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RATIO OF OXYGEN TO SULFUR IN THE IO PLASMA TORUS

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Abstract. Model calculations of collisional diffusive equilibrium in the Io plasma torus using the most recent estimates of reaction rates and electron excitation collision strengths indicate that oxygen and sulfur ions are partitioned roughly equally as major species, in conformity with Voyager EUV measurements of O II, S II, and S III emissions, and with recent rocket observations of O I and S I emissions.

Introduction

The relative abundance of oxygen and sulfur ions in the Io torus is important to major aspects of theories which attempt to describe the mechanisms of origination and maintenance of the system. The radiative cooling efficiencies of the two sets of species differ significantly and oxygen/sulfur partitioning therefore affects calculations of equilibrated temperatures, and energy injection rates required to maintain the torus. Moreover, partitioning of plasma species reflects the nature of Io's atmosphere and the processes by which mass is delivered to the torus (see, for example, Hunten [1985]). Oxygen/sulfur (OX/SX) ion partitioning in the hot torus based on ion emissions is not easily measurable by ground-based observation, and the Voyager EUV spectrometer (UVS) experimental data are the only observational result showing strong O II, S II, and S III lines in close spectral proximity. Recent analysis of rocket observations [Skinner and Durrance, 1986] has obtained measurements of O I and S I emission, and now provides an additional measure of OX/SX directly from the source particles. Results from the in situ Voyager plasma science (PLS) experiment in the hot torus are not yet at a sufficiently advanced stage [Bagenal and Shemansky, 1985] to provide useful limits on the OX/SX value. However, PLS results in the cold torus [Bagenal, 1985] do provide defined OX/SX partitioning. Quantitative results are basically consistent with OX/SX ~ 1.

Recent work by Moreno et al. [1985], hereafter referred to as MNK, has suggested that the torus is dominated by sulfur. MNK argue that the abundance of oxygen should be depressed relative to sulfur in the Io torus primarily on the basis of a combination of observations described by Brown, Shemansky, and Johnson, [1983], hereafter referred to as BSJ. The first observation in question was a Voyager I EUV spectrum initially analyzed by Shemansky and Smith [1981]. A ground-based observation obtained two years later, described by BSJ, fixed an upper limit on the abundance of O III in the plasma. The difficulty with this combination of observations as described by BSJ was that the analysis of Voyager EUV data required the sum of O II and O III abundances to be larger than the total amount of sulfur. If the ground-based observations placed the O III abundance at a negligible level, then the Voyager spectrum would necessarily be interpreted as being dominated by O II (see the detailed discussion by BSJ). The basis of the MNK argument is that the oxygen abundance must be small, because of their claim that large values of the [O II]/[O III] ratio cannot be obtained theoretically, and that the observations can actually tolerate much smaller abundances of oxygen, obviating the requirement of a large [O II]/[O III] ratio. In contrast, the earlier work by BSJ indicated that two factors were the most likely explanation: uncertainty in charge exchange or charge changing reactions and moderate changes in the torus from 1979 to 1981 between the times of observation. The temperature range of the torus as noted by BSJ places O III in the category of an unstable species; the production and loss rates of O III are extremely sensitive to both electron temperature and the temperature of the heavy plasma particles. This paper argues that large values of the [O II]/[O III] ratio can be obtained theoretically, given present knowledge of the plasma parameters, and the weight of observational evidence points to a plasma torus roughly equally partitioned between oxygen and sulfur.

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Spectroscopic Constraints

The quantities relevant to the discussion of spectroscopic constraints are the relative number densities of oxygen and sulfur ions in the plasma. MNK favor partitioning in the torus in the following proportions,

$$[\mathrm{O\ II}]/[\mathrm{S\ III}] < 0.48$$

$$[\mathrm{O\ II}]/[\mathrm{S\ II}] < 0.50$$

as maximum values in their analysis and judgment. Analysis of the Voyager 1 spectra near encounter produces the values 3.0 and 4.1 respectively, using present values of collision strengths. The latter ratios are based on the measured intensities of S III, S II, and O II multiplets at 680-700 Å, 765 Å, and 833 Å. The weak O II multiplet at 539 Å is not measured in these data because of overcompensation by the reduction scattering matrix in the short-wavelength region of the spectrum. The overcompensation appears to be caused by a change in the scattering properties of the instrument grating subsequent to launch. The history of the analysis process and a description of the uncertainty in determining intensities of weak emission near 539 Å is described in the appendix. The analysis of the EUV spectra is discussed in detail by Shemansky and Smith [1981] and subsequently by BSJ. The latter work produced an altered partitioning of ions, principally [O II]/[O III], on the basis of improved knowledge of collision strengths and other factors. These matters are discussed in detail by BSJ. Given the fact that the plasma torus is dominated by oxygen and sulfur species, the 833-A feature can be attributed only to either O II, O III or a combination of O II and O III (BSJ). The feature at 833 Å is consistently the brightest concentration of emission within a ±1-Å range, in the analyzed spectra. An investigation of other possible sources of 833-Å radiation was conducted by BSJ with the conclusion that the feature could be attributed only to oxygen; the search for other possible species is restricted by the requirement that emission at this particular wavelength must have collision strengths attributable to resonance (large collision strength) transitions in order to be compatible with the measured plasma number densities (BSJ). Both the Shemansky and Smith [1981] analysis and the BSJ analysis on this basis require that approximately 1/2 of the plasma number density be attributed to oxygen.

MNK argued that the observed Voyager EUV spectrum can be satisfactorily synthesized with their depleted oxygen model. However, the MNK synthesis applies only to a single feature in the spectrum, the O II 833-Å line. The relevant

TABLE 1. Relative Abundances of Oxygen and Sulfur Ions in the Io Plasma Torus

Transition[a]	λ, Å[b]	I[c]	I[d]	Ω/ω_i[e]	k, 10^{-9} cm^3 s^{-1}[f]	$[N_i]$[g]	$[N_i]$[h]
S III (1,11+12+13)	680	100	100	4.80	7.2	100	100
S II (1,18)	765	26	31	1.60	2.5	71	93
O II (1,4)	833	85	13	0.99	2.0	307	48
O III (1,5)	834		0.7	0.82	2.0		2.6

[a] S III: 1 ≡ $3s^23p^2\ ^3P$; 11 ≡ $3s^23p(^2P^0)3d\ ^3P^0$; 12 ≡ $3s^23p(^2P^0)4s\ ^3P^0$; 13 ≡ $3s^23p(^2P^0)3d\ ^3D^0$. S II: 1 ≡ $3s^23p^3\ ^4S^0$; 18 ≡ $3s^23p^2(^3P)3d\ ^4P$. O II: 1 ≡ $2s^22p^3\ ^4S^0$; 4 ≡ $2s\ 2p^4\ ^4P$. O III: 1 ≡ $2s^22p^2\ ^3P$; 5 ≡ $2s\ 2p^3\ ^3D^0$.

[b] Approximate wavelength (angstroms).

[c] Relative quantum emission rate from Shemansky and Smith [1981].

[d] Relative quantum emission rate using MNK model (column 2, Table 5, of MNK).

[e] Thermally averaged collision strength (Te=$6.5x10^4$ K) scaled by degeneracy of the lower state. Atomic data from Ho and Henry [1983a,b, 1984].

[f] Emission rate coefficients (Te=$6.5x10^4$ K) calculated according to the exact method of Shemansky and Smith [1981].

[g] Relative abundance calculated from the Voyager results using data of the third and sixth columns.

[h] Relative abundance of the MNK model (column c of Table 3, MNK).

question is the oxygen/sulfur ratio, and apparently because MNK apply a scale factor to the calculation that is not related to the relative intensities of the sulfur lines in the Voyager spectrum, the resultant discrepancy with the original analysis is a factor of 6 in the O II/ SII and O II/S III ratios. If the MNK result accounts for 55% of the O II line (MNK), the quantity of sulfur in the calculation is a factor of ~3 too large relative to the sulfur lines in the spectrum. Table 1 shows the measured relative brightness of sulfur and oxygen lines, collision strengths and rate coefficients. Normalization to the sulfur lines leads to a deficiency of a factor of 6 in the MNK model relative to observation of the 833-Å emission, as shown in Table 1. MNK appear to have made a basic indeterminate computational error, in stating that the Voyager spectrum can be modeled with their recommended ion partitioning. Figure 1 of the MNK paper, presented as a successful model of the Voyager UVS spectrum, is not relevant to the question of sulfur/oxygen partitioning because it shows only the O II 833-Å line. It is clearly impossible to fit the Voyager spectrum given the MNK model parameters as shown in Table 1, unless one arbitrarily adjusts relative collision strengths by a factor of 6.

MNK do suggest that collision strengths for the O II 833-Å multiplet are uncertain by factors of 2 or more, citing calculations by Shemansky [1980] and Davis et al. [1975] as showing an order of magnitude range of estimated collision strengths between 1 and 10. However, the Shemansky [1980] value in fact is 2.7 and refers to the magnitude at threshold. This agrees exactly with the threshold value given by Ho and Henry [1983a] although the [Shemansky, 1980] calculation is only a rough estimate based on the Coulomb approximation. The Davis et al. [1975] value must be empirically adjusted downward by the ratio of the experimental to theoretical [Davis et al., 1975] oscillator strengths to a value of 5. The most accurate calculation by Ho and Henry [1983a], giving a value of ~ 4 at energies of interest here, is applied to the BSJ and subsequent analyses. In summary the estimated thermally averaged collision strengths from the three sources are as follows:

	$\Omega(<10^4$ K)	Ω (6 x 10^4 K)
Davis et al. (1975) (corrected)	4.8	4.9
Shemansky [1980]	2.7	2.7
Ho and Henry [1983a]	2.7	4.0

The thermally averaged collision strengths are effectively invariant below Te=10^4 K because the specific collision strength is finite at threshold. This is a general characteristic of all ion transitions, caused by Coulomb interaction effects. The published estimates of collision strengths therefore differ by less than a factor of 2, in spite of the fact that the quality of the calculations is such that the earlier work should be disregarded in favor of the recent extensive calculation by Ho and Henry. The calculations resulting in Table 1 take full account of the energy dependence of the collision strength, and include nonlinear effects in the collisional system [Shemansky and Smith 1981]. The Ho and Henry [1983a] results are based on a close coupling multistate configuration interaction (CI) structure. The Ho and Henry [1983a] CI calculation of oscillator strength (fij) values is in close agreement with experimental measurement, an indication that the collision strengths as a conservative estimate are uncertain at the $\leq$30% level (R. J. W. Henry, private communication, 1985). It seems improbable that the O II 833-Å transition collision strengths are in error by a factor as large as 2.

Other Uncertainties in the Calculated Ion Partitioning

There are two factors affecting the relative population of O III in the torus plasma that require a critical examination. First, the ionization rate of O II, as the major source for production of O III is extremely sensitive to the electron temperature prevailing in the torus. At Te=$5x10^4$ K the rate coefficient for the reaction

$$\text{(R2)} \qquad e + O^+ \rightarrow O^{2+} + 2e$$

is 4 orders of magnitude below the peak value ($3x10^{-12}$ cm^3 s^{-1} compared to $3x10^{-8}$ cm^3 s^{-1}). This indicates that the rate coefficient at plasma torus temperatures is determined by near-threshold values of the cross section for (R2), or by the abundance of hot electrons. The rate coefficient is also extremely sensitive to small variations in temperature, with factor of 2 variations in rate resulting from a 10% change in temperature. The observational evidence suggests that mean electron energies have varied by at least this amount. The inclusion of trace amounts of high-temperature electrons [Scudder et al., 1981] will affect the population of O III differentially in relation to the other species (BSJ). The density of the high-temperature component in the dense region of the hot plasma torus is not well defined by direct measurement, and could easily be a variable quantity. The suggestion by MNK that the torus is basically an invariant entity is simply not supported by observation [cf. Sandel et al., 1979; Morgan, 1985; Judge and Shemansky, 1985,

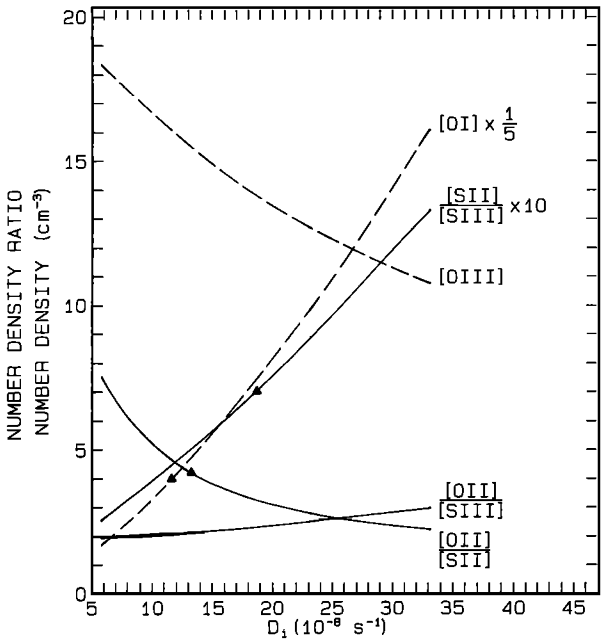

Fig. 1. Collisional diffusive equilibrium in an oxygen/sulfur plasma as a function of ion diffusive loss probability (Di), for conditions approximating observation near the time of Voyager 1 encounter. Dashed lines show selected species number densities. Solid lines show number density ratios. Plotted points show measured quantities (see BSJ). Plasma parameters: $[e]_1$ = 2000 cm^{-3}; $[e]_2$ = 0.6 cm^{-3}; Te_1 = 5.8 x10^4 K; Te_2 = 1.2x10^7 K; Y(O)/Y(S) = 4.0. Reaction rate coefficients are as given in Table 2 and BSJ.

Appendix]. Second, the loss of O III ions tends to be controlled by the charge exchange reactions

(R3) $O^{2+} + S^{+} \rightarrow O^{+} + S^{2+}$

(R4) $O^{2+} + S^{2+} \rightarrow O^{+} + S^{3+}$

in combination with diffusive loss and dielectronic recombination.

The stated uncertainty in the charge exchange reaction rates is a factor of about 2 at moderate interaction velocities and larger at low velocity [Johnson and Strobel, 1982]. The reactions (R3) and (R4) are rather sensitive to ion temperature in the range of values estimated for the plasma torus. A recent analysis by Bagenal et al. [1985] has revised ion temperatures upward by a factor of 2, raising the estimated rates for (R3) and (R4) substantially upward. Furthermore, the significant populations of S II ($3s^23p^3$ $^2D^0$) and O II ($2s^22p^3$ $^2D^0$) ions produced in the torus require investigation as charge exchange reactants, lending further uncertainty to the partitioning process in the equilibrated system. Dielectronic recombination coefficients are intrinsically more difficult to calculate than electron collision strengths. Recent experimental work [Mitchell et al., 1983; Belic et al., 1983] indicates coefficients for C II and Mg II larger than theoretical calculation by factors of 5 or more. Similar discrepancies are expected for other species, and a species such as O III would be affected differentially by a ~ 5-fold increase to a loss rate that would compete with (R3) and (R4). Uncertainties in the quantities discussed here are related to the resultant ion partitioning described in the following section.

In summary, the population of O III is extremely sensitive to plasma parameters under these conditions, and cannot be regarded as a definitive factor in the determination of the amount of oxygen in the torus. The production rate of O III is determined by ionization of O II at near-threshold energies where both laboratory and theoretical cross sections are uncertain by factors of the order of 2. Moreover, electron mean energy distributions are not known either instantaneously or over the long-term average, with enough accuracy to allow a production rate calculation of O III with better than factor of 2 accuracy, given exact cross sections. The loss process for O III is also uncertain by factors of the same order. An unfortunate combination of these quantities could leave a model calculation in error by an order of magnitude, without even considering uncertainty in collision strengths for emission lines. Although absolute rate coefficients change rapidly with temperature for these species relative rates do not, and a calculation at Te=5.5x10^4 K as opposed to one at Te=6.5x10^4 K for example, leaves the measured relative abundances basically unchanged in Table 1.

Model Calculation of Ion Partitioning

Figures 1 and 2 show model calculations of ion partitioning for various conditions using the method described by BSJ. The source particles, as in the BSJ and MNK calculations, are composed of neutral atomic oxygen and sulfur. A source rate ratio Y(O)/Y(S)=4.0 is applied in all cases calculated here (see BSJ). This is not necessarily an optimum value for modeling the data as described below. All of the model calculations shown by MNK are at least an order of magnitude smaller in this quantity, Y(O)/Y(S) $\lesssim$0.33. Reaction rates in the present calculations differ from those of MNK by more than ~10% for reactions 14, 19, 20, 24, and 25 as defined by BSJ (see Table 2). The rates for these reactions in principle are ultimately derived from BSJ and Johnson and Strobel [1982]. However, the values shown by MNK for reactions 14, 19 and 20 differ with the original source by factors ranging from 1.4 to 2.3

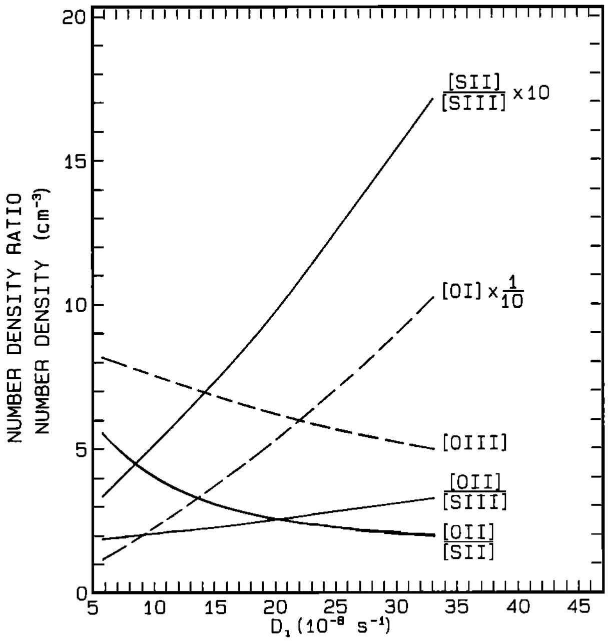

Fig. 2. Collisional diffusive equilibrium in an oxygen/sulfur plasma as a function of ion diffusive loss probability (Di), for conditions approximating observation in the Voyager post-encounter epoch. Plasma parameters: $[e]_1$ = 3000 cm^{-3}; $[e]_2$ = 0.0; Te_1 = 5.5x10^4 K; Y(O)/Y(S) = 4.0. See caption Figure 1.

TABLE 2. Prominent Differences in Reaction Rates Applied to Plasma Model Calculations

Reaction[a]	k, 10^{-9} cm^3 s^{-1} [b]	k, 10^{-9} cm^3 s^{-1} [c]
14	11.0	15.2
19	4.4	10.0
20	5.6	10.4
24	5.9	0.13
25	2.8	0.028

[a] Reaction numbers from Table 5 of BSJ: (14) $O^{2+} + S \rightarrow S^+ + O^+$; (19) $S^{3+} + O \rightarrow S^{2+} + O^+$; (20) $S^{3+} + O \rightarrow S^+ + O^{2+}$; (24) $O^{2+} + S^+ \rightarrow O^+ + S^{2+}$; and (25) $O^{2+} + S^{2+} \rightarrow O^+ + S^{3+}$.

[b] Present rate coefficients derived from Johnson and Strobel [1982].

[c] Rate coefficients of MNK.

(Table 2). Reactions 24 and 25 as defined by BSJ depend critically on the ion temperature, and the rates in this case are increased substantially because of the factor of 2 upward correction to the ion temperature established by Bagenal et al. [1985]. The rates applied here for reactions 24 (R3) and 25 (R4) are in the range $2\text{x}10^{-9}$ cm^3 s^{-1} to $6\text{x}10^{-9}$ cm^3 s^{-1} as derived from the Johnson and Strobel [1982] work. These rates differ by 2 orders of magnitude with the value used by MNK for (R4) and by a factor of about 45 for (R3). These rates are not clearly defined because at present the only detailed derivations of ion species energy distributions are theoretical [Smith and Strobel, 1985]. The Smith and Strobel [1985] calculations, however, require revision with substantial corrections to radiative cooling coefficients [Smith, 1986; Shemansky, unpublished manuscript, 1986]. Table 2 contains a list of the reactions in question and values of the rates applied here compared to those of MNK. Figure 1 shows a plot of species number densities and ratios as a function of ion diffusive loss probability. The electron densities and temperatures are the same as those applied to the MNK model. The combination of hot and cool electron populations is roughly equivalent to a single temperature electron gas at Te=$6.5\text{x}10^4$ K, recommended here for mean conditions in the dense region of the plasma at Voyager 1 encounter. The densities of O III shown in Figure 1 are comparable to the MNK value, in spite of the fact the present model injects oxygen at ~10 times the MNK relative rate. The observed species partitioning fits the model calculation in the ion diffusive lifetime range between 60 and 100 days (see the plotted points in Figure 1). The results shown in Figure 1 thus basically satisfy the observational constraints. Figure 2 shows similar calculations which may be more representative of the post-Voyager encounter epoch in which the plasma density is moderately higher, and the mean electron energy moderately lower. Although the plasma density is higher in this case, the [OIII] densities are below those for the case shown in Figure 1 by a factor of about 2, a consequence of the lower electron temperature. The [O III] densities shown in Figure 2 are near the upper limit set by BSJ, whereas typically [O II] >1000 cm^{-3} for the relative rates applied to the present calculation. Table 3 shows specific model calculations estimated to be applicable to the two cases, in comparison with the MNK results. Note that the present model calculations (for Voyager 1) in Table 3 conform to the electron physical parameters of MNK for comparative purposes and are therefore not an optimum fit to the Voyager UVS data. The Skinner and Durrance [1986] measurement of the source particle density ratio [O I]/[S I] = 5 is in basic agreement with a plasma population roughly equally partitioned in oxygen and sulfur ions as indicated by the model calculations in Table 3.

Summary

Model calculations of collisional diffusive equilibrium in the hot dense region of the Io plasma torus, using reaction rate coefficients within estimated uncertainties, show basic conformity with observational constraints. This is not to be taken as an implication that substantive questions relating to actual conditions in the torus have been settled. The model calculations of ion partitioning, for example, show distinct differences with estimates of S IV abundance obtained from Voyager data [see BSJ; Moos et al., 1985]. A solution of this problem may come at least partially from our changing knowledge of the S II emission system; models of this system have shown an increasingly complex EUV emission structure as time has progressed, overlapping with prominent S IV transitions. Recent work (Y. K. Ho, R. J. W. Henry, and D. E. Shemansky, in preparation, 1986) indicates that further significant changes will be introduced for forbidden S II transitions; allowed transitions remain as calculated by Ho and Henry [1983b].

A basic fact of the analysis of the Voyager EUV spectrum is the prominence of O II emission transitions in the multiplet near 833 Å. The oxygen/sulfur partitioning inferred from the Voyager spectrum, using current electron collision strengths, indicates approximately equal proportions of the two sets of species. The model calculations shown here, which conform to this division, require that oxygen atoms be injected into the torus at as much as 4 times the rate for sulfur. This result is in basic agreement with recent [O I] and [S I] measurements by Skinner and Durrance [1986]. The MNK model, which advocates oxygen/sulfur partitioning in a ratio of 1/3 or less, predicts relative intensities of oxygen and sulfur lines in the EUV spectrum which disagree by a factor of 6 or more with the observed Voyager spectrum.

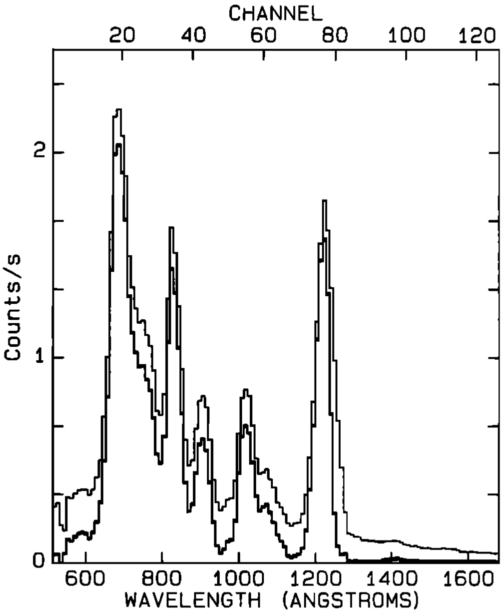

Fig. 3. Voyager 2 UVS spectrum of the dusk ansa of the Io plasma torus. The light line is a spectrum obtained 1979 day 208 beginning at 1701 UT; duration 83,700 s; range to planet 1.479 x 10^7 km. The spectrum is corrected for fixed pattern and background noise. The heavy line is the spectrum subsequent to correction by the scattering matrix operator, removing the internal scattered photon component from the spectrum. The spectrum includes interplanetary background (IPM) signal mainly at 1216 Å and 584 Å .

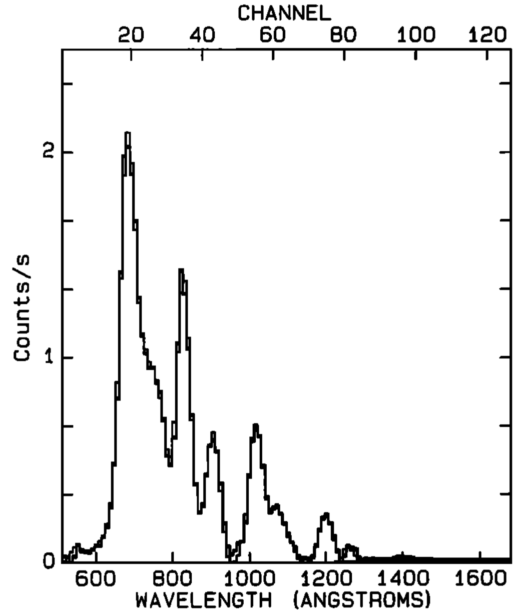

Fig. 4. The reduced spectrum of Figure 3 after removal of the IPM background (heavy line), compared to a model (light line), as described in the appendix.

Appendix

Analysis of Voyager EUV torus spectra; the O II 539 Å line

An upper limit on the intensity of the O II 539-Å line (<0.8 R) was obtained by Shemansky and Smith [1981] on the basis of analysis of a Voyager 1 (V1) spectrum. The Voyager UVS spectra are reduced using a scattering matrix operator (SMO) which compensates for internal scattering of photons caused mostly by the grating. The scattering matrix was developed using laboratory calibration data. It was subsequently found on the examination of stellar spectra that the applied matrix was overcompensating for the scattered photon component of the signal. This implies that scattering characteristics changed after launch, presumably caused by scrubbing of the gratings under constant hard vacuum. Consequently, weak signals such as the O II 539-Å line were seriously affected by overcorrection of scattering, particularly from nearby bright features at ~685 Å. A correction to the Voyager 2 (V2) SMO was made on the basis of observation of stellar emission and interplanetary medium measurements of the H Ly α line. An accurate correction is therefore developed for source features at wavelengths longward of 900 Å. The correction for source features shortward of 900 Å necessarily depends on a nonlinear extrapolation to 500 Å. We therefore have a basic uncertainty in the scattering properties of the instruments at short wavelength. A corrected SMO for V1 has not yet been established. Figure 3 shows plots of a V2 spectrum of the Io torus obtained on 1979 day 208, before and after the application of the SMO. Approximately 1/2 of the signal in the region shortward of 600 Å is composed of scattered photons in this particular spectrum. The original SMO attributes a large majority of the signal in this region to scattered photons. The spectrum shortward of 600 Å in Figure 3 shows no particularly well-defined features, and is typical of Voyager spectra of the torus. The spectrum shown is among the brighter emissions observed and is of very high quality because the integration time is ~ 22 hours. The 1σ statistical uncertainty of the signal in the reduced spectrum below 600 Å is ~ 10%. A weak peak in the spectrum occurs at the location of the interplanetary He 584-Å line. This component and the H Ly α line are removed in the analysis by subtraction of an interplanetary (IPM) background spectrum obtained in the same part of the sky. The reduced spectrum after subtraction of the interplanetary component is shown in Figure 4. Approximately 1/2 of the signal at 584 Å is attributable to the 584-Å IPM feature, and the residual signal is essentially featureless. The analysis of the < 600-Å part of the spectrum is further complicated by the fact that in both the V1 and V2 instruments, signal channels 3 and 4 are subject to strong fixed pattern threshold effects and the data in these channels are not usable as valid signal. The O II 539-Å line is centered on channels 3 and 4 in the V2 instrument and on channel 1 on V1. Thus in both cases the full profile of the line is not available for analysis. The continuumlike appearance of the signal at < 600 Å conforms with model calculations; several features, dominated by S II, contribute to this part of the spectrum. In 1981 the strengths of these lines were unknown quantities. Figure 4 shows a fit to the spectrum established using known multiplet structures of the torus species, but independent of model collision strength constraints. The brightnesses of selected multiplets in the spectrum are given in Table A1. The partitioning of the S IV 745-Å and S II 766-Å lines is uncertain in this particular spectrum, and the relative brightness values of these lines are much more uncertain than the statistical uncertainty derived from the 80,000-s integration time. The Shemansky and Smith [1981] analysis of the V1 spectrum obtained 1979 day 60 is also shown for comparison in Table A1, modified by subsequent changes in our knowledge of species properties. In particular a strong feature of S II (BSJ) is established at 765 Å, and the 906- to 910-Å feature is attributed to several multiplets of S II. Both spectra were obtained on the duskside of Jupiter near the torus ansa. The major differences between the spectra appear to be in electron temperature and emission brightness, rather than in oxygen/sulfur partitioning. The later V2 spectrum is brighter and suggests a substantially colder effective electron temperature as defined by the relative intensities of the S III 680- to 685-Å, 1020-Å and 1200-Å multiplets. The estimated electron temperatures are Te = 45,000 K and 65,000 K for the V2 and V1 spectra respectively. The estimated brightnesses of

TABLE 3. Model Calculations of the Io Torus Hot Plasma Partitioning Typical of 1979 and Later Conditions

	Present Work, V1[a]	Present Work, V2[b]	Model Calculations of MNK
O I	37.	48.	25.4
O II	848.	1343.	274.5
O III	13.8	6.3	14.0
O IV	0.7	0.006	0.3
S I	4.8	6.4	29.7
S II	259.	497.	516.1
S III	366.	543.	569.6
S IV	41.7	20.4	16.0
S V	1.4	0.03	...
$[e]_1$	2000.	3000.	2000.
$[e]_2$	0.6	0.0	0.6
$[Te_1]$, 10^4 K	5.8	5.5	5.8
$[Te_2]$, 10^7 K	1.2	...	1.2
$\bar{z}$	1.3	1.25	1.44
τ, days	62.	62.	33.2
$\Sigma Oi/\Sigma Si$	1.3	1.3	0.26
Y(O)/Y(S)	4.0	4.0	0.33

Densities in units of cm^{-3}.

[a] Present work, approximate Voyager 1 encounter conditions.

[b] Present work, approximate Voyager 2 postencounter epoch.

Table A1. Analyses of Voyager EUV Spectra

		Brightness, R	
λ, Å	Species	Present Work [a]	Shemansky & Smith [b]
539	O II	~6±4	...
550-610	S II, S IV	~7±3	...
641	S II	~ 15	...
661	S IV	67	56
680-685	S III	196	106
700	S III	237	130
725	S III	223	53
745	S IV	80	75?
765	S II	140	75?
833	O II, O III	480	200
906-910	S II	250	84
1020	S II, S III	256	108
1062	S IV	158	102
1194	S III	380	107
1256	S II	95	43

[a] Analysis of Voyager 12 1979 day 208 spectrum shown in Figure 4 (see text).
[b] From Shemansky and Smith [1981] Voyager 1 1979 day 60 modified to include subsequent changes in known spectral properties at 745 Å, 765 Å, and 906-910 Å (see text).

the weak multiplets at < 600 Å are very uncertain because of the factors discussed above. Table A1 contains no estimate of brightness for the V1 spectrum at < 600 Å because a corrected SMO has not yet been constructed. The weak features at < 600 Å are of the order of 1% of the major cause of the scattered photon contamination, the emissions at 680-700 Å.

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