HST Aurora Observations: Transient Water Vapor at Europa’s South Pole

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Icy surface, subsurface ocean - and plumes?

- Young surface: ~50 Myr
- Evidence for existence of water ocean under the icy crust
- Plume searches with Voyager and Galileo data (e.g. Helfenstein & Cook, 1983; Phillips et al. 2000)
  - No limb haze detected
  - No surface changes between Voyager and Galileo images detected
  - Easily detectable plumes will have optical depths >0.04 (detection of dust/ice component in visible light, Quick et al. 2013)
Probing the atmosphere and plumes through UV observations

- HST GHRS observations of atmospheric oxygen emissions (Hall et al. 1995, 1998): OI135.6 nm / OI130.4 nm ratio of 1.3 - 2.2 is diagnostic for:
  \[ e^- + O_2 \rightarrow O^* \rightarrow O + h\nu \]
  ➤ O\(_2\) atmosphere with N\(_{O2}\) \(~ 10^{18} - 10^{19}\) m\(^{-2}\)

- STIS and ACS images of Europa’s oxygen aurora revealed irregular emission patterns (McGrath et al., 2004, 2009, Saur et al. 2011)

- Possible causes:
  ➤ Influence of magnetospheric environment?
  ➤ Atmospheric inhomogeneity due to
    - Surface properties (Cassidy et al., 2007)
    - Plume activity? (Saur et al. 2011)
HST STIS observation campaigns

October 1999 – at pericenter
November 2012 – before pericenter
December 2012 – at apocenter

1999: PI M. A. McGrath
2012: PI J. Saur

Apocenter:
True anomaly $f \sim 180^\circ$
Pericenter:
True anomaly $f \sim 0^\circ$
STIS spectral image – 3 ‘colors’ all at once

November 2012

Albedo: ~1.5%
Oxygen aurora correlated to magnetospheric environment

- Brightness decreases with distance to the plasma sheet
- Bright emission symmetric around ‘magnetic’ poles
- Hemisphere that is facing the plasma sheet is brighter
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➤ These insights allow a better interpretation of the morphology
Coincident Lyman-\(\alpha\) and OI 130.4 nm surpluses

- Atmospheric Lyman-\(\alpha\) emission consistent with zero signal in 1999 and Nov. 2012
- Statistically significant persistent \(~500\) R Lyman-\(\alpha\) surplus above south pole in Dec. 2012 (4.0 \(\sigma\))
- Coincident above-limb OI 130.4 nm emission surplus of \(~30\) R (2.4 \(\sigma\))
- No local OI 135.6 nm surplus, but bright homogeneous south polar auroral emission
Persistent south polar Lyman-α and OI 130.4 nm emission during all 5 HST orbits in Dec. 2012

- Spatial persistency indicates atmospheric inhomogeneity
- Lyman-α surplus of ~500 R and OI 130.4 nm surplus of ~30 R
  ➤ Electron impact on H₂O generates Lyman-α and 130.4 nm but relatively little (undetectable) 135.6 nm emission (Makarov et al. 2004)
Brightnesses consistent with local water vapor plumes

- Analysis of brightness in 20°-wide bins around the limb
- Modeled aurora images for global O$_2$ atmosphere and local H$_2$O plumes assuming a homogeneous electron environment
- Emission surpluses consistent with two 200 km high and 250 km wide water vapor vapor plumes with column densities of \(~10^{20}\) m$^{-2}$
Water vapor abundance is time-variable

- Oct. 1999 & Nov. 2012 brightnesses limit H$_2$O densities to $\times$2 & 3 lower or more
- Tensile stresses on south polar fractures maximize at apocenter (black dots - Dec. 2012), but are low before and at pericenter (Nov. 2012 and Oct 1999)
- Similar tidal processes drive variations of Enceladus’ plumes (Hedman et al. 2013)
What is the nature of Europa’s plumes?

- Plume content of $\sim10^{32}$ H$_2$O molecules similar to O$_2$ content of global atmosphere.
- 200 km altitude requires ejection velocity on the order of 700 m/s corresponding to temperature of >230 K.
  ➤ Vapor ejected from narrow hot fractures?
- Plume particles do not escape but fall back to surface leading to a high re-deposition rate of $\sim3000$ kg/s.
- Variability in agreement with key prediction of tidal-flexing models for subsurface ocean.
- Are the plumes connected to subsurface liquid water?
- Composition and dust / vapor ratio?

Rathbun et al. (2010)
## Europa – Enceladus Plume Comparisons

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Europa</th>
<th>Enceladus</th>
<th>Ratio Europa/Enceladus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>1561 km</td>
<td>252 km</td>
<td>6.2</td>
</tr>
<tr>
<td>Gravity</td>
<td>1.314 m/s²</td>
<td>0.114 m/s²</td>
<td>12</td>
</tr>
<tr>
<td>Plume Height/Extent</td>
<td>200 km ± 100 km</td>
<td>~500 km</td>
<td>0.4</td>
</tr>
<tr>
<td>Plume Column Density</td>
<td>~1.5 × 10²⁰ m⁻²</td>
<td>~0.9 × 10²⁰ m⁻²</td>
<td>1.66</td>
</tr>
<tr>
<td>Plume Variability</td>
<td>&gt;3</td>
<td>~4 ± 1</td>
<td>~1 ?</td>
</tr>
<tr>
<td>Gas Velocity</td>
<td>~700 m/s</td>
<td>300 - 500 m/s</td>
<td>~1.75</td>
</tr>
<tr>
<td>Gas Outflow Rate</td>
<td>~5000 kg/s</td>
<td>~200 kg/s (vs. dust at 50 kg/s)</td>
<td>~25</td>
</tr>
<tr>
<td>Total Number of Water molecules</td>
<td>~10³²</td>
<td>~10³²</td>
<td>1</td>
</tr>
<tr>
<td>Measurement Sets To Date</td>
<td>1 detection</td>
<td>10’s – 100’s detections with several Cassini inst’s</td>
<td>~0.01</td>
</tr>
</tbody>
</table>
Visible/IR imaging

Imaging of low-optical-depth ice/dust plumes only in forward-scattered light

➤ No plume signs at Europa in high-phase-angle ice/dust images (Galileo, New Horizons)

Galileo SSI – f ~ 25°

New Horizons LORRI & MVIC - f ~ 90°
Summary

- HST/STIS spectral images of Europa’s aurora from November and December 2012 and 1999
- Oxygen aurora morphology and brightness on the disk correlated to magnetospheric environment
- Statistically significant and coincident surpluses of Lyman-α and OI130.4 nm emissions detected above the southern hemisphere in Dec. 2012
- Brightnesses consistent with 200 km high water vapor plumes with column densities of ~10^{20} m^{-2}
- Plumes are present near apocenter (Dec. 2012) and not detected close to pericenter (Nov. 2012, 1999) in agreement with tidal modeling predictions.

☞ Roth et al., 2014, Science, January 10 issue
“Transient water vapor plumes at Europa’s south pole”
Albedo inversion at Lyman-α

- Apparent anti-correlation of Lyman-α and visible albedo (McGrath et al. 2009)

- Far-UV albedo maps generated using inverted visible maps

- Modeling of spectral images of surface-reflected sunlight and subtraction from observations images
South polar region