THE ASTROPHYSICAL JOURNAL, 236: 1043–1054, 1980 March 15

RADIATIVE COOLING EFFICIENCIES AND PREDICTED SPECTRA OF SPECIES OF THE IO PLASMA TORUS

D. E. SHEMANSKY
Space Sciences Institute, University of Southern California
Received 1979 July 20; accepted 1979 October 1

ABSTRACT

Calculations of the physical condition of the Io plasma torus have been made based on the recent *Voyager* EUV observations. The calculations represent an assumed thin plasma collisional ionization equilibrium among the states within each species. The observations of the torus are all consistent with this condition. The major energy loss mechanism is radiative cooling in discrete transitions. Calculations of radiative cooling efficiencies of the identified species leads to an estimated energy loss rate of at least 2.5×10^{12} watts. The mean electron temperature and density of the plasma are estimated to be $T = 10^5$ K and $n_e \geq 2100$ cm^{-3}. The estimated number densities of S III, S IV, and O III are roughly 95, 80, and 190–740 cm^{-3}. Upper limits have been placed on a number of other species based on the first published *Voyager* EUV spectrum of the torus. The assumption that energy is supplied to the torus through injection of neutral particles from IO leads to the conclusion that ion loss rates are controlled by diffusion, and relative species abundances consequently are not controlled by collisional ionization equilibrium. However, the ionization equilibrium calculations do apply to the states within a given species.

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

I. INTRODUCTION

The presence of a plasma at or near the orbit of the Jupiter satellite Io was discovered by Kupo, Mekler, and Eviatar (1976) through observations of the S II forbidden lines at 6713 and 6731 Å. Subsequent observations have indicated that S II forms an unstable incomplete torus (Brown 1978; Mekler and Eviatar 1978). The recent *Voyager* observations of bright, short-wavelength transitions have now revealed a complete torus occupied by S III, S IV, O III, and possibly other species (Broadfoot *et al.* 1979). The temperature of the plasma is therefore higher than expectation based on the earlier observations, and the estimated power required to maintain the system must be increased by at least an order of magnitude. The torus is apparently capable of generating strong emission at transition energies of 25 eV or higher. The energy budget of the plasma is obviously an important quantity to determine if one is to gain an understanding of the physical processes that maintain the torus. The plasma is tenuous, and the dominant energy loss mechanism is atomic line radiation. For this reason it is of interest to have reasonably accurate knowledge of the radiative efficiencies and emission characteristics of the relevant species. The region of the spectrum containing bright torus emission is an unfamiliar one since astronomical sources with measurable emission below 911 Å are generally not observed. Atomic data in this region of the spectrum are by no means well established, and it has now become necessary to examine the uncertainties and conflicts in available information in some detail.

In this article, we discuss the quantities applied to the observed *Voyager* EUV emissions that allowed the estimation of plasma temperature and abundances of S III, S IV, and O III ions given in the Broadfoot *et al.* (1979) report. In addition, predicted emission rates of a number of transitions are provided, based on the *Voyager* measurements. The uncertainties in the relevant data and gaps in information are pointed out below. A number of the collision strengths given for allowed transitions have been calculated by the author using transition probabilities obtained by the Coulomb approximation method of Bates and Damgaard (1949). Radiative cooling curves for some of the species based on available data have been calculated, and a brief general discussion of the implied physical condition of the plasma is given in the following text.

II. EXCITATION MECHANISMS

The calculations leading to identification of species, estimation of number densities, and temperature reported by Broadfoot *et al.* (1979) are based entirely on the assumption of electron excitation of existing ground state ions. Processes of simultaneous ionization-excitation, radiative recombination, and dielectronic recombination were neglected because the rate coefficients are too low to contribute under the derived plasma condition. Solar resonance scattering is also entirely negligible as a contribution to the EUV ion emitters. The brightest solar resonance transition in the torus is expected to be the O III 834 Å line with a calculated intensity of 2 rayleighs (R), about 1% of the observed emission rate.

The energy distribution of the exciting electrons in the model calculations is further assumed to be Maxwellian. This assumption appears to be a reasonable one since the measured plasma density indicates a short electron relaxation time. Analysis of the *Voyager* EUV data places a lower limit on electron density of $N_e = 2100\ \mathrm{cm}^{-3}$ averaged over the 1 R_J half-width of the torus cross section (Broadfoot *et al.* 1979). This value for N_e is in fact roughly equal to the directly measured densities by the *in situ* radio emission experiment of Warwick *et al.* (1979). A temperature of 10^5 K then leads to a relaxation time of ~ 30 s by electron-electron elastic collisions, assuming a collision cross section of $10^{-13}\ \mathrm{cm}^2$. Bridge *et al.* (1979), on the other hand, have presented some evidence from *in situ* plasma measurements indicating a two-temperature electron distribution with characteristic energies of ~ 5 eV and 100 eV. It is not clear whether this can be regarded as a localized effect or a general effect. The process for maintaining such a distribution is also not obvious. In any case, it turns out that this particular two-temperature distribution cannot be recognized in the optical spectra as being different from a 10^5 K Maxwellian electron distribution. In this sense, the calculations presented here, within limits, can be taken as representative of mean electron energy if a unique electron temperature cannot be applied. Within a given species, the calculations of emission efficiency therefore represent a plasma in collisional ionization equilibrium (see Osterbrock 1963). However, the expectation that this assumption is valid for emission efficiencies within a species cannot be carried over into the calculation of relative species abundances such as those presented by Jordan (1968), Cox and Daltabuit (1971), and Shapiro and Moore (1976). The reason for this limitation of the application of ionization equilibrium is the high ion diffusive loss rate (Broadfoot *et al.* 1979) relative to predicted recombination rates implied by the energy budget of the torus.

In any thin plasma in collisional ionization equilibrium, the major energy loss process is through radiative transitions excited from the ion ground state by electron collisions (Osterbrock 1974). For this reason, the total radiative efficiency of the ion species represents a direct measure of energy loss efficiency by the plasma. Radiative transfer effects can be neglected in the calculation since even the most short-lived transition at 681 Å in S III has an optical depth less than 0.1. Thus the calculations of collisional ionization equilibrium for a given species presented below are expected to be an accurate representation of the excitation and energy loss processes in the plasma. As we have mentioned above, the equilibrium calculations cannot be carried one step further to determine relative species abundances because of the high diffussive loss rate.

III. COMPUTATIONAL DETAILS

The volume emission rate (I) of a transition is given by the equation

$$I = [N_i][N_e]\rho \text{ ergs cm}^{-3}\text{ s}^{-1}, \tag{1}$$

where N_i, N_e are ion and electron number densities and ρ is the radiative cooling coefficient. Excitation processes included in the calculation of ρ are direct electron excitation, radiative cascade, and nonradiative cascade. Deactivation processes include both radiative and nonradiative transitions. In principle, under these circumstances ρ has a dependence on N_e, but in most cases discussed here there is little or no N_e dependence. Note that ρ in these calculations relates to efficiency within a particular species, S III say, and does not refer to a normalized distribution of ions in the plasma.

The production rate of level $(j{:}J_j)$ per fine-structure source ion $[X(i{:}J_i)]$ is given by the equation (see Osterbrock 1963)

$$P(i, j{:}J_i, J_j) = [N_e]\,\frac{8.629(10^{-6})}{T_e^{1/2}}\left(\frac{\Omega(i, j{:}J_i, J_j)}{g_{J_i}}\right)\exp\left(-\frac{\Delta E}{kT_e}\right)\text{s}^{-1}, \tag{2}$$

where T_e is electron temperature, Ω is the electron collision strength, g_{J_i} is the lower level degeneracy, J is the total angular momentum quantum number, and ΔE is the energy of the transition. As the presence of the parameter T_e implies, equation (2) contains the assumption of a Maxwellian electron distribution. The collision strength, Ω, is taken as a constant in the calculation, although it generally has a slow dependence on energy for ion transitions averaged over the electron distribution. In most cases, the value of Ω is equated to the threshold value, but in others in which resonance structure is encountered, an averaged value is applied (see Seaton 1968; Osterbrock 1974).

The collision loss rate per excited ion (L) is similarly given by

$$L(i, j{:}J_i, J_j) = [N_e]\,\frac{8.629(10^{-6})}{T_e^{1/2}}\left(\frac{\Omega(i, j{:}J_i, J_j)}{g_{J_j}}\right)\text{s}^{-1}. \tag{3}$$

Since equations of detailed balance do not apply in the present calculation, the relative populations among multiplet levels of the ground state terms are subject to excitation-deactivation processes in the excited states. In many cases, the relative populations of the ground terms closely approximate the degeneracy ratios of the levels. Some species in which metastable levels differing in multiplicity from the ground state are excited at a high relative rate may deviate from the general rule. In some cases, such as S IV, it is necessary to assume that the relative ground-state fine-structure populations are populated in the ground-state degeneracy ratio because of unknown contributions from the quartet terms to the ground-state doublet. The effect of alteration of fine structure populations in the ground state is one of redistribution of line intensities within a given multiplet. These factors must be taken into account in those cases involving metastable levels which are to be used in obtaining direct measures of N_e.

The radiative cooling efficiencies for the species discussed below are thus calculated using the equations of statistical equilibrium, incorporating electron excitation (eq. [2]), electron deactivation (eq. [3]), and spontaneous emission.

IV. ATOMIC DATA

Atomic constants relevant to the calculation of line radiation are given in the accompanying tables. In most cases, experimental lifetime data have been used in preference to theoretical calculations. Virtually all of the collision strengths given are theoretical calculations based either on direct numerical integrations of wave functions employing various approximations (see Seaton 1968) or on measured and calculated radiative transition probabilities using an assumed Gaunt factor for allowed transitions. A number of the given transition probabilities for allowed transitions have been calculated by the author using the Coulomb approximation method of Bates and Damgaard (1949). This method generally provides an accuracy better than 40% for transitions not strongly affected by configuration interaction. However, large errors arise in the use of the Coulomb approximation in those cases in which configuration interaction of terms is large. The collision strengths for those cases in which the Coulomb approximation is expected to be accurate have been calculated using an assumed Gaunt factor of 0.2 (see Osterbrock 1963). There are some cases of importance to the analysis of the Io plasma torus data in which the Coulomb approximation clearly does not work. The collision strengths for those transitions heavily affected by configuration interaction are uncertain by roughly an order of magnitude. The data containing uncertainty of this order are pointed out in the tables, and applied values of the Gaunt factor other than 0.2 are indicated.

The tables of atomic data given here follow an integer identification scheme for the term designations in order to reduce the complexity of the tables. The terms are identified in order of increasing term energy as given in the A tables. Energy levels for the calculations were taken from Moore's (1971) tables. In order to conserve space, the fine-structure collision strengths indicated in equations (2) and (3) are not given. Instead the total multiplet strengths for the designated transitions, $\Omega(i, j)$, are provided along with the total transition probabilities, $A(i, j)$. The relationships between fine structure strengths and total multiplet collision strengths are given by

$$\Omega(i, j{:}J_j) = \sum_{J_i} \Omega(i, j{:}J_i, J_j) \tag{4}$$

and

$$\Omega(i, j) = \frac{(2S + 1)(2L + 1)}{2J + 1} \Omega(i, j{:}J_j), \tag{5}$$

where S, L, and J have their usual meaning. The relationships between the fine structure strengths in evaluating equation (4) for given L, S coupled transitions may be found in Allen (1963). Listings of fine-structure atomic constants may also be obtained by direct communication with the author. In some cases, more than one wavelength is associated with a single term transition in the B tables because of multiple branching of the transitions.

a) S II

Table 1A lists the terms that play a dominant role in a collisionally excited plasma. Table 1B gives the wavelength collision strengths and transition probabilities of the dominant transitions. The (2,1) transitions 6730 Å and 6716 Å have been observed in the Io plasma torus as noted above. Term 2 is populated by cascade from term 3 and, at the temperatures prevailing in the major part of the torus, may be populated in addition by transitions from terms 5

TABLE 1

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: S II

A.

Term Identification Number	Designation
1....................	$3s^2 3p^3\ {}^4S^o$
2....................	$3s^2 3p^3\ {}^2D^o$
3....................	$3s^2 3p^3\ {}^2P^o$
4....................	$3s 3p^4\ {}^4P$
5....................	$3s 3p^4\ {}^2P$
6....................	$3s^2 3p^2 4s\ {}^4P$
24..................	$3s^2 3p^2 5s\ {}^4P$

NOTE.—I.P. = 23.4 eV.

B.

λ (Å)	Transition (j, i)	Ω(i, j)	Ref.	$A(j, i)$ (s^{-1})	Ref.
6730.8[a] / 6716.2[a]....	2,1	5.7	2	4.3E−4 / 4.7E−4	4
3.2E6[a]......	2,2	5.6	2	3.5E−7	4
4076.4[a] / 4068.6[a]....	3,1	2.7	2	0.134 / 0.341	4
10355[a] / 10300[a]....	3,2	12.	2	0.28 / 0.39	4
2.06E6[a].....	3,3	1.3	2	9.1E−7	4
1256........	4,1	5.1	2	4.5E7	6
910.........	6,1	0.96	2	2.2E8	1
664.........	24,1	0.1	2	5.9E7	1

[a] Air wavelengths.

(1102 Å), 8 (1014 Å), 10 (996 Å), 12 (968 Å), 13 (958 Å), and 14 (938 Å). However, the collision strengths for electron exchange excitation of these EUV transitions are not known, and the emissions have not been identified in the *Voyager* spectra.

The transition 4,1 at 1256 Å is of some importance to the *International Ultraviolet Explorer* (*IUE*) observations of Jupiter and the *Voyager* observations as an EUV monitor of S II. The transition has an uncertain strength because of configuration mixing. A very optimistic Gaunt factor of 2 has been applied to 4,1 to produce an upper limit estimate of Ω, given in Table 1B.

Other transitions at 910 Å and 664 Å (Table 1B) are predicted to be weak, based on the Coulomb approximation calculation of transition probabilities.

b) S III

The S III atomic data are given in Tables 2A and 2B. The lifetimes of a number of the important EUV transitions have been measured. The Io torus spectrum in the EUV is dominated by the strong transitions (9,1), (10,1), and (11,1) at about 685 Å.

The transition (5,1) at 1018 Å is important from the point of view that its intensity relative to the 685 Å feature provides a measure of electron temperature. Unfortunately, the (5,1) transition is subject to strong configuration mixing, and the appropriate Gaunt factor for calculation of Ω is uncertain. An upper limit value has been given for Ω(1,5) in Table 2B. The same difficulty is encountered for the (4,1) transition at 1194 Å and 1200 Å with the added complication that term 4 may be populated by transitions from term 14. An estimate of Ω(1,14) is not available, but Berry *et al.* (1970) report that the 1127 Å (14,4) transition is strong in beam foil and discharge spectra. Emission at 1127 Å has not been reported by the Broadfoot *et al.* (1979) preliminary work on the *Voyager* EUV spectrum. This fact does not necessarily place a strong limit on the (14,4) contribution since the branching ratios from term 14 depend on a combination of Coulomb approximation calculations and the Berry *et al.* (1970) measurements of term 14 lifetime (see Table 2B). The calculation of Ω(1,5) and Ω(1,4) taking configuration mixing into account would be a considerable aid to the analysis of the EUV data.

Collision strengths for the electron exchange transitions (1,6), (1,7), and (1,12) are not known, and the uncertainty tends to complicate the analysis of the observed spectra. Transitions from terms 2 and 3 give rise to measurable near infrared emission.

c) S IV

Tables 3A and 3B give the atomic data for the dominant S IV transitions. Collision strengths for excitation of the quartet terms are not known, and could possibly account for a substantial fraction of absorbed electron energy. The intercombination transition (2,1) has not been observed, and the lifetime of term 2 is unknown (Wiese, Smith, and Miles 1969).

TABLE 2

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: S III

A.

Term Identification Number	Designation
1	$3s^23p^2\ ^3P$
2	$3s^23p^2\ ^1D$
3	$3s^23p^2\ ^1S$
4	$3s3p^3\ ^3D^o$
5	$3s3p^3\ ^3P^o$
6	$3s3p^3\ ^1D^o$
7	$3s3p^3\ ^1P^o$
8	$3s3p^3\ ^3S^o$
9	$3s^23p3d\ ^3P^o$
10	$3s^23p4s\ ^3P^o$
11	$3s^23p3d\ ^3D^o$
12	$3s^23p4s\ ^1P^o$
13	$3s^23p4p\ ^3D$
14	$3s^23p4p\ ^3P$
15	$3s^23p4p\ ^3S$
16	$3s^23p4d\ ^3F^o$
17	$3s^23p4d\ ^3D^o$
18	$3s^23p5s\ ^3P^o$
19	$3s^23p5s\ ^1P^o$

NOTE.—I.P. = 35.0 eV.

B.

λ (Å)	Transition (*j*, *i*)	Ω(*i*, *j*)	Ref.	*A*(*j*, *i*) (s^{-1})	Ref.
	1,1:0,1	0.94	2		
	1,1:1,2	2.3	2		
	1,1:0,2	0.51	2		
9069.4[a], 9532.1[a]	2,1	3.87	2	2.5E−2, 6.4E−2	4
3721.8[a], 3796.7[a]	3,1	0.75	2	0.85, 1.6E−2	4
6312.1[a]	3,2	1.34	2	2.54	
1194, 1202	4,1	7.7	1[b]	6.25E7	12, 17
1018	5,1	10.	1[b]	2.3E8	15, 17
1077	6,2	12.	1	4.0E9	1
796.7	7,2	2.4	1	2.6E9	1, 7
911.8	7,3	2.4	1	2.9E9	1, 7
726	8,1	4.5	1	8.3E9	1
701	9,1	12.1	1	8.3E9	8
683	10,1	15.1	1	1.1E10	8
680	11,1	24.6	1	1.1E10	7, 8
729.51	12,2	1.26	1	2.3E9	1
824.85	12,3	0.41	1	5.1E8	1
590	13,1	?	...	weak	
3710	13,9	...	...	strong	
4286	13,10	...	...	strong	
4469	13,11	...	...	strong	
580	14,1	?	...	weak	
1127	14,4	1.6	1	2.5E8	1, 12
3370	14,9	5.1	1	3.1E7	1
3850	14,10	39.	1	1.6E8	1
3990	14,11	18.9	1	7.0E7	1
574	15,1	?	...	weak	
3235	15,9	...	...	strong	
3663	15,10	...	...	strong	
488	16,1	small	...	weak	
2857	16,13	...	...	strong	
485	17,1	small	...	weak	
2720	17,13	22.8	1	1.6E8	1
2990	17,14	73.5	1	4.0E8	1
478	18,1	0.23	1	4.9E8	1
2500	18,13	21.4	1	3.2E8	1
2690	18,14	16.1	1	1.9E8	1
2786	18,15	5.8	1	6.2E7	1

[a] Air wavelengths.

[b] Present work assuming Gaunt factor of 2.0.

TABLE 3

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: S IV

A.

Term Identification Number	Designation
1....................	$3s^23p$ $^2P^o$
2....................	$3s3p^2$ ^4P
3....................	$3s3p^2$ ^2D
4....................	$3s3p^2$ ^2S
5....................	$3s3p^2$ ^2P
6....................	$3s^23d$ ^2D
7....................	$3s^24s$ ^2S
8....................	$3p^3$ $^4S^o$
9....................	$3p^3$ $^2P^o$
10....................	$3s^24p$ $^2P^o$
11....................	$3s3p3d$ $^4P^o$
12....................	$3s3p3d$ $^4D^o$
13....................	$3s^24d$ ^2D
14....................	$3s3p$ $^4P^o$
15....................	$3s^25s$ ^2S

NOTE.—I.P. = 47.29 eV.

B.

λ (Å)	Transition (j, i)	Ω(i, j)	Ref.	A(j, i) (s^{-1})	Ref.
105241....	1,1:0.5,1.5	1.3	2	7.7E−3	4
1385......	2,1	?	...	weak	
1073......	3,1	8.2	1[a]	1.4E8	12
816.......	4,1	1.0	1	2.3E9	8
750.......	5,1	6.8	1	5.7E9	8
660.......	6,1	9.8	1	7.1E9	8
554.......	7,1	0.98	1	6.1E9	4, 1
800.......	8,2	4.6	1	4.7E9	7
470.......	10,1	?	...	weak	
3097......	10,7	21.5	1	2.5E8	4
662.......	11,2	8.8	1	5.3E9	8
654.......	12,2	28.3	1	1.1E10	8
393.......	13,1	1.0E−3	1	3.7E6	1
521.......	14,2	0.28	1	3.5E8	1
370.......	15,1	8.6E−2	1	1.8E9	1

[a] Present work assuming Gaunt factor of 2.0.

The transition (3,1) at 1073 Å is subject to configuration interaction, and an upper limit to Ω(1,3) is given in Table 3B. A strong feature at 1070 Å attributed to S IV appears in the Io torus spectrum.

d) S v

Atomic data for the transitions of interest are given in Tables 4A and 4B. The strong S v lines at 786 and 696 Å are blended with other features in the *Voyager* EUV spectra and have not been identified by Broadfoot *et al.* (1979).

e) S VI

Atomic data are given in Tables 5A and 5B. The strong lines of S VI are at 933 Å and 650 Å, but have not been identified in the *Voyager* EUV spectta.

f) O II

Atomic data are given in Tables 6A and 6B. The strong features appear at 3727 Å (2,1), 833 Å (4,1), and 539 Å (6,1). The O II transitions have not been identified in the *Voyager* EUV Io torus spectra. A feature in the observed spectrum at 833 Å has been attributed to O III because of the lack of a measurable feature at 539 Å (Broadfoot *et al.* 1979).

g) O III

Atomic data are given in Tables 7A and 7B. As noted above, the 833 Å feature in the observed Io torus spectrum has been attributed to the O III (5,1) transition. The collision strength Ω(1,5) is somewhat

TABLE 4

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: S V

A.

Term Identification Number	Designation
1....................	$3s^2$ ^1S
2....................	$3s3p$ $^3P^o$
3....................	$3s3p$ $^1P^o$
4....................	$3p^2$ ^3P
5....................	$3s3d$ ^3D
6[a]...................	$3s3d$ ^1D
7....................	$3s4s$ ^3S
8....................	$3p3d$ $^3P^o$
9....................	$3p3d$ $^3D^o$

NOTE.—I.P. = 72.5 eV.

[a] Not listed by Moore 1971. $E = 270724$ cm^{-1}.

B.

λ (Å)	Transition (j, i)	Ω(j, i)	Ref.	A(j, i) (s^{-1})	Ref.
1198........	2,1	?	...	...	
768.48......	3,1	2.62	1	3.8E9	7
368.........	6,1	?	...	weak	
696.5.......	6,3	8.1	1	1.0E10	8

TABLE 5

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: S VI

A.

Term Identification Number	Designation
1....................	$3s$ ^2S
2....................	$3p$ $^2P^o$
3....................	$3d$ ^2D
4....................	$4s$ ^2S
5....................	$4p$ $^2P^o$
9....................	$5p$ $^2P^o$

NOTE.—I.P. = 88.029 eV.

B.

λ (Å)	Transition (j, i)	Ω(i, j)	Ref.	A(j, i) (s^{-1})	Ref.
933........	2,1	3.7	1	1.5E9	8
249........	5,1	0.12	1	1.9E9	(1, 8)
650........	5,3	1.6	1	2E9	(1, 8)

TABLE 6

Atomic Data for Observed Io Plasma Torus Species: O II

A.

Term Identification Number	Designation
1....................	$2s^22p^3$ $^4S^o$
2....................	$2s^22p^3$ $^2D^o$
3....................	$2s^22p^3$ $^2P^o$
4....................	$2s2p^4$ ^4P
5....................	$2s2p^4$ ^2D
6....................	$2s^22p^23s$ ^4P

Note.—I.P. = 35.108 eV

B.

λ (Å)	Transition (j, i)	Ω(i, j)	Ref.	A(j, i) (s⁻¹)	Ref.
3728.91[a] 3726.16[a]...	2,1	1.47	2, 18	{4.8E−5, 1.7E−4}	4
4.76E6......	2,2	1.16	2	1.3E−7	4
2471.17 2471.06....	3,1	0.45	2, 18	{6.0E−2, 2.4E−2}	4
	3,3	0.14	2	6.0E−11	4
833.........	4,1	2.7	1	8.3E8	14
539.........	6,1	1.0	1	1.1E9	14

[a] Air wavelengths.

uncertain because the measured lifetime of term 5 is about a factor of 4 longer than the value calculated using the coulomb approximation.

h) O IV

Atomic data are given in Tables 8A and 8B. The strong transitions are at 554 Å (5,1), and 780 Å (3,1). The Broadfoot *et al.* (1979) preliminary analysis of the Io torus EUV spectrum shows no measurable emission at 554 Å.

i) *Other Species*

A number of other species have been examined as possible members of the Io plasma torus population. The candidates included ion species of Ar, K, C, and Si. None of these species have been identified in the *Voyager* EUV spectrum, although a number of strong lines occur in the 500–1700 Å region, allowing calculation of upper limits on abundances. Many of the resonance transitions of Na II, Na III, K II, K III, and Ca III lie below 500 Å, beyond the range of the *Voyager* EUV instrument, making it difficult to set upper limits on abundances. Some of these species will be discussed in more detail below.

V. IDENTIFICATION OF EMITTING SPECIES AND PREDICTED INTENSITIES

The radiative cooling efficiencies of the species of interest are not only the quantities determining the energy budget of the plasma, but also play an essential role in the identification of the emitting species from observations with low-resolution spectrometers. The

TABLE 7

Atomic Data for Observed Io Plasma Torus Species: O III

A.

Term Identification Number	Designation
1....................	$2s^22p^2$ ^3P
2....................	$2s^22p^2$ ^1D
3....................	$2s^22p^2$ ^1S
4....................	$2s2p^3$ $^5S^o$
5....................	$2s2p^3$ $^3D^o$
6....................	$2s2p^3$ $^3P^o$
7....................	$2s2p^3$ $^1D^o$
8....................	$2s2p^3$ $^3S^o$
9....................	$2s2p^3$ $^1P^o$
10...................	$2s^22p3s$ $^3P^o$

Note.—I.P. = 35.146 eV.

B.

λ (Å)	Transition (j, i)	Ω(i, j)	Ref.	A(j, i) (s⁻¹)	Ref.
	1,1:0,1	0.39		2.6E−5	
	1,1:0,2	0.21	2	3.5E−11	4
	1,1:1,2	0.95		9.7E−5	
4931.8[a] 4958.9[a] 5006.8[a]...	2,1	2.5	2, 18, 11	2.8E−2	4
2322.......	3,1	0.3	2, 18, 11	0.23	4
4364.45....	3,2	0.58	2	1.6	4
834........	5,1	3.5	1	8.4E8	14
703........	6,1	2.6	1	1.7E9	14
535........	7,1	?		weak	
599.6......	7,2	3.5	1	6.8E9	4
508........	8,1	2.8	1	1.5E10	4
475........	9,1	?			
525.80.....	9,2	2.1	1	1.0E10	4
597.82.....	9,3	0.64	1	2.1E9	4
374........	10,1	0.85	1	3.8E9	4

[a] Air wavelengths.

efficiencies defined by equation (1) are discussed in the following text. The efficiency curves, strictly speaking, refer to an average electron density of ~ 2000 cm^{-3}. However, at densities of this order electron deactivation only plays a role in controlling excited state populations in the relatively rare cases such as the first quartet term of S IV, in which lifetimes are longer than several hours. The analysis process is therefore greatly simplified by considering the plasma to be thin from the point of view that almost all excited term populations are controlled by radiative deactivation.

Although the distribution of line wavelengths in a given species is unique, the low-resolution EUV spectra provided by the *Voyager* instrument do not have sufficient wavelength discrimination to allow unique emitter identifications on the basis of wavelength measurements alone. But the combination of known collision strengths and multiplet wavelengths can provide unique identifications in the case of low-resolution spectra. The characteristics of the individual emitters are discussed below.

The calculated values of ρ for S II as a function of electron temperature are given in Figure 1. The

1980ApJ...236.1043S

TABLE 8

ATOMIC DATA FOR OBSERVED IO PLASMA TORUS SPECIES: O IV

A.

Term Identification Number	Designation
1....................	$2s^22p\ ^2P^o$
2....................	$2s2p^2\ ^4P$
3....................	$2s2p^2\ ^2D$
4....................	$2s2p^2\ ^2S$
5....................	$2s2p^2\ ^2P$
9....................	$2s^23s\ ^2S$

NOTE.—I.P. = 77.394 eV.

B.

λ (Å)	Transition (j, i)	$\Omega(i, j)$	Ref.	$A(j, i)$ (s^{-1})	Ref.
	1,1:0.5,1.5	0.76	2		
790.........	3,1	1.5	1	6.3E8	14
609.........	4,1	0.74	1	3.4E9	14
554.........	5,1	3.1	1	6.3E9	14
279.9.......	9,1	0.13	1	6.4E9	1

REFERENCES TO TABLES 1–8

1. Present work calculated using the Bates and Damgaard (1949) method, with a Gaunt factor of 0.2 applied to the calculation of Ω.
2. Osterbrock 1974.
3. Moore 1971.
4. Wiese, Smith, and Miles 1969.
5. Wiese, Smith, and Glennon 1966.
6. Morton and Smith 1973.
7. Irwin and Livingston 1976.
8. Dumont, Garner, and Baudinet-Robinet 1978.
9. Allen 1963.
10. Bates and Damgaard 1949.
11. Henry and Williams 1968.
12. Berry *et al.* 1970.
13. Beyer, Maddox, and Bridewell 1973.
14. Pinnington *et al.* 1974.
15. Livingston *et al.* 1975.
16. Berry *et al.* 1971.
17. Aymar 1974.
18. Henry, Burke, and Sinflaim 1969.

prominent emitters as noted above are the 6720 Å (2,1), and the 1256 Å (4,1) transitions. The relative rates (4,1)/(2,1) have a strong dependence on temperature below 10^6 K. The curve shown for the (4,1) transition is an estimated upper limit value, and the real efficiency will probably be lower within an order of magnitude range after detailed calculations of configuration interaction have been undertaken. The (4,1) and (6,1) transitions have not been recognized in preliminary analysis of the *Voyager* EUV spectrum, but this result is still compatible with the observed (2,1) intensities as discussed below.

Term 2 is subject to cascade population from several higher doublet terms as pointed out above, at temperatures of at least 10^5 K. The contributions apparently are not strong enough to provide measurable emission in the EUV. This suggests that the total ρ shown in Figure 1 is likely to be within ~80% of the total species efficiency.

The identification of S III as the dominant emitter

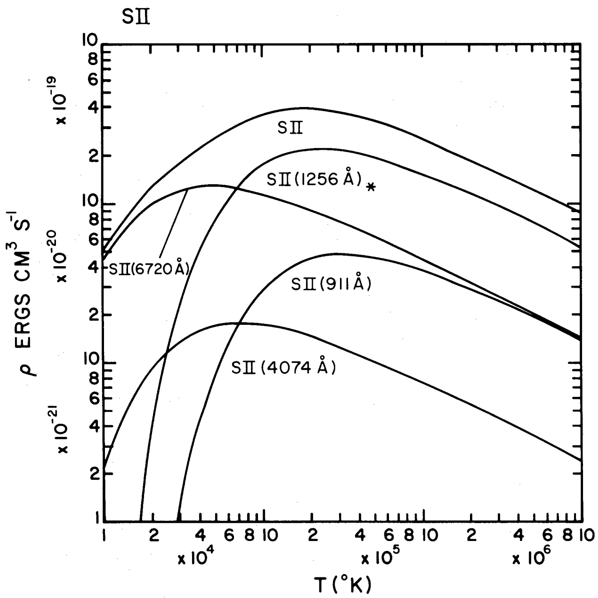

FIG. 1

FIGS. 1–9.—Radiative cooling coefficients of ion species. Asterisks show upper limits.

in the *Voyager* EUV spectrum of the Io plasma torus is based on the energy distribution shown in Figure 2. The distribution of wavelengths and intensities appears to be the only system compatible with the observed major features of the spectrum. The very efficient multiplet transitions (9,1), (10,1), and (11,1) account for most of the bright emission observed at 685 Å. An emission feature identified in the observed spectrum at 1020 Å has been attributed to the S III

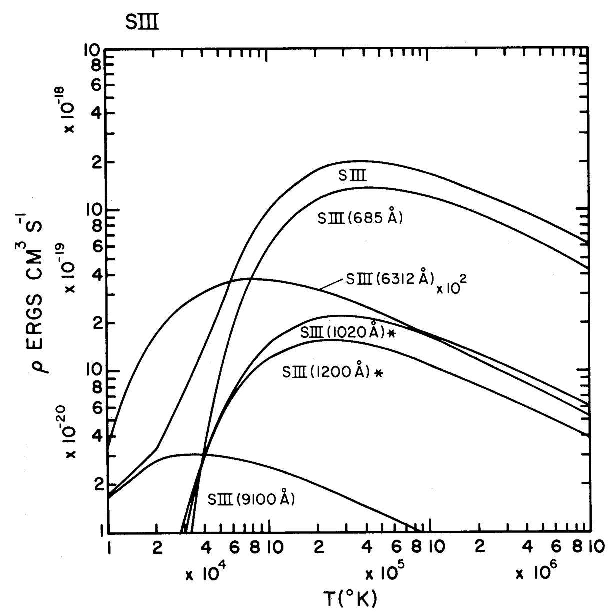

FIG. 2

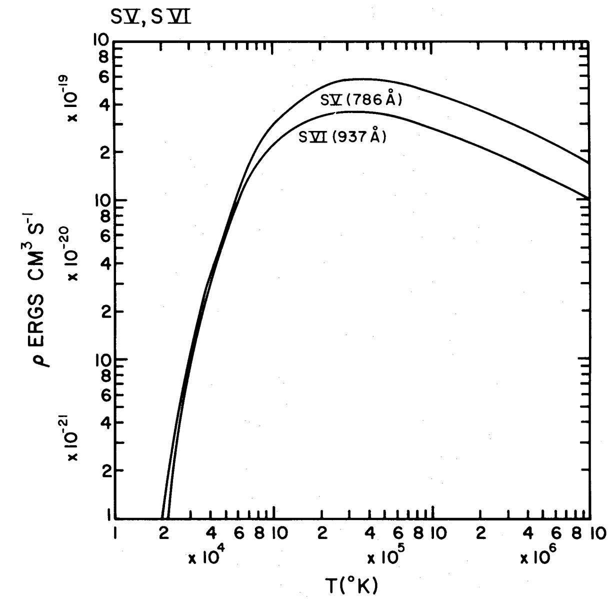

FIG. 4

(5,1) transition. Another emission feature at ~ 1200 Å blended with the H Lα line at 1216 Å is tentatively attributed to the S III (4,1) transition. The curves in Figure 2 for the (4,1) and (5,1) transitions are upper limits for reasons discussed above. The 1200 Å (4,1) values of ρ contain no estimates of cascade contributions.

The major consideration in identifying the observed features with S III was the ability to generate a strong emission at 685 Å without producing other emission lines that were incompatible with the observed spectrum in the 500–1700 Å range. In fact, most of the energy absorbed by S III at electron temperatures higher than 4×10^4 K is emitted at 685 Å. The total value of ρ plotted in Figure 2 is expected to be close to the real total radiative efficiency for S III.

Figure 3 shows the values of ρ calculated for S IV. The efficient transitions at 660 Å (6,1) and 1073 Å (3,1) are attributed to observed features in the Io torus (Broadfoot *et al.* 1979). The efficiency of the (3,1) transition is uncertain, and the given curve in Figure 3 is an upper limit estimate. The total value of ρ shown in the figure does not reflect contributions from the quartet terms, and the relationship to the real total radiative efficiency for S IV is uncertain. A substantial fraction of term 2 may be deactivated by electrons.

Figure 4 shows the calculated values of ρ for the strong S V 786 Å (3,1) and S VI 937 Å (2,1) transitions. The S V 3,1 transition falls in a region of blended emission lines in the *Voyager* EUV spectra. The spectrum analyzed by Broadfoot *et al.* contained no measurable emission at 937 Å.

Relatively strong features not accounted for by sulfur ions occur at 833 and 900 Å in the observed EUV torus spectra. Well-known strong lines of O II and O III occur at about 833 Å. The radiative cooling curves for O II and O III are shown in Figures 5 and 6. A lack of measurable emission at 539 Å tends to eliminate O II as a strong contributer to 833 Å emission. The emission lines of O III are compatible with the observed spectrum since the only measurable emission lines in the 500–1700 Å region are the 834 (5,1) and 703 Å (6,1) transitions according to the data in Table 5B and Figure 5. The fact that emission at 555 Å has not been detected tends to eliminate O IV as a strong contributor to the observed spectrum (Broadfoot *et al.* 1979, and Fig. 7).

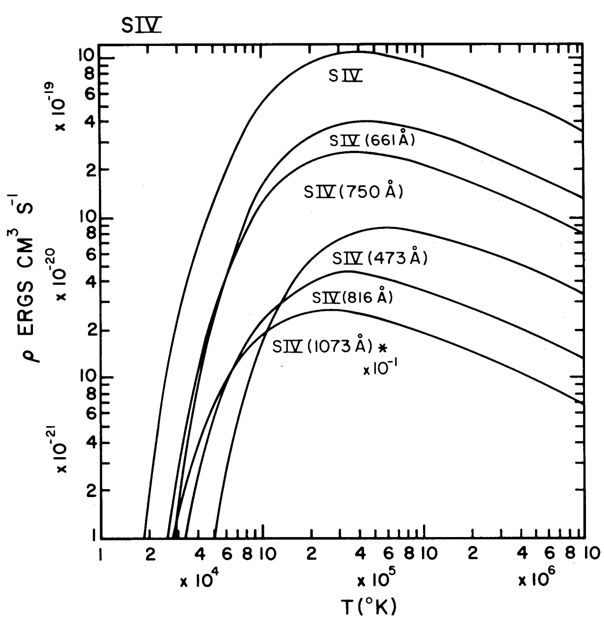

FIG. 3

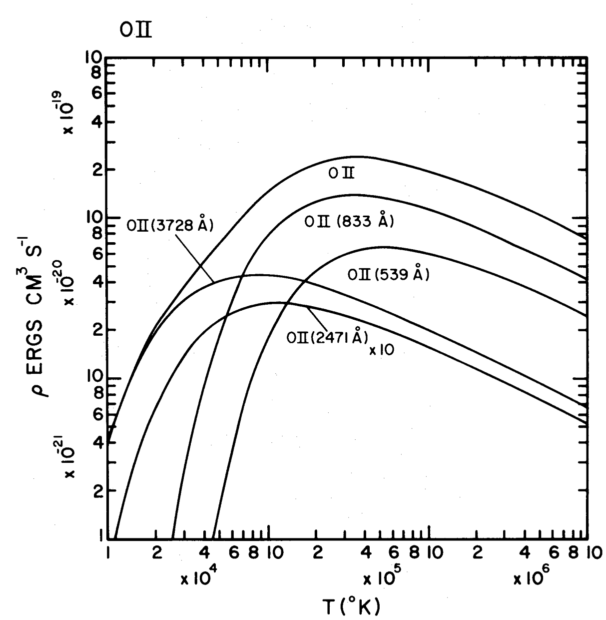

FIG. 5

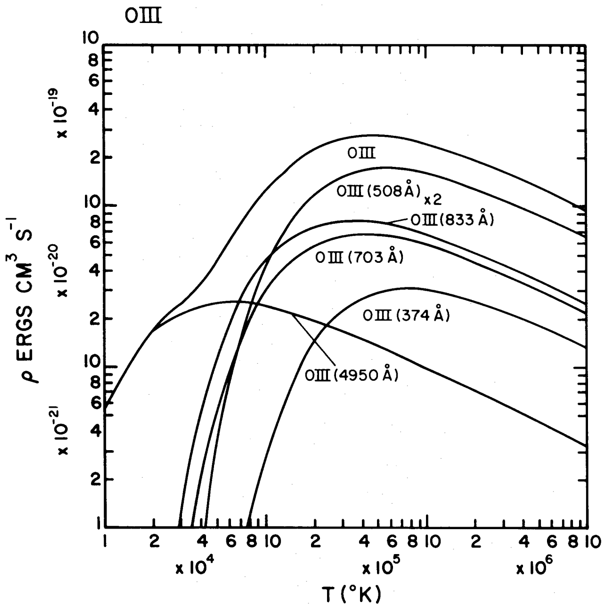

FIG. 6

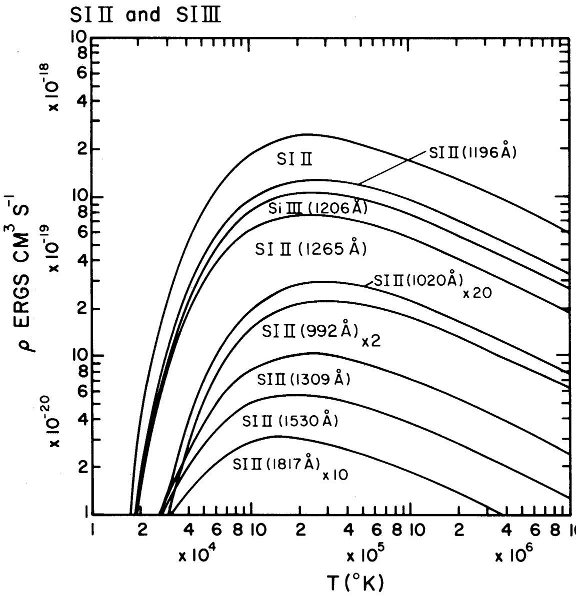

FIG. 8

Several strong emission lines of ionized silicon occur in the 500–1700 Å region. No lines of these species have been detected, and low limits can be set on number densities based on the EUV spectra. However, two strong multiplets of Si II at 1196 Å and 1265 Å blend with the S III and S II (4,1) transitions. Careful attention should be paid to these emission features to avoid misinterpretation. Figure 8 shows calculated values of ρ for Si II and Si III. Figure 9 shows the values of ρ for Si IV. More than 95% of the energy absorbed by Si IV passes through the 1400 Å transition.

A possible identification of the feature at 900 Å in the torus spectrum shown by Broadfoot *et al.* (1979) is C II. The calculated values of ρ show the 904 Å transition to be the strongest EUV emitter over a broad temperature range. The difficulty with this identification is that the strong C III transition at 977 Å has not been detected in the Broadfoot *et al.* (1979) spectrum.

The species Ar II has strong lines at 920 Å (2,1), with $\Omega(1,2) = 1.8$ calculated by the Coulomb approximation method. A feature at these wavelengths has not been detected in the Broadfoot *et al.* (1979) preliminary analysis.

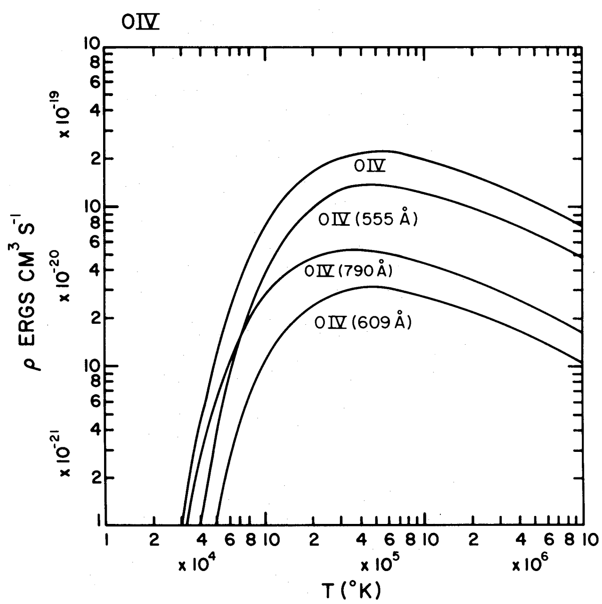

FIG. 7

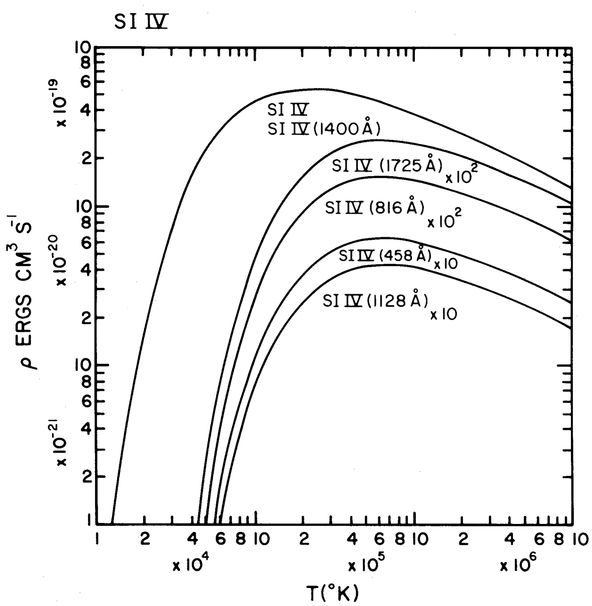

FIG. 9

TABLE 9

PREDICTED INTENSITIES[a] OF IO PLASMA TORUS EMISSION LINES ($T = 10^5$ K)

λ (Å)	S II	S III	S IV	O II	O III
508.........	...	...	...	...	51
539.........	...	...	...	< 1.3	...
661.........	...	...	56[b]	...	...
686.1.......	...	204[b]	...	...	...
703.........	...	...	...	...	104
750.........	...	...	50	...	...
816.........	...	...	10	...	...
833.........	...	...	...	< 9	
834.........	...	...	...	...	190[a]
1018.4......	...	80[c]	...	...	...
1073........	...	...	110[c]	...	...
1194, 1201......	...	60[c]	...	...	...
1256.1......	43[c]	...	...	...	...
3722........	...	5	...	...	...
3728........	...	...	...	< 22	...
4950........	...	...	...	...	140–570[d]
6312.1......	...	12	...	...	...
6716, 6731......	150[e]	...	...	...	...
9069.4......	...	34	...	...	...
9532.1......	...	86[f]	...	...	...

[a] In rayleighs.

[b] Intensity normalized to *Voyager 1* observation, with an estimated source path length of 8.8 R_J.

[c] Uncertain collision strength due to strong configuration mixing.

[d] The predicted intensity is uncertain because of configuration mixing in the upper state of the observed O III 834 Å line.

[e] Intensity from ground-based measurements. There is some uncertainty concerning the spatial location of the S II emission in relation to that of S III and S IV.

[f] Trauger *et al.* (1979) estimate 70–150 R from ground-based observations at the time of *Voyager 1* encounter.

The species K III has strong lines at 770 Å (2,1), which cannot be separated and identified in the blend of features in the observed spectra.

Predicted intensities of the various species in the Io plasma torus at 10^5 K are shown in Table 9. The S III emission rates are normalized to the observed feature at 685 Å. The indicated brightnesses refer to the peak brightness of the torus on the inner 1 R_J region at elongation, representing an approximate 8.8 R_J path length in the plasma. The predicted brightnesses of interest to ground-based observers are the 6312, 9069 and 9532 Å transitions of S III and the 4950 Å transitions of O III. Ground-based observations by Trauger, Münch, and Roesler (1979) during the *Voyager 1* encounter provided measured intensities of the S III 9532 Å transition in the range 70–150 R, in good agreement with the predicted values in Table 9. This tends to support the estimated mean electron temperature obtained from the *Voyager* data analysis. The intensities shown for the S II transitions (Table 9) are normalized to an emission rate of 150 R for the (2,1) transitions. Comparison of the S II rates to the higher stages of ionization should be made with caution. There is evidence suggesting the S II emission may arise mostly from a region inside the location of the Io orbit (Brown 1978; Trauger, Münch, and Roesler 1979). The temperature applied to S II in Table 9 may therefore not be applicable, and the predicted intensity for the S II (4,1) transition then tends to be an extreme upper limit.

VI. ELECTRON TEMPERATURE, ENERGY BUDGET

A determination of the total radiative cooling efficiency of the plasma torus depends on a determination of electron temperature. One direct measure can be made from the *Voyager* EUV spectrum in the relative emission rates of the 685 Å and 1020 Å features of S III. The application of the collision strengths in Table 2B to the observed data indicates a mean temperature of 10^5 K with temporal variations of a factor of ~ 2. The uncertainty in this estimate lies with an uncertain value of Ω for the 1020 Å transition. The variability in the relative intensities of the features in the *Voyager* spectra suggests that the mean temperature is certainly below 10^6 K (see Fig. 2), since relative intensities approach a constant at higher temperatures. On the other hand, the temperature cannot be reduced much below 10^5 K without experiencing difficulty in explaining the maintenance of the higher ionized species in the torus. Lower radiative efficiencies accompanying reduced temperatures would also predict minimum electron densities too high to be compatible with the direct measurements of Warwick *et al.* (1979). The Trauger, Münch, and Roesler (1979) measurement of the S III 9532 Å (2,1) transition is further evidence for a mean temperature of $\sim 10^5$ K since the relative rates of the 685 and 9532 Å transitions are very temperature sensitive (Fig. 2).

The total power radiated by the torus based on a temperature of 10^5 K is given for each identified species in Table 10. The calculated rates are based on the total ρ given in Figures 1–7, and therefore tend to be minimum estimates of total radiated power. The total radiated power could possibly be as high as $\sim 3.5 \times 10^{12}$ watts.

VII. NUMBER DENSITIES OF ION SPECIES

The measured brightness of the emitters combined with the known radiative cooling coefficients can

TABLE 10

IO PLASMA TORUS ENERGY LOSS RATES

S II..........	8×10^{10} W[a]
S III.........	10^{12} W
S IV.........	$> 4 \times 10^{11}$ W
O III.........	10^{12} W
Total......	$> 2.5 \times 10^{12}$ W
Production Rates[b]	
S ions.......	$\geq 4 \times 10^{-4}$ cm^{-3} s^{-1}
O III.........	5×10^{-4} cm^{-3} s^{-1}

[a] Upper limit because of an assumed full S II torus.

[b] Based on an assumed Io source of neutral particles; averaged over the torus half-width.

TABLE 11

IO PLASMA TORUS: ESTIMATED NUMBER DENSITIES AND ABUNDANCES

Ion	I.P. (eV)	N (cm^{-3})[a]	N (cm^{-2})[b]
S II	23.4	25[c]	1.6E12
S III	35.0	95	6.2E12
S IV	47.29	80	5.3E12
S V	72.5	< 12	< 8E11
S VI	88.0	< 2	< 1.3E11
O II	35.15	< 46	< 3E12
O III	54.93	190 → 740	1.2E13 → 4.9E13[d]
O IV	77.39	< 21	< 1.4E12
Si II	16.34	< 8	< 5E11
Si III	33.46	< 8	< 5E11
Si IV	45.13	< 10	< 6.6E11
Ar II	27.62	< 14	< 9E11
C III	47.86	< 2	< 1.3E11
H I	13.59	< 6	< 4E11[e]

NOTE.—Electron temperature 10^5 K.

[a] Averaged over torus half-width, $N_e = 2100$ cm^{-3}.

[b] Estimated at elongation, $l = 8.8\ R_J$.

[c] Assumes a full S II torus.

[d] Uncertain collision strength.

[e] Based on scattering efficiency of 1216 Å solar radiation.

provide measures of the product $N_i N_e$ (eq. [1]). The assumption of charge neutrality then leads to a lower limit to the quantity N_e and an upper limit to N_i. The electron number density estimated by Broadfoot *et al.* (1979) was $N_e \geq 2100$ cm^{-3} based on the values of ρ given in this article at 10^5 K. This lower limit estimate is approximately equal to the directly measured numbers by Warwick *et al.* (1979), averaged over the torus cross section. The implication is that the plasma is dominated by sulfur and oxygen ions, with some uncertainty associated with the number density of O III ions. Estimated number densities and abundances for the species discussed here are given in Table 11. The values given for S II are obtained from the ground-based data on the (2,1) transition. Note that the estimated number density based on the (2,1) intensity has very little temperature dependence between 2×10^4 and 10^5 K. It has been mentioned above that the S II data may not refer to the same spatial location as the *Voyager* data on the higher ionization species. Brown (1978) obtains much lower abundances for S II because of lower (2,1) transition intensities, 35 R compared to 150 R.

VIII. DISCUSSION

It is clear that the processes maintaining the Io plasma torus are extremely complex and variable. The observations of Io-controlled decametric radiation and torus radio emissions (Scarf *et al.* 1979; Warwick *et al.* 1979) suggest the presence of plasma instabilities. However, there appears to be little doubt that the torus emissions are dominated by electron excitation of a partially equilibrated distribution of ground state ions, rather than by the ionization-excitation characteristics of the source. Although the emission is unstable in intensity and spectral content, the torus is always complete and shows no apparent characteristics associated with the position of Io (Broadfoot *et al.* 1979). Therefore, if we assume that energy is delivered to the torus through ionization of neutrals supplied by Io, the characteristics of the source ionization-excitation process must be lost in subsequent ionization and excitation processes with the ambient electrons. On the other hand, calculations of collisional ionization equilibrium do not determine relative abundances of ion species since the loss processes are controlled not by recombination but by diffusion and possible encounters with Io. An energy loss rate of 2.5×10^{12} W implies a characteristic time of less than 5×10^5 s for loss of torus ions, assuming that energy is supplied through ionization of neutral particles and subsequent acceleration by Jupiter's magnetic field. Recombination times in the torus are roughly 8×10^9 s, 1×10^9 s, and 4×10^8 s for S II, S III, and S IV using a hydrogen-like ion approximation at 10^5 K (Bates, Kingston, and McWhirter 1962; cf. Brown 1976).

The simple mechanism of energy injection into the torus on which this discussion is based should be accepted with some degree of caution, from the point of view that the observations of S II suggest a more complex process. Some observations of the S II torus emission (Brown 1978; Trauger, Münch, and Roesler 1979) indicate that the emission volume is displaced radially inward from the observed location of the higher ionized species (cf. Bridge *et al.* 1979). Moreover, the ground-based data suggest a much lower temperature, $\sim 2 \times 10^4$ K, for both S II ions and electrons (Brown 1976; Trauger, Münch, and Roesler 1979).

An important consideration for the calculation of the supply rate of neutral atoms required to maintain the torus is the lifetime against ionization. Both sulfur and sodium have large comparable rate coefficients for ionization at 10^5 K, $\sim 5 \times 10^{-8}$ cm^3 s^{-1} (Peach 1968, 1969), and $\sim 10^{-7}$ cm^3 s^{-1} (Lotz 1967), respectively. Atomic oxygen has an ionization rate coefficient of 10^{-8} cm^3 s^{-1} at 10^5 K (Lotz 1967). The lifetimes of neutral sodium, sulfur, and oxygen in the torus are then roughly 1 hr, 2.5 hr, and 13 hr. A neutral particle at the Io escape velocity moves a distance of 1 R_J in 8 hr. We then expect substantial escape of neutral sodium and sulfur against ionization only during those times in which Io is near the edges of the torus, every 6.5 hours. Atomic oxygen escapes the torus under the above conditions in substantial numbers at all times. The short lifetime of neutral sodium in the torus introduces a complication in understanding the maintenance of the sodium cloud observed near Io. Smyth (1979) provides a description of the sodium cloud distribution based on a combination of earlier observations, which seems to indicate a fairly strong overlap with the location of the plasma torus. This suggests that the source strength of sodium atoms must be increased significantly in order to maintain the observed abundance, unless one invokes an extensive cooler region in the vicinity of Io. A large cooler region of the order of 1 R_J around Io would be difficult to reconcile with the *Voyager* EUV observations.

Atomic hydrogen is of special interest from the point of view that the *Pioneer 10* UV photometer (Carlson and Judge 1975) observed a partial torus of emission at Io interpreted as 1216 Å H Lα. The *Voyager 1* observations did not detect atomic hydrogen in the vicinity of Io (Broadfoot *et al.* 1979; Table 11). The nature of the *Pioneer 10* observations suggests that strong S III and S IV emission was not present at that time (Broadfoot *et al.* 1979). The plasma torus as it is presently constituted shows a neutral hydrogen lifetime of $\sim$26 hr. This is certainly long enough to allow escape from the plasma torus against ionization, but no resonance scattered H Lα has been observed.

The author wishes to thank R. A. Brown and H. W. Moos for helpful comments. This work was supported by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100.

REFERENCES

Allen, C. E. 1963, *Astrophysical Quantities* (2nd ed.; London: Athlone Press).
Aymar, M. 1974, *Physica*, **74**, 205.
Bates, D. R., and Damgaard, A. 1949, *Phil. Trans.*, **242**, 101.
Bates, D. R., Kingston, A. E., and McWhirter, R. W. P. 1962, *Proc. Roy. Soc. A*, **267**, 297.
Berry, H. G., Bromander, J. Curtis, L. J., and Buchta, R. 1971, *Phys. Scripta*, **3**, 125.
Berry, H. G., Schectman, R. M., Martinson, I., Bickel, W. S., and Bashkin, S. J. 1970, *J. Opt. Soc. Am.*, **60**, 335.
Beyer, L. M., Maddox, W. E., and Bridwell, L. B. 1973, *J. Opt. Soc. Am.*, **63**, 365.
Bridge, H., *et al.* 1979, AGU Spring Meeting, paper P70.
Broadfoot, A. L., *et al.* 1979, *Science*, **204**, 979.
Brown, R. A. 1976, *Ap. J.* (*Letters*), **206**, L179.
———. 1978, *Ap. J.* (*Letters*), **224**, L97.
Carlson, R. W., and Judge, D. L. 1975, *Icarus*, **24**, 395.
Cox, D. P., and Daltabuit, E. 1971, *Ap. J.*, **167**, 113.
Dumont, P. D., Garner, H. P., and Baudinet-Robinet, Y. 1978, *J. Opt. Soc. Am.*, **68**, 825.
Henry, R. J. W., Burke, P. G., and Sinflaim, A. L. 1969, *Phys. Rev.*, **178**, 218.
Henry, R. J. W., and Williams, R. E. 1968, *Pub. A.S.P.*, **80**, 699.
Irwin, D. G. J., and Livingston, A. E. 1976, *Canadian J. Phys.*, **54**, 805.
Jordan, C. 1968, *M.N.R.A.S.*, **142**, 501.
Kupo, I., Mekler, Y., and Eviatar, A. 1976, *Ap. J.* (*Letters*), **205**, L51.
Livingston, A. E., Dumont, P. D., Baudinet-Robinet, Y., and Garner, H. P. 1975, *Conf. Beam Foil Spectrosc.*, p. 339.
Lotz, W. 1967, *Ap. J. Suppl.*, **14**, 207.
Mekler, Y., and Eviatar, A., 1978, *J. Geophys. Res.*, **83**, 5679.
Moore, C. E., 1971, *NSRDS–NBS*, *35*, Vol. **1**.
Morton, D. C., and Smith, Wm. Hayden. 1973, *Ap. J. Suppl.*, **26**, 333.
Osterbrock, D. E. 1963, *Planet. Space Sci.*, **11**, 621.
———. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Peach, G. 1968, *J. Phys. B*, **1**, 1088.
———. 1969, *J. Phys. B*, **3**, 328.
Pinnington, E. H., Irwin, D. J. G., Livingston, A. E., and Kernahan, J. A. 1974, *Canadian J. Phys.*, **52**, 1961.
Scarf, F. L., Gurnett, D. A., and Kurth, W. S. 1979, *Science*, **204**, 991.
Seaton, M. J. 1968, *Adv. Atomic Molecular Phys.*, **4**, 331.
Shapiro, P. R., and Moore, R. T. 1976, *Ap. J.*, **207**, 460.
Smyth, W. H. 1979, *Ap. J.*, in press.
Trauger, J. T., Münch, G., and Roesler, F. L. 1979, AGU Spring Meeting, paper P74A.
Warwick, J. W., *et al.* 1979, *Science*, **204**, 995.
Wiese, W. L., Smith, M. W., and Miles, B. M. 1969, *NSRDS–NBS* 22, Vol. **2**.
Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, *NSRDS–NBS* 4, Vol. **1**.

D. E. SHEMANSKY.—Space Sciences Institute, University of Southern California, Tucson Laboratories, 3625 East Ajo Way, Tucson, AZ 85713