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DETERMINATION OF IONIC ABUNDANCES IN THE IO TORUS USING THE HOPKINS ULTRAVIOLET TELESCOPE

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ABSTRACT

During the Astro-1 mission in 1990 December, the Hopkins Ultraviolet Telescope was used to obtain a 415–1864 Å spectrum of the emissions from the Io torus with ~3 Å resolution in first order (830–1864 Å). The ~1274 s observation of the east ansa took place during orbital night when spectral contamination by terrestrial airglow was minimal. A list of the 31 strongest features shows that, apart from five features that are totally or partially terrestrial, all are due to O^+, S^+, S^{++} and S^{+++}. There is no evidence for elements other than oxygen and sulfur. However, the spectrum shows many additional weaker emission features so that the existence of minor species cannot be ruled out at this time. Because the HUT spectrum contains well resolved lines for all four of the major species, the mixing ratio (N_i/n_e) for each ion can be determined without using models of the spectral emissions, as is required for analysis of the *Voyager* UVS data, or a detailed geometric model of the torus plasma, as is required for *IUE* data. The relative concentration of O^+ determined from the HUT observation is 38% less than that obtained from the *Voyager* UVS data. O III] λλ1661, 1666 was detected at the 2 σ level.

Subject headings: planets: charged particles — planets: magnetospheres — planets: satellites — ultraviolet: spectra

1. INTRODUCTION

Ground-based (Kupo, Mekler, & Eviatar 1976), *Voyager* (Broadfoot et al. 1979) and near-Earth observations (Moos & Clarke 1981) have shown that material expelled by volcanic activity on Io (Peale, Cassen, & Reynolds 1979) finds its way into a plasma torus near the path of Io about Jupiter. (See the review by Brown, Pilcher, & Strobel 1983). Ultraviolet observations of the torus are of especial importance because the far and extreme ultraviolet emissions can come only from species located in the warm ($T_e \sim 60{,}000$ K) plasma near the center of the torus. Also, most of the strong spectral lines which dominate the radiative energy loss from the torus occur in this spectral region. The only prior ultraviolet observations of the torus with coverage below 1200 Å were obtained by the *Voyager* ultraviolet spectrograph (UVS). Because the UVS has a spectral resolution of 30 Å and the spectrum of sulfur ions in this wavelength region is complex, in order to analyze the data it was necessary to assume model spectra for each candidate ion and then adjust them for a best fit to the broad measured spectral profiles (e.g., Shemansky & Smith 1981). On the other hand, *IUE* spectra (Moos et al. 1985; McGrath et al. 1990) and rocket results reported to date (Durrance, Feldman, & Weaver 1983) cover only the spectral region above 1200 Å. This region includes no emissions from O^+; for *IUE* observations, the relative concentration of O^+ ions has been determined by using a detailed model of the plasma distribution to obtain the relative concentrations of S^+, S^{++}, and S^{+++} while requiring that the O^+ concentration be that necessary for plasma neutrality. Thus, it has been recognized for some time that there is a need for a spectrum of the torus extending to wavelengths well below 1200 Å with a few angstroms resolution for a number of reasons: to serve as a guide in interpreting the *Voyager* data, to provide a more direct measurement of the relative ionic concentrations, to search for new previously undetected species, and to identify for future missions (e.g., *HST*, Astro-2, and Lyman-FUSE) those spectral lines which will best serve as temperature and density diagnostics. We have obtained a spectrum of the east ansa at 3 Å resolution at a time when Io was well outside the slit. In this letter we identify the strong spectral features and determine the relative abundances of the primary species in the torus plasma. These values are critical for examining scenarios for plasma injection, transport and heating (Smith & Strobel 1985; Shemansky 1988). Examples of density and temperature sensitive emissions are also presented.

2. OBSERVATIONS AND SPECTRA

The observation was carried out with the Hopkins Ultraviolet Telescope (HUT) (Davidsen et al. 1991) as part of the Astro-1 space shuttle mission in 1990 December. The HUT instrument consists of a 0.9 m mirror that feeds a prime focus spectrograph with a photon-counting microchannel-plate detector and photodiode-array readout (Hartig et al. 1982; Long et al. 1985). The instrument covered 830–1864 Å in first order and 415–932 Å in second. The dispersion in first order was 0.51 Å per pixel, and the limiting spectral resolution for the 9″.4 by 116″ spectrograph aperture selected for this observation was ~3 Å in first order and ~1.5 Å in second order.

The observation of the east ansa began on 1990 December 10 at 2:12 UT. The data presented here were obtained in a

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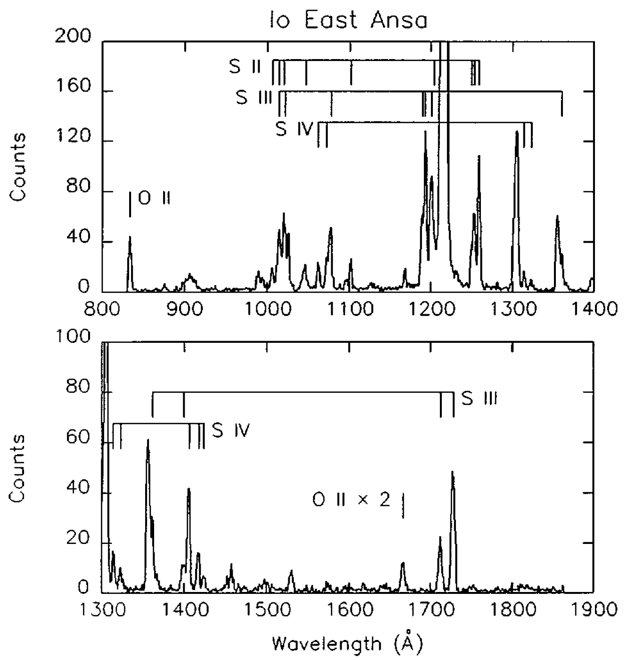

FIG. 1.—Emission spectrum of the east ansa of the Io torus obtained by the Hopkins Ultraviolet Telescope. The data are smoothed over three adjacent 0.51 Å pixels. Strong emissions from the Io torus are marked and listed in Table 1. The feature marked O II near λ1667 consists primarily of O II λ834 in second order. In addition, there probably is a small amount of O III] λλ1661, 1666 contributing to the feature. (See text.)

1274 s integration during orbital night when the line of sight through the terrestrial atmosphere was not illuminated by the Sun. The entrance slit of the spectrograph was centered at 5.9 R_J with the long dimension along the torus (where R_J) is the radius of Jupiter). The projected dimensions of the slit at a distance of 4.68 AU to Jupiter were 0.43 R_J by 5.52 R_J. During the observation, Io was near the east limb of the planet well away from the entrance aperture of the spectrograph.

Figure 1 presents a ~3 Å resolution spectrum of the east ansa. The data have been smoothed over three adjacent 0.51 Å pixels. A number of the strongest features are identified in Figure 1 including O II λ834 and a number of features due to S II, S III, and S IV. Table 1 lists 31 features which are readily identified in the spectrum. Most of these lines contain more than 100 photon events; the weakest, S IV λ1424, contains 47. Airglow contamination is negligible except for five features (H I λ1026, He I λ584 in second order, H I λ1216, O I λ1304 and O I λ1356). Examination of the O II λ834 brightness as a function of time and geographic position shows that it is not contaminated by terrestrial emissions.

The spectrum shows evidence for a small amount of O^{++}. A feature at λ1667 is largely due to O II λ834 in second order. However, a comparison with the expected ratio of second to first order determined by measuring terrestrial emissions in other observations shows an excess of 24%. This is attributed to O III] λλ1661, 1666 with a brightness of 2 ± 1 *R*. The detection is only at the 2 σ level. However, a similar result is obtained from a 6 Å resolution spectrum of the west ansa. The excitation coefficients of Aggarwal (1983, 1985) predict a brightness of 11 ± 5 *R* for [O III] λ5007 compared to the upper limits of 3 and 7 *R* for the east and west ansas, respectively, reported by Brown, Shemansky, & Johnson (1983). The properties of the torus may be variable, and this feature should be restudied.

An important question is whether elements other than oxygen and sulfur contribute to the spectrum. The work of Pettersson (1983) on the S II spectrum and the recent compilation of the energy levels of S I through S XVI by Martin, Zalubas, & Musgrove (1990) gives greater assurance to the identifications. Aside from five features due wholly or in part to terrestrial emissions, the strong features can all be assigned to the ions of oxygen and sulfur. The feature designated S II? in Table 1 is an intercombination transition predicted from known energy levels (Kelly 1987) that was probably quenched in the laboratory discharges used by Pettersson (1983). We conclude from this spectrum that there are no strong emission features from the Io torus due to elements other than sulfur and oxygen. This confirms the conclusion drawn from the analysis of the *Voyager* UVS torus data which has always had some uncertainty because of the low spectral resolution and the necessary spectral modeling (Shemansky & Smith 1981; Shemansky 1988).

The brightness in Rayleighs ($=10^6/(4\pi)$ photons cm^{-2} sr^{-1} s^{-1}) is listed for each of the features in Table 1. Although the slit was not uniformly filled, the values are averaged over the slit. The SPLOT routine in IRAF was used for blended features whose reported intensities are preliminary. In the case of S II λλ1250.6, 1253.8, 1259.5, although blending makes the relative intensities uncertain, the total multiplet brightness used to obtain the relative ionic concentration is accurate. The dark count is ~0.5 counts pixel^{-1}; as the line width is about 6 pixels, a peak value of ~3 events pixel^{-1} in a feature represents a significant detection. The total number of features in the spectrum with this value or higher is greater than 10^2. Because of the limited signal-to-noise and the large number of blends, a complete line list, a search for minor species, and more detailed comparisons with the *Voyager* spectra will require fitting the spectrum as well as modeling the torus emission processes. This will be addressed in a future paper.

Figure 2 displays a small portion of the spectrum containing emission lines whose relative intensities will vary with changes in the electron density and temperature. These and other lines in the spectrum can be used as diagnostics to measure the spatial and temporal dependence of the torus plasma param-

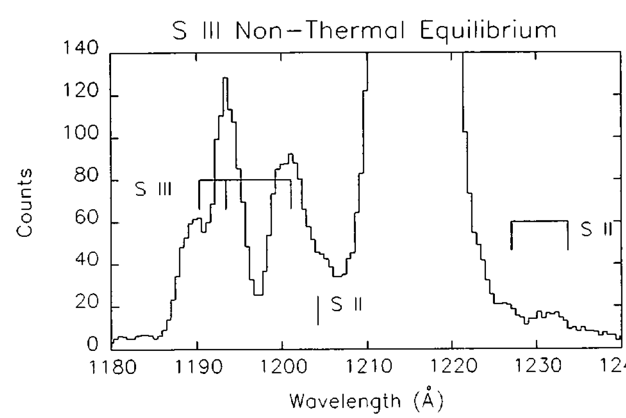

FIG. 2.—Examples of electron-density and temperature sensitive lines in the torus spectrum. The ratios between the S III multiplet deviate strongly from the 1:3:5 ratio which would be expected if the ground multiplet levels were in collisional equilibrium. The total intensity of the S III multiplet as well as those of the three marked S II lines depend on the electron temperature.

TABLE 1

STRONG EMISSION FEATURES FROM THE IO TORUS

Ion	λ_{vac} (Å)	Reference[a]	λ_{meas} (Å)[b]	$B(R)$
O II	833.5	K	833.5	52
S II	1006.2	P	1006.0[c]	5
S II, S III	1014.4, 1015.7	P, K	1014.2[c]	21
S II, S III	1019.5, 1021.2	P, K	1019.9,[c] 1021.9[c]	20
H I[d]	1025.7	K	1026.0[c]	10
S II?	1045.7, 1047.7	K	1046.9[c]	9
S IV	1062.7	K	1062.0	6
S IV	1073.3	K	1072.2[c]	9
S III	1077.1	K	1077.4[c]	14
S II	1102.4	P	1102.0	6
He I[d]	2 × 584.3	K	1168.7	5
S III	1190.2	K	1190.3[c]	14
S III	1194.0	K	1193.4[c]	32
S III	1201.3	K	1201.1[c]	22
S II	1204.3	P	1204.2[c]	4
H I[d]	1215.7	K	1215.5	[e]
S II	1250.6	P	1249.9[c]	9
S II	1253.8	P	1252.9[c]	18
S II	1259.5	P	1258.6	34
O I[d]	1302.9, 1304.9, 1306.0	P	1305.3[c]	65
S IV	2 × 657.3	K	1313.5	8
S IV	2 × 661.4	K	1323.3[c]	5
O I[d,f]	1355.6, 1358.5	K	1356.1[c]	26
S III[f]	2 × (677.8–681.0)	K	1361.3[c]	21
S III	2 × (698.7–702.8)	K	1399.3[c]	15
S IV	1404.8, 1406.1	K	1405.9	16
S IV	1416.9	K	1417.4	7
S IV	1423.9	K	1423.5	3
O II	2 × 833.5	K	1667.2	10
S III	1713.1	M	1712.9	16
S III	1729.2	M	1728.3	42

[a] (K) Kelly 1987; (P) Pettersson 1983; (M) Moos et al. 1983.
[b] Based on HUT nominal wavelength scale.
[c] Blend. Brightness value indicates strength but is preliminary.
[d] Totally or partially terrestrial in origin.
[e] Partially saturated.
[f] Both 1356.1 and 1361.3 features may contain O I and S III.

eters. The HUT spectra also provides a new starting point for analysis of *IUE* low spectral resolution torus measurements of the S III triplet, λλ1190.2, 1194.0, 1201.3. Previous *IUE* analyses (Moos et al. 1983, 1985) of these emissions partially blended with H I λ1216 have been hindered because the relative intensities among the triplet were not known. In addition, the contribution from S II λ1204, which Figure 2 shows to be small, was not known. The S III triplet shows strong evidence that the electron density is low enough to allow radiative depopulation of the upper level of the ground state multiplet. The measured brightnesses are in the ratios 1/2.3/1.6 whereas for collisional equilibrium with electrons at 60,000 K, ratios of 1/3/5 are expected. S III λ1201.3 is far too weak. There are six lines between the upper ^3D and ground ^3P which are grouped to form the three features according to the ground splitting. An estimate of relative electron excitation and radiative decay rates (Morton & Smith 1973) shows that the relative strength of λ1201.3 depends on the population of the uppermost $J = 2$ sublevel at 833 cm^{-1} in the ground ^3P and hence this level must have a population much smaller than that expected for collisional equilibrium. In addition, the S III and S II features in Figure 2 depend on the electron temperature. As discussed previously (Moos et al. 1983), the ratio of the S III triplet total intensity to S III λλ1713, 1729 is a potential electron temperature diagnostic. S II λ1204 is emitted by a level at 98,000 cm^{-1} while λλ1227, 1234 comes from 106,000 cm^{-1}. As 60,000 K corresponds to an energy of 37,000 cm^{-1}, the brightnesses will be strongly temperature-dependent.

3. IONIC DENSITIES

The spectral features show evidence for only four significant charge carriers: O^+, S^+, S^{++}, and S^{+++}. Because the HUT data provide accurate values of the brightnesses for all four of these species, one can determine the relative ionic abundances without a detailed model of the plasma density distribution. The brightness, B_i, of a particular line for a given ion can be written $B_i = \langle C_i M_i n_e^2 L \rangle$ where C_i is the excitation rate of the feature, $M_i = N_i/n_e$ is the relative concentration or mixing ratio for a given ion, n_e is the electron density, and L is the effective path length along the line of sight through the torus over which these quantities are averaged. Then, to a good approximation the mixing ratio for a given ion is $M_i = B_i/(C_i \langle n_e^2 L \rangle)$. the electron temperature was set at 60,000 K. The quantity $\langle n_e^2 L \rangle$ is the emission measure for a 1 cm^2 column along the line of sight, and is computed by summing the product $B_i Z_i / C_i$ over the four identified ionic species where Z_i is the ionization stage. This value of the emission measure is then used to determine M_i from the brightness.

TABLE 2

IONIC DENSITIES IN THE IO TORUS

Ion	λ (Å)	$B(R)$	C_i (10^{-9} cm^3 s^{-1})[a]	M_i (HUT)	N_i[b]	M_i (*IUE*)	M_i (*Voyager*)[c]
O^+	834	52	1.7	0.27	530	0.37	0.42
S^+	1251, 1254, 1260	61	2.9	0.18	356	0.14	0.13
S^{++}	1713, 1729	58	2.3	0.22	436	0.20	0.18
S^{+++}	1398–1424	26	5.4	0.04	81	0.03	0.02

[a] (O^+) Ho & Henry 1983a; (S^+) Ho & Henry 1983b; (S^{++}) Ho & Henry 1984; (S^{+++}) Dufton et al. 1982.
[b] $n_e = 2000$.
[c] Shemansky 1991.

Table 2 shows the measured brightnesses for four strong multiplets, the excitation rates, and the resulting relative concentrations. The excitation rate for O^+ has been multiplied by 0.83 to correct for depopulation of the ground level (Shemansky 1991). The value of the emission measure is not critical as it divides out in the calculation of the relative concentrations. Alternatively, one could calculate the ratios of the M_i and then use charge neutrality, $\sum M_i Z_i = 1$, to determine the mixing ratios. However, the actual value of the emission measure serves as a check. The emission measure per unit area column is 1.2×10^{17} cm^{-5}. The typical value of $n_e = 2000$ cm^{-3} implies an effective path length averaged over the slit of $\sim 3 \times 10^{10}$ cm $\cong 4\ R_J$, a reasonable value.

Table 2 also lists the ionic densities implied by the HUT results for a nominal electron density of 2000 cm^{-3}, the mixing ratios for an *IUE* observation near the time of the *Voyager 1* encounter with Jupiter (McGrath et al. 1990) and mixing ratios based on *Voyager* UVS data (Shemansky 1988, 1991). The values are similar, although the HUT values indicate a lower oxygen-to-sulfur ratio. The general agreement of the more model dependent approaches of *Voyager* and *IUE* with the HUT results raises confidence in the basic picture of the torus used in these analyses. The 38% difference between the relative O concentration obtained from the HUT observation and that derived from *Voyager* data is striking. Both determinations are based on the O II λ834 transition and used similar excitation rates, so that this must represent either a problem in the data and analysis or a change in the properties of the torus. The HUT ratio of O^+ to S^{++} can be increased to the *Voyager* value by decreasing the assumed electron temperature to below 50,000 K. It is hoped that detailed comparisons, e.g., using the HUT results to better model the *Voyager* spectra, will either bring the relative concentrations determined by different methods into better agreement or indicate long-term changes in the torus over the 12 yr period since the *Voyager* encounters.

The marginal detection of O III] $\lambda\lambda$1661, 1665 described in the previous section and the excitation rates of Aggarwal (1983, 1985) imply that the feature listed as O II λ834 is contaminated by only a small amount of O III λ834, $\sim$6%. Therefore, as a first approximation this contribution has been ignored. As the excitation rates are almost identical, the O^{++} concentration will be $\sim$6% of the O^+. The effect of this and additional unidentified species present in some small percentage will be a small increase in the emission measure and a similar decrease in the resulting mixing ratios.

4. SUMMARY

The HUT instrument has been used to obtain spectra (415–1864 Å) of the Io torus with much higher spectral resolution than previous data. Examination of the strong spectral features has shown no evidence for any elements other than oxygen and sulfur. Further analysis of the many weak features is required to determine if there is evidence for other minor species. Because the spectrum contained strong well-resolved emission features for the four major species, S^+, S^{++}, S^{+++}, and O^+, the relative concentrations were determined directly without requiring models of the spectra or plasma distribution. Examples of lines were presented which are sensitive to electron density and temperature and their significance for analysis of *IUE* spectra of the torus discussed.

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