Simulation of Io’s Emission Spectrum in Eclipse

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HST Observation Geometry

- HST/STIS eclipse observations done on 1999 Aug 7\textsuperscript{th} & 18\textsuperscript{th} during the HST Io campaign
- Two 12-minute exposures avg 16 min (NUV) and 27 min (VIS) into umbra
- Io is at min (NUV) and \~max (VIS) magnetic latitude in the plasma torus
- Pele is on the upstream side (relative to the plasma)
Fig. 3. Time-series of disk-integrated intensities from eclipse C. This figure shows the total brightness of Io as a function of time, from raw Cassini images taken under constant conditions. Solid lines show linear least-squares fits to the data; dashed lines show the formal uncertainty in the times of intersections of the fit lines.
### Table 1: HST/STIS Observations of Io in Jupiter Shadow

<table>
<thead>
<tr>
<th>Date</th>
<th>Obs start(^a)</th>
<th>Exp</th>
<th>Time into(^b)</th>
<th>Orbital longitude</th>
<th>Sub-Io(^c) CML</th>
<th>Io magnetic(^d) latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(UT)</td>
<td>(UT)</td>
<td>(sec)</td>
<td>(min)</td>
<td>(deg)</td>
<td>(deg)</td>
</tr>
<tr>
<td></td>
<td>(UT)</td>
<td></td>
<td>Total eclipse</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CCD/G430L**

<table>
<thead>
<tr>
<th>Date</th>
<th>Obs start(^a)</th>
<th>Exp</th>
<th>Time into(^b)</th>
<th>Orbital longitude</th>
<th>Sub-Io(^c) CML</th>
<th>Io magnetic(^d) latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 Aug 7</td>
<td>16:14:06</td>
<td>720</td>
<td>13-25</td>
<td>343</td>
<td>236</td>
<td>+8.8</td>
</tr>
</tbody>
</table>

**MAMA/G230L**

<table>
<thead>
<tr>
<th>Date</th>
<th>Obs start(^a)</th>
<th>Exp</th>
<th>Time into(^b)</th>
<th>Orbital longitude</th>
<th>Sub-Io(^c) CML</th>
<th>Io magnetic(^d) latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 Aug 18</td>
<td>6:54:26</td>
<td>800</td>
<td>1-14</td>
<td>342</td>
<td>114</td>
<td>−0.2</td>
</tr>
<tr>
<td>1999 Aug 18</td>
<td>7:10:09</td>
<td>700</td>
<td>17-29</td>
<td>344</td>
<td>120</td>
<td>+1.1</td>
</tr>
</tbody>
</table>

\(^a\)Time at observation start  
\(^b\)Umbral start time from JPL NAIF ephemeris  
\(^c\)The Jovian sub-Io longitude at mid-observation  
\(^d\)For 10° tilt of magnetic pole towards CML 202. Owing to centrifugal stretching, the Jovian plasma torus is tilted 3° relative to the magnetic equator.
Table 2: Configuration

<table>
<thead>
<tr>
<th>Date</th>
<th>Detector &amp; filter</th>
<th>Jupiter(^a)</th>
<th>Aperture(^b)</th>
<th>Io diameter</th>
<th>Solar phase angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>(UT)</td>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(&quot;)</td>
<td>(deg)</td>
</tr>
<tr>
<td>1999 Aug 7</td>
<td>CCD/G430L</td>
<td>226</td>
<td>-136</td>
<td>1.08</td>
<td>11.63</td>
</tr>
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<td>1999 Aug 7</td>
<td>CCD/G430L</td>
<td>226</td>
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<td>1.08</td>
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<tr>
<td>1999 Aug 18</td>
<td>MAMA/G230L</td>
<td>208</td>
<td>-118</td>
<td>1.12</td>
<td>11.08</td>
</tr>
<tr>
<td>1999 Aug 18</td>
<td>MAMA/G230L</td>
<td>208</td>
<td>-118</td>
<td>1.12</td>
<td>11.08</td>
</tr>
</tbody>
</table>

\(^a\)Position angle of Jupiter relative to aperture spatial (y) axis

\(^b\)Position angle of the aperture spatial axis in the Jovian system
Average CCD half-disk spectra (solid=SW; dashed=NE)
112 Å resolution element

Average CCD half-disk spectra (solid=SW; dashed=NE)
59 Å resolution element
Io/Sky for the two CCD eclipse phases (bolder: first exposure)
Combined unidentified spectrum at 31 Å resolution

Average CCD spectrum at 31 Å resolution

WAVELENGTH (Angstroms)

INTENSITY (Rayleighs/Å)

Avg Sky (4.6%)

Sky Difference (43%)
The figure shows two plots.

1. The top plot is a graph of intensity (in arbitrary units) against frequency (in wavenumbers). The frequencies range from 18000 to 24000 cm\(^{-1}\), and the intensities range from 0 to 20.

2. The bottom plot is a Fortrat plot (vibrational series of an electronic band) with measured line frequency against transition number. The measured line frequencies range from 24000 to 18000 cm\(^{-1}\), and the transition numbers range from 0 to 15.
HST/STIS Gr750 extracted spectrum of Io in eclipse showing NaD, O I 6300, O I 6364 and weaker emission at $\Delta\lambda \sim 31$ mA
Stretched 2-D image of Io with Gr750 showing emission from NaD, O I, & continuum
FIG. 1. Selected regions of a single raw spectrum of Io in eclipse. Shown are H\ensuremath{\alpha} 6563 A (no detection), [OI] 6300 A, Na D 5890 and 5896 A, and [OI] 5577 A. Regions have been individually scaled and wavelengths shifted to Io’s frame of reference.
First MAMA exposure: half disks (solid=SW; dashed=NE)

110 Å resolution element

Absolute difference from mean; RMS = 0.85 R/A

WAVELENGTH (Angstroms)

Second MAMA exposure: half disks (solid=SW; dashed=NE)

110 Å resolution element

Absolute difference from mean; RMS = 1.1 R/A

WAVELENGTH (Angstroms)
Average MAMA exposure: half disks (solid=SW; dashed=NE)

Absolute difference from mean; RMS = 0.76 R/A

Average MAMA spectrum at 110 Å resolution
Average MAMA spectrum at 39 Å resolution (solid)

dot–dash=SW half; dashed=NE half

Absolute difference from mean
RMS = 1.0 R/Å
Io's merged eclipse spectrum

showing effect of +/- 0.7% CCD sky subtraction
MUV 1 Spectrum

- 9 eV (lab data)
- 11 eV (lab data)
- 12 eV (lab data)
- 11.8 eV (interpolated)

MUV 2 Spectrum

Acceptance/Rejectance Algorithm:

1) Pick photon wavelength randomly:
   MUV 2: 2670 < λ < 6000 Å

2) Compute lab data wavelength, λ, nearest to λ and then intensity, I(λ,E_p) [Eqn. 5]

3) Repeat until intensity > random number (0,1)

Example 18 eV electron MUV 2 excitation:

1) Random wavelength = 3607 Å
2) Nearest lab data wavelength = 3608 Å, intensity = 0.26
3) Accept wavelength if random number < 0.26 otherwise repeat

Normalized Intensity

Wavelength (Å)

Normalized Intensity

Wavelength (Å)

Extrapolated spectrum
$T_e = 5\text{eV} + 5\% \text{ non-Thermal component.}$
Conclusions

The MAMA and CCD spectra are entirely iogenic emission.

Weakening S I, SO, and SO₂ emission between the eclipse-resolved MAMA spectra indicate ongoing atmospheric collapse due to freezeout.

An emission source is needed from ~3300 to ~5700 Å to fill in the spectral void left by the declining SO₂ emission tail. Its regular spectrum indicates a vibronic molecular band with a bending mode, suggestive of a triatomic molecule (S₂O? NonLTE SO₂??).

This unidentified emission was distributed asymmetrically across Io's disk, being brighter on the side closer to Jupiter, and so may be associated with the wake spot emission (or with greater volcanic production relative to SO₂ on that side).

The MUV 2 emission intensity does not depend strongly on which of the Pele type plumes are active; thus specific plume activity cannot be well constrained through examination of the disk-averaged MUV emission spectrum.

The best fit upstream electron temperature accounting for the peak intensity ratios and the absolute intensities is a thermal temperature of 5-6 eV and a non-thermal density that is 2-7% of the thermal density. For a 5% non-thermal component, a 5 eV thermal gas produces good agreement with the observation from 2400 to 3100 Å.
FIG. 2. Ioogenic emission detected in a single 600 s exposure begun 15 November 1998 05:43 UT. North is down and east to the right. The central meridian longitude of Io is 15 W. The wavelength scale has been shifted to Io’s frame of reference.
The early and later MAMA eclipse phases (early = heavy)

110 Å resolution element
Matching observed UV-V spectra

- “Nominal” activity of $S_2$-rich Pele-type plumes
- We subtract background light from the observation
  - Above $\sim3500$ Å, sunlight refracted and scattered by Jupiter’s atmosphere onto Io contributes an unknown absorption spectrum that is not modeled by our Io simulations
Matching observed UV-V spectra

- Upstream electron temperature of \(5–6\) eV \(\approx\) matches observed \(S_2\) & \(SO_2\) MUV2 intensity (\(~3000\text{Å}\) )
- \(SO\) \(A^3\Pi\) and \(B^3\Sigma\) band emission (\(2550\text{Å}\))
  - Dissociative excitation of \(SO_2\) (10.4 eV threshold) doesn’t produce enough
  - Estimate for direct e-SO excitation cross section brackets observed intensity (\(2550\text{Å}\))
Plume Source Geometry (Cont.)

Near-field

Ground level

Gas focusing

Denser ring along symmetry axis

Far-field

Focused gas is denser higher than gas moving straight up from the source

Side-view along the symmetry plane
Pele’s Vents

Galileo image of Pele’s caldera. >873K regions in red.

Number density contours near the simulated source at ground level.
Simulation on 64 processors with several million molecules per processor.
Pele’s Ring

Galileo image of Pele’s deposition ring on the surface of Io

Number density contours for a staged computation, with an inner domain from the previous slide fed into an outer domain on two processors