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MASS-LOADING AND DIFFUSION-LOSS RATES OF THE IO PLASMA TORUS

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ABSTRACT

Limits to the mass-loading and diffusion-loss rates of ions in the Io plasma torus have been calculated on the assumption that observed optical emissions are controlled by electron-ion collisions. Calculations of the yield of emission from the vicinity of Io limit the mass-loading rate to the order of 10^{27} s^{-1} for S II or O II, on the grounds that electron-excited emissions associated with the location of Io have not been observed in the optical spectrum. This mass-loading limit is dependent on the assumptions that Io is the source of torus particles and that most of the neutral atoms are converted to ions within 1 R_J of Io. According to the calculations presented below, the observed partitioning of sulfur ion species in the hot torus at the time of *Voyager 1* encounter indicates that the diffusion-loss time of the ions is of the order of $1/D = 100$ days. The two results limiting the mass-loading and diffusion-loss rates are compatible and suggest that the energy required to maintain the observed radiated power cannot be supplied by acceleration of ions formed at Io in Jupiter's rotating magnetic field.

Subject headings: planets: Jupiter — planets: satellites — plasmas

I. INTRODUCTION

The discovery of the hot plasma torus at the orbit of Io by the *Voyager* spacecraft experiments (see *Science*, 1979 June 1) has unveiled another order of complexity in Jupiter's magnetosphere. The combination of accumulated ground-based and spacecraft observations now indicates that the torus is bimodal and has maintained this condition in quasi-steady state for 2 years or more. The plasma torus structure contains a cool inner region ($T_e \sim 2 \times 10^4$ K) and a hot outer region ($T_e \sim 10^5$ K) with comparable electron densities, at Jupiter-centered radii of 5.3 R_J and 5.9 R_J (Trauger, Münch, and Roesler 1979, 1980; Pilcher 1980; Nash 1979; Smyth 1979; Broadfoot *et al.* 1979; Bagenal *et al.* 1980).

The vast majority of the flow of radiative energy in the torus arises in the hot outer region. The rate of energy loss by the torus is substantial, 3×10^{12} W (Broadfoot *et al.* 1979; Shemansky 1980) in radiation from sulfur and oxygen ions. The torus is thus an important factor in the dynamics of the Jupiter magnetosphere. The subjects of this article, viz., the determination of input of mass to the torus and the diffusive-loss rate, are essential for the identification of the mechanism for the delivery of energy to the plasma. It is generally believed that Io is the source of particles for the torus, and the total amount of energy involved beyond the radiative rate in the form of energetic heavy ions depends on a measure of Io's rate of delivery and the lifetime of the neutrals against ionization in the plasma. One assumption that can be made in obtaining an estimate of mass loading and diffusive loss (Broadfoot *et al.* 1979) is that the energy is derived from acceleration of the newly created ions from Io by the corotating field. The subsequent energy transfer to the plasma electrons occurs through Coulomb collisions. This assumption of heavy-ion relaxation, combined with the calculated radiative cooling rate (Shemansky 1980), sets a lower limit to the injection rate of neutrals and hence to the diffusive-loss rate of the plasma ions. An argument requiring serious modification of this process has developed based partly on the *Voyager* Plasma Science measurements (Bridge *et al.* 1979) and on theoretical ion-relaxation rates (Siscoe 1979, private communication; Eviatar, Siscoe, and Mekler 1979; Siscoe 1977). The argument basically is that measured ion energies in the hot torus are only 30 eV compared to the hundreds of electron volts generated by simple acceleration of newly formed ions by Jupiter's corotating magnetic field. This observation, coupled with the fact that the estimated relaxation time for energetic ions in an electron field is one to two orders of magnitude longer than the maximum diffusion-loss time required by the assumed energy source process, poses a serious difficulty with the original proposal for supplying energy. A solution suggested by Siscoe *et al.* (1979) involves increasing the mass loading at least one order of magnitude beyond the minimum rate required to provide the radiated energy. The suggested magnitudes of the mass-loading and plasma ion diffusion-loss rates are high enough to have two implications for physical processes that can be tested observationally. The first effect is that the immediate vicinity of Io in which ions are produced and injected into the torus should be optically active. Second, the high ion diffusion-loss rates imply that the partitioning of ion species in the torus should deviate significantly from a distribution in collisional ionization equilibrium. According to arguments developed in this article, based mostly on the accumulated optical observations, a high mass-loading rate for the hot torus is very difficult to accept. In fact the results indicate that the mass-loading rate is too low to supply the torus radiative energy through acceleration of newly formed ions by Jupiter's magnetic field. If this is correct, we must then search for another means of delivering energy to the electrons in the plasma. The following text includes discussions of torus structure, variability, composition, and source processes as these factors affect the arguments to varying degrees. The limitation of loading and loss processes is based on derived limits to the source processes near Io and on the partitioning of ion species in the torus. The implications and uncertainties of the results will be discussed.

II. TORUS MORPHOLOGY

The accumulation of observations of the plasma shows strong evidence for a bimodal torus. The ground-based observations, especially the more recent work by Brown (1978), Mekler and Eviatar (1978), Trauger, Münch, and Roesler (1980), and Pilcher and Morgan (1979), indicate a partial torus of S II at ion and electron temperatures of $\sim 2\times 10^4$ K. The mean location of the torus according to these observations is radially inward from Io's orbit. The S II emission shows a variability in intensity and longitudinal distribution. It appears never to form a full torus.

The in situ observations by the *Voyager* Plasma Science experiment (Bridge *et al.* 1979; Bagenal, Sullivan, and Siscoe 1980) agree with the ground-based observations in regard to radial location and temperature of the S II plasma. But, in addition, both the Plasma Science (Scudder, Sittler, and Bridge 1980) and the optical EUV (Broadfoot *et al.* 1979) instruments observed a hot outer torus with estimated electron and ion temperatures of $T_e \approx 10^5$ K and $T_i \approx 4\times 10^5$ K, respectively. The hot outer torus, centered at about the location of Io's orbit, radiates mostly in the EUV, and for this reason the ground-based observations had been blind to it until Trauger, Münch, and Roesler (1979) observed the S III λ9532 line on day 60/1979. On the other hand, the *Voyager* EUV spectrometer shows no easily measurable signal from the cool inner torus because the electron temperature is too low for efficient excitation in the EUV (Broadfoot *et al.* 1979; Shemansky 1980).

There seems to be general agreement that the inner torus is smaller and centered, on average, in the vicinity of 5.2–5.3R_J (Trauger, Münch, and Roesler 1980; Pilcher 1980; Bagenal, Sullivan, and Siscoe 1980; Nash 1979). The outer torus, as observed by the *Voyager* EUV spectrometer and the Plasma Science experiment, is centered at 5.7–5.9R_J (Broadfoot *et al.* 1979; Bagenal, Sullivan, and Siscoe 1980) and forms a full continuous torus with a radius of $\sim 1R_J$ (Broadfoot *et al.* 1979). The combination of the data produces a composite torus cross section in a longitudinal plane according to the rough sketch of Figure 1. Bagenal, Sullivan, and Siscoe (1980) show estimated isophotes of electron density in roughly the same configuration as that shown in Figure 1. According to the Plasma Science measurements (Bagenal, Sullivan, and Siscoe 1980), the boundary between the hot and cold sections of the torus is very narrow with a high temperature gradient.

The EUV spectrum shows short-term intensity variability over a period of hours by a factor of ~ 2 (Broadfoot *et al.* 1979), but it is not clear how much of the variability is really temporal as opposed to spatial. However, the hot torus has much more stability than the cold inner region in so far as it always forms a full continuous torus and appears to be locked to Jupiter's magnetic equatorial plane (Broadfoot *et al.* 1979). A systematic longer-term variation in EUV radiation has been observed, beginning at about day 160/1979, between *Voyager* encounters in which the torus showed

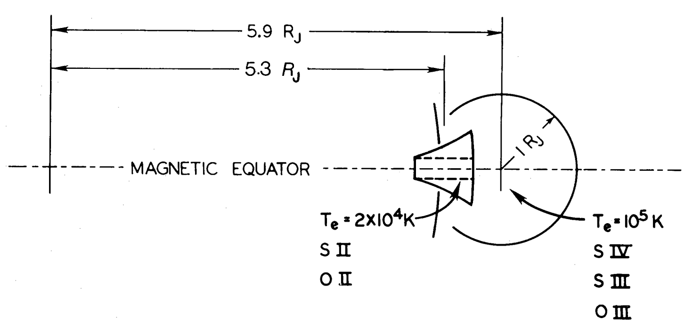

FIG. 1.—Composite sketch of the Io plasma torus cross section in a longitudinal plane, according to ground-based and *Voyager 1* spacecraft observations. The trapezoidal structure of the cool inner torus is approximately 0.4R_J and 1.4R_J along the field lines, and 0.5R_J in radial thickness.

lower electron temperatures and increasing intensities (Sandel *et al.* 1979). The intensity continued to increase up to the time of *Voyager 2* encounter.

In summary, the cold inner region, as observed in S II radiation according to the present interpretation, is a partial torus centered at $\sim 5.3 R_J$ from Jupiter, with extreme variations in dimensions and brightness. The cross sectional shape changes from day to day (Pilcher, 1980), but it typically has a wedge shape (Nash 1979), with inner-edge thickness of $\sim 0.4 R_J$ and outer-edge thickness of $\sim 1.4 R_J$. The ion and electron temperatures both appear to be $\approx 2 \times 10^4$ K. On the other hand, the hot outer region observed in EUV radiation is a full continuous torus centered at 5.9 R_J from Jupiter with a cross sectional diameter of 2 R_J. The electron temperature in the outer torus is $\sim 10^5$ K, and the ion temperature is estimated at 4×10^5 K.

III. COMPOSITION

Knowledge of the major constituents of the plasma is essential to the estimation of collisional ionization equilibrium distribution, energy relaxation times, and diffusive-loss rates. Prior to the time of *Voyager 1* encounter, the only directly observed constituent of the plasma at Io's orbital distance was S II, discovered by Kupo, Mekler, and Eviatar (1976). Other ions assumed to be present, based on observations of neutral emissions, were Na II and K II. Substantial numbers of protons were expected as a result of the *Pioneer 10* measurements of apparent atomic hydrogen emission (Carlson and Judge 1975). The more recent observations suggest that the torus is considerably different from the way it was in 1974 at the time of *Pioneer 10* encounter (Broadfoot *et al.* 1979; Shemansky 1980), and the following analysis is made on the basis that protons are now a neglible constituent. The more recent ground-based and spacecraft observations, as discussed below, indicate that ions of oxygen and sulfur are dominant in the torus.

The *Voyager* instruments measuring the composition of the plasma at Io were the plasma Faraday cup apparatus of the Plasma Science experiment (Bridge *et al.* 1979) and the EUV spectrometer (Broadfoot *et al.* 1979). Table 1 shows the results of the various spacecraft and ground-based observations for the hot and cold torus regions. The results derived for the EUV spectrometer observations are based on the measurements given by Broadfoot *et al.* (1979) at *Voyager 1* encounter. The given populations differ from those of Broadfoot *et al.* (1979) for several reasons: (1) The estimated electron density has been reduced from 2100 cm^{-3} to 1850 cm^{-3} in order to better reflect the average value observed in the hot torus (Bagenal, Sullivan, and Siscoe 1980; Warwick *et al.* 1979). This raises all of the ion densities by the ratio 2100/1850. (2) The large uncertainty in the O III density (Shemansky 1980) has been removed by recent calculations of collision strengths for the 834 Å transitions (Henry 1979, private communication). (3) The relative S IV density has been increased because of recent close-coupling calculations of collision strengths by Bhadra and Henry (1979). The new calculations which relate to allowed transitions in S IV are expected to be accurate to $\sim$20%. However, we note that there appears to be disagreement between observation and theoretical calculations relating to the forbidden ($^2P^\circ$–^4P) transition at 1400 Å (Shemansky and Smith 1980*a*). An additional complication in the analysis of the EUV data has been introduced by what now appears to be strong evidence for a nonequilibrium electron energy distribution in the torus (Scudder, Sittler, and Bridge 1980). The analysis by Scudder *et al.*, based on the *Voyager* Plasma Science experiment data, indicates a distribution in the dense region of the hot torus that can be described approximately by two temperatures. The cooler fraction in this distribution is at a temperature $T_{e_1} \sim 6 \times 10^4$ K, and the remainder can be described by $T_{e_2} \sim 10^6$ K. Although the fraction of the $T_{e_2} \sim 10^6$ K electrons in the denser regions of the torus is uncertain, Scudder *et al.* suggest that it is roughly 0.02%. The maintenance of such a distribution in a quasi-steady state against a high electron-electron relaxation rate (Shemansky 1980) is explained plausibly by assuming that the high-temperature component is not confined to the same range in magnetic latitude as the cool component (Scudder *et al.*). The analysis of the radiation spectrum is affected in two ways by the two-temperature electron distribution. The estimated ionization lifetimes tend to decrease with increasing numbers of hot electrons, producing changes in calculations of ion partitioning. In addition, the single-temperature EUV analysis given in Table 1 becomes an effective temperature, and the analysis of the spectrum assuming various mixing ratios of a $T_{e_2} \sim 10^6$ K-component requires a value for T_{e_1} below 1×10^5 K. The effect of the two-temperature spectral analysis produces relatively minor changes in estimated ion densities derived from the observed spectra, but the effect on the calculated partitioning of ions tends to be substantial and will be discussed in more detail below. The analysis of the *Voyager* EUV spectrum given here differs substantially from the calculations of Strobel and Davis (1980) who derive a lower electron temperature ($T_{e_1} \sim 4 \times 10^4$ K) for the hot torus with a $T_{e_2} = 10^6$ K-component. The Strobel and Davis (1980) analysis appears to depend on the assumption that diffusion-loss time is short. This then requires high S II/S III, S III/S IV, and O II/O III ratios and optically thick S III lines. The accumulated ground-based measurements discussed below and EUV observations (Shemansky and Smith 1980*b*) do not support these requirements. The Trauger, Münch, and Roesler (1979) ground-based observations place a very low upper limit (Table 1) on the S II/S III ratio. Although these observations of the hot torus were made on only two evenings, the fact that the S II/S III upper limit is one to two orders of magnitude below the ratio required to maintain a diffusive loss-time less than 10 days (see below) is a significant result. Pilcher (1980) in photographic observations has reported the detection of S II λ6700 emission in the hot torus on some occasions, indicating an intensity of the order of 100 R, a factor of 10 greater than the upper limit obtained from the Trauger, Münch, and Roesler (1979) measurements. Presumably, the average S II λ6700 intensity in the hot torus lies somewhere between < 10 R and 100 R. The very large variation suggested by these observations is significant insofar as variations of this magnitude are not observed in S III torus emission (Broadfoot *et al.* 1979). An upper limit S II/S III <0.2 based on a recent analysis of the *Voyager 1* EUV spectrum (Shemansky and Smith 1980*b*) indicates that average S II λ6700 emission is less than 100 R per line in the hot torus. Shemansky and Smith (1980*b*) also obtain an estimate O II/O III = 0.14 ± .07 from the *Voyager 1* EUV spectra representative of the average over a period of several months surrounding the time of Jupiter encounter.

The Trauger, Münch, and Roesler (1979, 1980) measurements were selected from among the ground-based measurements for inclusion in Table 1 because their measured S II line intensities are typical of the ground-based data and because they provide a direct measure of the S II (6700 Å)/S III (9532 Å) intensity ratio in the hot torus. The S II (6700 Å/S III (9532 Å) upper limit determined by the ground-based measurements is of considerable importance to the derivation of the ion diffusion-loss rate, and for this reason the S II/S III density ratio upper limit estimated here is discussed in detail. The calculated ratio S II (6700 Å)/S III (9532 Å), taking into account cascade processes in collisional ionization equilibrium, has very little dependence on electron temperature in the range 10^4-10^6 K. The calculated intensity and density ratios given in Tables 9 and 11 of Shemansky (1980) thus apply to any temperature in a reasonable range for the torus plasma. The upper limit of the density ratio S II/S III $\leq 4\times10^{-2}$ then contains essentially no free parameters, since a temperature estimate is not critical and the observations (Trauger, Münch, and Roesler 1979) were made with the same apparatus and viewing geometry at the time of *Voyager 1* encounter. The major uncertainty with this result is whether it can be accepted as an average torus emission over some period of time as 10 days.

Thus, the density ratios adopted here for the sulfur ions in the hot torus are S II:S III:S IV = <4:100:130, based on the *Voyager* EUV spectrometer and ground-based observations (Table 1).

The results for the in situ Plasma Science measurements of the hot torus are uncertain insofar as composition is concerned, because energy-per-charge peaks are not resolved (Sullivan and Bagenal 1979) and the analysis depends on whether one assumes a common

TABLE 1

MEASURED IO TORUS COMPOSITION

a) Voyager 1 Plasma Science Experiment[a] (energy/charge→mass/charge)

		HOT OUTER TORUS		COOL INNER TORUS	
A/Z^*	SPECIES	Density (cm^{-3})	Ion Temp. (10^5 K)	Density (cm^{-3})	Ion Temp. (10^5 K)
8	O III	158	...	26	0.35
	S V	?	...	...	...
$10\frac{2}{3}$	S IV	173	...	...	...
16	S III	556	4.9	...	...
	O II	?	...	345	0.27
23	Na II	?	...	?	...
32	S II	468	...	1120	0.25
64	S_2^+, SO_2^+, Zn^+	...	...	23	0.77
104	?	...	...	...	...
160	?	...	...	...	...
	e	2046	...	1730	...

b) Voyager 1 EUV Spectrometer[b]

	HOT OUTER TORUS	
SPECIES	Density (cm^{-3})	Electron Temp. (10^5 K)
O III	370	...
S IV	130	...
S III	100	...
e	≥ 1850	1

c) Ground-based Observations

	HOT OUTER TORUS		COOL INNER TORUS	
SPECIES	Density (cm^{-3})	Ion Temp. (10^5 K)	Density (cm^{-3})	Ion Temp. (10^5 K)
O II	...	...	530[c]	...
S II	<4[e]	...	630[d]	0.2
S III	110[e]	3	...	...

[a] In situ measurements at 6.0R_J (Bagenal and Sullivan 1980) in the hot torus and 5.3 R_J in the cool torus. Energy per charge peaks are not resolved in the hot torus. A/Z^* = mass per charge. The 6.0R_J data corresponds to a common speed model and the 5.3R_J data corresponds to an isothermal model.

[b] Densities are based on the EUV intensities given by Broadfoot *et al.* (1979). The O III density is obtained using the collision strengths calculated from Gaunt factors given by Henry (1979, private communication). The S IV densities are obtained from the Shemansky and Smith (1980*a*) calculations based on Bhadra and Henry 1980 collision strengths. Cool torus emissions have not been identified in the *Voyager* EUV spectra.

[c] Morgan and Pilcher 1979 (see Pilcher and Morgan 1979) have estimated 20 *R* per line in the O II 3720 Å transitions. The calculated density is based on the average cool torus cross section given in Fig. 1, and a calculated effective path length of 1.7R_J for a full torus. Radiative cooling coefficients are given by Shemansky 1980.

[d] Trauger *et al.* 1980 estimate a total of 100 *R* in the S II λ6700 lines, averaged over a circular field of 1.5R_J diameter. The calculated density is based on the source geometry described in note (c), above. Radiative cooling coefficients are given by Shemansky 1980.

[e] Trauger *et al.* 1979 estimate an average 100 *R* in the S III λ9532 line using the same instrumentation described by Trauger *et al.* 1980. The density is calculated assuming the field was filled by the source. Trauger *et al.* 1979 place an upper limit of 10 *R* per line on the S II 6700 Å transitions in the hot torus.

ion velocity or a common ion temperature. Bagenal, Sullivan, and Siscoe (1980), in a more recent analysis, find substantial numbers of particles with a mass per charge of 32 in the range shown in Table 1. If all of these particles are taken to be S II, one would expect ~1 kR per line in S II λ6700 emission at orbital elongation. This is in strong disagreement with observation, and it is suggested that the in situ measurements may contain substantial numbers of O_2^+ or simply represent a measurement at one point in time.

The presence or absence of protons is important to the determination of relaxation times in the torus as well as to Io geophysics. Unfortunately, we do not have a direct measure of protons because the *Voyager* Plasma Science experiment, once it entered the torus, was limited to a mass-per-charge value of 6 at the low end of the spectrum. The *Voyager* EUV spectrometer did not detect atomic hydrogen emissions in the torus (Broadfoot *et al.* 1979). One would not expect to observe H Lα emission due to recombination, because the rate is very low at $T_e = 10^5$ K. Atomic hydrogen has a lifetime of 26 hr against ionization in the hot torus (Shemansky 1980). A particle at the escape velocity for Io takes 8hr to move a distance of $1R_J$. One may then expect a substantial hydrogen cloud in analogy to sodium if Io were a productive source. But the spectrum shown by Broadfoot *et al.* (1979), with Io in the field of view, does not contain measurable H Lα emission. This places an upper limit of ~6 cm^{-3} for atomic hydrogen in the torus. Thus, the plasma torus appears to be dominated by heavy ions. Heavy ions also dominate the plasma in the magnetosphere beyond Io's orbit, according to the *Voyager* Plasma Science measurements at $20R_J$ (Sullivan and Bagenal 1979).

TABLE 2

PLASMA TORUS SOURCE REACTIONS

No.	Reaction	A.P. (eV)	Ref.
1....	$SO_2+e \rightarrow SO+O$ I$+e$	5.61	1,2
2....	$SO_2+e \rightarrow S$ I$+O_2+e$	5.86	1
3....	$SO_2+e \rightarrow SO_2^+ +2e$	12.3	2,3
4....	$SO_2+e \rightarrow SO^+ +O$ I$+2e$	16.2	3
5....	$SO_2+e \rightarrow S$ II$(^2D_0)+O_2+2e$	17.5	3
6....	$SO_2+e \rightarrow S$ I$(^3P)+O_2^+ +2e$	17.5	3
7....	$SO+e \rightarrow SO^+ +2e$	≤ 11.0	3
8....	$SO+e \rightarrow S$ I$+O$ I$+e$	5.357	3
9....	$O_2+e \rightarrow O$ I$+O$ I$+e$	5.08	4
10....	$O_2+e \rightarrow O_2^+ +e$	12.05	4
11....	S I$+e \rightarrow$ S II$(^4P)+2e$	20.22	
	S II$(^4P) \rightarrow$ S II$+h\nu$(1256 Å)	...	
12....	O I$+e \rightarrow$ O I$(^3P)+e$	9.50	
	O I$(^3P) \rightarrow$ O I$+h\nu$(1304 Å)	...	
13....	O I$+e \rightarrow$ O II$(^4P)+2e$	28.49	
	O II$(^4P) \rightarrow$ O II$+h\nu$(833 Å)	...	

REFERENCES.—(1) Herzberg 1966. (2) Dibeler and Liston 1968. (3) Reese *et al.* 1958. (4) Herzberg 1950.

IV. LIMITS TO THE NEUTRAL PARTICLE SOURCE RATES

The major neutral source particle for the torus originating on Io is SO_2, according to measurements by the *Voyager* IR experiment (Pearl *et al.* 1979) and related calculations (Johnson *et al.* 1979; Kumar 1979). The details of how oxygen and sulfur particles are delivered to the torus are not obvious because of a serious deficiency of appropriate laboratory measurements. However, the important consideration here is that in any of the channels available to the dissociation or dissociative ionization of SO_2, the probability is very high that at least one of the products will be a neutral atom. Table 2 shows the dissociative channels and appearance potentials for electron excitation of SO_2 and its products. There are no quantitative rates for electron or photon interaction with SO_2. The majority ionization channels are SO_2^+ and SO^+ (Reactions 3 and 4, Table 2) in a ratio of 1:0.75 for both electrons and photons above 16 eV (Dibeler and Liston 1968; Reese, Dibeler, and Franklin 1958). Presumably, the neutral dissociative reactions 1 and 2, Table 2, dominate in the torus, accompanied by some SO_2^+ on the injection of SO_2 molecules. Whatever the ratios of the products are, the ultimate majority product is neutral atoms for the electron energies we are dealing with here; simultaneous dissociation-ionization, leaving an atomic ion product, is a relatively inefficient process (see Reese, Dibeler, and Franklin 1958).

Once one accepts the assertion that the final stage in the production of torus plasma is electrons in collision with atoms, one can place limits on the magnitude of the source rate through examination of expected emission rates from excitation and simultaneous ionization-excitation. These processes must occur in the near vicinity of Io, otherwise the neutral species are lost to the torus, in a period of 8 hr at the escape velocity. The lifetimes of neutral sulfur and oxygen against ionization in a 10^5 K plasma are 2.5 hr and 13 hr, respectively (Shemansky 1980). One may then expect a loss of substantial numbers of O I under these conditions, even neglecting any kinetic energy that may be acquired in the dissociation process. This argument has some dependence on the energy distribution of the neutral source particles. If substantial numbers of particles have velocities above the escape velocity but still low enough to reenter the torus at some other location, part of the ion source function will be spatially diffuse.

Whatever the loss rate of neutrals may be, the assumption that energy is supplied by acceleration of newly formed ions in the torus requires the introduction of a minimum of 2×10^{28} s^{-1} of sulfur and of oxygen ions (Broadfoot *et al.* 1979). The process of ionization of each species is accompanied by radiative transitions. We consider the yield of the following reactions (See Table 2):

$$\text{S I}+e\rightarrow\text{S II}(^4P)+2e, \qquad (11)$$

$$\text{S II}(^4P)\rightarrow\text{S II}+h\nu(1256\ \text{Å})$$

$$\text{O I}+e\rightarrow\text{O I}(^3P)+e,$$

$$\text{O I}(^3P)\rightarrow\text{O I}+h\nu(1304\ \text{Å}); \qquad (12)$$

$$\text{O I}+e\rightarrow\text{O II}(^4P)+2e,$$

$$\text{O II}(^4P)\rightarrow\text{O II}+h\nu(833\ \text{Å}). \qquad (13)$$

The yield probability per ion for reactions 11, 12, and 13 is shown in Figure 2 as a function of electron temperature. The yields for reactions 11 and 13 are based on the calculated cross sections of Peach (1968, 1969). The values for reaction 12 are obtained from measured and calculated ionization cross sections for O I (Peach 1986, 1969) and the measured cross section of Stone and Zipf (1973), reduced by the factor 1.7 (Zipf 1979, private communication). The production of 2×10^{28} ions s^{-1} then yields 1×10^{27} photons s^{-1}, 1.7×10^{27} photons s^{-1}, and 8×10^{27} photons s^{-1} in 1256 Å S II, 833 Å O II, and 1304 Å O I radiation (Table 3). The EUV spectrum shown by Broadfoot *et al.* (1979) contained Io in the field of view at a range of 4.8×10^{6} km. The predicted surface brightness equivalent in 1256 Å, 833 Å, and 1304 Å radiation at this range then reduces to 180 R, 270 R, and 1300 R (Table 3). The strong emission line at 833 Å in the Broadfoot *et al.* (1979) spectrum (200 R) is not modulated by the presence of Io in the field of view. Broadfoot *et al.* (1979) place an upper limit of 50 R for emission near 1200 Å, and this also applies to the region near 1300 Å. According to Broadfoot *et al.* (1979), there is no recognizable signal associated with Io in the torus spectrum. The results described here are summarized in Table 3. Thus, according to these calculations, the minimum particle injection rate forced by the assumption described above implies relatively strong radiative processes in the vicinity of Io that have not been observed. The uncertainties and implications of this calculation will be discussed below.

V. THE PARTITION FUNCTION OF SULFUR IONS IN THE TORUS.

The partition function of sulfur ions in the torus, once we believe we have a measure of the distribution, can provide a direct estimate of the diffusion-loss rate. The measure of sulfur ion partition accepted here for the time of *Voyager 1* encounter indicates a very low S II/S III ratio as discussed above. The Trauger, Münch, and Roesler (1979) data indicate S II/S III $\leq 4\times10^{-2}$, and the *Voyager* EUV data (Shemansky and Smith 1980*b*) give S II/S III ≤ 0.2. The EUV result represents

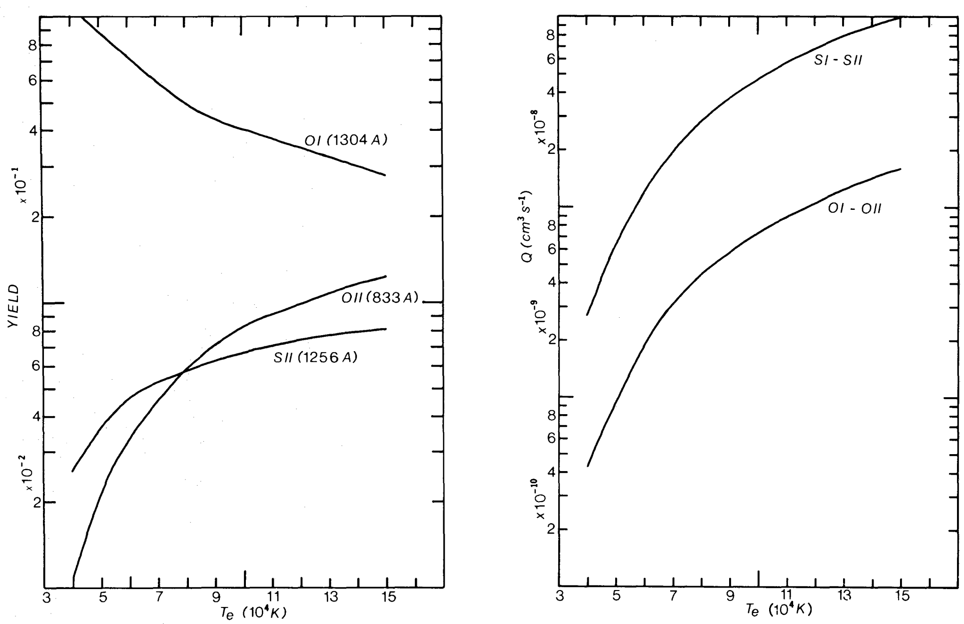

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*) Yield of oxygen and sulfur emissions as a function of electron temperature, for reactions 11, 12, and 13 (Table 2). (*b*) Rate coefficients Q(cm^3 s^{-1}) for the ionization of oxygen and sulfur. The curves are calculated from data given by Peach 1968, 1969 and Stone and Zipf 1972. (See text).

TABLE 3

CALCULATED EMISSION RATES FROM IO SOURCE PROCESSES

Species (1)	Reaction (2)	Photon Rates[a] (photons s^{-1}) (3)	Flux[b] (photons cm^{-2} s^{-1}) (4)	Equivalent[c] Surface Brightness (R) (5)	Observation (R) (6)
S II (1256 Å) ..	11	1.1×10^{27}	370	180	<50
O II (833 Å)...	13	1.7×10^{27}	570	270	<50
O I (1304 Å) ..	12	8×10^{27}	2800	1300	<50

[a] Based on yield curves of Fig. 2, $T=10^5$ K, and an assumed ionization rate of 2×10^{28} s^{-1}.
[b] Flux at a range of 4.8×10^6 km from the source.
[c] Surface brightness (Rayleigh) equivalent to the flux in column (4) for the *Voyager 1* EUV spectrometer.

typical spectra in the months surrounding *Voyager 1* encounter, whereas the Trauger, Münch, and Roesler (1979) measurements were obtained on only two occasions. The ratio S III/S IV = 0.8 (Table 1) is based on the Broadfoot *et al.* (1979) *Voyager 1* EUV intensities, the Shemansky (1980) radiative cooling efficiencies for S III, and the Bhadra and Henry (1980) efficiencies for S IV. The immediate implication of this distribution of sulfur ion species in comparison with collisional ionization equilibrium calculations (Jacobs *et al.* 1979) is that the effective electron temperature is at least 8×10^4 K. It will be shown in the following discussion that the measured sulfur ion species distribution also implies a low diffusion-loss rate, although the argument depends on some assumptions to be discussed below.

Relative ion densities in a thin plasma for adjacent ionization levels of a given species in collisional ionization equilibrium are determined by the relative values of recombination and ionization rate coefficients for those particular species. That is,

$$N(n)/N(n+1)=\alpha(n+1)/Q(n), \qquad (14)$$

where $N(n)$ and $N(n+1)$ are densities of ions having ionization levels of n and $n+1$, $\alpha(n+1)$ is the total effective recombination rate coefficient for species ($n+1$), and $Q(n)$ is the ionization rate coefficient for species n. The rate coefficients for multiple processes are neglible in a thin plasma. In this sense the ion partition function is in collisional detailed balance, as indicated by equation (14). The introduction of the diffusive-loss process produces open channels in the statistical equilibrium distribution, and the ion populations then become a coupled system. The population rate of change of species $N(n)$ with the introduction of diffusive loss must then be written

$$\begin{aligned} d[N(n)]/dt = &-[N_e][N(n)][Q(n)+\alpha(n)] \\ &-[D(n)][N(n)] \\ &+[N_e][N(n-1)]Q(n-1) \\ &+[N_e][N(n+1)]\alpha(n+1), \qquad (15) \end{aligned}$$

where $D(n)$ is the diffusion-loss coefficient and N_e is electron density. If we assume a steady state, the system of coupled equations (15) reduces to

$$N(0)=\rho/([N_e]Q(0)+D(0)), \qquad (16)$$

where ρ is the source function,

$$N(0)/N(1)=Lx(1)L(1)/[N_e]Q(0), \qquad (17)$$

$$\frac{N(n)}{N(n+1)}=\frac{Lx(n+1)L(n+1)}{[N_e]Q(n)}, \qquad (18)$$

$$Lx(n)=1-\frac{[N_E]^2Q(n)\alpha(n+1)}{Lx(n+1)L(n+1)L(n)}, \qquad (19)$$

$$L(n)=D(n)+[N_E](Q(n)+\alpha(n)), \qquad (20)$$

$$Lx(n_{max})=1, \qquad (21)$$

where n_{max} is the top of the chain of ionization levels. The tendency at a given plasma electron temperature, on the introduction of a finite diffusive loss, is to reduce the relative population of each succeeding level of ionization, and the effect is thus to give the appearance of a lower-temperature plasma.

The solutions to equation (18) for S II/S III and S III/S IV, using the rate coefficients applied by Jacobs *et al.* (1979), are shown in Figure 3 as a function of temperature, with the diffusion-loss coefficient as parameter. The range of measured values also is shown in the figure. The effect of introducing a two-temperature electron distribution can be judged by comparing Figures 3*a*, 3*b*, and 3*c*, which show the ion number density ratios for electron mixtures containing 0%, 1%, and 5% $T_{e_2}=10^6$ K electrons. The exact value of T_{e_2} is not critical to the calculation for temperatures above 4×10^5 K. Figure 3 shows the ion density ratios to be rather sensitive to small inclusions of hot electrons. This is due to large differences in ionization rate coefficients for the higher ionization stages at the low and high electron temperatures. The effective recombination rates in the three cases remain essentially unchanged; recombination rates are controlled by the cool electrons. Note that for the range of electron mixtures considered here, the S II/S III ratio for a given diffusive-loss time increases with increasing numbers of 10^6 K electrons, while the S III/S IV ratio decreases under the same conditions. For this reason the estimated ion density ratios adopted here are consistent with a single value for the diffusion-loss time with 0% and 1% hot electrons but not at 5% (Fig. 3*c*). The analysis of the EUV spectrum in each case of Figure 3 produces a different electron temperature T_{e_1}. Thus, the estimated temperature of the *Voyager 1* spectrum is $T_{e_1}=10^5$ K for the case of Figure 3*a* (0%), $T_{e_1}=8.5\times10^4$ K for Figure 3*b* (1%), and $T_{e_1}=6\times10^4$ K for Figure 3*c* (5%). If we assume a temperature of 10^5 K in Figure 3*a*, the upper limit for S II/S III $\leq 4\times10^{-2}$ represents a diffusion-loss time of $1/D\approx600$ days. The lower value for S III/S IV $=0.8$ also corresponds to about the same loss rate, although in this case the value of D is much more sensitive to the exact value of the ratio. The upper value of the range S III/S IV $=1.0$ corresponds to the ratio obtained using finite mixing ratios of 10^6 K electrons in the spectral analysis. As shown in Figure 3, a decrease in the estimated electron temperature (T_{e_1}) results in a longer diffusive-loss time. The upper limit S II/S III $<4\times10^{-2}$ for the case of zero diffusive loss corresponds to a lower limit to the electron temperature of 8×10^4 K in Figure 3*a*, and a similar value is obtained from the upper limit of the measured S III/S IV ratio. The quantity that tends to set a well-defined limit on diffusive-loss time is S II/S III because of the fact that the calculated ratio for a diffusive-loss time of the order of $1/D=100$ days limits at a ratio S II/S III $=0.1$ for temperatures above $T_e=10^5$ K. The reason for this is that a 100 day diffusion loss time becomes comparable to the minimum total recombination time (120 days) for S III at $T_e=10^5$ K, and the S II/S III ratio then tends to be controlled by the ratio of the ionization rate coefficients, as the recombination channel S III→S II declines with increasing temperature. The ionization rate coefficient ratios themselves tend toward a constant value with increasing temperature.

If we make the conservative assumption S II/S III $<$ 0.2 as indicated by the *Voyager* EUV data, then the three-electron mixtures of Figure 3 indicate diffusion-loss times of >30 days (0%), >100 days (1%), and indeterminately long (5%). The measured ratio S III/S IV $=0.8\rightarrow1.0$ correspondingly gives ~100 days (0%), 40 days (1%), and <10 days (5%). The measured data as presented here thus do not provide a consistent diffusion-loss time for a 5%, 6×10^4 K/10^6 K electron mixture, but are compatible with ≤1% inclusions of $T_{e_2}=10^6$ K electrons. The combined ground-based and *Voyager* EUV data thus point toward a ion diffusion-loss rate of the order of $1/D=100$ days. The most sensitive quantity to the diffusive-loss rate is the S II/S III ratio at the temperatures that prevail in the hot torus.

It is important to note that diffusion-loss times of 100 days or shorter tend to result in a temperature independent S II/S III ratio above $T_e=10^5$ K (Fig. 3). The determination of the diffusion-loss rate from this ratio, therefore, does not depend on the exact value of the electron temperature. The steady state equation (18) eventually breaks down at higher temperatures if the diffusion-loss rate is dominant over the recombination rate, because at some point the lifetime for S II against ionization becomes shorter than the 13 hr period of the passage of a given torus volume past Io. This point occurs at about $T_e=2\times10^5$ K for S II in the torus. Plasma temperatures this high should then produce Io modulated intensity variations along the hot torus. Variations of this kind have not been reported.

VI. DISCUSSION AND CONCLUSIONS

Although there are uncertainties in the calculations of the mass-loading and diffusive-loss limits presented here for the hot torus, the results as a whole point toward low mass-loading rates and long diffusive-loss times.

a) *Mass Loading Limit*

The above calculations of expected emissions from the source region around Io contain a number of assumptions concerning the details of the interactions. However, none of these assumptions appears to make a qualitative difference to the conclusions. The purpose of the calculation was to determine whether or not the loss of energy from the hot torus could be supplied by acceleration of newly formed ions by the corotating magnetic field. The fundamental assumption in the calculation was that the majority process leading to the production of atomic ions was electron impact on free atoms. This assumption seems to be safe insofar as we are dealing with a low-density plasma below $T_e=10^6$ K, where multiple dissociation-ionization processes are very inefficient. Thus, whatever the source molecule is, it is probable that most of the ionizations that take place are due to electron impact on O I and S I. The most likely source molecule, as pointed out above, is SO_2. Trace amounts of SO_2^+ have in fact been observed in the torus by the *Voyager* Plasma Science experiment (Sullivan and Bagenal 1979). We then expect reactions 1–4 of Table 2 to be the dominant primary reactions. The rate coefficients and kinetic energy excesses are not known for any of these primary processes. The relative numbers of neutral molecules that actually escape the torus is not known therefore, and we cannot predict an accurate sulfur/oxygen ratio for the torus plasma. Whatever the efficiencies of reactions 1–4 may be, we do require the injection of at

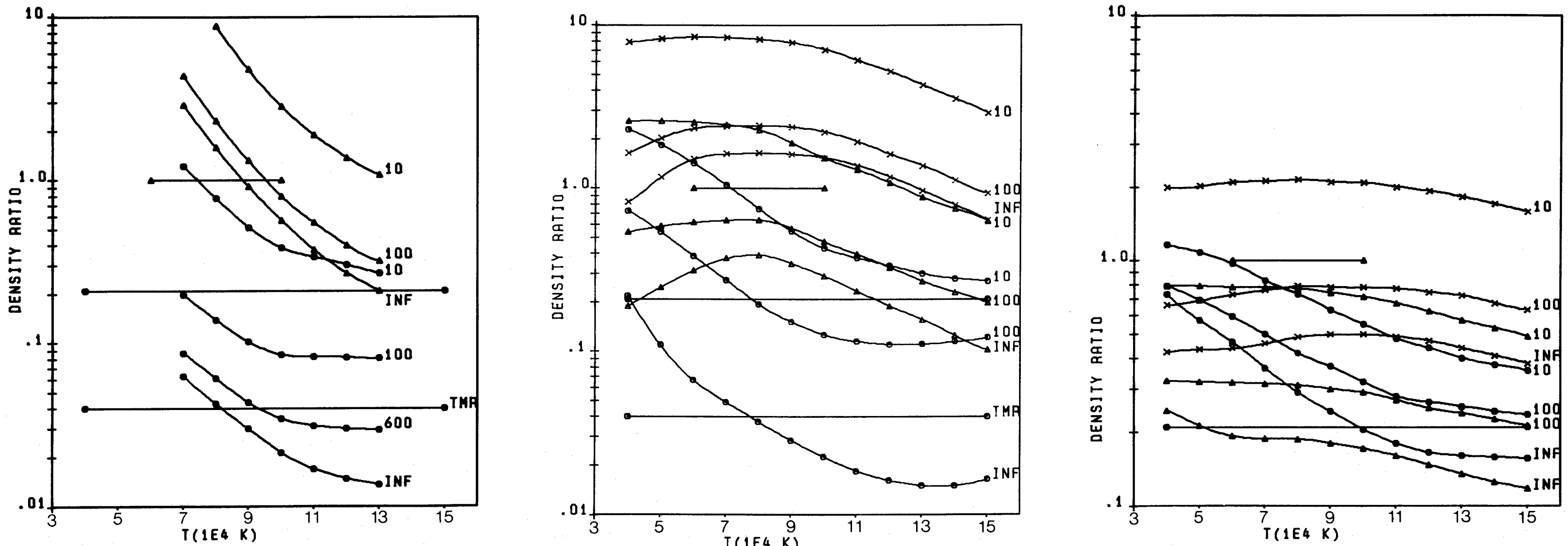

FIG 3*a* FIG 3*b* FIG 3*c*

FIG. 3.—The partitioning of sulfur ions as a function of temperature and diffusion-loss time. The curves show the calculated ratios S II/S III ⊙⊙⊙, S III/S IV △△△, and S IV/S V XXX, calculated for diffusion-loss times of $1/D = \infty$, 600 d, 100 d, and 10 d. The horizontal line TMR is the upper limit S II/S III ratio obtained from the Trauger *et al.* 1979 ground-based observations of S II 6700 Å and S III 9532 Å lines. The remaining horizontal lines are the S II/S III upper limit and S III/S IV measured ratio obtained from the *Voyager 1* EUV spectrum (Shemansky and Smith, 1980*b*). The lengths of the horizontal lines indicate the temperature range over which the ratios calculated from the data are valid. The electron density for each case is $N_e = 1850$ cm^{-3}. (*a*) Calculated ion number density ratios for a Maxwellian electron gas. (*b*) Calculated ion number density ratios for a two-temperature electron gas composed of a component $T_{e_2} = 10^6$ K constituting 1% of the total density. (*c*) Calculated ion number density ratios as in (*b*), but with a 5% inclusion of $T_{e_2} = 10^6$ K electrons.

least 2×10^{28} ions s^{-1} into the hot torus if ion-electron partitioning is to be the primary source of energy. If O I and S I enter the hot torus, we expect strong EUV emissions on O I, O II, and S II in the near vicinity of Io (see Table 3). This statement is dependent to some degree on the kinetic energy of the neutral atoms. It is certainly true if the majority of atoms enter the plasma below the Io escape energy. It is also true if the majority of atoms enter the hot torus from Io with energies beyond the Jupiter escape energy. If, however, the majority of atoms enter the system in bound Jupiter orbits above the Io escape energy, then one may expect a more spatially diffuse injection of neutrals as source particles for ion production. In this special circumstance, the detection of simultaneous ionization excitation becomes more difficult. The emission-rate calculation assumes an effective $T_e = 10^5$ K plasma temperature, implying that the neutral atoms enter the hot torus plasma directly from Io. The accuracy of this assumption depends on the nature of Io's atmosphere and the mass-loading rate. If the interface with the hot torus plasma involves a layer of cooler plasma in the vicinity of Io, $T_e = 4 \times 10^4$ K, say, then the yield of O II and S II emission would decline drastically according to the data in Figure 2. However, the lifetime of O I against ionization increases more than one order of magnitude between $T_e = 10^5$ K and 4×10^4 K (Fig. 2), requiring a much more dense interface to achieve the requisite ionization rate within the cool region. But under these same circumstances, the yield of O I (1304 Å) emission increases (Fig. 2), and one would expect even greater (1304 Å) emission as a signature of the source process. Thus, one expects substantial radiative emission from the source process near Io, whether or not the interface involves the presence of a dense low-temperature plasma. Measurable Io associated EUV emission has not been observed (Broadfoot *et al.* 1979), placing the upper limit to the mass-loading rate at the order of 10^{27} ions s^{-1}.

b) *Ion Partitioning and Diffusive Loss*

The other evidence presented above leading directly to a low diffusive-loss rate, and hence to a low mass-loading rate, is the optical determination of the partitioning of sulfur ions in the hot torus. The estimated ratios S II:S III:S IV, accepted here, lead to the conclusion that the diffusion-loss time is of the order of $1/D = 100$ days. Assuming that the relative ion densities accepted here are correct, the uncertainties in the estimated diffusion-loss times lie in the confidence we have in the calculated ionization rate coefficients, recombining coefficients, and the assumption of a steady state in the calculation. The most uncertain quantity among the rate coefficients is the dielectronic recombination rate which dominates recombination at the temperatures of interest here. The Jacobs *et al.* (1979) calculation of these quantities is detailed, although it does not include the contribution to the total by forbidden transitions. The confidence in calculations carried out to this level appears to be ~30% (Raymond 1978). The electron temperature of the plasma is an important quantity since ionization and recombination rate coefficients have a strong temperature dependence. Scudder, Sittler, and Bridge (1980) appear to have established that the electron energy distribution in the torus is not in thermal equilibrium and must be described approximately by two temperatures. This can be compatible with the ion partitioning estimates given here, provided that the hot $\sim 10^6$ K electrons constitute 1% or less of the electron population in the dense regions of the hot torus. The determination of electron temperature from the EUV observations depends on estimated relative line intensities of S III, and S IV obtained from synthesis of the observed spectrum (Shemansky and Smith 1980*b*). There may be some uncertainty in the estimated electron temperature because of uncertain relative collision strengths, but predicted S III line intensities in the near-infrared based on the EUV analysis are in good agreement with observations (Shemansky 1980; Shemansky and Smith 1980*b*), indicating that the effective electron temperature is accurate. A further constraint on the optically determined temperatures arises in the requirement for charge neutrality. The observed intensities are approximately proportional to $[N_e]^2$, and the measured $[N_e]$ then places an upper limit on effective electron temperature. It has been pointed out above that the introduction of a hot electron component forces a lower majority electron temperature (T_{e_1}) in the analysis of the observed spectrum, and the estimated temperature $T_{e_1} = 8.0 \times 10^4$ K is obtained for an inclusion of 1% $T_{e_2} = 10^6$ K electrons. This derived temperature appears to be compatible with the Scudder, Sittler, and Bridge (1980) analysis. However, the optically measured ion partitioning in the dense region of the torus cannot support relative numbers of hot electrons greater than 1%.

The estimated ion density ratios obtained from the various observations contain some uncertainty, but one must nevertheless come to the conclusion that the diffusion-loss time is long. If, for the sake of argument, we assume that diffusion-loss time is short, then the conclusion on the basis of the discussion in the previous section must be that the neutrals enter the torus in a spatially diffuse distribution. The source function of ions must then be homogeneous in the torus, a valid condition for the implied assumptions in the partitioning calculation. If the diffusion-loss time were very short, say less than 5 days, then the majority ions in the torus would be S II and O II because of lack of residence time for the production of substantial quantities of the higher species. However, we do observe O III, S III, and S IV in substantial quantities in the dense regions of the hot torus. The existence of these ions requires residence times of at least 10 days. We are then in a domain in which the steady state calculations of ion partitioning are valid, since periodicities in the torus system that may modulate the source function are much shorter than 10 days.

c) *Predicted Ion Distribution*

According to the arguments presented here, the relative ion densities in the hot torus do not differ drastically from predicted collisional ionization equilibrium calculations neglecting diffusion loss. The predicted ion densities based on the *Voyager 1* EUV measurements (Broadfoot *et al.* 1979), the Jacobs *et al.* (1978, 1979) calculations of recombination rate coefficients, and recent collision strengths for O III and S IV (Henry 1979, private communication; Bhadra and Henry 1980; Shemansky and Smith 1980*a*) are given in Table 4 for an electron temperature of 10^5 K and diffusion-loss time of 600 days, corresponding to a one-temperature electron distribution. Table 4 also shows the predicted distribution for a 1% inclusion of $T_{e_2}=10^6$ K electrons in a majority gas of $T_{e_1}=8\times10^4$ K electrons, with a diffusion-loss time of $1/D=40$ days. The real distribution probably lies somewhere between the two cases. The total number density of oxygen and sulfur ions in Table 4 accounts for an average electron density of 1850 cm^{-3}. The recent analysis of the *Voyager 1* EUV spectrum (Shemansky and Smith 1980*b*) shows the presence of a line feature at 785 Å that can be interpreted as a combination of S V and O IV lines, arising from number densities of the order of those given in Table 4.

d) *The Energy Budget*

If we accept the calculations presented here, the supply of energy required to maintain the loss in observed radiation cannot be obtained from newly formed ions accelerated by Jupiter's magnetic field. The estimated mass-loading rates are qualitatively too low to account for 3×10^{12} of radiative energy. Some other mechanisms for delivery of energy to the torus electrons therefore must dominate. The interaction of the torus with the Jupiter magnetosphere is certainly not well understood. The torus shows a complex bimodal structure with a very high temperature gradient that appears to be difficult to model as a steady state condition (Siscoe *et al.* 1979), and the relationship of the structure to the energy source is not obvious. Neubauer (1979) has suggested that energy may be delivered by reflected Alfven wave interactions with Jupiter's ionosphere, but the amount of energy involved is not certain.

TABLE 4

PREDICTED ION DENSITIES (cm^{-3}) IN THE HOT PLASMA TORUS

	O II	O III	O IV	O V	S II	S III	S IV	S V	N_e
1[a]	40	370	85	...	4	100	160	20	1850
2[b]	175	234	94	13	30	100	100	25	1850

[a] $T_e=10^5$ K, $1/D=600^{\rm d}$.

[b] $T_{e_1}=8\times10^4$ K; $T_{e_2}=10^6$ K (1%), $1/D=50^{d}$.

NOTE.—The densities are calculated for ionization equilibrium with the indicated diffusion-loss times and electron energy distributions.

VII. SUMMARY

Calculations of the limits to mass-loading and diffusion-loss rates of the hot Io plasma torus, based mostly on the combined recent ground-based and spacecraft observations of discrete radiation, strongly suggest that ions accelerated by Jupiter's magnetic field are not the primary source for the energy lost by radiation. This conclusion depends on two considerations relating to the spectral characteristics of the hot torus.

(1) Strong emission lines in O I, O II, and S II transitions, expected to arise in the near vicinity of Io on the assumption that accelerated ions supply the required energy, have not been detected. The estimated upper limit to mass loading is of the order of 10^{27} ions s^{-1}.

(2) The observed partitioning of sulfur ion densities is indicative of a low diffusion-loss rate. The observed S II/S III number density ratio in the hot torus is small, whereas the S III/S IV ratio is ~1. The quantity most sensitive to the diffusion-loss time is the S II/S III ratio. The observations of radiative emission from the hot torus both in the EUV and near infrared regions of the spectrum indicate S II/S III <0.2. Steady state calculations of ion partitioning in the torus then require an average diffusive-loss time longer than 30 days. The introduction of a nonequilibrium distribution in electron energy tends to increase this lower limit, and the estimated diffusion-loss time is of the order of 100 days. This result implies that the partitioning of ions is partially controlled by recombination. The calculations leading to this result depend to some degree on a reasonably homogeneous mix of ions in the dense region of the hot torus. The long diffusive-loss time tends to establish this condition.

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