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A DEFICIENCY OF O III IN THE IO PLASMA TORUS

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ABSTRACT

A search for the O III 5007 Å line in the hot region of the Io plasma torus has set a stringent upper limit on O III abundance (<4 cm^{-3}). Plasma model calculations of electron collisional ionization-diffusive equilibrium, constrained by observations of other species in the torus, predict much higher O III concentrations. We suggest that an explanation of the apparent O III deficiency may lie in fast ion-ion and ion-atom charge exchange reactions, and a depleted high energy electron component in the post-*Voyager 2* epoch. We use theoretical estimates of a number of charge exchange reactions in a model calculation to predict plasma species partitioning, but it is necessary to assume that the O III is kinetically hot in order to approach the observational limit on concentration. The observed behavior of S II and kinetic energy measurements of S II and S III are also not satisfactorily accounted for in the present calculations in which charge exchange reactions are included. We suggest that an understanding of such peculiarities in the torus plasma may lie in further investigation of ion-ion reactions. We certainly require further observations of emission-line shapes in the torus to establish kinetic energy distributions. An attempt to observe the Cl III lines at 5518 Å and 5538 Å has set emission rate upper limits of 2 R at 5.9 R_J. We report further observations of the S III 6312 Å line at 5.9 R_J giving an average intensity of 58 R with variations ± 40 R.

Subject headings: planets: satellites — plasmas

I. INTRODUCTION

The remarkable differences in the morphology of the Io plasma torus indicated by EUV observations relative to the results of ground-based optical studies have produced serious difficulties in understanding the physical processes controlling the plasma. The interpretations have been so distinctly different that it is difficult to discuss the inferred reactions in terms of known processes occurring in the same plasma volume. The discrepancies have been discussed by Shemansky and Smith (1981), Brown, Pilcher, and Strobel (1982), Shemansky and Sandel (1982), and most recently by Brown and Shemansky (1982). The latter authors suggest that at least one of the interpretations, namely that radical plasma mass variations are displayed by S II red line intensities, may be in error. This interpretation, among others, depends on the assumption that the partitioning of ions in the torus is controlled by electron-ion collisions. We are thus drawn to the conclusion that the assumption cannot be entirely correct, and indeed it now appears that ion-ion and ion-atom reactions are fast enough to influence the condition of the plasma (Brown, Pilcher, and Strobel 1982). In this paper we present further evidence for the importance of such reactions based particularly on observations severely limiting the abundance of O III during the post-*Voyager 2* encounter period. Our estimated O III concentration is so low that it amounts to a deficiency not easily explained. We point out below that the O III deficiency places rather strong limits on the physical condition of the plasma.

The partitioning of an element's ions among different charge states is governed by the competition of ionization, recombination, diffusive loss and source processes. Sulfur and oxygen are the dominant constituents of the plasma torus. Shemansky (1980) has analyzed the *Voyager 1* ion measurements with an equilibrium model including only electron collisions and diffusion, and he concluded that the apparent sulfur ion partitioning could be explained if the diffusive loss time were about 100 days. The recognition that charge exchange reactions are significant in the dense regions of the torus seriously affects these calculations, but it is shown below that the estimated ion diffusive loss time remains large compared to estimates made on other grounds (Dessler 1980; Eviatar and Siscoe 1980; Hill 1980).

The UVS determinations of O II and O III densities at *Voyager 1* encounter are uncertain due to the overlap of their primary UV emissions at 833 Å (Shemansky and Smith 1981; Brown, Pilcher, and Strobel 1982). Unlike

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O II, S II, and S III, optical emission from O III has not been previously detected from ground-based observations. Moos and Clarke (1981) have reported a marginal *IUE* detection of emission at 1664 Å, which they ascribe to O III, but both the identification and its inversion in terms of O III concentration must be regarded as uncertain. Accepting the Moos and Clarke (1981) observation forces downward the amount of O III estimated by Shemansky and Smith (1981) at *Voyager 1* encounter, and the expected amount of O III in the *Voyager 2* post-encounter epoch must be reduced even further because of reduced plasma temperature and higher density at that later time.

The current theoretical and observational efforts were motivated by the insight that such species-specific ionization channels as ion-ion and ion-atom charge exchange can cause significant departures of ion partitioning from predictions based solely on electron processes. We have searched for an O III 5007 Å feature without success using a spectroscopic system with proven capability to record faint Jovian optical emissions at high spectral resolution. We also report (1) the results of a search for Cl III 5518 Å and 5538 Å features to test a hypothesis that part of the UVS 833 Å feature may be due to Cl III emission at 834 Å, and (2) 11 new observations of S III 6312 Å emission. We present model calculations including charge exchange reactions estimated to be significant on theoretical grounds, and we show that they do indeed affect ion partitioning, but questions still remain concerning both the observed phenomena and the adequacy of our investigation of heavy particle reactions.

II. OBSERVATIONS

We report observations of the Io plasma torus obtained in 1981 February and May using the echelle spectrograph (Chaffee 1974) and the intensified Reticon detector (Davis and Latham 1979) of the Smithsonian's Fred L. Whipple (formerly Mount Hopkins) Observatory. Performance and calibration parameters are given in Table 1. The wavelength and intensity standards were a thorium-argon lamp and the Jupiter disk center, respectively, and exposures of each were interleaved with torus observations. The entrance aperture for these observations had projected dimensions 0″.9 × 6″.7 or 0.05 × 0.3 R_J, and it was positioned by computer-controlled telescope offsets to 5.9 R_J east or west of Jupiter to the point where the centrifugal symmetry surface (Hill, Dessler, and Michel 1974) intersected the plane of the sky.

Table 2 is a log of our O III and Cl III observations. We summed spectra taken east or west of Jupiter separately and subtracted a smoothed Jupiter spectrum to remove scattered-light Fraunhofer absorption features which are noticeable in the raw data. The residual spectra, which display detector dark counts plus possible telluric airglow and Jovian emissions, are shown in Figures 1 and 2. Airglow-only exposures are shown for comparison. The arrows in the torus spectra indicate the Doppler-shifted locations of the expected features assuming rigid corotation with Jupiter. Brown (1982*b*) reports that S II near Io's orbit is transported with only ∼92% of Jupiter's angular speed, but the associated small change in the Doppler shift would not noticeably change the predicted locations. We set upper limits of <3 R (east) and <7 R (west) to O III 5007 Å emission, and <2 R to Cl III 5518 Å and 5538 Å features. These upper limits apply to ions which have cooled significantly from the corotational pickup energy. As pointed out by Brown and Ip (1981) and Brown (1982*a*), there is diminishing observational sensitivity to hotter ions since their signature is smeared out. In the current case, the upper limits to hot ions gyrating at the pickup speed would be at least 10 times higher than the quoted values.

Table 3 is a log of our S III 6312 Å observations, all of which were obtained 5.9 R_J east of Jupiter. The brightness uncertainties are photon-statistical, derived from the number of photon events recorded in the emission feature after subtraction of the local scattered continuum signal and dark counts. The average S III 6312 Å intensity is 58 ± 40 R, where the uncertainty is the standard deviation of the individual measurements. The value 48 ± 5 R was reported for the first detection of this line by Brown (1981).

a) *Comparison of Reduced Observations*

To determine the ion partitioning of oxygen, we must combine a variety of observations, each having one or more pieces to contribute to the puzzle. It is also necessary to discuss the sulfur system, a coequal plasma component that has been intensively studied. Table 4

TABLE 1

SPECTROGRAPH PARAMETERS AND JUPITER SURFACE BRIGHTNESS

Emission	Line	Echelle Order	Reciprocal Dispersion	σ[a] (mÅ)	Jupiter Disk Brightness[b] (MR Å^{-1})
O III	5007 Å	113	2.1 Å mm^{-1}, 0.031 Å pixel^{-1}	75	4.8
Cl III	5518 Å, 5538 Å	102	2.3 Å mm^{-1}, 0.034 Å pixel^{-1}	83	5.1
S III	6312 Å	90	2.6 Å mm^{-1}, 0.039 Å pixel^{-1}	94	5.6

[a] The standard deviation of the Gaussian function best describing the measured instrumental line profile.

[b] Based on the equatorial Jovian reflectivities of Woodman *et al.* 1979 and the solar spectral irradiance of Arvesen, Griffen, and Pearson 1969.

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TABLE 2

LOG OF Cl III AND O III OBSERVATIONS

ID	Species	Date (1981)	UT[a] (hr)	Exposure (hr)	Position[b] (R_J)	λ_{III}[c] (deg)
897/24	[Cl III]	May 21	10.00	2.00	...	...
27	[Cl III]	May 22	3.66	1.00	5.9 west	344, 20
30	[Cl III]	May 22	4.77	1.00	5.9 west	24, 61
898/1	[Cl III]	May 22	5.89	1.00	5.9 west	65, 101
4	[Cl III]	May 22	7.05	1.06	5.9 west	107, 145
7	[Cl III]	May 22	8.21	1.00	5.9 west	149, 185
10	[Cl III]	May 22	9.85	2.00	...	...
900/14	[O III]	May 25	3.97	1.00	5.9 east	267, 303
17	[O III]	May 25	5.21	1.01	5.9 east	311, 348
20	[O III]	May 25	6.35	1.03	5.9 west	173, 210
23	[O III]	May 25	7.51	1.00	5.9 east	35, 71
26	[O III]	May 25	9.69	3.10	...	...

[a] Universal time at midpoint of observation.

[b] Offsets from Jupiter along the intersection of centrifugal symmetry surface with the plane of the sky through Jupiter. An ellipsis indicates an airglow spectrum obtained with telescope stationary.

[c] The System III (1965) longitudes at the exposure start and stop of the intersection point of the line of sight with the plane of the sky through Jupiter.

gives the relevant measurements. The photometric data, columns (2)–(6), applies approximately to the elongation of the hot plasma torus near 5.9 R_J, Io's orbital distance from Jupiter. The in situ plasma science experiment data, column (7), have been normalized to a mean electron density $[e] = 1600$ cm^{-3} and apply to 5.0 R_J in a restricted longitude range at the time of *Voyager 1* encounter.

The photometrically determined densities are based on an assumed 8.8 R_J mean path length and electron temperatures and collision strengths mostly discussed elsewhere (Shemansky and Smith 1982; Brown, Pilcher, and Strobel 1982). The O I 6300 Å (^3P–^1D) collision strengths are obtained from the close coupling calculations of Henry, Burke, and Sinfailam (1969) (see Brown 1981; Smyth and Shemansky 1982), and we regard them as well established since the parameters entering the calculation show a good degree of stability. A similar comment applies to O III 5007 Å (^3P–^1D). Recent calculations in the disorted wave approximation by Bhatia, Doschek, and Feldman (1979) show good agreement with earlier estimates (Osterbrock 1974), and the strength of this line is qualitatively confirmed by the relative ease with which the line is detected in such sources as the Cygnus Loop nebula (Miller 1974). The calculation of the effective excitation rate coefficient of the O III 5007 Å (^3P–^1D) transition is based on collisional equilibrium calculations including 12 terms of the O III system (Shemansky and Smith 1981) using the Bhatia, Doschek, and Feldman (1979) energy-dependent collision strengths. The rate coefficient shows little dependence on electron temperature and density

TABLE 3

LOG OF S III OBSERVATIONS

ID	Date (1981)	UT[a] (hr)	Exposure (hr)	λ_{III}[b] (deg)	$4\pi J$ (6312 Å) (R)
779/8	Feb 22	7.95	0.52	243, 262	99 ± 23
10	Feb 22	8.52	0.50	264, 282	103 ± 25
23	Feb 22	11.45	0.51	11, 29	29 ± 24
25	Feb 22	12.00	0.50	31, 49	3 ± 27
780/8	Feb 23	06.50	0.50	342, 0	45 ± 19
10	Feb 23	07.17	0.50	6, 24	29 ± 18
12	Feb 23	07.92	0.67	30, 55	49 ± 16
781/17	Feb 24	07.88	0.67	180, 204	40 ± 17
782/10	Feb 24	12.00	0.17	338, 344	32 ± 42
11	Feb 24	12.17	0.17	344, 350	134 ± 42
13	Feb 24	12.40	0.17	353, 359	74 ± 40

[a] Universal time at midpoint of observation.

[b] The System III (1965) longitudes at the exposure start and stop of the intersection point of the line of sight with the plane of the sky through Jupiter. All observations were obtained at 5.9 R_J east of Jupiter.

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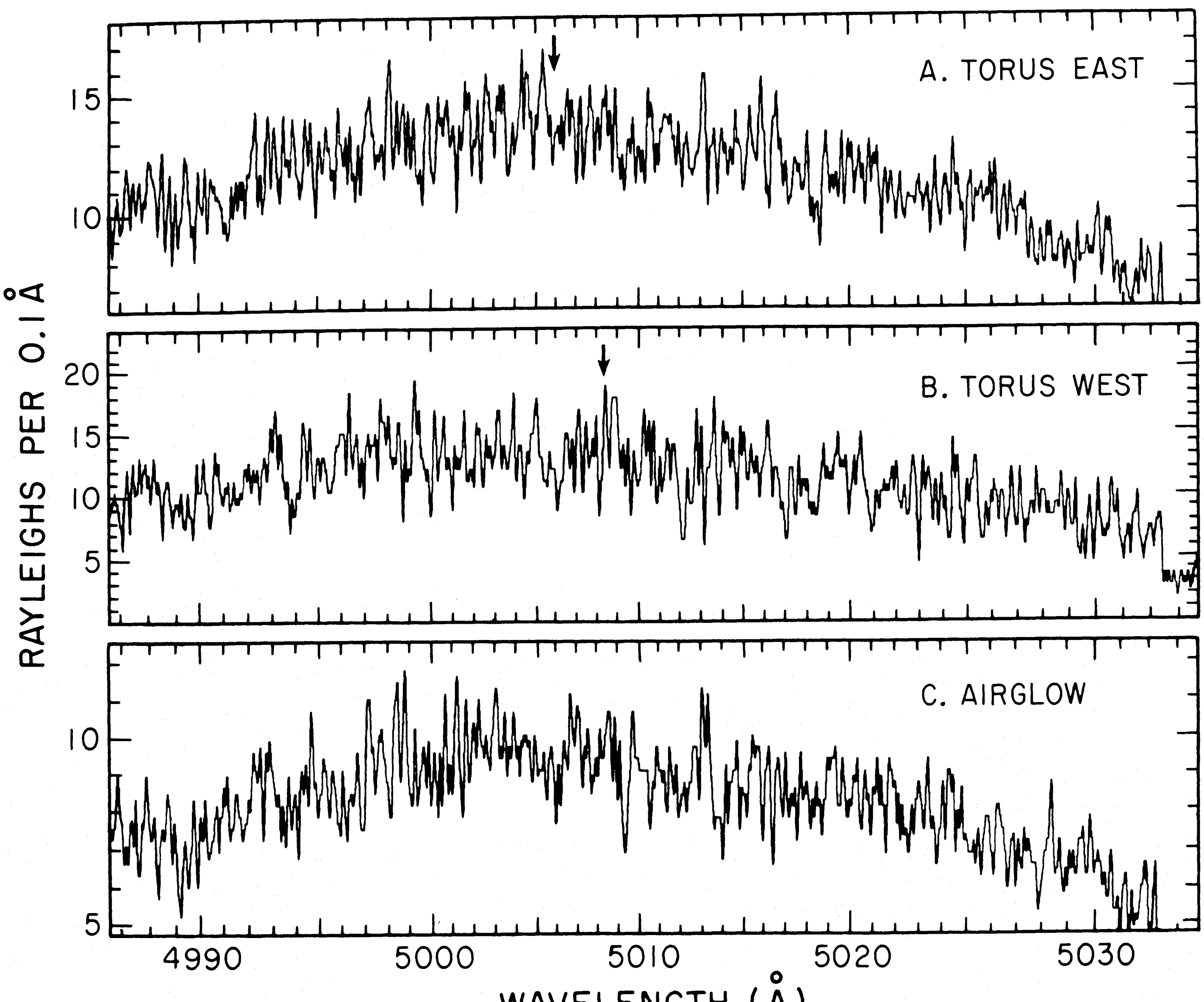

FIG. 1.—The search for the O III 5006.85 Å line in the Io plasma torus. Arrows indicate the expected position of the line. Observations were made 5.9 R_J east and west of Jupiter by computer offset. Spectrum A: Torus east spectrum after subtraction of a smoothed Jupiter background spectrum, indicating <3 R at 5006.85 Å. Spectrum B: Torus west spectrum as in Spectrum A, indicating <7 R at 5006.85 Å. Spectrum C: Telluric airglow comparison spectrum. See text.

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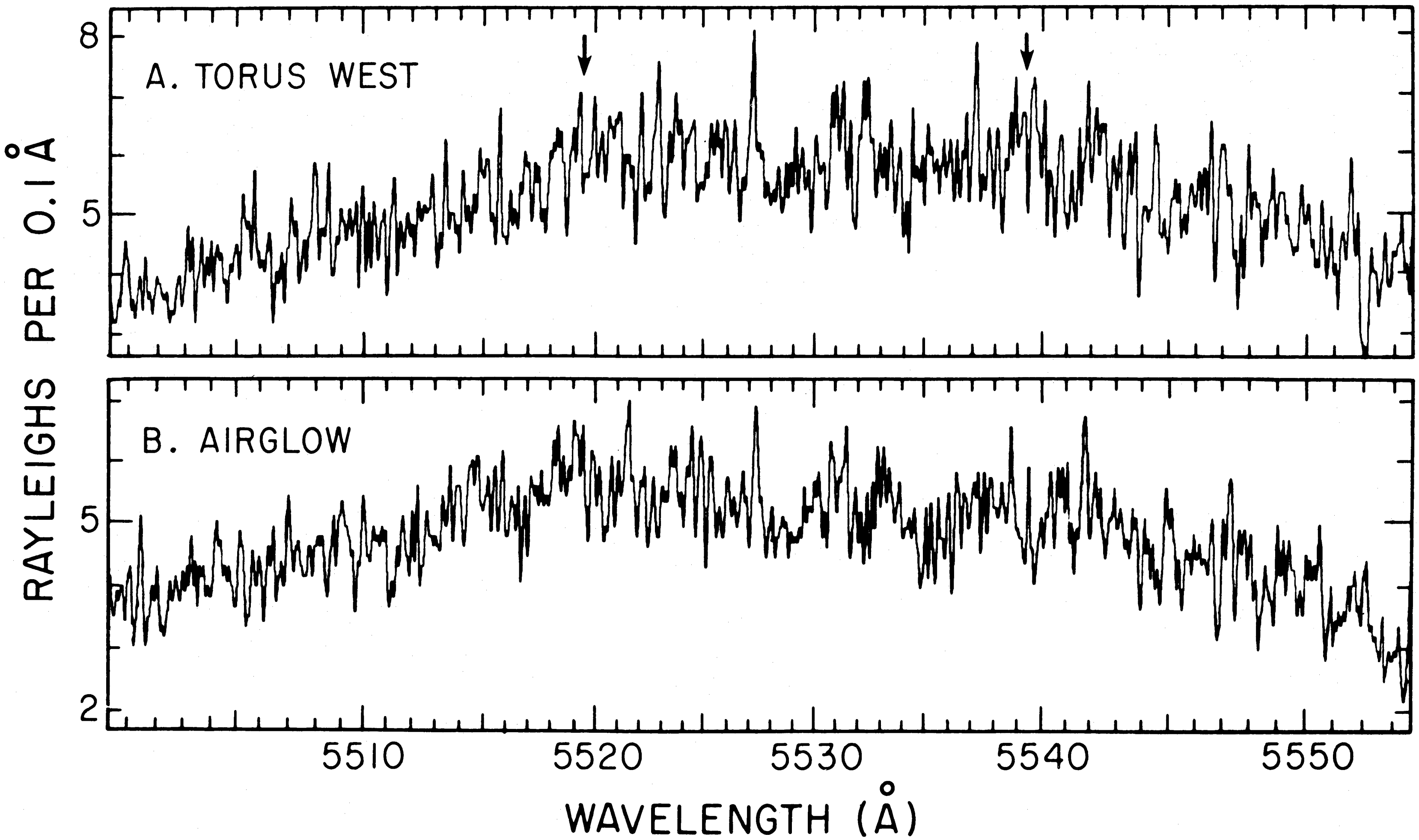

FIG. 2.—The search for the Cl III lines at 5517.66 Å and 5537.6 Å in the Io plasma torus. Arrows indicate the expected positions of the lines. Offset as in Fig. 1. Spectrum A: Torus west spectrum after subtraction of a smoothed Jupiter background spectrum, indicating <2 R in the Cl III lines. Spectrum B: Telluric airglow comparison spectrum. See text.

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TABLE 4

REDUCED OBSERVATIONAL DATA

Species (1)	Observation[a] (2)	Observation[b] (3)	Observation[c] (4)	Observation[d] (5)	Observation[e] (6)	Observation[f] (7)
S II (910 Å)	...	...	20 ± 10	...	...	...
S II (765 Å)	...	...	62 ± 10	...	...	...
S II (6731 Å)	425 ± 230	215 ± 28	...	240	...	...
S II (1256 Å)	...	...	...	...	43	...
S III (3722 Å)	...	17 ± 8	...	...	...	...
S III (6312 Å)	58 ± 40	...	...	...	...	...
S III (685 Å)	...	...	235 ± 30	...	...	...
O I (6300 Å)	8 ± 4	...	...	...	...	...
O II (3726 Å)	...	36 ± 7	...	...	...	...
O II (833 Å) } O III (834 Å) }	...	...	200 ± 30	...	...	...
O III (5007 Å)	< 3	...	...	...	...	...
O III (1664 Å)	...	...	...	...	< 12	...
[S II]/[S III]	0.39	0.22	0.71	...	...	0.85
[O II]/[S III]	...	0.29	2.8	...	...	0.81
[O II]/[O III]	> 100	...	> 4.4	...	...	2.4
[O I]	13	...	...	...	...	...
[O II]	...	98	480	...	...	210
[O III]	< 4	...	< 110	...	< 100	88
[S II]	173	74	120	115	115	220
[S III]	390	340	170	...	...	260
[S IV]	...	...	115	...	...	145
[*e*]	1980	2330	1600	...	...	1600

[a] Brown and collaborators. Brown and Shemansky 1982: observations obtained 1981 Feb and Apr at 5.9 R_J: S II (6731 Å), [S II]. Current paper: observations obtained 1981 Feb at 5.9 R_J: S III (6312 Å), [S III]. Brown 1981: observations obtained 1980 Mar at 5.0 and 5.9 R_J: O I. Smyth and Shemansky 1982: density estimate for [O I].

[b] Morgan and Pilcher 1982: observations obtained 1979 Jan, Feb, and Mar over the range 4–7 R_J.

[c] Current reanalysis of *Voyager 1* EUV measurements: observations obtained 1979 Mar 1 at 5.7 R_J.

[d] Trafton 1980: observations obtained 1979 Feb 27 at 6.0 R_J.

[e] Moos and Clarke 1981: observations obtained 1979 Mar 1 and 3 and May 20 at 6.0 R_J.

[f] Bagenal 1981: in situ observations 1979 Mar 5 at 6.0 R_J.

over the factor of ~2 range of estimated central torus values, and therefore the calculated number density has good stability against uncertainty in the plasma parameters.

Ground-based S II red doublet observations display strong variations with magnetic longitude (Trafton 1980; Pilcher and Morgan 1980; Morgan and Pilcher 1981; Trauger, Münch, and Roesler 1980), whereas EUV emission from S III, which has been presumed to depend on S II as a source of S III population, has shown no such variability at all (see Shemansky and Sandel 1982; Sandel and Broadfoot 1982). However, recent work by Brown and Shemansky (1982) has raised questions concerning the interpretation of the S II red line observations. This lastest work finds no functional dependence on magnetic longitude at 5.9 R_J, although there are strong variations in line intensity. According to Brown and Shemansky (1982), the strong intensity variation in the S II red lines does not reflect similar variations in plasma density. Further, these authors show the *Voyager* EUV observations of S II are compatible with the ground-based red line observations at the same epoch, but only after correction to a misclassified multiplet and its collision strength. This is shown in Table 4; the data given in columns (4), (5), and (6) from *Voyager* EUV and ground-based observations show a consistent estimate of mean S II density of 120–115 cm^{-3} in the hot torus at the time of *Voyager 1* encounter, assuming an electron temperature of $T_e = 8.0 \times 10^4$ K (Brown and Shemansky 1982). On this basis, our judgment is that S II is a minor constituent well mixed into the hot torus, as discussed by Brown and Shemansky (1982), although it shows strong variability in time and local volume against a relatively constant total plasma density. The processes driving this instability remain to be identified. [S II]/[S III] ratios obtained from the data in Table 4 range from 0.22 to 0.85. The very low value [S II]/[S III] = 0.22 from Morgan and Pilcher (1982) presents a serious problem of consistency among the observations that apparently cannot be attributed to differences in absolute photometry. The mean value of the Morgan and Pilcher estimate of S II 6731 Å emission rate is in good agreement with the value given by Trafton (1980) for the *Voyager 1* encounter epoch. The low [S II]/[S III] ratio obtained from the Morgan and Pilcher (1982) data is therefore driven by a rather high value for the intensity of the S III 3722 Å line. Questions concerning absolute photometry in the 3700 Å region seem to be obviated by a rather *low* value obtained by Morgan and Pilcher for the O II (3726 Å) line compared to the predicted emission rate obtained from the reanalyzed *Voyager* EUV data. As a result the [O II]/[S III] ratio obtained from the Morgan

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and Pilcher (1982) data is an order of magnitude lower than the value obtained from the *Voyager* EUV observations. The uncertainty in the *Voyager* EUV observations in this respect arises in the fact that O II and O III both contribute to the strong feature at 833 Å (Shemansky and Smith 1981). If we limit the amount of O III in the *Voyager 1* epoch torus in accord with the Moos and Clarke (1981) upper limit for the O III (1664 Å) line, it is necessary to place 5 times more O II in the torus to account for the 833 Å line than the Morgan and Pilcher measure of O II 3726 Å emission would allow. The dilemma is that the very bright and persistent 833 Å EUV line cannot be reasonably attributed to any species other than O II and O III. The only other viable species with an emission line near 833 Å is Cl II (834.7 Å). The partitioning of chlorine ion species is expected to be similar to that of sulfur, and so the upper limit placed on the Cl III 5518 Å line in the observation reported here tends to eliminate Cl as a measurable torus constituent. We are left with no apparent explanation for the strong differences between the Morgan and Pilcher (1982) results as opposed to the *Voyager* EUV and Brown ground-based observations. The *in situ Voyager* plasma science data cannot contribute to this issue since O II and S III have the same mass-to-charge ratio, and differentiation between these species is difficult in that experiment especially in the hot region of the torus (Bagenal 1981; Bagenal and Sullivan 1981). Although there is no clear explanation for the strong differences in these observations, we suggest that the weight of evidence lies with the EUV and ground-based near-infrared observations.

The [O II]/[O III] ratio is obtained from the combined measurements of O III 5007 Å and S III 6312 Å from Table 4, column (2) which gives an [O III]/[S III] ratio, and the Table 4, column (4) data which provides an [O II]/[S III] ratio. With a relatively minor adjustment for the different epochs (see Sandel *et al.* 1979 and Brown and Shemansky 1982), we obtain a value [O II]/[O III] > 100. This ratio is extreme, given our present knowledge of the plasma torus parameters. Barring charge exchange reactions, one expects the [O II]/[O III] ratio to be similar to that of [S III]/[S IV], and present evidence sets the value of the latter in the range of 1 to 2 in the *Voyager 1* encounter EUV data (Shemansky and Smith 1981). The extremely low upper limit to the O III density (<4 cm^{-3}) set by the 5007 Å measurement places a severe limitation on the condition of the plasma, as discussed below.

b) Charge Changing Reactions

The fact that the estimated O III density is so far removed from expectation for an electron-controlled plasma suggests strongly that heavy particle collisions have a controlling influence in the dense regions of the torus. Our current model has been expanded to include both electron processes and ion reactions found on the basis of theory to have significant rate coefficients. In the following we describe our approach to quantitative estimation of the rates of heavy particle interactions and list the reactions included in the present calculations.

When the velocity between a colliding ion and a neutral is much less than the velocity of the bound electrons, electron exchange often becomes the dominant inelastic collision process. At these lower velocities the electrons adjust nearly adiabatically to the motion of the nuclei and the transitions occur at well-defined internuclear separations (Johnson 1982). Collisions of this kind cannot be described by impulse or binary encounter interactions, contrary to the suggestion by Kunc and Judge (1981); rather, the behavior of the interaction potentials associated with the states of the colliding particles must be examined and the cross sections are therefore very system dependent.

For collisions of the type

$$\text{A III} + \text{B I} \rightarrow \text{A II} + \text{B III} \,,$$

the incoming state of the complex is weakly attractive at large separations, and the outgoing state is repulsive. Consequently, the reaction is exothermic and goes to states of higher net binding energy at low interaction velocities. For the velocities and binding energies of current interest, we expect an energy difference of the order of 3–5 eV, which becomes available as post-collision kinetic energy. In charge-symmetric collisions of the type

$$\text{A II} + \text{B I} \rightarrow \text{A I} + \text{B II} \,,$$

or

$$\text{A III} + \text{B I} \rightarrow \text{A I} + \text{B III} \,,$$

the incoming and outgoing potentials are similar and weakly attractive at large separations. Therefore, in this case reactions in which the net binding energy changes very little are favored processes.

Using semiempirical methods (Olson 1972; Olson, Smith, and Bauer 1971; Johnson and Boring 1978; Olson and Salop 1976) modified to take into account the high spin and angular momentum multiplicities of the colliding particles, cross sections have been estimated to within a factor of 2. The reactions considered here and their estimated rate coefficients are given in Table 5. This list is not comprehensive but contains all reactions we have currently identified as being of significant strength; these are further discussed by Johnson and Strobel (1982).

The reactions show three tendencies. First, the ions tend to terminate in lower charge states. Second, ionization is transferred from the hot plasma ions to the cooler neutrals. Third, the binding energy of oxygen outer electrons is significantly larger than that of sulfur. This third factor reduces the density of highly ionized oxygen relative to sulfur and reduces the total amount of oxygen species relative to sulfur.

The interaction velocity in ion-neutral reactions is in the range 50–60 km s^{-1}, because the ions are known to be near corotation with Jupiter's magnetic field (see Brown 1982*b*), and the neutrals orbit with roughly the

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TABLE 5

PLASMA REACTIONS

No.	Reaction	Q (10^{-9} cm^3 s^{-1})	R (10^{-12} cm^3 s^{-1})
1	$O + e \rightarrow O^+ + 2e$	0.78[a]	0.76[a]
2	$O^+ + e \rightarrow O^{2+} + 2e$	8.9×10^{-3} [a]	7.1[a]
3	$O^{2+} + e \rightarrow O3^+ + 2e$	3.7×10^{-3} [a]	14.0[a]
4	$O^{3+} + e \rightarrow O^{4+} + 2e$	2.1×10^{-3} [a]	...
5	$S + e \rightarrow S^+ + 2e$	3.5[a]	11.8[a]
6	$S^+ + e \rightarrow S^{2+} + 2e$	0.133[a]	20.9[a]
7	$S^{2+} + e \rightarrow S^{3+} + 2e$	1.52×10^{-2} [a]	70.5[a]
8	$S^{3+} + e \rightarrow S^{4+} + 2e$	4.1×10^{-3} [a]	78.3[a]
9	$S^{4+} + e \rightarrow S^{5+} + 2e$	3.1×10^{-3} [a]	...
10	$O + O^+ \rightarrow O^+ + O$	12.0	...
11	$O + S^+ \rightarrow O^+ + S$	0.06	...
12	$S + O^+ \rightarrow S^+ + O$	8.0	...
13	$S + S^+ \rightarrow S^+ + S$	16.0	...
14	$O^{2+} + S \rightarrow S^+ + O^+$	11.0	...
15	$O^{2+} + S \rightarrow S^{2+} + O^+ + e$	3.0	...
16	$S^{2+} + O \rightarrow S^+ + O^+$	6.0	...
17	$O^{2+} + O \rightarrow 2O^+$	0.2	...
18	$S^{2+} + S \rightarrow 2S^+$	0.6	..
19	$S^{3+} + O \rightarrow S^{2+} + O^+$	2.8	...
20	$S^{3+} + O \rightarrow S^+ + O^{2+}$	5.6	...
21	$O^{2+} + O \rightarrow O + O^{2+}$	5.0	...
22	$S^{2+} + S \rightarrow S + S^{2+}$	7.0	...
23	$S^{3+} + S \rightarrow S^{2+} + S^+$	20.0	...
24	$O^{2+} + S^+ \rightarrow O^+ + S^{2+}$	0.13	...
25	$O^{2+} + S^{2+} \rightarrow O^+ + S^{3+}$	1.70	...

NOTE.—Q = rate coefficient; R = recombination coefficient.
[a] $T_{ec} = 5 \times 10^4$ K; $T_{eh} = 7.0 \times 10^6$ K; [eh]/[ec] $= 2 \times 10^{-4}$.

orbital speed of Io. The ion-ion reaction rates (Table 5, reactions 24 and 25) are more uncertain because we do not have extensive measurements of the kinetic energy distributions, and there is no clear indication of how the distributions may have changed with the moderate changes in the torus detected between *Voyager 1* and *Voyager 2* encounters. The ion kinetic energy distributions are an important question for torus reactions and probably hold the key to our understanding of torus physics. We do have measurements at *Voyager 1* encounter by the in situ plasma science experiment (Bridge *et al.* 1979; Bagenal and Sullivan 1981; Bagenal 1981) and ground-based observations of S III 9532 Å emission-line width in the hot torus (Trauger, Münch, and Roesler 1979) which indicate the majority had energies of ~30 eV. However, Brown (1982*a*) in later measurements of the S II red doublets detected much higher energy non-Maxwellian ions and makes the important point that emission from kinetically hot particles tends to be hidden from the observer. The ion energy distributions are very difficult to calculate theoretically due to our uncertainties about the governing ion source and equilibration processes. These matters are discussed further below. We base the estimated rates for reactions 24 and 25 on the assumption that the sulfur ions are the fast components, although it is also possible that O III is energetic in the plasma. The rate for reaction 24 is determined by the Brown (1982*a*) measured distribution. The rate for reaction 25 is based on an assumed 200 eV energy for S III, which is near the high limit of the bounds set by the Brown (1981) observations of the S III 6312 Å line. Ion-ion reactions tend to have a very strong dependence of rate on interaction energy at the low end because of the repulsive nature of the incoming potential. Reactions 24 and 25 are slow with cross sections $\sigma < 10^{-17}$ cm^2 at sulfur ion kinetic energies at or below 55 eV. The rates applied in these reactions are based on the Brown (1982*a*) and Brown (1981) measures of S II 6700 Å and S III 6312 Å emission-line shapes, but there is a possibility these may not be typical. The potential importance of reactions 24 and 25 is discussed below.

c) *The Plasma Model*

The model calculations we describe here are based on an assumed steady state in the hot torus. There are clear observational indications that the torus is affected by transient processes (Brown, Pilcher, and Strobel 1982; Brown and Shemansky 1982), but the plasma density as a whole has shown considerable stability on time scales of ~1 year and shorter (Shemansky and Sandel 1982; Sandel and Broadfoot 1982; Brown and Shemansky 1982). Injections of neutral atoms into the plasma with a steady 10 hr period would not particularly affect the present calculations because the damping times for the ions in the plasma are much longer. Catastrophic single events such as that proposed by Richardson *et al.* (1980) (however, see Richardson and Siscoe 1982), would seriously affect a model of the

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plasma, especially the ion-ion reaction rates, which would take on a strong time dependence during the course of the event. However, the remote observations of the torus do not show evidence for such an event within the 6 month time period surrounding *Voyager 1* encounter, as required by the Richardson *et al.* (1980) hypothesis, aimed at explaining the temperature structure of the inner torus.

The calculations presented here relate to the hot torus central dense region near 5.7 R_J. This is a strong plasma source region controlling the partitioning of the plasma ions. The current calculations are therefore meant to be illustrative rather than an attempt to model the entire torus structure along the line of sight of an observation. Our model includes all of the reactions listed in Table 5 plus ion diffusive loss and constant source terms. The equilibrium equation for a given ion, N_i, having ionization level i thus takes the form:

$$\frac{dN_i}{dt} = 0 = -Y_i + \sum_{j=0}^{i-1} N_i(P_{ji} - L_{ji}) + N_i(P_{ii} - L_{ii} - D_i) + \sum_{j=i+1}^{n} N_j(P_{ji} - L_{ji}) , \quad (1)$$

where P_{ji} and L_{ji} are production and loss terms determined by the reactions in Table 5, D_i is the ion diffusive loss probability, and Y_i is a source term. The source term Y_i represents an inhomogeneous source which does not have a dependence on any of the species in the local volume. The determination of Y_i is discussed below. The production and loss terms in general, including the case $j = i$, contain species number densities, N_k, and therefore equation (1) represents a nonlinear system that must be solved through iteration. An unstated equation included in this calculation is one of charge neutrality in the computational volume. For the case involving neutral equilibrium in equation (1) ($i = 0$), the first term involving summation over j is degenerate and not present in the equation. In addition the production and loss terms

$$P_{j0} = 0 , \quad \text{all } j ,$$
$$L_{j0} = 0 , \quad j > 0 ,$$

for both oxygen and sulfur. All of the P_{j0} terms are set to zero because those reactions in Table 5 which produce neutral atoms do so at high kinetic energy and the particles leave the reaction volume in too short a time interval to play a part in subsequent reactions. The oxygen and sulfur ions considered in these calculations are coupled by the heavy particle reactions and we apply two linked matrix equations of the form

$$\boldsymbol{N} = \boldsymbol{A}^{-1}\boldsymbol{Y} , \quad (2)$$

where $\boldsymbol{N}$ and $\boldsymbol{Y}$ are the population and source vectors and $\boldsymbol{A}$ is a matrix containing the production and loss terms. Equation (2) is reduced through an iterative calculation, in which electron temperature and densities, *relative* values of Y_i, and absolute values of D_i are fixed. There is no internal means of determining the relative values of Y_i. We have found that setting the neutral source ratio

$$Y(\mathrm{O})_0 = 2 \cdot Y(\mathrm{S})_0 , \quad (3)$$

provides good agreement with observations of relative numbers of total oxygen and total sulfur species in the torus. Because of the fact that electron density is fixed to a selected value in this calculation, the absolute values of Y_i must be determined as part of the iterated solution of equation (1), along with the heavy particle populations, N_i.

The relative numbers of hot and cold electrons ($[e_h]/[e_c]$) in the torus and the ion diffusive loss probability, D_i, are model parameters traditionally taken to have considerable freedom, as discussed more fully below. Other parameters that have some limited freedom are the electron density and temperature of the cold electrons, T_{ec}. The temperature dependent rates for the electron collision reactions in Table 5 are determined from the same data applied by Shemansky (1980) to the S II–S VI species. The rate coefficients for S I are derived from the corrected Peach (1971) cross section calculations (see Peach 1968, 1969), and the coefficients for the oxygen species are taken from the measurements of Brook, Harrison, and Smith (1978), Hamdan, Birkinshaw, and Hasted (1978), and Aitken and Harrison (1971). The measured cross sections produce rate coefficients that do not differ substantially from the theoretical rates for the oxygen systems used earlier by Shemansky (1980). Rates for dielectronic and radiative recombination are derived from the same sources referenced by Shemansky (1980).

The plasma torus structural model used in these calculations is based on the Smyth and Shemansky (1982) model for the *Voyager 2* post-encounter epoch in which the electron density reaches a peak of 4000–5000 cm^{-3} at 5.7 R_J with a cold electron temperature of $T_{ec} \approx 5 \times 10^4$ K. This model appears to be compatible with post-1979 observations of S II EUV and red line emissions, according to calculations by Brown and Shemansky (1982). The crucial assumption made in this calculation (discussed in more detail below) relates to the peak region of the hot torus and is that the source particles are neutral atoms of oxygen and sulfur. The calculations we present here therefore strictly refer to the peak density region of the hot torus at 5.7 R_J, where diffusion of ions presumably goes inward and outward with no accumulation of ions from radially adjacent volumes of the torus. Thus we set

$$Y_i = 0 , \quad i > 0 \quad (4)$$

in the present calculations, and the sole source for maintaining the system is neutral atoms (Y_0). The present evidence seems to point to a distributed source of neutral atoms, and if this is correct, then the combined observations discussed earlier place rather stringent limits on the important plasma parameters.

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d) *Ion Partitioning*

If we assume a reasonable degree of homogeneity in the hot torus, the remote measurement of partitioning of ions and neutrals in the gas provide measures of a number of plasma parameters. It is of interest in this case to examine the available measures of relative densities of the S and O species in the torus for compatibility as referring to the same plasma volume. According to Brown and Shemansky (1982) S II, which has been in question as a bona fide resident of the hot torus, shows the same electron temperature as the higher ion species in the hot torus and should be considered as a well mixed component. The EUV feature at 833 Å (attributed mostly to O II) in the *Voyager* UVS spectra which has been reported as being in a constant ratio with the S III 685 Å lines as a function of radial position is also taken as an indication of a substantial degree of homogeneity as a mean torus condition (Shemansky and Sandel 1980).

The observed [S II]/[S III] ratio implies a certain minimum electron temperature on the basis of collisional ionization equilibrium (Shemansky 1980). Any additional loss process included in a statistical equilibrium plasma model, such as diffusive loss of ions, raises the electron temperature required for system maintenance. In this case the measured [S II]/[S III] ratio requires $T_{ec} > 4.0 \times 10^4$ K. The [O II]/[O III] ratio can also be taken as an indicator of minimum electron temperature, but achieving the same degree of ionization in oxygen requires substantially more energetic electrons. There are two factors that affect the two sets of species to significantly different degrees.

1. According to Scudder, Sittler, and Bridge (1981) there is an inclusion of higher energy electrons in the hot torus that requires consideration of a two-temperature model. The inclusion of small amounts of high temperature electrons $T_{eh} = 10^6$–10^7 K ($<1\%$) does not significantly affect the [S II]/[S III] ratio (Shemansky 1980), but it does have a strong effect on the magnitude [O II]/[O III], as the present model calculations show. A 0.2% inclusion of high temperature electrons reduces [O II]/[O III] to ~ 5, almost independent of the temperature (T_{ec}) of the dominant cooler electrons, an order of magnitude below the present lower limit for the hot plasma torus. Although Scudder, Sittler, and Bridge (1981) are uncertain of the accuracy their ratio $[e_h]/[e_c]$, the value they obtain is very low, $\sim 0.03\%$, for the dense region of the hot torus. The present results for [O II]/[O III] support this result, since even a ratio of $[e_h]/[e_c] = 3 \times 10^{-3}$ has a significant effect, driving the [O II]/[O III] ratio downward.

2. Diffusive loss exerts increasing control over the populations of ions as a function of increasing ionization level. As a consequence, the calculation of a collisional equilibrium in a plasma with the inclusion of a diffusive loss term tends to produce apparent cooler distributions in ion partitioning relative to expectation in electron collisional ionization equilibrium (Shemansky 1980). The present model calculations of oxygen neutral-ion partitioning as a function of ion diffusive loss time and fractional amount of hot electrons are shown in Figure 3. The chosen conditions for electron density are $[e_c] = 5000$ cm^{-3}, and $[e_h]/[e_c] = 0.0$, 2×10^{-4} and 2×10^{-3}. The electron temperatures are fixed at $T_{ec} = 5 \times 10^4$ K and $T_{eh} = 7 \times 10^6$ K to conform with the *Voyager 2* epoch model. The dependencies of the particle densities on ion diffusive loss time ($\tau = 1/D$) show the general trend discussed by Shemansky (1980) but modified by charge exchange reactions. The O I and O III populations show distinctly different dependencies on the plasma parameters. The neutral population, [O I], shows a strong dependence on the ion diffusive loss probability, but a weak dependence on the $[e_h]/[e_c]$ ratio. The [O I] dependence on D is simply driven by the rate at which new ions must be created to maintain the system against diffusive loss. Over the range of diffusive loss times in Figure 3, 10–300 d, the population of O I decreases from ~ 600 cm^{-3} to ~ 6 cm^{-3}, showing an amplified sensitivity. The O III population shows a peak in its dependence on D for lower values of $[e_h]/[e_c]$ because of partial control by reaction 20 which produces O III on the destruction of O I and S IV. The strong dependence of [O III] on the fractional amount of $[e_h]$ stems from the fact that only the high energy tail of the $[e_c]$ distribution is capable of ionizing O II. Thus even with $[e_h]/[e_c] = 2 \times 10^{-4}$, the hot electron population controls the production rate of O III. The estimated peak values of the O I and O III densities based on the Brown (1981) and present measurements are plotted as horizontal lines in Figure 3. The intercept of the O I estimated density with the model calculation corresponds to an ion diffusive loss time of $\tau \sim 130$ d. The upper limit density of O III can only be matched in this model at very short diffusive loss times, which is incompatible with the amount of O I and with the observed [S II]/[S III] ratio. The implication seems to be that O III is removed at a higher rate than the present set of reactions will allow.

The production and loss rates of the plasma species for a 100 d ion diffusive loss time and $[e_h]/[e_c] = 2 \times 10^{-4}$ in the equilibrated system are given in Table 6. The calculated populations for $\tau = 100$ d and $\tau = 10$ d, with $[e_h]/[e_c] = 2 \times 10^{-4}$ are given in Table 7, along with the scaled observational data for the *Voyager 2* epoch, and comparison data from the *Voyager 1* EUV encounter taken from Table 4.

III. DISCUSSION

The observations limiting the amount of O I and O III in the Io torus appear to place stringent limits on the plasma properties through the constraints provided by the present model. If we accept the assumptions behind that model, the ion diffusive loss time must be ~ 130 d, and the $[e_h]/[e_c]$ ratio must be severely restricted in the dense region of the torus to $\sim 5 \times 10^{-5}$ or lower. Even these stringent limits do not allow the O III density reduction required to meet the observational limit. The question that we must examine here is what latitude is available in the model assumptions. The most crucial assumption is that the source particles entering the

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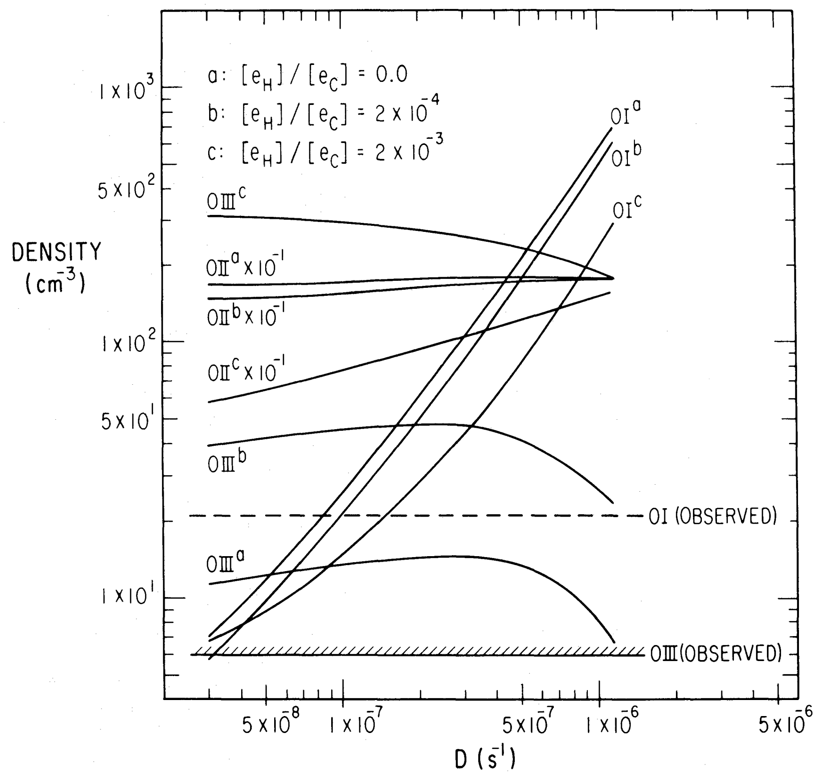

FIG. 3.—Model calculations of steady state oxygen plasma species partitioning at the location of peak electron density (5.7 R_J) in the *Voyager 2* epoch torus (Smyth and Shemansky 1982). The variables in this calculation are ion diffusive loss rate (D) and the electron energy composition ($[e_h]/[e_c]$). The electron density is fixed at $[e_c] = 5000$ cm^{-3}, with $T_{ec} = 5 \times 10^4$ K. The estimated value of [O I] and the upper limit for [O III] based on observations described in the text, are shown as horizontal lines. Other details are given in the text.

reaction volume and maintaining the plasma, are neutral atoms. Once this assumption is made the ion diffusive loss time is constrained by the observations to roughly 100 d whether or not charge exchange reactions are included in the calculations. The effect of charge exchange reactions is to increase the source rate and consequently the injection rate of neutrals into the outer magnetosphere through reactions 10–13 (Table 5).

The conversion of the present model calculation to total neutral particle injection rates is $\sim 7 \times 10^{27}$ s^{-1} for O I and $\sim 3.5 \times 10^{27}$ s^{-1} for S I, with only a fraction of the 1×10^{28} s^{-1} total ($\sim 20\%$) contributing directly to the maintenance of the torus. The possibility that ions enter the reaction volume directly as source particles would tend to change the constraint on the model in regard to ion diffusive loss time. This possibility seems to be limited, although the matter requires a thorough investigation. The direct injection of substantial numbers of ions generated on Io seems to be ruled out by observations which have shown no measurable emission in predictable EUV transitions (Shemansky 1980). The entry of SO_2 into the torus is probably equivalent to the direct injection of neutral atoms because neutral dissociation on electron impact is likely to be fast; the dissociation energy is as low as 5.61 eV (Herzberg 1966). However, SO_2 is also easily ionized with a rate coefficient of 2×10^{-8} cm^3 s^{-1} at $T_e = 8 \times 10^4$ K (from Orient and Srivastava 1982), and the branching ratio with the neutral dissociative process is unknown. Bagenal and Sullivan (1981) report the possible detection of SO_2^+ in *Voyager* plasma science in situ data, but this result can be interpreted differently, as discussed by the latter authors. The basic difficulty here is a lack of knowledge of SO_2 physical chemistry and the unknown atmospheric structure of Io. The assumption of the present model in estimating the 10 h mean densities of the source O I and S I particles is that of Smyth and Shemansky (1982) in which the atoms enter Jupiter orbits through uniform injection from Io at the escape velocity. This assumption produces predictable neutral cloud distributions around Io's orbit, the presence of which should be investigated with improved observational tools.

To some degree the deficiency in O III is a problem separable from the question of the nature of the source particles. Shortening the diffusive loss time to the point ($\tau < 10$ d) at which a suitably low value of [O III] can be obtained from the model appears unacceptable, even if our assumption concerning the nature of the source particles were incorrect. A short diffusive loss time requires an [S II]/[S III] value an order of magnitude larger than the observations will permit, and on this basis an ion diffusive loss time $\tau > 40$ d is required. This places us in a regime in the model calculations in

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TABLE 6A

PLASMA SPECIES VOLUME PRODUCTION AND LOSS RATES

Species	Rate[a]	O I	O II	O III	O IV	S I	S II	S III	S IV	S V	e
O I	a	...	9.40−5	2.62−5	...	...	1.50−4	1.31−5	...	...	9.33−5
	b	...	...	6.55−7	...	...	9.18−7	1.50−4	3.83−5	...	...
O II	a	...	...	7.01−5	...	...	9.03−5	...	...	...	7.01−5
	b	4.55−4	...	...	...	9.03−5	...	...	...	...	6.01−6
O III	a	...	8.54−5	...	8.37−7	...	3.58−6	3.75−6	8.00−5	...	1.81−6
	b	6.11−6	...	...	...	4.55−6	3.75−6	8.00−5	...	...	1.62−6
O IV	a	...	...	...	...	...	...	...	...	...	4.56−8
	b	...	...	...	...	...	...	...	...	...	2.98−7
S I	a	...	3.58−6	...	...	...	1.57−4	9.76−7	...	...	1.25−4
	b	...	9.03−5	4.55−6	...	...	...	4.46−6	2.79−5	...	...
S II	a	...	9.18−7	...	...	...	...	4.24−4	...	...	4.24−4
	b	9.18−7	...	3.75−6	...	7.29−5	...	...	...	...	3.75−5
S III	a	...	1.50−4	...	...	...	4.66−6	...	7.92−5	...	7.92−5
	b	1.50−4	...	8.00−5	...	5.67−5	...	...	...	...	1.08−4
S IV	a	...	1.31−5	...	...	...	2.62−5	2.79−5	...	3.98−6	3.98−6
	b	3.93−5	...	...	...	2.79−5	...	...	...	...	6.86−5
S V	a	...	...	...	...	...	...	...	...	...	1.17−7
	b	...	...	...	...	...	...	...	...	...	2.99−6
e	a	6.01−6	1.62−6	2.98−7	...	3.75−5	1.08−4	6.86−5	2.99−6	...	...
	b	9.33−5	7.61−5	2.46−6	3.44−7	1.25−4	4.61−4	1.88−4	7.26−5	3.11−6	...
Y		7.44−4	...	...	...	3.77−4	...	...	...	...	...
D		...	1.82−4	5.25−6	4.93−7	...	7.35−5	1.20−4	2.25−5	8.82−7	5.78−4
Total		7.44−4	3.48−4	9.66−5	8.37−7	3.77−4	5.40−4	5.42−4	1.61−4	3.99−6	8.04−4
$\tau(d)$		0.37	52.3	5.4	58.9	0.22	13.6	22.2	14.0	22.1	...

NOTE.—Each column lists production and loss rates for the species indicated at the top of the column. $T_{ec} = 5 \times 10^4$ K; [ec] = 5000 cm^{-3}. $T_{eh} = 7.0 \times 10^6$ K; [eh] = 1 cm^{-3}.

[a] a: Production rate ($cm^{-3}\ s^{-1}$); b: Loss rate ($cm^{-3}\ s^{-1}$).

TABLE 6B

PLASMA SPECIES VOLUME PRODUCTION AND LOSS REACTIONS

Species	Rate[a]	O I	O II	O III	O IV	S I	S II	S III	S IV	S V	e
O I	a	...	1, 17	20	...	...	16	19	...	...	9.33−5
	b	...	...	17, 21	...	...	11	16	19, 20	...	...
O II	a	...	...	2	...	...	12	...	...	...	7.01−5
	b	10	...	...	...	12	...	...	...	...	6.01−6
O III	a	...	15, 17		3	...	14	24	25	...	1.81−6
	b	17	24, 25		...	14, 15	24	25	...	...	1.62−6
O IV	a	...	...	...	...	...	...	...	...	...	4.56−8
	b	...	...	...	...	...	...	...	...	...	2.98−7
S I	a	...	15	...	...	...	5, 18, 23	15	...	...	1.25−4
	b	...	12	14, 15	...	...	...	18	23	...	...
S II	a	...	11	...	...	...	...	6	...	...	4.24−4
	b	11	...	24	...	13	...	...	...	...	3.75−5
S III	a	...	16	...	...	...	16, 18	...	7	...	7.92−5
	b	16	...	25	...	18, 22	...	...	...	...	1.08−4
S IV	a	...	19	...	...	...	20	23	...	8	3.98−6
	b	19, 20	...	...	...	23	...	...	...	...	6.86−5
S V	a	...	...	...	...	...	...	...	...	...	1.17−7
	b	...	...	...	...	...	...	...	...	...	2.99−6
e	a	1R	2R	3 R	...	5 R	6 R	7 R	8 R	...	...
	b	1	2, 1 R	3, 2 R	4	5	6, 5 R	7, 6 R	8, 7 R	9	...
Y		7.44−4	...	...	...	3.77−4	...	...	...	...	...
D		...	1.82−4	5.25−6	4.93−7	...	7.35−5	1.20−4	2.25−5	8.82−7	5.78−4
Total		7.44−4	3.48−4	9.66−5	8.37−7	3.77−4	5.40−4	5.42−4	1.61−4	3.99−6	8.04−4
$\tau(d)$		0.37	52.3	5.4	58.9	0.22	13.6	22.2	14.0	22.1	...

NOTE.—Reaction numbers (Table 5) corresponding to the data quantities in Table 6A. Numbers followed by the character R refer to electron recombination reactions.

[a] a: Production reaction numbers; b: Loss reaction numbers.

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TABLE 7

Voyager 2 Epoch Io Plasma Number Densities at 5.7 R_J

Species (1)	Observation[a] (2)	Observation[b] (3)	Model[c] (4)	Model[d] (5)	Model[e] (6)
O I	21	...	24.1	588	25.8
O II	...	1500	1574	1759	1646
O III	<6	<344	45.4	23.4	6.0
O IV	...	...	4.3	0.3	0.15
S I	...	...	7.2	110	7.8
S II	437	375	635	2494	741
S III	682	531	1037	343	1198
S IV	...	359	194	4.6	67.1
S V	...	...	7.6	0.06	0.71
e_c	5000	5000	5000	5000	5000
e_h	...	$\simeq 1$	1	1	0.25
T_{ec}	...	8×10^4	5×10^4	5×10^4	5×10^4
T_{eh}	...	...	7.3×10^6	7.3×10^6	7.3×10^6
Y(O I)	...	...	7.44×10^{-4}	1.61×10^{-2}	8.11×10^{-4}
Y(S I)	...	...	3.77×10^{-4}	8.15×10^{-3}	4.10×10^{-4}
D	...	...	1.157×10^{-7}	1.157×10^{-6}	1.157×10^{-7}
$\sum O_i/\sum S_i$	...	1.5	0.88	0.80	0.83

[a] Data from Table 4, col. (2) scaled to peak of *Voyager 2* model at $[e] = 5000$ cm^{-3}.
[b] Voyager 1 data from Table 4, col. (4) scaled to peak of *Voyager 2* model at $[e] = 5000$ cm^{-3}.
[c] Model calculation for $\tau = 100$ d diffusive loss time.
[d] Model calculation for $\tau = 10$ d diffusive loss time.
[e] Model calculation for $\tau = 100$ d assuming O III ion temperature $T_i = 250$ eV (see text).

which we require additional charge exchange reactions or faster rates for the relevant reactions in Table 5, along with a low $[e_h]/[e_c]$ ratio, in order to satisfy the observational constraint.

One further area of uncertainty lies with the rates of the ion-ion reactions 24 and 25 (Table 5). We do not have satisfactory measures of the velocity distributions of the reactants in these cases. In the present model the production of O III is dominated by electron ionization of O II. The temperature of O II in the plasma depends on the residence time and the rate of the symmetric charge exchange reaction 10. In the present model calculation, the rate of this reaction is approximately equal to the rate of loss of O II. If we apply the method of Shemansky and Sandel (1982), the temperature of O II in the model would be only ~40 eV if reaction 10 were excluded. The symmetric exchange process in combination with reaction 20 may then produce a higher O III ion temperature, but the rates appear not to be high enough to produce a dramatic effect. A temperature of ~200 eV would increase the rate of reaction 24 by an order of magnitude over the value given in Table 5, producing a shortened lifetime and a lower population for O III. If we assume that O III is at the corotational pickup energy and reduce $[e_h]/[e_c]$ to 5×10^{-5}, the O III population can be reduced to the observed upper limit. We note that very hot O III is less observable, so the observational upper limit is also raised. In this case, reactions 24 and 25 increase to 5.5×10^{-9} cm^3 s^{-1} and 2.6×10^{-9} cm^3 s^{-1}, respectively, and the lifetime of O III is reduced to $\tau = 1.5$ d from the 5.4 d value given in Table 6. The resultant plasma particle populations for this case are given in Table 7, column (6). The 1^{d}5 lifetime is sufficiently short to prevent substantial cooling of the ambient O III before it is removed by the loss reactions (see Shemansky and Sandel 1982) if we assume the relaxation process is controlled by Coulomb collisions. Thus the depleted O III densities may possibly be explained by the present calculations if the O III is near the corotational pickup energy. This requires a hot population of O II and/or a faster rate for reaction 20. A hot population of O II appears to be an unlikely prospect if one accepts the *Voyager 1* plasma science measurements (Bridge *et al.* 1979; Bagenal and Sullivan 1981) which indicated ~30 eV for the kinetic energy of the dominant ions near 5.7 R_J. However, according to our understanding of the plasma science experiment, this result does not preclude the presence of minor hot components in the energy distributions because energy resolution is difficult in the hot torus. Brown (1982*a*) in particular shows strong evidence for a S II energy distribution that cannot be fitted with a single Maxwellian function.

An additional observed phenomenon that is not satisfactorily addressed by the present model relates to the Brown and Shemansky (1982) observations of variability in [S II]. Those authors conclude that most of the variability occurs within a plasma volume having a relatively constant electron density, implying decoupling of S II as a controlling factor for plasma density. Although the present model predicts an [S II]/[S III] ratio consistent with the other observational constraints, the major source for S III production is ionization of S II (see Table 6). The model will therefore not allow the high degree of variability in the [S II]/[S III] ratio that the observations indicate. Moreover, the model is not

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compatible with the observation that S III is kinetically hotter than S II (Brown 1981, 1982*a*; Roesler *et al.* 1982). Trauger, Münch, and Roesler (1979) have reported a line width measurement of the S III 9532 Å emission obtained near the time of *Voyager 1* encounter, which corresponds to a temperature of ~ 30 eV. The intensity of this line in the Trauger *et al.* (1979) observation would account approximately for the EUV S III emission measured by Shemansky and Smith (1981). This earlier estimate of S III temperature is somewhat cooler than the value measured by Brown (1981), but if we compare emission lines on the basis of line width alone, S III remains kinetically hotter than the Brown (1982*b*) observations of S II. The weight of evidence thus seems to be toward higher kinetic energies in S III relative to S II. This would be consistent with decoupling between S II and S III and the established strong relative variability of [S II]. The model lifetime of S II is ~ 16 d at 5.7 R_J (Table 6). The lifetime actually shortens at radial distance up to 7 R_J because of increasing electron temperature in the model. Thus we expect S II lifetimes in the range $\tau = 4$–14 d, which appears to be compatible with most observations. However, the observations do show evidence which suggests the present set of reactions in Table 5 is not complete.

IV. SUMMARY

The observed O III abundance in the post-*Voyager 2* epoch hot outer torus shows a clear deficiency relative to expectation for a low density plasma controlled by electron collisions. The introduction of charge exchange reactions to the model calculations does suppress O III relative to the total plasma density but not to the extent required by the mean upper limit of <4 cm^{-3}. The reactions considered in the present calculations (Table 5) could account for the depressed O III concentration if the O III population were kinetically hot, >150 eV, but this requires a substantially higher rate for reaction 20 in combination with a decreased population of the hot electron component. One of the more serious uncertainties in the model calculation is our lack of knowledge of the kinetic energy of the reactants in ion-ion collisions. The dominant production process for O III in the present calculation using the nominal reaction rates is ionization of O II. The rate of O II ionization is critically dependent on the number of hot electrons $[e_h]$ in the dense region of the torus, and the $[e_h]/[e_c]$ ratio must be suppressed substantially below the value measured by Scudder, Sittler, and Bridge (1981) at *Voyager 1* encounter, in order to keep the O III population down. Another alternative for the suppression of O III is to decrease the ion diffusive loss time in the torus to below 10 d, but this is not compatible with the observed numbers of O I in the torus or with the observed [S II]/[S III] ratio. The constraints place the ion-diffusive loss time in the torus at ~ 100 d. It is difficult to place an uncertainty on this value, but given the assumption in the calculation, we estimate $\pm 50\%$.

A further indicator that the present model does not satisfactorily account for the plasma torus ion partitioning is the fact that observations (Brown 1981, 1982*a*) indicate S III is kinetically hotter than S II, and that [S II] shows substantial decoupling from [S III] (Brown and Shemansky 1982). The model with the application of the present rates indicates that the dominant production mechanism for S III is ionization of S II, and therefore cannot account for the observations. We suggest that further charge exchange reactions be investigated. The inclusion of ion-neutral charge exchange reactions in the calculations indicates that substantial numbers of neutral atoms are injected into Jupiter's magnetosphere without playing a role in the mass loading of the plasma torus.

We have set a very low upper limit on Cl III 5518 Å and 5538 Å line emission rates (<2 R) suggesting that chlorine does not play a role in the torus plasma. We report further observations of the S III 6312 Å line in the hot torus at 5.9 R_J, indicating an 58 ± 40 R emission rate.

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