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IO: IUE OBSERVATIONS OF ITS ATMOSPHERE AND THE PLASMA TORUS

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ABSTRACT

Two of the main components of the atmosphere of Io, neutral oxygen and sulfur, were detected for the first time in 1986 with the *IUE*. Four observations have yielded brightnesses that are similar, regardless of whether the upstream or the downstream sides of the torus plasma flow around Io is observed. A simple model requires the emissions to be produced by the interaction of O and S columns in the exospheric range with ~2 eV electrons. Cooling of the 5 eV torus electrons would be required prior to their interaction with the atmosphere of Io. Several inconsistencies in the characteristics of the spectra that cannot be accounted for in this model require further analysis with improved atomic data. The Io plasma torus has been monitored with the *IUE* since March 1979. This study has established the long-term stability of the warm torus. The observed brightnesses have been analyzed using a model of the torus, and variations of less than ~30% in the composition are observed, the quantitive results being model dependent.

Keywords: Io atmosphere, Io torus, Jupiter

1. INTRODUCTION

The products of the active volcanoes discovered by *Voyager 1* on Io form a torus of plasma at the orbit of this Jovian satellite. Although the charateristics of the plasma torus are relatively well known, the processes through which it is replenished by Io are not well understood. Most of the volcanic ejecta is not energetic enough to escape Io and thus condenses on the surface. However, direct surface sputtering by the torus ions has been found to be an inefficient supply mechanism. As a consequence, an atmosphere has been postulated as an intermediate agent to replenish the torus, but many questions remain unanswered. What is the nature of the atmosphere? Which are the interaction mechanisms between the Io torus plasma and its surface and atmosphere? What is the variability and stability of the system?

Until recently, very few direct observations of Io's atmosphere existed. In 1986, two of the main atmospheric constituents were detected for the first time with the *International Ultraviolet Explorer* (*IUE*). The results obtained so far for a total of four such *IUE* observations are presented in Section 2.

The Io plasma torus has been observed with the *IUE* since March 1979, when *Voyager 1* made *in-situ* measurements of the torus. A systematic study of the properties and long-term behaviour of the torus has since been underway and the most current results of this study are presented in Section 3.

2. THE ATMOSPHERE OF IO

Pioneer 10 discovered an ionosphere on Io, and the *Voyager 1 IRIS* measured an SO_2 surface density ≤ 0.032 cm atm (p $\sim 10^{-7}$ bars) resulting from either sublimation of SO_2 frost or a volcanic plume. At least 20% of the surface of Io is covered by SO_2 frost of volcanic origin. The atmosphere could thus be dominated by sublimated SO_2 and be collisionally thick or thin, or it could even be episodic, driven by volcanoes. Many models of the atmosphere exist, and some favor a relatively thick atmosphere that can maintain both an ionosphere and an exosphere that could be composed mainly of atomic oxygen and sulfur, the photochemical products of SO_2. Others advocate a thin atmosphere due to the rather limited amount of SO_2 surface frost. In any case, neutral oxygen and sulfur are expected to be two of the main atmospheric constituents.

The first detection of emissions of oxygen and sulfur on the atmosphere of Io was made with the *IUE* in 1986 (Ref. 1). Four short-wavelength (1150 – 1950 Å), low-dispersion spectra (Fig. 1) have been obtained as Io orbited east and west of Jupiter (Fig. 2). Excellent pointing accuracy was maintained throughout the 14-hour observations of this moving target, allowing for a positive detection of the emissions. The emissions were found to originate from a region inside ~4 Io radii from the surface.

The observed oxygen and sulfur multiplets are: a blend of OI λ1304 and SI λ1299, OI] λ1356, SI λ1429,

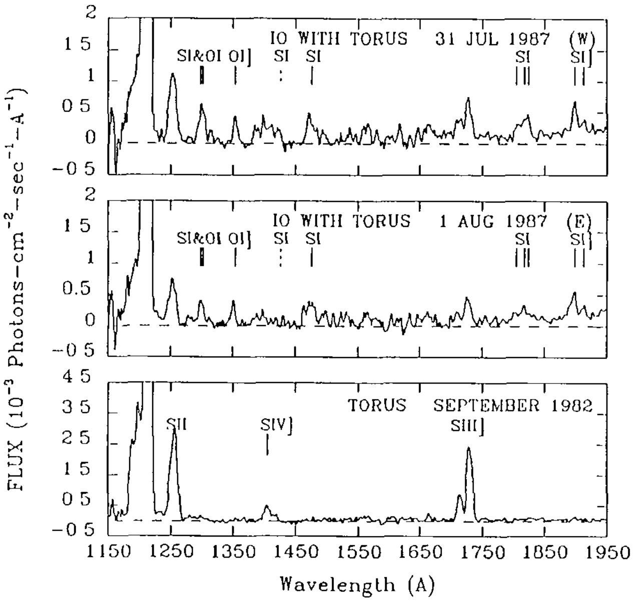

Figure 1. *IUE* spectra of Io and torus (top) and (center) from the 1987 observations, together with a torus spectrum (bottom). The emissions originating from Io are marked in the top and center spectra, while those originating from the torus are marked in the bottom spectrum.

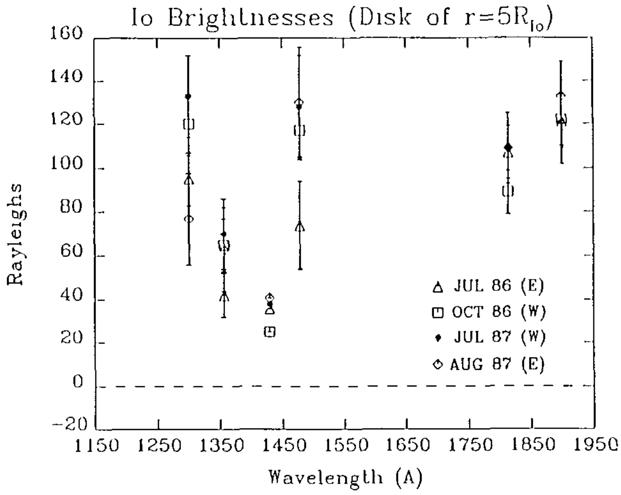

Figure 3. Measured brightnesses for the four Io observations plotted as a function of wavelength, derived using an emisison disk of a radius of 5 Io radii.

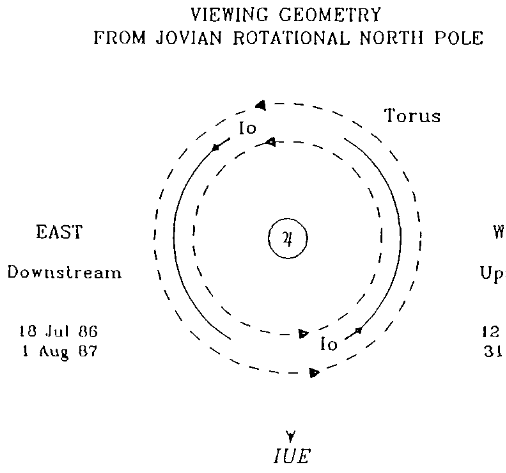

Figure 2. Viewing geometry depicted from the north pole of Jupiter for the Io observations. The trajectory of Io as it orbited east and west of Jupiter throughout the observations is marked with a solid line. The torus, indicated by the dashed lines, is flowing past Io.

SI λ1479, SI λ1814, and SI] λ1900, 1914. The measured brightnesses of the four spectra are very similar within the estimated errors (Fig. 3). Some models predict different atmospheric properties for regions corresponding to the upstream (west) or downstream (east) sides of the torus plasma flow (at 57 km/sec) around Io, and to the day or night sides. Our observations have viewed both the upstream and the downstream on the day side. The similarity in the spectra obtained should therefore constrain any atmospheric model.

Various spin-forbidden transitions were observed, suggesting electron impact excitation. In fact, the emissions were expected to be produced by the interaction of 5 eV torus electrons with the exosphere. To study this possibility, the emissions were modeled assuming electron-impact as the only excitation process. For sulfur, only the theoretical data of Ho and Henry (Ref. 2) is available, and it includes only three of the observed transitions. From these data, a ratio of the observed emissions was predicted as a function of electron temperature. The measured ratios agree with an electron temperature of ~2eV (Fig. 4). The OI λ 1304 electron-impact data has been recently measured in the laboratory by Doering (Ref. 3) to have a resonance near threshold which agrees with that predicted by Rountree and Henry (Ref. 4). The theoretical data of Rountree (Ref. 5) for the OI] λ1356 emission includes another resonance near threshold and was used to model the ratio of these two oxygen emissions as a function of electron temperature The measured ratio also are compatible with an electron temperature of ~2eV (Fig. 5).

The derived column densities, 9.4×10^{-14} cm^{-2} and 2.4×10^{-14} cm^{-2} for oxygen and sulfur, respectively, are in the exospheric range. Therefore, in this model, an unknown mechanism is required to cool the torus electrons from 5eV to 2eV previous to their interaction with the exosphere. One further inconsistency in this model is that resonance scattering of the solar O and S lines was ignored in the analysis because the g-factors are smaller than the excitation rate due to 5eV electrons, but for emissions produced by 2eV electrons the excitation rate becomes comparable to the g-factors for some of the multiplets.

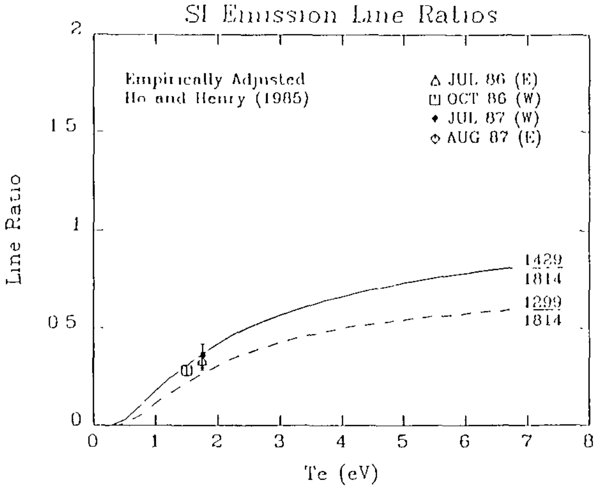

Figure 4 Line ratios of the sulfur emissions multiplets SI λ 1429, SI λ 1479, and SI λ 1299 calculated from the atomic data of Ho and Henry (Ref. 2) The measured values are indicated

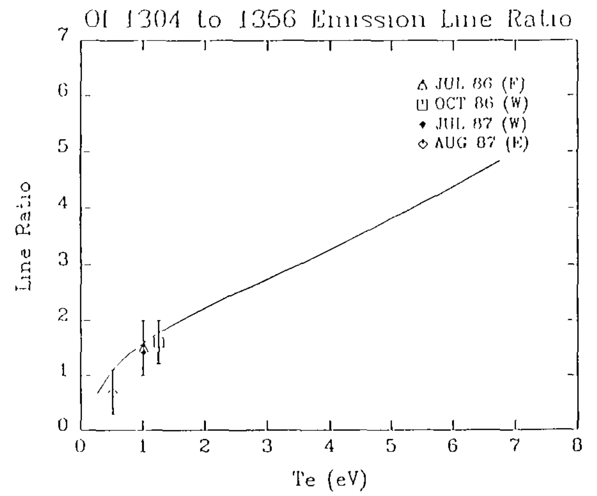

Figure 5. OI λ 1304 to OI] λ 1356 line ratio obtained from the theoretical data of Rountree and Henry (Ref 4) and Rountree (Ref 5) Both data include a resonance near threshold, and cascade effects have been added to the OI λ 1304 data. The mesured values are indicated.

Furthermore, there are some inconsistencies in the characteristics of the spectra that do not agree with the theoretical atomic data, namely the presence of the bright SI λ 1479 emission multiplet compared to the almost undetectable SI λ 1429 emission multiplet. A rocket-spectrum of the torus (Ref. 6) shows these two sulfur emissions in agreement with the theoretical predictions. Therefore, other excitation processes should be significant on Io. We are presently studying other possibilities such as electron-impact on SO_2 and cascade effects and recombination of S^+, as suggested by the work of Judge (Ref. 7). Again, the atomic data is very limited for these excitation processes

Although a satisfactory explanation of the *IUE* observations of the atmosphere of Io cannot be supplied yet, these observations should prove useful in the future as improved atomic data becomes available and more observations are performed. The *IUE* is valuable for studying Io's main atmospheric constituents and should thus provide insight into the nature of Io's atmosphere and its interaction with the torus Future observations should also measure any temporal variations and provide a basis for observations by *Galileo* and *HST*.

3. THE IO PLASMA TORUS

The plasma torus is composed primarily of ions of sulfur and oxygen. Its composition is determined mainly by the electron density (n_e) and temperature (T_e), with average values measured by *Voyager 1* of $\sim$2000 cm^{-3} and $\sim$5 eV, respectively. The torus has a scale height of about one Jovian radius, and is centered at the orbit of Io with its centrifugal axis tilted 7° away from the Jovian rotational axis As the plasma corotates with the Jovian magnetic field, it wobbles with respect to a given line of sight throughout a $\sim$10 hour Jovian rotation A torus ansa at 5.9 Jovian radii, where the column sampled is maximum, was viewed thoughout most of the exposures (Fig. 6) The integration time is typically between 6 to 14 hours and the spectra obtained represent longitudinal averages. (Ground-based observations of the torus are much shorter and sample the torus longitudinally)

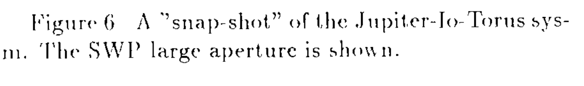

Figure 6 A "snap-shot" of the Jupiter-Io-Torus system. The SWP large aperture is shown.

The observed torus emission features are SII λ 1256, SIII] λ 1729, and SIV] λ 1406 (Fig. 1), whereas oxygen ions cannot be detected with the *IUE*. The measured brightnesses vary because of the different viewing geometries, but the ratio of the brightnesses does not vary as much. In order to compare the observations, a model of the torus has to be employed. The original model is described in detail in Skinner (Ref. 8) and Moos *et al.* (Ref. 9), in this work some model parameters have been up-dated and the data set has been extended.

The model predicts an average brightness for each of the emission features by estimating the volume emission rate integrated over all the portions of the torus falling in the field-of-view thoughout the observation. This volume emission rate is a function of the electron temperature, electron density and ion density and the following representative, longitudinally-averaged spatial profiles for these quantities are adopted:

- the electron temperature and density profiles in the torus centrifugal plane (Fig. 7) derived from the *Voyager 1* observations (Ref. 10);
- the electron density at a distance z from the centrifugal plane approximated with a scaling law (Ref. 11) and using the revised scale height of ~1 Jovian radius (Ref. 12);
- ion densities assumed to be constant fractions of the electron density and to follow the same spatial profile, since the plasma is assumed to be homogeneously mixed; and
- the electron temperature dependence in the volume emission rate is included in the thermally averaged collision strength (Fig. 7) of the S II 1256 Å transition (Ref. 13), but no temperature dependent atomic data is available for the SIV] λ 1406 emission. Since the atomic data for the SIII] λ 1729 emission is rather uncertain, the theoretically calculated, temperature-dependent values of Ho and Henry (Ref 14) have been employed.

The ratio of the measured to model-predicted brightness and the requirement of local plasma neutrality are used to predict the characteristics of the torus plasma, namely the electron concentration relative to the *Voyager 1* case, R, and the S^+, S^{+2}, and S^{+3} mixing ratios or fractional concentrations, M II, M III, and M IV. The results, presented in Figures 8 and 9, are: R = 1.07 ± 9%, M II = 0.10 ± 30%, M III = 0.22 ± 17%, and M IV = 0.021 ± 35%, plus a mixing ratio of 0.39 inferred for O^+. (The large variability of M IV is partly due to the uncertainty in the low-level SIV] λ 1406 signal.)

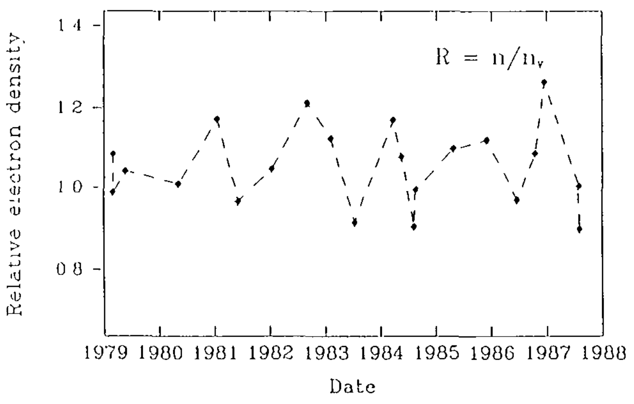

Figure 8. Modeled electron concentration, R, relative to the *Voyager 1* case versus date

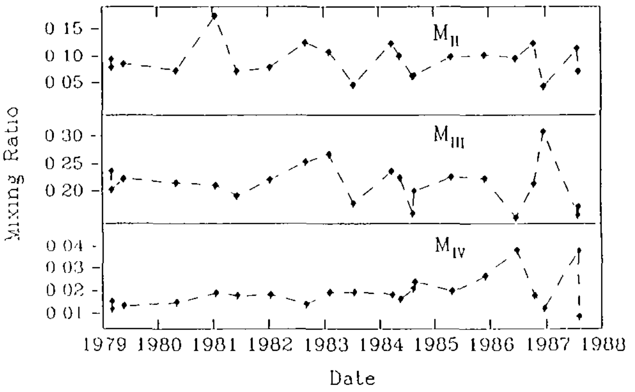

Figure 9. Modeled S^+, S^{+2}, and S^{+3} mixing ratios or fractional concentrations, M II, M III, and M IV, versus date.

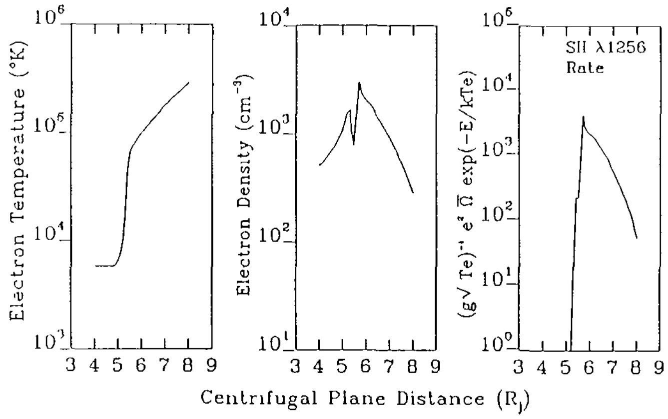

Figure 7. Model profiles as a function of radial distance from Jupiter of the density and temperature of the torus electrons (left and center) on the torus centrifugal plane, derived from the *Voyager 1* observations (Ref. 10). Also plotted (right) is the profile of the thermally averaged collision strength of the S II 1256 Å multiplet.

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The results indicate that, despite short-term variations of less than ~30%, the torus has remained stable since the *Voyager 1* encounter in 1979 through mid-1987 S^{+}, S^{+2}, S^{+3}, and O^{+} would carry respectively 10%, 44%, 6%, and 39% of the charge. These results bring our *IUE* estimates of the torus plasma charge distribution close to the estimates derived from the *in-situ (PLS)* plasma measurements and the ultraviolet spectra (*UVS*) of *Voyager 1* as reviewed by Bagenal (Ref 15) Even though the model cannot distinguish relatively small, simultaneous changes in the electron temperature and density and its quantitative results are thus model dependent, the qualitative result of the long-term stability of the torus is quite firm

It is important to continue these *IUE* observations as they constitute a unique, long-term study of torus plasma density and will be an invaluable link between the *in-situ measurements of Voyager 1 and those of HST, ASTRO,* and *Galileo.*

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