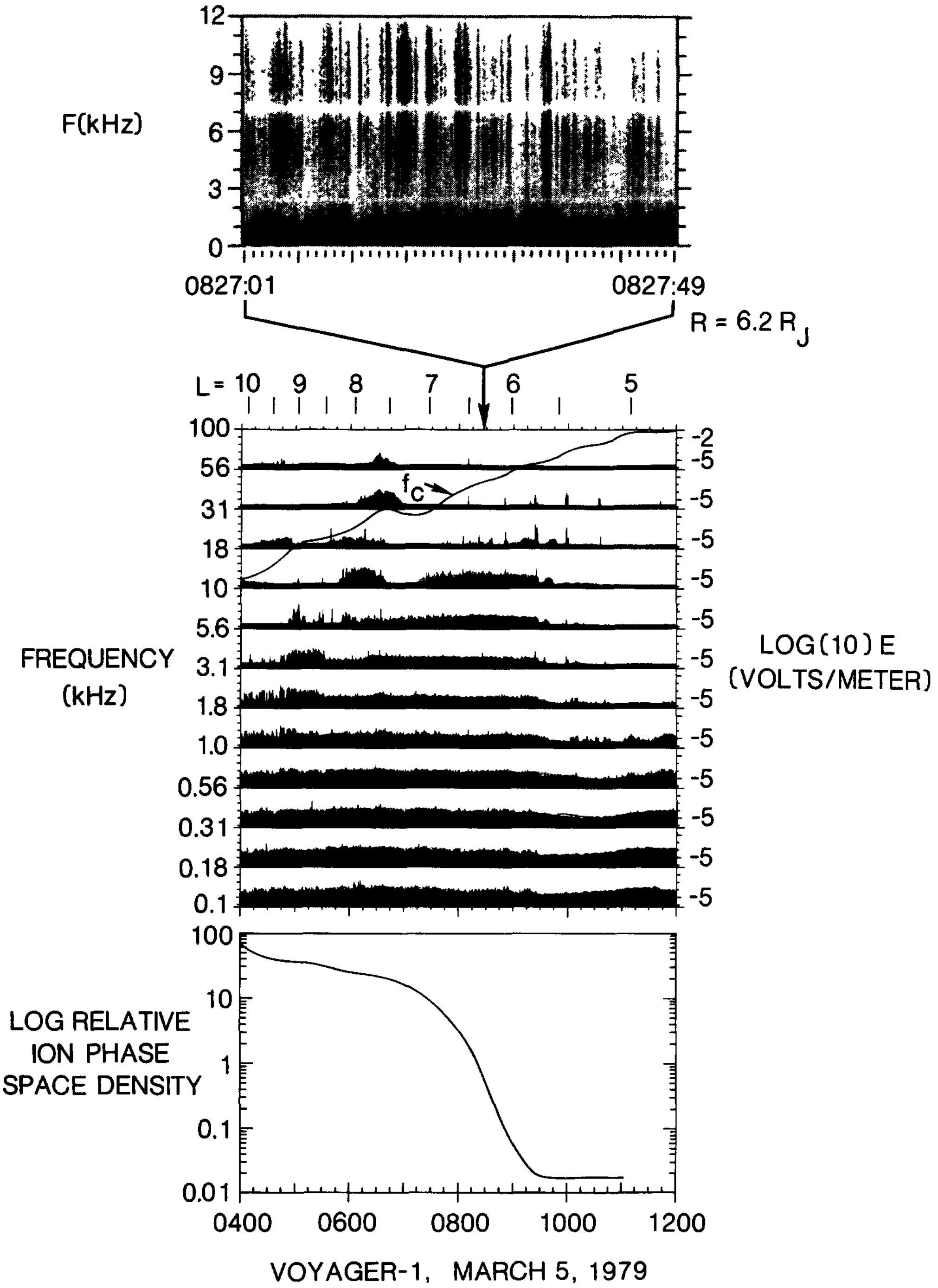

Figure 6. The bottom panel show the ion phase space density determined from 0.5 to 4.0 Mev ion differential flux observations (after Armstrong et al., 1981). The center panel contains bandpass channel amplitude measurements in equal logarithmically spaced frequency intervals from 0.1 to 56 KHz obtained by the Plasma Wave instrument. The top panel shows a wideband frequency-time diagram which demonstrates the impulsive nature of the electric field emissions.

Since the early theories of Piddington and Drake (1968) and Goldreich and Lynden-Bell (1969), most models for the production of decametric radiation involve the generation of field-aligned currents by the electromagnetic dynamo interaction between Io and Jupiter's corotating magnetic field (Smith et al., 1976). These currents flow between Io and the Jovian ionosphere and are carried, at least partially, by field-aligned electron beams which radiate electromagnetic waves near the electron cyclotron or upper hybrid frequencies along the Io flux tube (Gurnett, et al., 1979b). Analogous electro beams are observed in the discrete aurora at earth and the terrestrial kilometric radiation (Gurnett, 1974).

A prime objective of the Voyager 1 encounter was to fly through the Io flux tube to search for the decametric producing interactions. Although little evidence of the Io interaction was found in the energetic particle observations, the magnetometer experiment detected a large amplitude magnetic perturbation in the vicinity of Io (Ness et al., 1979a) which is readily interpreted as the flow of a strong, nearly field-aligned current. The current interaction has the form of a large amplitude Alfvèn wave (Neubauer, 1980; Belcher, et al., 1981) which is launched toward Jupiter from Io's ionosphere, or, if Io possesses an intrinsic magnetic field, from Io's magnetosphere (Kivelson et al. 1979). Depending on the assumed current configuration, the total current flowing in the Io-Jupiter circuit could be as large as $2.8\text{x}10^{6}$ amps and it could dissipate as much as $1.3\text{x}10^{12}$ watts (Acuna et al., 1981).

If only the Io flux tube were active, only a single decametric arc would have been detected, rather than the observed multiple arc pattern. Neubauer (1980) and Gurnett and Goertz (1981) pointed out, however, that the high mass density in the Io torus results in a low Alfvèn speed; hence, the Alfvèn wave return signal which is reflected from the Jovian ionosphere will miss Io. These authors suggested that the reflected Alfvèn wave bounce between the conjugate Jovian ionospheres, thus forming a standing wave pattern which produces an azimuthally distributed, but quantized, image of the initial Io-generated field-aligned current (see Figure 7, bottom panel). Gurnett and Goertz (1981) estimate that the standing Alfvèn wave system would produce decametric arcs which are temporally separated by about the observed few minutes, and that the Alfvèn waves could persist for as many as 100 bounces without serious damping.

In summary , although the Io-generated electron beam was not observed by Voyager (perhaps, due to the distorion of the magnetic field so that Voyager did not pass directly through the Io flux tube) the large field-aligned current produced by the hydromagnetic

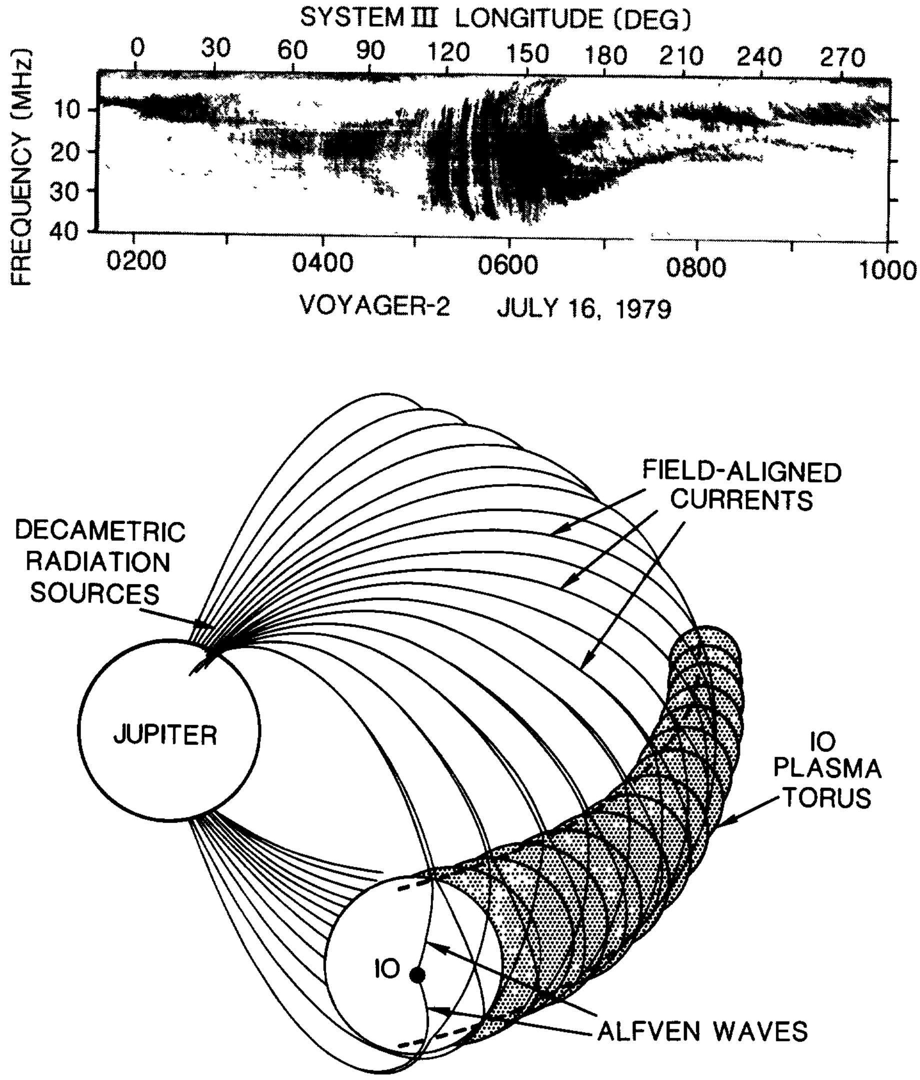

Figure 7. The top panel is a frequency-time display of the decametric arcs discovered by the Planetary Radio Astronomy experiment (adapted from Warwick et al., 1979a). The bottom panel presents a schematic illustration of the Alfvèn wave model of the Io-Jupiter interaction (after Gurnett and Goertz, 1981). Io launches Alfvèn waves which carry field-aligned current toward Jupiter's ionoshpere. Decametric emissions are generated by electron beams associated with the field-aligned currents.

Io-Jupiter interaction was detected. The PRA observation of multiple decametric arcs suggests that the hydromagnetic field-aligned currents which are stimulated by Io affect an extensive azimuthal region of the hot plasma torus. These torus field-aligned current systems constitute a direct analog to the terrestrial auroral currents, thus establishing the generality of the production of field-aligned currents and auroral processes which result from the hydromagnetic coupling between planetary magnetospheres and ionospheres.

Plasma Torus and Auroral Energetics

Although future analyses will undoubtedly yield revisions and refinements, at present a rather consistent understanding of the Io torus region has emerged from the synthesis of the Voyager observations. The torus' radial structure consists of a cool inner region inside and a hot outer region outside of Io's orbit. The in situ plasma measurements from PLS and PRA investigations and the nebular analysis of the EUV observations are in broad agreement that: (1) the ion composition is dominantly sulfur and oxygen; (2) the ion temperature is $T_i \sim 5x10^{5\circ}$ K in the hot torus and $T_i \sim 10^{4\circ}$ K in the cool torus; (3) the electron density is high, reaching 3200 cm^{-3} just inside Io; and (4) the electron temperature is $T_e \sim 8x10^{4\circ}$ K with a high energy nonthermal tail in the hot torus and $T_e \sim 10^{4\circ}$ K in the cool torus. The source of the heavy ion plasma is the dissociation and ionoization by electron impact of SO_2 which is injected into the torus by volcanoes and vents on Io.

The total power which is emitted as line radiation by the hot plasma torus is approximately $3x10^{12}$ watts. Unlike photo-ionized H II regions and planetary nebulae, this power must be continuously supplied to the hot torus electrons by the dissipation of mechanical and/or hydromagnetic energy. If the Io torus also supplies the energy for the Jovian aurorae, the power dissipation rate increases to at least $1.2x10^{13}$ watts and may be as high as 10^{14} watts, depending on the latitudinal extent of the aurora and the efficiency of converting particle energy to luminosity.

In their first paper, Broadfoot et al. (1979) suggested that the energy for powering the torus line radiation came from the inertial loading of the magnetosphere by the injection and ionization of neutrals from Io. A newly created ion experiences a radial acceleration by the corotation electric field; the magnetic Lorentz force then accelerates the moving ion in the azimuthal direction. After about one gyro-period, the ion's velocity reaches the corotation velocity, and the radial acceleration ceases. Since the corotation speed near Io is 56 km/sec, sulfur and oxygen ions acquire 520 and 260 ev, respectively. In hydromagnetic language, a radial current exerts an azimuthal $\underline{J}x\underline{B}$ stress on the new ions, accelerating them to the corotation speed. The radially outward current closes by flowing along field lines to the Jovian ionosphere, across the magnetic field in the conducting ionosphere, and back out along field lines to the torus. In the ionosphere, the $\underline{J}x\underline{B}$ stress exerts a spin-down torque against the neutral atmosphere, whose reaction torque attempts to enforce corotation of the torus field lines. Hence, the energy acquired by the accelerated ions is ultimately supplied by Jupiter's rotational kinetic energy.

In order to supply the 3×10^{12} watts for the line radiation by inertial loading, approximately 2×10^{28} ions/sec must be created and accelerated to the corotation speed; supplying the auroral luminosity would require greater than 10^{29} ions/sec. However, from the absence of an Io EUV enhancement, Shemansky (1980) set an upper limit to the Io production rate of 10^{27} ions/sec, one to two orders of magnitude smaller than required to account for the torus energetics. A possible resolution that the Io-injected neutrals travel far from Io before being ionized, thus allowing a stronger, but spatially diffuse, Io source. In addition, the observed ion temperature in the hot torus ($T_i \sim 50$ ev) is smaller by a factor of 4 to 10 than the expected temperature based on the corotation energy. Of course, ions must transfer energy to electrons by collisions in order to maintain the line radiation. However, the electron-ion energy Coulomb exchange time is about 10 to 100 times longer than the maximum estimated radial diffusion loss time from torus region (Shemansky, 1980), so that the ion corotation gyro-energy would be lost from the torus before coupling to electrons could occur. Finally, if the precipitation of the moderate (kev) to high (> 100 kev) energy electrons in the torus is responsible for producing the auroral luminosity, the electron precipitation lifetimes would be considerably shorter than the time scale on which inward radial diffusion from the middle magnetosphere could resupply the torus electron population. Hence, maintaining the torus auroral electrons against precipitation would require strong local acceleration, which has not been observed (Thorne, 1981 a,b).

Although the ultimate energy source for the torus and aurorae is still likely to be Jupiter's rotation, the dynamical processes which couple that energy into the torus plasma and energetic auroral particles are probably more complex than the straightforward inertial loading of field lines near Io. Since the torus and auroral energies are large, a plausible hypothesis is that the dissipation of Jupiter's rotational energy occurs on relatively large spatial scales, perhaps involving the middle and outer magnetosphere, and that the dissipated energy is partitioned into many different degrees of freedom (Gold, 1976; Dessler, 1980; Eviatar and Siscoe, 1980). For example, the Jovian auroral luminosity may not peak on the field lines which thread the Io torus, but on those which connect to the middle and outer magnetosphere. Acceleration processes associated with field-aligned auroral currents might produce moderate to high energy electrons and ions in the middle magnetosphere which radially diffuse into the Io torus. Goertz (1980) has suggested that the aurorae might result from the inward transport and precipitation of energetic protons within the torus. Thorne (1981 a,b) has developed this concept to include the production of secondary 20-40 ev ionospheric electrons by the precipitating protons. A significant fraction of the secondaries escape from the ionosphere and become trapped in the torus, thus providing the electron energy for maintaining the torus line emission. Another possibility is that the torus thermal electrons are heated by resonant and non-resonant interaction with the $(n+1/2)f_c$ harmonic waves which are excited by loss-cone anisotropies in the moderate energy (kev) electron distribution.

In summary, the torus and auroral energetics cannot be understood solely in terms of local torus dynamics. The torus is coupled to the middle magnetosphere by the inward radial diffusion of energetic particles and by the outward radial transport of the torus heavy ions. Thus, we must turn to the Voyager observations of the middle and outer magnetosphere in order to understand the overall binary character of Jupiter and Io.

3. JUPITER'S MIDDLE MAGNETOSPHERE

The Pioneer investigators divided the distant magnetosphere of Jupiter into two regions — a middle magnetosphere between 15 and 50-70 R_J, and an outer magnetospheric boundary layer of variable thickness (10-30 R_J) next to the magnetopause. In the magnetosphere, the Pioneer magnetic field (Smith et al., 1974) and energetic particle measurements revealed a "magnetic disk" — a radially stretched, weak magnetic field near Jupiter's magnetic equator that was encountered every ten hours as corotation swept the disk over the spacecraft. Energetic particle fluxes increased at every minimum. Pressure balance arguments indicated that particles with energies less than a hundred kev, the lowest measured, had a ratio of plasma to magnetic field pressure, β, of order unity at the center of the disk. Thus, the magnetodisk is also referred to as a plasma or current sheet. Several R_J above and below the disk, the plasma pressure was negligible. From the angular distributions of the energetic protons, McDonald et al. (1979) concluded that the middle magnetospheric plasma tended to flow in the corotation direction, although both the direction and flow velocity showed great variability (Schardt et al., 1981). In addition, field-aligned beams of energetic protons and electrons were occasionally observed to flow outward from Jupiter (Van Allen et al., 1974), suggesting that auroral acceleration processes occur on middle magnetospheric field lines.

The two Voyager passes through the middle and outer magnetospheres provided the first opportunity to make comprehensive plasma measurements in all energy ranges and to investigate the nightside, tailward region which had not been probed by the Pioneer spacecraft. Four Voyager instruments are pertinent to our discussion: a magnetometer to measure the local vector magnetic field; a plasma wave instrument to measure the local electron plasma frequency and thereby infer the electron density; the Low Energy Charged Particle analyzer (LECP) to measure ions above 30 kev energy; and the Plasma Science instrument (PLS) to measure 10 ev - 6 kev electrons and ions. Magnetic field measurements are unambiguous, and estimation of the electron density n_e from the observed plasma frequency is straightforward (Scarf et al., 1981a). Direct determination of n_e has also proven to be reliable (Scudder et al., 1981). However, calculation of the ion number and charge density, composition, temperature, and flow velocity from either LECP or PLS data requires certain model-dependent assumptions. For this reason, all controversies have not been sorted out at this time; therefore, we will outline those areas where there seems to be general agreement.

The Voyagers' plasma instruments cannot uniquely determine the ion composition for energies below E_0 = 200 kev. Above E_0, solid state detectors provide ion discrimination (Krimigis et al., 1979a,b; Vogt et al., 1979); since only energy per unit charge is measured below 200 kev, the ion data is ambiguous without an independent assessment of composition. The LECP and PLS teams approach this problem in different ways. The LECP team assumes that the composition directly measured above E_0 also pertains at lower particle energies, which provide the bulk of the ion energy density. In addition, for $E < E_0$, the LECP responds more sensitively to heavy ions when it is looking in the flow direction $\vec{v}$ than it does looking perpendicular to $\vec{v}$. Thus, some assumption about $\vec{v}$ is necessary to sort out composition ambiguities. These ambiguities affect the calculations of number and energy densities. The PLS team's approach assumes that multiple ion species should have a common bulk speed in the corotation direction. When the bulk speed exceeds the ion thermal velocity, the relative ion composition can be determined. Another useful constraint upon ion data reduction is the enforcement of overall charge neutrality using electron density measurements. Hence, in determining the bulk plasma motions, the flow velocity vectors derived from either data set are those most consistent with the analysis procedure; nowhere has there been published an error estimate.

Magnetodisk Plasmas

The magnetodisk plasma is roughly confined to within 4-5 R_J of the centrifugal or magnetic equator and carries an azimuthal current which generates the radially extended Jovian magnetic field (Figure 1). The high magnetic pressure above and below the current sheet is balanced in the vertical direction by the high pressure plasma in the weakly magnetized central region of the disk. Although the Pioneer magnetic field and energetic proton (> 100 kev) measurements certainly showed the presence of the plasma sheet, the Voyager LECP (Krimigis et al., 1979a) discovered that the dominant contribution to the plasma pressure was provided by thermal ions with a temperature of 20-30 kev. Figure 8 shows the thermal and energetic ($>10^3$ kev) ion differential intensity which was measured by the Voyager 2 LECP during a magnetodisk crossing at 58 R_J on the dayside (Krimigis et al., 1981). Under the assumption that the ions below 100 kev are protons, the thermal ion distribution is well-fit by a convecting Maxwellian with a temperature of 29 kev and a number density of $8\text{x}10^{-4}$ cm^{-3}. The high energy, power law tail of the ion distribution passes through the proton differential intensity measurement (square) near 700 kev, thus strengthening the assumption that the lower energy ions are protons. The pressure of the Maxwellian ions is comparable to the magnetic pressure measured in the region above the magnetodisk, where the plasma density is much lower.

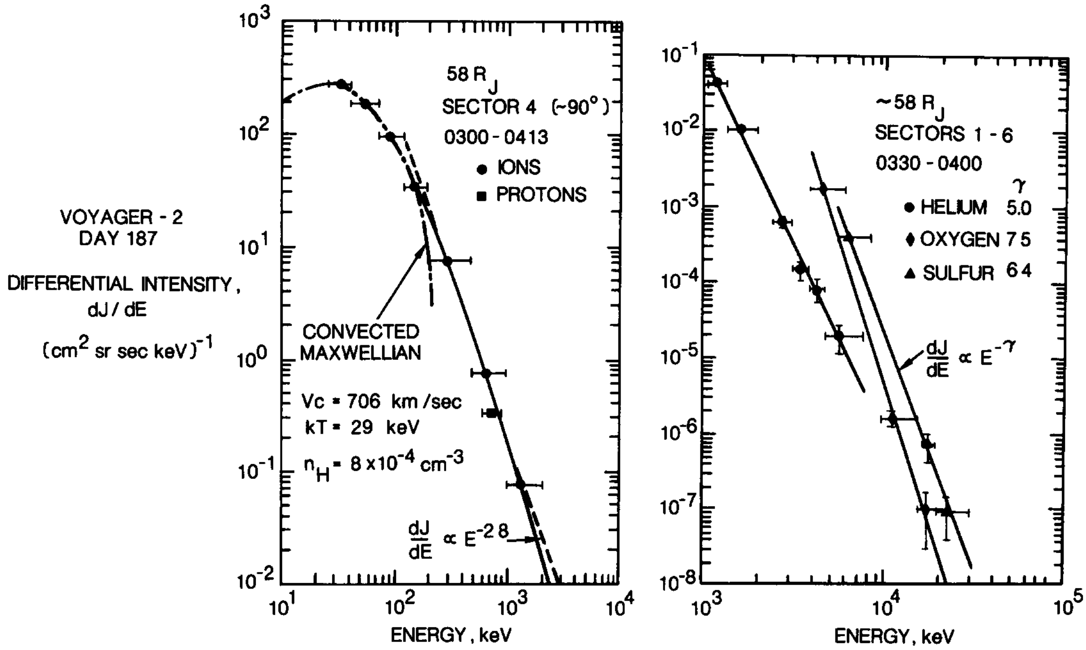

Figure 8. The differential intensity of low energy (left) and energetic (right) ions measured by the Voyager 2 Low Energy Charged Particle experiment during a plasma sheet crossing at 58 R_J on the dayside (adapted from Krimigis et al., 1981). The low energy ion measurements (solid circles) were obtained when the detector was viewing at 90° to the corotation direction, and are believed to be due to protons. The square near 700 Kev is from a proton detector, and it falls on the high energy tail of the low energy ion distribution. The high energy (71 Mev) spectra resolve the ion composition. The high sulfur abundance implies a Jovian origin.

The Plasma Science Instrument discovered a very low energy ion component in the middle magnetosphere which apparently results from the outward radial transport of plasma from the Io torus. The PLS most sensitively discriminates the charge-to-mass ratio when the flow velocity is supersonic. In the vicinity of the centrifugal, not magnetic, equator, the PLS detected a thin layer of dense, cold plasma with typical number densities of 0.1 cm^{-3} and ion temperatures of 10 to 100 ev (McNutt, et al., 1981). The cold ion layer is embedded within the hot ion plasma magnetodisk and is enriched in heavy ions, O^+, O^{++}, S^{+++}, and perhaps S^+, thus suggesting its torus origin. The electrons which charge neutralize this heavy ion disk (Figure 1) are cool, with a temperature of a few 10's of ev. Both the heavy ion and cool electron temperatures are considerably higher than would be expected if the plasma were transported outward adiabatically from the inner magnetosphere. Hence, the heavy ions probably experience some non-adiabatic heating, perhaps due to plasma wave turbulence (Barbosa, 1981).

Although the presence of low energy heavy ions in the middle magnetosphere was anticipated (Hill and Michel, 1976; Eviatar et al., 1978), the LECP detection of very energetic heavy ions was a surprise (Krimigis et al., 1979a). The right hand panel of Figure 8 shows the differential intensity of > 1 Mev helium, oxygen, and sulfur ions (Hamilton et al., 1981). The abundance ratio of O/He is close to solar flare or coronal values, but the ratio of S/He is more than an order of magnitude higher than solar (Krimigis et al., 1979a). Hence the high energy sulfur ions, and perhaps some or all of the energetic oxygen, have their origin in the Jovian magnetosphere, probably from the Io torus, thus suggesting that powerful acceleration processes operate within the magnetosphere.

The Question of Corotation

The single over-riding issue for understanding the dynamics of the middle magnetosphere is whether or not, or to what extent does, the plasma and magnetic field corotate with Jupiter. Deviations from strict corotation measure the amount of mass which is being transported outward from the inner magnetosphere (Hill, 1979). The spin-up torques exerted on the outflowing material dissipate the rotational energy of Jupiter's upper atmosphere. In addition to providing the corotation flow kinetic energy, some of the dissipated rotational energy must also go into heating the plasma locally within the magnetodisk and/or into sustaining field-aligned auroral potential drops which accelerate particles to moderate to high energies (Dessler, 1980; Eviatar and Siscoe, 1981).

Although the Voyager plasma measurements provided significant new information on the question of corotation, the ambiguities associated with determining the ion composition prevent a conclusive answer at this time. A comprehensive study of the thermal (~30 kev) and energetic ion flows was carried out by the LECP investigators (Krimigis et al., 1979a,b; Krimigis et al., 1981; Carbary et al., 1981). Figure 9, which has been adapted from Krimigis et al. (1981), shows the Voyager 1 and 2 hourly average flow vectors which were determined by a Compton-Getting fit to the measured directional anisotropies of the moderate energy ions. The flow anisotropies of > 500 kev protons and energetic Z > 6 heavy ions are essentially identical to those in Figure 9 (Carbary et al., 1981). For reference, the dashed lines correspond to "typical" magnetopause shapes which are drawn to intersect the Voyager magnetopause encounters. Within the middle magnetosphere, inside 50 R_J on the dayside and out to 130 to 150 R_J on the nightside, the flow velocity is essentially in the corotation direction and it tends to decrease with decreasing radial distance, as expected for rigid corotation. For the differential intensity shown in Figure 8, the flow velocity was within 3% of the corotation velocity, indicating that nearly perfect rigid corotation can occur. However, significant deviations from corotation in both magnitude and direction are also observed, with the flow being much more variable between 50 and 130 R_J on the nightside; note the occasional reversals in the (hourly average) flow direction.

The PLS investigators have also examined the question of corotation in the heavy ion disk. The PLS data reduction assumes that the plasma flows in the corotation direction and that the ion composition is similar to that in the inner magnetosphere. By using an azimuthal flow velocity model which increases linearly with distance out to 20 R_J and remains constant at 200 km/ sec beyond 20 R_J, McNutt et al., (1981) obtained estimates of the heavy ion density which are consistent with the measured PLS cool electron density.

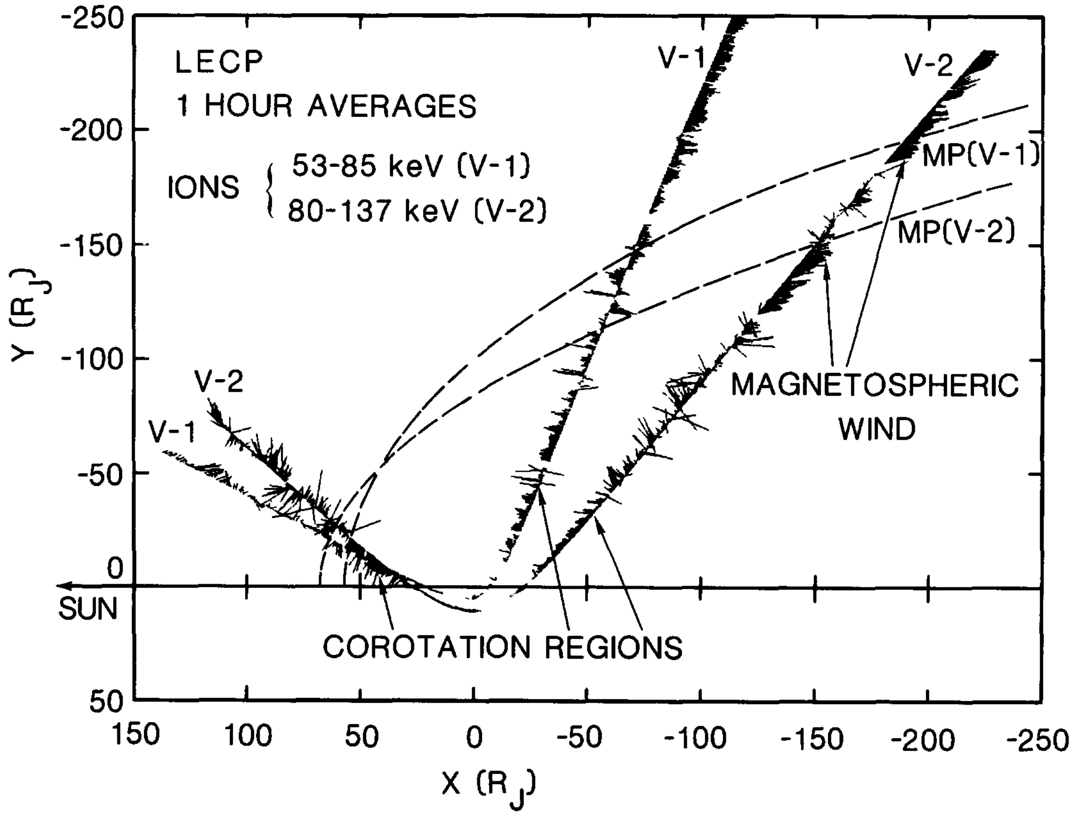

Figure 9. The hourly average directional flow anisotropies measured by the Low Energy Charged Particle experiment plotted along the Voyager 1 and 2 encounter trajectories (adapted from Krimigis et al., 1981; see also Carbary et al., 1981). The length of the vector measures the relative strength of the flow anisotropy. Corotation flow is observed within 50 R_J. Between 50 and 130 R_J, the flow direction and magnitude are variable, and deviate from corotation. An anti-sunward magnetospheric wind is observed both inside and outside the magnetopause (dashed lines).

The clear differences between the LECP and PLS determinations of the corotation flow have not been resolved at this time. Of course, in principle, the low energy heavy ion disk could flow with a different (generally lower) speed than the moderate to high energy ions; the implied violation of hydro-magnetic, frozen-in flow would suggest a high dissipation rate in the plasma sheet, probably involving significant magnetic field reconnection. Thus, although we infer that ions tend to corotate in the middle magnetosphere, the extent to which corotation is enforced is still uncertain. Consequently, we cannot estimate the radial component of the ion flow velocity and, therefore, directly determine the rate of radial mass transport.

Escaping Energetic Particles and the Magnetospheric Wind

Since Jupiter's magnetosphere possesses internal plasma sources — the Io torus and possibly the aurora — plasma, in steady state, must escape from the magnetosphere via radial transport through the dayside magnetopause and/or anti-sunward flow down the Jovian magnetic tail (Hill, et al., 1974; Kennel and Coroniti, 1975). On the approach to Jupiter, the Pioneer spacecraft detected several flux enhancements of several Mev electrons which showed evidence of 10-hour modulation (Chenette et al., 1974). Apparently, these electrons escaped from the Jovian magnetosphere and propagated into the upstream solar wind along the interplanetary magnetic field. Subsequent analysis of earth-orbiting spacecraft measurements demonstrated that the Jovian relativistic electrons can follow the solar wind field to earth (Teegarden et al., 1974), so that Jupiter must be regarded as a significant source of heliospheric cosmic rays.

Although the Pioneers did not detect Jovian ions until arriving near the bow shock, the Voyager LECP measured energetic ion flux enhancements from 860 R_J upstream to beyond 1200 R_J downstream of Jupiter (Zwickl et al., 1981). Figure 10 shows the energetic ion events which were detected on the Voyager 1 and 2 inbound and the Voyager 1 outbound passes. Solid circles denote events lasting from a few minutes to three hours, and solid squares denote events of more than eight hours duration. The energetic ions were detected only when the solar wind magnetic field connected the spacecraft to Jupiter's magnetosphere. The two panels show the ion composition for a Voyager 1 event near the magnetopause and one near 200 R_J upstream; these events are marked by dark squares on the trajectory. The energetic ions are enriched in $Z > 6$ heavy particles relative to the solar and interplanetary ions that stream away from the sun, thus confirming that the energetic ion source is within Jupiter's magnetosphere and is not due to solar wind particles which have been accelerated by or reflected at the bow shock.

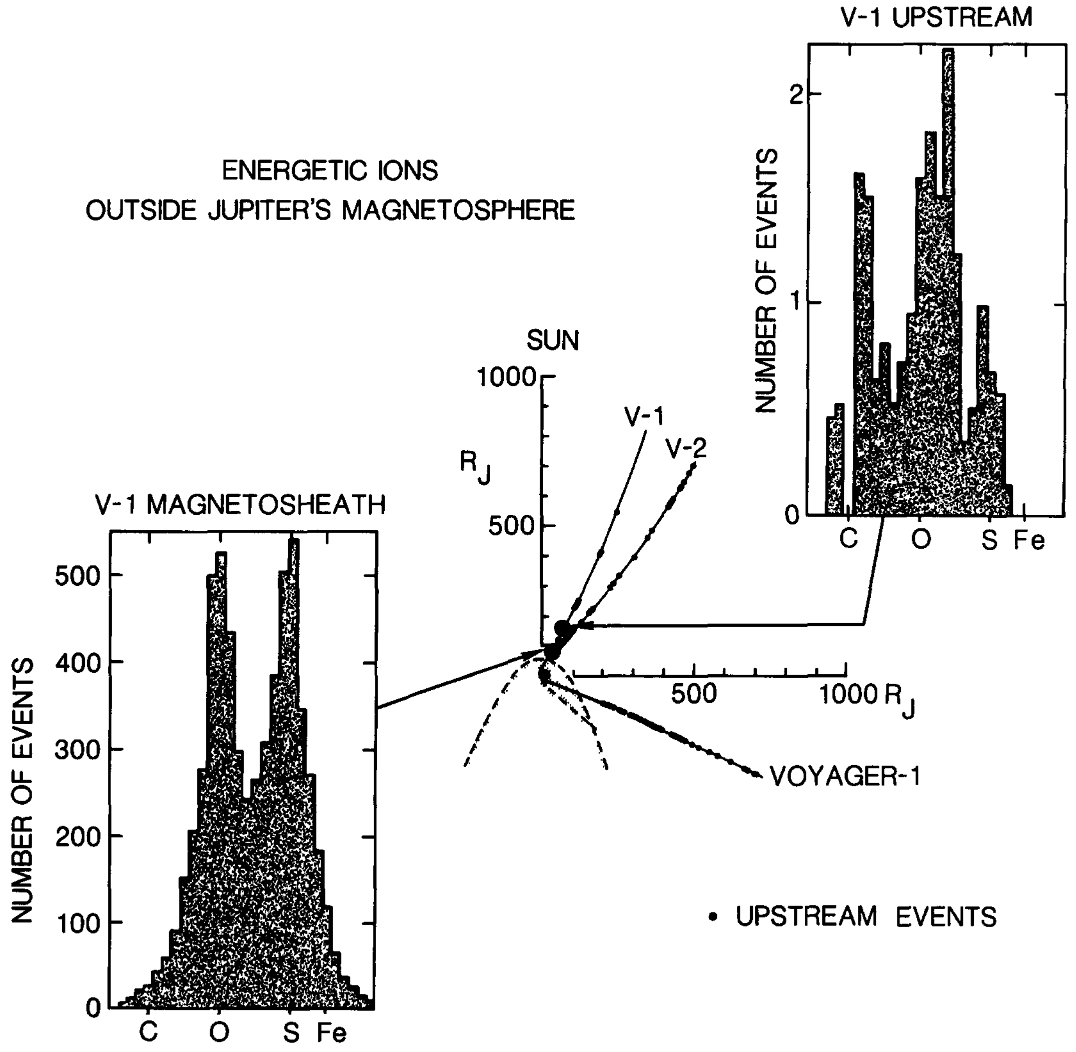

Figure 10. The detection of energetic ions which escape from the Jovian magnetosphere (adapted from Zwickl et al., 1981). Small black dots indicate the Voyager 1 and 2 locations at the ion flux enhancement events relative to Jupiter. Voyager 2 outbound data are missing due to solar conjunction. The left and right-hand panels show the ion composition obtained at the locations of the two large black dots. Note the high sulfur abundance confirming a Jovian origin.

On the outbound passes, the Voyager LECP found evidence that high fluxes of thermal (~ 30 kev) magnetodisk ions continuously escape into the magnetosheath and solar wind. Figure 9 shows that as Voyagers 1 and 2 approached the dawn magnetopause, a strong tailward ion flow developed within the magnetosphere in a region which resembles a boundary layer (see Figure 1). The ion flow continued to be observed in the magnetosheath and out to several hundred R_J in the solar wind. Krimigis et al. (1981) refer to this flow as the "magnetospheric wind." Measurements above 200 kev, which resolve composition, confirm the lower energy ion flow anisotropies, and the > 200 kev heavy ion composition unambiguously places the source of the wind inside the Jovian mangetosphere.

The escape of the thermal plasma sheet ions represents a significant particle and energy loss from the magnetosphere. As an estimate, Krimigis et al. (1981) assume that the wind flows throughout the nightside in a sheet of 5 R_J thickness at a mean distance of 170 R_J. A typical ion density $n \sim 2 \times 10^{-4}$ cm and flow speed $\vec{v} \approx 500$ km/sec implies that 2×10^{27} ions above 30 kev energy escape each second. Since the total number of such ions in the magnetosphere is 10^{34}-10^{35}, the mean ion residence time is 10^6-10^7 seconds — 10 days to several months. If the escaping ions have 100 kev mean energy, the energy loss rate is 2×10^{20} ergs/sec. Since the magnetosphere dissipates a total of 3-10×10^{21} ergs/sec (Kennel and Coroniti, 1977a), it invests a significant fraction of its entire energy dissipation rate in escaping energetic ions.

In summary, the plasma sheet in the middle magnetosphere is populated by thermal (~ 30 kev) ions which have the dominant pressure, by cold heavy ions which are centrifugally confined, and by energetic heavy ions. Assuming that the ~ 30 kev ions are largely protons, it is tempting to speculate that the energetic particles come from Jupiter, perhaps accelerated by auroral processes near Jupiter's hydrogen atmosphere, whereas the heavy ion disk comes from Io. Both components are evidently slowly transported radially outward through the middle magnetosphere, and at least the ~ 30 kev ion component and the energetic heavy ions escape into the solar wind. Important information about radial transport is undoubtedly contained in the time dependences of the magnetic field and in the radial components of the imperfectly inferred flow vectors. However, there is still disagreement about the magnitude of the dominant azimuthal component, and so experimental definition of radial transport awaits further data reduction.

4. JUPITER'S MAGNETIC TAIL AND INTERACTION WITH THE SOLAR WIND

In the terrestrial magnetosphere, magnetic field line reconnection (Dungey, 1961) and/or viscosity (Axford and Hines, 1961) couple energy and momentum from the shocked solar wind across the magnetopause and stretch the earth's magnetic field into a long tail that extends perhaps 1000 R_E down-stream (Dungey, 1965). The tail is split into northern and southern half-cylindrical lobes of opposite magnetic polarity, separated by a current sheet across which the magnetic field rotates in direction and diminishes in magnitude.

If the terrestrial reconnection rates are scaled to Jupiter, the Jovian magnetosphere could have a magnetic tail which is several AU long (Kennel, 1973; Kennel and Coroniti, 1977a; Siscoe, 1979). The Pioneer encounters provided no direct evidence for a magnetic tail since their trajectories sampled only the local dawn to local noon quadrant. Although current sheets associated with a radially stretched magnetic field were detected, they occurred in the quasi-corotation middle and outer dayside magnetosphere. However, Krimigis et al. (1975), Mewaldt et al. (1975) and Pesses and Goertz (1976) did infer the existence of a long Jovian tail from studying the escape of Jovian cosmic ray electrons and their propagation through the heliosphere.

The Jovian Tail

In contrast to the Pioneer trajectories, both Voyagers left the magnetoshere further downstream from Jupiter, and Voyager 2 definitively detected the beginning of the Jovian magnetic tail. Figure 11 plots subsets of hourly averaged magnetic field vectors for the outbound portions of the Voyager 1 and 2 trajectories (Behannon et al., 1981; see also Ness et al., 1979a,c). Each vector's length is logarithmically scaled to the observed magnitude as indicated. Within 25-30 R_J, the field is in the magnetic meridian plane; near 100-125 R_J, the field is more or less parallel to the ecliptic plane and aligned along the magnetopause surface. The field vectors make a gradual transition between these two orientations at 0400 LT (Voyager 1 outbound), whereas, further downstream at 0240 LT (Voyager 2 outbound), the tail-like orientation of the magnetic field is established by 50 R_J. The magnetic field is more chaotic beyond 130 R_J where the LECP detected the magnetospheric wind.

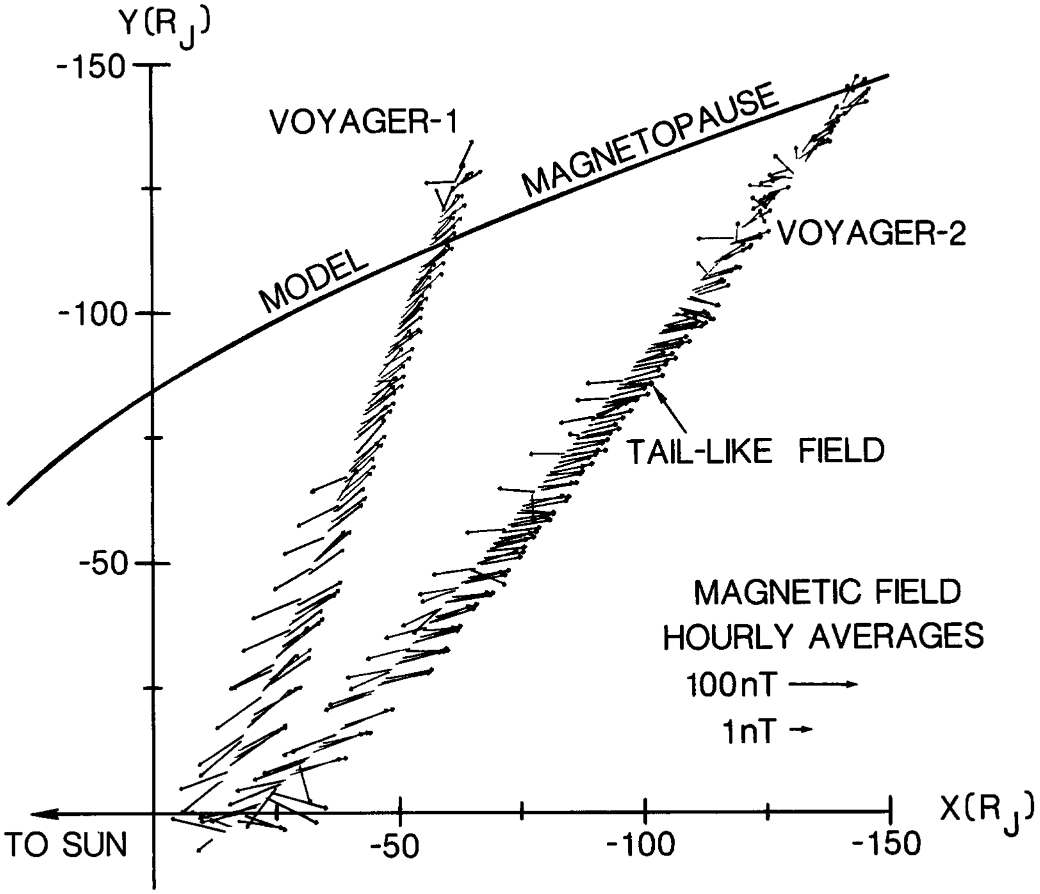

Figure 11. The hourly average magnetic field vectors, on a log scale, measured by the Voyager magnetometer experiment (adapted from Behannon et al., 1981; see also Ness et al., 1979b). A tail-like field orientation is clearly evident beyond 50 R_J on the Voyager 2 outbound pass. The solid line is a representative magnetopause location.

Quasi-periodic crossings of the current sheet from the northern (field away from Jupiter) to the southern (field toward) tail lobes are apparent in Figure 11. Generally, the more distant current sheets are more irregualr. Lanzerotti et al. (1981a) find that > 30 kev ion energy density can account for the observed diamagnetic decreases. A mixture of 85% hydrogen and 15% heavy ions by number is most consistent with the requirement that the plasma plus magnetic pressure remain constant across the current sheet. A simple model of current sheet motion, together with the measured crossing durations and inferred sheet normal directions, leads to a typical sheet thickness of 5 R_J (Behannon et al., 1981 see also Connerney, et al., 1981).

The Tail Lobes

Although the discovery of the magnetic tail suggests that the Jovian magnetosphere has a significant reconnection interaction with the solar wind, a tail-like magnetic field configuration might be produced by a strong tailward flow of plasma escaping from the

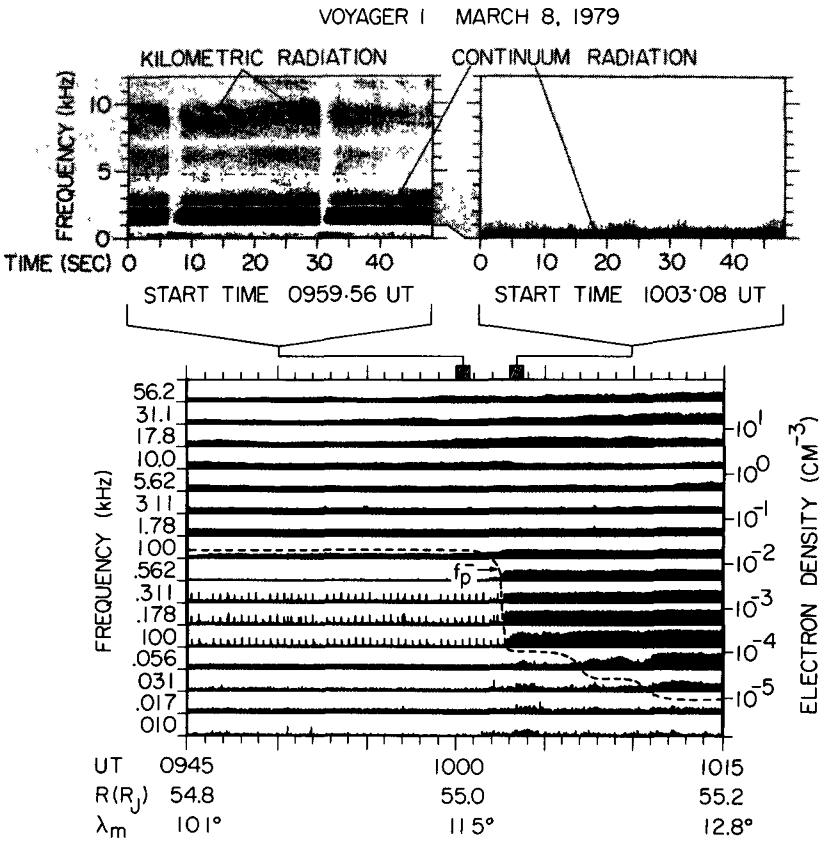

Figure 12. Plasma wave measurements in the very low density lobes of the Jovian magnetic tail. The bottom panel contains the digital outputs from the 0.01 to 56.0 KHz bandpass channels; and equivalent electron density scale for which the electron plasma frequency equals the observed frequency is shown on the right-hand side. The dashed line is the local electron plasma frequency (f_p). The top two panels show broad band frequency-time diagrams for the plasma sheet (left) and tail lobe (right). The low frequency cut-off of the electro-magnetic continuum radiation indicates that the electron density in the tail lobes is 10^{-5} cm $^{-3}$.

nightside middle magnetosphere (Hill, et al., 1974; Kennel and Coroniti, 1977b). However, a fundamental difference exists between a tail formed by reconnection and one formed by plasma outflow — the lobes of the reconnection tail should have a very low plasma density since the magnetic field lines are open to the solar wind.

The Jovian plasma wave instrument revealed that the nightside tail lobes contain the hardest vacuum yet encountered in space, a vacuum which may be comparable to the intergalactic medium. The plasma wave instrument measures the local plasma density by utilizing the property that electro-magnetic plasma waves propagate only above the electron plasma frequency (f_p) and reflect from those points where their frequency matches f_p. In the terrestrial magnetosphere a continuum of electromagnetic waves is trapped in the low electron density region that is bounded on the outside by the magnetosheath and on the inside by the high-density inner magnetosphere; the continuum radiation propagates in the tail lobes where the plasma density is typically 10^{-3} cm^{-3}.

Jovian continuum radiation was detected by the Voyager PWS immediately upon entering the dayside magnetosphere (Scarf et al., 1979a), but the most intense signals were observed in the nightside tail lobes. Figure 12 shows plasma wave data acquired for a half-hour period on March 8, 1979, during which Voyager 1 exited, at 1003 UT, from the plasma sheet into the tail lobe (Gurnett et al., 1980). The bottom inset displays the electric field amplitudes measured in a sequence of band-pass channels whose center frequencies are logarithmically spaced between 0.01 kHz and 56.2 kHz. The top two insets contain 48 seconds of 0.05 kHz - 12 kHz broadband data taken before and after tail lobe entry. Prior to 1003 UT, the only signal below 1 kHz was due to spacecraft sources. The broadband display beginning at 0959:56 UT shows continuum radiation near but above 1 kHz, and kilometric radiation at higher frequencies. The low frequency cutoff of the continuum (dashed line) indicates that inside the current sheet the plasma frequency was 1 kHz and the electron density was $10^{-2}cm^{-3}$, consistent with direct particle measurements. Tail lobe entry was marked by a sudden drop of the continuum cutoff to 31 Hz, implying that the electron density fell to $10^{-5}\,cm^{-3}$. The tail lobe continuum was so intense that the kilometric signal was overwhelmed in the 1003:08 UT broadband display, which has a small dynamic range in amplitude. The lowest tail lobe density detected by the Voyager PWS was $3x10^{-6}\,cm^{-3}$, a density which is comparable to the closure density for typical values of the Hubble constant.

Figure 13 compares continuum radiation power spectra measured when Voyager 1 was in the dayside plasma sheet and in the tail lobe (Gurnett et al. 1980). By integrating the tail lobe spectrum over frequency, we find that the continuum radiation energy density will exceed that of the plasma if the mean particle energy is less than a few hundred ev. Thus, the electro-magnetic wave pressure could well be comparable with the plasma pressure and could help maintain the high vacuum of the tail lobes by pushing plasma into the distant tail and preventing the entry of solar wind plasma into the lobes.

Distant Tail Encounters

The PWS detection of a very low density tail lobe strongly supports the suggestion that the Jovian magnetosphere has a significant reconnection interaction with the solar wind. However, Kurth et al. (1981) have found evidence that the structure and dynamics of the Jovian tail may be more complex than would be anticipated by analogy with the earth's tail. The middle panel of Figure 14 shows the portions of the Voyager 2 trajectory in which continuum radiation was detected. The solid lines denote times in which the Plasma Science Instrument confirmed that Voyager 2 was inside the magnetopause, and the crosses, observations of continuum radiation that apparently escaped into the solar wind. A sketch of the expected magnetopause position is included for reference. Since the magnetopause responds to changing solar wind dynamic pressure, the tail magnetopause is scaled to noise radii of 60 R_J and 100 R_J — about the range of observed mangetopause distances on the dayside.

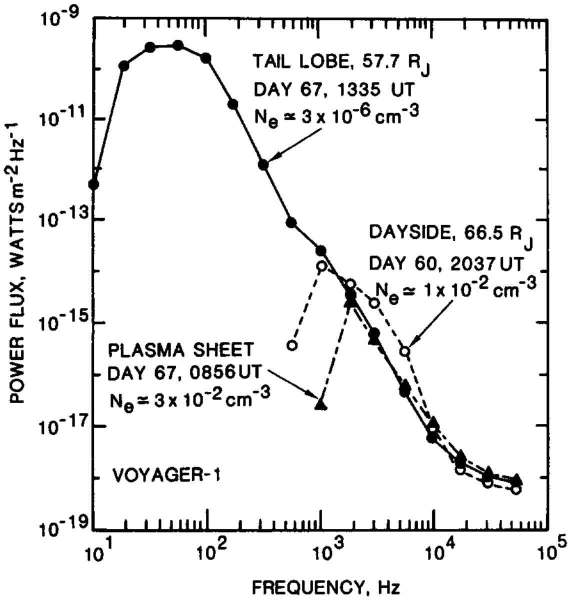

Figure 13. The power spectral density of electromagnetic continuum radiation which is trapped in the magnetospheric cavity (after Gurnett et al., 1980). On the dayside the spectrum terminates between 0.5 to 1.0 KHz, indicative of a relatively high electron density. On the nightside, the spectrum extends to extremely low (10 - 20 Hz) frequence, indicating an electron density of $3 \times 10^{-6} cm^{-3}$ in the tail lobes.

The bottom panel of Figure 14 shows wave electric field measurements for August 8-10, 1979, when Voyager 2 was about 355 R_J from Jupiter. From the plasma frequency cut-off (dashed line), the electron density is inferred to have decreased to about 10^{-3} cm $^{-3}$ in two succesive tail crossings. Since the magnetopause position is highly variable, the magnetopause crossings on August 8-10 are not unexpected. However, the magnetopause encounters on September 15-17 were entirely unexpected. In these crossings, labeled B in the top and middle panels, the magnetosphere was encountered about 700 R_J from Jupiter and, more importantly, some 500 R_J from the tail axis, where no conventional reasoning would have placed the tail magnetopause. The continuum radiation measurements indicate that n_e dropped from 0.3 cm $^{-3}$, typical of the solar wind, to about .04 cm^{-3} inside the magnetopause. Voyager 2 magnetic field measurements suggest that Jupiter's bow shock may have been encountered during the data gap on September 16 and that the magnetic field was tail-like in the low density region. PLS measurements confirm the low densities and indicate that a high speed solar wind event was in progress.

At present, we can only offer speculative physical explanations for the Voyager distant tail encounters. Kurth et al. (1981) suggest that Jupiter's tail is filamentary, in analogy with optical observations of comet tails. Perhaps the Jovian magnetosphere was distorted by a high-speed solar stream. Perhaps a large-scale enhancement of the magnetodisk plasma pressure temporarily pushed the dawn magnetopause far from the Sun-Jupiter axis. Another possibility involves the storage of magnetic energy in the tail due to dayside reconnection. If the open tail lobe field lines suddenly reconnect, as happens at earth during magnetospheric substorms, magnetic tension stresses would drive a strong convective flow toward Jupiter's nightside (Kennel and Coroniti, 1977a). Corotation torques would sling the convective flow toward dawn, where the flow dynamic pressure would push the magnetopause outward.

It had been anticipated that data collected during the summer of 1981 would provide further opportunities to study Jupiter's distant tail, when Voyager 2 would cross the tail or wake about 7000-8000 R_J (3-4 AU) downstream (Scarf, 1979) where the scaling of terrestrial magnetospheric theory suggests it may extend. In fact, Jupiter's tail was encountered again in February, 1981, at a distance of 6200 R_J (Scarf, et al., 1981b).

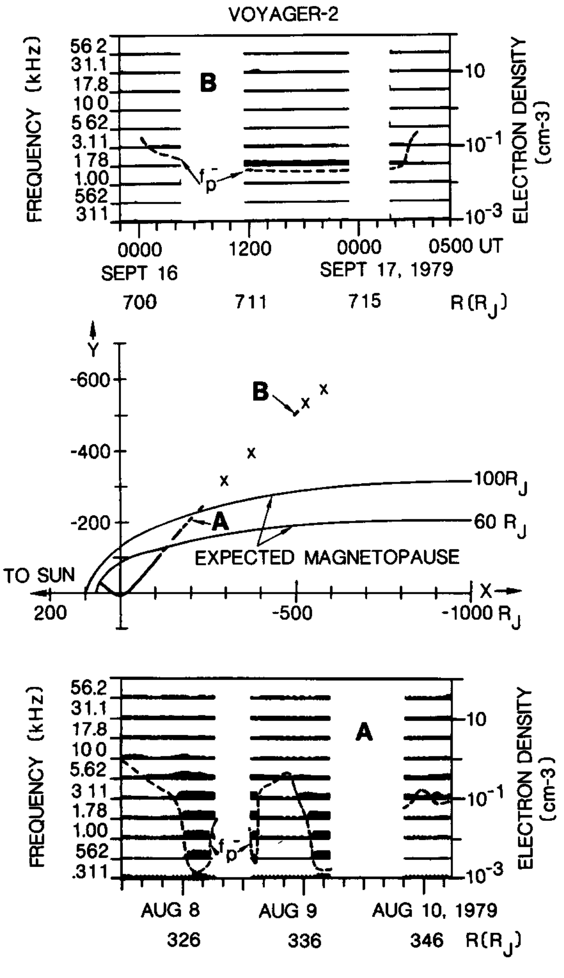

Figure 14. The middle panel shows the spatial locations at which the Voyager 2 Plasma Wave instrument detected electromagnetic continuum radiation (adapted from Kurth et al., 1981). The solid lines indicate that Voyager 2 was inside the magnetopause, and the crosses indicate that the continuum radiation must have escaped into the solar wind. The top and bottom panels show the bandpass channel measurements with an equivalent electron density scale. The dashed line represents the local electron plasma frequency. Event A occurred near an expected location of the magnetopause. Event B suggests that the tail magnetopause can extend to great distance from the sun-Jupiter line, far beyond the expected magnetopause position.

5. DISCUSSION

Planetary and astrophysical magnetospheres can be approximately divided into several categories. The terrestrial magnetosphere is dominated by the reconnection interaction between the geomagnetic and interplanetary fields; the interaction greatly distorts the earth's field and couples solar wind energy into the magnetospheric cavity, which is dissipated as auroral luminosity. In pulsar magnetospheres, the energy source is rotational; when combined with a strong pair-production particle source near the neutron star's polar cap, the loss of rotational energy sustains the pulsar's luminosity and drives a relativistic stellar wind outflow. In some binary X-ray sources mass transfer from a normal or giant star maintains accretion onto a magnetized neutron star; here, the energy source is gravitational, and the neutron star magnetosphere is a barrier which shapes its release. Although less certain, a normal star can orbit within the magnetosphere of its white dwarf companion; the hydromagnetic interaction which couples the two stars by field-aligned currents may control the stellar rotation rates and the binary's orbital evolution. Undoubtedly, the above list is not complete.

The interesting, and perhaps unique, characteristic of the binary Jupiter-Io magnetosphere is that it combines aspects of all of the above categories. Io's vents and volcanoes provide an intermittent mass source which is transported throughout the magnetosphere, inertially loads the Jovian magnetic field. In the attempt to enforce corotation of the heavy ions, the rotational energy of Jupiter's upper atmosphere is dissipated into hot plasma, energetic particles, and auroral luminosity. The hydromagnetic interaction between Io and Jupiter's ionosphere maintains a complex system of field-aligned currents which generate escaping decametric and kilometric radio waves. Hot plasma in the middle magnetosphere, whose energy source is probably rotational, escapes into the solar wind; the plasma outflow may resemble a planetary version of a stellar wind. The escape of energetic particles makes Jupiter a source of heliospheric cosmic rays. Finally, the reconnection interaction of the Jovian magnetosphere with the solar wind creates a long, earth-like magnetic tail and it may provide additional energy for the outer magnetosphere's dynamics.

Figure 15 presents a post-Voyager impression of the Jupiter-Io binary magnetosphere. In what follows, we will attempt to integrate the Voyager observations into a synthetic

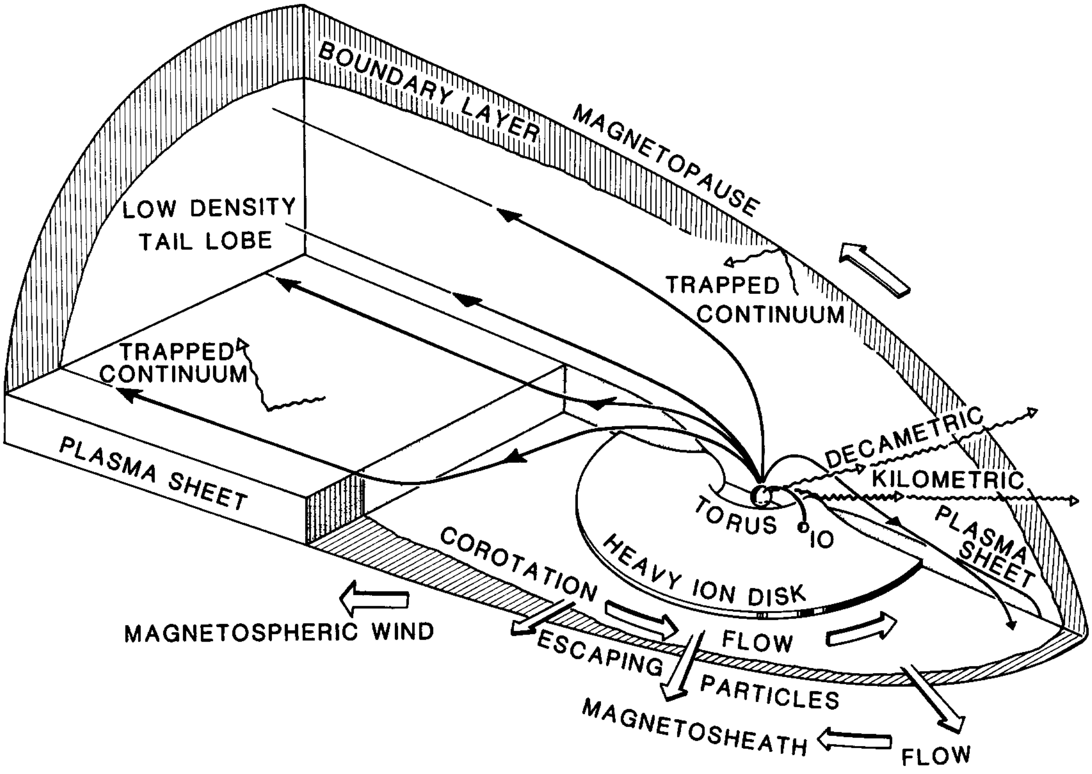

Figure 15. A schematic summary of the Jupiter-Io magnetosphere. Volcanos and vents on Io inject SO_2 neutrals which are ionized and form a heavy ion torus. Field-aligned currents which couple Io and the torus to Jupiter's ionosphere generate decametric and kilo-metric radio waves which escape from the magnetosphere. Outward radial diffusion transports the torus ions into the middle magnetosphere and populates a cold heavy ion disk. A hot ion plasma sheet surrounds the heavy ion disk; the hot plasma may be accelerated out of the Jovian ionsophere by auroral processes which are driven by field-aligned currents. Plasma sheet ions escape into the magnetosheath as a magnetospheric wind. Dayside magnetic field reconnection creates a long magnetic tail with extremely low density lobes. Electromagnetic continuum radiation is trapped in the low density magnetospheric cavity.

model of the magnetospheric particle sources, energetics, and large-scale transport. Although the model is clearly simplistic and subject to revision, it can provide a framework for assessing the general significance of the Jupiter-Io system. The Voyager measurements raised two fundamental problems on the global structure of the magnetosphere. If the Io particle injection rate is limited to 10^{27} ions/sec, the observed auroral luminosity of 1.2×10^{13} watts and torus EUV line emission of 3×10^{12} watts cannot be simply explained by the dissipated power within the torus which results from accelerating the new ions to the corotation speed. The escape of hot magnetodisk ions to the solar wind drains at least 2×10^{13} watts from the middle magnetosphere; roughly 10^{27} hot ions escape each second. The mean residence time of a hot magnetodisk ion is 10^{6-7} seconds; the radial diffusion time scale for the outward transport of heavy ions from the torus is also of order 10^{6-7} seconds. The numerical coincidence of inner and middle magnetospheric powers, particle number fluxes, and particle lifetimes may be fortuitous. On the other hand, the coincidence may indicate that the inner and middle magnetospheres form a tightly coupled dynamical system, a possibility which we now pursue.

Even if the Io mass injection rate is substantially higher than Shemansky's upper limit, as is possible if the neutrals are actually ionized over a large region of the torus, the corotation power dissipated solely within the torus is still likely to be insufficient. Hence, a reasonable possibility is to assume that the rotational energy is dissipated over the much greater volume of the middle magnetosphere. The power maintaining the torus EUV emissions and that portion of the Jovian aurora on field lines connecting to the torus is subsequently transported inward to the torus by radial diffusion and/or convection. Both the Pioneer and Voyager observations of the radiation belts in the inner magnetosphere can be quantitatively understood by assuming that energetic particles radially diffuse inwards from the middle magnetosphere and are lost to the atmosphere by precipitation. Medium (~kev) and high ($\sim$ 100 kev) energy electrons are scattered by whistler mode chorus and hiss and by electrostatic electron cyclotron waves. The precipitation energy fluxes can account for a significant fraction of the observed auroral luminosity. In addition, inward diffusing energetic ions can deliver a comparable energy flux to the atmosphere and produce secondary ionospheric electrons which, when back-scattered into space, might help maintain the torus EUV emissions.

If energetic particles diffuse inward, particles whose source is in the inner magnetosphere will diffuse outward. Indeed, the heavy ion disk which was detected within the hot plasma magnetodisk is most simply explained by the outward transport of torus ions. For the same heavy ion mass flow, the resultant inertial loading of the middle magnetosphere is capable of extracting a greater rotational energy from Jupiter's atmosphere due to the increased torque which is needed to enforce corotation at larger radial distances. A likely consequence of strong corotational dissipation in the middle magnetosphere is that a significant fraction of the observed Jovian auroral luminosity comes from field lines connecting to this region. To develop this point, we will now review the magnetohydrodynamics of corotation and its relation to auroral processes.

Corotation

Jupiter exerts a torque on mass diffusing radially outwards in the attempt to accelerate it to the corotation speed. The torque is communicated between Jupiter's upper atmosphere and the magnetospheric plasma by a system of field-aligned currents. These currents close by flowing perpredicular to the magnetic field in the plasma sheet, where they exert a spin-up torque, and in Jupiter's ionosphere, where a reaction torque is exerted on the neutral atmosphere. The field-aligned currents flow whenever there develops a lag from corotation. The field-aligned current density which threads the plasma sheet is proportional to the radial gradient of the corotational angular velocity, $d\Omega/dr$.

The efficiency with which Jupiter's atmosphere couples its angular momentum to the ionosphere is uncertain. Kennel and Coroniti (1975) noted that ionospheric neutrals would be rapidly decelerated by inertial loading unless either the ionospheric coupling region occurred at a deeper atmospheric level than indicated from photo-ionization models, or there were rapid upward or lateral transport of atmospheric angular momentum by eddy diffusion. Hill (1979) suggested that the imperfect conductivity of the ionosphere would result in the slippage of field lines relative to the atmosphere. The Voyager observations that the magnetodisk plasma has a significant azimuthal velocity and that mass must be transported outwards nonetheless indicates that the atmosphere does couple efficiently to the magnetosphere.

To date, the Voyager plasma measurements have not provided a definitive assessment of the degree of corotation lag. The PLS investigators found that a constant azimuthal velocity beyond 20 R_J yielded the best fit to the low energy ion measurements. If correct, $d\Omega/dr$ would decrease as r^{-2}, and field—aligned currents should be distributed throughout the middle magnetosphere. However, the LECP investigators argued that rigid corotation persited to much larger radial distances. Even so, the LECP hourly average anisotropy vectors are variable in magnitude and direction, suggesting that there are local departures from perfect corotation. If the outward radial transport is accomplished by large scale convection cells, the deviations from corotation would imply local, transient field-aligned currents.

Auroral Processes

On balance, a system of field-aligned currents probably connects Jupiter's ionosphere with the plasma sheet and heavy ion disk in the middle magnetosphere. We now review what terrestrial auroral experience suggests are the implications of having field-aligned currents. If the currents are sufficiently large, the electrostatic potential difference between the ionosphere and distant magnetosphere is not zero, thus violating ideal hydromagnetics. The magnetosphere has a large inductance so that the potential adjusts in order to maintain an approximately constant current. On field lines carrying an outward directed current from the ionosphere, the potential drop accelerates a downward electron beam which, upon impacting the atmosphere, creates a spatially thin, discrete auroral arc; the spatially diffuse aurorae is produced by the wave turbulent scattering of trapped magnetospheric electrons. An electron beam is also believed to generate the terrestrial kilometric radiation. The upward parallel electric field accelerates ionspheric ions toward the magnetosphere. Strong plasma turbulence, which is excited by the current, can also heat ions in the perpendicular direction, resulting in their becoming trapped in the magnetospheric mirror field. Clearly, a downward field-aligned current simply reverses the parallel electric field; electron beams now travel into the distant magnetosphere, whereas the downward accelerated ions may create a weak aurora.

Auroral Plasma Source

Some evidence exists that large potential drops do occur on Jovian middle magnetospheric field lines. Pioneer 10 and 11 energetic particle investigators reported field-aligned fluxes of both electrons and protons whose origin is consistent with auroral acceleration (Baker and Van Allen, 1976). On Voyager, Hamilton et al. (1981) detected field-aligned beams of 1 MeV H_3^+ molecules in the middle magnetosphere. The most likely, and possibly only, source of H_3^+ is upward auroral acceleration from Jupiter's atmosphere.

Field-aligned fluxes of energetic particles were only infrequently detected by the Pioneers and Voyagers, suggesting that very large potential drops (~Mev) may develop only under extreme circumstances. However, the question remains as to whether the observed ~ 30 kev thermal plasma sheet ions have an auroral origin. The composition of 30 kev ions is uncertain. If they are dominantly hydrogen, as suggested by Lanzerotti et al. (1981a), their source could be Jupiter's hydrogen atmosphere.

Recently, Barbosa (1981) has suggested that field-aligned ions could populate the plasma sheet by pitch-angle scatering which is induced by an electromagnetic two-ion beam instability. He finds that the threshold beam flux for instability, integrated over the area of the plasma sheet, is comparable to the total number flux of ions which escape in the magnetospheric wind. Recall that the energy loss rate in escaping 30 kev ions is comparable to the observed auroral luminosity. Hence, if it is auroral dissipation which maintains the 30 kev plasma sheet ions against escape losses, the downward accelerated electron beam would create an auroral arc with the observed intensity. Since the acceleration torque on the plasma sheet requires a radially outward current to enforce corotation, the auroral arc would be located on field lines which thread the transition region separating the inner and middle magnetospheres, probably between 15 and 30 R_J.

If the thermal plasma sheet ions are dominantly heavy, however, their source would be the outward diffusing torus plasma. The upper limit to the Io injection number flux of 10^{27} ions/sec is comparable with the escape flux in the magnetospheric wind, thus suggesting a possible source-sink relationship. However, a physical process which would accelerate the cold torus plasma and produce the observed bi-modal distribution of 100 ev and 30 kev ions is difficult to realize. The answer to the LECP composition ambiguity might be settled by determining the precise latitudinal location of the aurora. If strong auroral emissions occur on middle magnetospheric, rather than just on torus, field lines, the plasma sheet would almost certainly contain energetic hydrogen.

Plasma Transport

The dissipation of the atmosphere's rotational energy requires that torus heavy ions be radially transported outward through the middle and outer magnetosphere. In the inner magnetosphere, radiation belt observations strongly suggest that the transport is by radial diffusion. Within the orbit of Io, the diffusion is probably driven by atmospheric neutral wind turbulence (Brice and McDonough, 1973). Beyond Io, where the heavy ion corotation flow and the magnetic field energy densities become comparable, the plasma inertia can drive interchange instabilities that result in radial diffusion. Richardson and Siscoe (1981) have shown that the heavy ion density profile observed by the PLS is consistent with interchange marginal stability. Another possible transport mechanism is a large scale corotating convection cell driven by azimuthal asymmetry in the Io torus mass loading (Hill, *et al.*, (1981).

The nature of radial transport in the middle magnetosphere is uncertain. The earliest models (Michel and Sturrock, 1974; Kennel and Coroniti, 1975) simply assumed that as soon as the corotation energy density exceeded the magnetic energy density, near 20-40 R_J, the plasma broke out into a planetary version of a stellar wind. A super-Alfvènic wind, with comparable radial and azimuthal velocities, was not observed in the middle magnetosphere by either Voyager plasma instrument. However, Kennel and Coroniti (1977a) have suggested that the dynamic pressure of the solar wind could suppress a super-Alfvènic wind on the dayside, so that the radial outflow would occur as a sub-sonic "breeze."

The radial transport is probably not adequately described by either a stellar wind or breeze solution. The magnetic field in the plasma sheet is observed to have an average southward normal component (Smith *et al.*, 1974; Ness *et al.*, 1979b), which stellar wind theory usually neglects. It is the radial current crossed into the normal component which accounts for the corotation acceleration torque. Consequently, the radial outflow remains coupled to the ionosphere; new particles and energy are continuously added to the flow. If an analogy does exist with stellar winds, the middle magnetosphere might most closely resemble the transition region which lies in between the base of the stellar atmosphere (lower corona) and the Alfvèn critical point. The theory of thermally driven winds requires a heat addition to the flow in order to accelerate through the critical point. The transition region might well be turbulent, containing large-scale convection cells which transport heat and plasma. The variable flow anisotropies observed by the Voyager LECP do suggest that the middle magnetosphere is turbulent. Perhaps the radial transport is a combination of outflow and convection cell turbulence.

On the nightside, the downstream pressure is low, so that a super- Alfvènic wind might develop (Hill et al., 1974; Kennel and Coroniti, 1977a). However, the Voyager discoveries of a magnetic tail and low density tail lobes suggest that reconnection does occur between the Jovian and interplanetary magentic fields at the dayside magnetopause. Tail reconnection would drive a sunward convection flow which might clash with and/or suppress any nightside radial outflow. Corotation torques should accelerate the convection flow toward dawn. Near the magnetopause, a boundary layer should form in which the outward diffusing plasma of Jovian origin should mix with the sunward convecting plasma of solar wind origin (note the flow streamlines from the tail towards Jupiter in Figure 1). However, thus far, neither a convective flow component from reconnection nor a dawnside ion composition gradient have been identified in the Voyager data.

Summary

In the truest sense, Jupiter and Io do combine to create a binary magnetosphere. In diffusing outward from the torus, Io plasma inertially loads the magnetic field in the middle magnetosphere. The resulting corotation lag induces field-aligned currents and the auroral acceleration processes associated with them near Jupiter's atmosphere. Aurorally accelerated ions and electrons populate the plasma sheet and diffuse inward to supply the energy for the torus EUV and auroral emissions. Downward accelerated electron beams produce an auroral arc near the inner to middle magnetosphere transition. Io ions and auroral ions eventually escape to the solar wind. We emphasize that the above discription is but one reasonably self-consistent synthesis of the present observational understanding and is highly uncertain in its details.

Clearly, we are at early phase in the study of the binary magnetosphere of Jupiter and Io. Further detailed and refined analyses of the Voyager data will reveal new physical processes and clarify the understanding of those which are now but dimly perceived. Together, the Pioneer and Voyager encounters will have provided a rich framework for the Galileo mission's intensive investigation of the binary magnetosphere.

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