Current questions in UV planetary science

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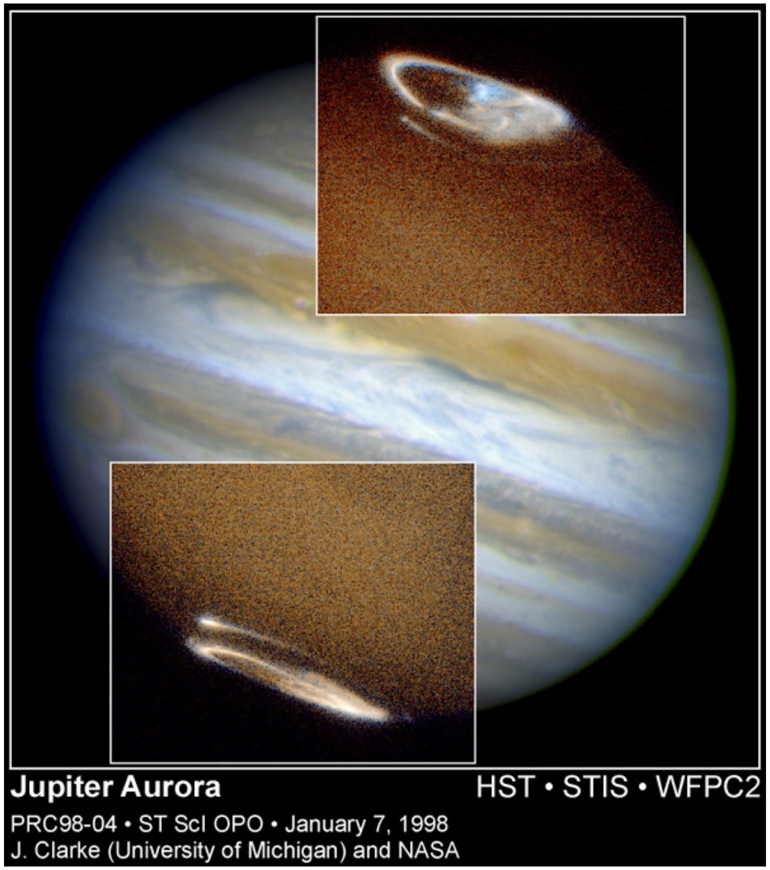
Topics by body

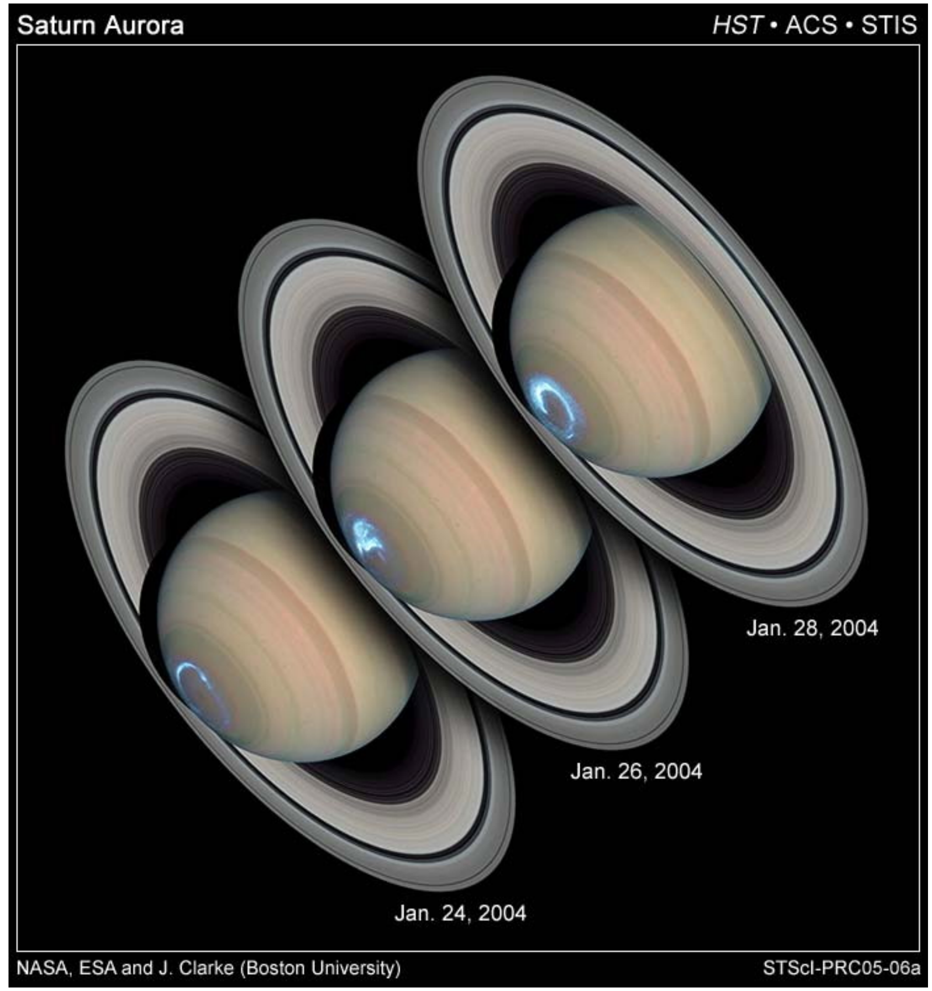
- Mercury:
  - Thin atmosphere, solar wind interactions, space weathering?, polar water frost deposits?
- Venus
  - Atmospheric studies, solar wind interactions
- Moon
  - Recent work by LAMP team – polar water frost deposits, surface composition, space weathering
- Mars & moons
  - Ozone variability, H_2O, CO_2, SO_2? H_2O_2?
- Asteroids
  - Surface composition, space weathering effects (compare to weathering rates on Moon)
  - Main belt comets
- Jupiter & moons & system (eg Io torus)
- Saturn & moons & rings & system
- Uranus & moons
  - Atmospheres; aurorae; atmosphere-surface interactions; seasonal variations
- Neptune & moons
  - Atmospheres; aurorae; atmosphere-surface interactions; seasonal variations
- Pluto & moons
  - Atmospheres; atmosphere-surface interactions
- Primitive bodies (KBOs, Trojans, Centaurs etc)

Topics by field

- Auroral studies
- Atmospheric composition
- Effects of radiolysis, photolysis
  - Surfaces & atmospheres
- Effects of sputtering
  - Production of thin atmospheres
  - Surface chemistry
- Searches for geologic activity
  - Stellar, solar occultations
- Surface composition
  - *effects of weathering

Jupiter, Saturn aurorae





HST, Cassini, (Juno)

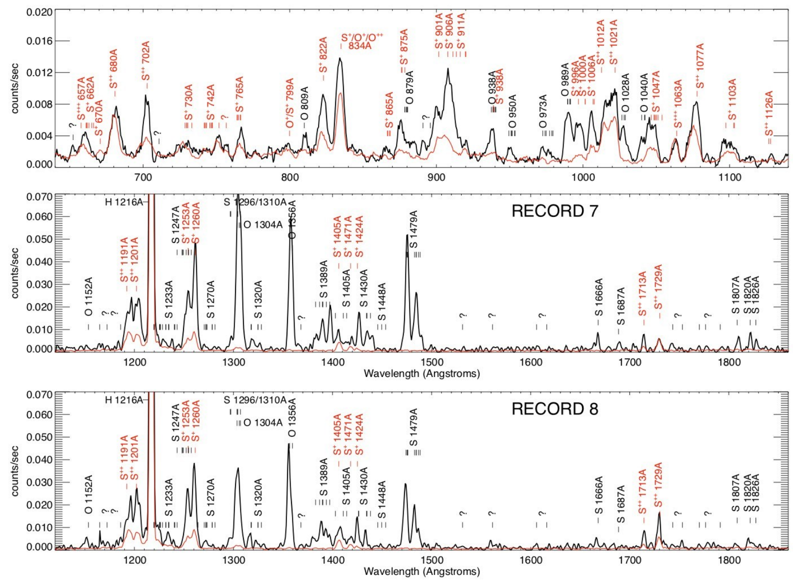
The far-ultraviolet emissions are dominated by the hydrogen Lyman-alpha and the H_2 Lyman and Werner system bands. UV observations have measured the temporal variability within the aurora and temperature variations within the auroral ovals seen at both poles. These variations are reflections of possible distortions in the magnetic field of Jupiter.

Io’s Atmosphere, Aurorae and Torus

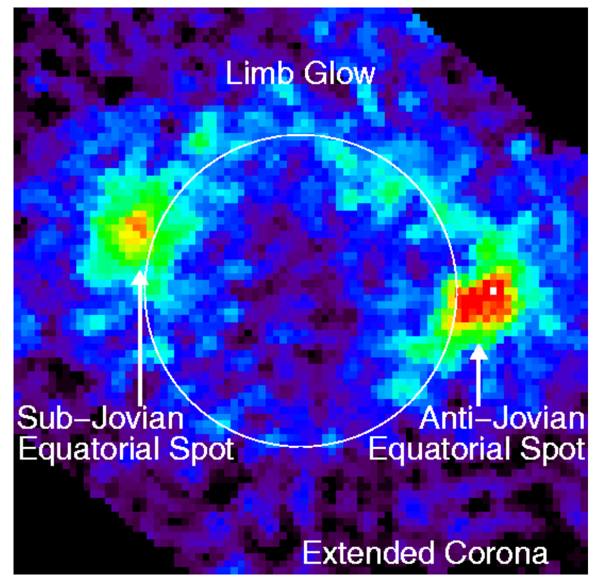
Io has one of the most unique atmospheres in the solar system: the primary sources of the atmosphere are volcanic emissions and sublimation of SO_2 frost on the surface. The result is a tenuous, patchy atmosphere made up of SO_2, SO, S_2, S and O; trace species include Na, K, Cl, NaCl and H. Much study of Io’s atmospheric processes has been made at UV wavelengths. The IUE, HST and the Galileo UVS have made measurements of Io at near-UV wavelengths (200-350 nm). Far-ultraviolet (110-100 nm) observations from HST and Cassini UVIS identified emissions from neutral oxygen and sulfur and have been used in mapping the density of the atmosphere.

Intriguing auroral features are a consequence of Io’s SO_2 atmosphere, resulting from electron impact excitation of atomic oxygen and sulfur, and electron dissociation and excitation of SO_2, and have been observed at visible and FUV wavelengths. The Io flux tubes (IFT) and the Io plasma torus are the two primary sources of electrons in the Io environment. Due to the 10° tilt of Jupiter’s magnetic field, Io is alternately above and below the magnetic equator (depending upon Io’s System III Jovian magnetic longitude), the primary region of the torus electrons. Furthermore, the tangent points between field-aligned electrons and Io’s atmosphere change as Jupiter rotates. The interaction of the torus electrons and the IFT electrons with Io’s atmosphere has been detected at FUV wavelengths. Equatorial spots have been observed to wobble up and down, reflecting the changing location of the IFT tangent points in time. The equatorial spot on the anti-jovian hemisphere has been measured to be brighter than the spot on the sub-jovian hemisphere, likely due to the motion of electrons through Io’s atmosphere by the Hall effect, with hotter electrons on the anti-Jovian side.

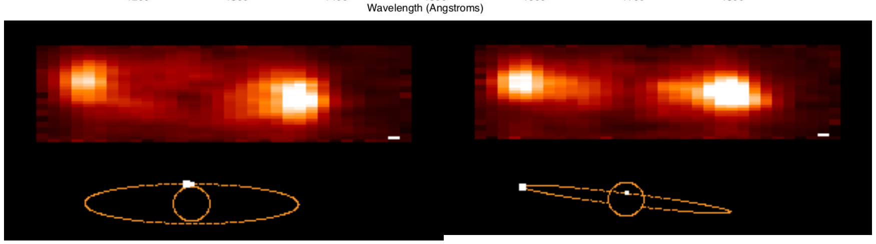
Oxygen, sulfur, and sodium ions are the major constituents of the torus, and protons are present at ~10% abundance; chlorine ions have also been detected. The torus is not uniform, and the density of ions shows various asymmetries dependent on Io’s position and dawn–dusk timings, in addition to temporal variations.



Cassini UVIS spectra of Io, torus



STIS image of (courtesy K. Retherford).

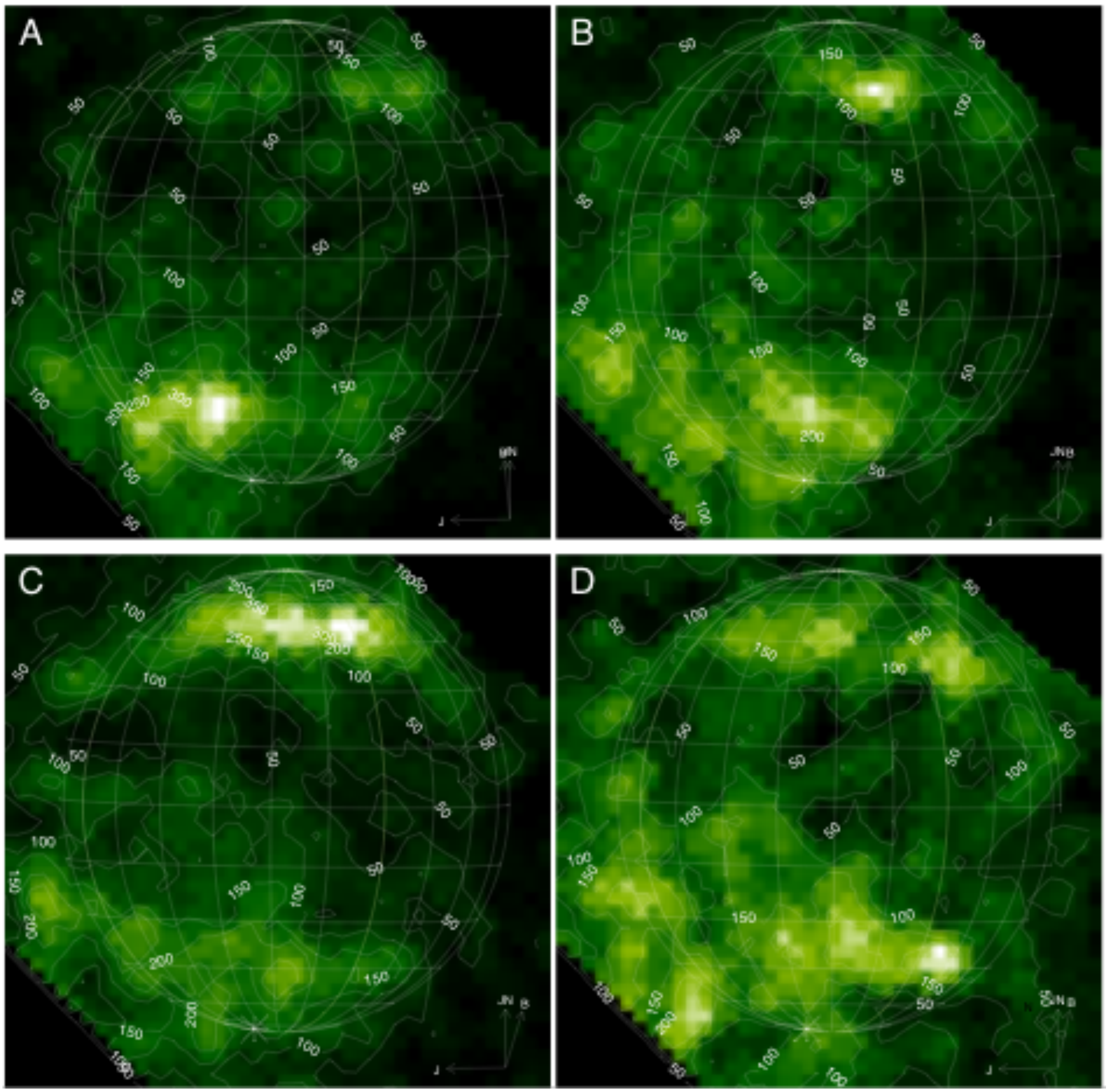


Cassini UVIS images of the Io torus (courtesy Ian Stewart).

Ganymede's Atmosphere and Aurorae

Ganymede's aurorae are the result of the interaction between Ganymede's O_2 atmosphere and the magnetic field lines. First detected as a double-peaked emission line in HST spectra (Hall *et al.*, 1998), the aurorae were imaged using STIS (Feldman *et al.,* 2000). The aurorae appear to exhibit a persistent overall pattern of emission at high latitudes on the upstream (trailing) hemisphere, emission at low latitudes on the downstream (leading) hemisphere, and emission at a lower latitude in the north than in the south. The morphology does not appear to be related to either Jupiter or Ganymede's magnetic field orientations in any obvious way.

Long-term UV imaging of Ganymede's atmosphere and aurorae in the Jupiter system is critical for the investigation of this phenomenon.



STIS images; Feldman et al.

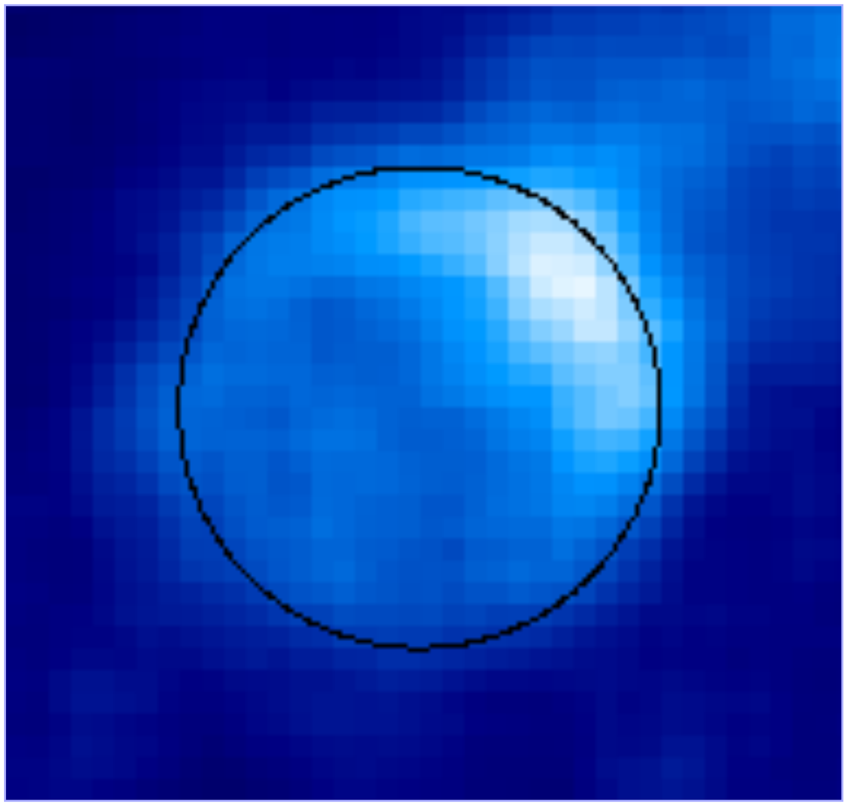
Callisto’s Atmosphere

Callisto may have a much thicker atmosphere than either Europa or Ganymede (Liang et al. 2005). The CO_2 component of the atmosphere was first detected by Galileo NIMS (Carlson 1999) but modeling suggests a more robust atmosphere (Strobel et al. 2002). Consistent with this, the ionosphere (Kliore et al. 2002) is also more substantial and appears to be present only when the trailing hemisphere is illuminated by the Sun. Since no emission features were detected at FUV wavelengths that would be a result of electron excitation and dissociation of CO_2 (Strobel et al. 2002), it was suggested that the interaction between the ionosphere and Jupiter's magnetosphere effectively reduces the electron impact induced emission rate.

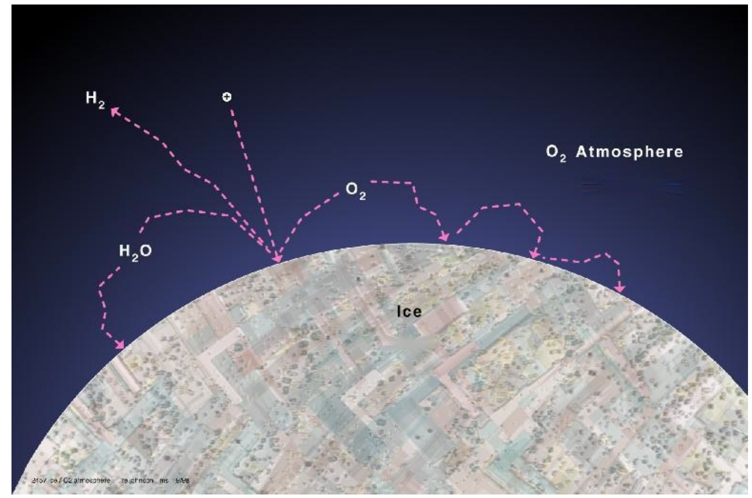
The most effective way to investigate Callisto’s atmosphere may be through stellar occultations to measure gaseous absorptions.

Europa's Atmosphere and Plume Searches

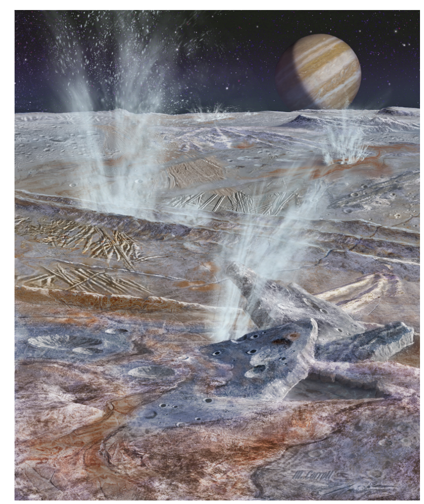
Ultraviolet investigations facilitate the study of Europa's atmosphere, and can also probe the possibility of current activity at Europa, with ties to the subsurface ocean and habitability. Europa is known to have a thin ($N \sim 1 \times 10^{15}$ cm^{-2}) O_2 atmosphere as detected by HST (Hall *et al.*, 1995, 1998) and the Cassini UVIS (Hansen *et al.,* 2005). The primary source of the atmosphere is likely sputtering of the surface ice. The distribution of O_2, as shown in HST/STIS images, appears to be asymmetric. This atmospheric asymmetry must be further probed, to understand its persistence and source. An additional possible source of Europa's atmosphere is venting from the subsurface ocean; such venting or transient gaseous activity could be due to present-day geologic surface activity. The highest sensitivity to a small column of gas will be achieved using UV observations.



Europa's atmosphere as imaged in 135.6 nm using HST/STIS (McGrath *et al.,* 2004). What is the source of the spatial asymmetry? Is the atmosphere variable with time? Could venting from the subsurface ocean contribute to the atmosphere (as with Enceladus), or is sputtering the sole source?

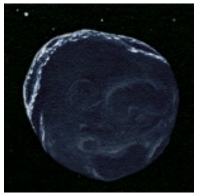


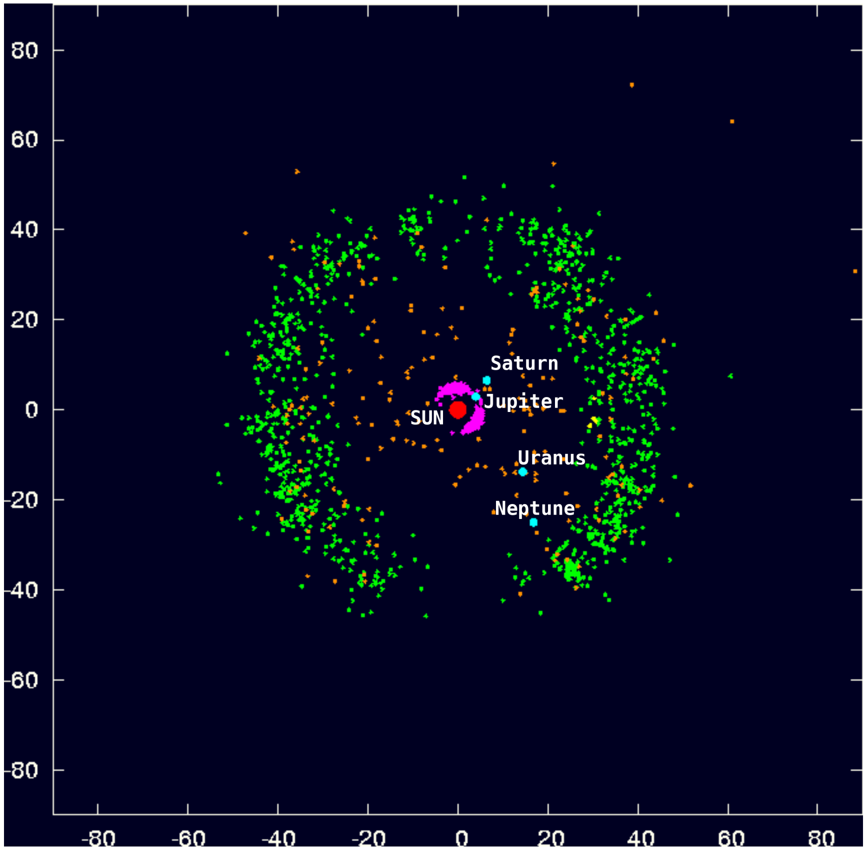
Sputtering at Europa contributes to trapped volatiles in the ice matrix, and is a source of the O_2 atmosphere. Figure courtesy Bob Johnson.

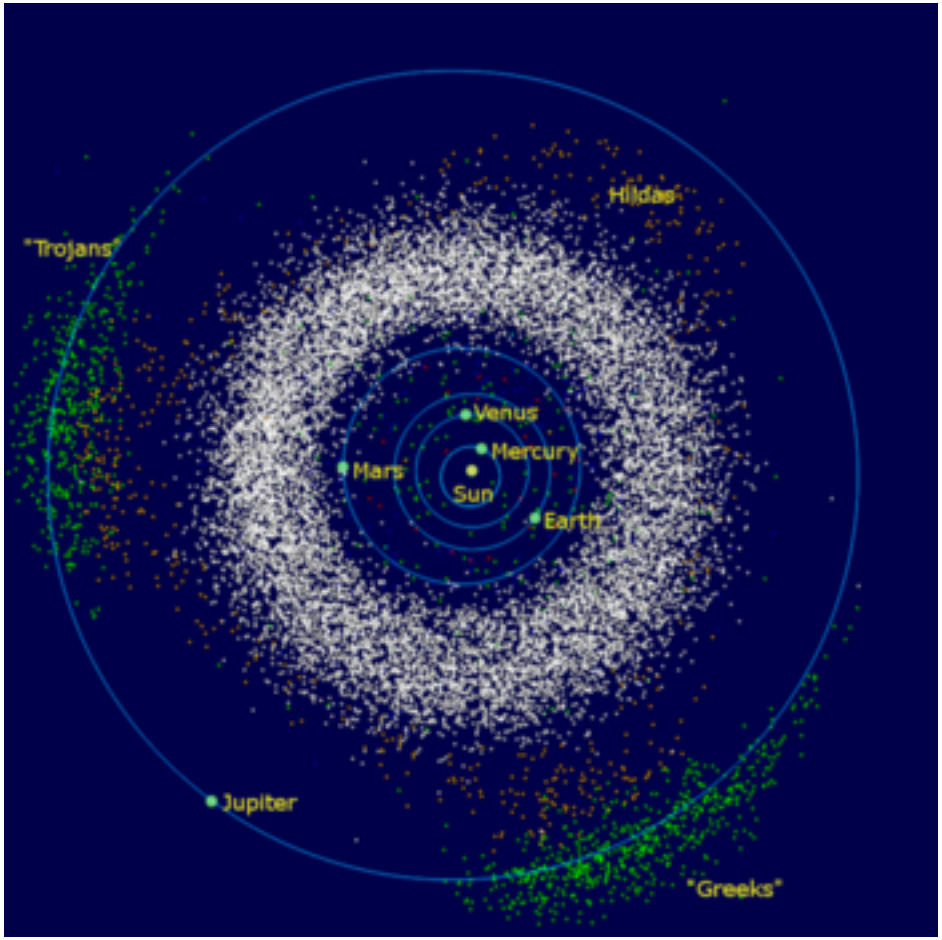


Artist's conception of possible plumes on Europa. Courtesy Michael Carroll.

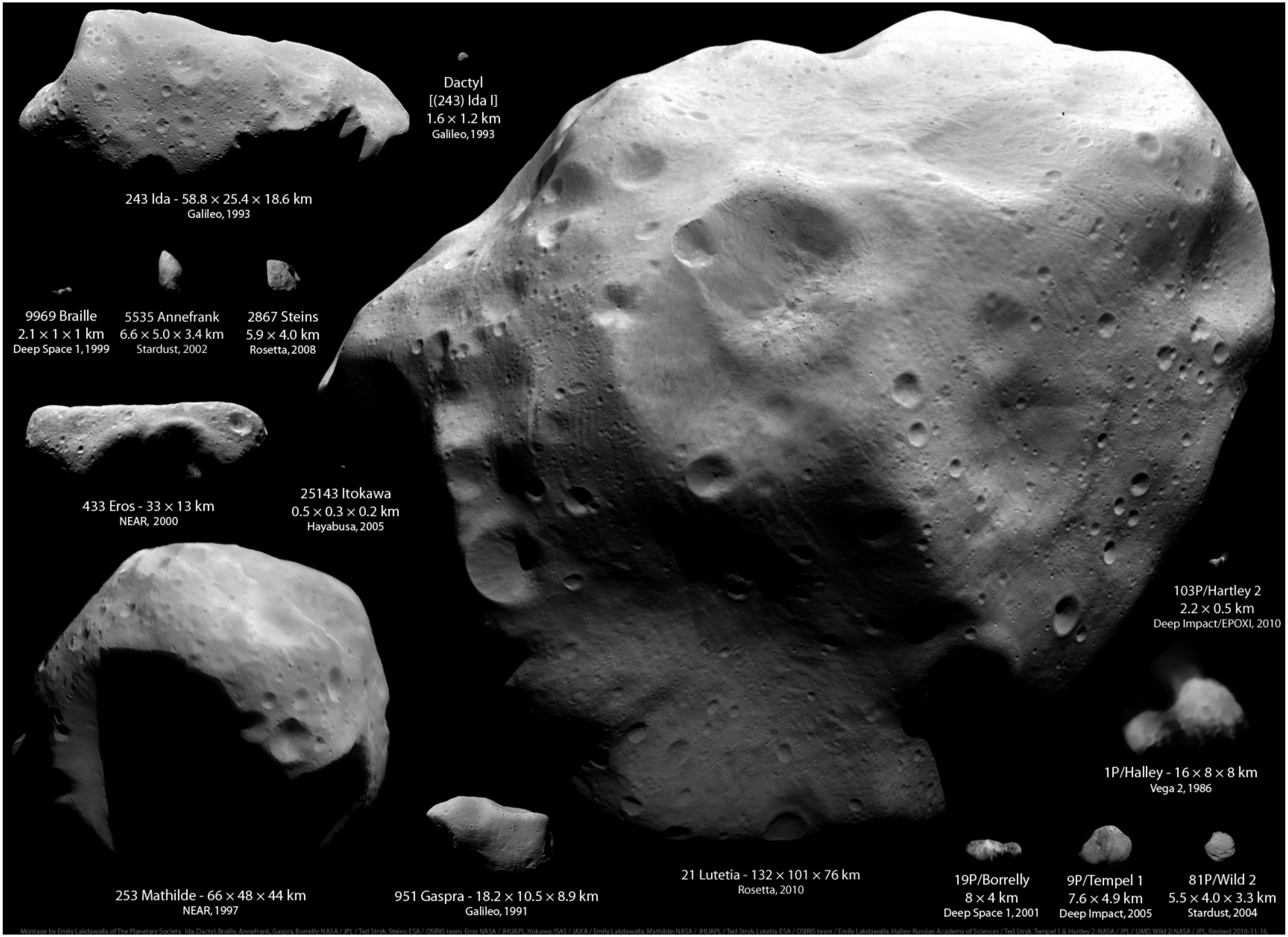
Primitive bodies: any activity? What is surface composition?





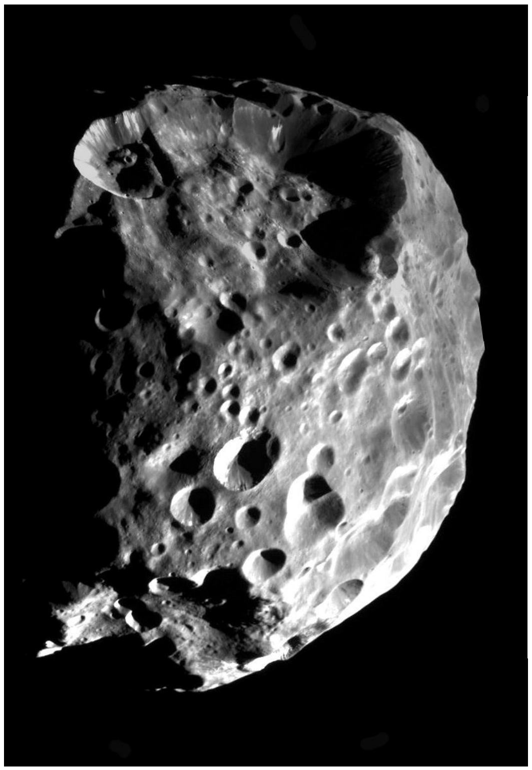


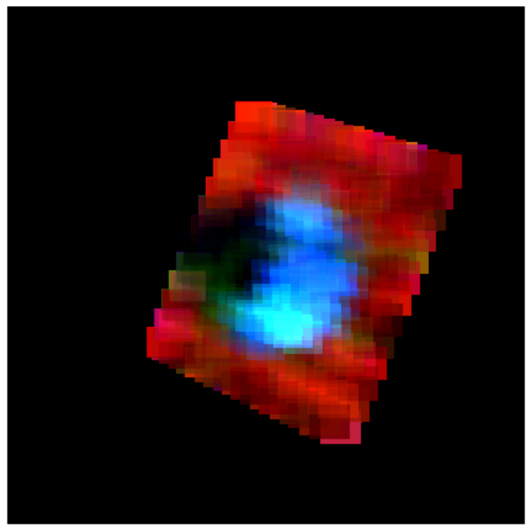
These are bodies with links to the early solar system: largely unaltered



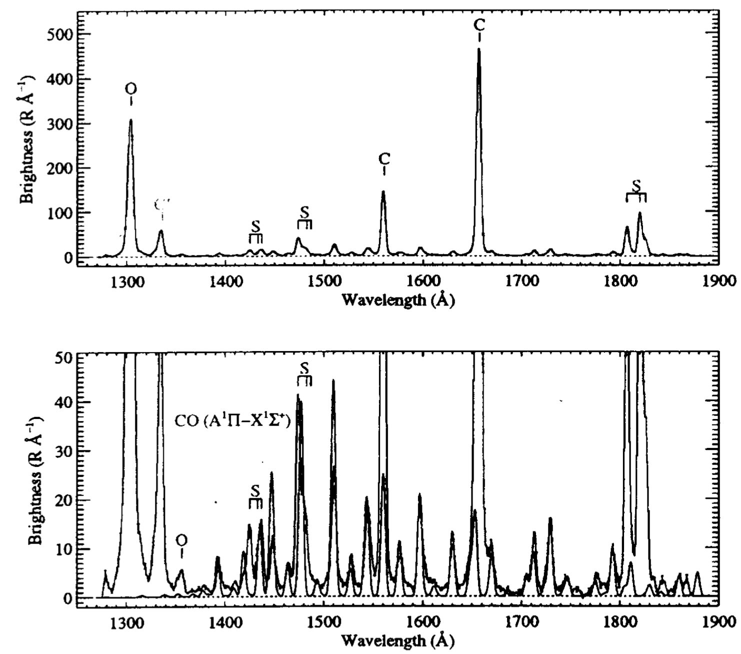
Montage courtesy E. Lakdawalla

Phoebe: a captured KBO?



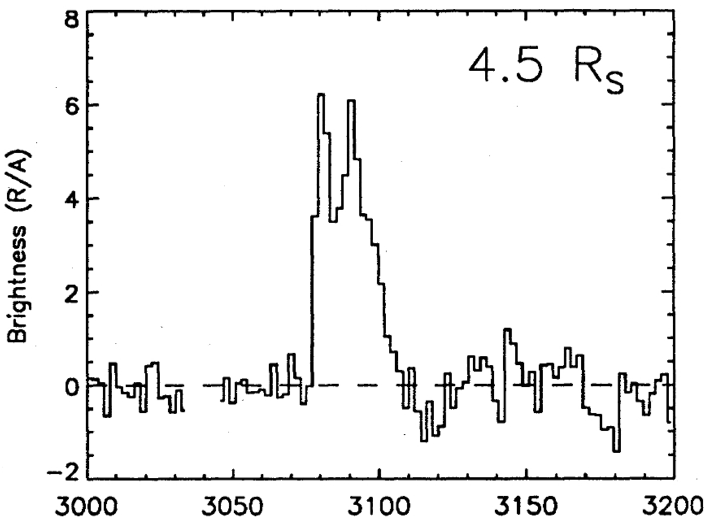


No FUV emissions detected by Cassini UVIS – the situation may be different at other primitive bodies



HST/FOS spectrum of comet Hale-Bopp, Feldman 1997

Saturnian system: OH



HST/FOS

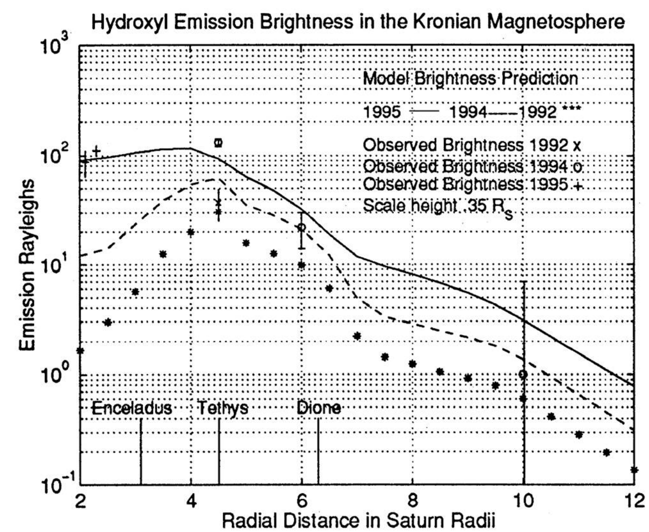
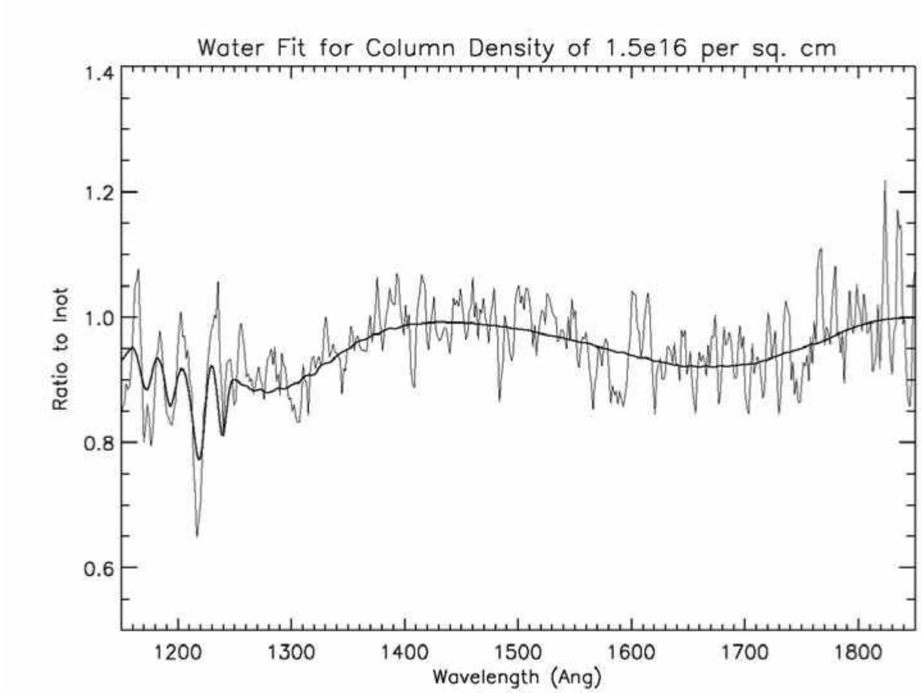
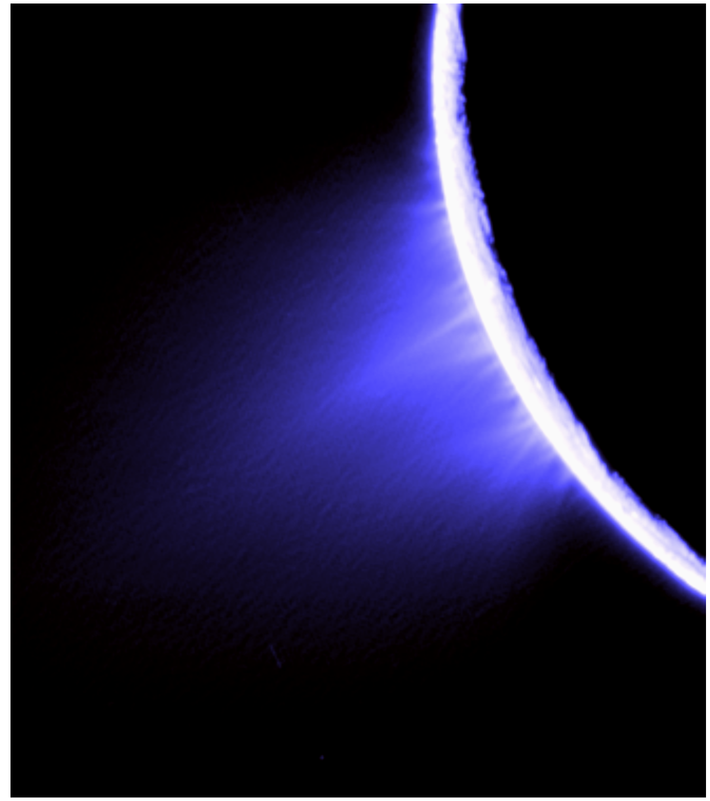


Figure 5. Brightnesses of OH inferred from HST observations (points) with 1σ errors. Model OH emission profiles for the 3 epochs are shown by the lines.

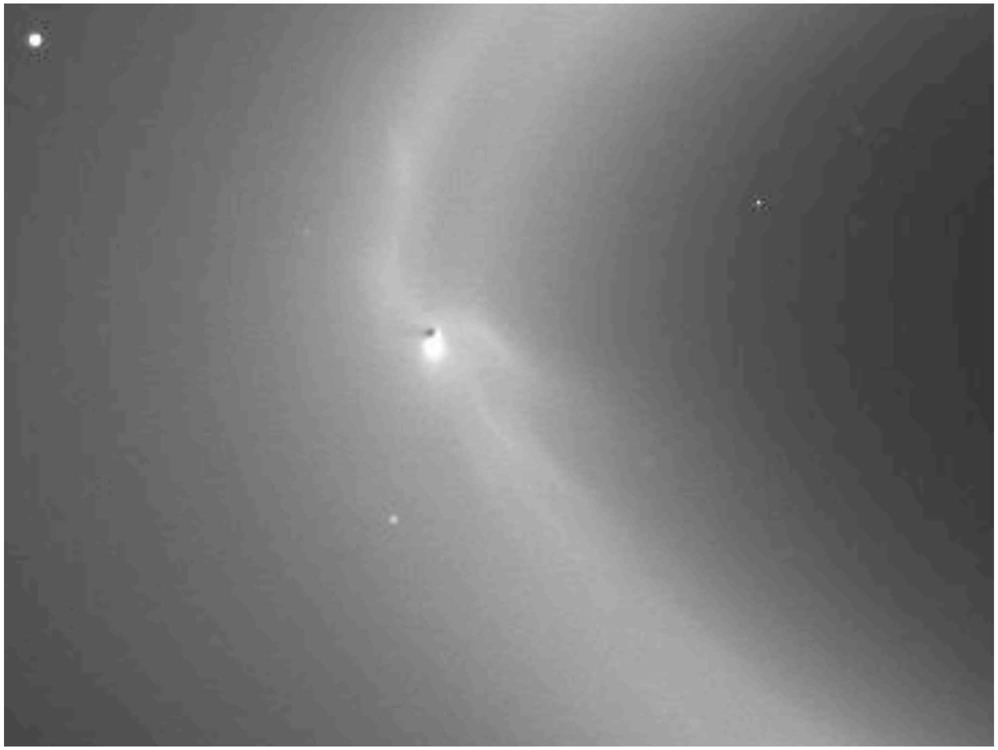
Shemansky et al 1993; Richardson et al 1998

Enceladus: south polar plume discovered in 2005





(Left) UVIS detection of H_2O vapor in the Enceladus plume (Hansen *et al.,* 2005). (Right) visible images of the plumes exhibit dust grains, not gas (Porco *et al.,* 2005).



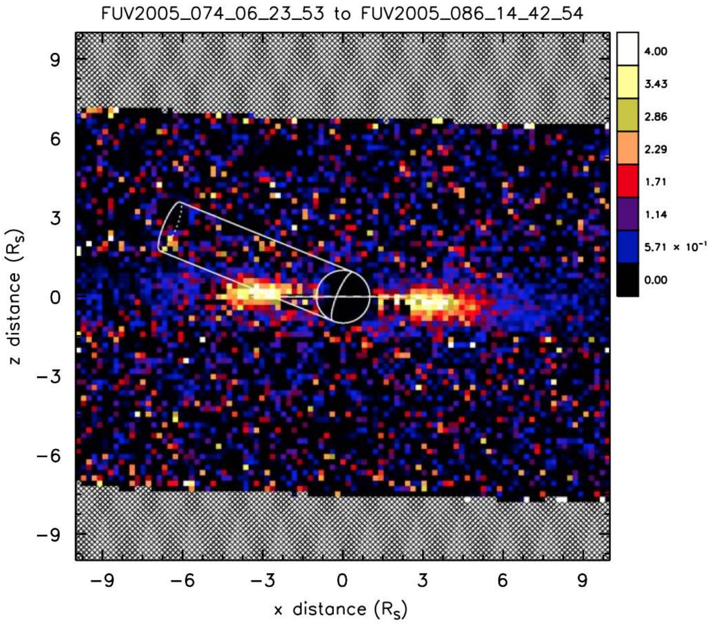


Fig. 18. OI 1304 Å map of Group 7 (2005-074), as defined in Tables 1 and 2, rendered at a resolution of $0.1 \times 0.1 R_S$. Note that the intensity scale has a maximum value of 4 Rayleighs per mosaic element.

Melin et al. 2009

Models of Saturn system OH and O

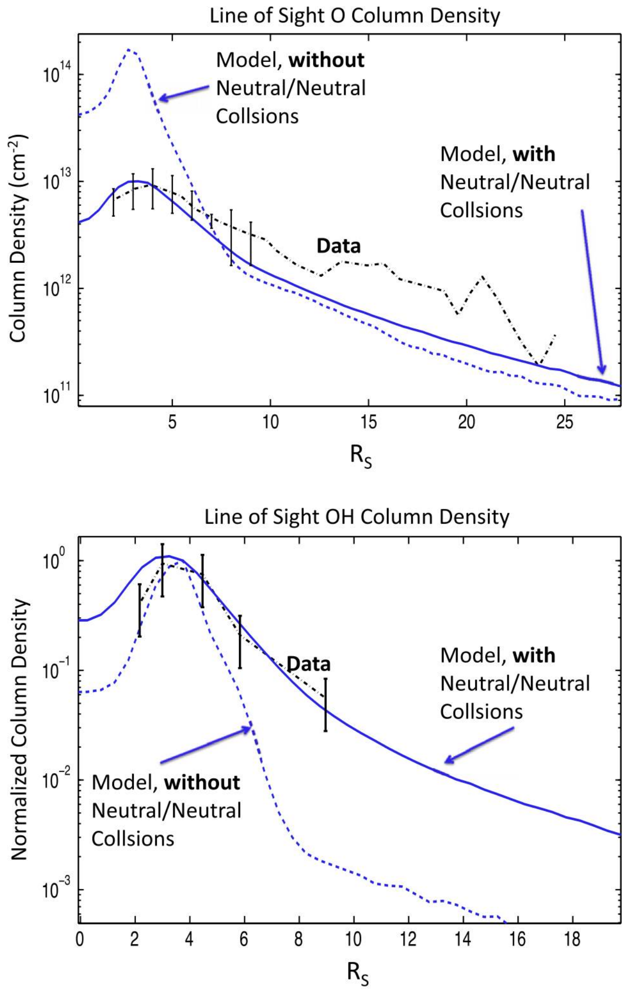
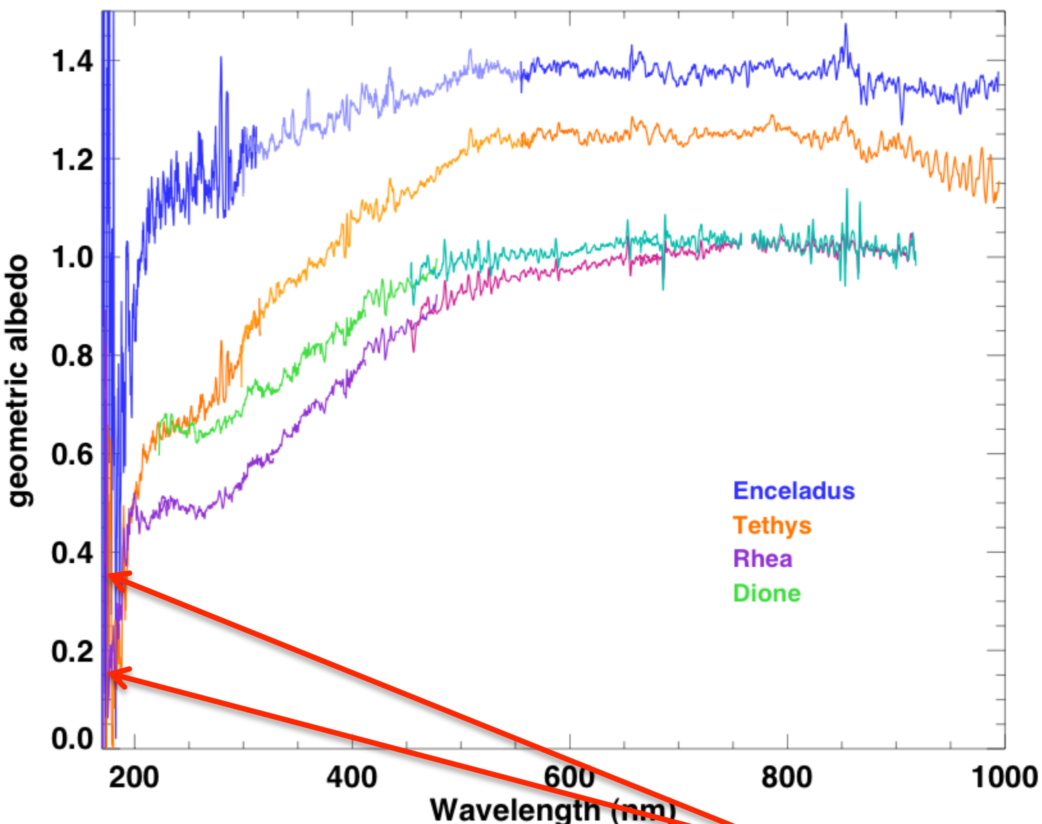


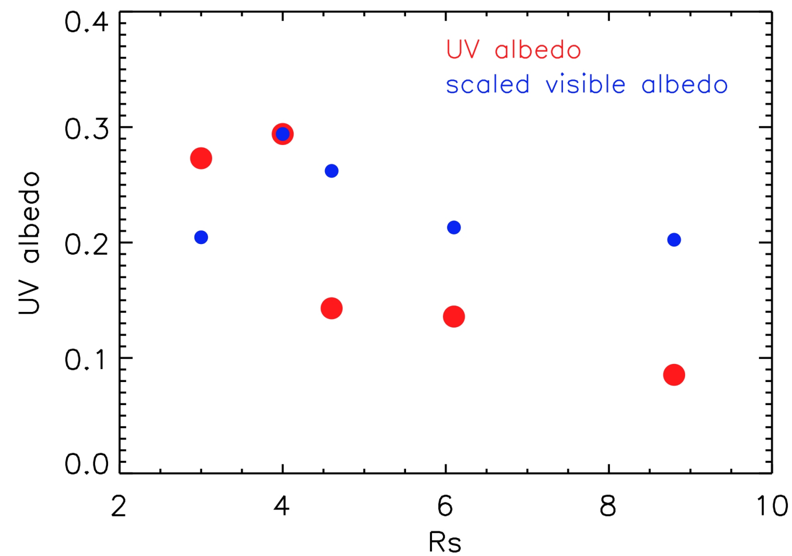
Fig. 5. Comparison of modeled *line-of-sight* column densities with observations from Melin et al. (2009). The OH column density was normalized to 1 at 4 R_S in the absence of an absolute scale. Note that the O cloud is much broader than the OH cloud and that the OH profile is slightly different than that used by previous modelers, as discussed in the introduction.

Cassidy & Johnson 2010

Saturnian satellites: absorbing in the NUV; dark in the FUV

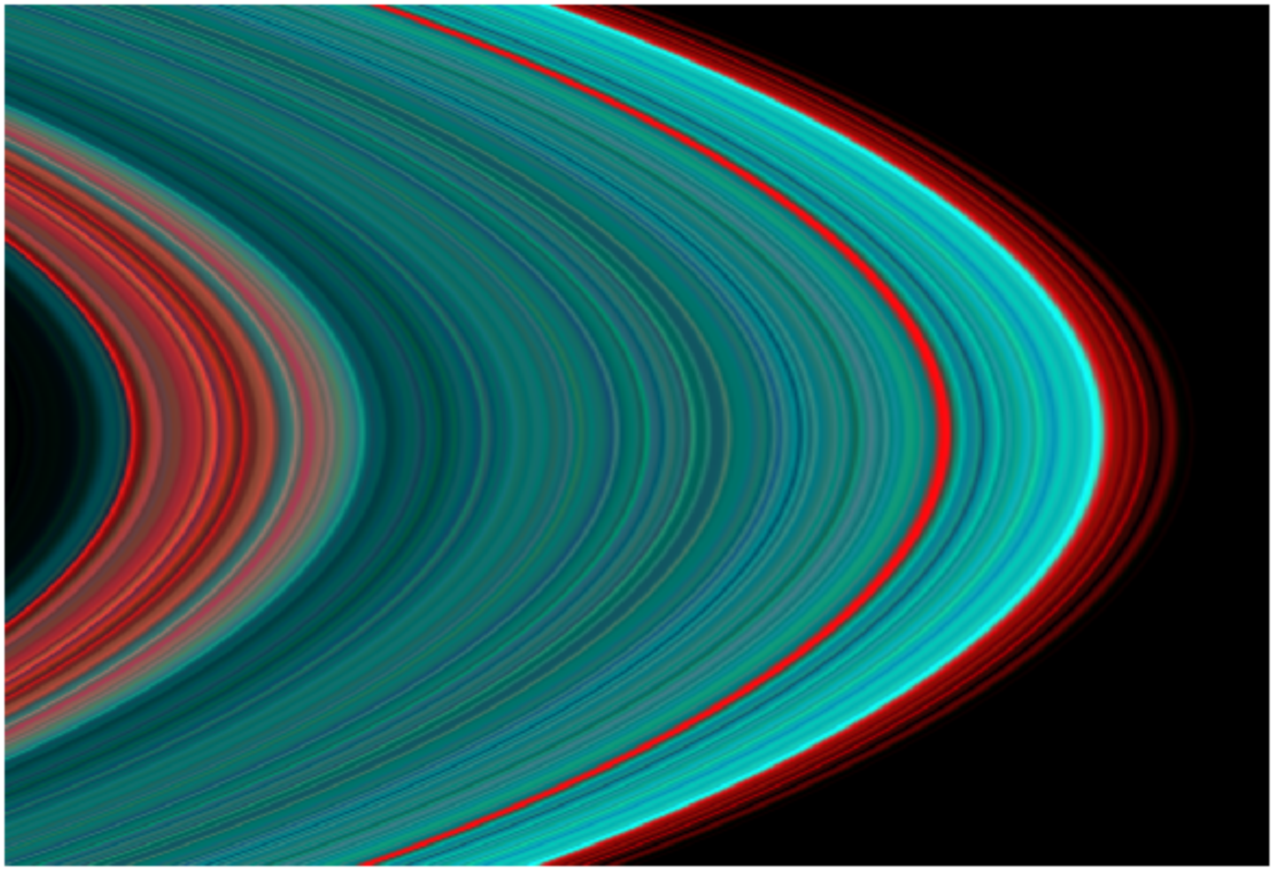


STIS Noll et al.

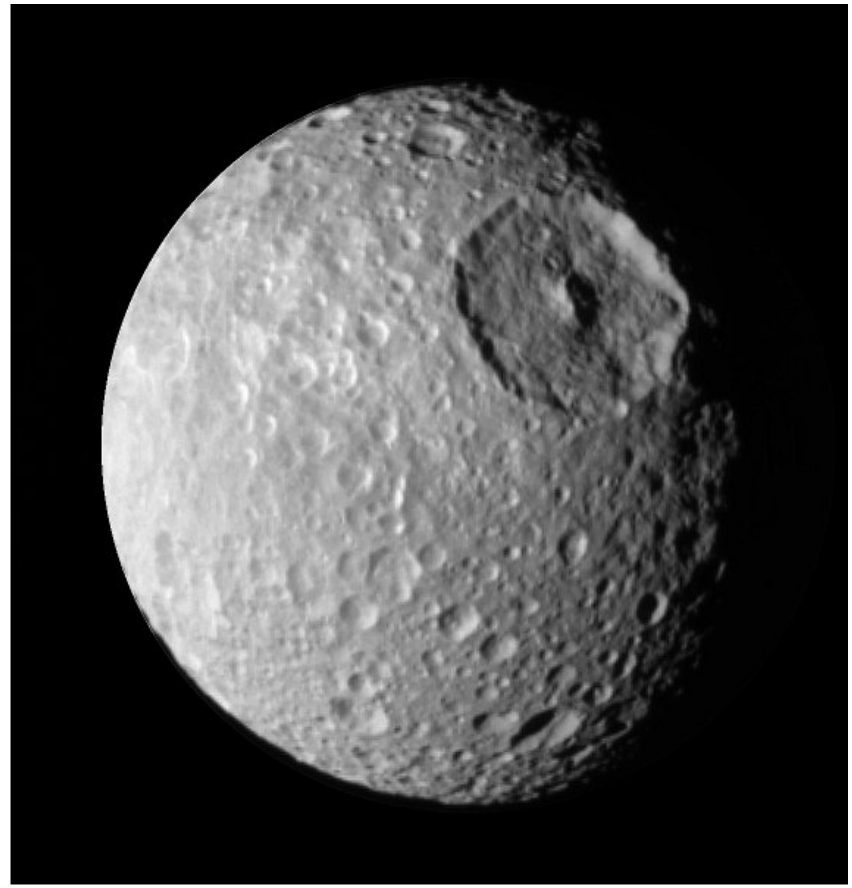


FUV albedo compared to visible

Cassini UVIS measures surface albedos (100-190 nm) in this range: there is a pretty sharp UV dropoff near 200 nm (NH_3?), as well as a slower absorption throughout the NUV (H_2O_2?)

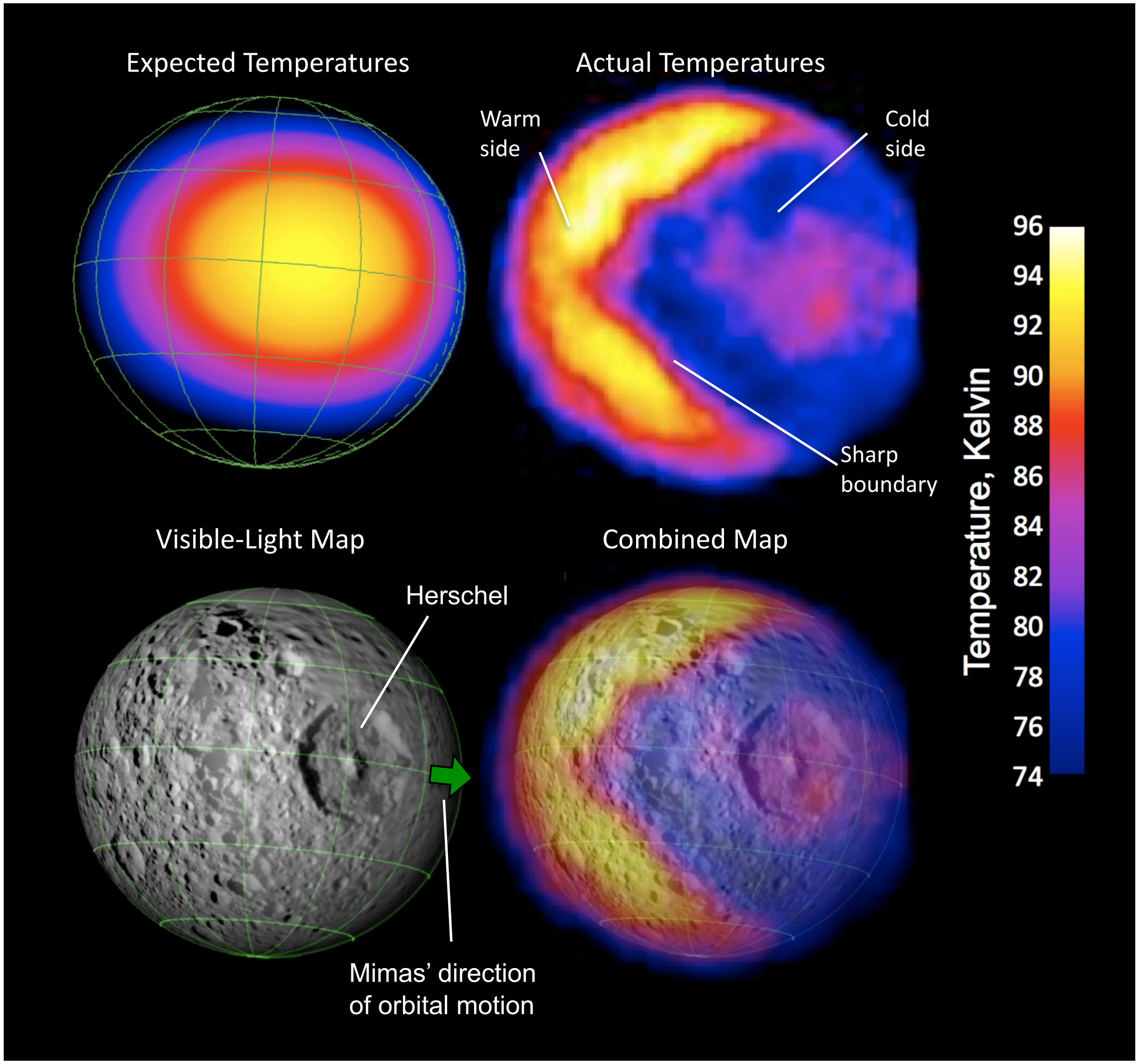


Saturn’s rings are radially variable in FUV brightness; dark in FUV compared to visible



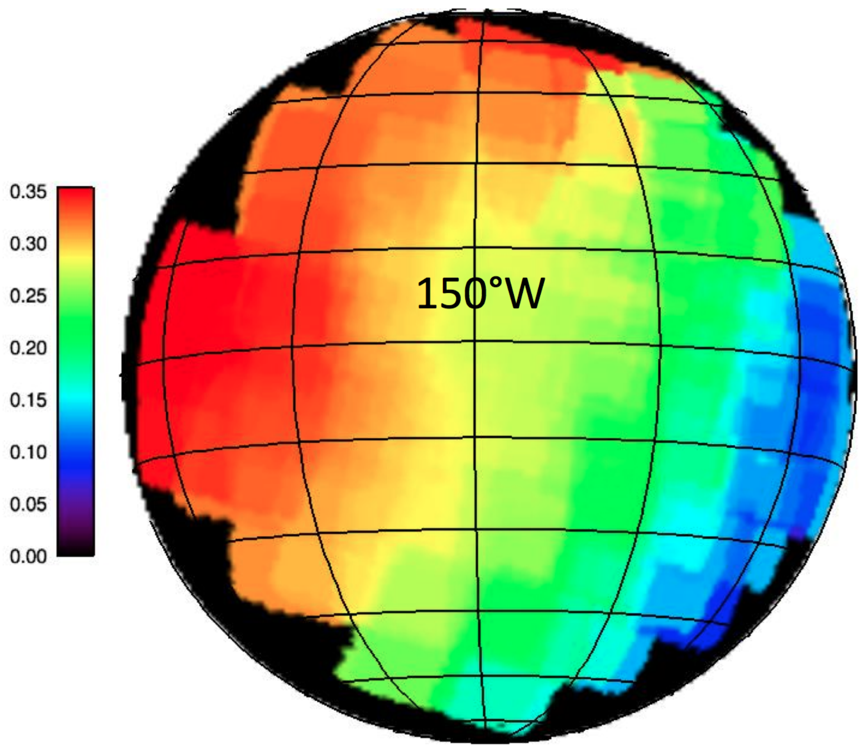
Mimas

Bizarre Temperatures on Mimas: Thermal Map from Cassini's Feb. 13, 2010 Fly-by

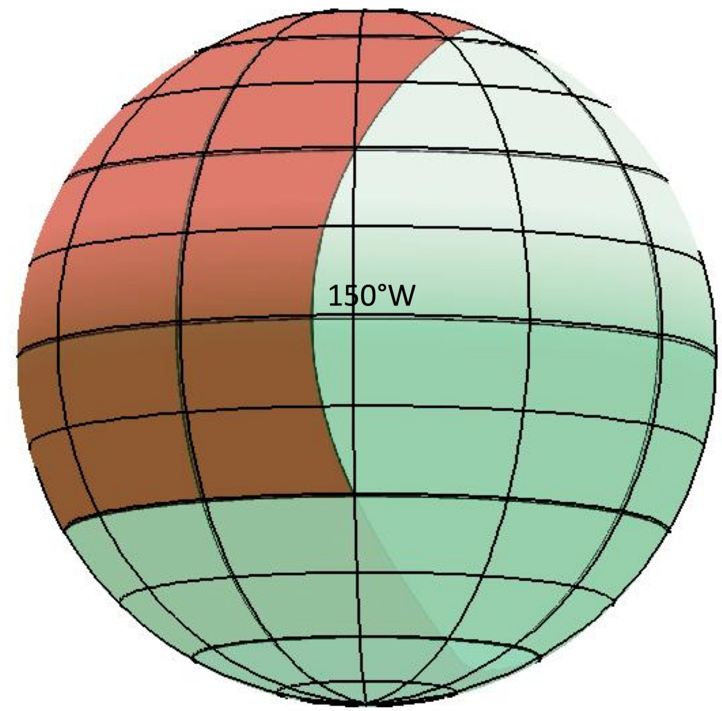


- The most detailed temperature map ever made of Mimas was obtained by Cassini's CIRS during its recent flyby.
- The temperature distribution (upper right) is completely unexpected. Mimas has a warm side, and a cold side that's up to 15 Kelvin (34 Fahrenheit) colder, with a sharp, V-shaped boundary between them.
- Maybe the giant crater Herschel is somehow responsible for the cold temperatures that surround it?
- But the cold side is also the side that faces forward in Mimas' orbit around Saturn: Is there a connection?
- There are strong arguments against either explanation! Cassini scientists will be puzzling over this for a while, and are planning new Mimas observations to help resolve the mystery.

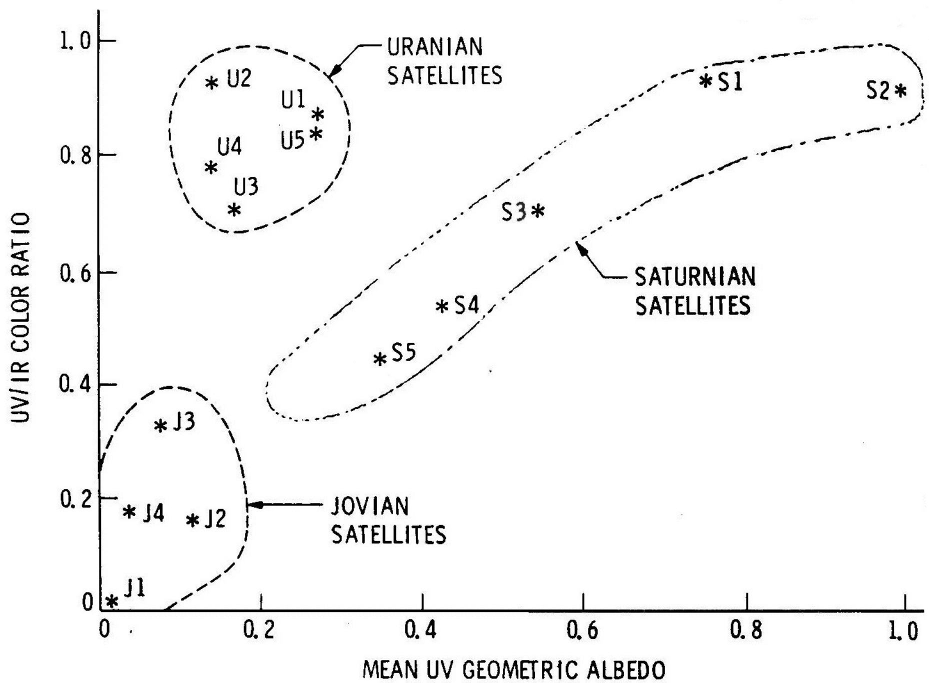
Mimas: FUV signature



170-190 nm albedo



Model: photolysis-derived H_2O_2 + E-ring grains



Nelson & Lane 1987

In terms of surface compositions, different classes of bodies can be grouped and studied by UV albedo, as compared with visible albedo.

in understanding surface composition, it's important to consider the UV in addition to longer wavelengths

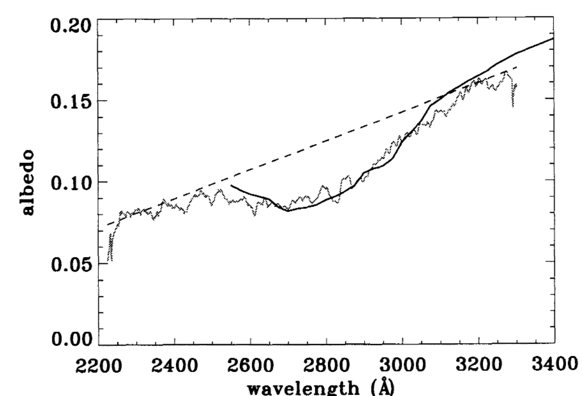
Big questions & issues
(a selection)

- Saturnian system & satellites
  - Why are rings and moons so red? (UV-Vis)
  - Variability in Enceladus plume activity? (system neutrals)
  - Temporal (seasonal) variability in satellite surface compositions?
- Io
  - Auroral, atmospheric variability and plasma interactions
  - Torus variability
- Europa
  - Geologically active today?
- Callisto
  - We need to characterize the atmosphere
- Ganymede
  - Understand moon's magnetosphere through auroral observations
  - Moon-magnetosphere interactions
- Primitive bodies
  - Which classes of meteorites come from which classes of asteroids, and how diverse were the components from which asteroids were assembled?
  - How variable are comet compositions, and how heterogeneous are individual comets?
  - What are the abundances and distributions of different classes of asteroids, comets, and KBOs?
  - How do the compositions of Oort cloud comets differ from those derived from the Kuiper Belt?
- Neptune, Uranus & moons
  - exploratory UV studies
- Hot topics: possible upcoming missions (planetary decadal survey)
  - Primitive bodies (Trojans, asteroids, comets)
  - Uranus orbiter
  - Io observer
  - Europa orbiter
  - Ganymede orbiter

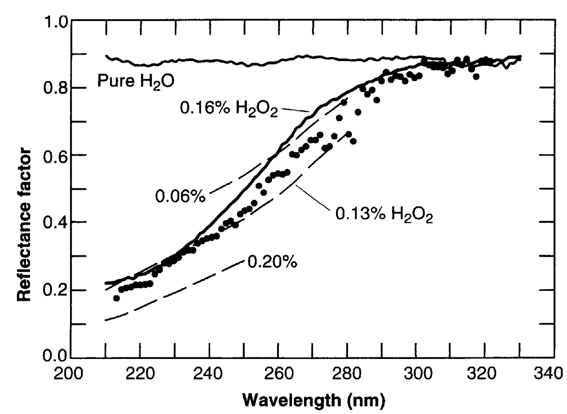
Extra slides

Surface Studies

Ultraviolet spectroscopic measurements of the surfaces of the Galilean satellites have led to the discovery of a number of species, in particular those that are products of radiolysis in the ice. Discovery of an absorption band at 280 nm in IUE spectra suggested evidence for sulfur implantation on the trailing hemisphere of Europa (Lane *et al.,* 1981); the absorption appears to be strongest in the recently-active regions (Hendrix *et al.,* 2002), as shown in disk-resolved Galileo UVS data. Hydrogen peroxide (H_2O_2) has been detected in the icy regions of Europa and possibly on the other icy moons as well (Carlson *et al.,* 1999; Hendrix *et al.,* 1999b). Ozone (O_3) exists on the trailing hemisphere of Ganymede (Nelson & Lane, 1987; Noll *et al.,* 1996) and is most abundant in the polar regions (Hendrix *et al.,* 1999a); the oxygen-rich ice is consistent with the loss of H to the exosphere (Barth *et al.,* 1997). At Callisto, Galileo UVS spectra suggest the presence of organics at high southern latitudes; at low latitudes, the organics may be weathered by UV photolysis and charged particle bombardment, resulting in dark, red spectra (Hendrix & Johnson, 2008



Europa's trailing hemisphere 280 nm absorption feature (Noll *et al.,* 1995).



Europa's H_2O_2 feature (Carlson *et al.,* 1999).

Galilean satellites

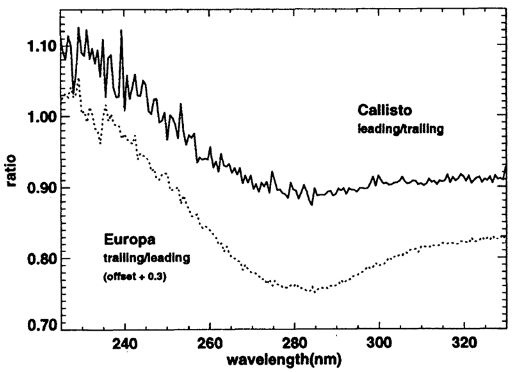


Figure 2. The ratio of Callisto's leading and trailing hemisphere spectra (solid) and a similar ratio of Europa's trailing to leading hemisphere, offset by +0.3 units (dotted) are strikingly similar.

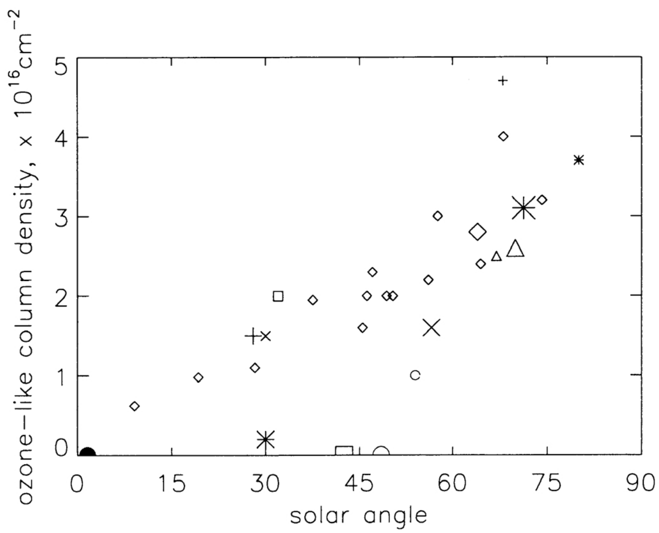
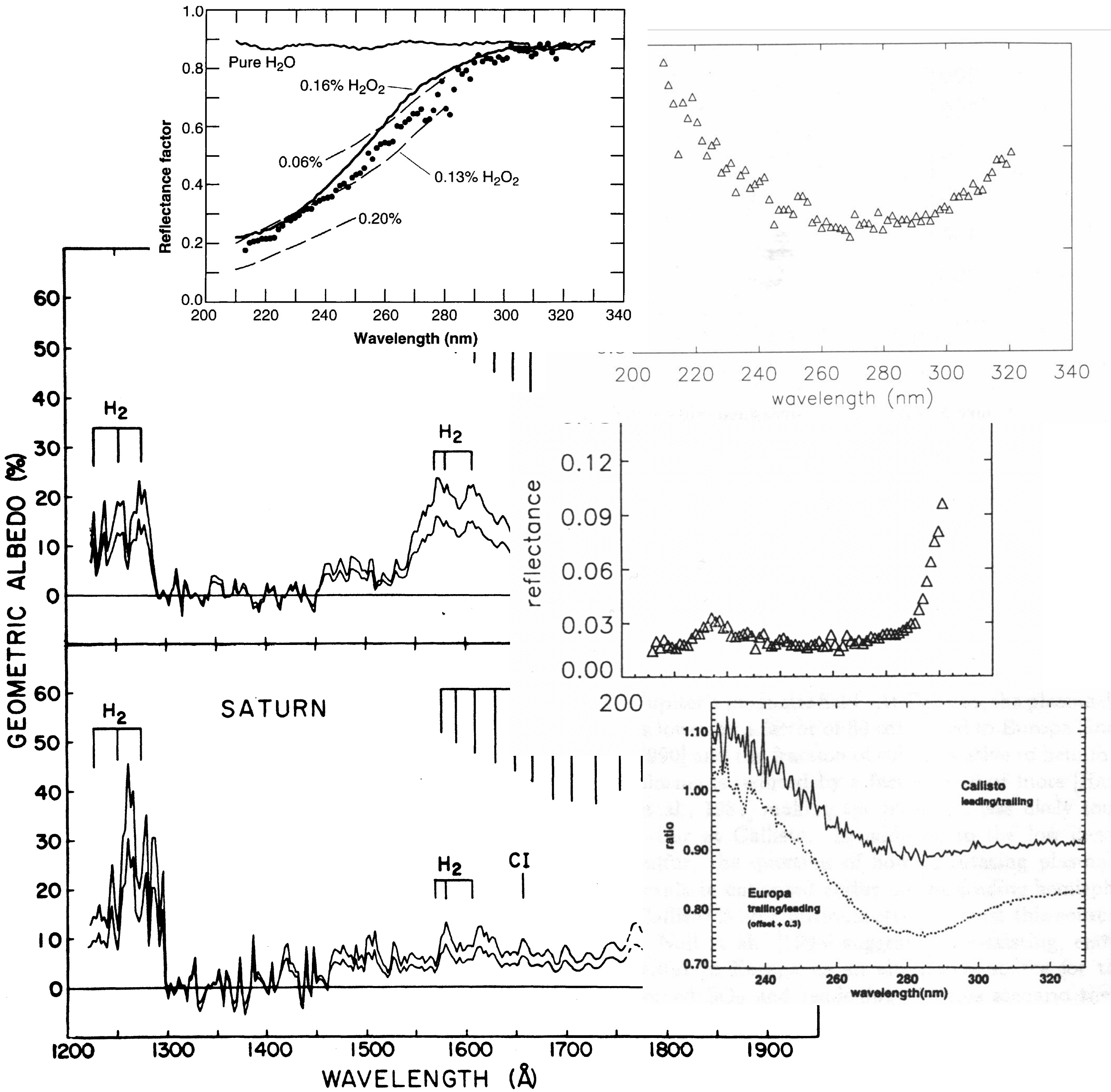
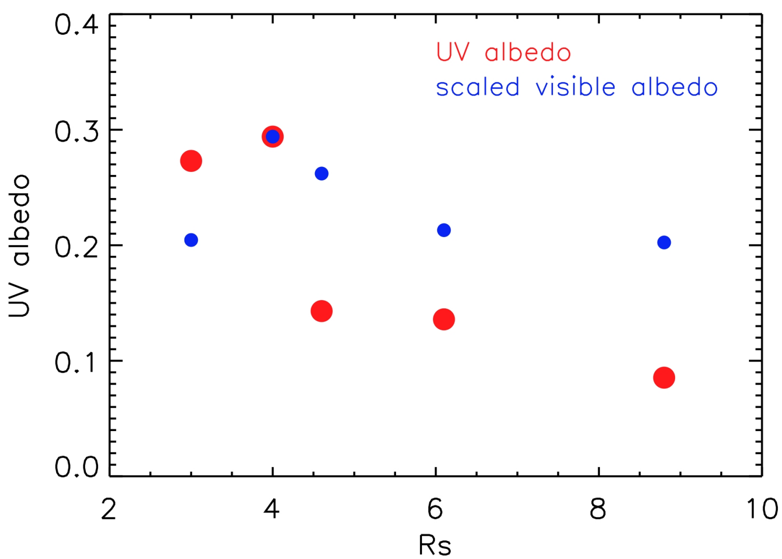


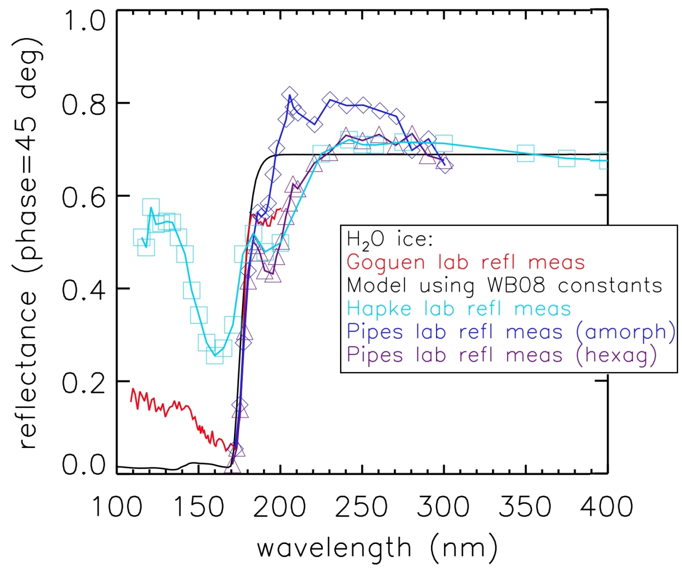
Figure 5. Ozone-like column density versus solar zenith angle. Small diamonds and solid circle, GLOBAL; small plus, PTAH; large cross, small and large asterisks, and small triangle, NORTH POLE; small circle, HILAT; large diamond, AMON; small square, NIPPUR; large plus, BRITRL; large triangle, TAMMUZ; small cross, SIPPAR; large circle, DRKLIT; large square, BRILED; medium asterisk, MEMPHIS.

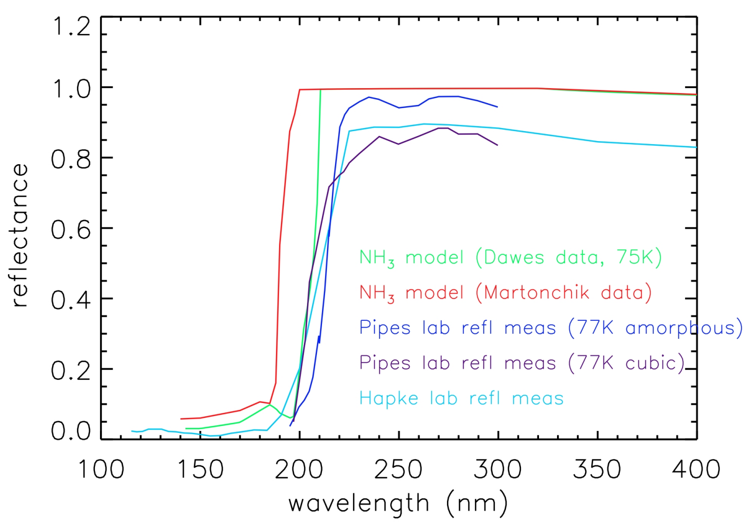


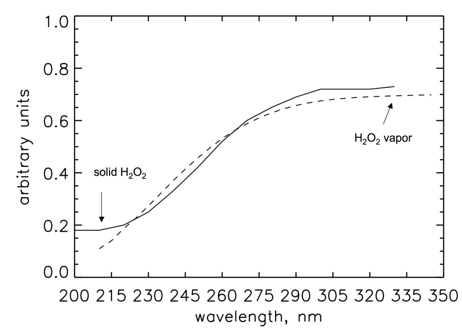
Pure H2O
0.16% H2O2
0.06%
0.13% H2O2
0.20%
Reflectance factor
Wavelength (nm)
wavelength (nm)
reflectance
Callisto
leading/trailing
Europa
trailing/leading
(offset + 0.3)
ratio
wavelength(nm)
GEOMETRIC ALBEDO (%)
H2
SATURN
CI
WAVELENGTH (Å)

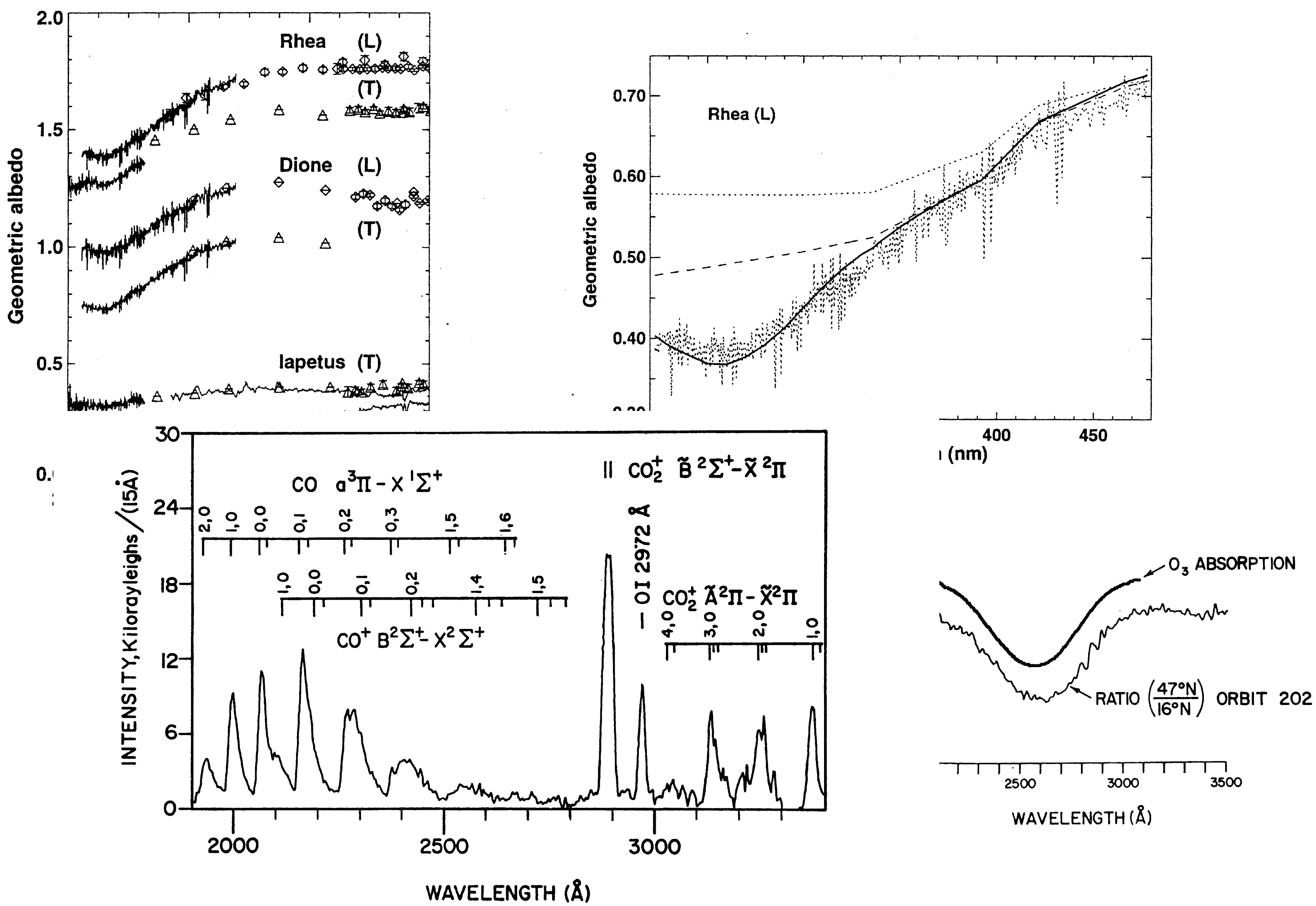
Surface species: ices











Rhea (L)
(T)
Dione (L)
(T)
Iapetus (T)
Geometric albedo
2.0
1.5
1.0
0.5
Rhea (L)
Geometric albedo
0.70
0.60
0.50
0.40
400
450
(nm)
CO a³Π - X ¹Σ⁺
2,0 1,0 0,0 0,1 0,2 0,3 1,5 1,6
1,0 0,0 0,1 0,2 1,4 1,5
CO⁺ B²Σ⁺- X²Σ⁺
CO₂⁺ B̃ ²Σ⁺- X̃ ²Π
OI 2972 Å
CO₂⁺ Ã²Π - X̃²Π
4,0 3,0 2,0 1,0
INTENSITY, Kilorayleighs /(15Å)
30
24
18
12
6
0
2000
2500
3000
WAVELENGTH (Å)
O₃ ABSORPTION
RATIO (47°N / 16°N) ORBIT 202
2500
3000
3500
WAVELENGTH (Å)