European Space Agency

"Exploring the Universe with JWST"

49th ESLAB symposium

JWST Exploring the Giant Planet Systems *

(* excluding Titan and stellar occultations)

Heidi B. Hammel

JWST Interdisciplinary Scientist

Association of Universities for Research in Astronomy (AURA), Washington, DC, USA

SOURCE MATERIAL , ACKNOWLEDGEMENTS, THANKS

Solar System Observations
with the James Webb Space Telescope

James Norwood, Heidi Hammel, Stefanie Milam, John Stansberry, Jonathan Lunine, Nancy Chanover, Dean Hines, George Sonneborn, Matthew Tiscareno, Michael Brown, and Pierre Ferruit

Publications of the Astronomical Society of the Pacific, submitted 2015

OUTLINE

Definition of "system" and motivations

Jupiter and Saturn

Uranus

Neptune

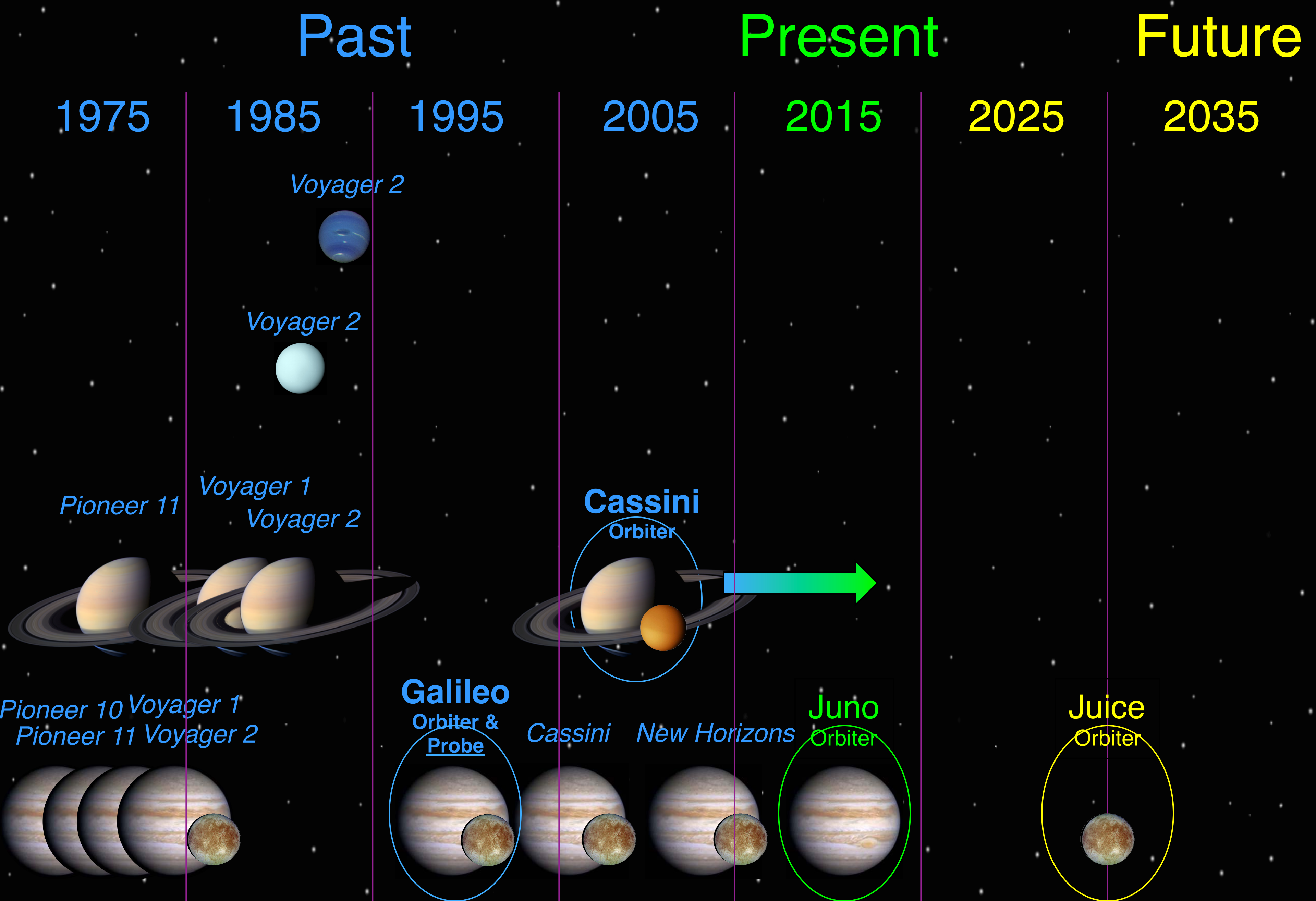
Summary

Giant Planet Systems

- Definition of “system”: atmosphere; interior; magnetic field; rings; moons
- **“The story of the Giant Planets is the story of our Solar System”** and, ultimately, the story of habitability of our Solar System
- Archetypes and/or extrema for exoplanets
- *In situ* laboratories for astrophysical processes
- Still have far more questions than answers

H. B. Hammel
12 Oct 2015

Giant Planet Exploration

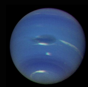


H. B. Hammel
12 Oct 2015

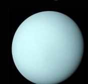
Giant Planet Exploration

Past				Present		Future
1975	1985	1995	2005	2015	2025	2035

Voyager 2



Voyager 2



Jupiter and Saturn

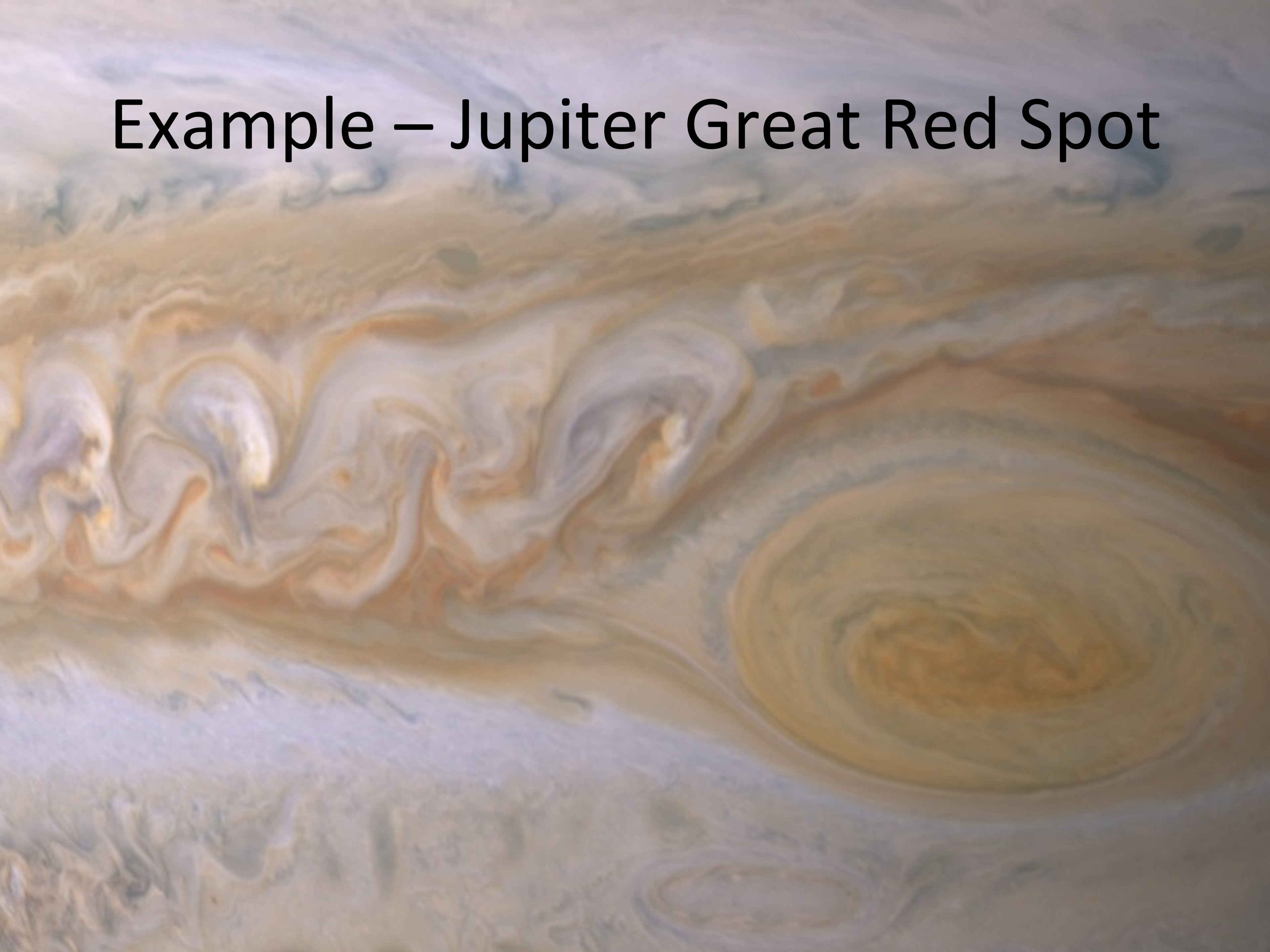
J & S motivation (example)

Extend, enhance, and complement IR observations of Jupiter and Saturn made in preceding decades by Voyager, Galileo, Cassini, New Horizons, Spitzer, Hubble (soon Juno, future ESA/JUICE and NASA/Europa)

Q: How does atmospheric circulation detected at the cloud tops relate to deeper atmospheric motions and heat transport from the interior?

Q; What is the link between atmospheric dynamics, chemistry, and cloud microphysics?

Example – Jupiter Great Red Spot



Example – Jupiter Great Red Spot

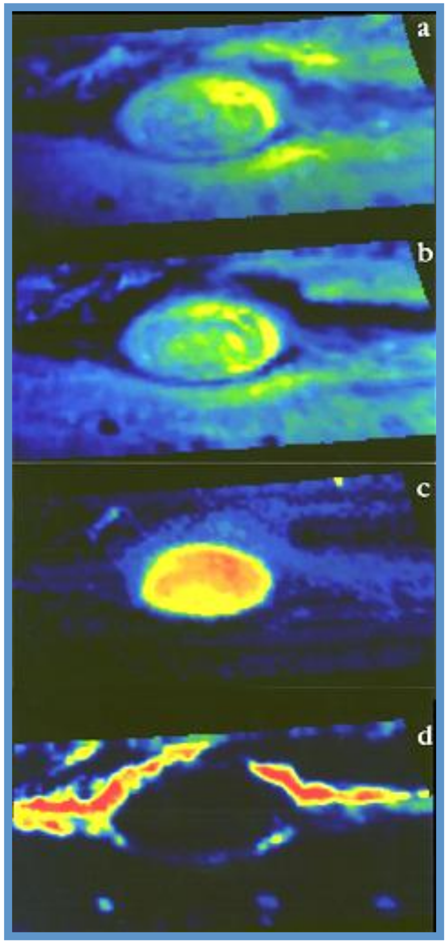
a) **False color** in the (barely visible) red

b) **NH_3 ice abundance**
red = most
blue = least

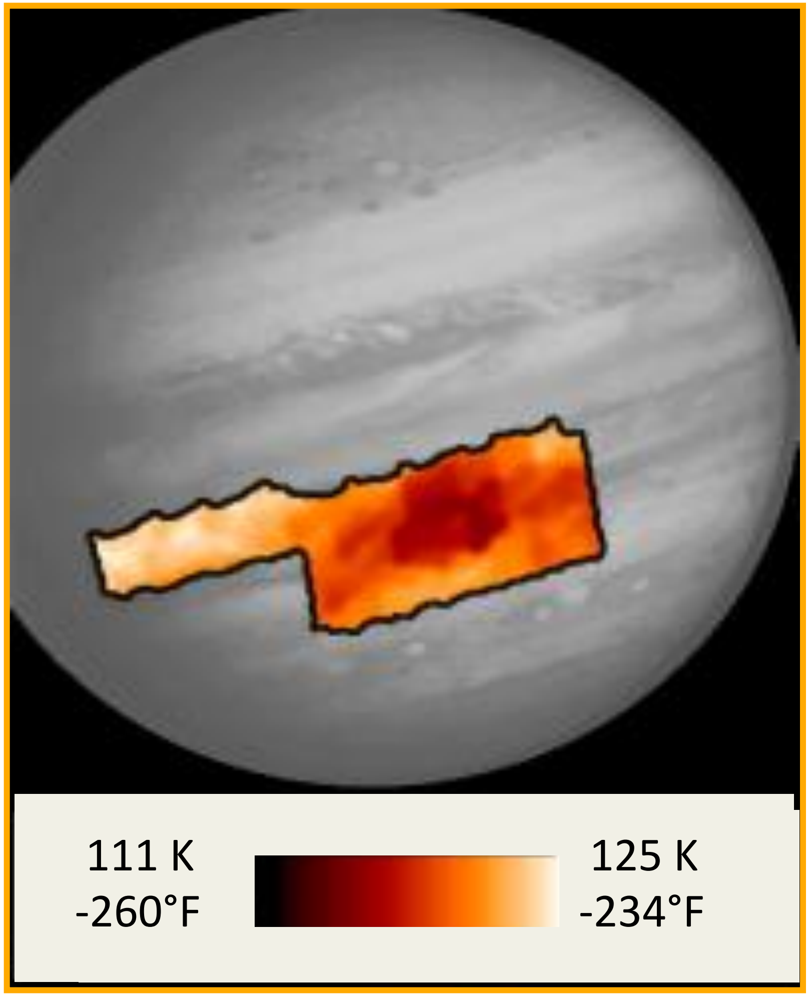
c) Cloud height
red = high
blue = deep

d) Cloud thickness
red = thick
blue = thin

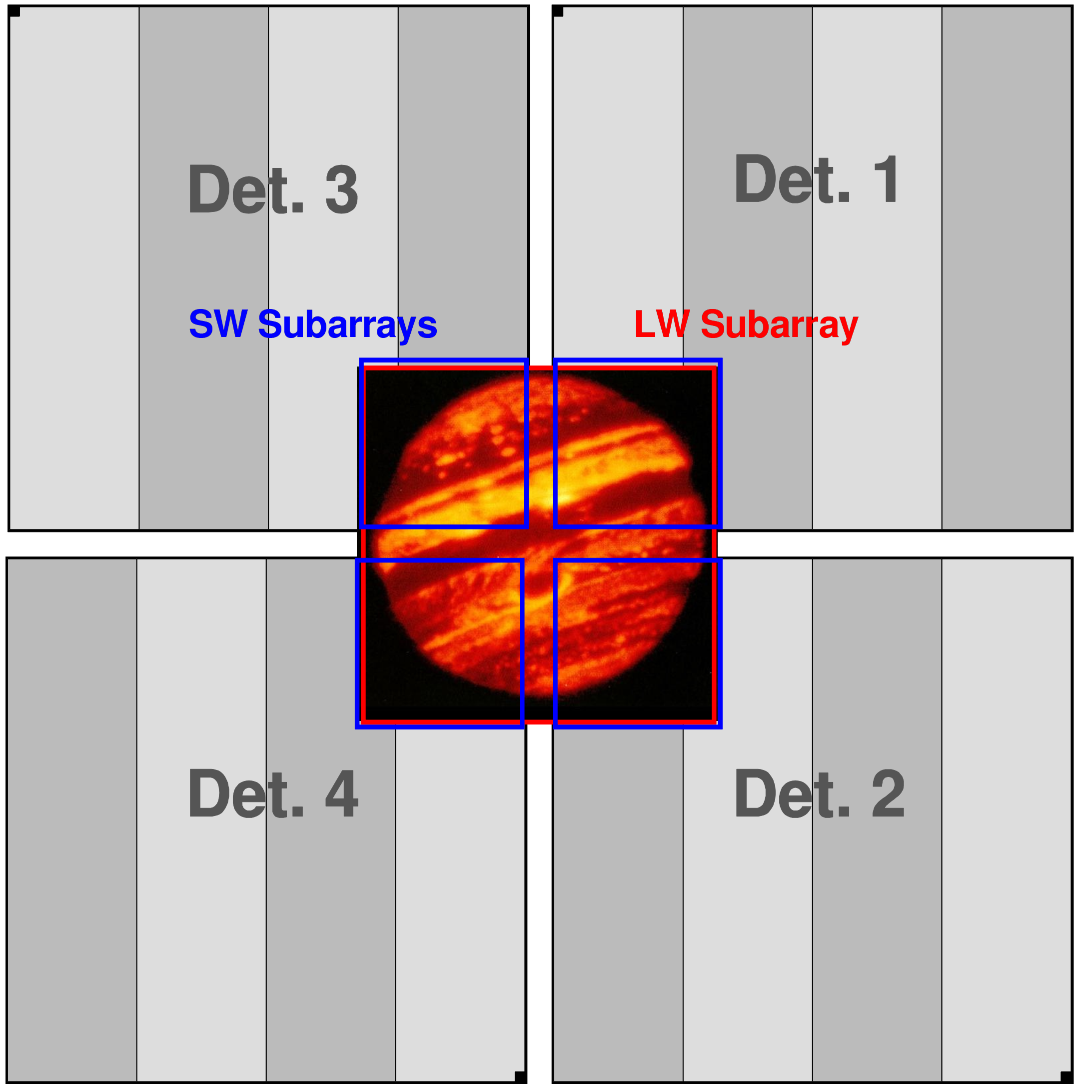
NIMS



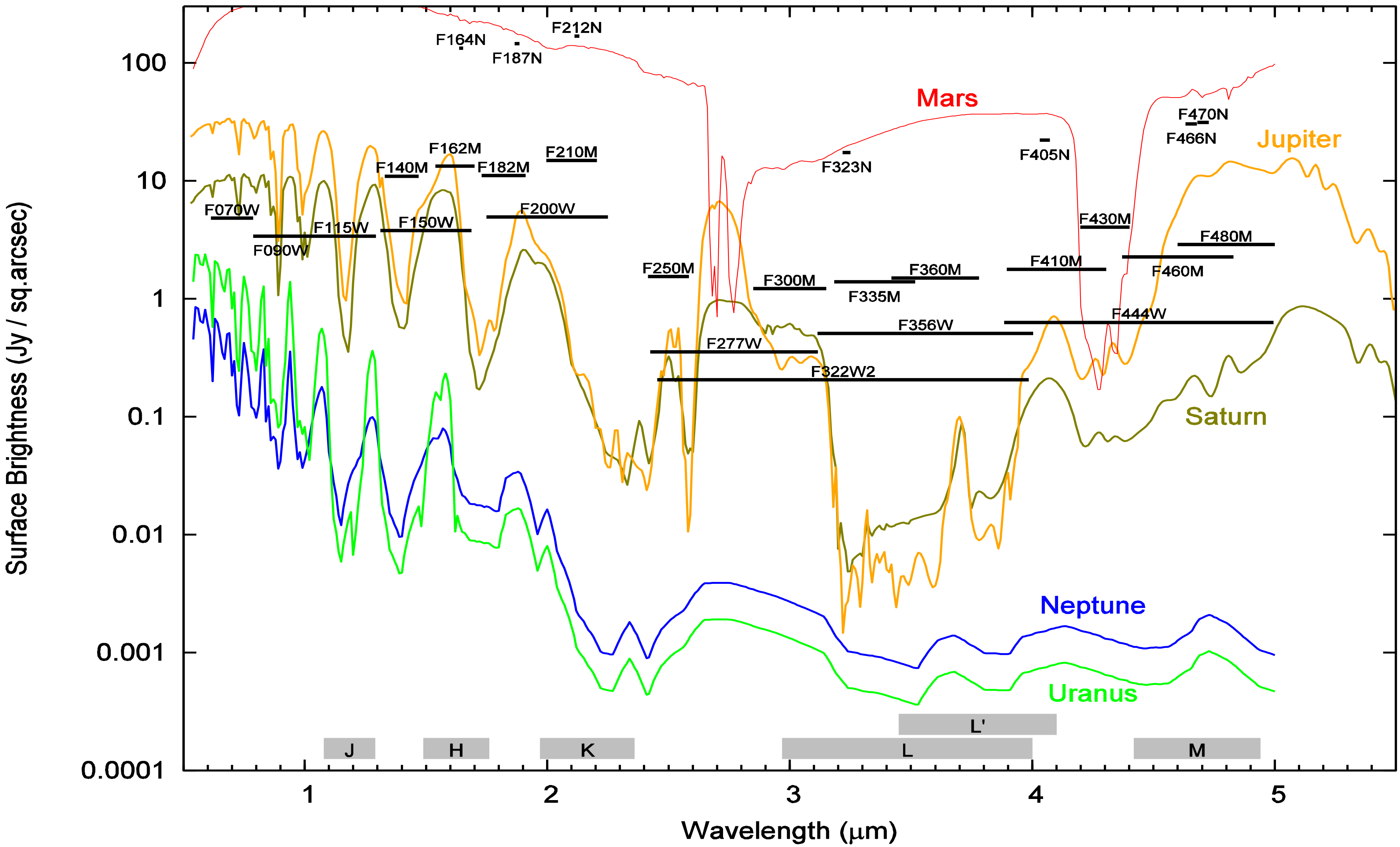
Photopolarimeter/Radiometer



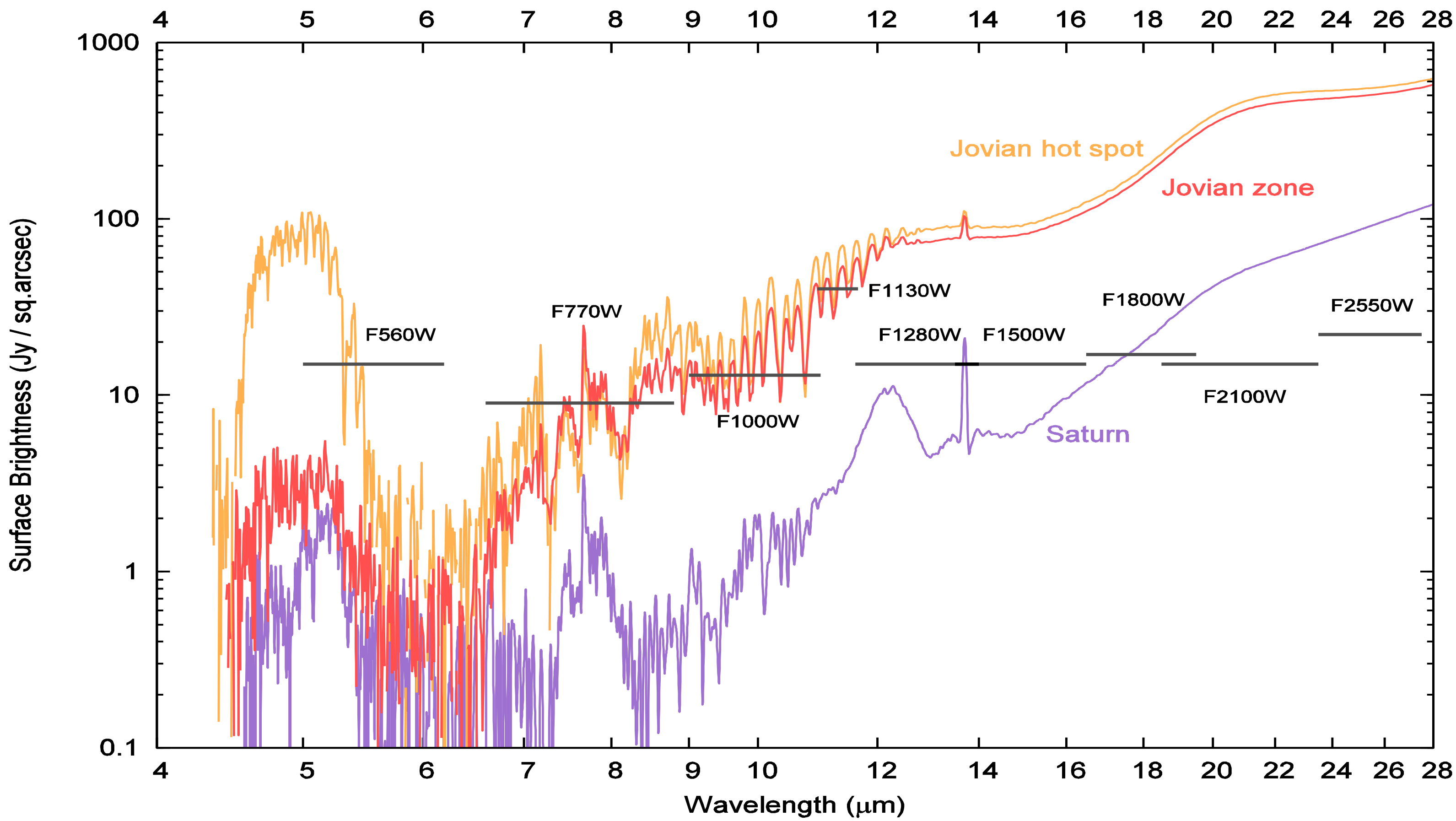
One configuration for observing Jupiter with NIRCam subarrays



NIRCam: Jupiter and Saturn saturate shortward of ~1.5 µm, but observations w/ medium bandwidth filters longward of F140M may be ok (see next slide); in the longwave channel they an be observed in many filters w/out saturating

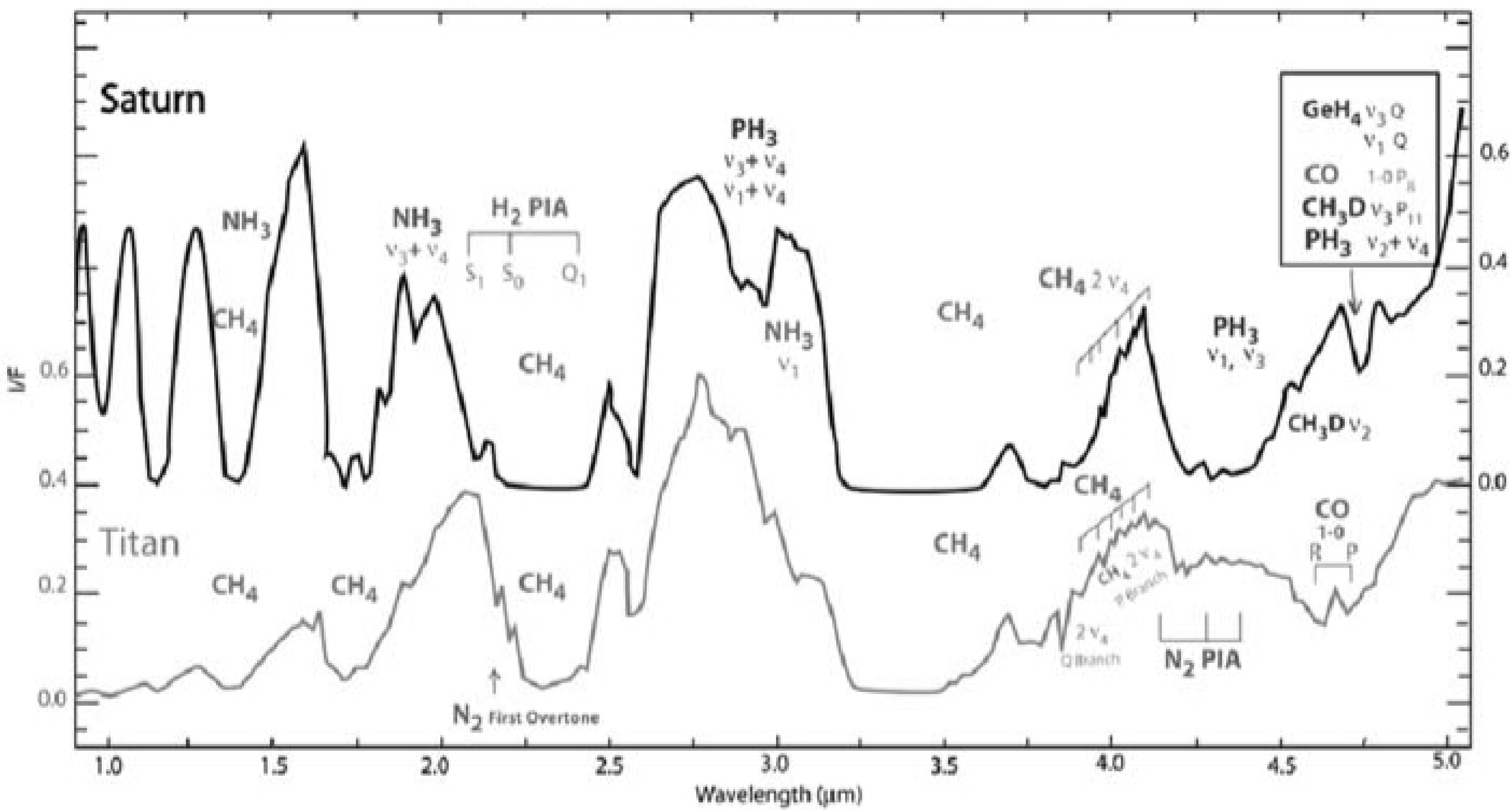


Spatially-resolved mid-infrared spectra



Gas giant IR spectra are shaped by gaseous absorption and emission features, and vary across the planets. Spectra of a **Jupiter hot spot (gold)**, a **Jupiter zone (red)**, and **Saturn (purple)**, compared to saturation limits of MIRI filters assuming SUB64 sub-array viewing with minimum integration time (G. Bjoraker, pers. comm.)

JWST Saturn spectra cf. Cassini VIMS



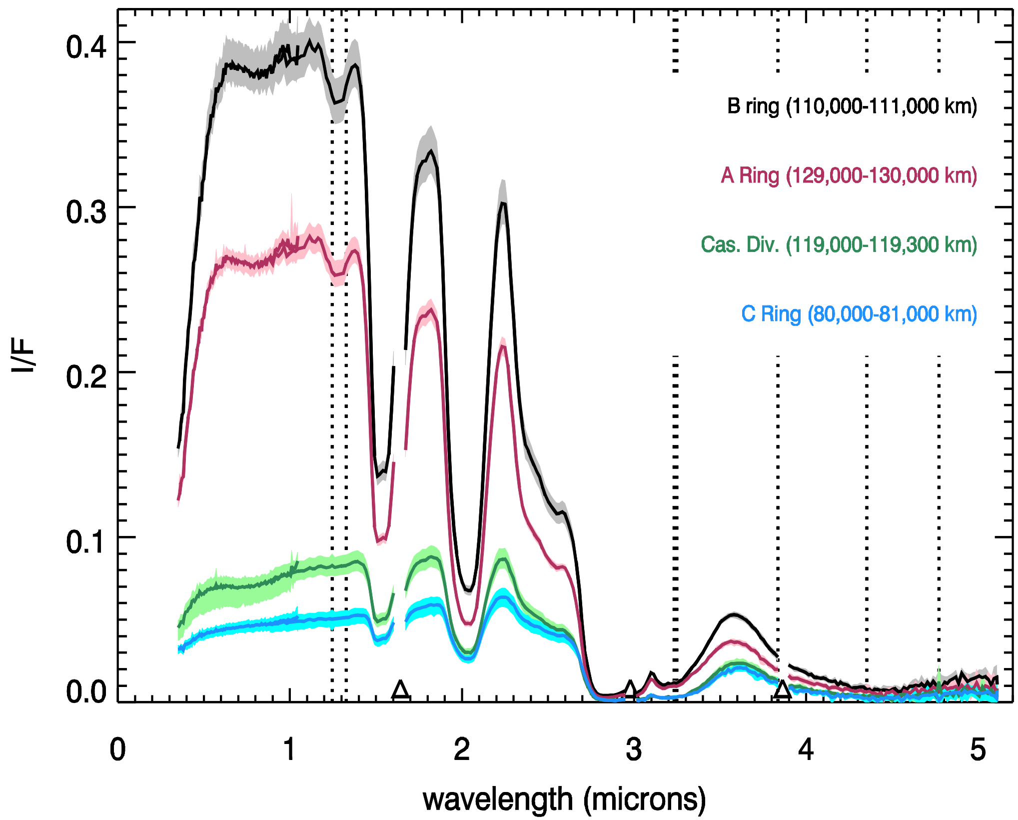
VIMS spectrum of Saturn (darker line) over a spectral region comparable to that of NIRSpec. The spectral resolution of the VIMS data is ~200; **NIRSpec** will match or exceed this. Figure from Baines et al. (2005).

Jupiter's moons, including Europa

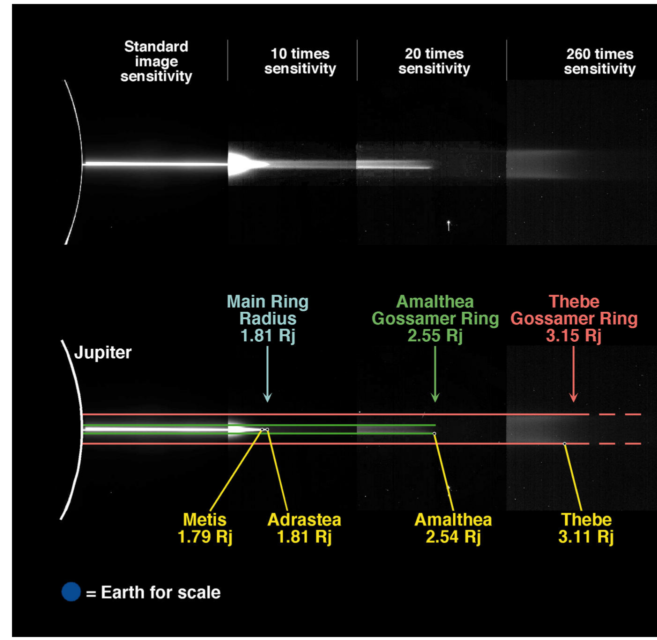
Europa (and the other icy Galilean satellites) are poorly characterized beyond 5 µm, and in particular between 5 and 15 µm. **MIRI spectra** covering this wavelength range as a function of longitude would allow several key scientific investigations, including the following:

- Search for the strong **spectral signature of hydrated minerals**
- Exploration of **the radiolytic carbon cycle**; laboratory experiments have shown strong carbonic acid features at 5.83 µm, 6.63 µm, and 7.65 µm
- Search for **carbonyls (C=O) and amides (H-N-C)** via the broad 6-7 µm water ice feature, whose shape is modified by these species
- Search for **organic features (C-C, C-H, C=C)** in the 6-8 µm region; laboratory experiments show that radiolytic processing of hydrocarbons produces distinct absorptions in the 6-8 µm range
- Discovery of **unexpected spectral features**, indicative of a major chemical pathway previously unknown on Europa and the other satellites.

Saturn and Jupiter Ring Systems



Saturn's rings: Cassini VIMS got detailed spectra (above); **JWST can explore seasonal and time-variable** effects (e.g., spokes, clumps, etc)



JWST spectra of Jupiter's rings will be revolutionary; no spectra of quality exist at low phase angles; Galileo took high-phase-angle spectra of Jupiter's rings, but these do not reveal spectral features that JWST may see.

Uranus

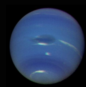
H. B. Hammel
12 Oct 2015

Giant Planet Exploration

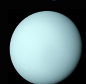
Past | Present | Future

1975	1985	1995	2005	2015	2025	2035

Voyager 2



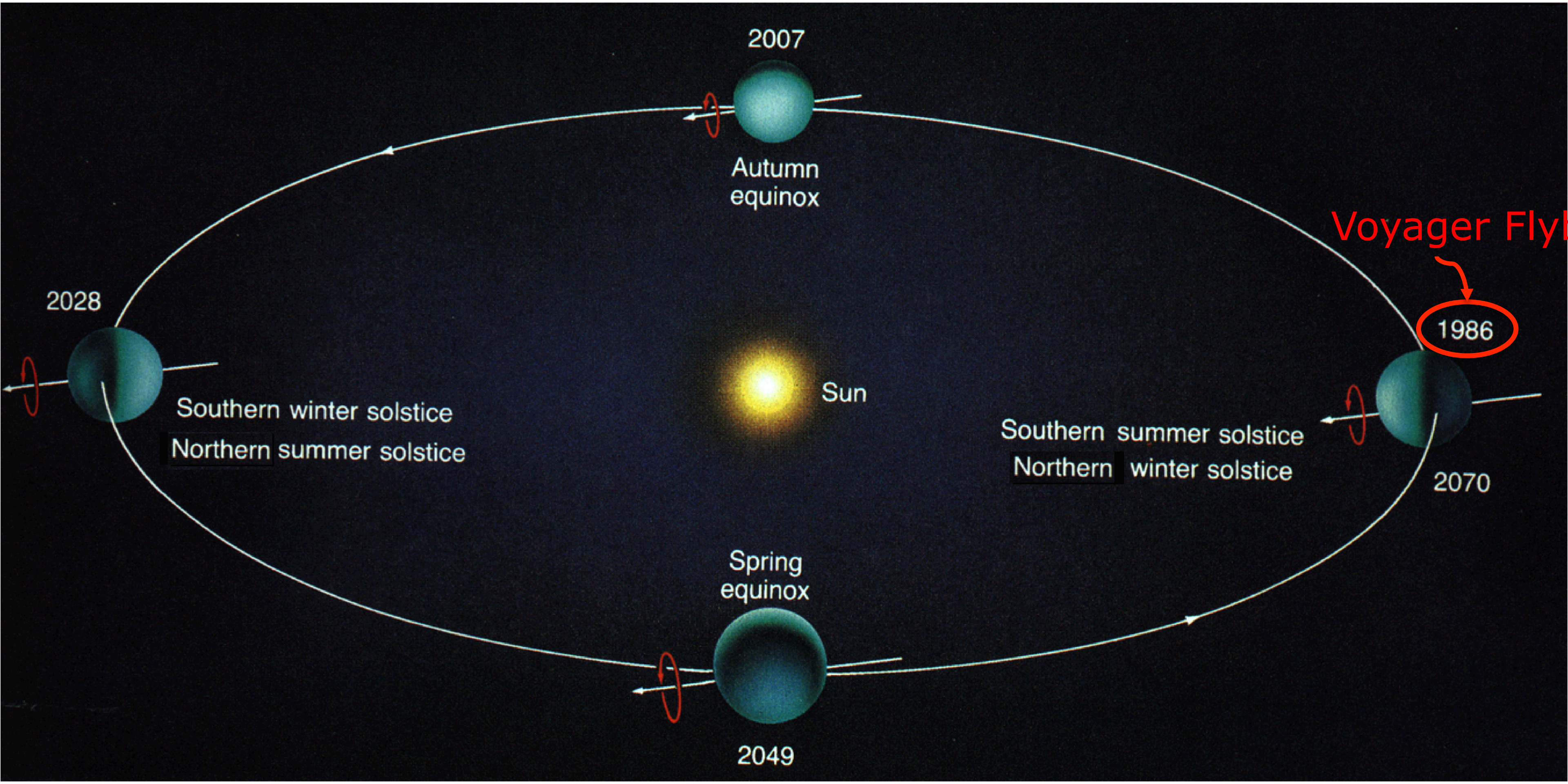
Voyager 2



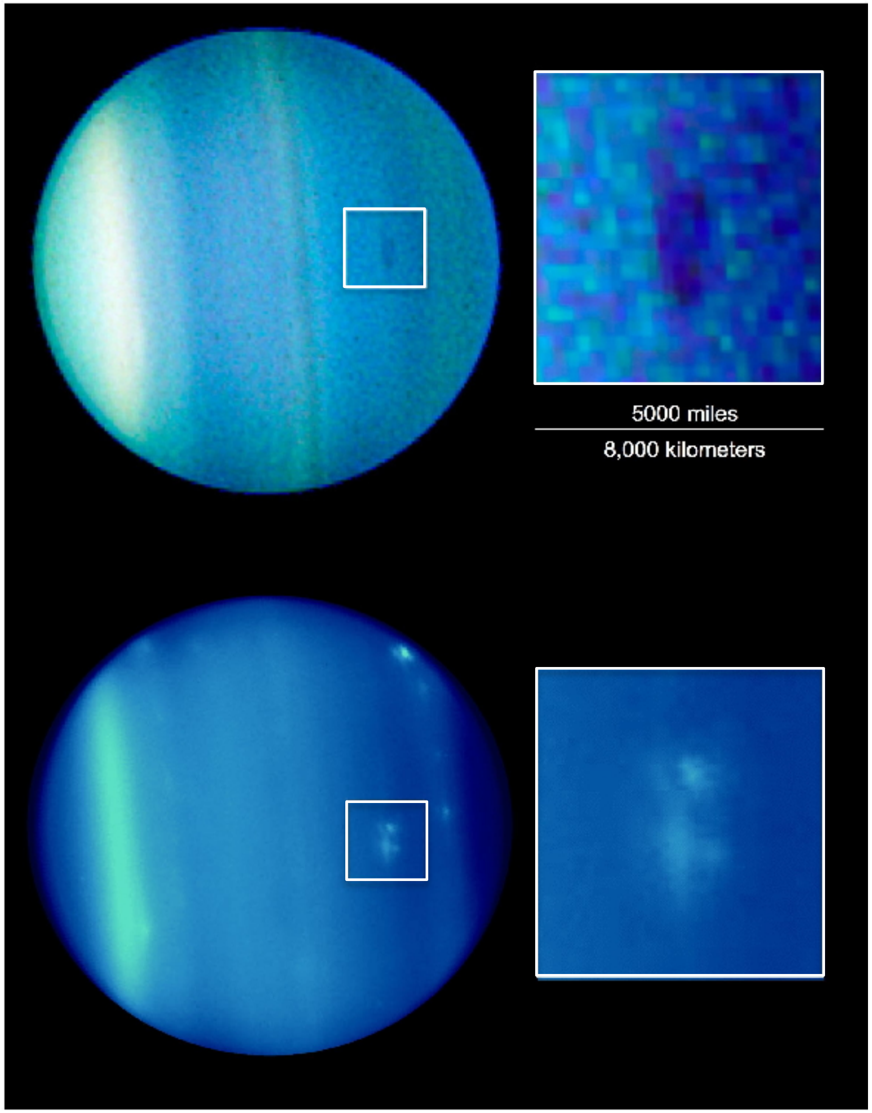
Voyager Uranus in 1986

Smith et al. 1986

Uranus
extremum seasonal change



dynamic atmosphere of uranus



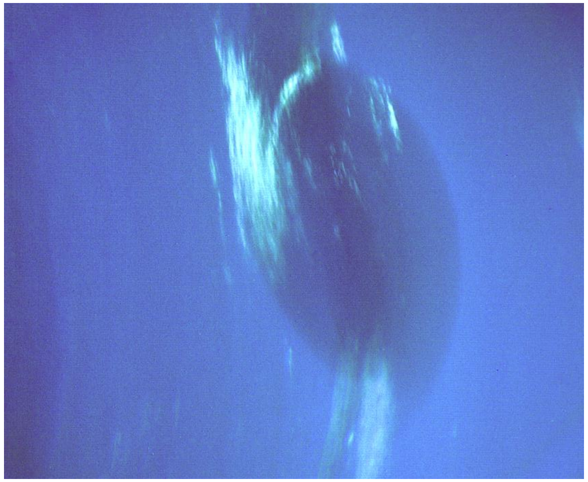
Hammel et al. 2009

Uranus in 2006

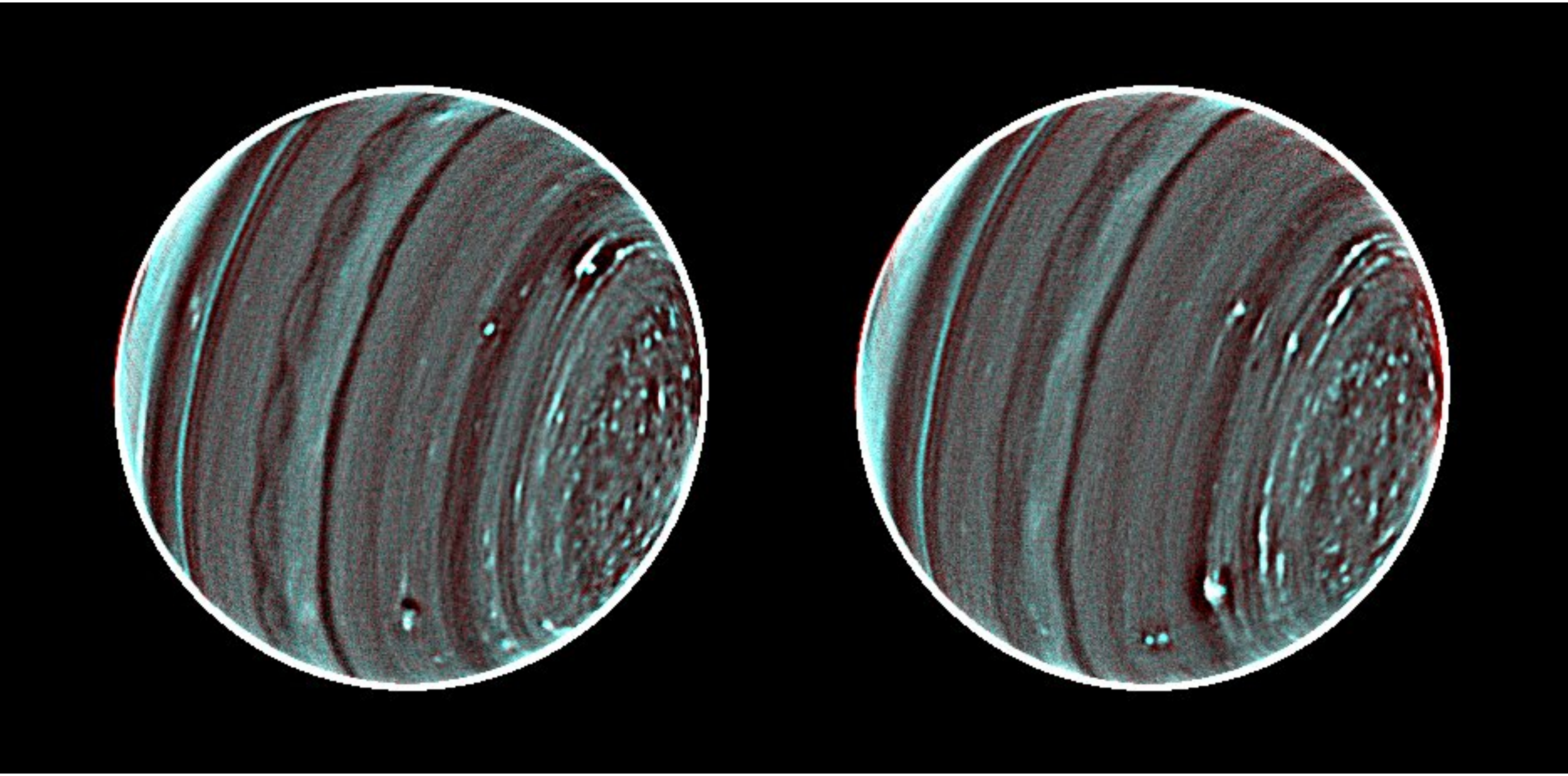
Upper: Hubble spies Great Dark Spot in the atmosphere of Uranus

Lower: Keck images the GDS's Bright Companions

For comparison: 1989 Voyager view of Neptune's Great Dark Spot and its Bright Companions (rotated 90°)
(this GDS had disappeared by 1994)

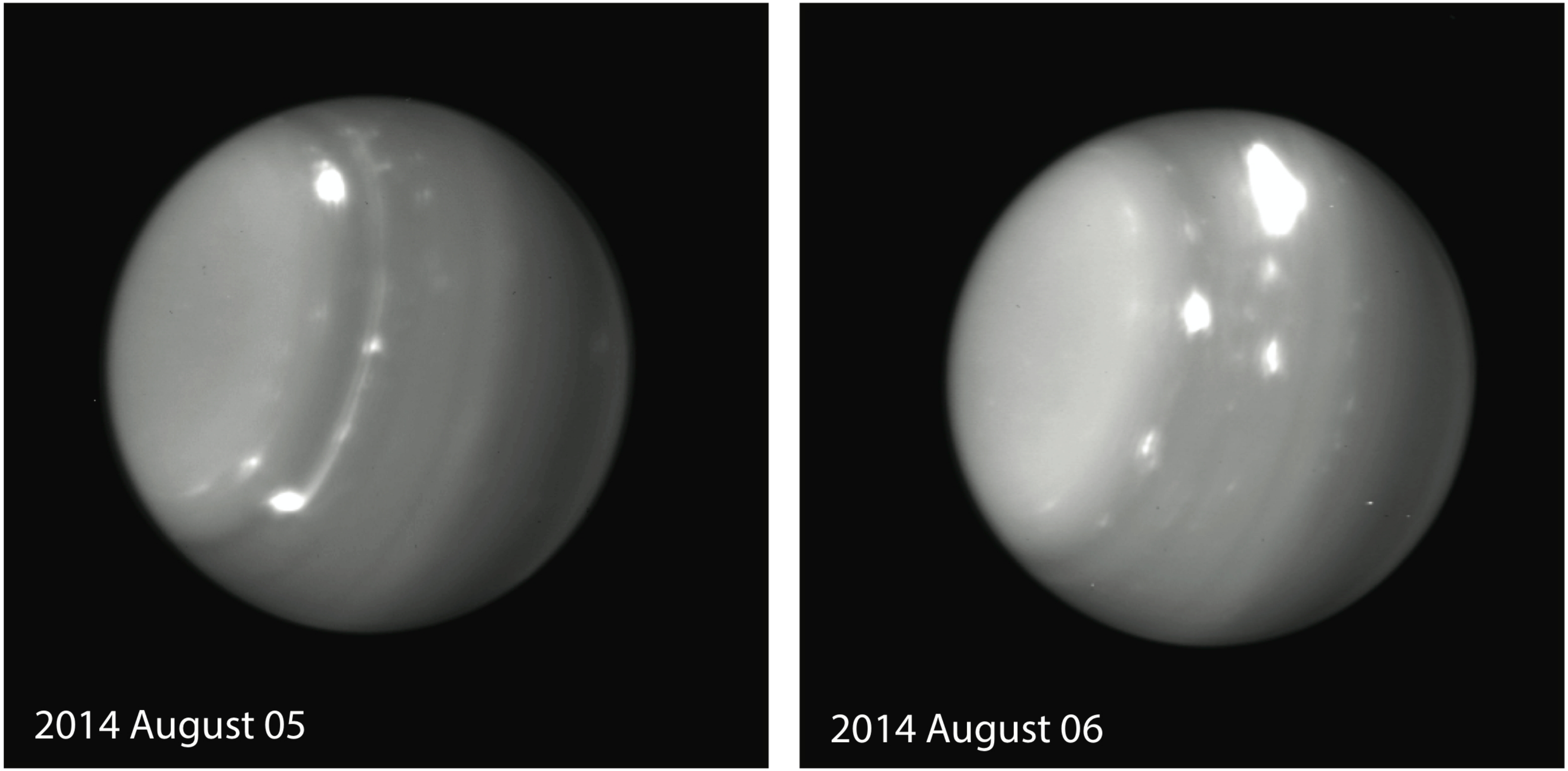


2012: Keck “images” of Uranus



Larry Sromovsky, Pat Fry, Heidi Hammel, Imke de Pater
Keck Observatory, H band (1.6 microns), July 2012

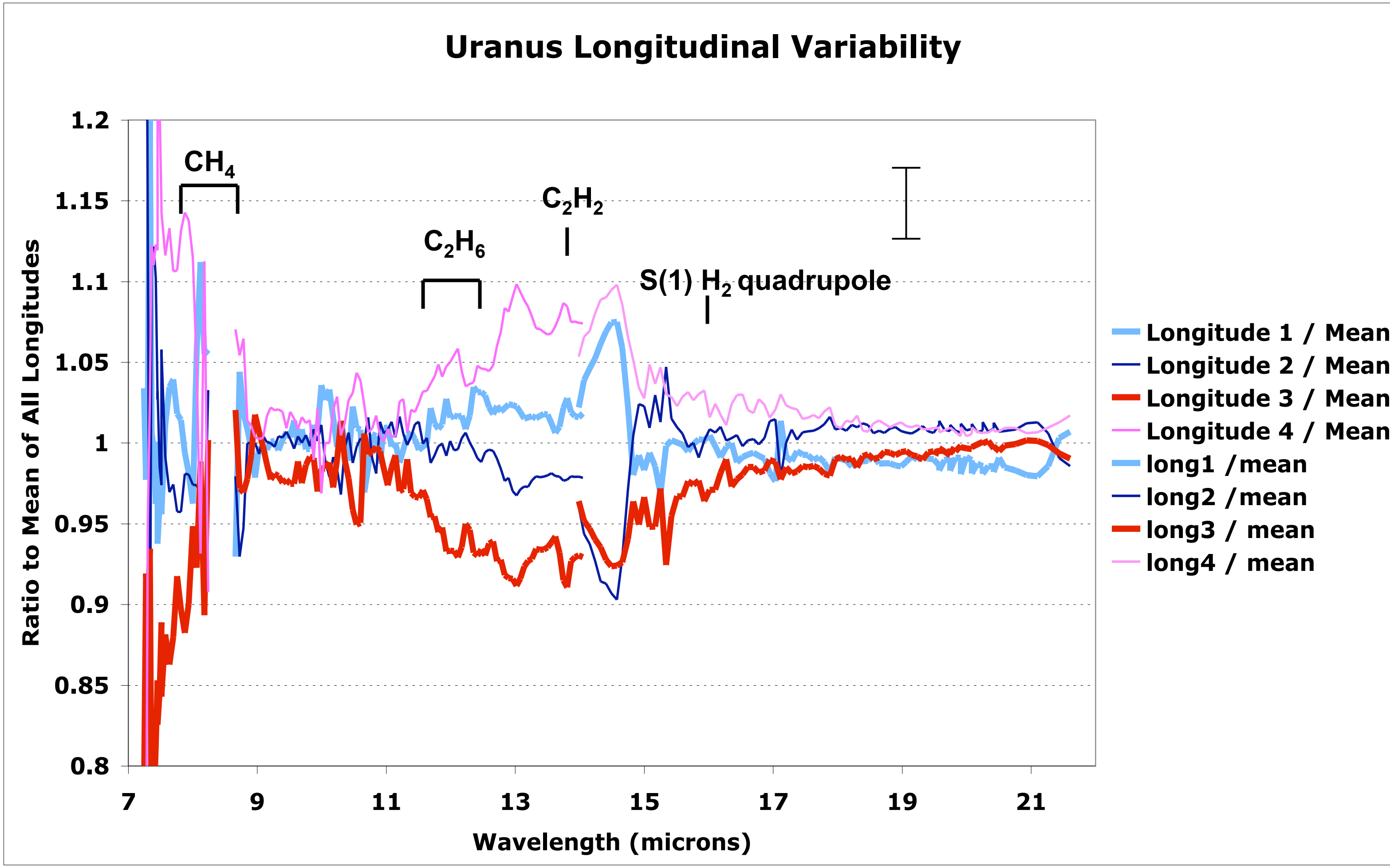
Uranus in mid 2014



Credit: I. de Pater (UC Berkeley) and Keck

uranus infrared spectra vary – but why?

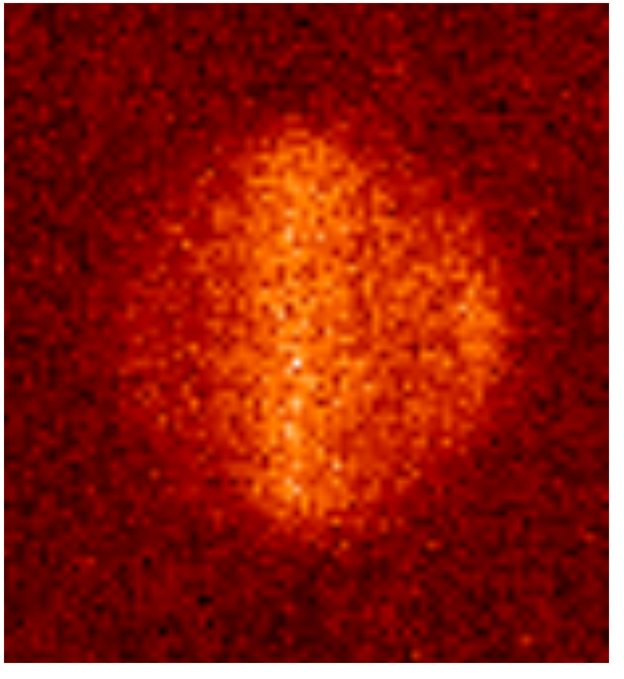
Comparison of 4 longitudes vs. mean of all four reveals variation in hydrocarbons



To what spatial feature does this Spitzer variability correspond?

Uranus in the mid infrared

2006 September 3
VLT/VISIR 18.7-μm image
G. Orton and colleagues



O MIRI resolution

Uranus as an Extremum

Circulation & Dynamics | Composition & Chemistry | Structure & Clouds

Uranus' radical obliquity presents an extreme test of our 'understanding' of how a giant planet atmosphere works … an end-member resides within our solar system!

Overarching questions

What implications do extreme seasonal variations and the (perhaps?) negligible internal flux have for Uranus' dynamics, composition and vertical structure?

Do these implications drive the observed differences from Neptune, and what are the broader implications for Uranus- or Neptune-sized exoplanets?

Future Observational Requirements:

- Continued observations from ground-based telescopes
- **JWST!**
- Far future: orbital reconnaissance capable of global coverage (2D), multi-spectral remote sensing (3D), and monitoring with time (4D), supplemented with *in situ* probe(s) for direct comparison of gas/aerosol composition with Galileo/Jupiter.

Uranus Atmosphere: Future Directions I

Circulation & Dynamics | Composition & Chemistry | Structure & Clouds

What powers the circulation, dynamics, meteorology, and evolution of Uranus?

- Why does Uranus difffer from Neptune? Which is the archetype and why?
- What causes the differences in banding, zonal winds and cloud activity between ice and gas giant circulations?
- How is Uranian 'weather' related to the deep interior, and how deep do the winds/plumes/vortices extend?
- What is the balance between intrinsic luminosity and sunlight?
- What is the seasonal dependence of insolation & energy emission, both horizontal and vertical: phase lag, temperature, activity?

- *Future observations must correlate visible changes (in cloud albedo, winds, vortices, etc.) with environmental processes (e.g., latent heat from condensation, meridional overturning, seasonal variability, etc.)*
- *Goal: understand the processes controlling the changing face of Uranus to compare with the other giants.*
- *Long term, continuous 'time-domain science' will be required, tuned to the timescales of interesting phenomena.*
- ***JWST can make significant contributions.***

EYE CHART

Uranus Atmosphere: Future Directions II

Circulation & Dynamics | **Composition & Chemistry** | Structure & Clouds

What is the origin of the chemical species that make up Uranus?

- Are elemental abundances (C, He, O, N, S, P, Noble gases) and isotopic ratios (^{13}C, ^{15}N, ^{18}O, D/H) consistent with planetary formation hypotheses?
- How does upper atmospheric chemistry vary globally and with temporal/seasonal/external forcing; why/how does this differ from the other giants?
- Are deep atmospheric observations dominated by thermal or chemical processes?
- What is the distribution of cloud-forming volatiles (esp. CH_4), disequilibrium species, and photochemical products?
- What does upper atmospheric chemistry tell us about the external supply (comets, micrometeoroids, connection to satellites/rings) of material to Uranus? What about a giant impact in the past?

- *Future observations must map the spatial distribution of chemical species in Uranus' atmosphere and monitor their temporal variability*
- *Goal: understand how Uranus' origins and continued evolution may differ from the other giant planets.*
- ***JWST can do the required spectroscopy.***

EYE CHART

Uranus Atmosphere: Future Directions III

Circulation & Dynamics | Composition & Chemistry | **Structure & Clouds**

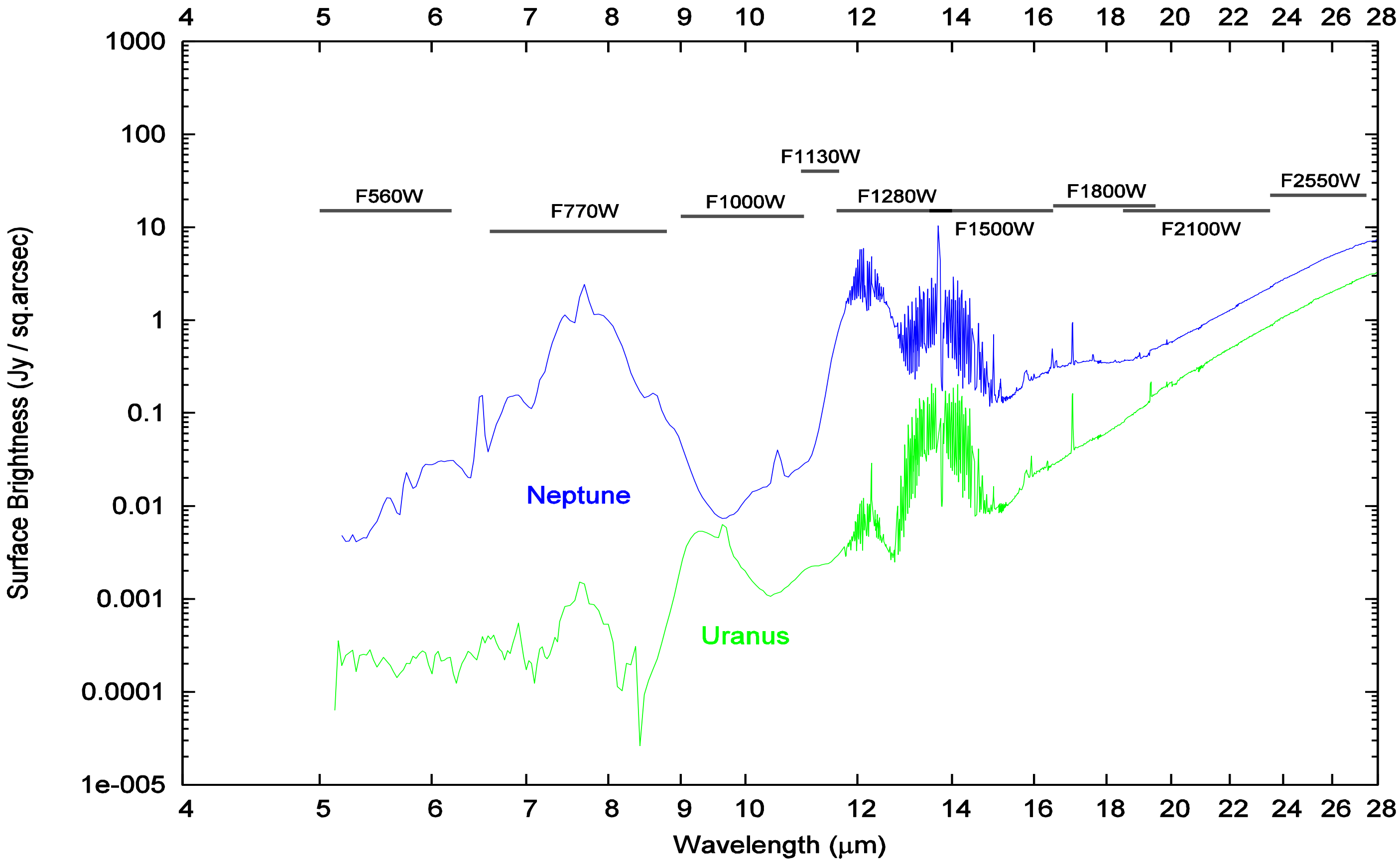
What determines the vertical structure, clouds and energy transfer mechanisms from the deep interior to the upper atmosphere/ thermosphere? What drives zonal variability?

- What are the principle constituents of the cloud decks; does a deep H_2O cloud exist?
- What more can we *really* learn from reflected sunlight observations? What is the depth of the weather layer?
- What determines the spatial and temporal variability of discrete cloud features, how does this relate to environmental variations and composition (dark ovals, bright clouds)?
- How is internal energy transported from the interior, through the weather layer and into the upper atmosphere (i.e., what is the importance of convection and waves?)?

EYE CHART

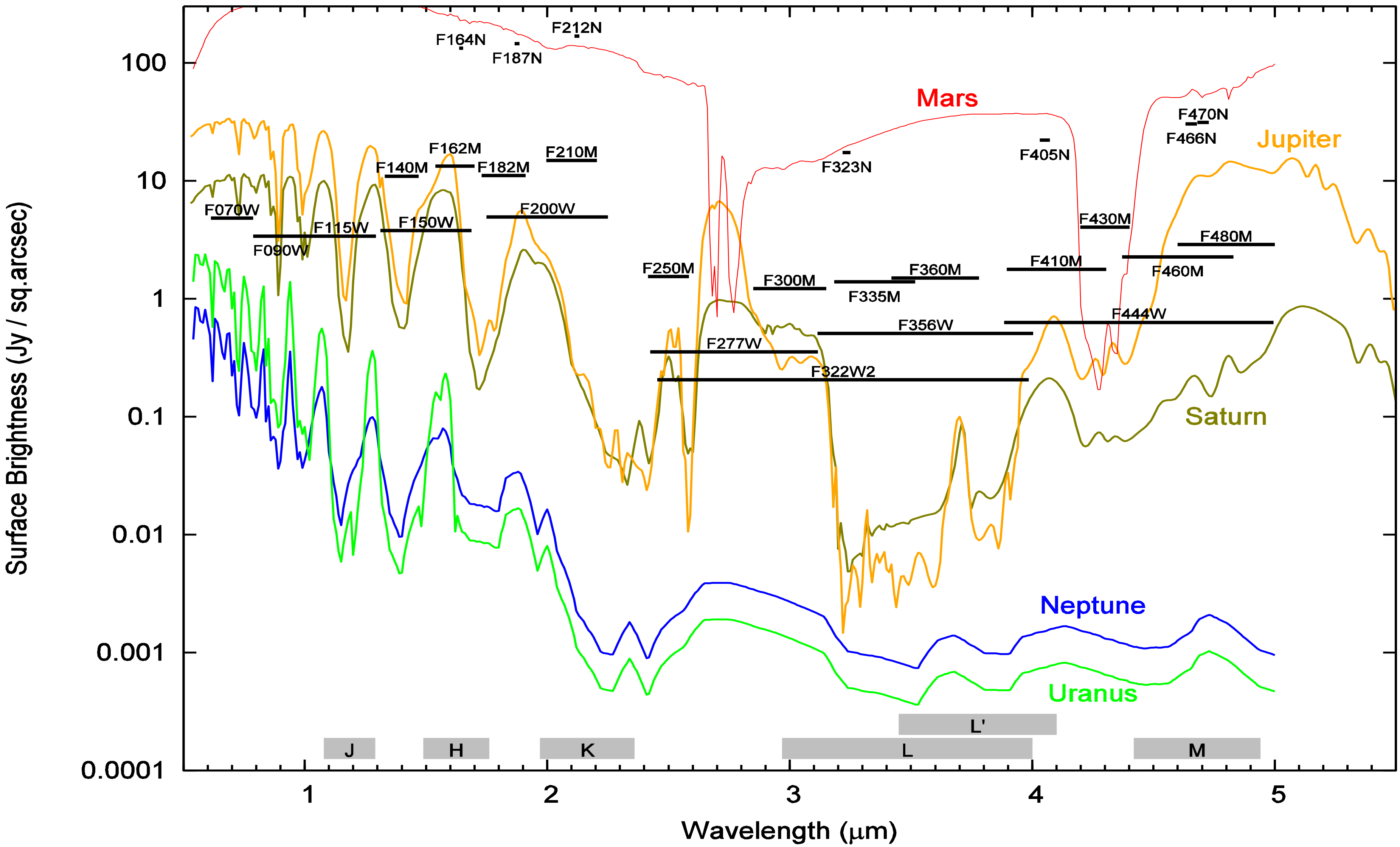
- *Future Uranus observations must move beyond 2D imaging, and probe the vertical structure of the atmosphere to relate it to (i) the interior and (ii) the tenuous ionosphere/thermosphere.*
- *Assessment of the cloud composition, vertical structure and relation to the deeper convective troposphere is essential.*
- ***JWST can make seminal contributions.***

Uranus with MIRI



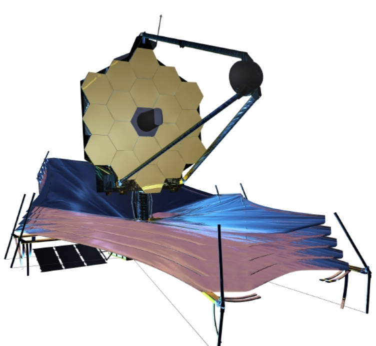
Spitzer/IRS spectra of **Uranus** and Neptune (Orton et al. 2014) compared to saturation limits of MIRI filters, assuming SUB64 sub-array imaging with minimum integration time (a factor of ~33 shorter than without sub-arrays). Uranus will require sub-arrays for F2100W and F2550W.

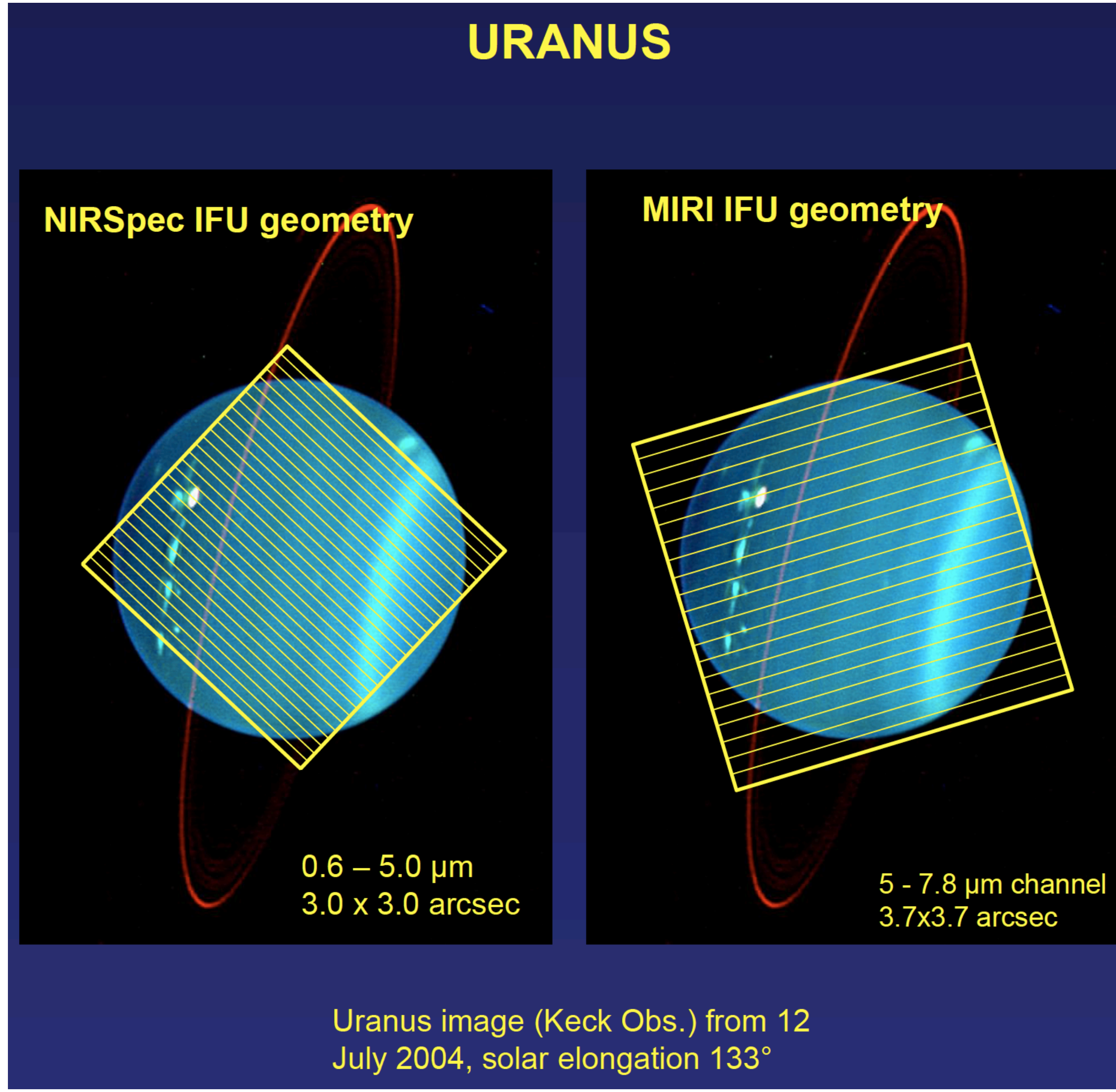
NIRCam: Uranus



Uranus with JWST/MIRI

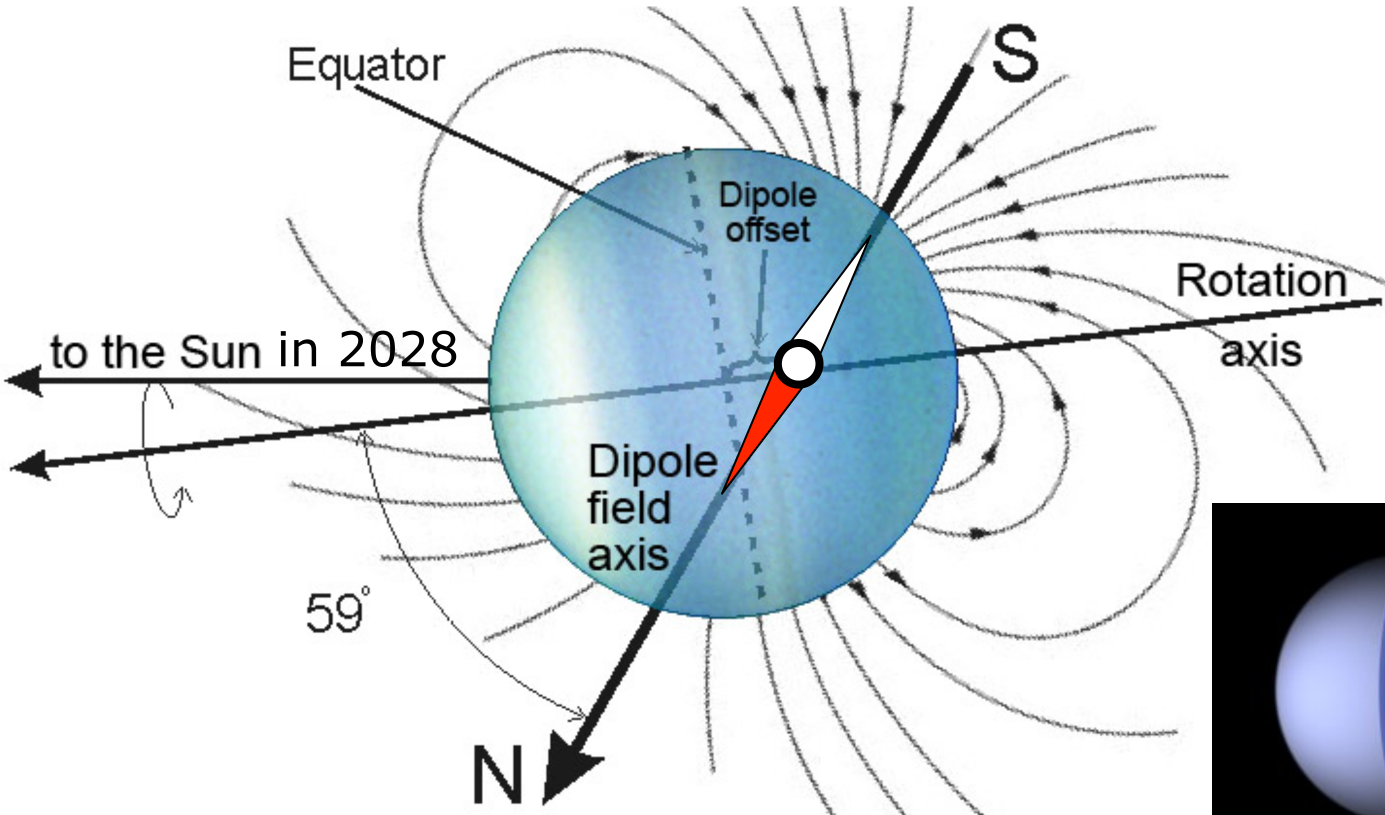
(note: can observe several times per year)

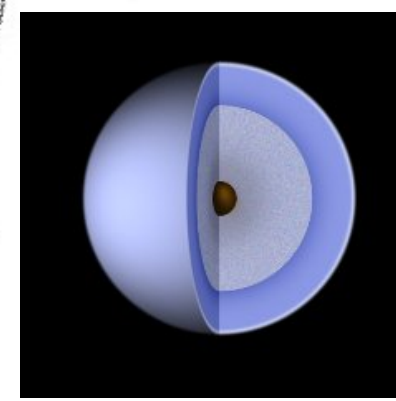




From Sonneborne et al. poster at DPS meeting, 2013

unusual magnetic field of uranus



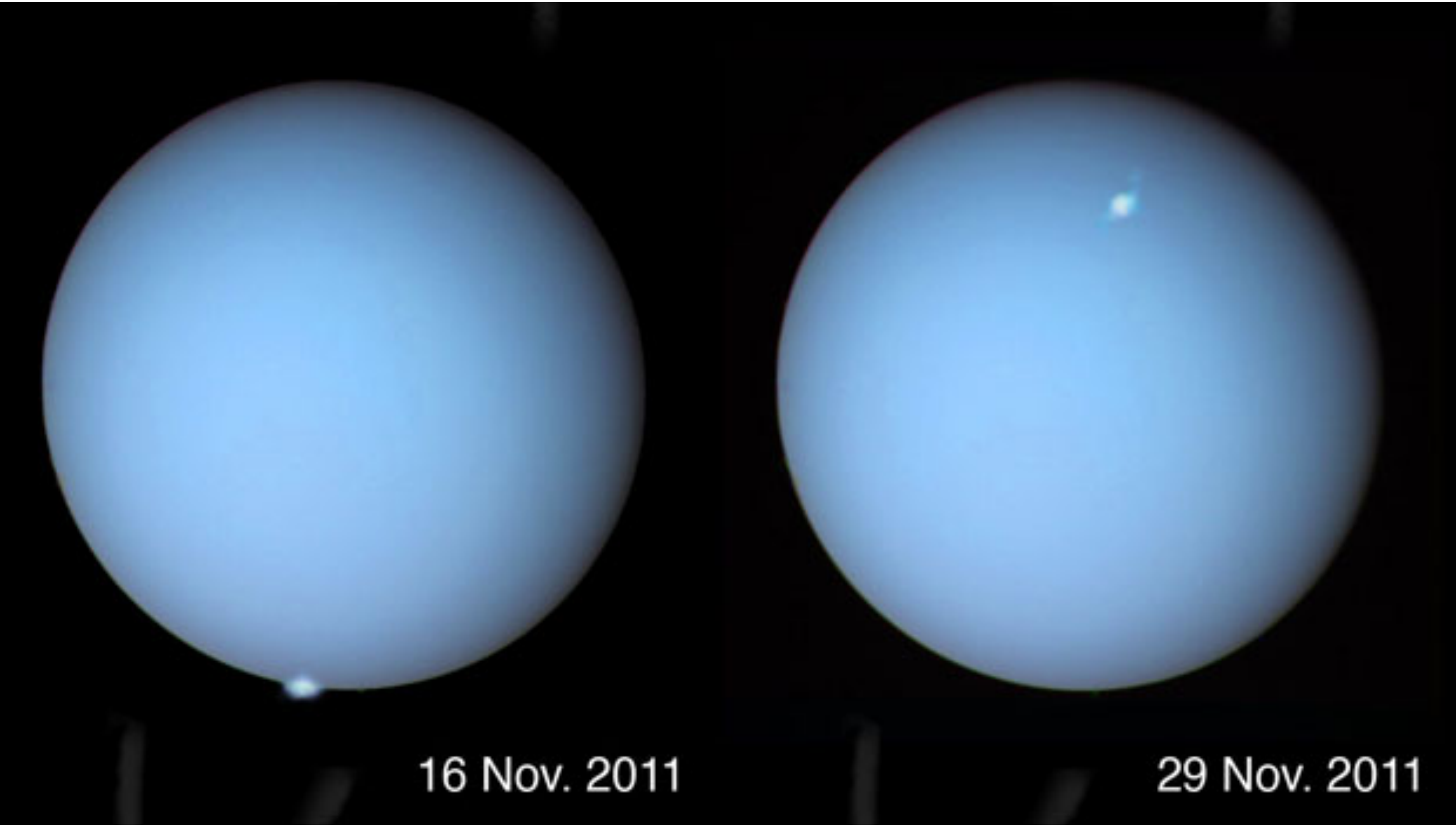


Dipole tilted 59° from the planet's rotation axis

Dipole offset from the planet's center by about 1/3 of Uranus

Uranus image from the Hubble Space Telescope

Hubble images: Uranus aurora 2011



Hubble UV images combined with planet in "true" color
Lamy et al. 2012

Aurora of Uranus in the infrared

Infrared (3-4 microns) H3+ at Uranus: Trafton et al. 1999, *Ap J* **524**, 1059, UKIRT w/ CGS4

IRTF limitations: spatial limitations from the Earth's atmosphere and 3-m telescope; key H3+ lines obscured spectrally by absorption in the Earth's atmosphere

JWST disk-resolved infrared spectroscopy can spatially resolve the auroral source regions on Uranus

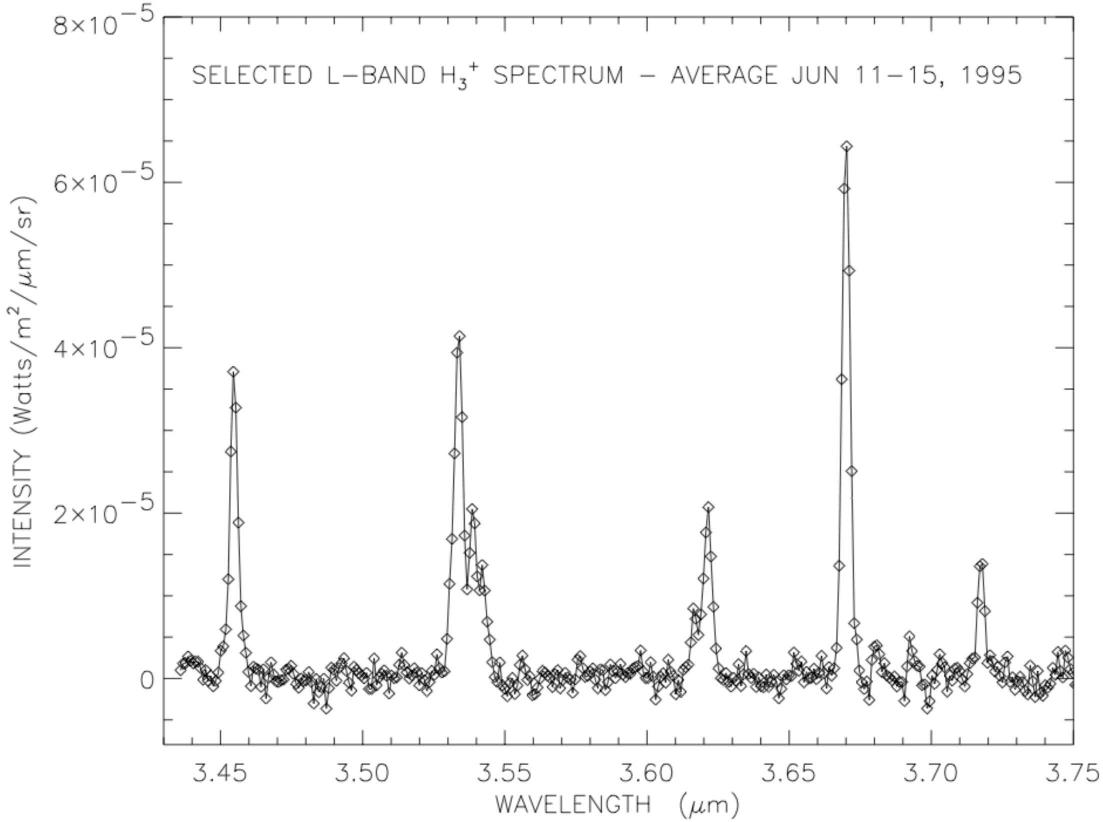
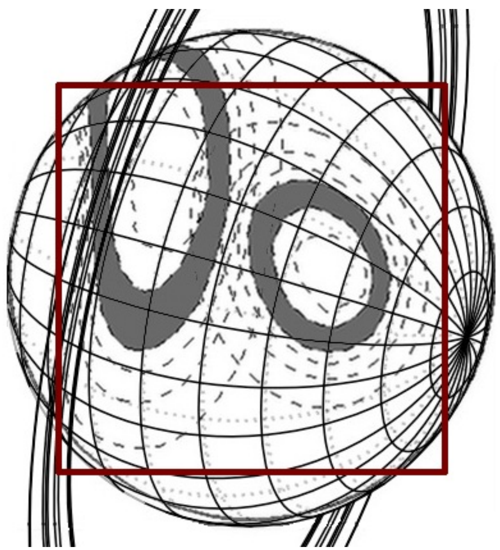


FIG. 3.—Spectrum of Uranus's H_3^+ manifolds obtained with CGS4 during 1995 June, used for our study of the H_3^+ intensity variation along the central meridian (see Table 8).

Aurora of Uranus with JWST

Observation - acknowledgement to Tom Stallard (U. Leicester) for graphics

- A series of observations of the disk of Uranus using the NIRSpec IFU
- Spacing out observations over Uranus' 18-hour rotation will allow full and detailed mapping
- Auroral features may only occur in particular alignments between the plane's magnetic field and the Sun, which will be revealed once the rotational phase of the planet is known
- Temperature will be calculated to show the extent of auroral heating, and how this contributes to the slow heating and cooling of the atmosphere



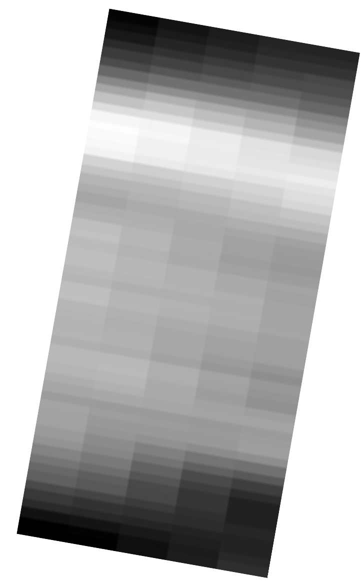
NIRSpec IFU mapped onto the disk of Uranus

Lines of latitude and longitude shown, as well as the rings

Superimposed contours are the magnetic field model for Uranus

Shaded in grey are locations where the aurora are most likely to appear when facing Earth/JWST

The rotational phase of these aurorae are not known

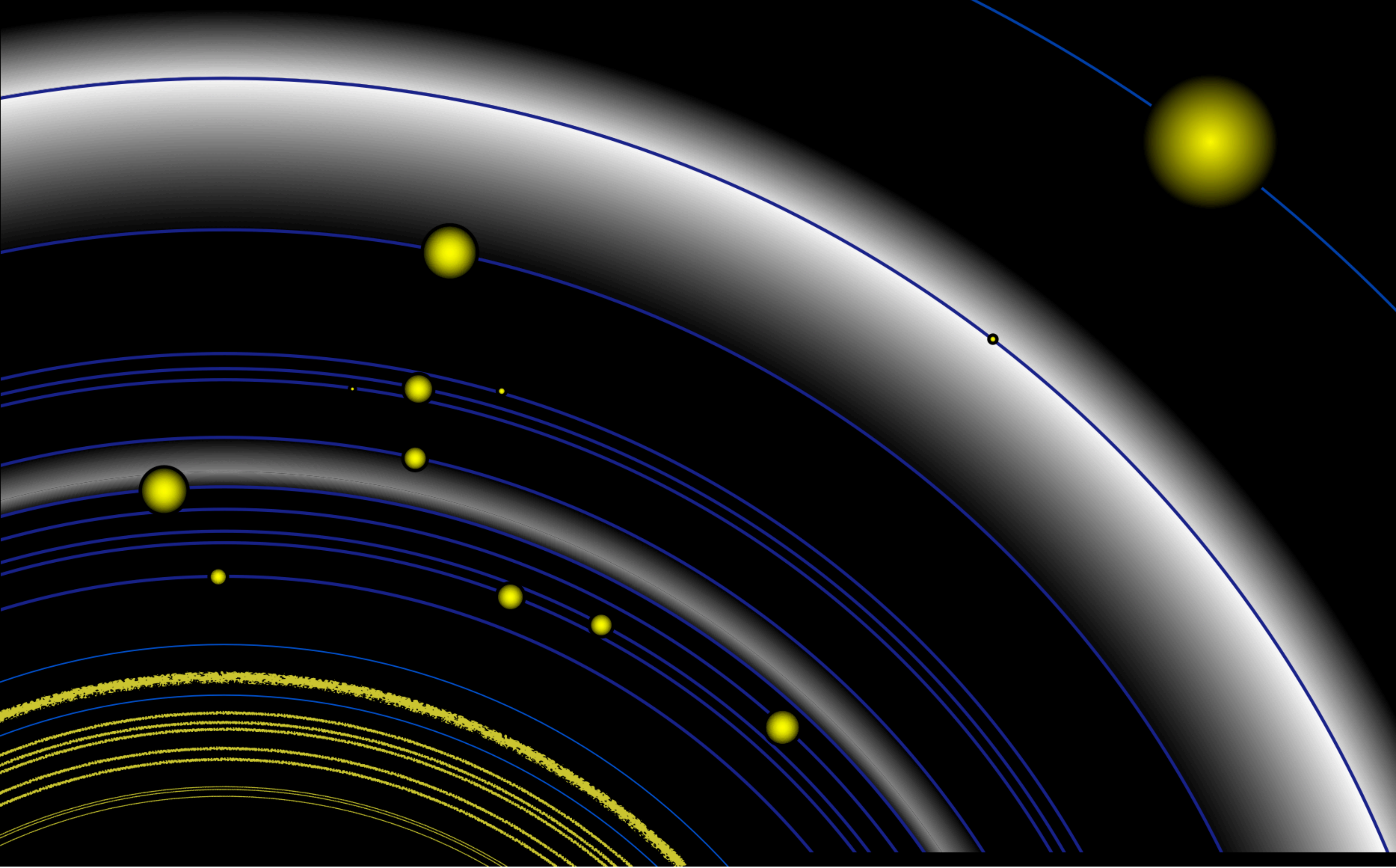


Recent observations of the H3+ emission from VLT, rotated to match with the mapping shown left

A long slit was slid across the surface to create map, required long integration times with resultant spatial smearing

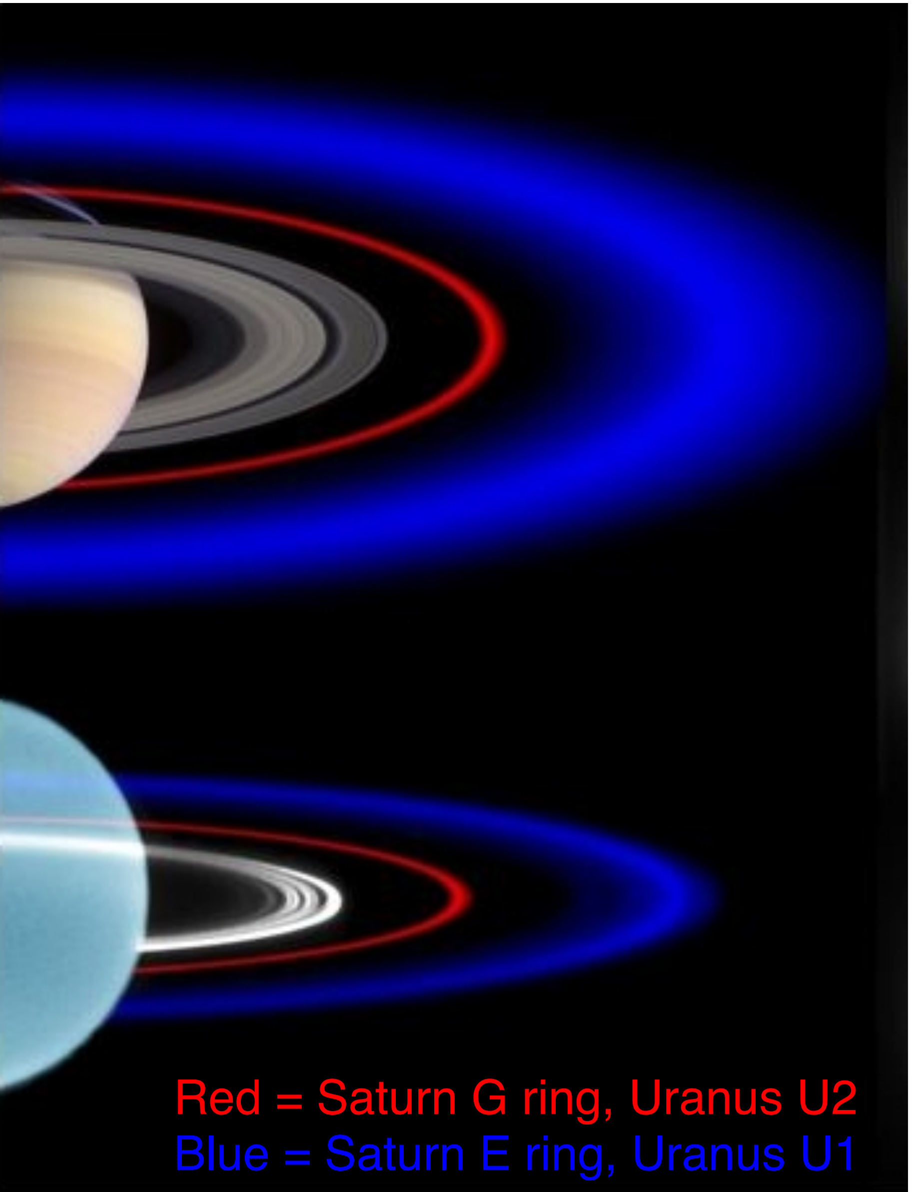
Uranian ring-moon system

most densely packed in the Solar System



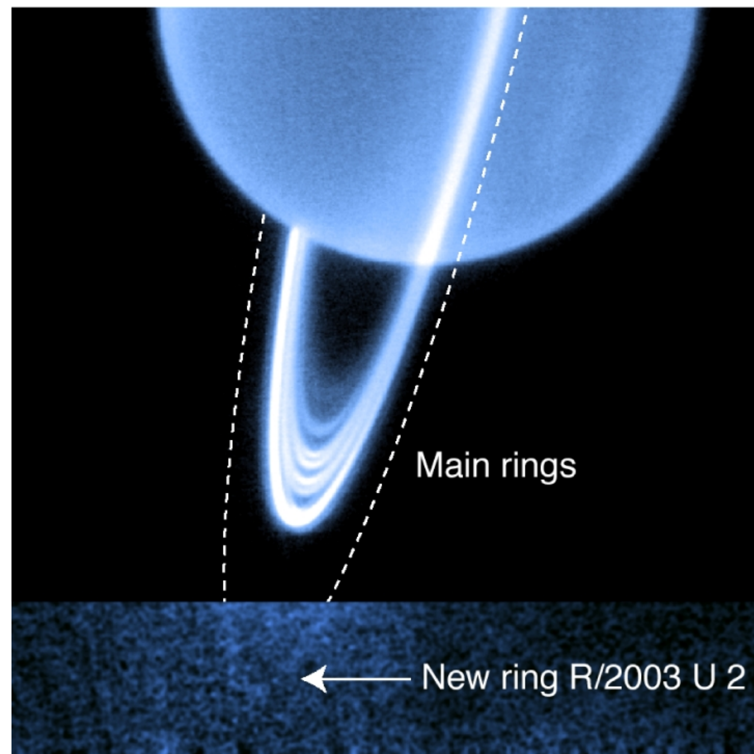
rings of Uranus

de Pater et al. 2006



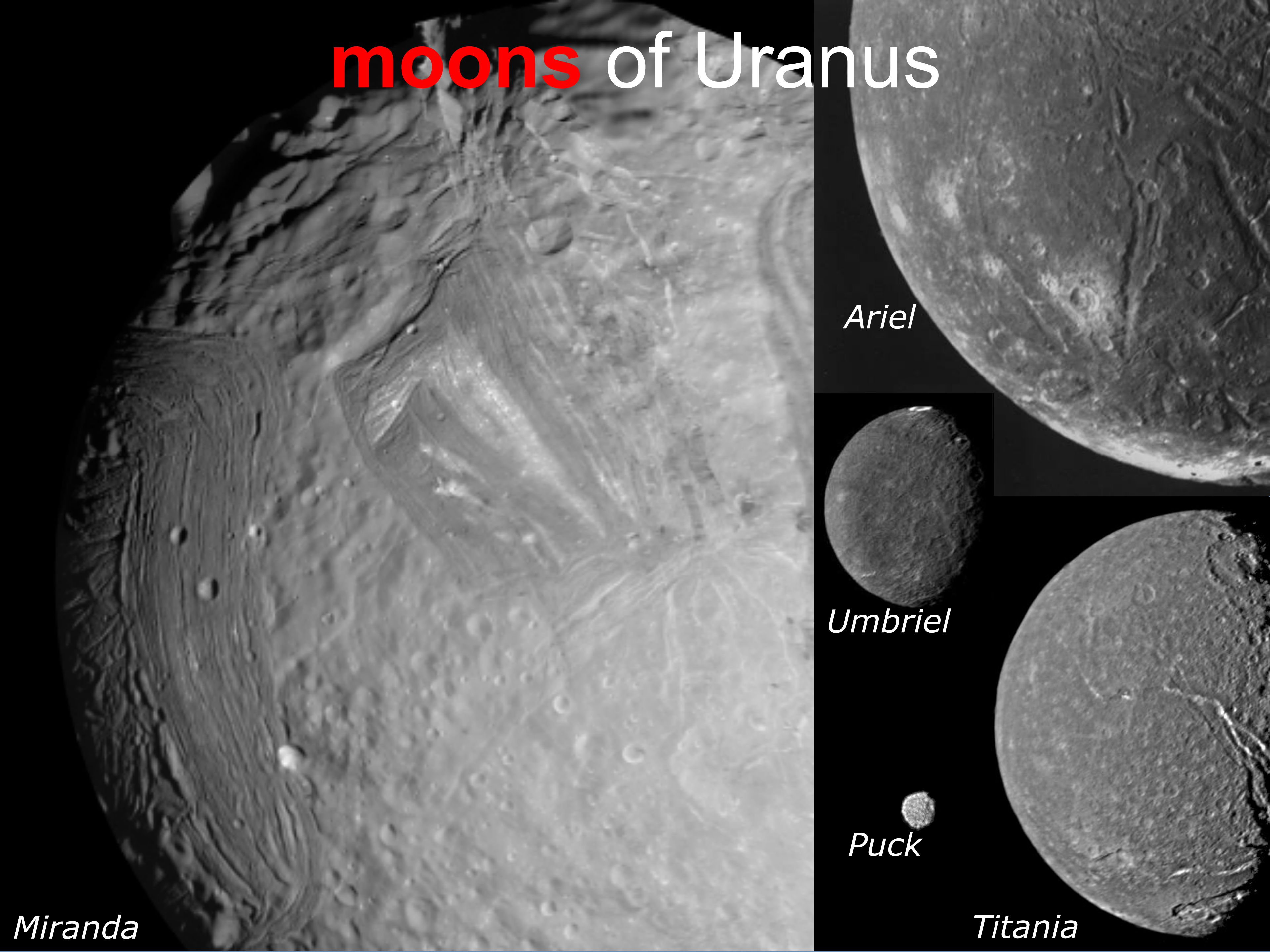
new rings discovered in 2005 with Hubble

ring colors determined in 2006 with Keck

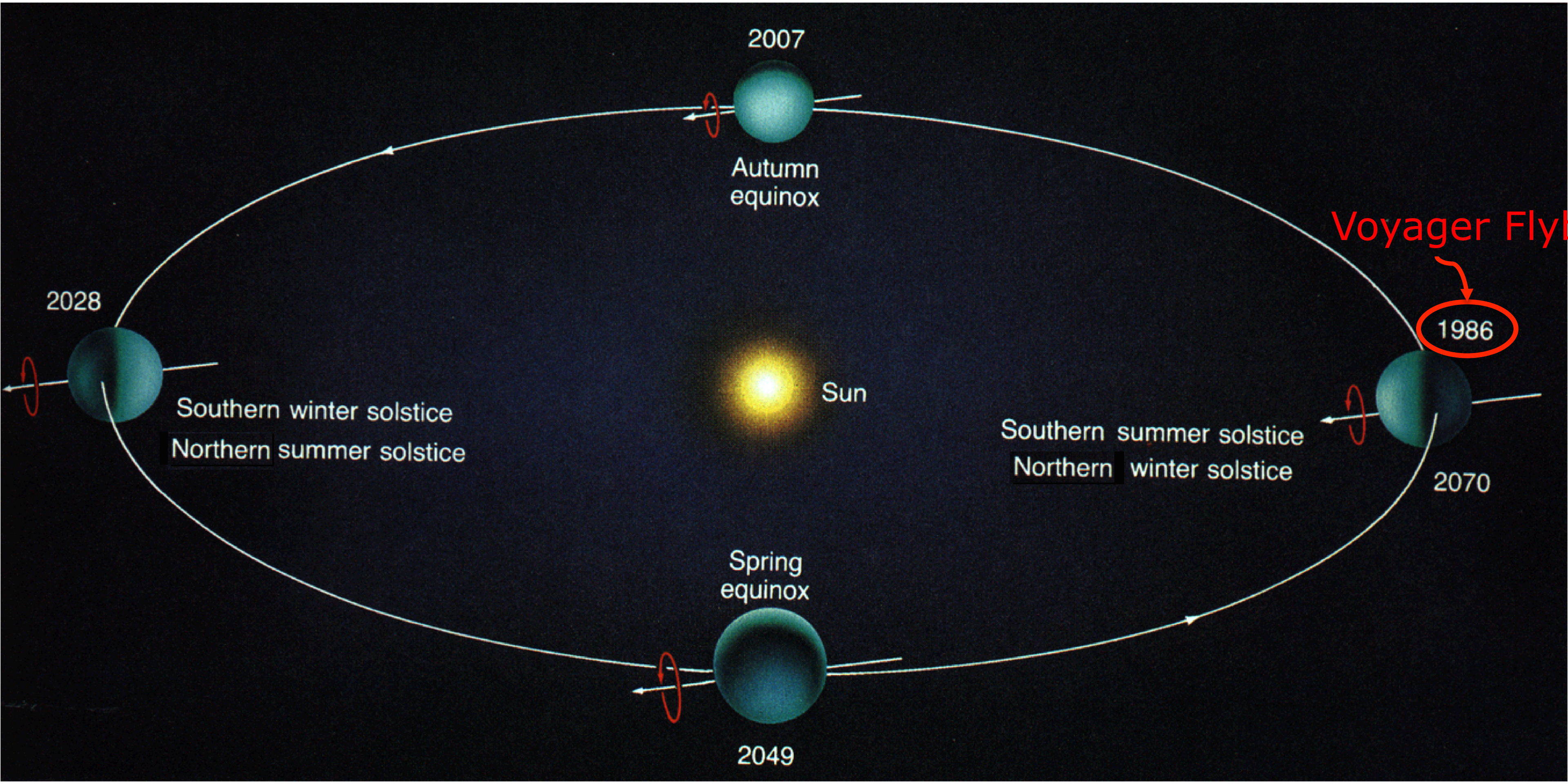


de Pater et al. 2006

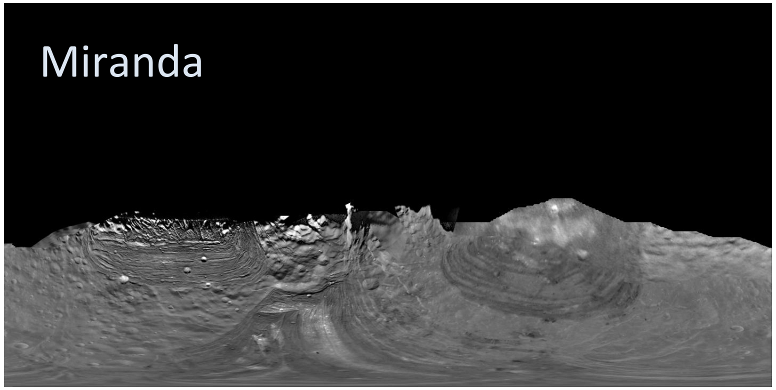
moons of Uranus

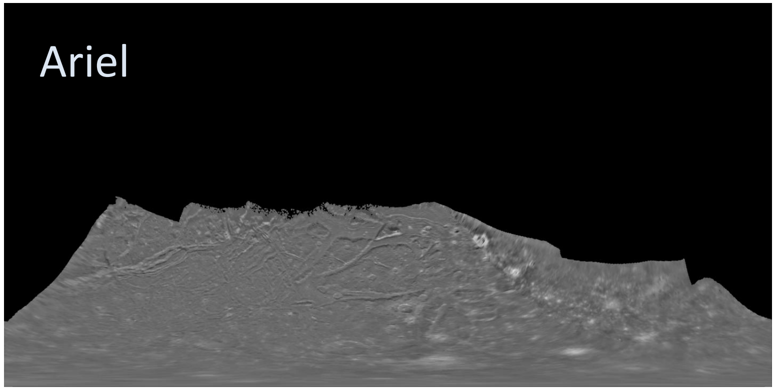


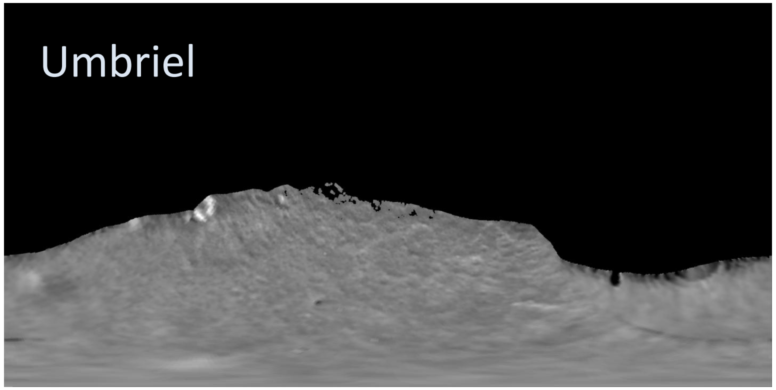
Uranus
extremum seasonal change

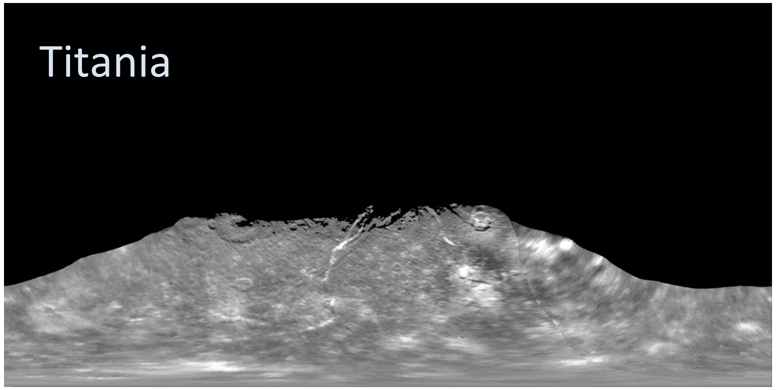


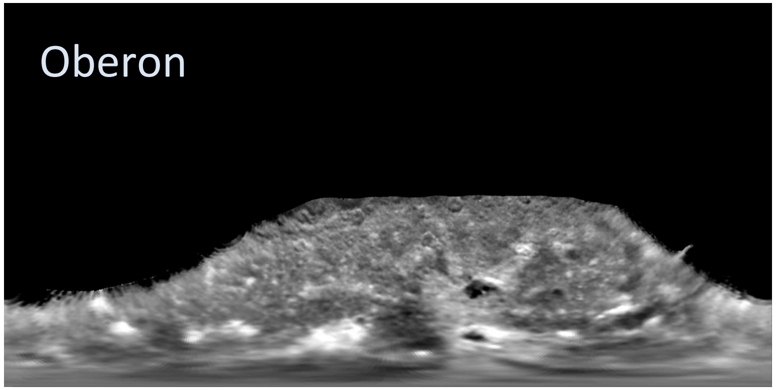
Voyager had limited view of Uranian moons







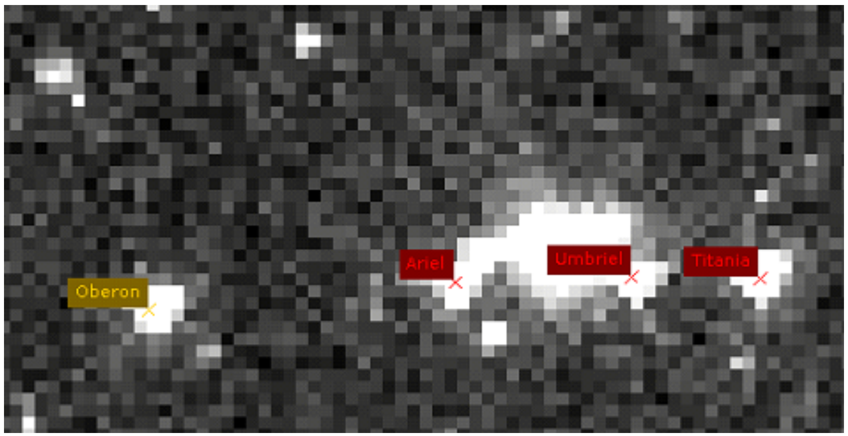


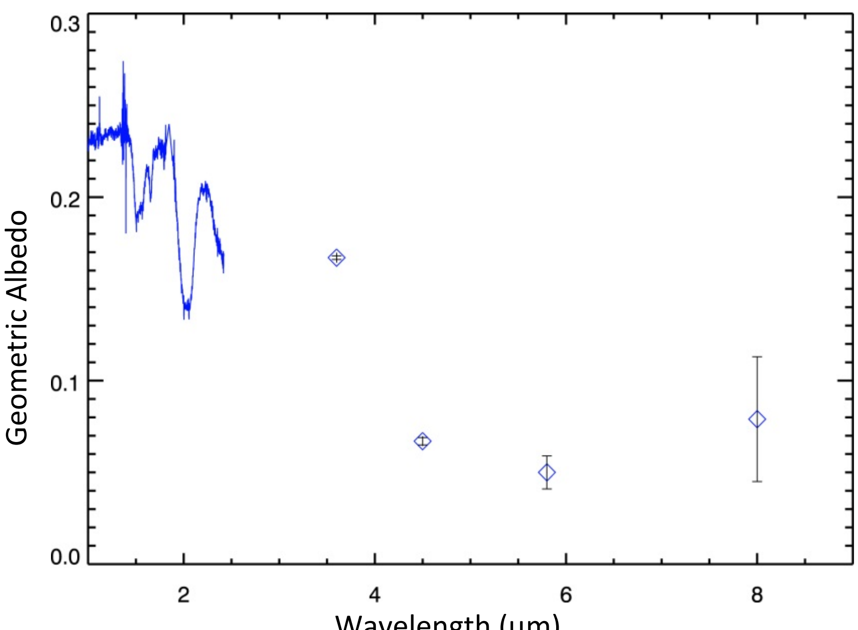


Spitzer/IRAC Observes the Uranian Satellites

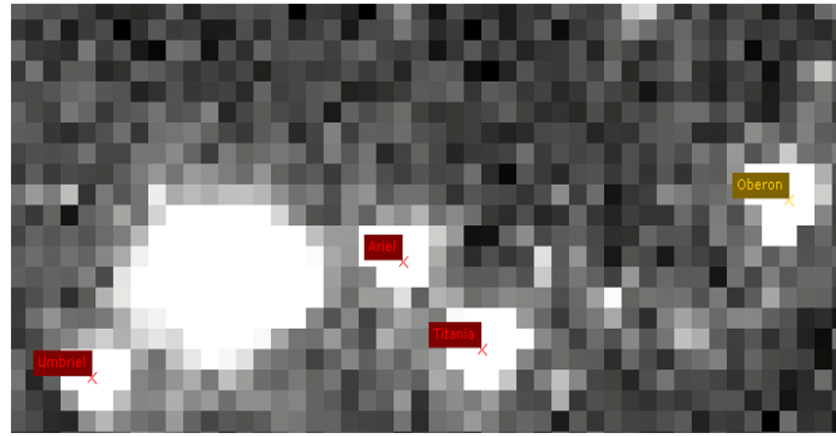
4 channels centered near 3.6, 4.5, 5.8, and 8.0 μm

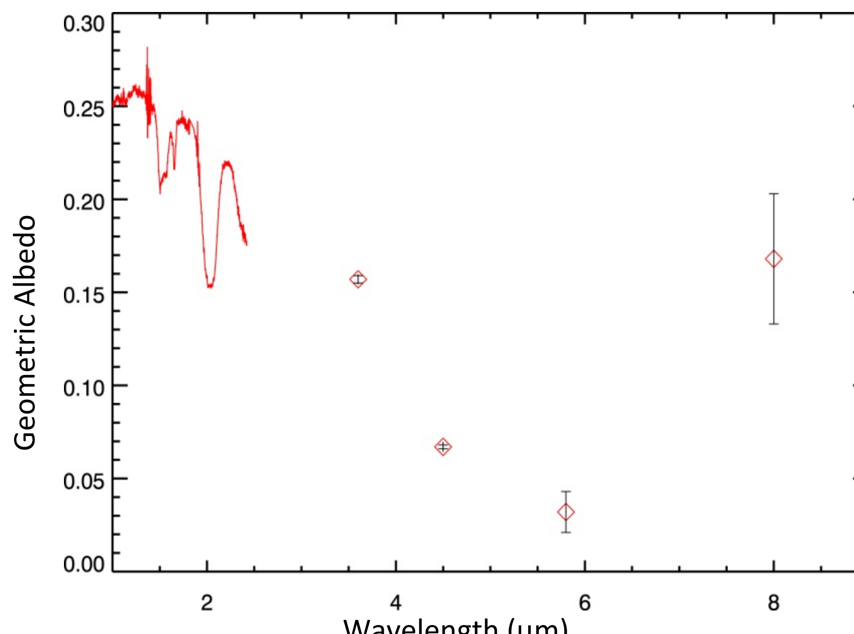
Oberon leading hemisphere





Oberon trailing hemisphere





Richard Cartwright et al., "Uranus Beyond Voyager 2", Workshop in Meudon, September 2013

Possible NIRSpec observations of *unimaged* hemispheres of Uranian moons?

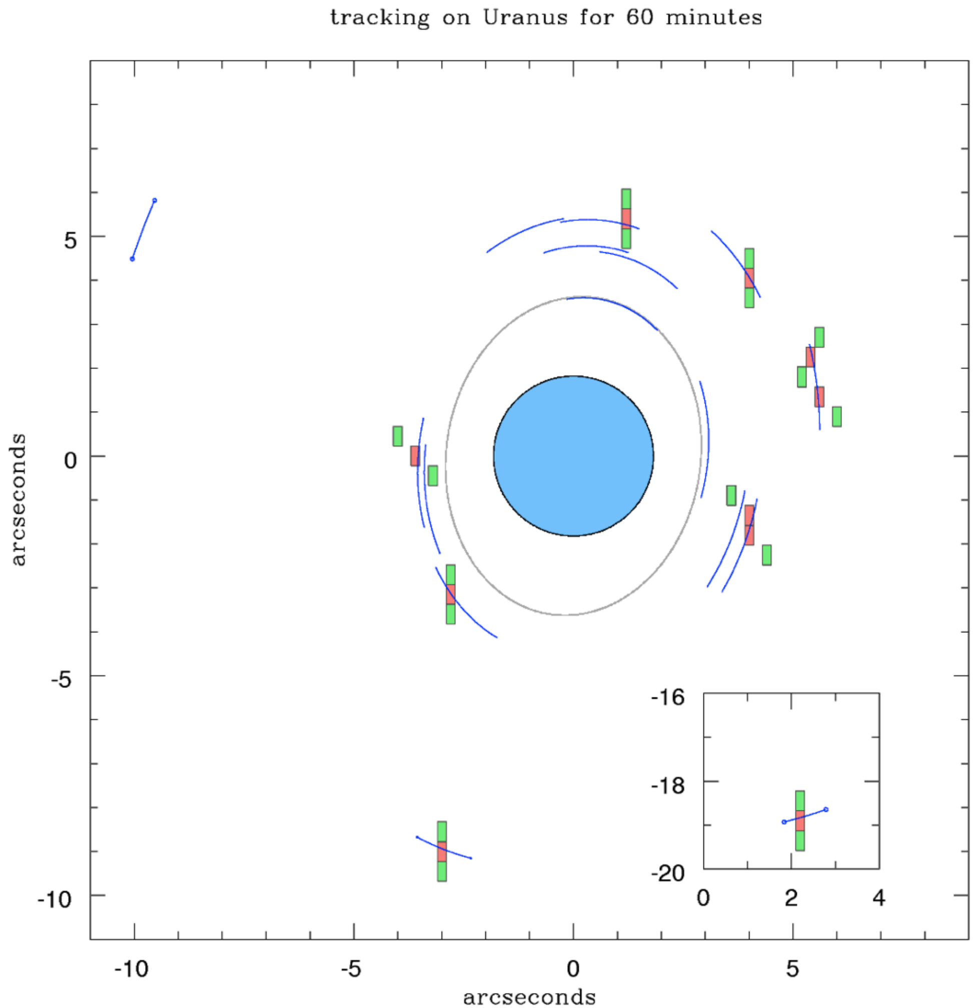
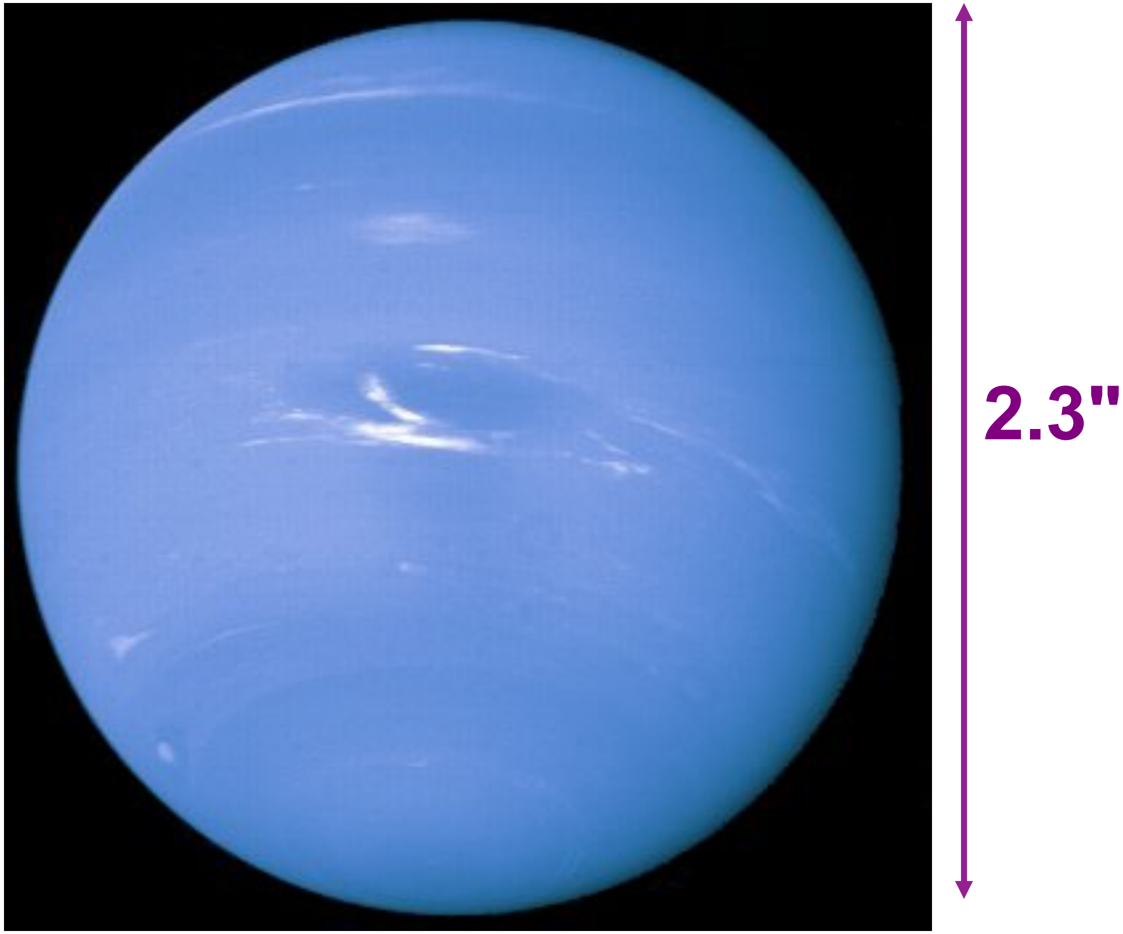


Figure 11. An example MSA configuration for observing the inner Uranian system for one hour, at a randomly chosen time on September 28, 2020 (a valid time for observing Uranus with JWST). Uranus is shown at center, with the Epsilon Ring in gray. Open apertures are shown as rectangles: red for apertures that will result in object spectra, and green for nearby "empty" spectra to use for calibration. Observed satellites include (from top to bottom) Cupid, Puck, Mab (with two apertures), Cressida, Perdita (with two apertures), Desdemona, Miranda, and Umbriel (inset). Ariel, at left, is unobservable in this arrangement as it will saturate. The shortest-timespan spectrum will be that of Cupid, at 6.8 minutes. This scenario will produce satellite spectra totaling 2.1 hours.

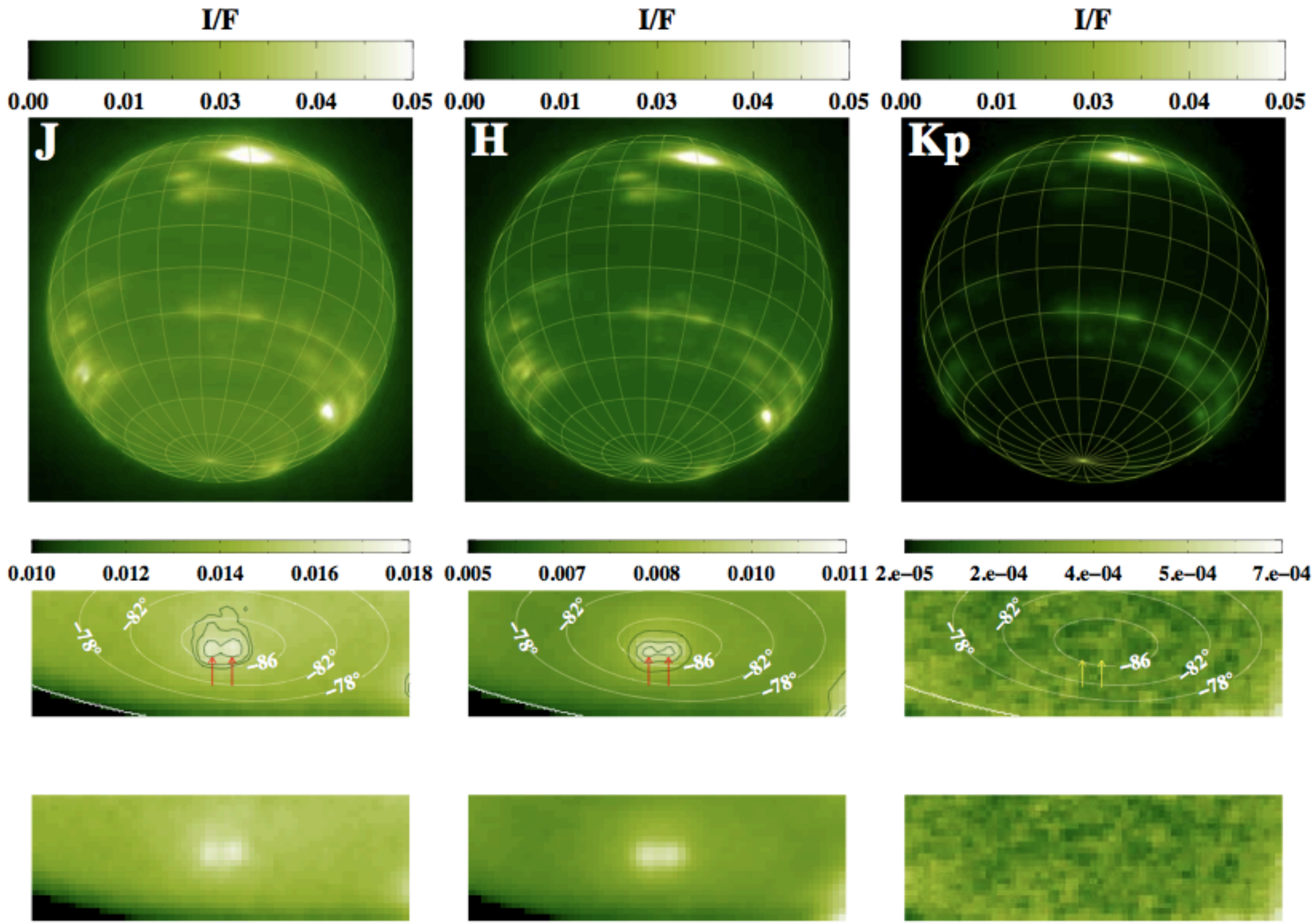
Neptune

Voyager Neptune in 1989



Smith et al. 1989

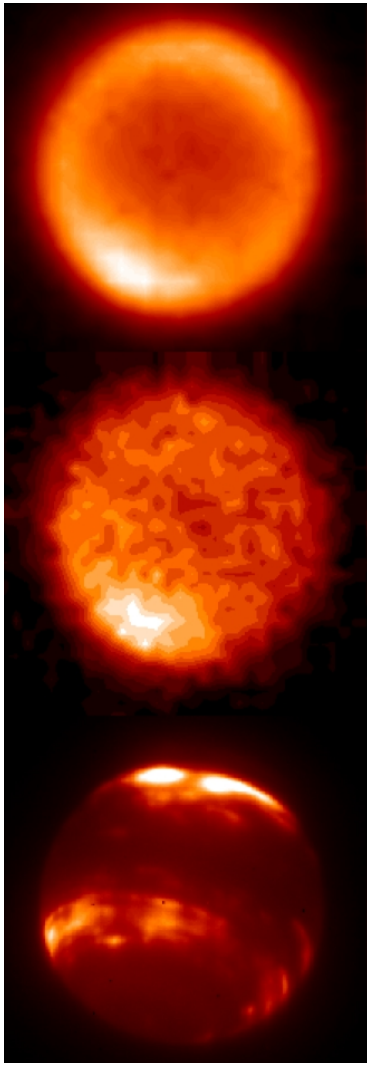
Keck: atmospheric detail on Neptune



Seeing Double at Neptune's South Pole

Luszcz-Cook, de Pater, Adamkovics, and Hammel (2010), Icarus 208, 938

Simultaneous imaging of Neptune with Keck and Gemini



Gemini/Michelle at 11.7 μm
Ethane Emission
from the stratosphere

Gemini/Michelle at 7.7 μm
Methane Emission
from the stratosphere

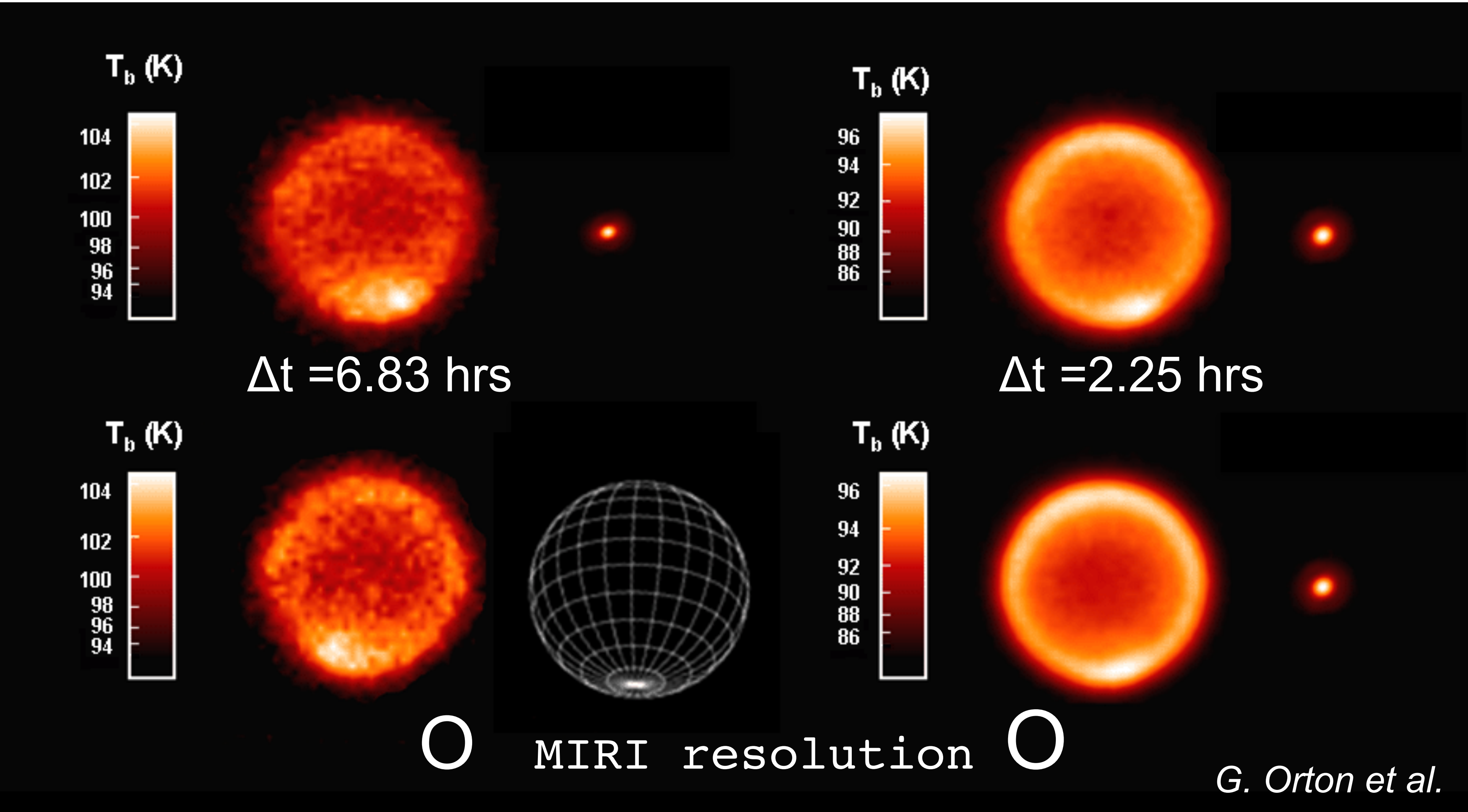
Keck/NIRC2+AO at 1.6 μm
Sunlight Scattering from
tropospheric Clouds

All 3 images taken
within a few minutes
on 5 July 2005

Hammel et al. (2007), AJ

Neptune's stratospheric emission

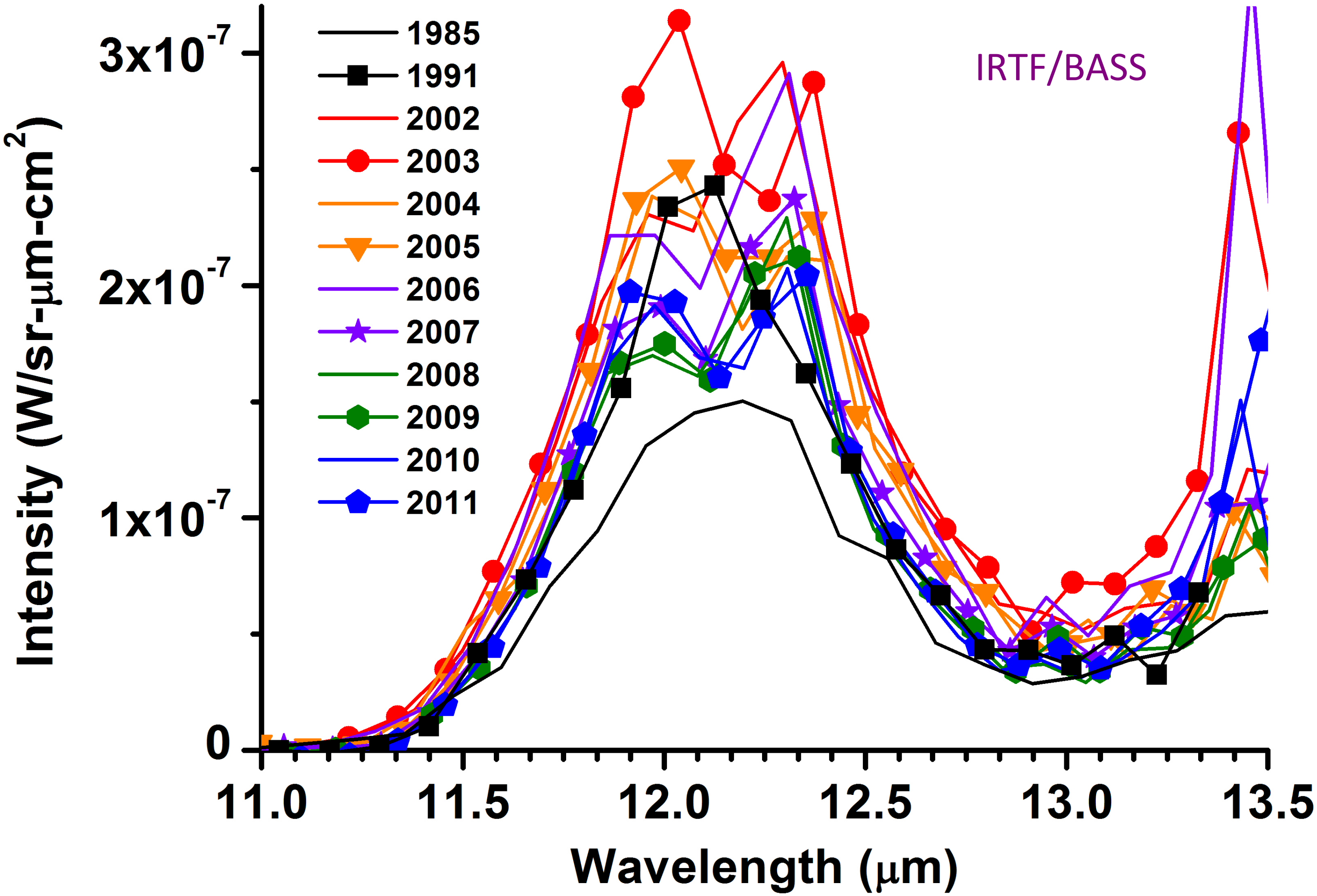
CH_4 C_2H_6



BASS Team at
NASA Infrared Telescope Facility

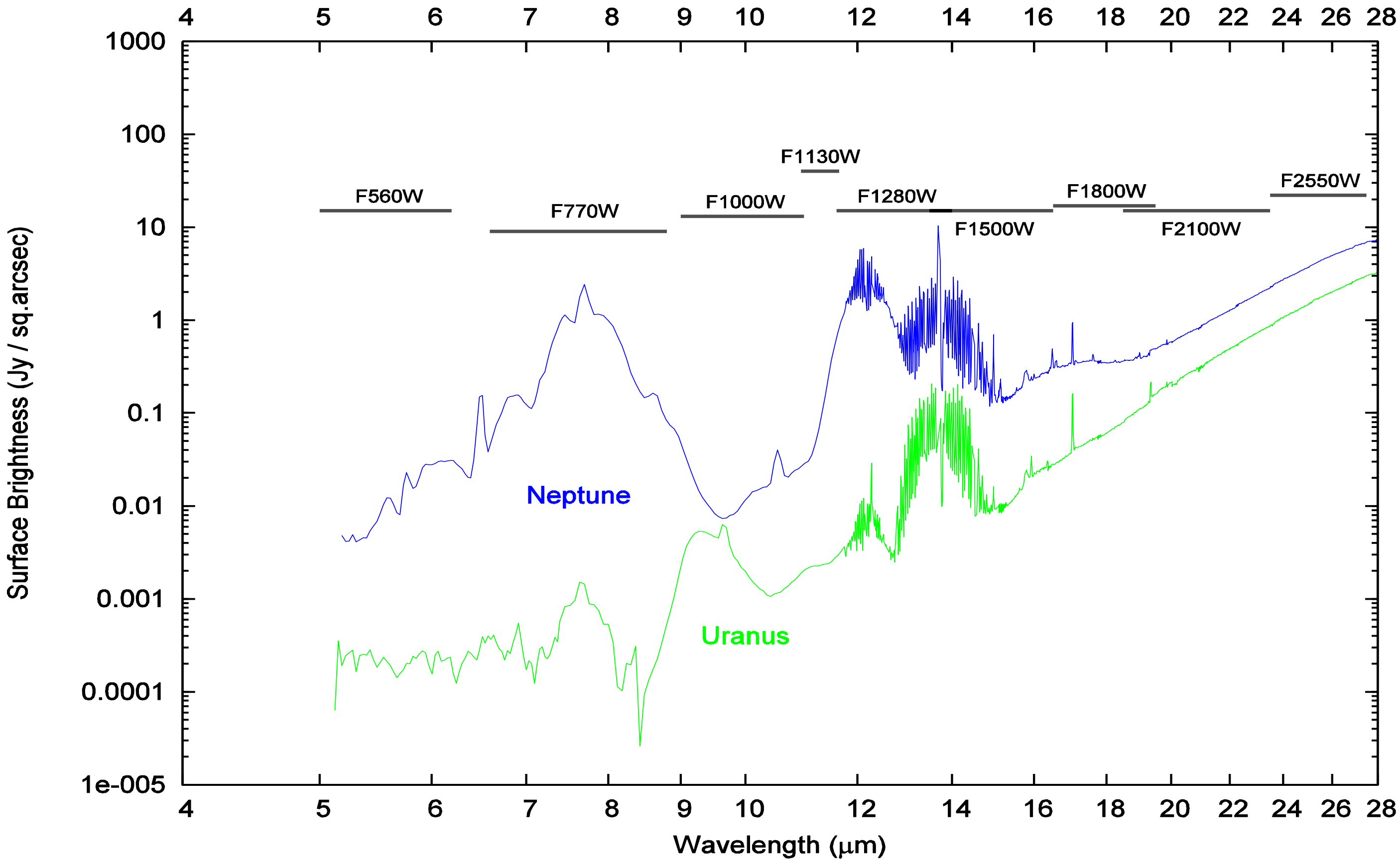
neptune's mid-infrared ethane emission varies

Simplest interpretation is increase in stratospheric temperature



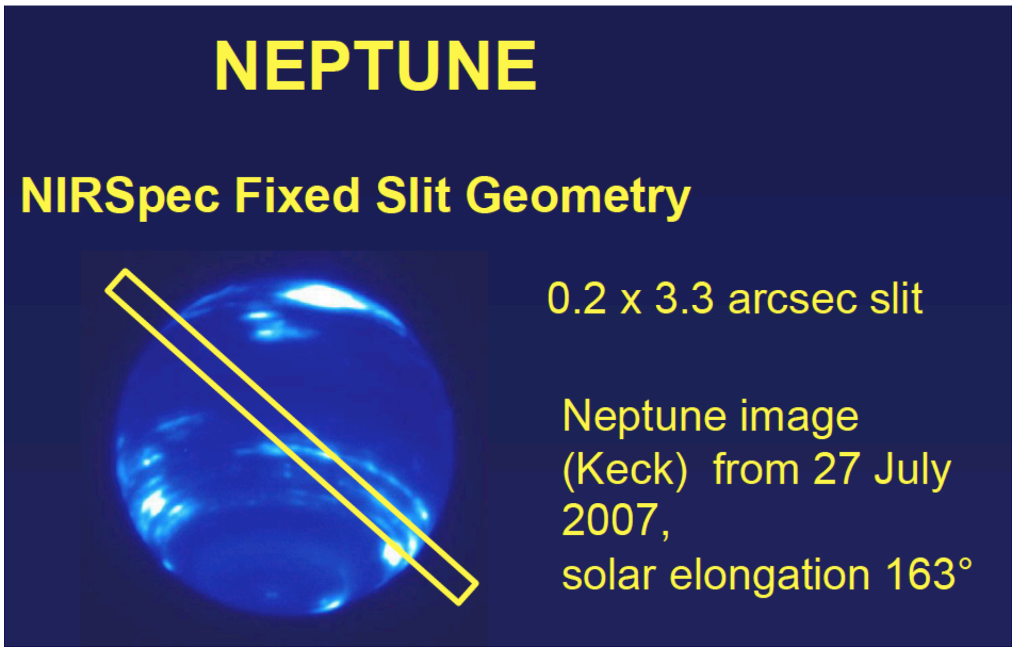
Thru 2005: Hammel et al. 2006, *Ap.J.* 644, 1326; post 2005, Hammel et al., in preparation

Neptune with MIRI

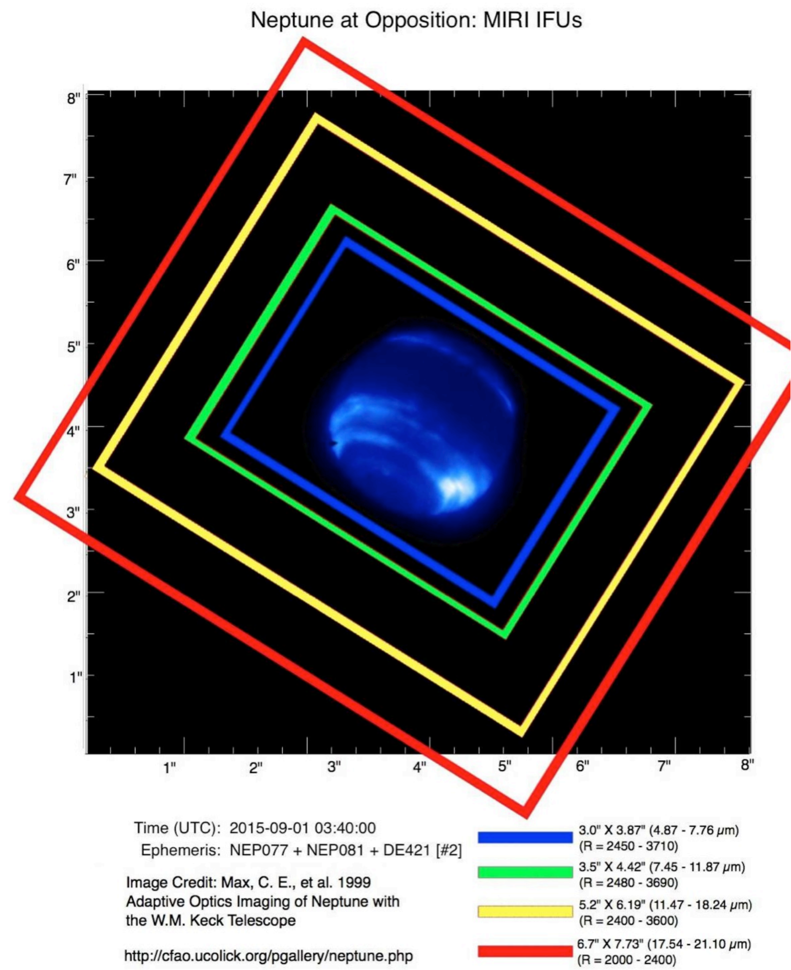


Spitzer/IRS spectra of **Neptune** and **Uranus** (Orton et al. 2014) compared to saturation limits of MIRI filters, assuming SUB64 sub-array imaging with minimum integration time (a factor of ~33 shorter than without sub-arrays). Neptune will be observable without sub-arrays in F560W, F1000W, F1130W, and possibly F1800W. Uranus will require sub-arrays for F2100W and F2550W.

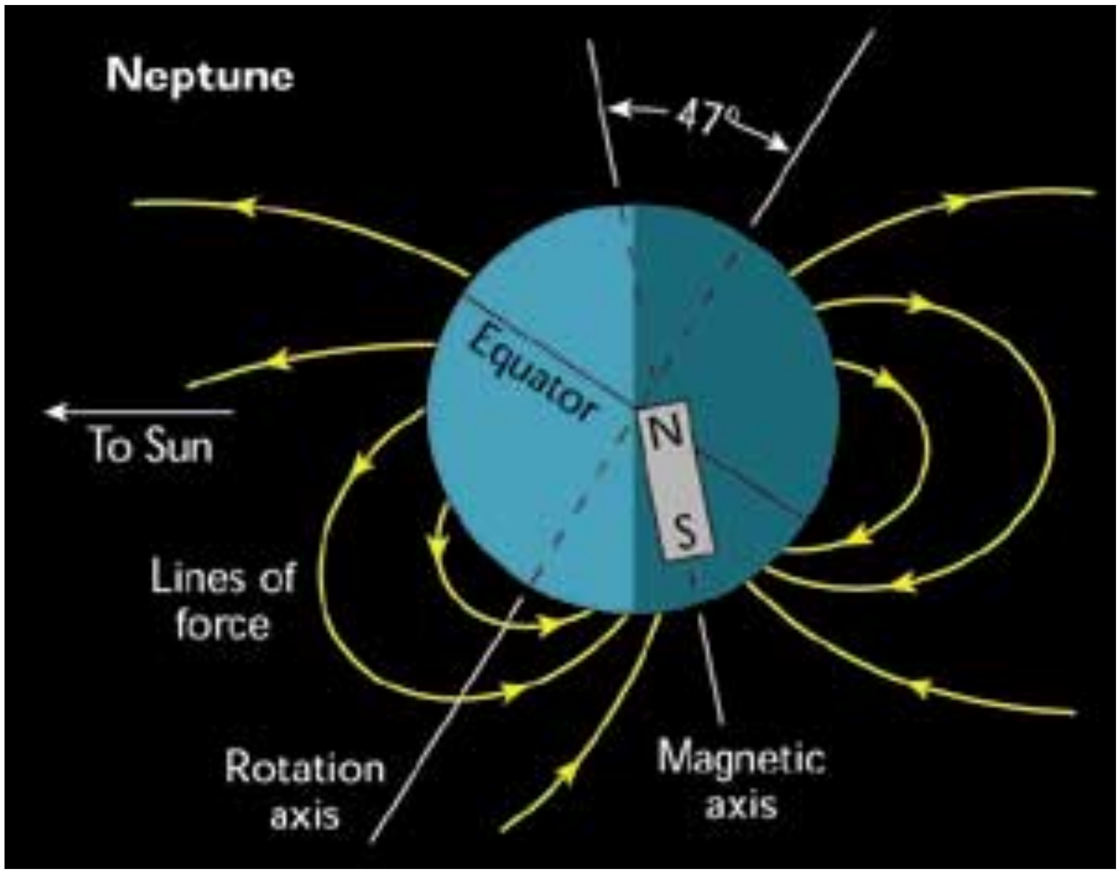
Neptune with JWST



From Sonneborne et al. poster at DPS meeting, 2013



Neptune's odd magnetic field

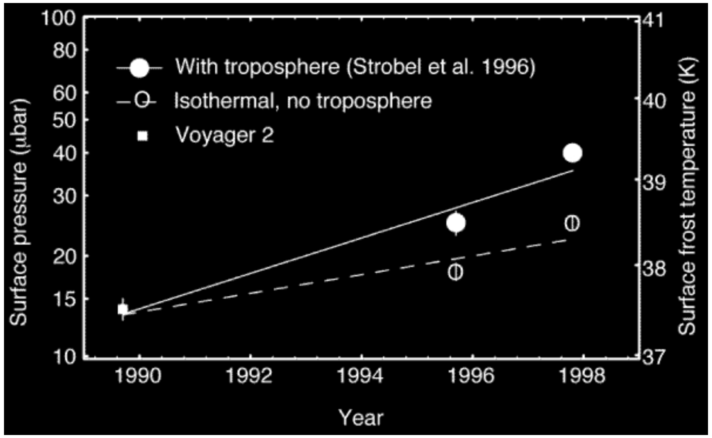


very complex; **undetected from Earth**

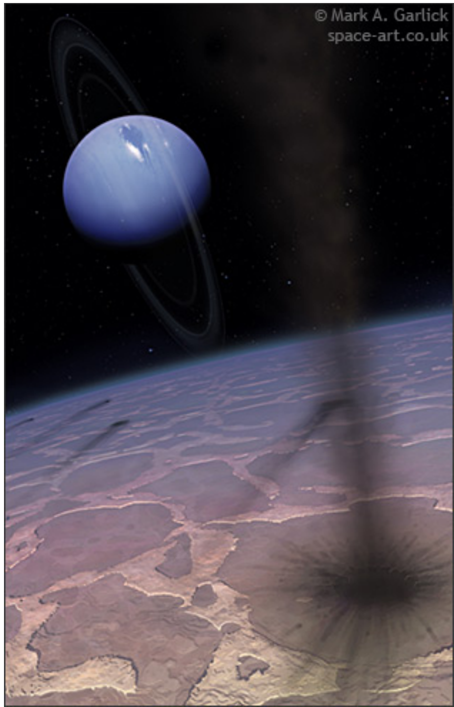
Neptune's moon Triton

Triton's atmosphere has changed significantly since the 1989 Voyager flyby

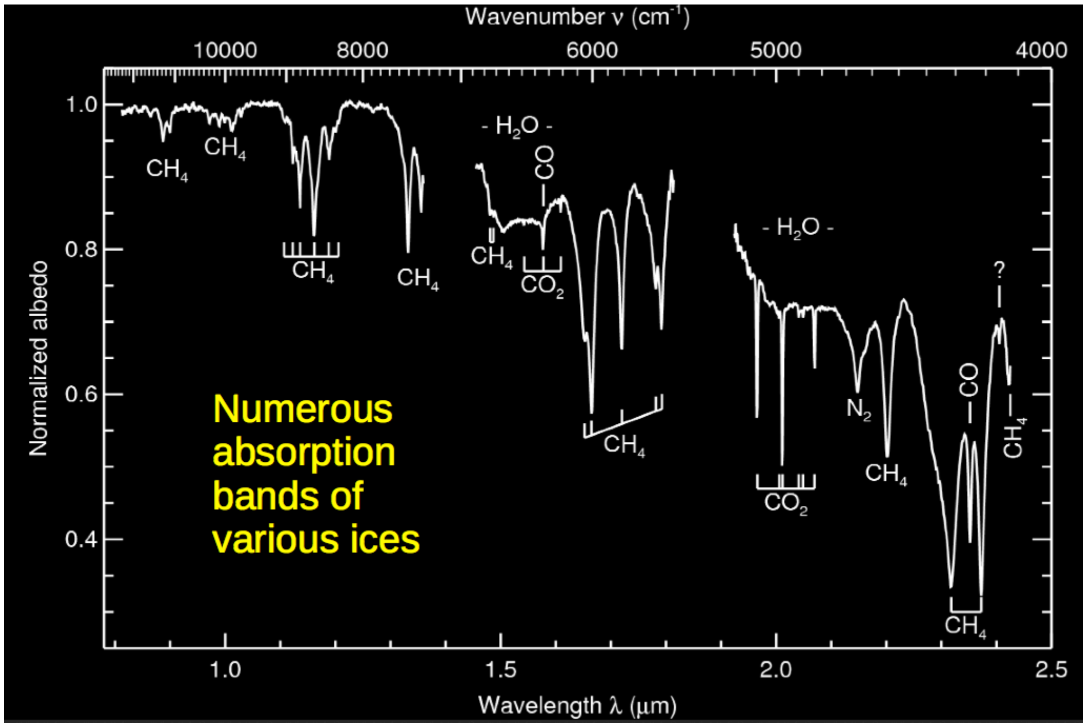
–Nitrogen and methane ices migrate seasonally from hemisphere to hemisphere and the atmospheric pressure increases and decreases seasonally

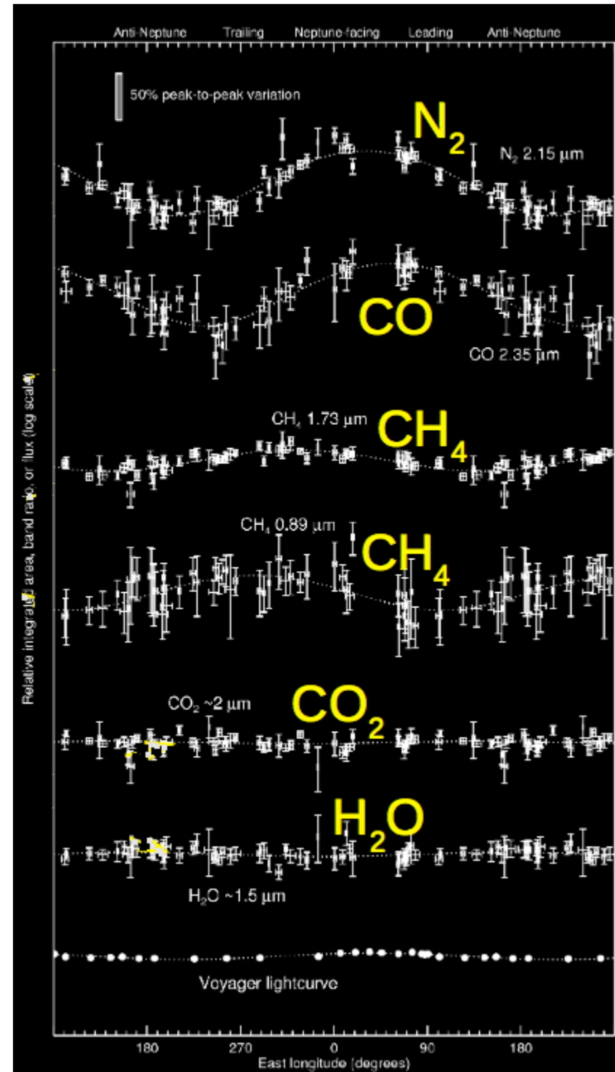


Elliot et al. 1998



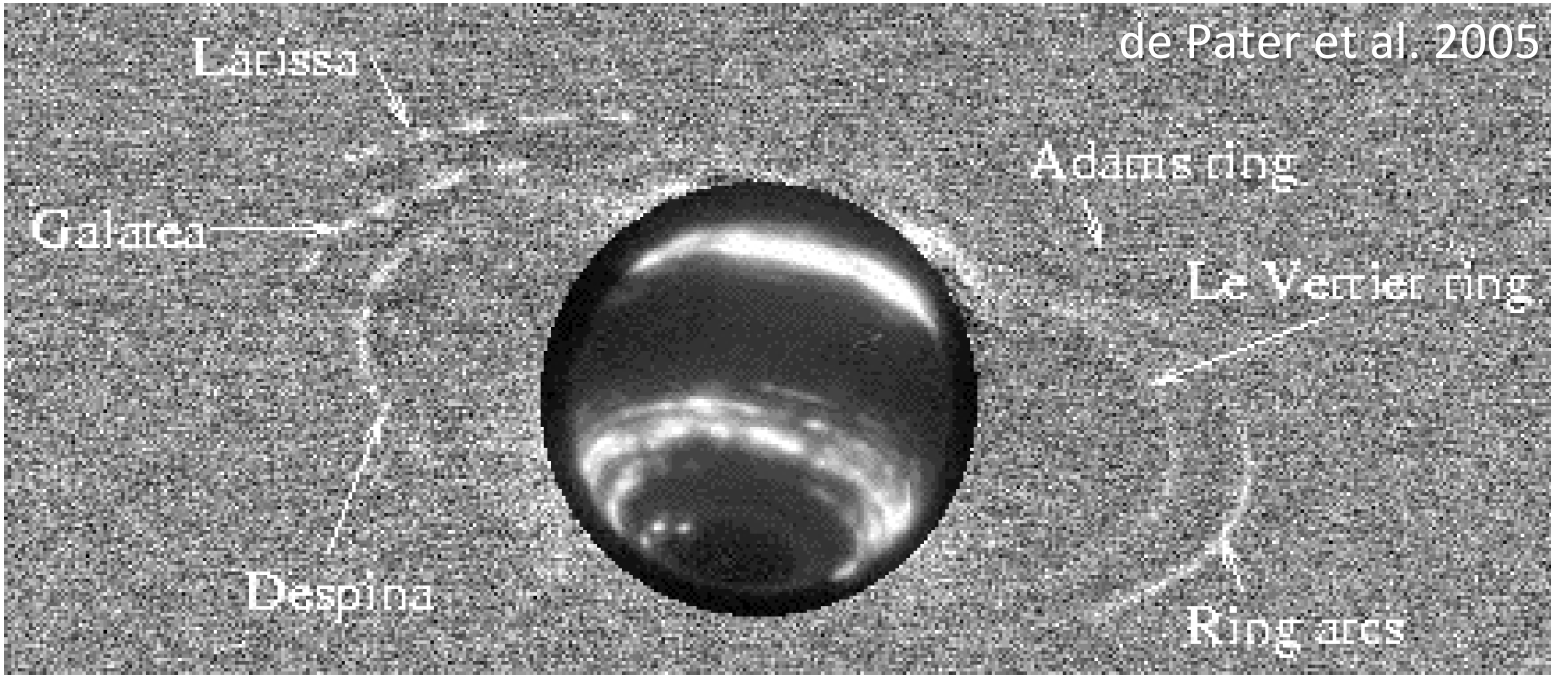
Triton variability driven by seasonal volatile migration?





- Grundy, Young, Stansberry, Buie, Olkin, and Young 2010. Near-infrared spectral monitoring of Triton with IRTF/SpeX II: Spatial distribution and evolution of ices. Icarus 205, 594-604

Neptune’s odd “clumpy” ring system

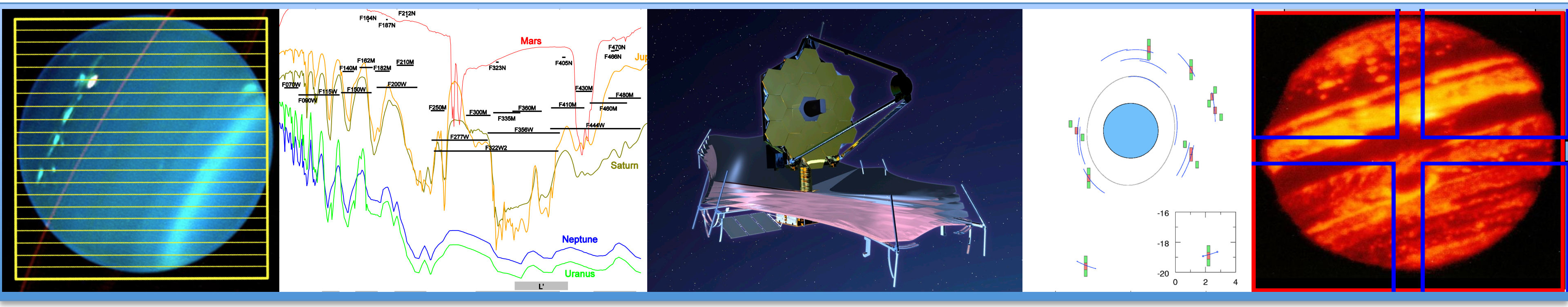


Neptune’s ring system has changed since 1989

arcs evolved within <8 yrs

Matt Tiscareno’s white paper re JWST outer planet ring observations: “**JWST will provide major advances in resolving and separating the main rings of Uranus and Neptune**, improving upon HST and ground-based observations of their fine structure.”

JWST = rich source of outer planet data due to sensitivity, spatial resolution (intrinsic and for context), and capability of time domain



Probe atmospheric dynamics and chemistry

Study auroral activity via H3+ infrared emission

Spectroscopy of moons and rings to characterize uncharted territory and assess temporal variations

Set the stage for future planetary missions to the outer solar system: Jupiter, Saturn, Uranus, and Neptune

JWST will significantly advance our knowledge of the local giant planet systems