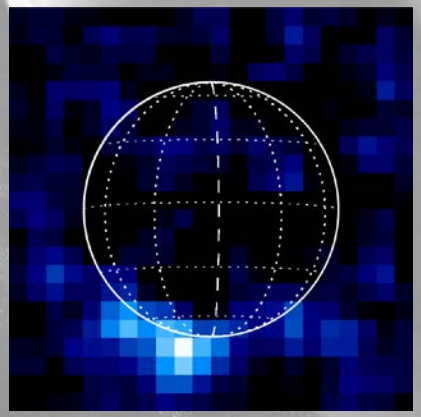
HST Aurora Observations: Transient Water Vapor at Europa's South Pole



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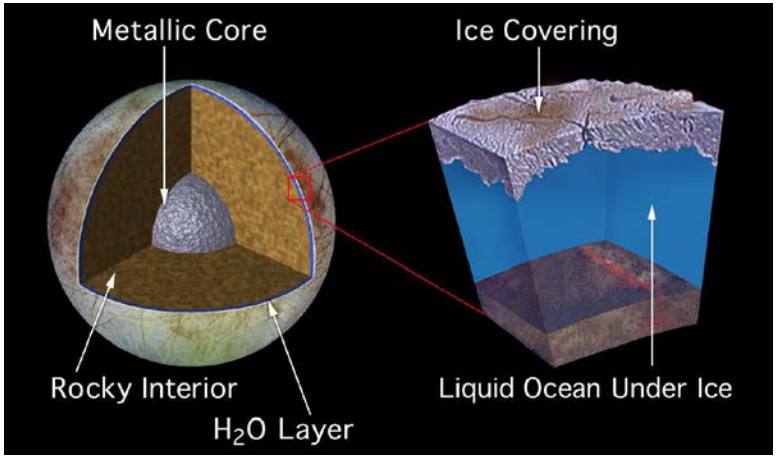
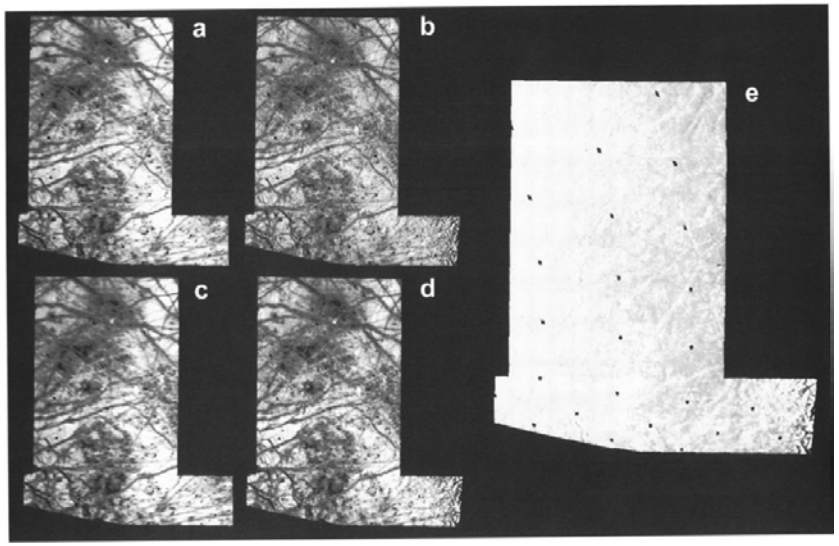
Icy surface, subsurface ocean - and plumes?

- 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)



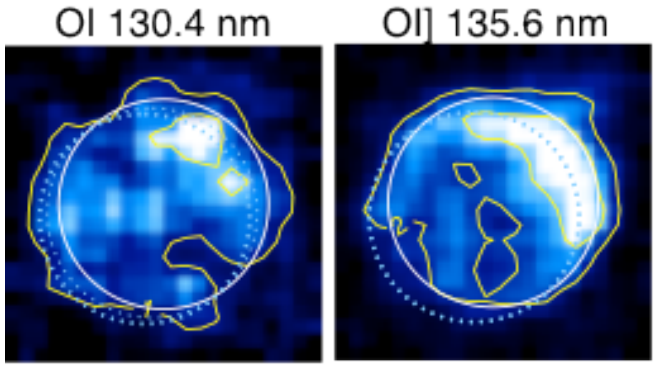


Probing the atmosphere and plumes through UV observations

- 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 $N_{O2} \sim 10^{18} - 10^{19}$ m^{-2}

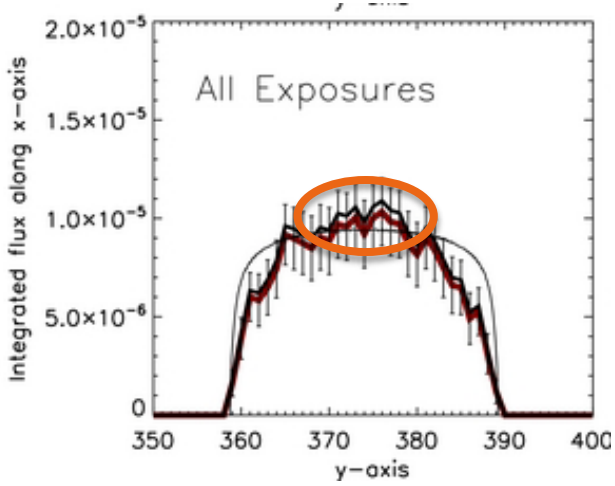


McGrath et al. 2009 (reprocessed)

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

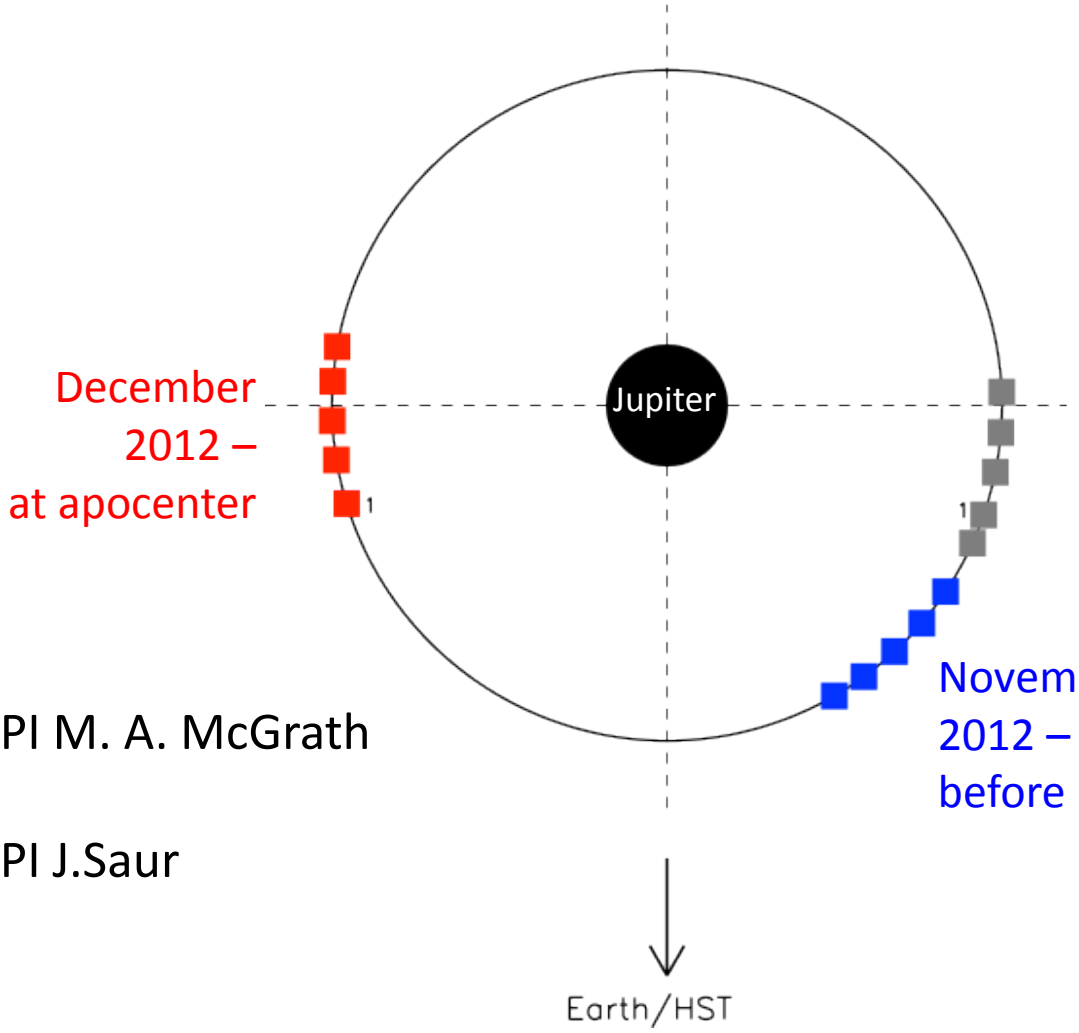
  ➤ Influence of magnetospheric environment?

  ➤ Atmospheric inhomogeneity due to
  - Surface properties (Cassidy et al., 2007)
  - Plume activity? (Saur et al. 2011)

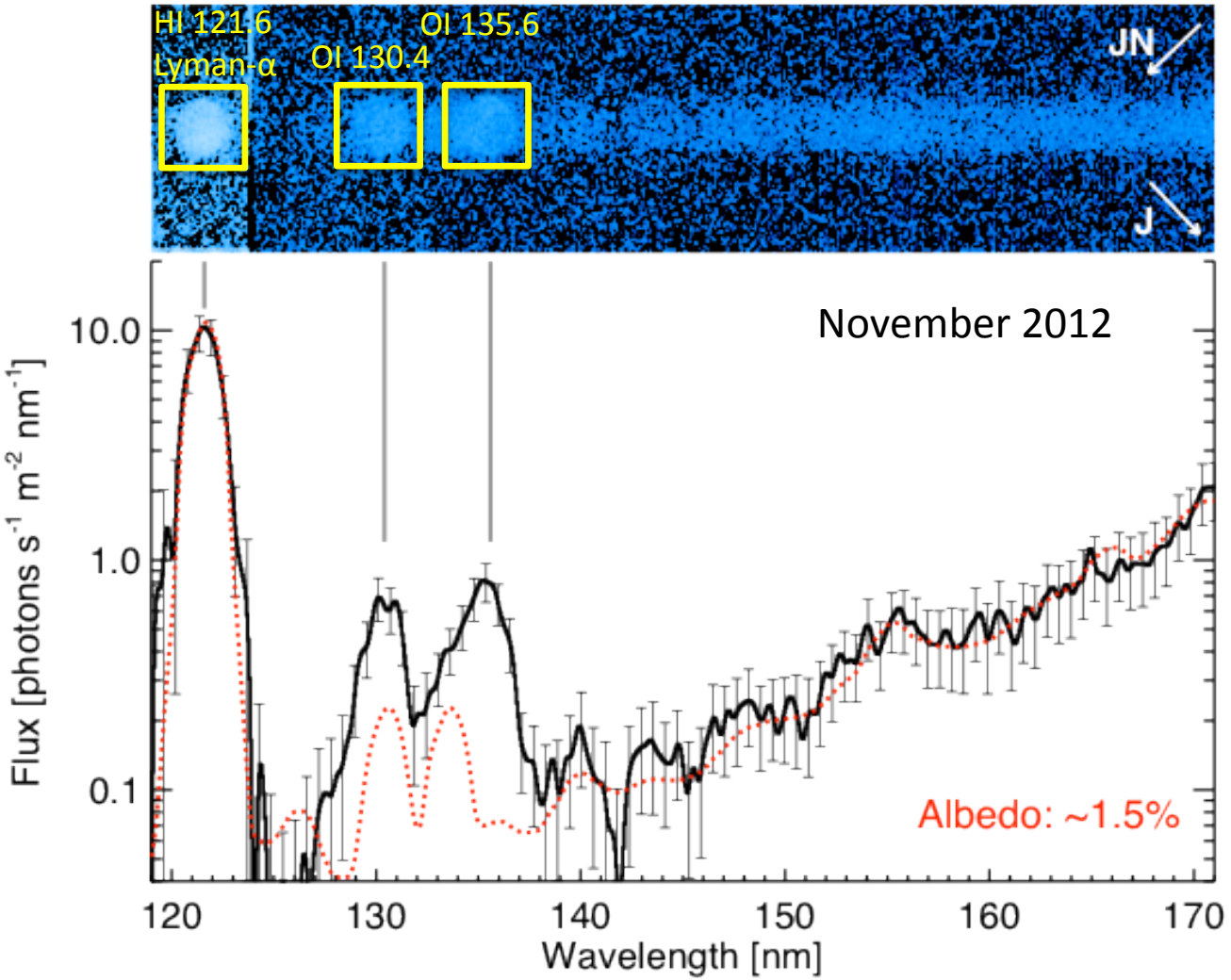


HST ACS - Saur et al. 2011

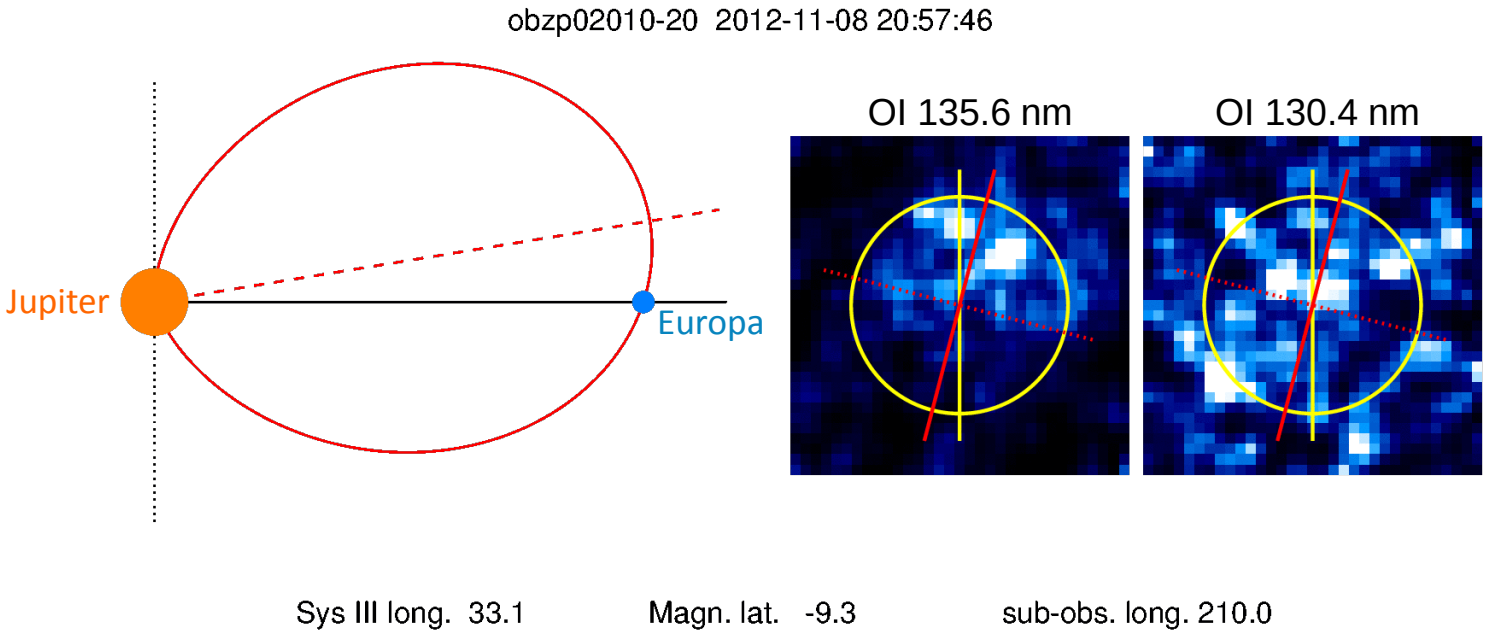
HST STIS observation campaigns Oct. 1999, Nov. 2012 and Dec. 2012



STIS spectral image – 3 ‘colors’ all at once



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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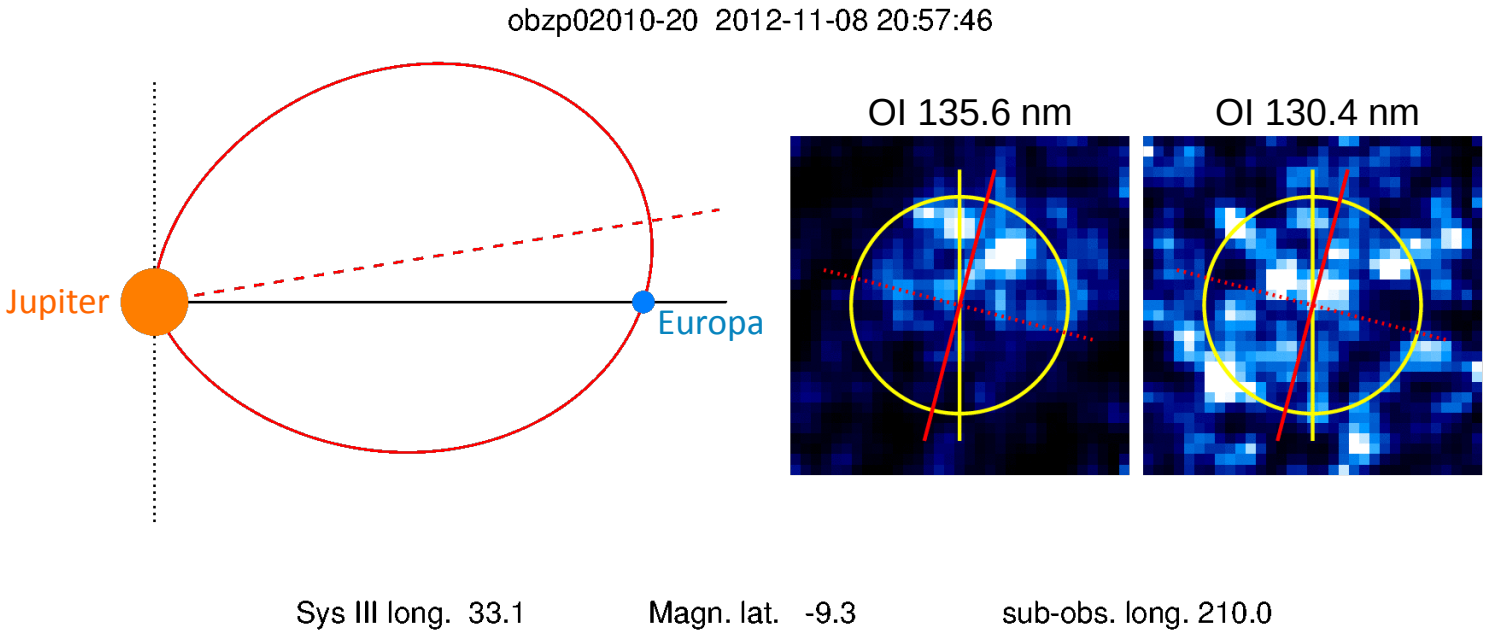

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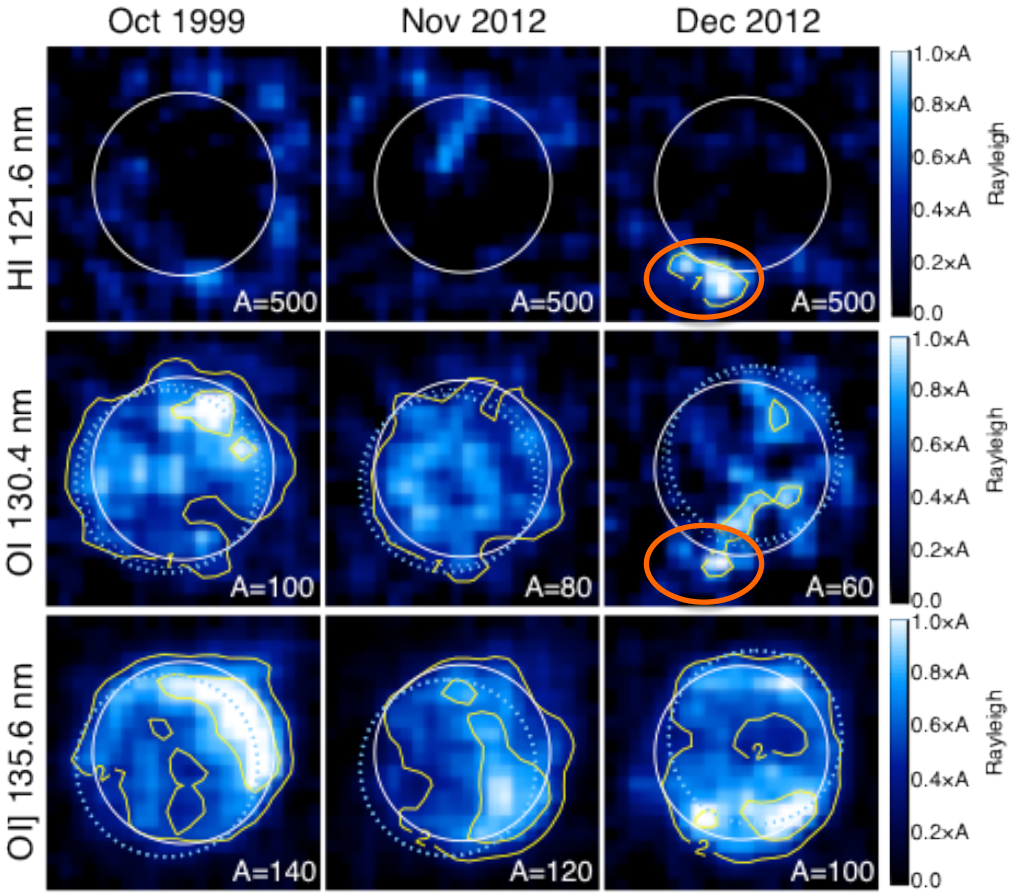
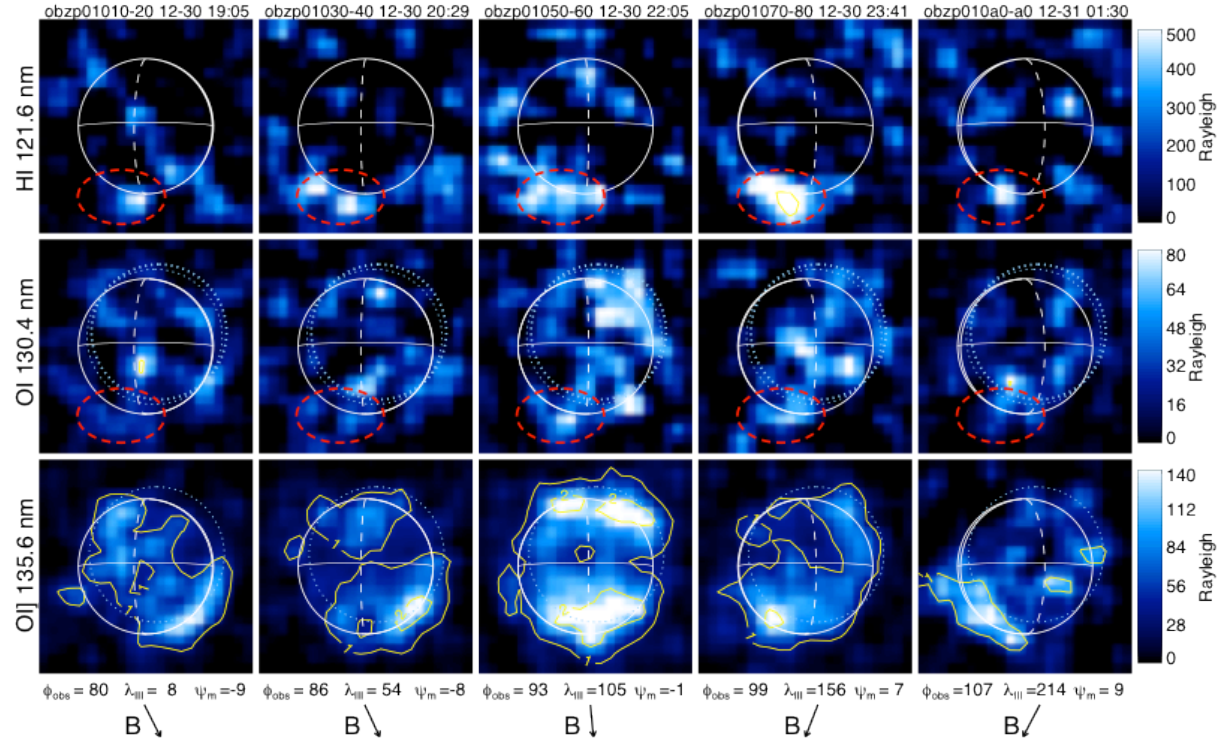
➤ These insights allow a better interpretation of the morphology

Coincident Lyman-α and OI 130.4 nm surpluses

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

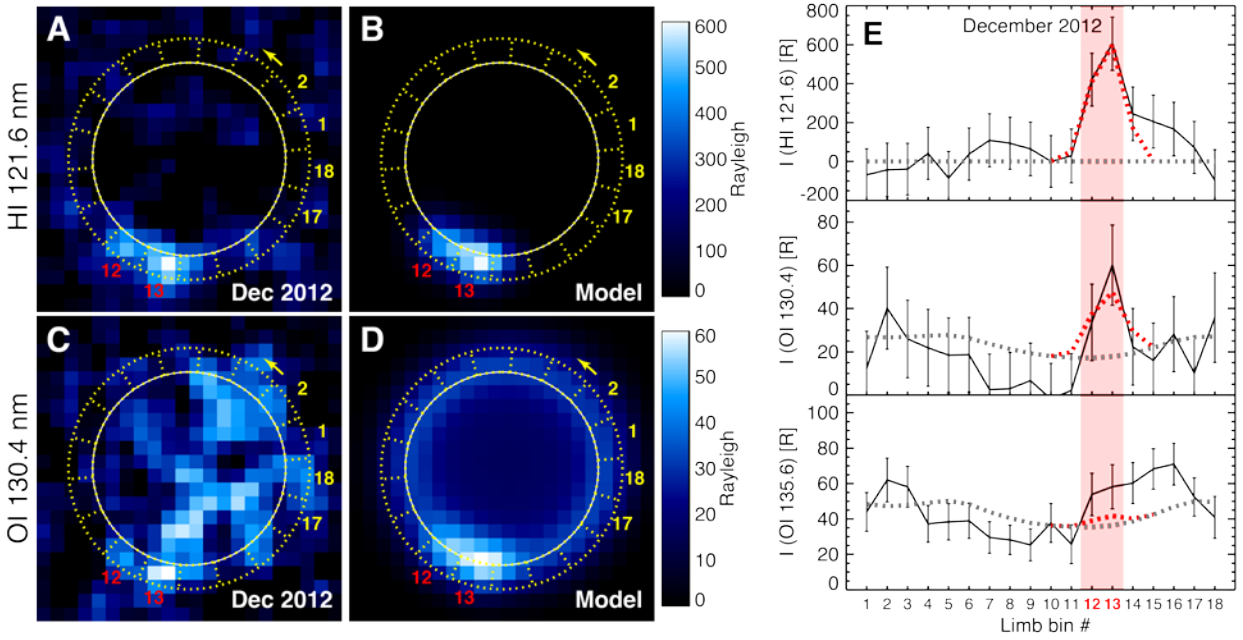


Persistent south polar Lyman-α and OI 130.4 nm emission during all 5 HST orbits in Dec. 2012



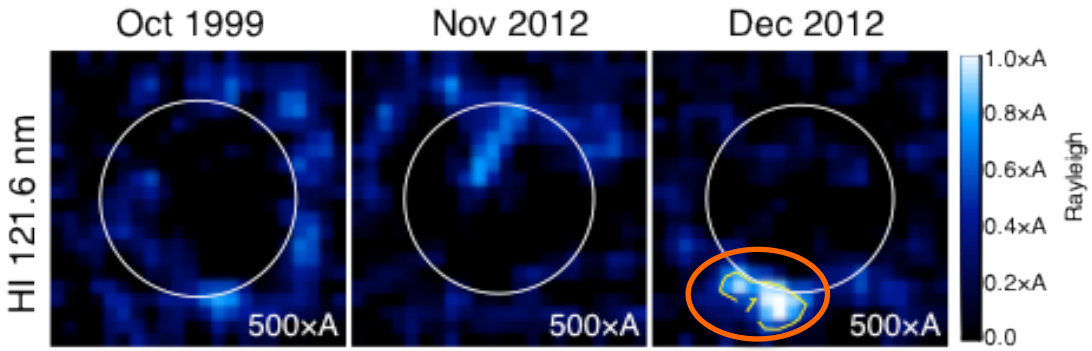
- Spatial persistency indicates atmospheric inhomogeneity
- Lyman-α surplus of ~500 R and OI 130.4 nm surplus of ~30 R
  ➤ Electron impact on H_2O generates Lyman-α and 130.4 nm but relatively little (undetectable) 135.6 nm emission (Makarov et al. 2004)

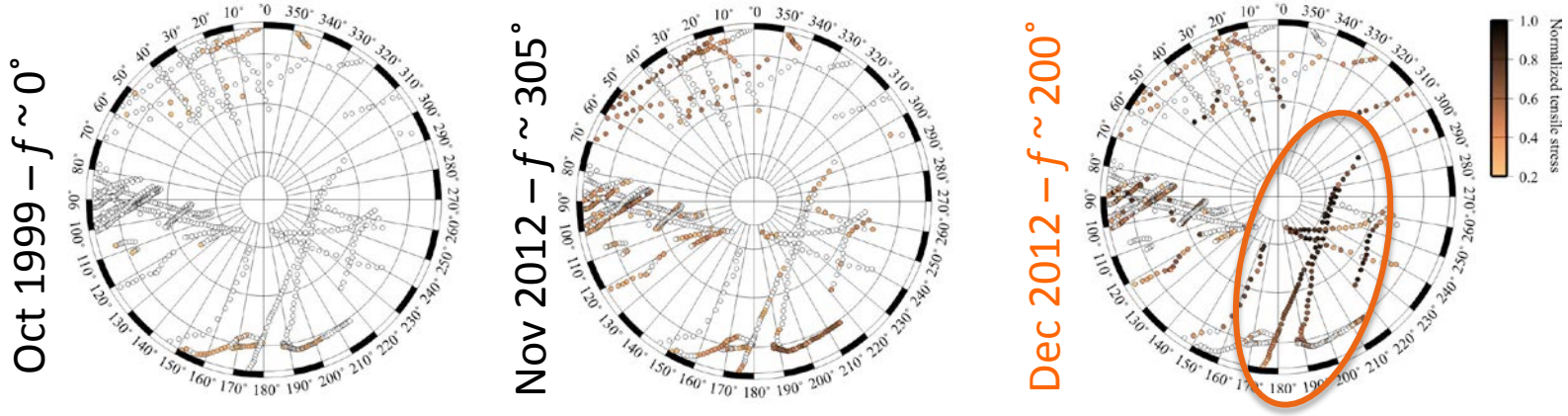
Brightnesses consistent with local water vapor plumes



- Analysis of brightness in 20˚-wide bins around the limb
- Modeled aurora images for global O_2 atmosphere and local H_2O 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

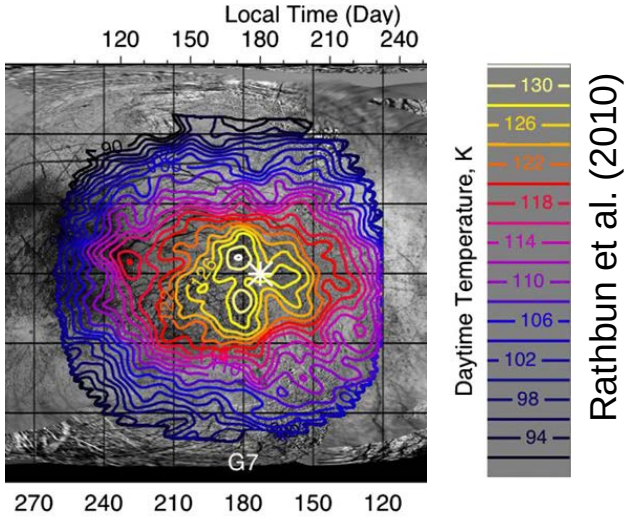


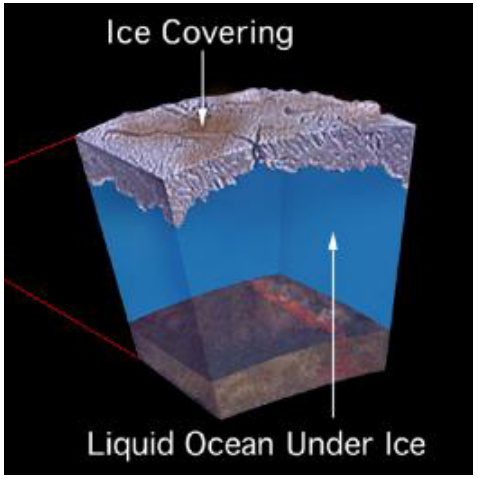


- Oct. 1999 & Nov. 2012 brightnesses limit H_2O densities to ×2 & 3 lower or more
- Tensile stresses on south polar fractures maximize at apocenter (black dots - Dec. 2012), but are low before and at pericenter (Nov. 2012 and Oct 1999)
- Similar tidal processes drive variations of Enceladus' plumes (Hedman et al. 2013)

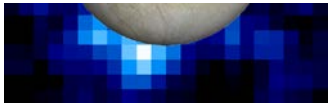
What is the nature of Europa's plumes?

- Plume content of ~10^{32} H_2O 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 ~3000 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?





Europa – Enceladus Plume Comparisons

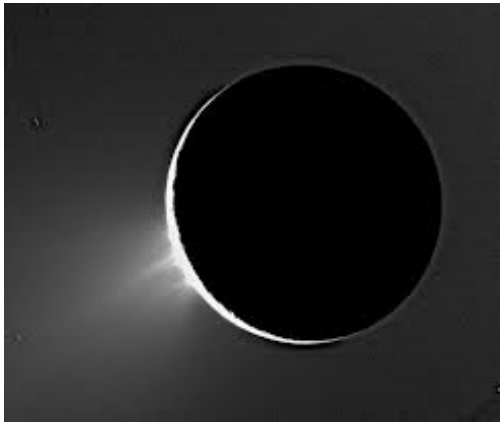
Characteristic	EUROPA 	ENCELADUS 	Ratio Europa/ Enceladus
Radius	1561 km	252 km	6.2
Gravity	1.314 m/s²	0.114 m/s²	12
Plume Height/Extent	200 km ± 100 km	~500 km	0.4
Plume Column Density	~1.5 × 10^{20} m^{-2}	~0.9 × 10^{20} m^{-2}	1.66
Plume Variability	>3	~4 ± 1	~1 ?
Gas Velocity	~700 m/s	300 - 500 m/s	~1.75
Gas Outflow Rate	~5000 kg/s	~200 kg/s (vs. dust at 50 kg/s)	~25
Total Number of Water molecules	~10^{32}	~10^{32}	1
Measurement Sets To Date	1 detection 1 Hubble instrument	10's – 100's detections w/ several Cassini inst's	~0.01

Visible/IR imaging

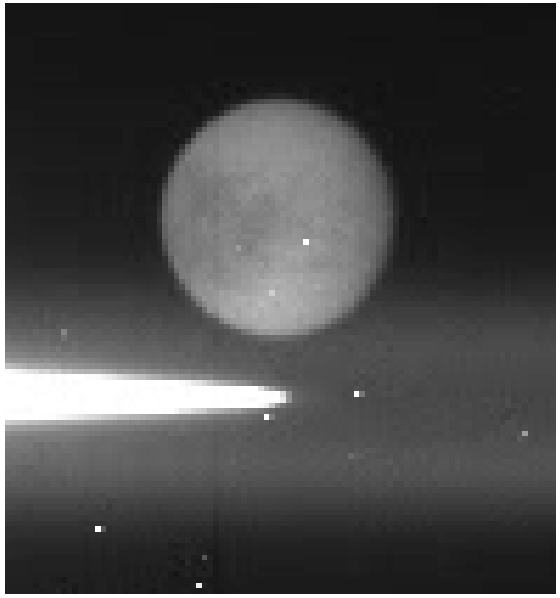
Imaging of low-optical-depth ice/dust plumes only in forward-scattered light

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

Enceladus (Cassini)



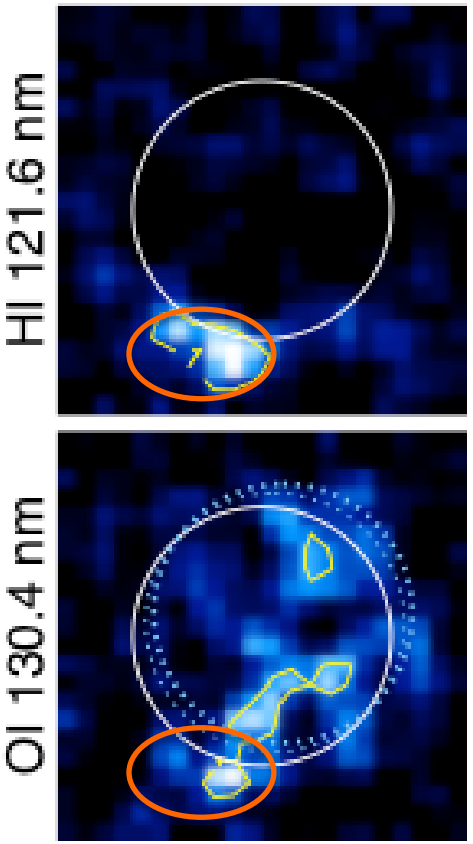
Galileo SSI – f ~ 25º



New Horizons LORRI & MVIC - f ~ 90º

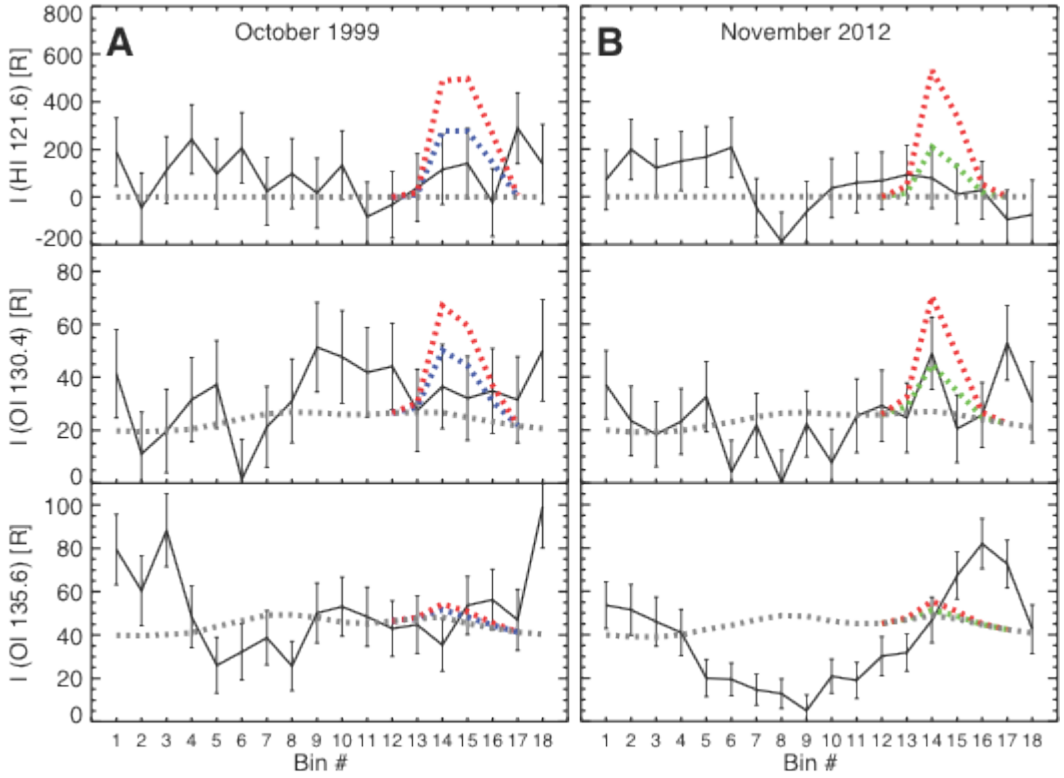
Summary

- HST/STIS spectral images of Europa' 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.



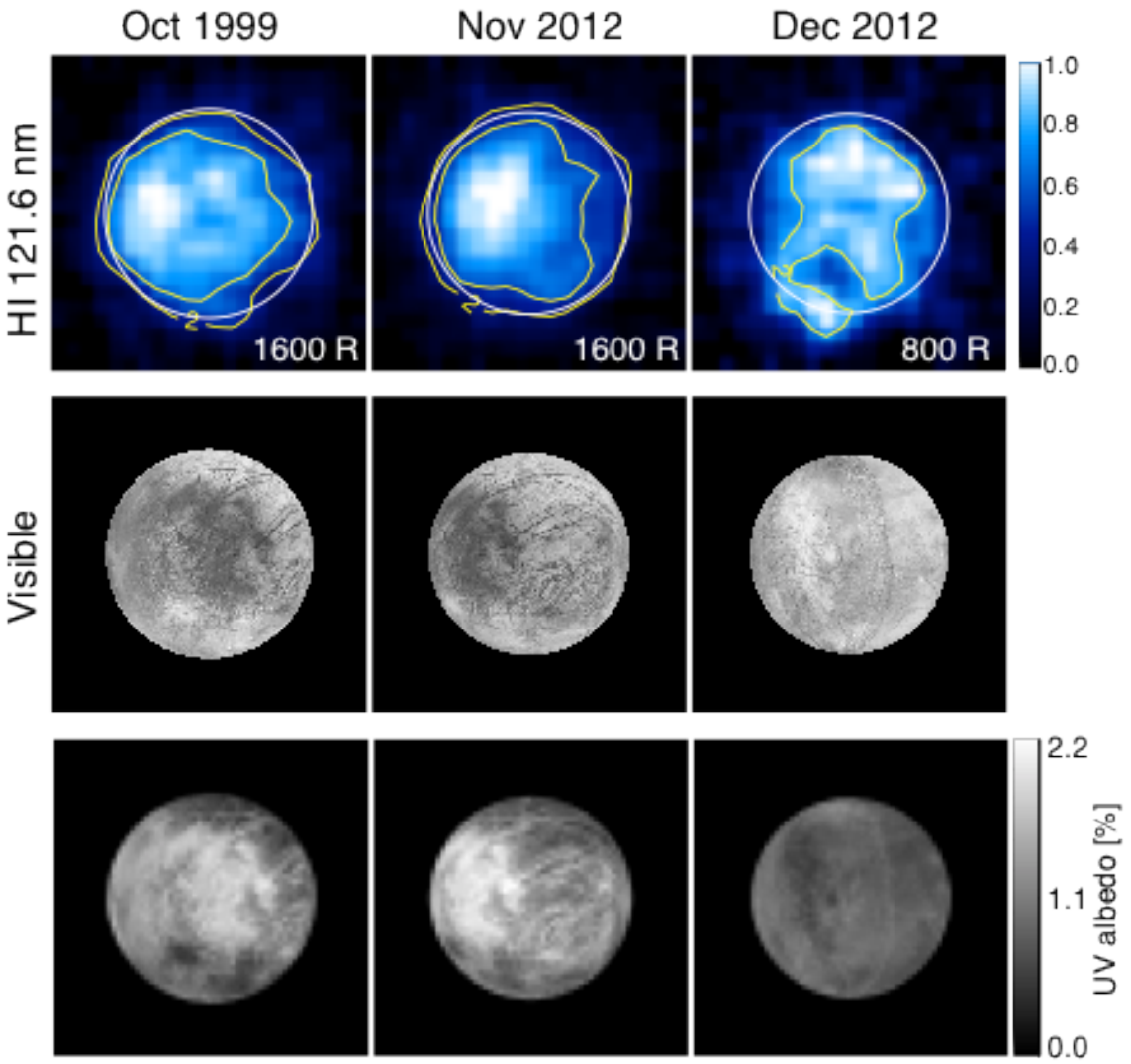
☞ Roth et al., 2014, Science, January 10 issue
"Transient water vapor plumes at Europa's south pole"

Plumes not detected in Oct. 1999 and Nov. 2012



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