A Multi-Wavelength Study of Io's Atomic Oxygen and Sulfur Emission

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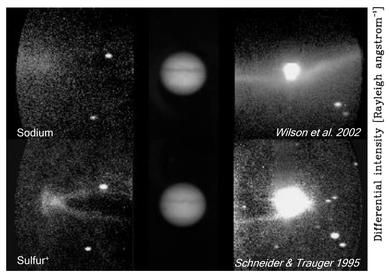
Abstract

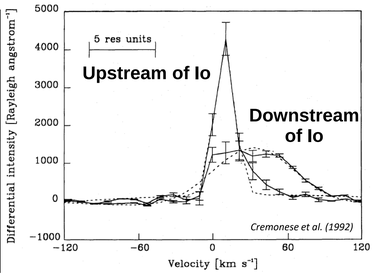
Electrons impacting Io's atmosphere produce line emission via direct excitation of atoms, and via the dissociative excitation of Io's molecular atmosphere. We report the first observations of O I multiplets at 7774Å & 8446Å, as well as an S I triplet near 9225Å, seen in Jupiter's shadow. Past laboratory studies have predicted that these lines appear as prompt emissions from dissociative excitation of SO . Such features offer a new tracer to understand the breakdown of Io's bulk atmosphere by superthermal electrons in the plasma torus. They also offer a metric for the importance of the dissociative excitation contribution to the FUV emissions, since they cascade to produce the intense O I 1356Å, 1304Å and S I 1900Å multiplets, respectively. However, further work is needed to fully disentangle the relative roles of electron impact excitation versus dissociative excitation and/or recombination of molecular ions. Synthetic spectra show that direct excitation by thermal electrons with densities and energies characteristic of the torus' ribbon can reasonably fit the FUV sulfur line ratios observed by HST/COS. Extending such models to previously unexplored wavelengths predicts that the forbidden [S I] 25.245μm line should easily stand out above Io's thermal continuum. Non-detection in our preliminary analysis of SOFIA/EXES data consequently indicates either collisional quenching, or a surprising absence of cold electrons within a few hundred km altitudes.

Far UV: An Oxygen Jet

Io's well-known to eject a fast "jet" of escaping neutral sodium, which is energized by the rapid plasma torus rotation and the recombination reaction:

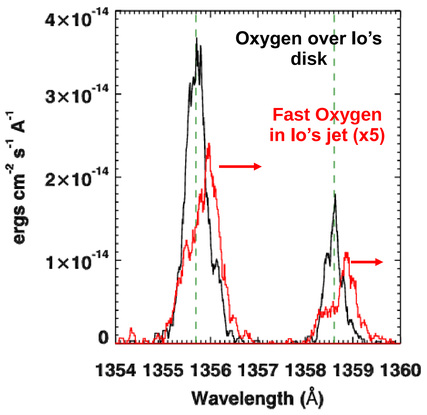
$NaCl + \gamma \rightarrow NaCl^+$ $\quad$ $NaCl^+ + e^- \rightarrow Na^* + Cl$





We used Hubble's COS high dispersion spectrograph to search for analogous fast S and O jets via reactions involving ion recombination or charge exchange. We looked for Doppler shifts in atomic lines by first pointing to Io, then offsetting a few arcsec to its right in the geometry above.

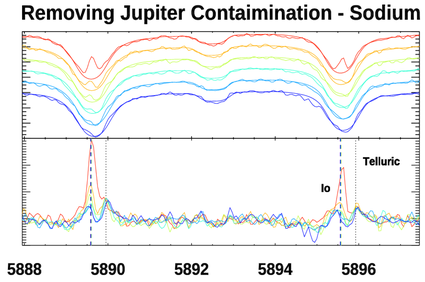
Results showed fast oxygen jets was present, but not a sulfur jet. Jet emissions were red-shifted ~0.3Å or 60 km/s. This is consistent with the plasma torus co-rotation speed and even faster than Na, suggesting a $O^+ \leftrightarrow O$ charge exchange process, not SO_2^+ dissociative recombination. The sulfur counterpart is plausibly absent since S^{++} and not S^+ is the locally dominant charge state, whereas abundant singly charged oxygen reacts more efficiently.



Optical: New O and S Airglow Lines

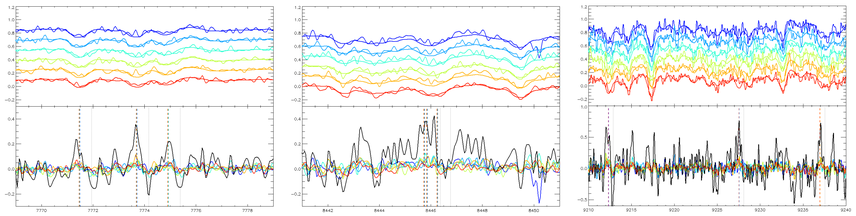
In the optical, Io's bright surface reflectance swamps faint oxygen emission, so it must be observed in Jupiter's shadow. This requires blind non-sidereal tracking, which is tricky, so Io's fainter optical emissions aren't well explored.

We used the Apache Point 3.5m echelle, re-centering on another satellite every ~10 min. Bright Jovian scattered light was fit and removed:



Apache Point Observatory 3.5m

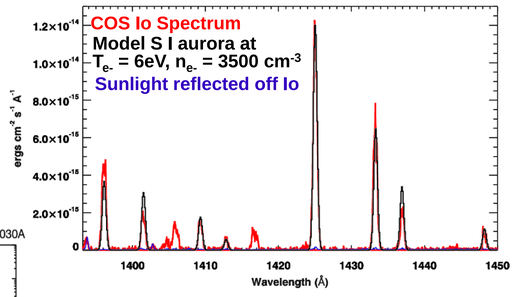
Electron excited Na and [O I] 5577Å, 6300Å and 6364Å are evident in full shadow. Doppler shifts separate Earth and Io oxygen lines. Ajello et al. (2008) showed electrons smashing SO_2 also produce triplet atomic emissions in the far red with high cross-sections. The threshold for these is near 25eV. Co-adding all our frames confirmed that 7774Å, 8446Å and 9225Å emissions can all be measured in eclipse at ~100R.

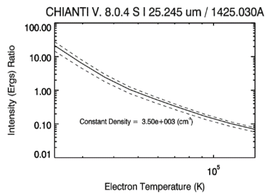


Mid-IR: Plausible Quenching

Aside from the 18.9μm absorption Tsang & Spencer use to monitor SO_2, Io's mid-IR spectrum remains largely unexplored. We attempted first detection of forbidden [S I] at 25.245μm with SOFIA-EXES. Several clues suggest this ground-state transition is a good target...

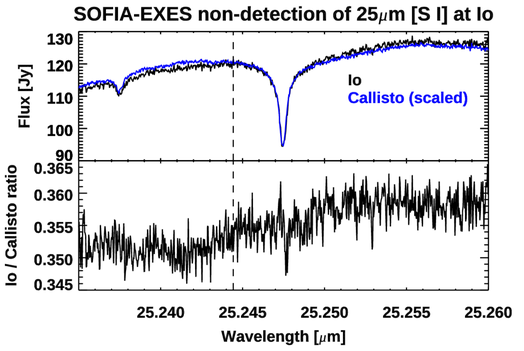
Cascade from above. Lines HST/COS measured at 1433.3Å, 1409.3Å & 1396.1Å all leave S atoms in a $3s^23p^4$ J = 1 state, which then cascades as 25.245μm:





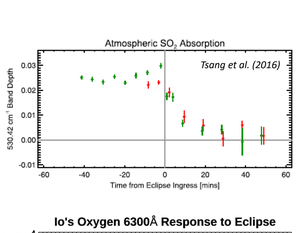
Direct impact excitation by cold electrons. Scaling the FUV sulfur predicts electron impacts additionally contribute ~27 Jy, assuming a 5eV Maxwellian e^- population, as in the plasma torus.

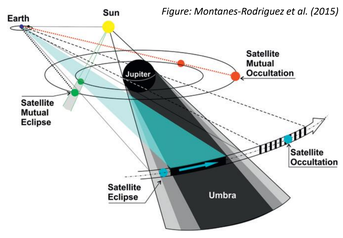
EXES' non-detection has an upper limit of only 3 Jy. This requires $T_{e^-} \geq 12$eV to be consistent with the Far-UV S brightness, which seems unrealistically high. However, with a 12 min lifetime and only 0.05eV energy, collisional de-excitation seems a likely explanation.

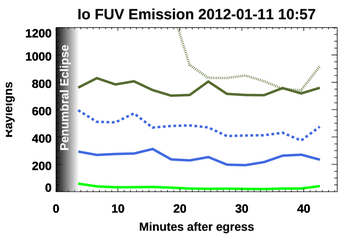


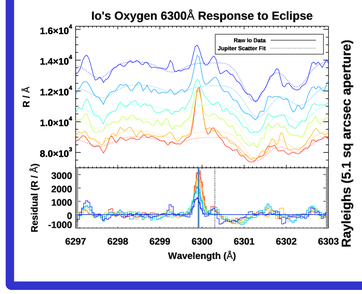
Response to Eclipse by Jupiter

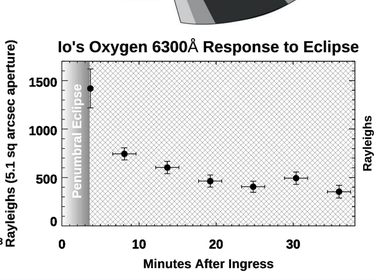
Sublimation of SO_2 turns off as Io cools in shade. The bulk atmosphere has been observed to mostly collapse within 20 min following ingress (Tsang et al. 2016). Optical sodium and oxygen aurora also seem to respond quickly. However, higher energy UV transitions exhibit little response at all, both at ingress and egress.

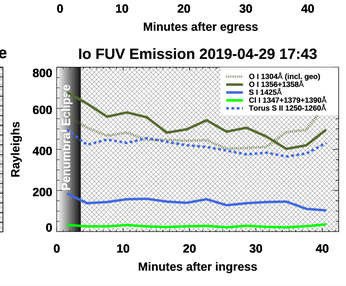












Interpretation & Conclusions

- Optical aurora respond more dramatically to eclipse than FUV aurora, both in NaCl (volcanic) and SO_2 (sublimation) products. This wavelength dependence may reflect the electron supply in these different energy ranges.
- 9 far red airglow lines are observed for the first time in another planet's atmosphere. Past lab experiments show these trace from hot electron impacts with ≥25eV.
- Hot electron supply seems independent of photo-ionization and sublimation effects. Both far red emissions and FUV lines associated with their cascade remained strong 30+ mins into eclipse, well after the sublimation atmosphere has collapsed.
- In forbidden lines, collisions with neutrals may quench [S I] @ 0.05eV / 12min lifetime. Higher energy plasma collisions do not quench [O I] @ 2eV / 2min lifetime.
- Neutral oxygen was observed with Doppler shifts near the torus co-rotation velocity—well above Jupiter's escape speed. We interpret this as evidence for local O charge exchange at the Io-torus interaction. This O "jet" feature was not seen in S, and was not detected at Jovian dawn.

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