15

Energetics, Luminosity, and Spectroscopy of Io's Torus

Darrell F. Strobel
The Johns Hopkins University, Baltimore

Abstract

This chapter gives a review of the Io torus on the following topics: composition, temperature, luminosity, energetics, interaction of Io's atmosphere corona with the plasma torus, time constants, and variability. Convergence is finally being reached on the steady-state composition and temperature of the plasma torus. The luminosity of the torus during the Voyager encounters was larger (0.4–0.8 eV cm^{-3} s^{-1}) than originally inferred as a consequence of improved atomic physics. The energy crisis may have been finally resolved by including heating of the thermal plasma by inflowing energetic (~1–20 keV) ions from the outer magnetosphere, but more quantitative calculations and direct measurement of these ions are needed. There is significant variability in torus plasma properties with the extreme conditions being represented by the periods of the Pioneer and Voyager encounters when the average electron density may have differed by as much as a factor of 25.

INTRODUCTION

It has been approximately seven years since the review articles of Pilcher and Strobel (1982) and Brown et al. (1983a) were published. In that period of time, considerable progress has been made, although at a pace somewhat slower than would have been predicted then. The Io torus in all of its ramifications has proven to be elusive in the diagnosis of the essential physical processes that control its behavior, evolution, and structure in spite of the measurements by Pioneer and Voyager spacecrafts and continued ground-based and International Ultra-Violet Explorer (IUE) observations.

As scientists, we were ill prepared to deal with the phenomena associated with the Io torus. The Pioneer measurements were interpreted conventionally by preconceived notions that did not alert us to the wealth of scientific phenomena awaiting discovery. An additional clue was reported by Brown (1974) shortly after the Pioneer 10 encounter, namely sodium D-line emission in the vicinity of the innermost galilean satellite, Io. This was followed by the detection of emission from forbidden red lines of SII (Kupo et al., 1976) and the interpretation by Brown (1976) of a plasma in the inner magnetosphere of Jupiter around Io with temperature of $\sim(2.5 \times 10^4)$ K and density of 3200 cm^{-3}. From an historical point of view, it is interesting that these observations and their interpretation had little, if any, impact on planning the Voyager 1 encounter in terms of expected scientific results.

The discovery of active volcanism on Io during the Voyager 1 encounter, which amply illustrated the old saying that "one picture is worth a thousand words," provided the ultimate clue and revolutionized the study of the inner jovian magnetosphere. Progress from the spectroscopist's perspective was still slow because much of the atomic physics needed to interpret the Voyager ultraviolet spectrometer (UVS) and ground-based data was either uncertain or unknown. As an example, the energy levels of SII ion were incorrectly assigned above 14 eV (Brown and Shemansky, 1982), which resulted in the prediction of strong emission from the SII ($3p^3\ ^4S^0$–$3p^23d\ ^4P$) multiplet at 863 A rather than the correct wavelength of 765 A. Accurate theoretical collision strengths (normalized electron impact excitation cross sections) for almost all of the important multiplets in the extreme ultraviolet (EUV) spectra of the Voyager UVS experiment were not available in 1979. Only a dedicated effort by Henry and his colleagues (Ho and Henry, 1983, 1984, 1985; and Tayal and Henry, 1987) has rectified this situation in recent years. However, there are no experimental measurements to verify the accuracy of these calculated collision strengths, although experimental measurements of oscillator strengths for allowed transitions provide some verification in the asymptotic limit of the Born approximation.

Although the international workshop was on *Time-Variable Phenomena in the Jovian System,* it is important before addressing such phenomena to establish what we think we know for sure in a steady-state sense or, more specifically, at the time of the Voyager 1 encounter when we have the most comprehensive data set available. Our confidence in our knowledge of the structure of the Io torus at that time will dictate how bold we can be in characterizing time-dependent phenomena.

COMPOSITION

Perhaps the most accurately known and most agreed upon property of the Io plasma torus is the electron and total ion charge density as a function of radial and latitudinal position. It is based on measurements of the plasma science experiment (PLS) and the planetary radio astronomy (PRA) experiment with concurrence from the UVS experiment and is illustrated in figure 91 along with the trajectory of the Voyager 1 spacecraft. To first order outside of Io's orbit (5.9 R_J) the mixing ratio of individual ion densities to electron densities is a conserved quantity with radial distance out to about 7.5 R_J. During the Voyager 2 encounter, four months later, the UVS spectra suggest that the electron density increased by $\sim$50 percent to an average "spectroscopic" value of 3000 cm^{-3} (Shemansky, 1987).

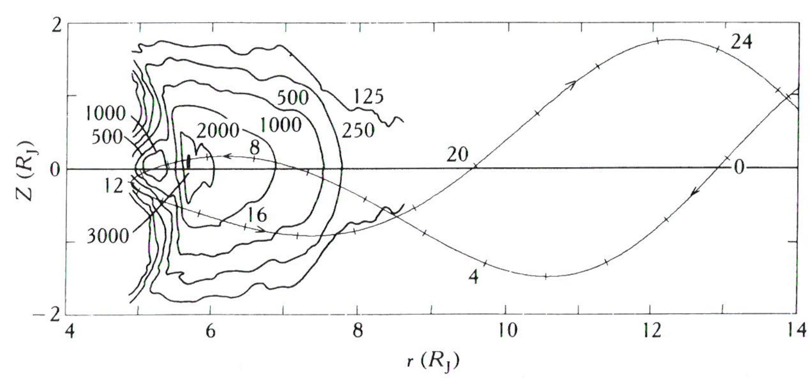

Figure 91. Total ion charge density contours for the Io plasma torus from Bagenal et al. (1985) superimposed on the Voyager 1 trajectory plotted as a function of radial distance from Jupiter's center and vertical distance Z relative to the centrifugal equator. After Sittler and Strobel (1987). Copyright by the American Geophysical Union.

In contrast, the actual ion densities or mixing ratios are probably the least accurately known property of the torus over the last eight years as figure 92 demonstrates. Here the ion densities normalized to an electron density of 2000 cm^{-3} are shown for conditions in the hot, outer torus (5.9–7.5 R_J) at the Voyager 1 encounter as a function of essentially our learning curve. For example, in the 30-day science report Broadfoot et al. (1979) reported only OIII with no mention of OII, whereas after Brown et al. (1983b) placed an upper limit of 5 cm^{-3} on OIII in the post-Voyager epoch this constraint has generally been regarded to be applicable also to the Voyager 1 encounter period. However, the only measured constraint on OIII density is an upper limit of 110 cm^{-3} from IUE observations during the encounter period (Moos and Clarke, 1981). This sad state of affairs (figure 92) resulted from the inability of the UVS experiment to distinguish OII from OIII, which have their principal spectral signatures at 833–835 A and the inability of the PLS experiment to separate OII from SIII because of their equal mass to charge ratios. The initial lack of accurate atomic physics parameters and nondetection of the OII 539 A multiplet (see discussion by Shemansky, 1987) were also contributing factors to the inability to obtain accurate ion composition from in situ and remote observations (figure 92).

The current and hopefully correct values of the ion densities at the time of the Voyager 1 encounter may be

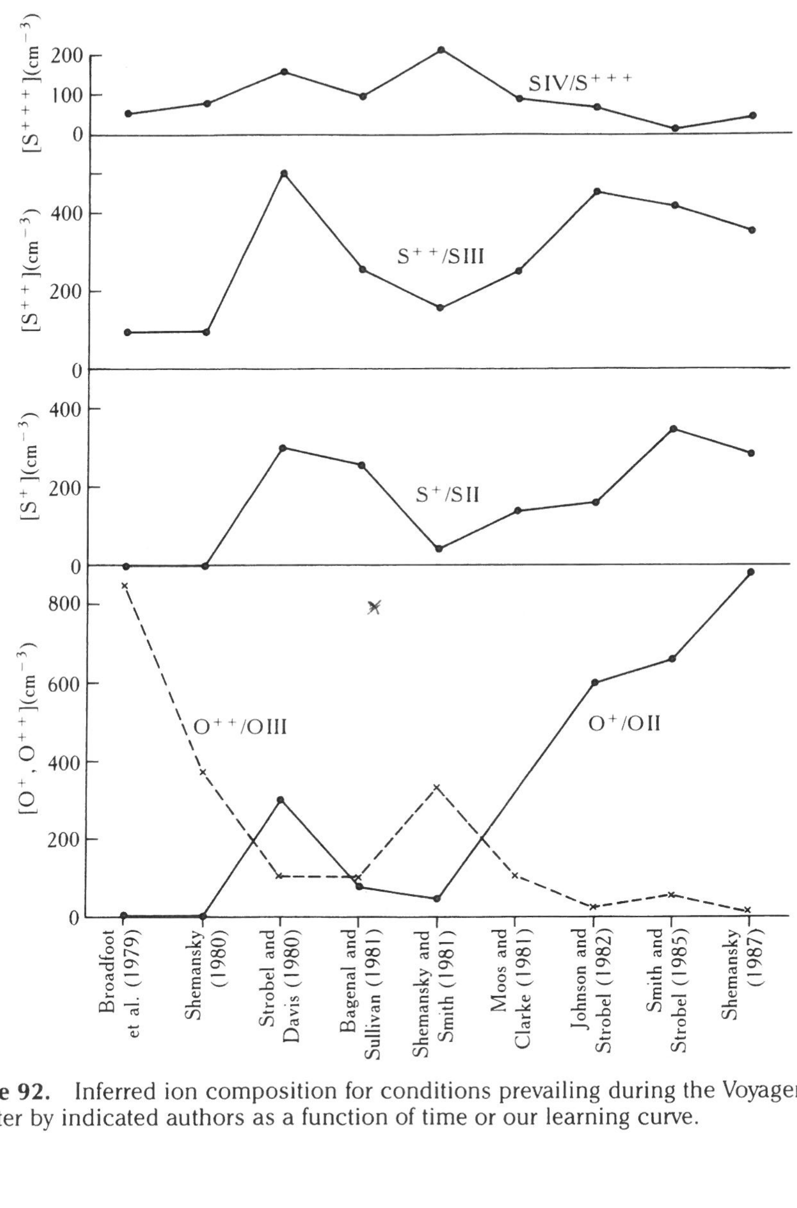

Figure 92. Inferred ion composition for conditions prevailing during the Voyager 1 encounter by indicated authors as a function of time or our learning curve.

obtained from the last two entries in figure 92: calculations of Smith and Strobel (19835) and Shemansky (1987) constrained by UVS spectra. The principal differences are in the partitioning of OII relative to SII and SIII and the calculated electron temperature. Smith and Strobel (1985) did not attempt to do a detailed spectral fit of the data, whereas Shemansky (1987) did. In spite of this difference, there is now fairly good agreement in their results when compared to the earliest analyses in figure 92. It must be remembered that these results are applicable to the hot, outer torus where ion mixing ratios are approximately invariant with radial positions and latitude. With the aid of figure 91, the respective ion density contours can be approximately constructed by exploiting this invariance. In a chapter by Bagenal (this volume) the equivalent PLS results (in table 14) may be compared with figure 92. It can be seen that these two independent techniques for determining ion composition are finally converging to similar mixing ratios.

Beyond the outer boundary of the hot torus (7.5 R_J) there is evidence for a transition to more highly ionized oxygen and sulfur in the UVS spectra at 8 R_J (Shemansky and Strobel, unpublished work). This coincides with the rapid rise of the thermal electron temperature from 5 to 20–30 eV. Unfortunately low plasma densities at these radial distances produce weak radiation and hence poor signal to noise for remote ultraviolet (UV) sensing of this region.

The cold, inner torus (5–5.6 R_J) does not generate a detectable UV signature by virtue of its cold electron temperature. Our primary means of probing this region are the in-situ PLS measurements reviewed by Bagenal and ground-based observations, of which the CCD imaging measurements of Trauger (1984) have provided the most definite results but have received only preliminary analysis. The latter technique allows remote sensing of the forbidden lines of SII and SIII and retrieval of electron densities in the 5.3–5.6 R_J region in the range of 1000 cm^{-3} and ion temperatures which are typically ~2 eV.

In the post-Voyager epoch Trauger (1984) found a thin (0.2 R_J), ribbonlike structure extended along the flux tubes at ~5.8 R_J with ~50 eV SII and SIII ions superimposed with 7–35 eV SII ions, which he called the hot inner torus. Electron densities are typically in the range of 3000–4000 cm^{-3} in this structure with SII and SIII densities in the range of 500–800 cm^{-4}. This high density structure is evident in the Voyager data shown in figure 91, where it is the 3000 cm^{-3} contour at 5.8 R_J just above $z = 0$. System III variations were reported by Trauger.

TEMPERATURE

In the hot outer torus, the primary measurement of electron temperature comes from the PLS experiment (Sittler and Strobel, 1987) and indicates an effective electron temperature of 5–6 eV with the thermal core (cold component) at $T_c \sim 5$ eV and a hot component with $T_H \sim 100\ T_c$ and density $n_H \sim 2$–$3\ cm^{-3}$. The hot component is extremely important in the ionization of ions with large ionization potentials, but does not contribute significantly to the electron excited radiative output of the torus. The calculations of Smith and Strobel (1985) and Shemansky (1987) give average electron temperatures of 4.75 and 5.3 eV, respectively, and in the latter calculation the cold component is 5 eV. Thus, there is good agreement on the temperature of the cold, thermal component, in spite of the difficulty in deducing it from the primary measured quantities in the PLS experiment. These in-situ temperatures were measured and inferred during the Voyager 1 encounter only, as Voyager 2 did not pass through the hot, outer torus. Analysis of Voyager 2 UVS spectra suggests that the average electron temperature was nearly 2 eV colder (Shemansky, 1987).

In the cold, inner torus the electron temperature is too low to be measured directly and must be inferred from the ion temperature. Sittler and Strobel (1987) displayed values of $T_e = T_i$, which is only valid in the absence of significant heat sources in the inner torus, such as charge exchange of cold ions with neutrals and corotation electric field acceleration of new ions to pickup gyroenergies. Their values may only be upper limits as a consequence. In the ribbon structure region at ~5.8 R_J, Sittler and Strobel (1987) suggest $T_e \sim 2$–3 eV, whereas at 5 R_J, $T_e \sim 1$ eV.

LUMINOSITY

The Io plasma torus radiates copious amounts of energy in the EUV, UV, and visible parts of the spectrum through electron impact excitation of the principal ions SII, SIII, and OII with smaller contributions from SIV and OIII, whose concentrations are considerably less. For conditions at the Voyager 1 encounter the total radiative power loss was ~0.4 eV $cm^{-3}\ s^{-1}$ (~[3 × 10^{12}] W), whereas during the Voyager 2 encounter it was approximately twice as large (Shemansky, 1987). The most accurate and detailed radiative cooling rates for individual ions were calculated by Shemansky (1988a) as a function of electron temperature. In the case of SII, it is necessary to include a very large number of lines, many of which were unknown at the time of the Voyager 1 encounter, to get an accurate result. In the hot, outer torus cooling is dominated by OII, SII, and SIII ions. At the cold electron temperatures in the inner torus the forbidden red lines of SII, the dominant ion, are an important mechanism for cooling this region.

ENERGETICS

Given the copious amounts of UV radiation emitted by the Io plasma torus ($\sim[3\text{–}6 \times 10^{12}]$W) a source of at least this magnitude is required to maintain a steady state energy balance. The fuel for this power loss suggested by Broadfoot et al. (1979) and based on theoretical ideas of Siscoe and Chen (1977) is mass loss from Io followed by either electron impact or charge exchange ionization and subsequent acceleration by the $\mathbf{v} \times \mathbf{B}$ corotation electric field to attain a gyroenergy of $\sim$0.25–0.6 keV. The details of the precise mechanism(s) for injection of neutral or ionized material from Io into the torus is still uncertain. Candidates are sputtering by torus ions from the surface if the atmosphere is "thin" (Matson et al., 1974) and from the atmosphere if it is "thick" (Haff et al., 1981; McGrath and Johnson, 1987), thermal escape from the exosphere of a thick atmosphere (Kumar, 1984; Summers et al., 1988), and ionization of neutral species in the corona by electron impact or charge exchange. A number of authors, since the original suggestion by Broadfoot et al. (1979), have advocated that sufficient neutrals escape Io, are ionized, and are energized by the corotation electric field to account for all the required energy to fuel the plasma torus (e.g., Brown, 1981; Barbosa et al., 1983; Smith and Strobel, 1985). This theory, called neutral cloud theory, has been pronounced a failure by Shemansky (1988a) on the basis of his more accurate and much larger radiative cooling rates. A characteristic feature of previous models, in particular the Smith and Strobel (1985) model, is that with their smaller, now incorrect, atomic physics parameters SIII had the largest radiative cooling rate per ion along with a large collisional heating rate of electrons per ion. According to the results of Smith and Strobel the preferred equilibrium state of the torus is one with SIII as the dominant sulfur ion, in which case it is the dominant electron heater and the dominant radiator. With the radiative cooling rates of Shemansky (1988a) SII is the dominant radiator at typical electron temperatures in the torus ($\sim$1–5 eV). It is so efficient that in a neutral cloud theory model the electron temperature is suppressed and never attains a sufficient value to produce significant SII density by electron impact ionization. This violates the inferred density ratio of SII:SIII $\sim$0.7 from ground-based observations (Trauger, 1984; Pilcher and Morgan, 1985) and Voyager UVS data. Local, homogeneous models of the torus that incorporate the most accurate radiative cooling rates cannot produce this ratio if corotation electric field acceleration of ions is the only energy source, because they predict essentially a singly ionized plasma (Shemansky, 1988a).

Shemansky (1988a) suggests a solution to this problem by introducing an ad hoc heat input to the electrons to solve the energy crisis of insufficient electron temperature. He suggests two possibilities: dominance of charge exchange over electron impact ionization in the torus interaction with Io's corona and/or a heterogeneous source of energetic electrons. The model results of Smith and Strobel (1985) in conjunction with Voyager PLS data (Bagenal, this volume) can eliminate the first suggestion. In figure 93 from Smith and Strobel (1985) it is noted that injection of ions at the pickup energy and a power rate of 0.35 eV cm^{-3} s^{-1} drives the ion velocity distribution so non-Maxwellian that the predicted PLS and actual PLS data would bear no resemblance to each other. Given the fact that the Smith and Strobel (1985) work has approximately the "correct" composition and temperatures one can deduce from their results that the maximum amount of power transferred by the pickup mechanism to the ions is in the range 0.15–0.2 eV cm^{-3} s^{-1} (figures 12 and 13 in Smith and Strobel, 1985). Any additional amount of power input to and flowing through the ions would produce ion velocity distribution functions with suprathermal tails inconsistent with PLS data. Thus, additional energy must be supplied to the ions.

Smith et al. (1988) propose a solution to this energy crisis from the same source as the solution to the jovian auroral energy crisis, namely inward diffusing energetic oxygen and sulfur ions (Gehrels and Stone, 1983; Thorne, 1983). These ions were created in the outer magnetosphere by electron impact ionization of fast neutrals produced by charge-exchange reactions in the Io plasma torus and energized by magnetic pumping (Goertz, 1978) and other acceleration mechanisms. The most energetic ions are scattered by wave-particle interactions in the strong diffusion limit down the magnetic field lines and precipitate in Jupiter's auroral zones. There is a threshold energy resonance $E_{res} \sim B^2/8\pi n_e$, where B is the magnetic field strength and n_e

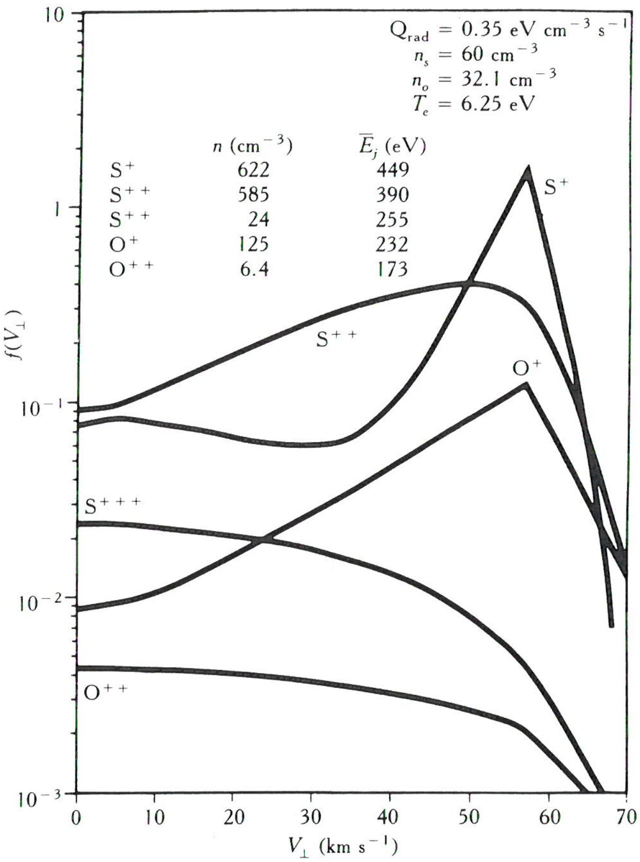

Figure 93. Ion velocity distribution for a case where the radiative power loss is 0.35 eV cm^{-3} s^{-1} with indicated ion composition and average energies. After Smith and Strobel (1985). Copyright by the American Geophysical Union.

is the electron density. At $L \sim 8$, $E_{res} \sim$ 6–20 keV for typical torus parameters. Thus ions with less energy diffuse inward to the hot torus where they collisionally transfer their energy preferentially to the electrons, as shown in figure 94 by the fact that the ion collisional cooling time constant is independent of energy down to ~100 eV. This power (~[1 − 15 × 10^{12}]W) can be transferred in sufficient quantities within the lifetime of these energetic ions against charge exchange. Direct measurements and more quantitative calculations are needed to put this explanation of the energy crisis on a convincing basis.

It thus appears that the failure of previous neutral cloud theories was the myopic view that the Io plasma torus was self-contained and that all ions were energized within the torus by the pickup mechanism (corotation electric field acceleration). The neutral clouds are the source of the mass, but the energization takes place equally within the torus by the pickup mechanism and in the outer magnetosphere by other mechanisms. Clearly the magnetosphere must be viewed as a whole, and processes occurring in remote regions can have pronounced consequences elsewhere in the magnetosphere.

Interaction of Io's Atmosphere-Corona with the Plasma Torus

Sittler and Strobel (1987) observed a symmetrical decrease in the cold, thermal electron temperature by ~0.7 eV in an Io-centered coordinate system with maximum decrease occurring at closest approach and the nominal passage through the predicted Io flux tube. They attributed the observed localized cooling of electrons to thermal conduction along magnetic flux tubes intersecting a dense corona and suggested that plasma interaction with Io's neutral corona should produce an observable UV signature. The existence of a dense corona around Io was also required theoretically by Summers et al. (1988) to account for the high-velocity sodium (Na) jets observed by Trauger (1984). Further support for a neutral corona is provided by the remarkable measurement of the Na density distribution around Io by Schneider et al. (1987) and further discussed in Schneider et al. (1988).

Ballester et al. (1987) on the basis of these interferences performed two 14-hour IUE observations, which resulted in the first detection of emission from neutral oxygen and sulfur UV multiplets at or near Io, $\leq 5\,R_{Io}$ in radius (figure 95). Their observations and two subsequent ones display remarkable symmetry, independent of whether Io is viewed on the upstream or downstream side of torus plasma flow past Io. The observation of the OI 1356 A and SI 1900, 1914 A semiforbidden (^3P–$^5S^0$) multiplets implies electron impact excitation. The fact that the UV emission is symmetrical in spite of the geometry of the impacting torus plasma with Io implies that the excitation electrons have much larger velocities than the relative (to Io) corotation velocity of the impacting plasma. For example, 5 eV electrons have an average velocity of ~10^8 cm s^{-1}, which is a factor of ~20 greater than relative corotation velocity and hence would impact Io almost isotropically.

The absence of the SI 1429 A multiplet, which was detected by Durrance et. al (1983) in the torus away from Io where it was presumably produced by electron impact on sulfur atoms, and the presence of the SI 1479

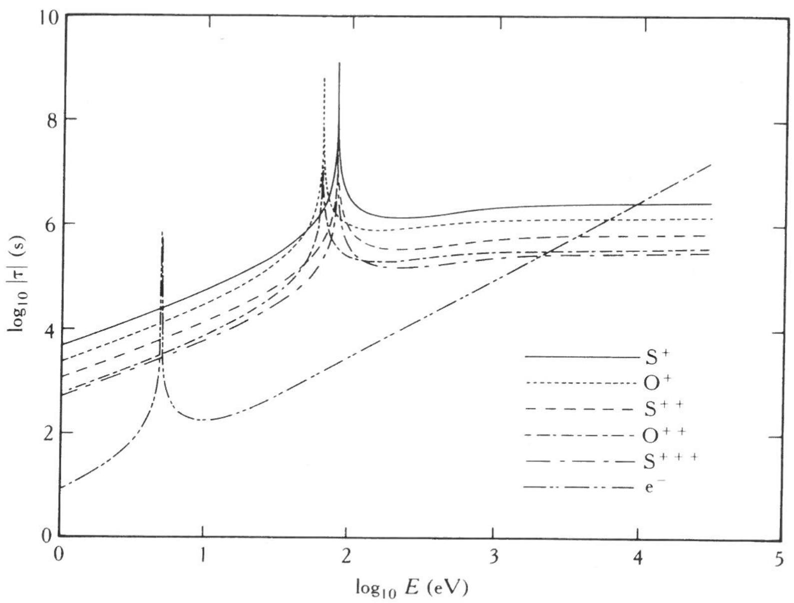

Figure 94. Time constants for test electrons or ions at a given energy to initially approach thermal equilibrium. Assumed composition is [e] = 2000, [SI] = 6, [SII] = 280, [SIII] = 400, [SIV] = 25, [OI] = 30, [OII] = 800, [OIII] = 15 cm^{-3}, T_e = 5, and T_i = 100 eV.

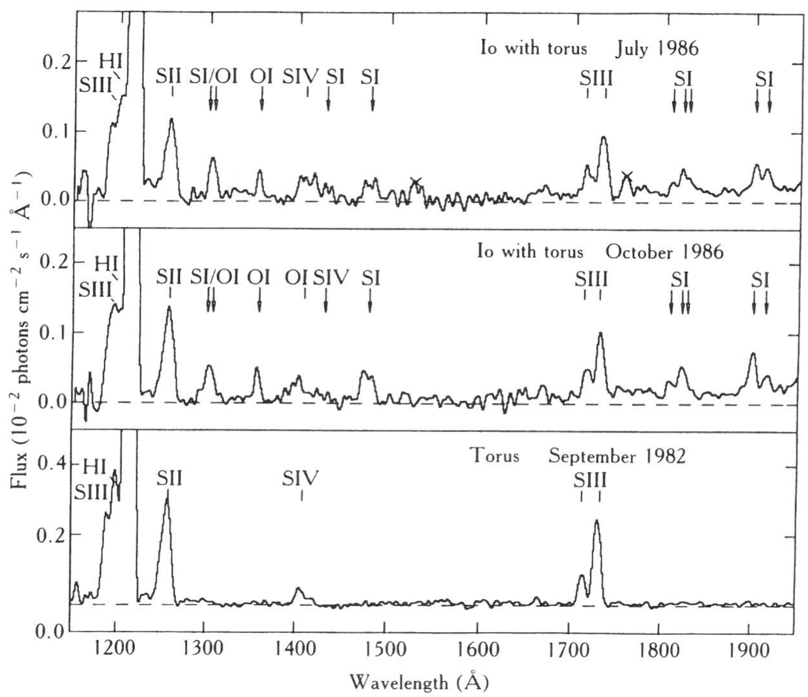

Figure 95. IUE spectra of Io and torus (*top and center*) from the 1986 observations, together with a comparison torus spectra. *Arrows* mark Io emission features, *ticks* mark torus emission features (and the geocoronal HI Lyman alpha), and features marked with an *X* are camera artifacts. After Ballester et al. (1987). Copyright by the American Astronomical Society.

A multiplet (not detected by Durrance et al.) in the IUE spectra clearly implies the observation of a plasma interaction more complex than simple electron impact on oxygen and sulfur atoms in Io's corona. According to theoretical calculations by Ho and Henry (1985) the SI 1479 A multiplet is extremely weak and the SI 1429 A multiplet should be a prominent feature of electron impact spectra unless the electron temperature is extremely cold. In fact, only in laboratory spectra of electron impact on SO_2 gas at 50–200 eV does the 1479 A multiplet appear prominently. But the observed IUE spectra are not consistent with the spectra of electron impact on SO_2 either, because the SI 1429 A and SI 1814 A multiplets are ~60 percent of the intensity of the SI 1479 A multiplet (Ajello, 1987) and thus not compatible with the observed upper limits on SI 1429 A: SI 1479 A and SI 1429 A: SI 1814 A intensity ratios of ~0.4 and 0.3, respectively. It must also be kept in mind that the threshold energy to produce the SI 1479 A multiplet is ~20 eV, as the SO_2 molecule must be split into three atoms. Given the brightness of this feature it seems that the exciting electrons must be hotter than 5 eV, if it is due to electron impact of SO_2.

Recent experimental work by Doering and Gulcicek (1987) suggests that the shape resonance calculated theoretically by Rountree and Henry (1972) and Rountree (1977) is a real feature in the OI 1304 A cross section. It also appears in the OI 1356 A cross section. The consequence of these resonances is to substantially enhance the electron impact rates of OI at very low electron temperatures and reduce the required OI column density by an order of magnitude over the values given in Ballester et al. (1987), if plasma interaction with a neutral corona were the correct description of the observations.

Given the uncertainty in the interpretation of these IUE observations, it is legitimate to ask what we know for sure. The ratio of the lines in the SI 1814 A multiplet are not in the optically thin ratio of 5:3:1. The line corresponding to the transition to the lowest fine structure level ($J = 2$) of the ground state (^3P) is depleted in intensity and indicative of optical thickness effects. Thus the minimum SI column density sampled by UV photons is at least 2×10^{12} cm^{-2}. The intensity ratio of SI 1429 A:SI 1814 A constrains the temperature of the exciting electrons to be no more than 2 eV to the extent that most of the SI 1814 A intensity is produced by electron impact on SI. Approximately 50 percent of its intensity should be due to this source based on the intensity predicted by scaling the SO_2 laboratory cross sections to the observed SI 1479 A intensity to infer the maximum contribution from electron impact on SO_2. Until accurate cross sections are available for $e + SO_2$ over a considerable energy range further progress cannot be made. Based on the observed IUE intensities it is improbable that electron impact ionization in the Io corona is a major source of mass loading of the Io plasma torus (<2 percent of the required amount).

It should also be noted that self-consistent numerical models of the interaction between the plasma torus and Io predict large current flows in the ionosphere of Io (~[1 − 2 × 10^6]A, Wolf-Galdrow et al., 1987). If plasma instabilities result from such large currents it may be possible that local acceleration of plasma to sufficient energy in the atmosphere-ionosphere is partially responsible for the observed IUE spectra and the auroral-like emissions detected by the Voyager camera on Io's nightside (Cook et al., 1981).

TIME CONSTRAINTS

Before the discussion of time-dependent and time-variable phenomena in the Io torus it is a good idea to get some feel, based on known physical processes, for the rates or time constants with which the torus plasma properties can respond to external and internal perturbations. The following composition is assumed for the torus: [e] = 2000, [SI] = 6, [SII] = 280, [SIII] = 400, [SIV] = 25, [OI] = 30, [OII] = 800, [OIII] = 15 cm^{-3}, $T_e = 5$, and $T_i = 100$ eV. Time constants can be appropriately scaled for other total charge and neutral densities. To the extent that plasma rigidly rotates with the planet as a result of the corotation electric field, an observer in an inertial frame of reference would see a $9^h55^m29.7^s$ periodicity. Due to the finite torque that the atmosphere can exert on the plasma, eventually the plasma must cease corotating. The resulting slippage increases its period with increasing radial distance (Hill, 1980). The period of Io around Jupiter is 42.5 hr and thus the plasma sweeps by Io with an effective period of ~13 hr.

Approximately 50 percent of the energy input to the torus is ionization of neutrals and acceleration of the new ions by the corotation electric field to gyroenergies ~270 eV for O+ and 540 eV for S+ (Shemansky, 1988a; Smith et al., 1988). From figure 95 the time constant for collisional energy loss to cool these ions and heat the electrons is 1 × 106 and 2 × 106 s, respectively. Thus, the addition of more hot ions will require approximately a week to affect the electron temperature unless the plasma density is substantially increased. In contrast the newly created electrons acquire only ~10^{-2} eV, but are quickly heated by ambient electrons with a time constant of <100 s. The fresh ions also have a "pancake" pitch angle distribution, which gets isotropized with a time constant of (T_i/T_e) times the collisional energy loss time constant or $\sim 10^7$ s (Smith and Strobel, 1985, Barbosa and Moreno, 1988). Thus, the ions would be expected to be anisotropic for confinement or residence times shorter than 10^7 s.

Lifetimes against electron impact ionization in the hot torus range from $\sim(5 \times 10^4)$ for SI and 5×10^5 for OI to 5×10^7 s for SIV and OIII. These time constants should be compared with those of charge-exchange processes, although the distribution of neutral O and S atoms is not well known in the hot torus. For the five dominant ions in the torus (SII, SIII, SIV, OII, and OIII) typical time constants for charge exchange are in the range of 2–7 $\times 10^6$ s. Charge-exchange processes are dominant for highly ionized species in the hot torus and for all ions in the cold, inner torus where the lower electron temperature renders electron impact ionization uncompetitive.

The energy content of the plasma torus is $\sim(1.5 \times 10^5)$ eV cm^{-3} s^{-1}. With a radiative power loss of $\sim$.04 eV cm^{-3} s^{-1} (Shemansky, 1988a) the radiative time constant is $\sim(4 \times 10^5)$ s. This implies that in the absence of a continuous energy source the electrons would cool down substantially in about five days. Of course the radiative time constant would substantially increase as the electrons cool down and the plasma becomes a less efficient radiator. The radiative time constant is thus one of the shortest time constants governing plasma processes in the torus.

The mechanism(s) for radial diffusion in the plasma torus is severely constrained by Voyager PLS data (Richardson and McNutt, 1987), but the observationally inferred values of the radial diffusion coefficient are in the range of $D_{LL} \sim (1\text{–}4 \times 10^{-6})$ s^{-1}, for which one nominally would derive a radial diffusion time constant of $(\Delta L)^2/D_{LL}$. A more rigorous analysis by Cheng (1986) gives $N/(d/dL((D_{LL}/L^2)dNL^2/dL))$ or 6×10^6 s for the radial diffusion time constant defined from the continuity equation. This is also the time constant for net ion mass loss from the hot outer torus, because the radial outward flow is the dominant loss process for ion mass in this region and is balanced by electron impact ionization of SI and OI plus those charge-exchange reactions that generate a net increase in ion mass. One can also introduce a time constant for energy generation by ionization of neutrals by both electron impact and charge-exchange and subsequent acceleration by the corotation electric field. According to the results of Smith and Strobel (1985) the total charge-exchange rate is twice the magnitude of total electron-impact rate in the hot torus and the ratio of the average ion temperature to initial gyroenergy of fresh ions is $\sim$0.25. Thus the time constant for energy generation is $\sim(4 \times 10^5)$ s, precisely equal to the radiative time constant.

VARIABILITY

Neutral and plasma properties of the torus are inferred to be variable on the basis of observable properties such as spectroscopic intensities and in-situ measurements of plasma composition and temperatures. In general, the shorter-lived species exhibit more variability than longer-lived species, in particular at visible wavelengths in contrast to EUV wavelengths. For example, the forbidden red line emission has been reported to be much more variable than the EUV emission of SIII (Sandel and Broadfoot, 1982a). In addition to time variability, torus properties vary with longitude, latitude, and radial distance (e.g. figure 91). From in-situ measurements (e.g., electron temperature) along the Voyager 1 trajectory, it is extremely difficult to distinguish radial, longitudinal, and latitudinal variations. In the absence of further in-situ measurements it is almost impossible to make significant progress on local variations in Jupiter's rotating frame of reference, as remotely sensed plasma properties involve averaging along the line of sight. The focus in this section, as a consequence, will be on time variations in an inertial frame of reference.

Persistent System III longitudinal variations in SII brightness in the inner and outer torus were reported very early by Pilcher and Morgan (1980), Trafton (1980), and Trauger et al. (1980). However, Brown and Shemansky (1982) found no evidence for variation in the intensity of SII red lines with System III longitude or the intensity ratio of the red lines, which is proportional to electron density, with System III longitude. In addition, the EUV brightnesses from the Voyager UVS were initially reported to show no obvious System III longitude variation (Sandel and Broadfoot, 1982a, Shemansky and Sandel, 1982). Roesler et al. (1984), however, discovered that the brightnesses of the torus in the visible and EUV do have a periodicity with a period $\sim$3 percent longer than the System III period. Sandel and Dessler (1988) have proposed a System IV longitude system whose period is almost precisely 3 percent longer than System III's. This coordinate system successfully organizes the data of Roesler et al. (1984) and Brown and Shemansky (1982) with brightness peaks at 180° longitude. In addition, it is consistent with the narrow-band kilometric radio emission, which also exhibits a period longer than System III by 3 percent (Kaiser and Desch, 1980). The theory of torus-plasma slippage in response to mass loading was developed by Hill (1979, 1980) and is one possible explanation for the existence of the System IV period. An alternate explanation for the System IV period has been advanced by Dessler (1985) who argues that Jupiter's magnetic field possesses a high-latitude component that rotates 3 percent slower than the low-latitude, System III magnetic field.

The situation appears to be more complex than this according to Pilcher and Morgan (1985). They observed brightness peaks in the 180–230° System III longitude region for both SII and SIII visible emissions. These two ions account for approximately 30–50 percent of the total ion density and thus their observations suggest increased mass in the "active sector" longitudes, as designated by the magnetic anomaly model of Dessler and Hill (1975). In addition, they interpret their observations to require a local plasma source in the active sector that apparently drifts to higher magnetic longitudes and produces the observed temporal variations in the distribution of SII emission with longitude. Sandel (1988) notes that the available SIII 9532 A emission data of Pilcher and Morgan (1985) are for times when the System III and IV coordinates are aligned. Thus, for the short duration of their observations, it is impossible to distinguish between them. For Sandel and Dessler (1988), it is important that the Roesler et al. (1984) SIII data that exhibits System IV periodicity not be in conflict with the similar Pilcher and Morgan data. However for the SII visible radiation Pilcher et al. (1985) and Pilcher and Morgan (1985) present a strong case for System III longitude variation. However OII emissions show substantially smaller or negligible longitudinal variations in intensity (Morgan, 1985a). It is clear that further observations are needed to clarify the nature of the observed SII and SIII brightness variability and whether the local (restricted ranges of longitude) plasma source is a characteristic feature of the plasma torus and whether the torus oscillates among a number of quasi-stable states that lead to the complex observed temporal variations.

Sandel and Broadfoot (1982a, b) discovered a local time variation or asymmetry in the EUV luminosity of the torus with peak brightness at 1900 LT and modulated by the position of Io. The luminosity is brighter downstream from Io. Shemansky and Sandel (1982) concluded this asymmetry must be due to a variation in electron temperature rather than plasma composition and mass. Barbosa and Kivelson (1983) and Goertz and Ip (1983) proposed the existence of a dawn-to-dusk electric field to produce the local time asymmetry. Electron temperature changes are also responsible for the Io-related enhancement in EUV emission (Sandel and Broadfoot, 1982b) by $\sim(4 \times 10^{11})$ W or ~20 percent of the total radiative power loss of the torus. This power is a factor of two larger than an estimate by Sittler and Strobel (1987) from the Io-related decrease in electron temperature.

There is some evidence for variations in plasma properties on a longer time scale. The Voyager 1 and 2 encounters were separated by about four months and Shemansky (1987) has inferred from the UVS spectra an increase in the average electron density from 2000 to 3000 cm^{-3} and a decrease in the average electron temperature by 1.7 eV from the Voyager 1 to Voyager 2 encounter. The Trauger (1984) observations in the post-Voyager epoch also support a case for increased electron density by at least 30 percent. Likewise Morgan (1985b) found that his 1981 ground-based observations of SII and OII emissions required an electron density profile in the hot outer torus about 1.5–2 times the Voyager 1 profile to fit the SII and OII line ratios. In addition, Morgan deduced that the SII ion temperatures were approximately a factor of two colder than observed by Bagenal et al. (1985) during the Voyager 1 encounter and that the OII density to electron density ratio was significantly reduced in 1981. Another feature of Morgan's (1985a) data is the occasional observation of extreme line ratios for SII 6716 A: SII 6731 A in the range of 0.02–0.22, which can best be understood in terms of high density clumping of torus plasma ($n_e > 5 \times 10^4$ cm^{-3}), which constitutes approximately 3 percent of the volume (Morgan, 1985a). The time scale for the appearance of high density clumps is short, apparently less than a day according to table III of Morgan (1985a).

The only long-term monitoring of the UV emission of the hot, outer torus has been by IUE, from which spectra in the 1100–1800 A region have been obtained since the Voyager 1 encounter period in early 1979. Typical brightness of SII, SIII, and SIV multiplets in this wavelength region varied by a factor of three over the period 1979 to 1985 (Moos et al., 1985). Part of this variability may be due to observing geometry effects. In fact, Moos et al. (1985) computed the ratio of SII:SIII and SIII:SIV brightnesses and found that these ratios vary substantially less (~30 percent). It is tempting to argue that taking ratios removes the geometry effects and thus the variability of torus emissions over a half of a solar cycle is small. But it must be remembered that the spectral features monitored by IUE do not directly yield either electron density (OII has no spectral signature in this wavelength interval) or electron temperature. From an intercomparison of the Voyager 1 and 2 encounter EUV data Shemansky (1987) deduced an increase in electron density with an accompanying decrease in electron temperature. The brightness of a UV multiplet would increase in response to this density change, but decrease in response to the temperature change. Thus the absence of variability in the ratio of emission brightnesses does not necessarily imply that plasma properties are constant. Moos et al. (1985) constructed a "zero-dimensional" model with a number of assumptions including a negligible variation in electron temperature with time and concluded that the variability of the electron density over the six year period was only 14 percent. However, the actual electron density variation could have been substantially greater if electron temperature variability were included.

The other important evidence for long-term variability in the Io plasma torus is a comparison of UV measurements made by Pioneer 10 (Judge and Carlson, 1974) and Voyager 1 and 2 (Broadfoot et al., 1979, Sandel et al., 1979). A reanalysis of the Pioneer 10 data shows that the torus luminosity was a factor of ~25 weaker than during the Voyager encounters and that the torus was not continuous with longitude in that there were gaps in its luminosity during the Pioneer encounter (Shemansky, 1988b). The substantially reduced torus brightness suggests that the average electron density was reduced to ~500 cm^{-3} at the time of the Pioneer encounter (Shemansky, 1988b). Stated another way, there is no possibility by virtue of intercomparisons with other measurements of interplanetary HI-Lyman alpha and HeI-584 A radiation that the Io plasma torus had the same luminosity during the Pioneer and Voyager encounters. Additional support for lower electron densities during the Pioneer encounter is provided by magnetic field perturbation observations associated with the passage of the spacecrafts through standing Alfven wave patterns. Walker and Kivelson (1981) found the Alfven Mach number to be ~0.03 during the Pioneer 10 encounter, which is 0.2 times the Voyager 1 encounter value. Because the Alfven speed is inversely proportional to the square root of the electron density, this would imply an increase in the electron density by a factor of 25 from the Pioneer to the Voyager epoch. Although this is not in good agreement with the density inferred by Shemansky, it can be brought in much better agreement by noting that the luminosity scales linearly with electron density rather than the square of the electron density when the electron-ion collision frequency significantly exceeds the reciprocal of the ion residence time (see eq. [28] and figure 8 in Smith and Strobel, 1985).

CONCLUDING REMARKS

There is strong evidence for significant variability in plasma composition, temperature, and mass in the Io torus on both the short- and long-time scales. Most of these variations are not understood in a quantitative, let alone predictive manner. Particularly perplexing are apparent multiple periodicities displayed by SII red line intensities. Equally perplexing are the indications of severe inhomogeneities in the torus concentrations and temperature (i. e., the high-density clumps or sheets of plasma). Is this an infrequent occurrence or does this phenomenon play a central role in the structure of the plasma torus? Do the implied severe depletions of plasma mass during the Pioneer encounters relative to the Voyager encounters suggest that volcanism on Io was substantially less active then? Clearly more observations are needed to address these and other questions which are necessary to unravel the mysteries of the variable jovian systems.

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