16

Torus–Magnetosphere Coupling

Fran Bagenal
Massachusetts Institute of Technology, Cambridge

Abstract

To understand temporal variability of the jovian magnetosphere, it is necessary to study the coupled system of the Io plasma torus, the magnetosphere, and Jupiter's ionosphere. At present, efforts have been concentrated on separate elements of the system.

Progress has been made in both measuring and modeling the plasma conditions in the cold and warm regions of the torus. Models of the warm torus developed by Shemansky (1987b) show that the observed plasma conditions require an additional source of energy in the torus, comparable to that picked up by the ions in plasma production (3×10^{13} W). Estimates of mass-loading on the ionosphere and the concomitant perturbation in the plasma flow suggest it may not be possible to produce this much power in a small region such as Io's atmosphere, as Shemansky proposes. A fully self-consistent, three-dimensional plasma model of the magnetosphere-atmosphere interaction is urgently required. A recent analysis of the Voyager plasma science data in the region between the warm torus and the plasma sheet ($L = 6$ to 12) indicates that there is an additional source of plasma between 9 and 11 R_J, possibly the ionization of neutral material from Europa or recycling of material from the Io torus. In addition to a thermalized ion population with $T_i \sim$ 50 eV there is a hot population with temperatures > 1 keV that comprises up to 35 percent of the total charge density. To ascertain if this hot population could be acting as an intermediary and transferring energy from the inwardly diffusing energetic particles to provide the 10^{13} W to the torus, we need a comprehensive model of the region between the torus and the plasma sheet, including ionosphere-magnetosphere coupling.

INTRODUCTION

The Io plasma torus is the main source of plasma for the jovian magnetosphere. At the same time, it is the interaction of the streaming magnetospheric plasma with Io (or its atmosphere/ionosphere) that may be the source mechanism. The magnetosphere is coupled to Jupiter (the "flywheel") by field-aligned currents that close in the ionosphere (the "clutch"). Thus, the ionosphere tries to enforce corotation throughout the mag-

netosphere. Conversely, mass-loading and radial motion in the magnetosphere drive currents in the ionosphere. In the outer regions of the magnetosphere, particles are accelerated to high energies (by some as yet undetermined mechanism). The energetic particles diffuse inward toward the torus and "disappear" between $L \sim 12$ and $L \sim 6$. Some of these particles precipitate into the ionosphere, where they cause intense auroral emissions. Particle precipitation may in turn modify the electrical conductivity of the ionosphere and hence affect the rate of radial motion in the magnetosphere. Particle precipitation will also generate secondary electrons that could be a significant source of energy for the torus plasma and supply a background population of protons. The remaining energetic particles continue to diffuse inward through the torus, where they may heat the torus plasma. This complicated three-way coupling between the torus, magnetosphere, and ionosphere is sketched in figure 96. The main elements of the system are reasonably well understood: (1) The cold inner torus has been explored both from ground-based observations (Trauger, 1984) and by Voyager 1 (Bagenal, 1985). Recent work by Barbosa and Moreno (1987) has provided a fairly comprehensive theoretical model. (2) The composition of the warm outer torus has been well determined by Voyager and International Ultraviolet Explorer (IUE) ultraviolet (UV) observations (Shemansky, 1987b; Moos et al., 1985). The Voyager plasma science (PLS) instrument has provided good determinations of the ion (Bagenal et al., 1985) and electron (Sittler and Strobel, 1987) temperatures. The data have led to considerable theoretical work on centrifugally driven radial diffusion (Summers and Siscoe, 1985) and steady-state models of the torus plasma with a source cloud of neutral sulfur and oxygen atoms (Barbosa et al., 1983; Smith and Strobel, 1985; Moreno et al., 1985; Shemansky, 1987b). (3) The properties of the plasma sheet have been well determined by Voyager PLS (McNutt et al., 1981), and the radial forces on the plasma in the plasma sheet seem to be reasonably balanced (Vasyliunas, 1983; McNutt, 1984; Mauk et al., 1986). (4) The energetic particle populations have been measured extensively by the Pioneer and Voyager spacecraft (Schardt and Goertz, 1983). In particular, Gehrels and Stone (1983) show a dramatic decrease in oxygen and sulfur ions at 10s MeV energies between $L \sim 12$ and $L \sim 6$ (with the strongest losses outside $L \sim 8$). (5) The auroras have been measured by rocket-borne detectors, IUE and Voyager (see Clarke et al., this volume). Herbert et al. (1987) have reviewed the evidence for 3–8 $\times$ 10^{12} W of emission from an oval skirting the $L \sim 6$ field lines at the time of the Voyager 1 encounter.

However, there remain important elements of the system that are not well determined: (1) To understand the coupling between the torus and the magnetosphere

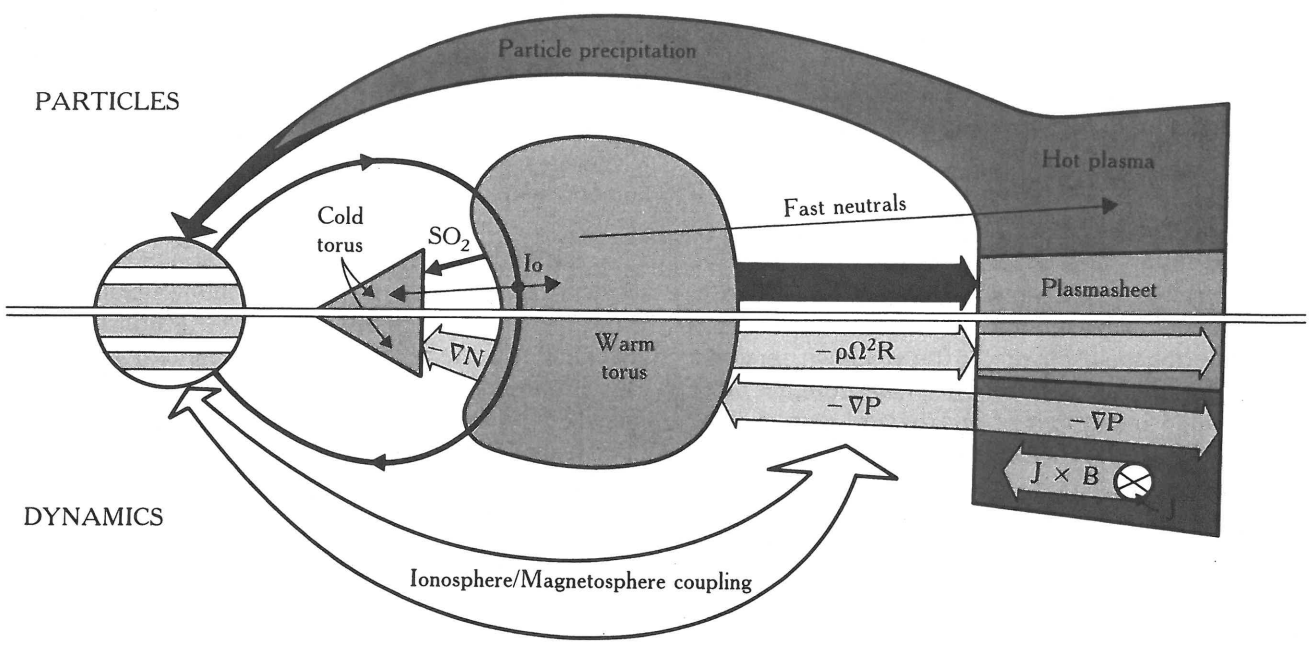

Figure 96. Coupling between the torus, magnetosphere, and ionosphere.

we need to know the properties of the plasma between $L = 6$ and 15. The extraction of plasma parameters from the PLS data, which has been particularly difficult in this region, is the major subject of this chapter. (2) It is important to know the electrical conductivity of Jupiter's ionosphere for determining the degree to which the magnetosphere is coupled to the planet's rotation. Estimates range from 0.1 mho to 10 mho (Strobel and Atreya, 1983). (3) Whether the source of the aurora is electron or ion precipitation is a topic of current debate (see Clarke et al., this volume). The resolution of this matter has important implications for both particle transport and the ionospheric conductivity. (4) Cheng et al. (1983) show Voyager low energy charged particle (LECP) data for their upper energy channels (>0.2 MeV) but the lower-energy channels (30–200 keV) of the LECP detectors were heavily saturated inside $L \sim 10$. There were no Voyager measurements of ions between 6 keV and 30 keV; we will have to wait for Galileo to reveal the particle properties in this important intermediate energy range.

The elements of this torus-magnetosphere-ionosphere system are usually studied separately but the strong coupling between them requires that the system be studied as a whole. Clearly, the system will suffer temporal variability, and the study of how each element varies will give clues of the coupling processes. Unfortunately, many aspects of the magnetosphere can be measured only locally. We have two Pioneer plus two Voyager passes through the jovian magnetosphere but it is hard to separate temporal variations from longitudinal, latitudinal, and radial variations. As far as the Voyager PLS data are concerned, Voyager 1 to Voyager 2 comparisons are limited to outside 10 R_J and have revealed considerable differences in the middle magnetosphere due to changes in the solar-wind conditions (McNutt et al., 1987). Because of the nature of the PLS data inside 12 R_J, we are only just beginning to understand the Voyager 1 inbound pass, even after eight years' work. Luckily, we are not confined to local measurements; valuable information about the magnetosphere can be obtained remotely. Although somewhat limited in spatial coverage, to a line of sight measurement and in coverage of ionic species, UV and optical measurements of the torus emissions will always be the major means of monitoring plasma conditions in the torus. Radio emissions also reveal properties such as electron density and temperature (see chapters by Zarka and Genova, and DePater and Klein in this volume). Of particular importance to the torus-magnetosphere coupling problem, Jones (1987) reports a possible means of monitoring the radial density gradient over the several months of the two Voyager encounters. The time is now ripe for a synthesis of the results from various Voyager and Pioneer experiments, in combination with theoretical models, to study the whole torus-magnetosphere-ionosphere system.

COLD TORUS

It was from the cold, inner region of the torus that emission was first detected and the cold torus remains the best-understood part of the jovian magnetosphere, but it is rather a backwater since only about 2 percent of plasma (and a much smaller fraction of energy) diffuses inward from Io. Hence, although its effect on the inner radiation belts, Amalthea, and the rings may be significant, its net influence on the magnetosphere is small.

Remote observations of S^+ and O^+ show the cold torus to be persistent but having variations in n_e and T_e and with longitude and time (Brown et al., 1983; Trauger, 1984). The Voyager PLS instrument made detailed measurements of S^+, O^+, S^{2+}, O^{2+}, and $SO_2{}^+$ ions and their temperature, T_i in to 4.9 R_J (Bagenal, 1985). Nevertheless, some aspects of the cold torus remained puzzling: Why did the ratio of oxygen to sulfur not decrease inward as one would expect (Johnson and Strobel, 1982); why was there so much O^{2+} when T_e is <1 eV; and how did the $SO_2{}^+$ ions survive so far from Io? Moreover, the presence of a hot component to the ion distribution indicated a local source of pick-up ions (Bagenal, 1985). Richardson and Siscoe's (1983) models of plasma diffusing inward from Io could not generate radial profiles of both density and temperature that were compatible with the data. Many of these questions may have been resolved by Barbosa and Moreno (1987), who have considered the photodissociation of SO_2 and the reactions of the dissociation products and the surrounding plasma. A key reaction in their model is a near-resonant charge-exchange reaction between SO and S^+, which may account for the removal of sulfur inward of Io. This fairly comprehensive model needs to be fully tested on details of the Voyager data, but it may prove to be a valuable tool for exploring possible explanations of the longitudinal and temporal variability of the inner torus.

The transition from the warm to the cold torus is very sharp: There is a clear change in the nature of the PLS spectra between consecutive measurements on both the inbound and outbound legs of the Voyager 1 trajectory. The high-resolution spectra in figure 97 show

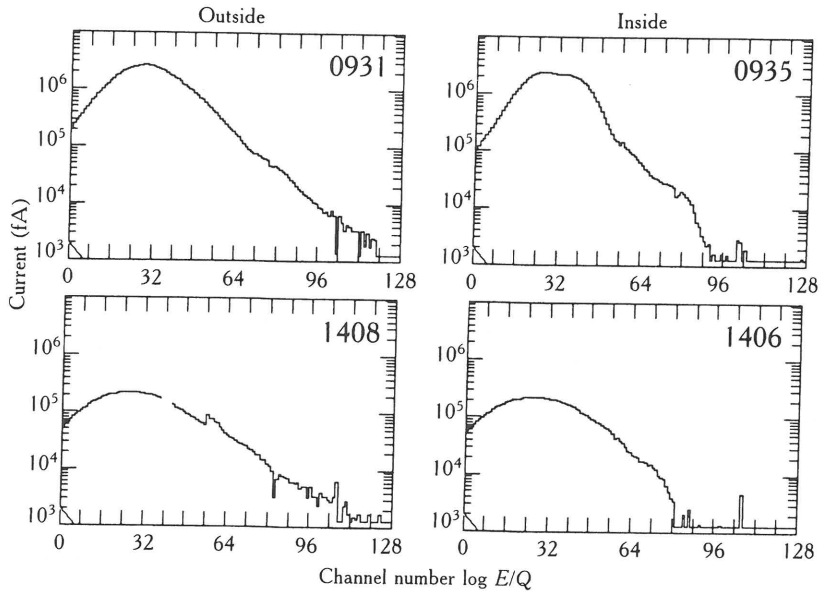

Figure 97. Voyager 1 PLS energy-per-charge spectra obtained on 5 March 1979 near the boundary between the warm and cold regions of the Io torus. The fluxes measured inbound (*below*) were much lower than on the inbound leg (*above*) because the spacecraft was farther from the centrifugal equator and the detector was pointed away from the corotating flow.

how the tail to the ion distributions at higher energies is greatly reduced inside the boundary. More precise timing of the boundary crossings can be obtained from the low-resolution data obtained between the spectra shown in figure 97. In figure 98 the magnetic L-shell values have been plotted for the times of the inbound and outbound crossings using the full O4 (Acuña), and offset tilted dipole (OTD) approximation to the O4 magnetic field model (Acuña et al., 1983). For both magnetic field models the L-shells of the inbound and outbound crossings are remarkably close, the separation ΔL being less than 0.07 and 0.04, respectively, for the

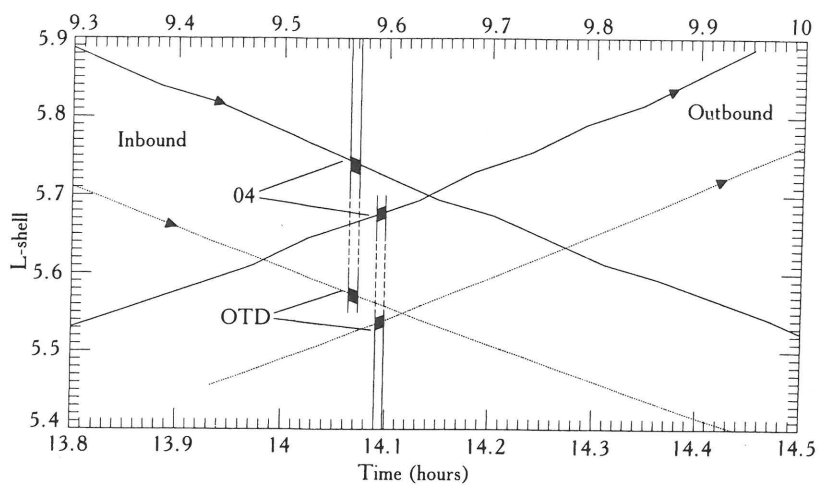

Figure 98. Magnetic L-shell of Voyager 1 for the inbound (*upper time axis*) and outbound (*lower time axis*) crossings of the inner torus boundary for the full O4 (*full lines*) and OTD (*dotted lines*) magnetic field models. The vertical lines attached to the upper (lower) axis correspond to the times of consecutive measurements on the inbound (outbound) passes.

O4 and OTD models. In both cases, the inbound crossing was at a larger L-value, which is consistent with an asymmetry in the ion drift paths due to a dawn-dusk electric fields but the magnitude is rather less than the value of ~0.1 derived for the Voyager 1 trajectory from the estimates of the electric field by Barbosa and Kivelson (1983) and Ip and Goertz (1983). The boundary L-shell ($L = 5.711 \pm 0.032$ for the full O4 model and $L = 5.557 \pm 0.017$ for the OTD model) coincides with the location of the maximum in flux tube content (NL^2, where N is the total number of ions per unit L-shell) and the location of a sharp decrease in temperature (Bagenal, 1985). It is the torus divide: the separation between inward and outward diffusion. Linker et al. (1985) have been able to produce such a boundary well inside Io's orbit by including the effects of Jupiter's gravitational potential on the trajectories of low-velocity neutral atoms sputtered from Io.

WARM TORUS

Moos et al. (1985) have reported that five years of IUE observations indicate the temporal variability of the warm torus is small. The mixing ratios of S^+, S^{2+}, and S^{3+} appear to vary less than 28 percent and the electron density and temperature are inferred to vary by only ±10 percent and ±14 percent, respectively. On the other hand, Shemansky (1987a) reports considerable variation in the torus conditions between Voyager 1 and Voyager 2, inferred from ultraviolet spectrometer (UVS) data. He reports a relatively small change in composition (toward lower ionization states, compatible with a slightly reduced electron temperature), but he infers a 50 percent increase in electron density. Certainly, measurements of the variability will enhance our understanding of the processes. But at present we need to understand the Voyager 1 epoch.

Table 14 shows the composition of the warm torus as derived from various observations and theoretical models. It seems quite extraordinary that it has taken eight years for a general consensus to have been reached on the composition of the warm torus. There are several factors that have contributed to this delay, but the main issues have been (1) the lack of accurate atomic data for the interpretation of UV data and theoretical models (Brown et al., 1982; Shemansky, 1987a) and (2) the need to calculate the response of the PLS instrument to trans-sonic flows. From the IUE and UVS data the best-determined parameter is the ratio S^+/

Table 14. Composition of Warm Torus

	H^+	O^{2+}	S^{3+}	O^+	S^{2+}	S^+	N_e	T	T_{hot} 16	T_{hot} S^+	$\bar{T}$
UVS Voyager 1[a]			**16**	**39**	**32**	**13**	2250				
IUE[b]			**4**	**50**	**40**	**6**					
DES[c]		<1	<1	**49**	**5**	**46**	2000				
DES[d]		**3**	**6**	**42**	**36**	**13**	2000				
B&M[e]		**9**	**6**	**40**	**34**	**11**	2000				
UVS Voyager 2[f]		<1	**2**	**45**	**36**	**17**	3000				
PLS1[g]											
Thermal	50	51	75	652	250	217	2149	55			
	±23	**±42**	**±21**	**±96**	**±39**	**±59**		**±13**			
Hot				384		20.4			O^+ 173	980	
				±79		**±25**			**±29**		
No hot S^{2+}	**2.3**	**4.7**	**10.5**	**48.3**	**23**	**11**					92.6
35 percent S^{2+}	**2.3**	**4.7**	**10.5**	**36.3**	**35**	**11**			S^{2+} 346		100
PLS2[h]											
Thermal	50	15	45	553	393	258	2260	62			
	±30	**±54**	**±27**	**±137**	**±52**	**±69**		**±18**			
Hot				427		20.4			O^+ 184	980	
				±88		**±27**			**±33**		
No hot S^{2+}	**2.2**	**1.3**	**6**	**43.5**	**35**	**11.4**					99.5

Bold numbers are percentages of charge density. Densities are in *ions* cm^{-3} and temperatures are in eV. [a] Shemansky (1987b) Voyager 1 spectrum at 5.75 R_J. [b] Moos et al., (1986) standard model with 1.17 R_J scale height. [c] Shemansky (1987b) model from neutral cloud theory. [d] Shemansky (1987b) modified theory with electron heating. [e] Barbosa and Moreno (1987). [f] Shemansky (1987a) Voyager 2 spectrum. [g] Fit to PLS data at $L = 6.0$. [h] Fit to PLS data with reduced O^{2+} and S^{3+}.

S^{2+}, which is 0.6–0.7 by number (0.3–0.35 by charge). Shemansky (1987a) now claims that the ratio S^{2+}/O^{+} is well determined at 0.4 by number (0.8 by charge). Unfortunately, there are no detectable O^{+} emission lines in the IUE spectral range. When it comes to higher ionization states there may be some disagreement over S^{3+} with Shemansky (1987b) reporting larger abundances from the Voyager 1 UVS measurements (16 percent by charge) than measured by IUE (4 percent by charge) and predicted by various theoretical models (Shemansky, 1987b; Barbosa and Moreno, 1987). There are not direct measurements of O^{2+} abundance since the O^{2+} line at 833 Å is swamped by a near coincident O^{+} line in the UVS spectra (which has 30 Å resolution) and again there are no O^{2+} lines in the IUE range. The lack of O^{2+} emission at 5007 Å reported by Brown et al. (1982) puts an upper limit on the abundance of O^{2+} ions (1 percent) that is even less than the low densities from theoretical models. This may be true temporal variability and further ground-based observations of the 5007 Å line would be particularly useful. Note that the theoretical model of Barbosa and Moreno (1987) includes as much as 9 percent O^{2+} (by charge) to account, in part, for the large abundance of O^{2+} observed in the cold torus (Bagenal, 1985).

In analysis of the PLS data in the warm torus, we have been guided by the above constraints on the ion composition. The plasma flow is trans-sonic and the individual spectral peaks of the different ionic species cannot be resolved. The lack of a unique determination of plasma parameters in the warm torus has been acknowledged from the beginning, and our recent efforts have been to derive levels of uncertainty in the parameters. First of all, the broad, central maximum in the spectra is consistent with corotating ions with an atomic mass-to-charge ratio (A/Z) of 16 dominating the plasma. We therefore constrained the plasma flow velocity to that of corotation, assumed the bulk of the ions to have the same temperature, and started with a composition that is roughly consistent with the UV emissions.

To match the PLS data at lower energies we included a small percentage of protons (at the same temperature as the bulk of the ions). To match the PLS data at higher energies we had to introduce hot components at A/Z equal to 16 and 32. Even with all the above constraints, we are left with 11 free parameters to fit rather featureless spectra. Furthermore, there is the underlying problem that the velocity distribution of each ionic species is probably not the Maxwellian function we must assume for our analysis (as discussed below).

In table 14 we show the results of two fits to a spectrum obtained at $L = 6.0$ (PLS1 and PLS2). In both cases, the uncertainties are quite large for the minor species (O^{2+}, S^{3+}, and S^{+}). Although the differences between the two cases are within the uncertainties for each parameter, it is interesting to note that when the fraction of ions at higher ionization state (i.e., O^{2+} and S^{3+}) are reduced (in the second case, PLS2) the fraction of $A/Z = 16$ ions and the ion temperature T_i increase. The temperatures of the thermal component, T_i are consistent with the earlier estimates that were corrected by Bagenal et al. (1985). However, in both cases the hot component contributes about 20 percent of the total charge density and nearly doubles the average ion temperature. At $L \sim 6$ Sittler and Strobel (1987) report an electron temperature of 5 eV. The issue we must now address is how the torus maintains these temperatures.

Brown's (1974) detection of neutral sodium and the Pioneer detection of UV emission from what was thought to be a hydrogen cloud near Io (Judge and Carlson, 1974) (now known to have probably been emission from heavy ions) led Hill and Michel (1976) to suggest that the ionization of neutral material near Io's orbit could produce centrifugally confined plasma in the inner magnetosphere of Jupiter. Siscoe (1977) derived the pick-up (so-called "tin-can") velocity distribution and suggested the heavy ions should have temperatures on the order of a few hundred eV. Siscoe and Chen (1978) and Siscoe (1978) developed models of a plasmasphere, including heavy ions, produced by a source at Io. Thus, it was initially puzzling when Voyager found ion temperatures of only a few 10s of eV. Goertz (1980) then proposed that the lower ion temperatures might be explained if the ions could be produced in a small region close to Io. To see why this would be so let us consider the pickup process in more detail (figures. 99–101).

The rest frame of the plasma is by definition that where

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} = 0. \qquad (16.1)$$

In the case of the jovian magnetosphere the conductivity of the ionosphere and the plasma conductivity parallel (but not perpendicular) to the magnetic field is sufficiently high to ensure that magnetic field lines are equipotentials and any plasma injected into the magnetosphere will be accelerated up to corotation with the planet (which becomes the rest frame of the plasma). On the ionization of a neutral the new ion and electron have a velocity close to that of the original neutral

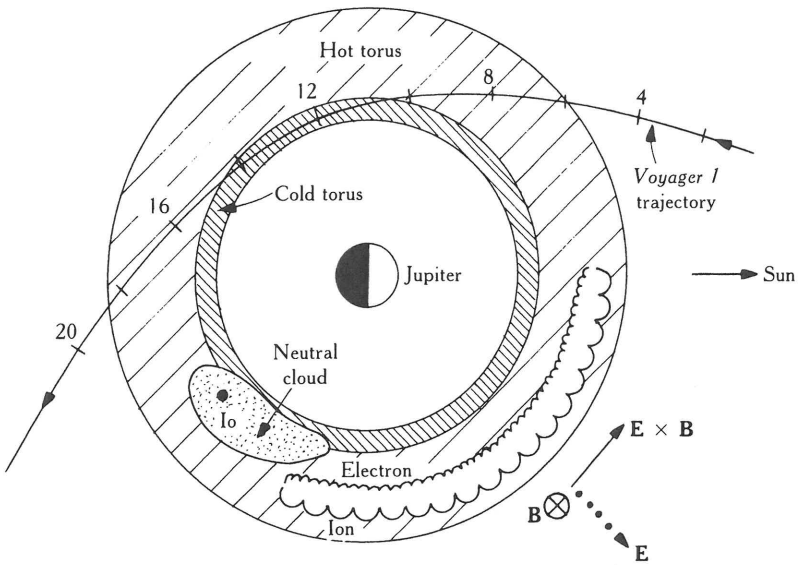

Figure 99. Ion pick-up in the Io plasma—the equatorial plane.

(close to the orbital velocity of Io ~ 57 km^{-1} relative to the corotating rest frame of the plasma). The new ion and electron therefore see an electric field

$$\mathbf{E}_{co} = -\mathbf{V}_{co} \times \mathbf{B}.$$

This electric field causes the ion and electron to drift with a velocity

$$\mathbf{V}_{drift} = \frac{\mathbf{E}_{co} \times \mathbf{B}}{B^2}$$

(in the same sense) around the planet. The newly picked-up ions and electrons also commence to gyrate (in opposite directions) perpendicular to the local magnetic field direction. The difference in their gyroradii ($r \equiv mV_\perp/qB = mV_{co}/qB$) causes a small radial displacement, giving rise to a radial current. This can be thought of as a pick-up current (that connects to the ionosphere by way of field-aligned currents) and the $\mathbf{J} \times \mathbf{B}$ force on the new plasma that enforces corotation (figure 100). However, the initial charge separation produces an electric field in the opposite direction to the corotational electric field. If there is enough ionization in a small enough region, this polarization electric field will cancel a significant fraction of the corotational electric field. The corotating plasma then sees

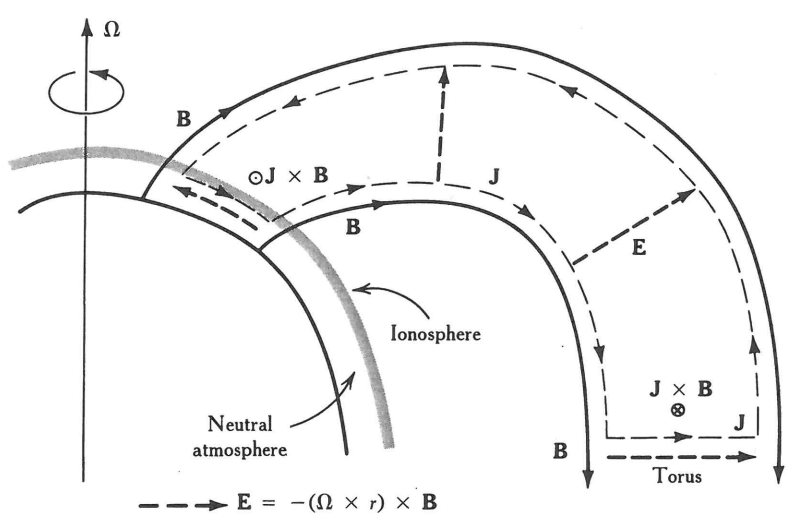

Figure 100. Ion pick-up in the Io plasma—a meridional plane.

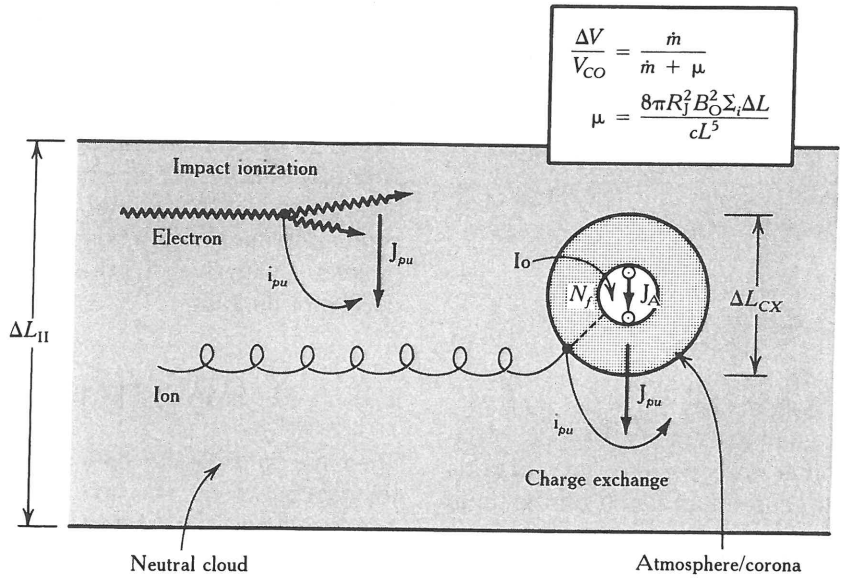

Figure 101. Ion pick-up in the Io plasma. Pick-up currents and mass-loading due to (1) impact ionization (II) in an extended neutral cloud and (2) charge exchange (CX) in Io's atmosphere.

this (polarization) electric field and slows down to satisfy eq. (16.1) in the plasma rest frame. Hence, considerable local ionization screens out the corotational electric field and the gyro energy of the locally picked-up ions is correspondingly reduced. Goertz (1980) proposed that ionization of material in the small region of Io's atmosphere might explain why the torus ions have temperatures considerably less than the full 540 and 270 eV pick-up energies for oxygen and sulfur ions. However, it was then realized that the plasma radiates a considerable fraction of its energy (Broadfoot et al., 1979). Initial calculations of the energy injection rate from ionization of new material at the full pick-up energy could reasonably balance the radiation output (Barbosa et al., 1983; Smith and Strobel, 1985), but Shemansky (1987b) has recently calculated, using more accurate values for the radiated power, diffusive loss time, and atomic data, that an appreciable additional source of energy is required to explain the observed plasma parameters (specifically, T_e, n_e and the S^+/S^{2+} ratio). Shemansky calculates that 0.3 eV cm^{-3} s^{-1} is required, corresponding to a total power of 7×10^{13} W for a torus volume of $2\pi 6 \times 1 \times 1 R_J^3$.

Shemansky points out that increasing the source strength and decreasing the diffusive loss time (to maintain the observed density) actually lead to a lower electron temperature. Although each ionization produces a hot ion, it also produces a cold electron ($T_{e,\,\text{pick-up}} < 0.01$ eV). Furthermore, there is insufficient time for the ion to transfer its energy by way of Coulomb collisions to the electrons. A mechanism is therefore required that adds energy to the system without increasing the total density. Shemansky proposes that this could be done with charge-exchange reactions in a dense atmosphere of Io. The high density is required to increase the probability of a charge-exchange reaction toward unity. Very low electron temperatures are also probably required to reduce the chances of electron impact ionizations. The charge-exchange mechanism would also conveniently produce fast neutrals that could heat up Io's atmosphere. However, there could be a serious problem with Shemanky's suggestion. Let us return to the pick-up process illustrated in figures 99–101.

The pick-up current is given by (Hill et al., 1983)

$$\mathbf{J}_{pu} = q_i S \mathbf{r}_i, \tag{16.2}$$

where S is the ion source strength (ions m^{-3} s^{-1}) and $r_i = m_i E/q_i B^2$ is the local ion gyro radius. Thus,

$$\mathbf{J}_{pu} = \frac{m_i S}{B^2} \mathbf{E}, \tag{16.3}$$

where $\dot{m}$ is the rate of mass production (g m^{-3} s^{-1}). If each ion picks up a gyro speed of $V_{co} - \Delta V$, then the total power gained by the torus (and lost by Jupiter) is

$$P = \frac{1}{2} \dot{m} (V_{co} - \Delta V)^2. \tag{16.4}$$

However, we must balance the net torque generated by the addition of mass against the counter torque supplied by the ionosphere's conductance (Hill, 1979). This leads to an expression for the local deviation from corotation due to mass-loading (Eviatar et al., 1983)

$$\frac{\Delta V}{V_{co}} = \frac{\dot{m}}{\dot{m} + \mu}, \tag{16.5}$$

where

$$\mu = \frac{8\pi\Sigma R_J^2 B_o \Delta L}{c^5 L^5}, \tag{16.6}$$

Σ is the ionospheric conductivity, B_o is the magnetic field in the ionosphere, and ΔL is the radial width of the source region. Note that charge-exchange reactions draw the same pick-up current and load on the ionosphere as impact ionization ($r_e \ll r_i$) (figure 101). Combining eqs. (16.4) and (16.5) we have

$$P = \frac{1}{2}\dot{m}V_{co}^2\left[1 - \frac{\dot{m}}{\dot{m} + \mu}\right]^2. \tag{16.7}$$

This equation says that if μ is small (e.g., Σ and ΔL small), then there is a large deviation from corotation in the source region ($\Delta V \rightarrow V_{co}$) and little power is extracted (i.e., leading to T_i small). Conversely, if μ is large, the deviation from corotation is small and the maximum power is extracted and the ions have the full pick-up energy. For Jupiter at $L \sim 6$

$$\mu = 3.2 \times 10^8(\Delta L)\left[\frac{\Sigma}{1 \text{ mho}}\right] \text{g s}^{-1}. \tag{16.8}$$

The total mass-loading on the torus is estimated to be 10^{30} amu s^{-1}, or 2×10^6 g s^{-1}. Thus, for an extended cloud of $\Delta L \sim 1R_J$ the conductivity has to be less than 5×10^{-4} mho for there to be appreciable deviation of the plasma flow from corotation and the full power of $1/2\, \dot{m}\, V_{co}^2 \sim 3 \times 10^{13}$ W is provided to the pick-up ions. However, if we try to extract the same sort of power from a small region in Io's atmosphere, as suggested by Shemansky (1987b), then for $\Delta L \sim 0.025$ ($1\, R_{Io}$) and $\Sigma = 1$ mho, $\mu = 8 \times 10^6$ and $\Delta V \sim 20$ percent V_{co}. The plasma is slowed down appreciably and the energy extracted is much less than the pick-up energy. Moreover, the effect of the field-aligned (Birkeland) currents that close the current loop between the radial pick-up currents and the ionosphere must be taken into consideration when calculating the deflection of the plasma flow. The effect will be qualitatively the same as Io's Alfven currents (Goertz, 1980; Neubauer, 1980) to deflect the plasma around the source region. Thus a proper self-consistent, three-dimensional plasma calculation is needed to model the interaction of the torus plasma with Io's atmosphere. We must also conclude that it is unlikely that charge-exchange of corotating plasma with Io's atmosphere will provide the necessary energy to heat the torus electrons. One energy source for the torus that has largely been forgotten was proposed by Thorne (1980), who suggested that the energetic particles that stimulate the auroral emission could generate (hot) secondary electrons and (cold) protons. Below we propose an alternative source of energy for the torus.

TORUS-PLASMA SHEET REGION

There are considerable difficulties in analyzing the PLS ion data between $L = 6$ and 11. The most serious problem is that we do not know the velocity distribution of each ionic species. The plasma is not fully collisional and therefore the distribution functions probably deviate appreciably from a Maxwellian. Newly picked-up ions are expected to have a ring distribution in velocity space, whereas the interaction with a population of energetic particles is expected to produce a tail to the distribution that would fall off as a power law at higher energies. With trans-sonic magnetospheric plasma flowing obliquely into the detectors, the instrumental response cannot be simplified and its calculation for even Maxwellian functions is very time-consuming. Moreover, with a hot, multi-species plasma the spectral peaks of the ionic species are not resolved, and hence the ion bulk velocity and composition cannot be determined independently. The strategy has been to look for constraints on the composition. At $L \sim 6$ we used the ratios S^+/S^{2+} and S^{2+}/O^+ determined from UV observations (discussed above). At radial distances $>11.5\, R_J$, there are regions where the plasma is sufficiently cold that the composition and velocity are well determined from resolved peaks in the ion spectra. Thus, between 6 and 11.5 R_J we made an educated first guess at the composition and then investigated the range of parameters (velocity, temperature, and ion densities) that produce a reasonable fit to the data. In each case, a resolution matrix can be calculated and shows the degree to which the parameters are independent and how well the parameters are resolved in the data at a particular location in parameter space (which can be up to 15 dimensions). But it is impossible to tell if there is another equally good solution some distance away. This problem of nonuniqueness is exacerbated by the underlying limitations of not knowing the true distribution function. As if this were not enough, we are plagued with the quirk of nature that gives the two most abun-

dant ions in the torus, O^+ and S^{2+}, the same atomic A/Z ratio of 16. Since the PLS detector differentiates by energy-per-charge, the corotating O^+ and S^{2+} ions produce superposed peaks in the PLS ion spectra. The situation is improved somewhat by making the probably reasonable assumption that most of the heavy ions are thermalized (with T_i the same for all species) comprising what we call the thermal component. The high-energy part of the spectrum is modeled with a sum of two or three Maxwellian functions corresponding to O^+, S^{2+}, and S^+ ions at much higher temperatures. However, the composition of the ions that make up this, the hot component, is not well constrained.

The ionic composition that is derived from our analysis is shown in figure 102. Remember that the composition is well determined inside $L \sim 6$ and outside $L \sim 11.5$. The significant changes in the composition between these two locations are (1) the fraction of the total positive charge density provided by the $A/Z = 16$ species drops from ~0.7 at $L = 6$ to something between 0.3 and 0.55 in the plasma sheet; (2) the charge fraction of each of the higher-ionization states, O^{2+} and S^{3+}, increases from about 10 percent at $L \sim 6$ to ~15 percent or more in the plasma sheet. However, the charge fraction of S^+ remains about 10 percent outside the cold torus (where it is the dominant species). These results are qualitatively consistent with the increased ionization over the time the plasma takes to diffuse away from the source near Io and as the electrons heat up outside $L \sim 7$ (Sittler and Strobel, 1987). Note that both Trauger (1984) and Moos et al. (1985) have reported a reduction in the S^+/S^{2+} ratio between $L = 6$ and $L = 7$, whereas Moos et al. (1985) also reported a slight increase in S^{3+}/S^{2+}.

Despite the difficulties analyzing the data between $L = 6$ and 11.5 we have been able to extract some important plasma properties. The first major result is that the mean ion temperature reaches 1 keV in the transition region between the torus and the plasma sheet. Figure 103 shows that not only does the temperature of the thermal component rise from 50–60 eV at $L \sim 6$ to 400–500 eV at $L \sim 9$–11, but the existence of a substantial hot component (~30 percent of the charge density), which is at least five times hotter, raises the average ion temperature considerably. The "high" temperature of $1.4 \pm 0.6 \times 10^6$ K (120 ± 51 eV) for S^{2+} ions at 6.5 R_J reported by Roessler et al. (1982) is quite consistent with the Voyager values of $\bar{T}$ at 6.5 R_J. The

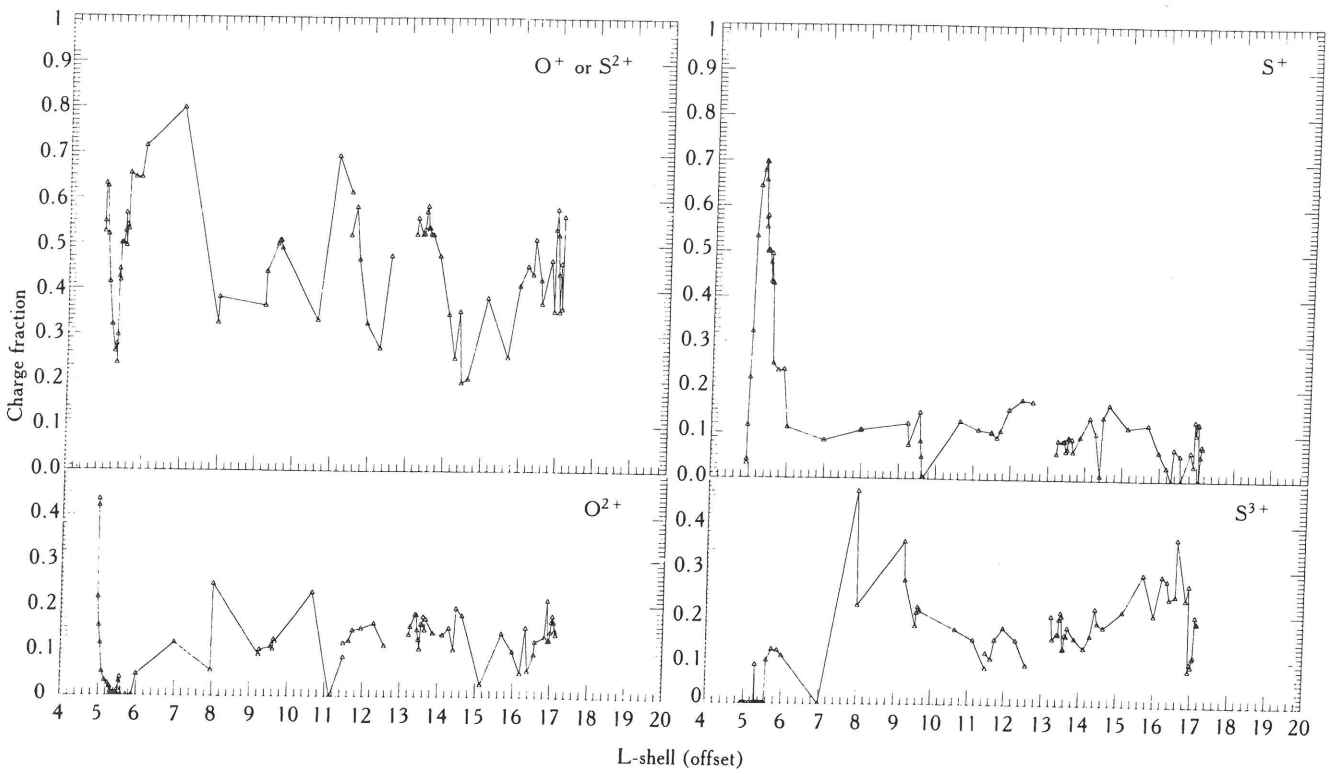

Figure 102. Ion composition from analysis of the PLS ion data on the Voyager 1 inbound pass.

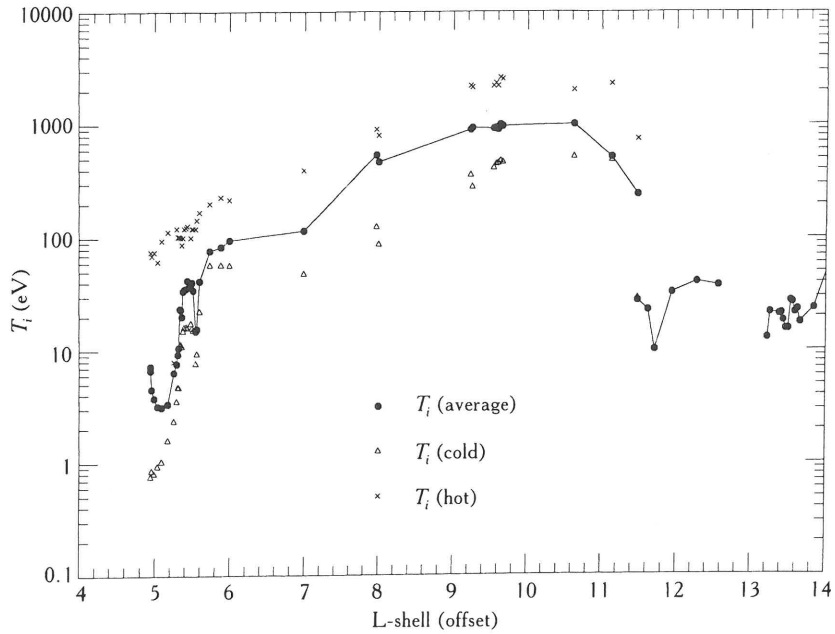

Figure 103. Ion temperatures derived from the PLS data on the Voyager 1 inbound pass.

Voyager PLS detectors were pointed roughly perpendicular to the ambient magnetic field and therefore these ion temperatures are $T_{i\perp}$. The thermal component is probably fairly isotropic but the hot component, a large proportion of which is presumably recently picked-up ions, could have very large thermal anisotropies with $T_{i\parallel} \ll T_{i\perp}$ (e.g., calculations by Barbosa and Moreno, 1987).

In figure 104 the temperatures of the electrons derived by Sittler and Strobel (1987) are plotted for the Voyager 1 inbound pass. The first thing to note is that the average electron temperature remains ~10 times

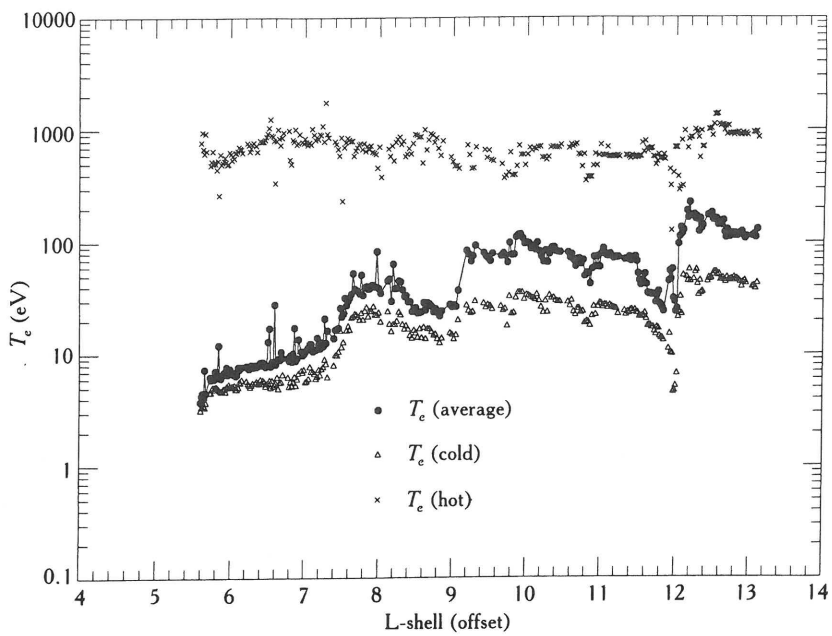

Figure 104. Electron temperatures derived from the PLS data on the Voyager 1 inbound pass. From Sittler and Strobel (1987).

less than the average ion temperature, except outside $L \sim 12$, where $T_e > T_i$. (Note that the hot component has not been included in the fits to the ion data outside 11.5 R_J.) The ratio T_i/T_e remains roughly constant while the density drops by over two orders of magnitude from the dense, almost collisional regime at $L \sim 6$ to $L \sim 11$. Second, there is a sharp rise in both T_e and T_i at the outer boundary of the warm torus between $L \sim 7$ to 8. (Further work is needed to determine if the dip in T_e between $L = 8$ and 9 is matched by a drop in T_i.) Not surprisingly, the electrons are more thermalized than the ions with the hot electrons comprising a small fraction of the total density. It is interesting to note that there is a sharp change in the fraction of hot electrons at about $L \sim 9$, outside (inside) of which n_{hot}/n_e is ~ 10 percent (<1 percent). This is the very location ($L \sim 9$ to 11) where we find we are unable to find a satisfactory fit to the ion data unless we allow the azimuthal component of the bulk velocity to have a substantial (~40 percent) lag behind corotation. The innermost well-resolved spectrum in the plasma sheet shows only a 20–25 percent lag at 11.5 R_J. Thus, there must be considerable mass-loading and/or radial transport between 9 and 11 R_J, but by 11.5 R_J the ionosphere has been able to torque the magnetospheric plasma back up toward corotation.

For investigations of the radial transport of plasma we have calculated the quantity NL^2 (where N is the total number of ions per unit L-shell) using ambipolar diffusion of a multi-species plasma for the latitudinal distribution along the (OTD) magnetic field (Bagenal and Sullivan, 1981; Bagenal, 1985). Our preliminary results suggest the radial profile of NL^2 flattens between $L \sim 8$ and 11. This implies there is either a local source of material or enhanced radial transport, consistent with the substantial deviation from corotation at the same radial distance. Previous analyses of the plasma data (using crude approximations to the instrument response) indicated a sharp drop in NL^2 between $L \sim 7$ and 8. This "ramp" was interpreted by Siscoe et al. (1981) as the outer boundary to the torus where outwardly diffusing torus plasma was impounded by the pressure gradient forces of the inwardly-diffusing energetic particles. Summers and Siscoe (1985) later inferred that a population of <3.8 keV ions would be required to produce the ramp. Our recent analysis certainly reveals that there is a substantial population of keV ions outside $L \sim 8$ but further work is needed to determine if the torus plasma is indeed impounded.

We conclude that between the torus and the plasma sheet there are three main ion populations, which are schematically illustrated in figure 105. First, there is a thermal population ($T_i \sim 50$ eV) that dominates the plasma in the torus. This population diffuses outward (possibly cooling semiadiabatically) to the plasma sheet were the cold ions are centrifugally confined to the equator. Second, there is a hot population that consists of mainly pick-up ions at $L \sim 6$ (with $T_i \sim 300$ eV and $T_{\parallel} \ll T_{\perp}$). Between $L \sim 7$ and 8 the hot population begins to dominate the ion distribution, swamping the thermal population in the PLS spectra (though the actual number density remains <35 percent). Between $L \sim 7$ and 12 possible sources of these hot ions could be (1) charge exchange with fast neutrals from the torus (Barbosa et al., 1984); (2) ionization-charge exchange of neutral material from Europa; and (3) Coulomb (or wave induced) interaction with energetic particles that are diffusing inward. Outside $L \sim 12$ the hot population is not confined to the equator but spread over a large region. For the third population we lumped together all particles with energies above the 6 keV threshold of the PLS instrument. The most energetic particles (>20 MeV/nucleon-gauss, i.e., >3 MeV heavy ions at $L \sim 8$) have to be produced by an acceleration mechanism in the outer magnetosphere (reviewed by Hill et al., 1983; Barbosa et al., 1984). Heavy ions with energies <3 MeV (at $L = 8$) could have been generated by the re-ionization of fast neutrals produced by charge-exchange reactions in the torus. The ions pick up large gyro-motions in the outer magnetosphere and are heated futher (adiabatically) as they diffuse inward. Gehrels and Stone (1983) estimated the >200 MeV/gauss (~1.6 MeV at $L \sim 8$) particles could carry 10^{13} W across $L \sim 10$ (10 times more power than that carried out by the outwardly-diffusing torus particles). Paonessa (1985) has also calculated that the LECP particles between 40 and 500 MeV/gauss (~500 keV at $L \sim 8$) could carry 5×10^{12} W inward. It has generally been assumed that the remainder of the 10^{14} W needed to power the aurora is provided by less energetic particles. The trouble is that we do not have radial profiles of particles with energies between 6 and 200 keV from which to calculate the power they could deliver to the aurora and to calculate any remaining energy that could be available to heat the torus plasma.

Furthermore, even if there is enough energy available, the problem is transferring the energy from the inwardly diffusing energetic particles to the electrons at $L \sim 6$. We argue that the hot population observed by PLS could act as the intermediary. Although the ions are actually diffusing slowly outward, they interact with the inwardly diffusing energetic particles and energy is cascaded through the ion populations to the electrons that in turn stimulate the UV emissions in the torus.

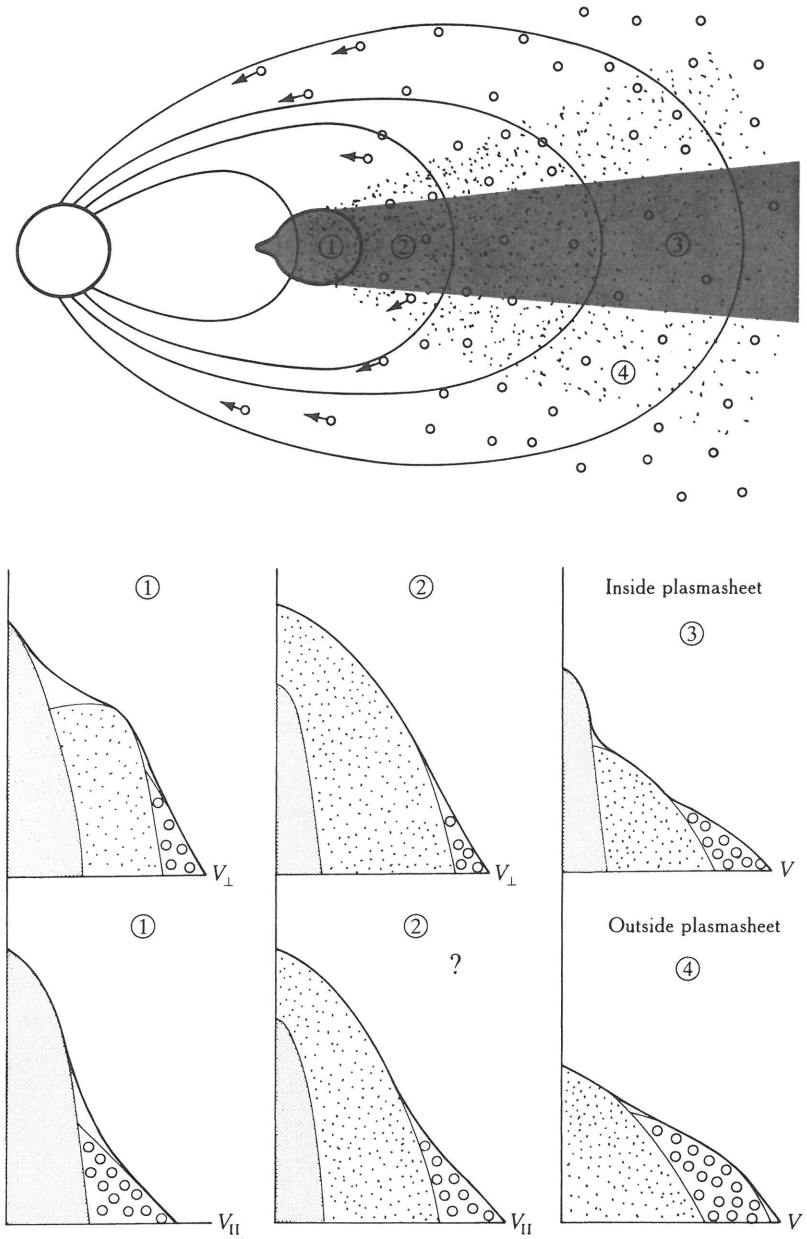

Figure 105. The three ion populations in the torus-plasma sheet region. The numbered regions are (1) the warm torus, (2) L = 8–12, (3) inside the plasma sheet (<12 R_J), and (4) outside the plasma sheet in the middle magnetosphere.

Barbosa and Moreno (1987) show time scales for the energy transfer by Coulomb collisions between keV particles to be of the same order as diffusive time scales (i.e., ~30 days). Thus, energy could be transferred inward at the same rate as the plasma is diffusing outward. If we take the energy density of the hot component at $L \sim 8$ ($nkT \sim (6 \times 10^4)$ eV cm^{-3}), a diffusive velocity of 0.5 km s^{-1}, and an area of $2\pi 8 \times 4R_J^2$, then we find a power of $\sim(5 \times 10^{12})$ W would be transferred into the torus. If the energy rates are faster, then the source could be much larger.

SUMMARY

1. The torus, magnetosphere, and ionosphere are strongly coupled; to understand time-variable phe-

nomena in the jovian magnetosphere, we need to look at the whole system.

2. The cold, inner torus is well described for the Voyager 1 epoch, and Barbosa and Moreno (1987) have provided a reasonably comprehensive model. We now need to apply such a model to details of the Voyager data and to understand the observed longitudinal and temporal variations.

3. Agreement has been reached on the composition of the warm torus at the time of the Voyager 1 encounter. To obtain the observed conditions with a steady-state neutral cloud source an additional energy source of $\sim 10^{13}$ W is needed (Shemansky, 1987b).

4. There may be a problem with Shemansky's mechanism for providing a heat source by charge-exchange reactions in Io's atmosphere because a concentrated source screens out the corotational electric field. We need a full three-dimensional model of plasma-neutral interaction near Io.

5. Plasma parameters determined from PLS data provide evidence of source of plasma at $L \sim 9$. Possible sources are the ionization of neutral material from Europa or recycling of torus material.

6. There are three ion populations: (a) thermal ions ($T_i \sim 50$ eV) from Io plasma torus which diffuse out to plasma sheet; (b) a hot population ($T_i \sim 300$ eV), which could be (i) local pick-up ions from Europa material, (ii) recycled torus fast neutrals, (iii) torus ions heated by interaction with an energetic population; (c) an energetic population that has diffused inward from the outer/middle magnetosphere.

7. We need a detailed theoretical model that includes (a) centrifugally driven radial diffusion; (b) the effect of changes in ionospheric conductivity due to precipitating particles on the rate of radial diffusion (Summers, 1987); (c) an accurate (nondipolar) magnetic field model; (d) at least two dimensions, because of latitudinal separation of ion populations; (e) interactions between the many populations: (i) neutrals from Io, Europa, and charge-exchange reactions (ii) thermal, hot, and energetic ion and electron populations.

ACKNOWLEDGMENTS

The author would like to thank John Richardson, Richard Selesnick, and Ralph McNutt for their collaboration in work for this paper (which was supported under JPL/NASA contract number 957781).

References

Acuña, M. H. Private communication.

Acuña, M. H., K. W. Behannon, and J. E. P. Connerney (1983). Jupiter's magnetic field and magnetosphere. In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.), pp. 1–50. Cambridge Univ. Press, New York.

Bagenal, F. (1985). Plasma conditions inside Io's orbit: Voyager measurements. *Geophys. Res.* 90:311.

Bagenal, F., R. L. McNutt, J. W. Belcher, H. S. Bridge, and J. D. Sullivan (1985). Revised ion temperatures for Voyager plasma measurements in the Io plasma torus. *J. Geophys. Res.* 90:1755.

Bagenal, F., and J. D. Sullivan (1981). Direct plasma measurements in the Io torus and inner magnetosphere of Jupiter. *J. Geophys. Res.* 86:8447.

Barbosa, D. D., F. V. Coroniti, and A. Eviatar (1983). Coulomb thermal properties and stability of the Io plasma torus. *Astrophys. J.* 274:429.

Barbosa, D. D., A. Eviatar, and G. L. Siscoe (1984). On the acceleration of energetic ions in Jupiter's magnetosphere. *J. Geophys. Res.* 89:3789.

Barbosa, D. D., and M. Kivelson (1983). Dawn-dusk electric asymmetry of the Io plasma torus. *Geophys. Res. Lett.* 10:210.

Barbosa, D. D., and M. Moreno (1987). A comprehensive model of ion diffusion and charge exchange in the cold Io torus. *J. Geophys. Res.* submitted.

Brown, R. A. (1974). Optical line emission from Io. In *Exploration of the solar system* (A. Woszczyk and C. I. Iwaniszewska, eds.), pp. 527–531. D. Reidel, Hingham, Mass.

Brown, R. A., C. B. Pilcher, and D. F. Strobel (1983). Spectrophotometric studies of the Io torus. In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.) pp. 197–225. Cambridge Univ. Press, New York.

Brown, R. A., D. E. Shemansky, and R. E. Johnson (1982). A deficiency of O III in the Io plasma torus. *Astrophys. J.* 264:309.

Cheng, A. F., C. G. Maclennan, L. J. Lanzerotti, M. T. Paonessa, and T. P. Armstrong (1983). Energetic ion losses near Io's orbit. *J. Geophys. Res.* 88:3936.

Eviatar, A., R. L. McNutt, J. D. Sullivan, and G. L. Siscoe (1983). Heavy ions in the outer kronian magnetosphere. *J. Geophys. Res.* 88:823.

Gehrels, N., and Stone (1983). Energetic oxygen and sulfur ions in the jovian magnetosphere and their contribution to the auroral excitation. *J. Geophys. Res.* 88:5537.

Goertz, C. K. (1980). Io's interaction with the plasma torus. *J. Geophys. Res.* 85:2949.

Herbert, F., B. R. Sandel, and A. L. Broadfoot (1987). Observations of the jovian UV aurora by Voyager. *J. Geophys. Res.* 92:3141.

Hill, T. W. (1979). Inertial limit on corotation. *J. Geophys. Res.* 84:6554.

Hill, T. W., A. J. Dessler, and C. K. Goertz (1983). In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.), pp. 353–395. Cambridge Univ. Press, New York.

Hill, T. W., and C. F. Michel (1976). Heavy ions from the galilean satellites and the centrifugal distortion of the jovian magnetosphere. *J. Geophys. Res.* 81:4561.

Ip, W.-H., and C. K. Goertz (1983). An interpretation of dawn-

dusk asymmetry of UV emission from the Io plasma torus. *Nature* 302:232.

Jones, D. (1987). Io plasma torus and the source of jovian narrow-band kilometric radiation. *Nature* 327:492.

Judge, D. L., and Carlson (1974). Pioneer 10 observations of the ultraviolet glow in the vicinity of Jupiter. *Science* 183:317.

Linker, J. A., M. Kivelson, M. Moreno, and R. J. Walker (1985). Explanation of the inward displacement of Io's hot plasma torus and consequences for sputtering sources. *Nature* 315:373.

Mauk, B. H., and S. M. Krimigis (1987). Radial force balance within Jupiter's dayside magnetosphere. *J. Geophys. Res.* 92:9931.

McNutt, R. L. (1984). Force balance in the outer planet magnetospheres. In *Physics of space plasmas* (T. Cheng, ed.), pp. 179–210. Scientific Publishers, Cambridge, Mass.

McNutt, R. L., J. W. Belcher, and H. S. Bridge (1981). Positive ion observations in the middle magnetosphere of Jupiter. *J. Geophys. Res.* 86:8319.

McNutt, R. L., P. S. Coppi, R. S. Selesnick, and B. Coppi (1987). Plasma depletions in the jovian magnetosphere: Evidence of transport and solar wind interaction. *J. Geophys. Res.* 92:4377.

Moos, H. W., T. E. Skinner, S. T. Durrance, P. D. Feldman, M. C. Festou, and J.-L. Bertaux (1985). Long-term stability of the Io high-temperature plasma torus. *Astrophys. J.* 294:369.

Moreno, M. A., W. I. Newman, and M. Kivelson (1985). Ion partitioning in the hot Io torus: The influence of S_2 outgassing. *J. Geophys. Res.* 90:12065.

Neubauer, F. (1980). Nonlinear standing Alfven wave current system at Io: Theory. *J. Geophys. Res.* 85:117.

Johnson, R. E., and D. F. Strobel (1982). Charge exchange in the Io torus and exosphere. *J. Geophys. Res.* 87:385.

Paonessa, M. (1985). Voyager observations of ion phase space densities in the jovian magnetosphere. *J. Geophys. Res.* 90:521.

Richardson, J. D., and G. L. Siscoe (1983). The problem of cooling the cold Io torus. *J. Geophys. Res.* 88:2001.

Roessler, F. L., R. J. Oliversen, F. Scherb, J. Lattis, T. B. Williams, D. G. York, E. B. Jenkins, J. L. Lowrance, P. Zucchino, and D. Long (1982). Fabry-Perot/CCD observations of [SIII] and [SII] emissions from the Jupiter plasma torus. *Astrophys. J.* 259:900.

Schardt, A. W., and C. K. Goertz (1983). In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.), pp. 157–191. Cambridge Univ. Press, New York.

Shemansky, D. E. (1987a). Ratio of oxygen to sulfur in the Io plasma torus. *J. Geophys. Res.* 92:6141.

Shemansky, D. E. (1987b). Energy branching in the Io plasma torus: Failure of neutral cloud theory. *J. Geophys. Res.*, submitted.

Siscoe, G. L. (1977). On the equatorial confinement and velocity space distribution of satellite ions in Jupiter's magnetosphere. *J. Geophys. Res.* 82:1641.

Siscoe, G. L. (1978). Jovian magnetosphere. *J. Geophys. Res.* 83:2118.

Siscoe, G. L., and C. K. Chen (1978). Io: A source for Jupiter's inner plasma sphere. *Icarus* 31:1.

Sittler, E. C., and D. F. Strobel (1987). Io plasma torus electrons: Voyager 1. *J. Geophys. Res.* 92:5741.

Smith, R. A., and D. F. Strobel (1985). Energy partitioning in the Io plasma torus. *J. Geophys. Res.* 90:9469.

Strobel, D. F., and S. K. Atreya (1983). Ionosphere. In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.), pp. 51–68. Cambridge Univ. Press, New York.

Summers, D., and G. L. Siscoe (1985). Coupled low-energy ring current plasma diffusion in the jovian magnetosphere. *J. Geophys. Res.* 90:2665.

Summer, D., R. M. Thorne, and Y. Mei (1987). A model of plasma diffusion in the inner jovian magnetosphere incorporating precipitation induced conductivity. *Astrophys. J.*, submitted.

Thorne, R. M. (1980). Jovian auroral secondary electrons and their influence on the Io plasma torus. *J. Geophys. Res. Lett.* 8:509.

Trauger, J. T. (1984). The jovian nebula: A post-Voyager perspective. *Science* 226:337.

Vasyliunas, V. M. (1983). Plasma distribution and flow. In *Physics of the jovian magnetosphere* (A. J. Dessler, ed.), pp. 395–454. Cambridge Univ. Press, New York.