Atmospheric Dynamics & Meteorology of the Icy Giants

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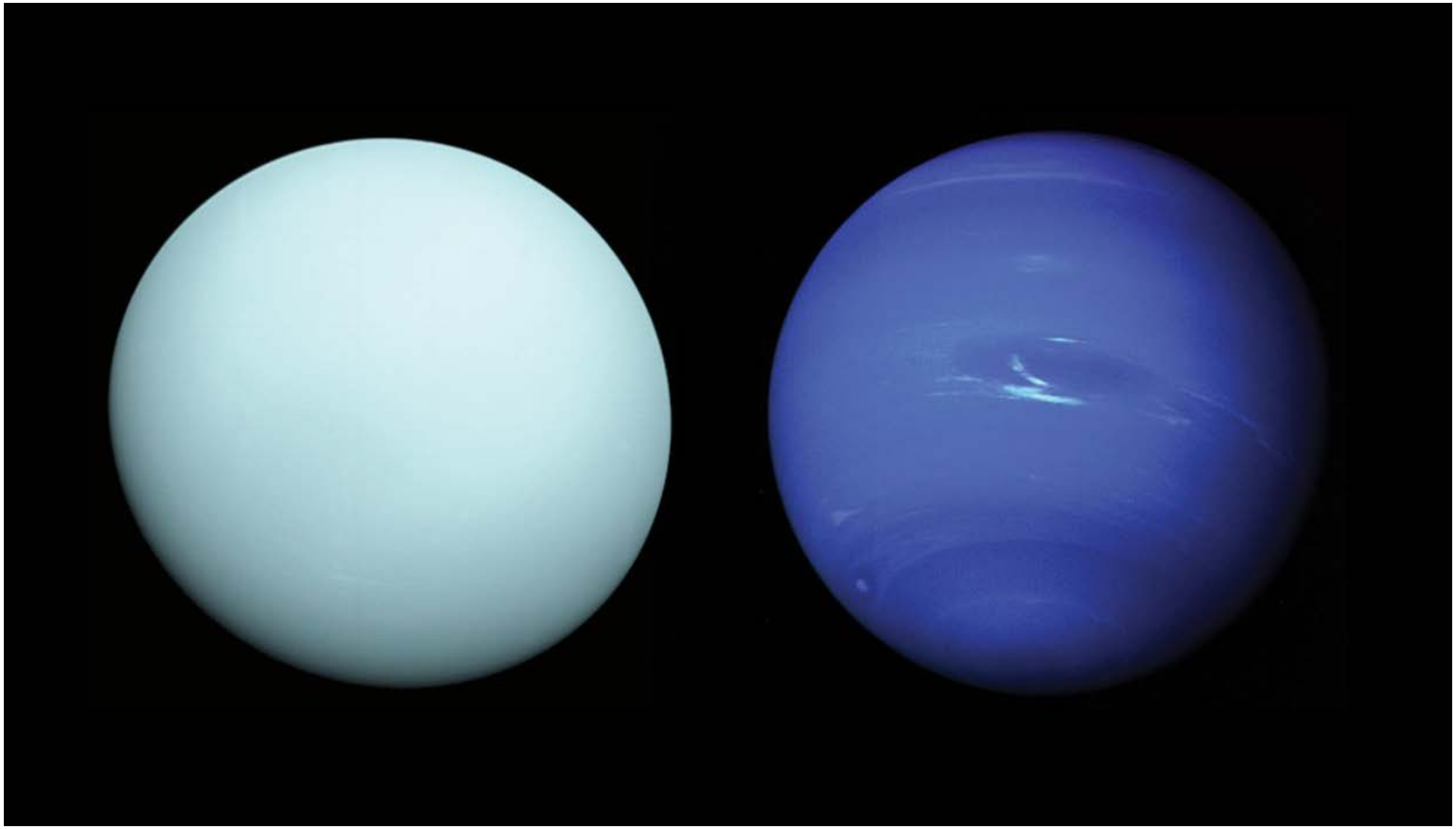


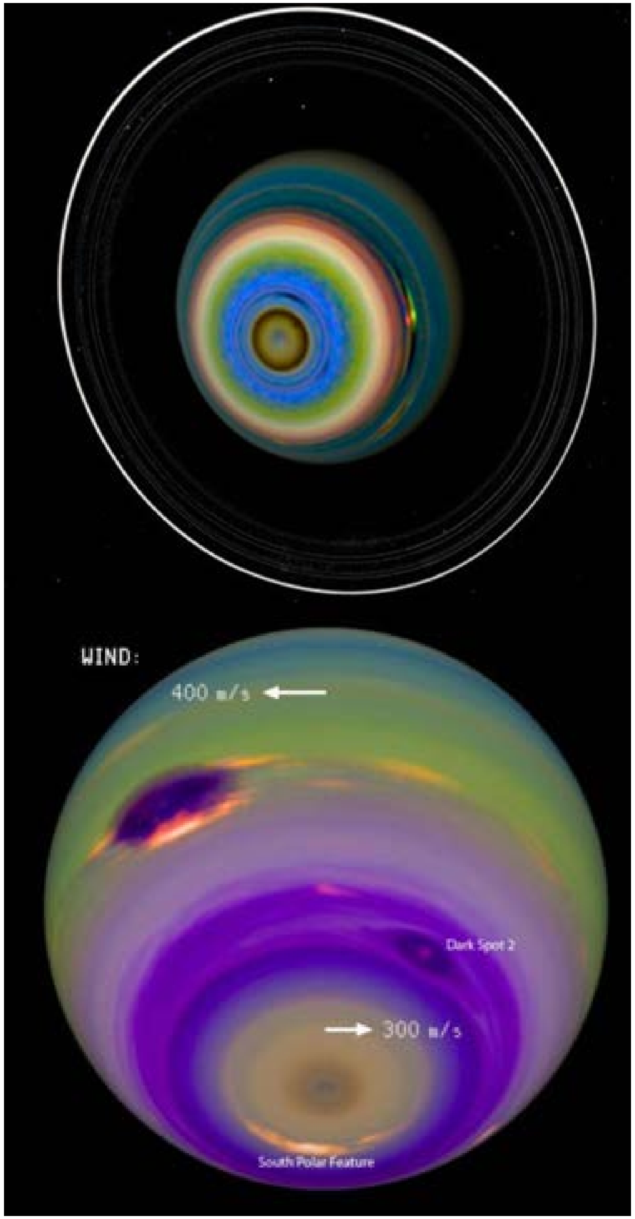
Outline

1) Uranus and Neptune atmospheres

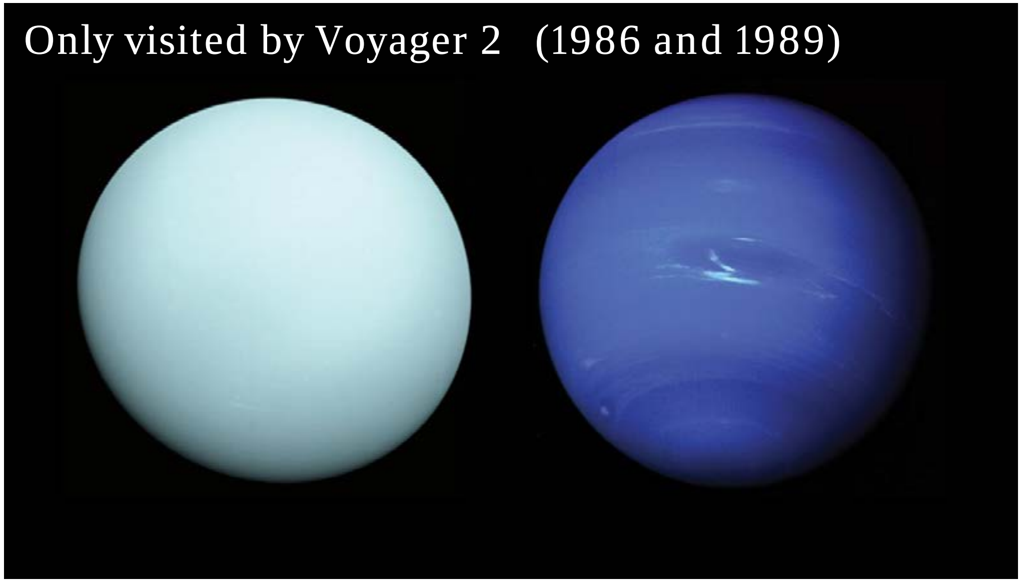
- General properties and visual aspect
- **Uniqueness of Uranus and Neptune**
- Winds, heat sources & seasons
- Clouds and weather layers
- Neptune dark vortices & numerical models
- Moist convection: Storms & inhibition of convection

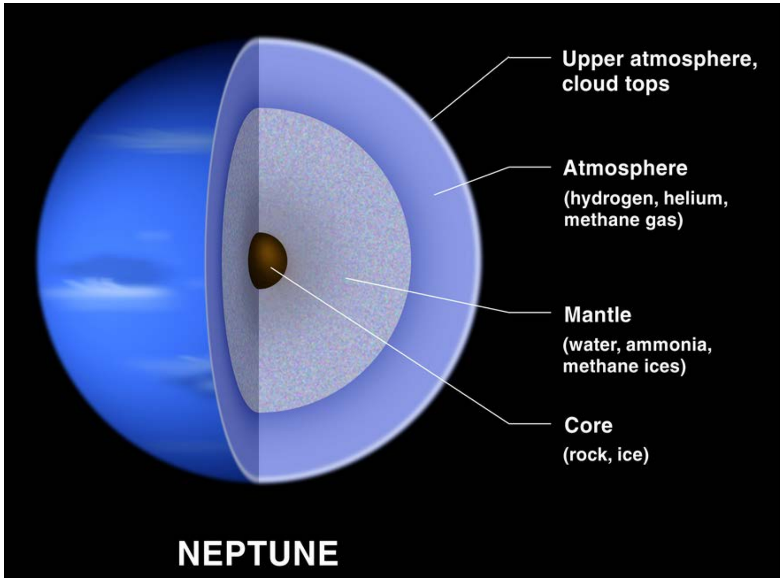
2) Astronomy observations from Spanish Telescopes & the future (JWST/ELT)

3) Space missions to the Icy giants (ESA Voyage 2050 call)



The Icy Giants: Uranus and Neptune





Masses: **14.5** & **17.1** Earth masses,
Radii: R = 25,559 km (4.01 R_{Earth}) & R = 24,766 km (3.88 R_{Earth})
Rotation period: 17h 14min 24s & 16h 6min 36 s → **Fast rotation**

“Geostrophic balance”
Pressure gradient equilibrated by Coriolis forces

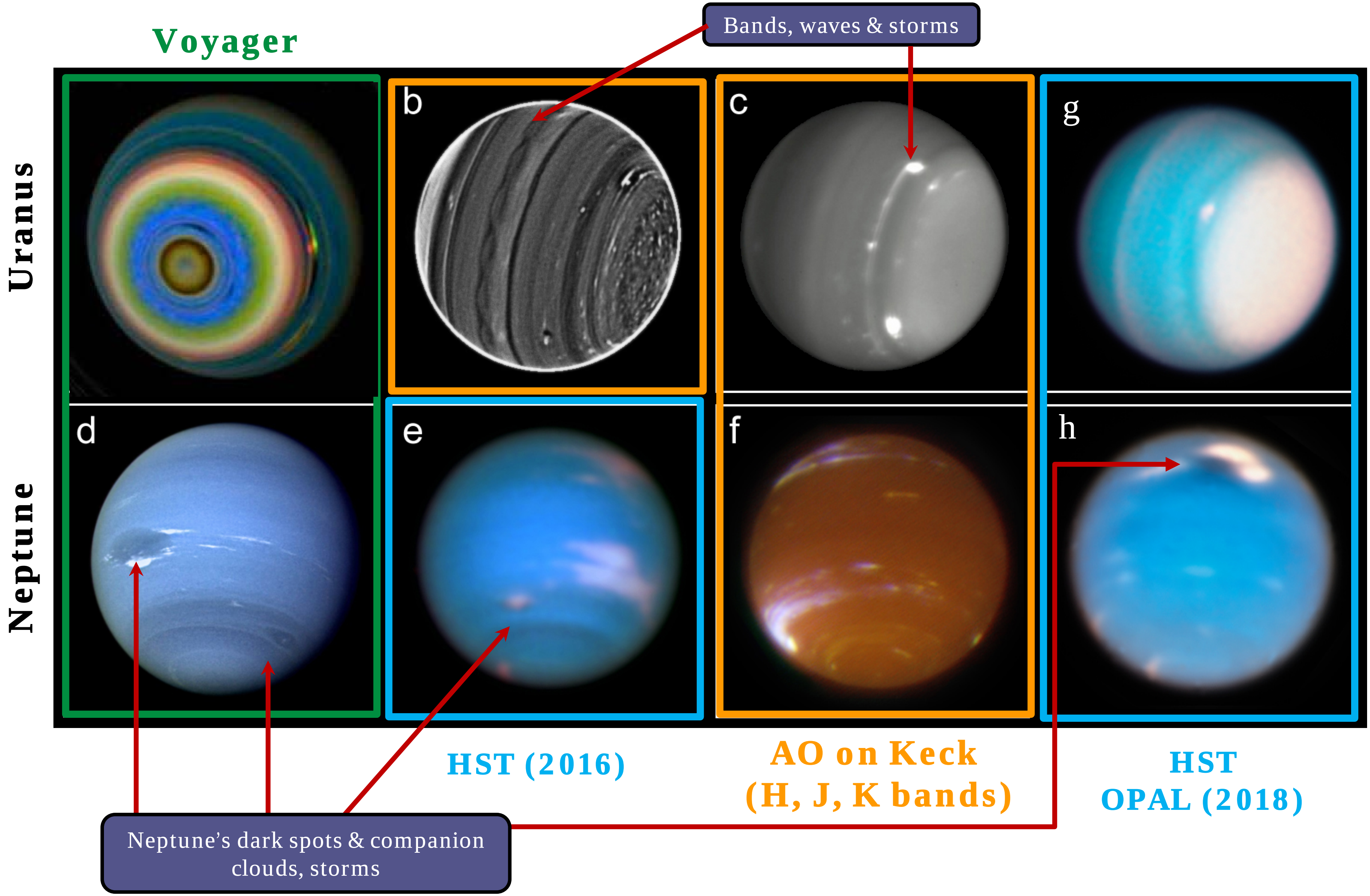
Zonal winds

Composition:
Mostly **ices** with **hydrogen/helium atmospheres (5,000 km)**
Higher abundance of He and much higher abundances of gases like methane compared to Jupiter and Saturn (**20-50x**)

Orbits:
Uranus a = 19.2 AU (**P = 84 years**), Axial tilt: 97.9°
Neptune a = 30.1 AU (**P = 165 years**), Axial tilt: 29.6°

Temperatures: 79 (Uranus) – 70 (Neptune) K at 1 bar

The visual aspect of Uranus and Neptune



Uniqueness of Uranus and Neptune

Uranus ane Neptune have unique meteorologies:

- ***Long Seasons***
- ***Extreme winds under low energy input (unrelated with visible bands) & vertical shears (Neptune) Very different jet systems to the Giant planets!***

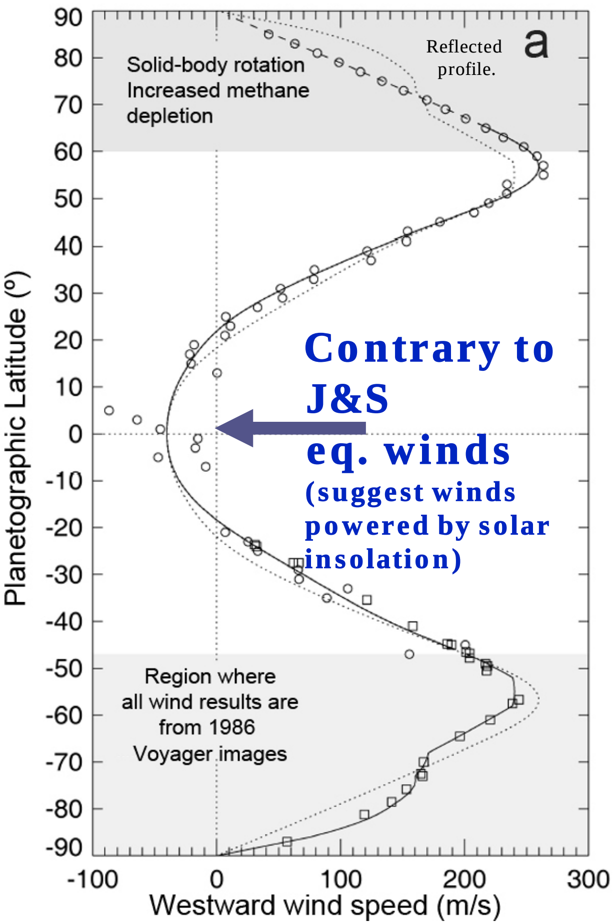
- ***Methane & H2S clouds***
- ***Storms (convective or not) in both planets***
- ***Dark Vortices (deep) & white companion clouds (shallow)***
- ***Atm. waves***

Atmospheres constrained by an unique property

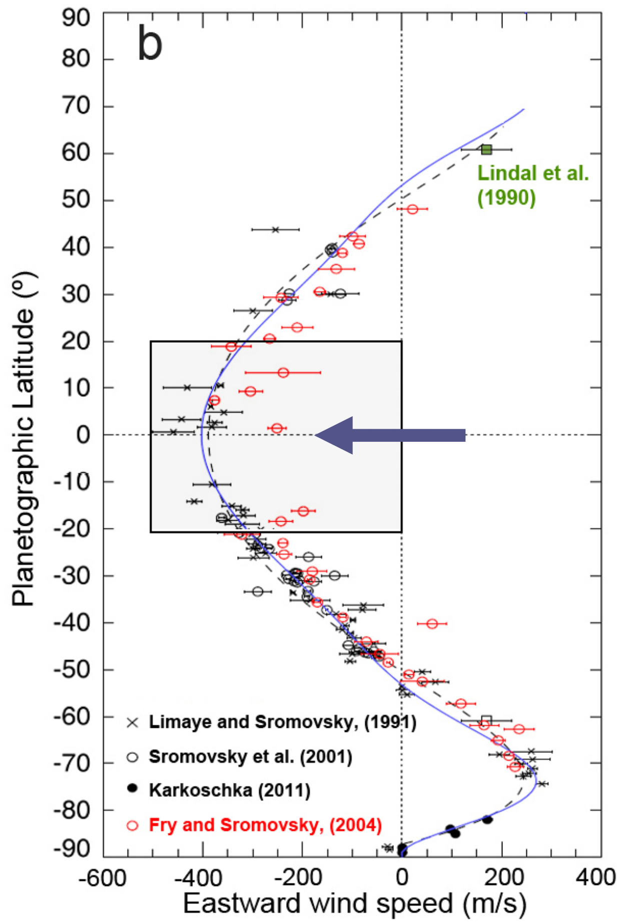
- ***20-50 higher abundances of “heavy” condensables compared to Jupiter & Saturn → Vertically extended “multi-layered deep weather layers” probably more complex than in Jupiter & Saturn***

Intense zonal winds, low irradiation

Figures a and bfrom *Sánchez-Lavega et al. in "Zonal jets" (2016). Figures based in data compiled by Larry Sromovsky*



Contrary to J&S eq. winds
(suggest winds powered by solar insolation)



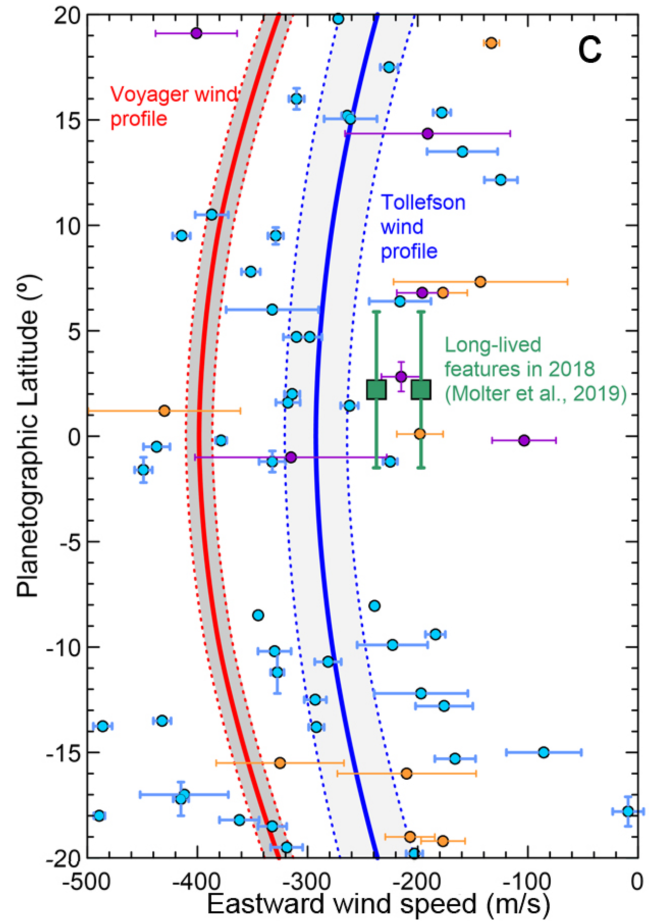


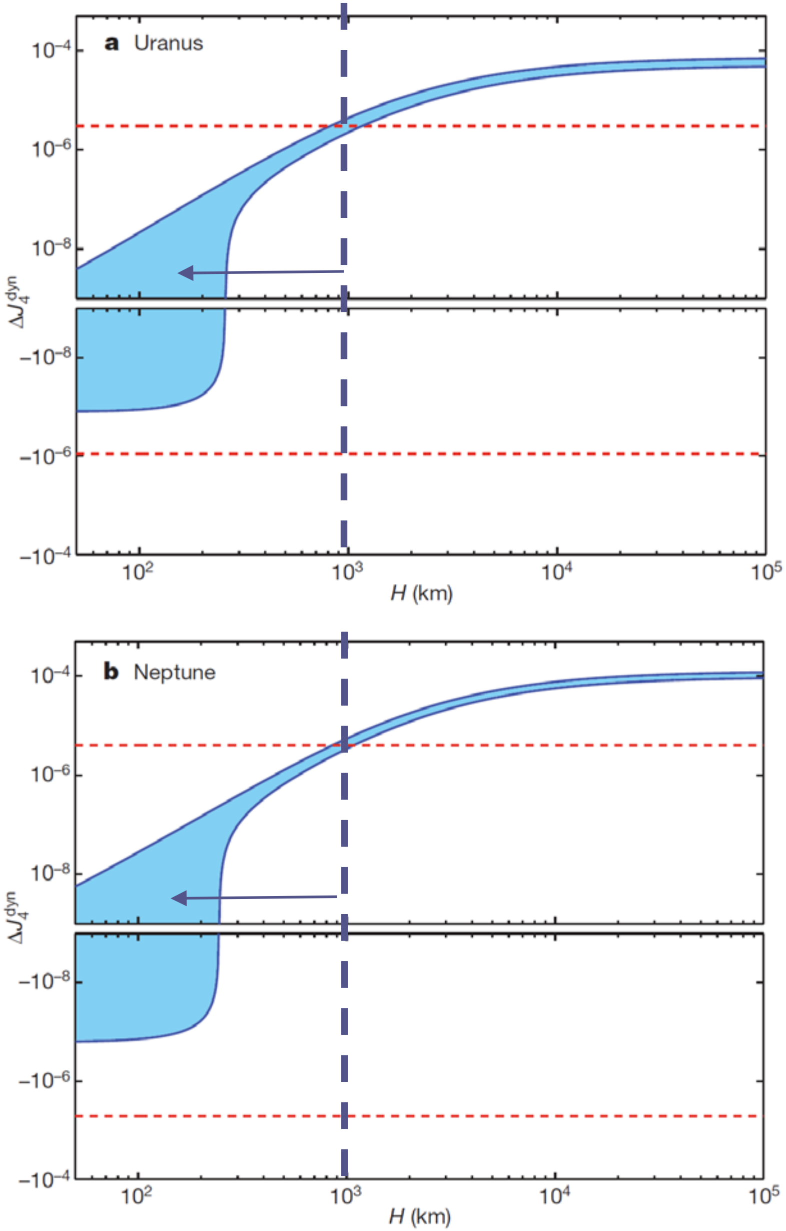
Figure c adapted from Molter et al. 2018

Solar constant at Uranus' orbit: ~3.5-3.9 W/m^2

Solar constant at Neptune's orbit: ~1.5 W/m^2

Wind shear combined with time variability

Intense zonal winds, low irradiation and shallow winds



Kaspi et al., Nature, 2013

$$V_G(r,\theta) = -\frac{GM}{r}\left\{1 - \sum_{n=2}^{\infty} J_n \left(\frac{R}{r}\right)^n P_n(\mu)\right\}$$

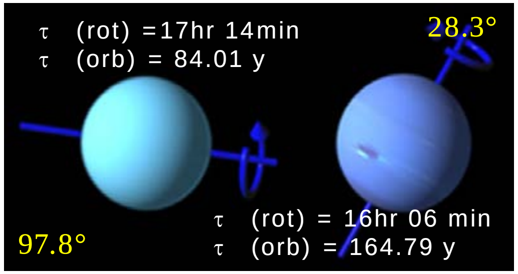
Figures show:
Predictions of the Gravitational harmonics (J_4) from interior models
and range of values constrained by measurements during the Voyager 2 flyby

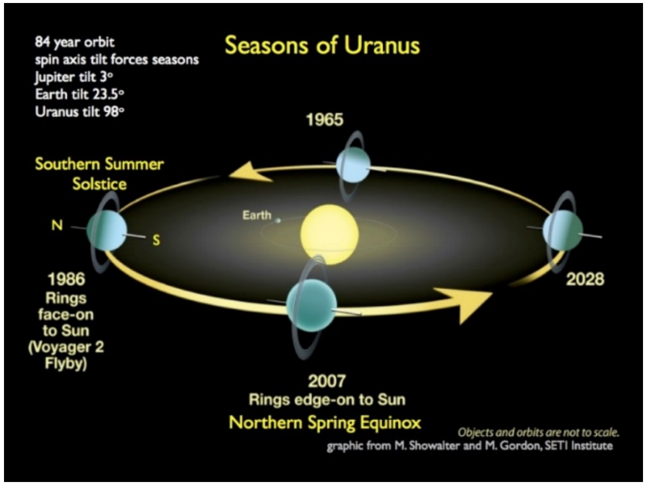
Depth less than 1,000 km (shallow winds, not column winds)

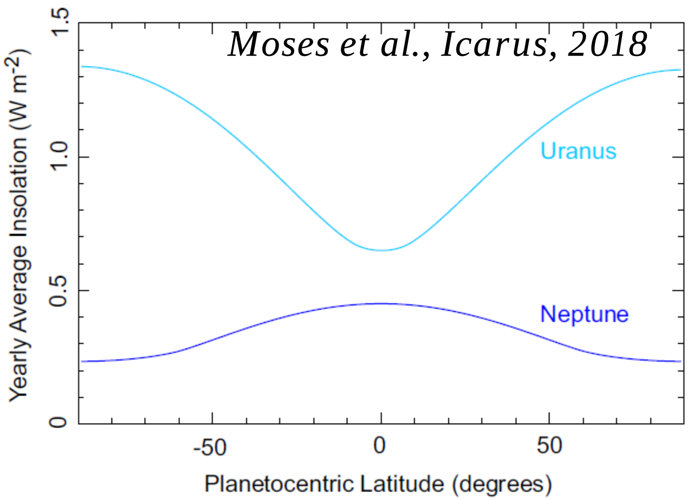
Less than 2,000 bar in Uranus
Less than 4,000 bar in Neptune

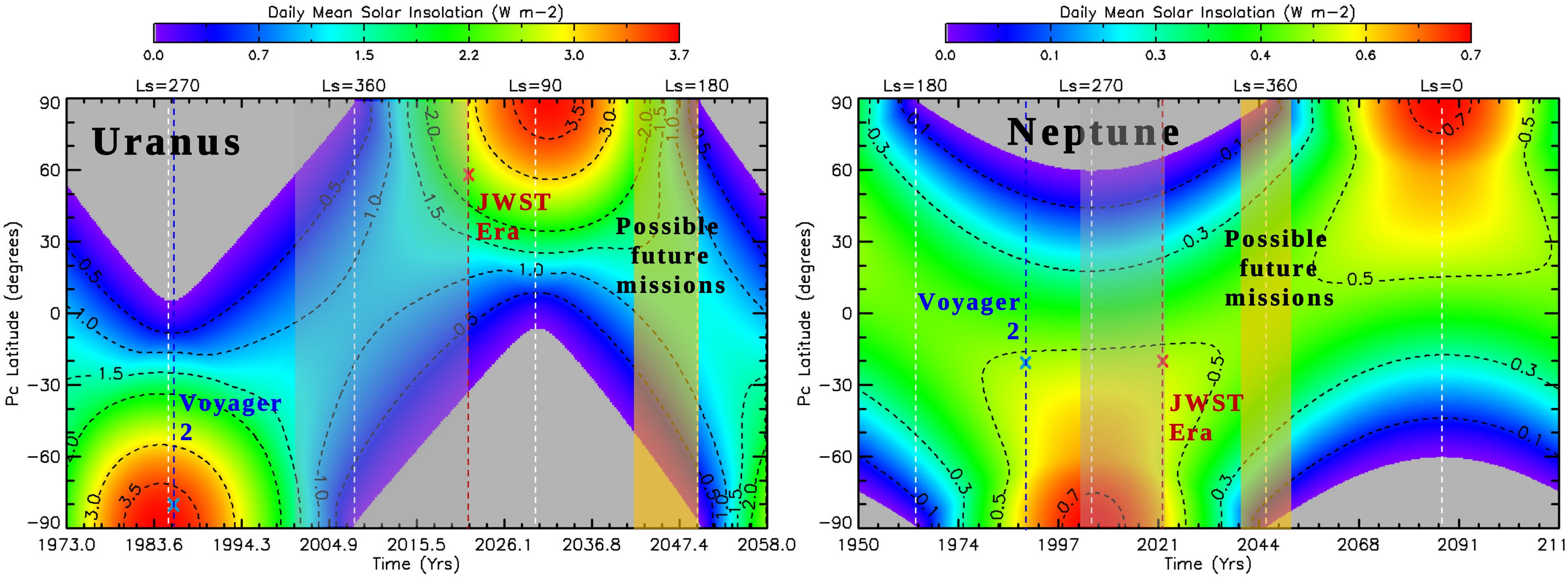
Only 20% of the hydrogen-helium envelope

Geostrophic atmospheres under strong seasonal effects



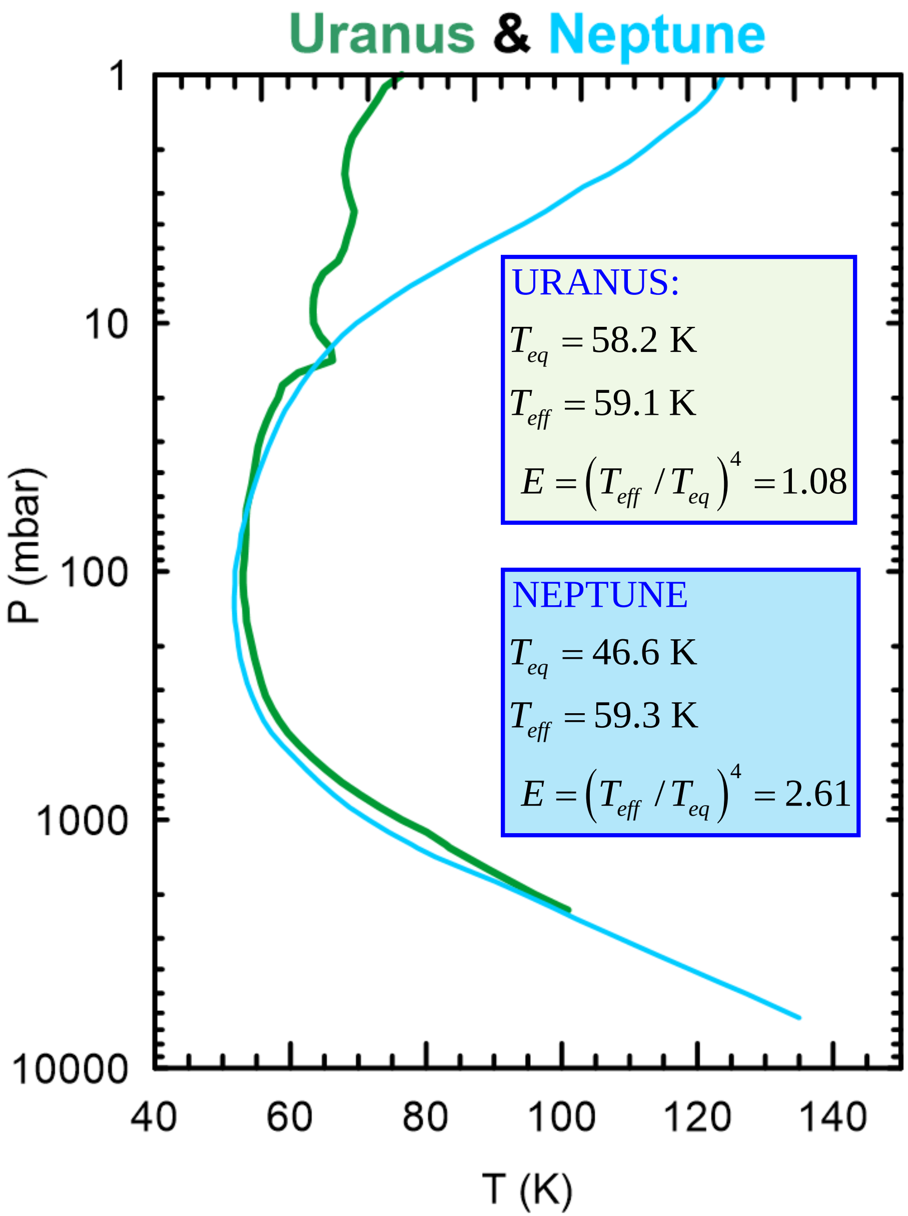


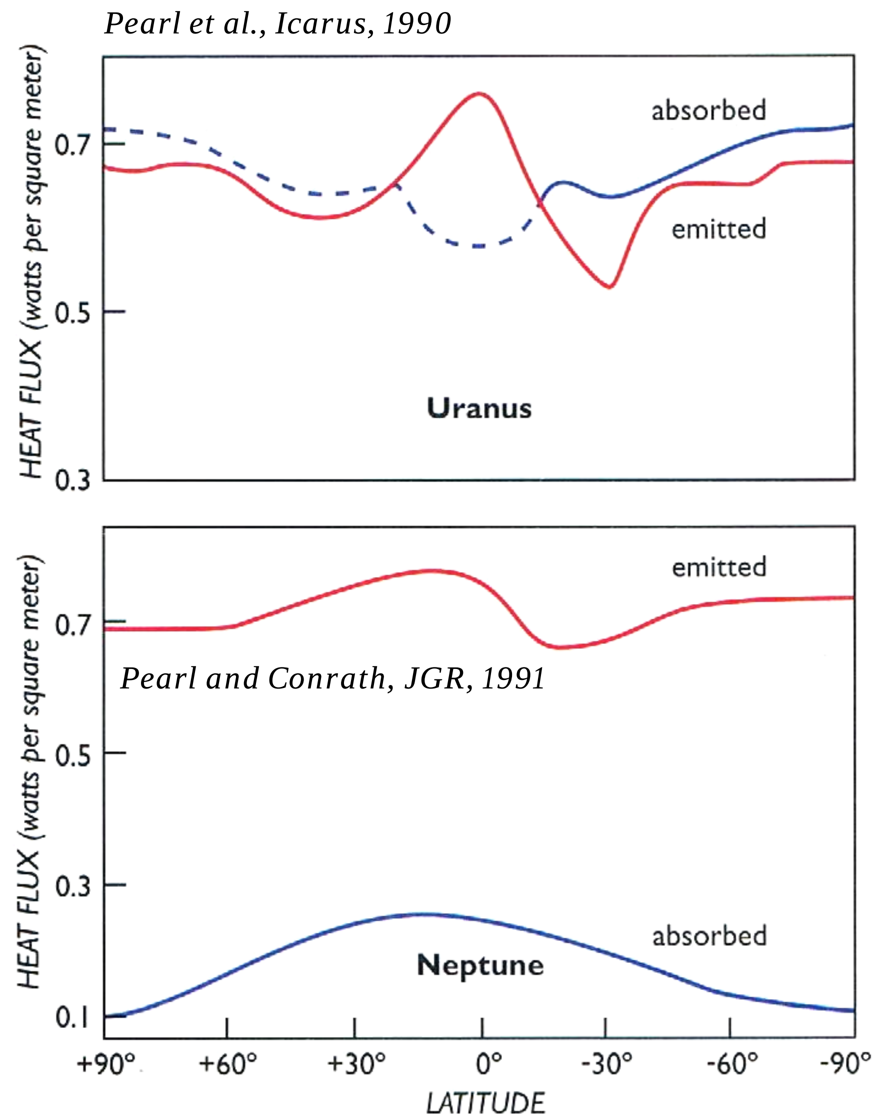




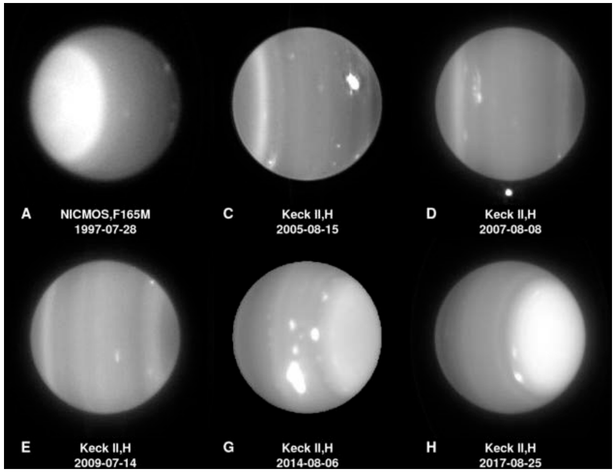
Hueso and Sánchez-Lavega (Space Sci. Rev. in prep.)

+ Internal heat source (latitudinal dependent) in Neptune

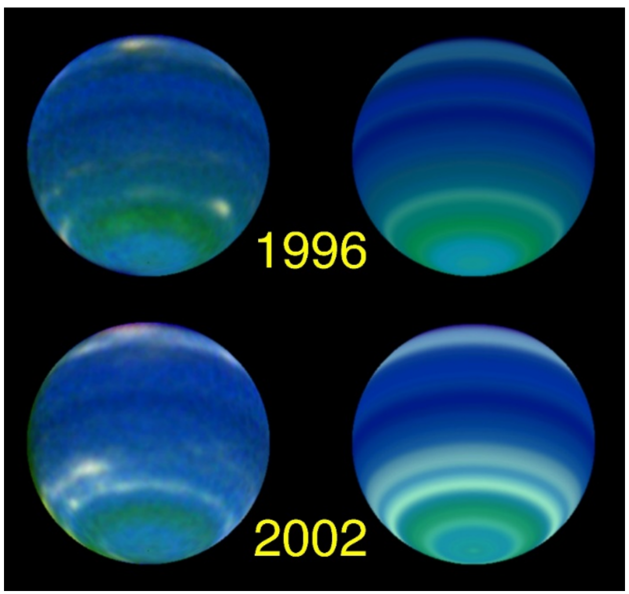




Global albedo variability: Seasonal effects & more

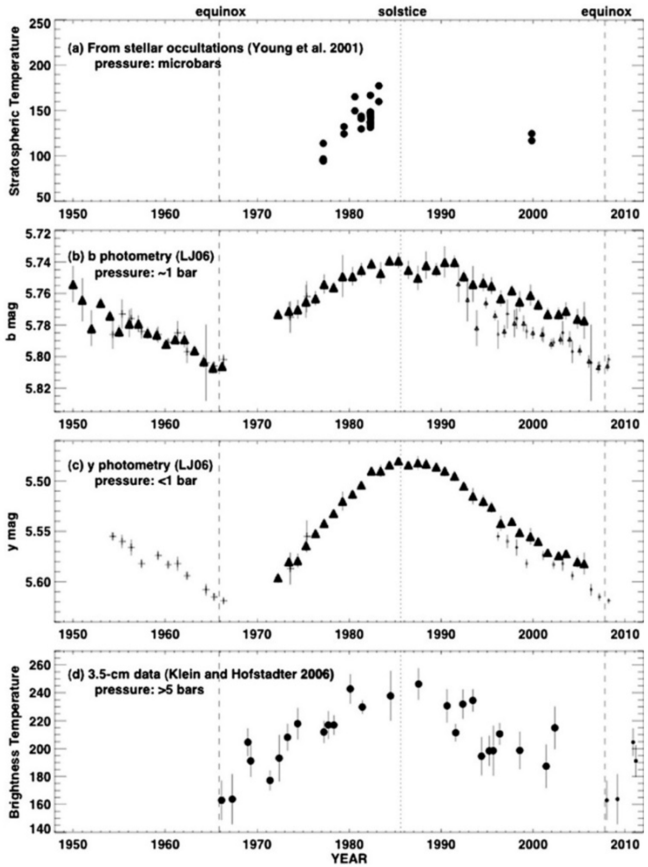


Sromovsky et al., Icarus, 2019

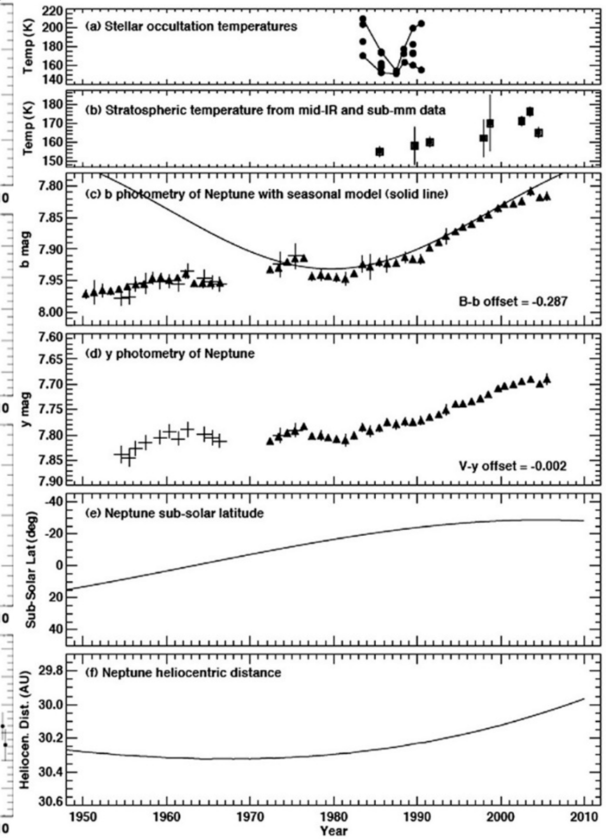


Sromovsky et al., Icarus, 2003

Uranus



Neptune

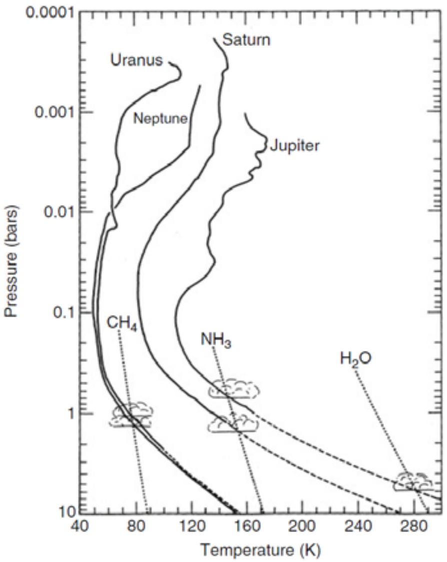


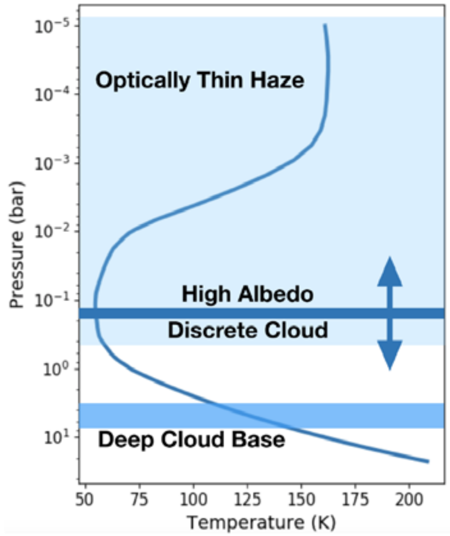
Lockwood, G.W., Jerzykewicz, Icarus, 2006
Hammel and Lockwood, Icarus, 2007

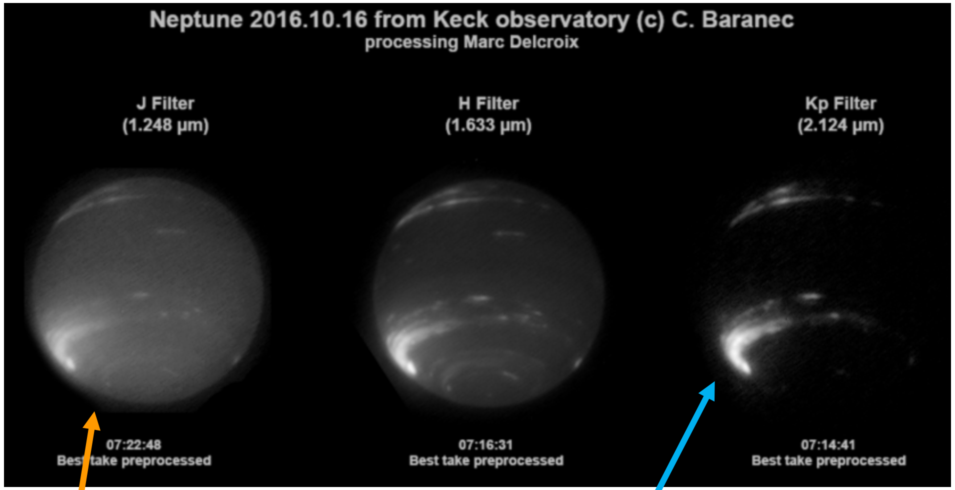
Uranus variability roughly matches the seasonal cycle.

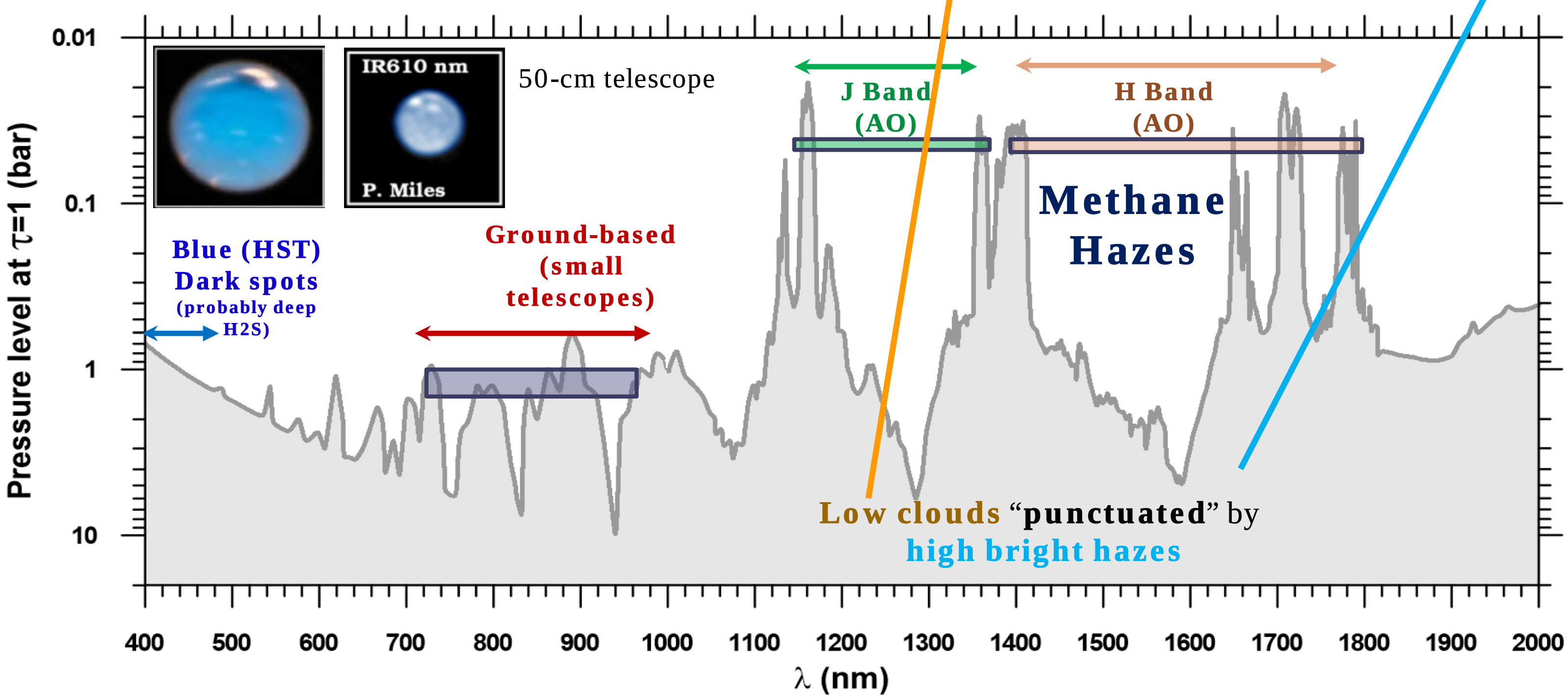
Neptune variability does not match the seasonal cycle and influences of GCR have been suggested.

Thermal structure → Vertical structure → Observed levels



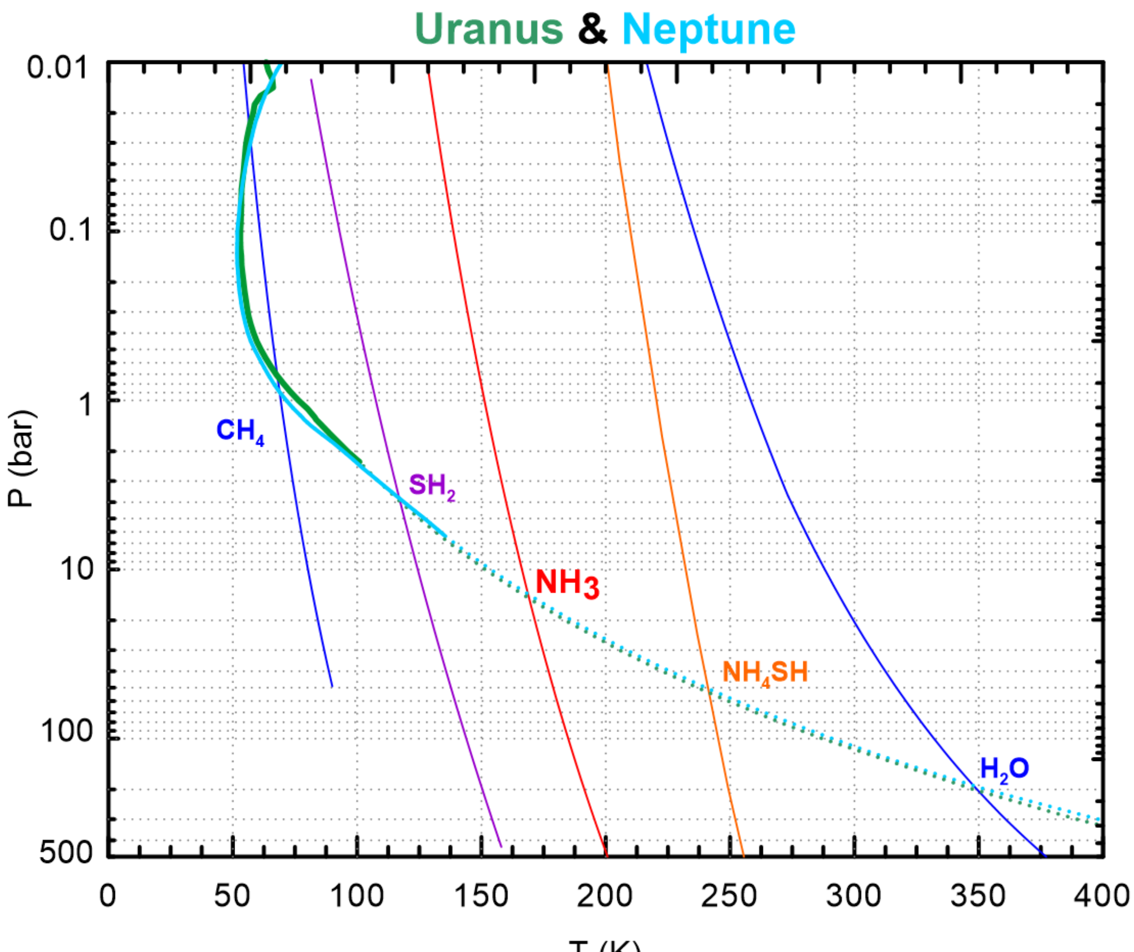






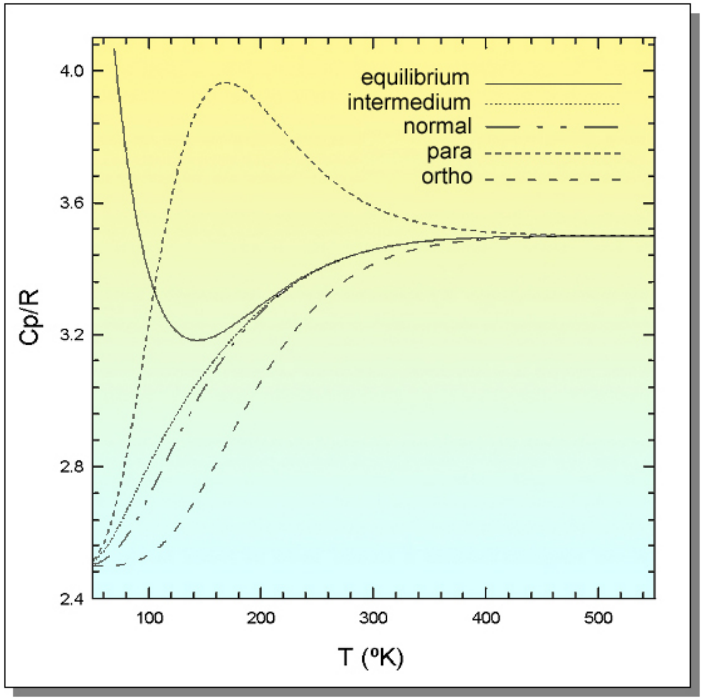
Hueso et al. (2017)
with data from
Simon et al. (2016)
Irwin et al. (2016)

Down to the bottom of the "weather layer"



$$\frac{dT}{T} = \frac{R^* / \mu}{C_P} \frac{dP}{P}$$

Difficulties include Cp(T),
heat "stored" in the deep "normal" H2



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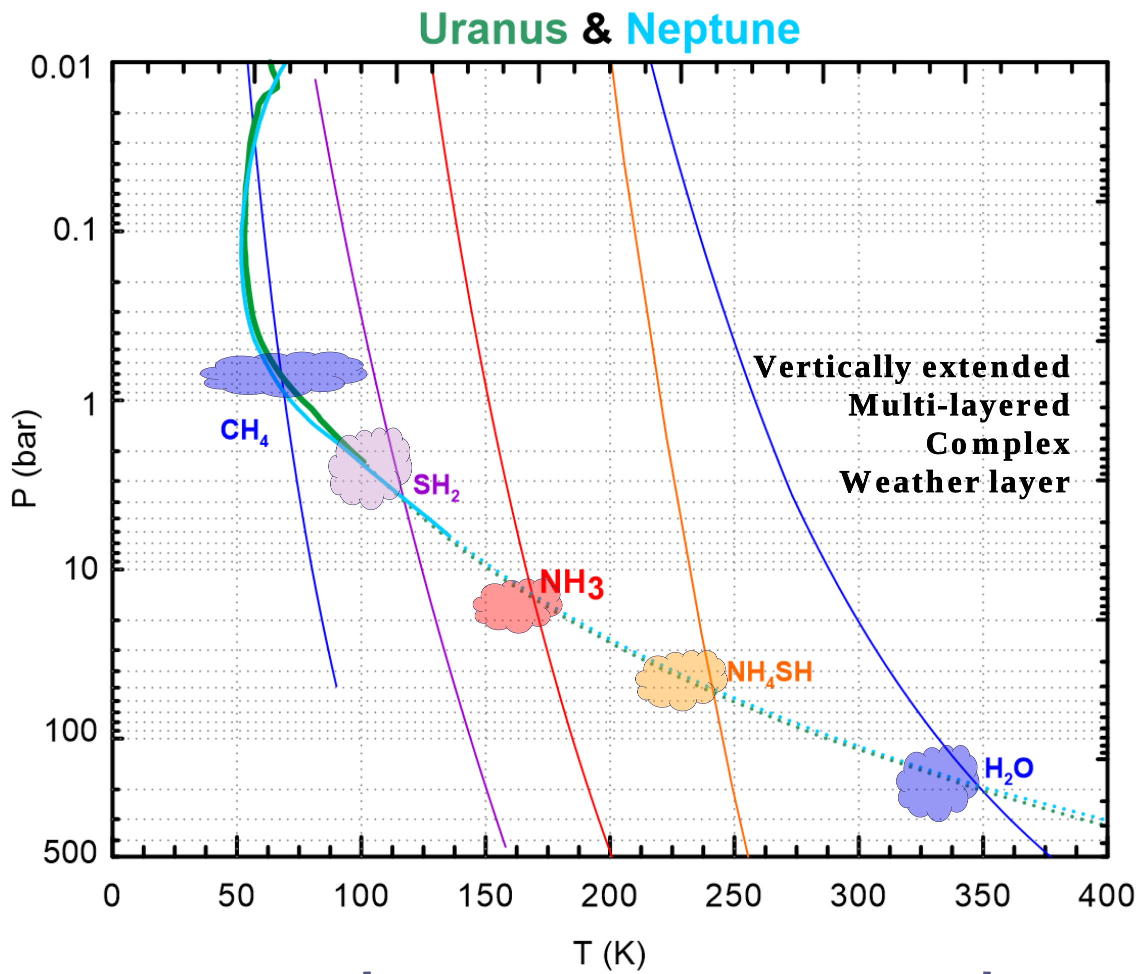

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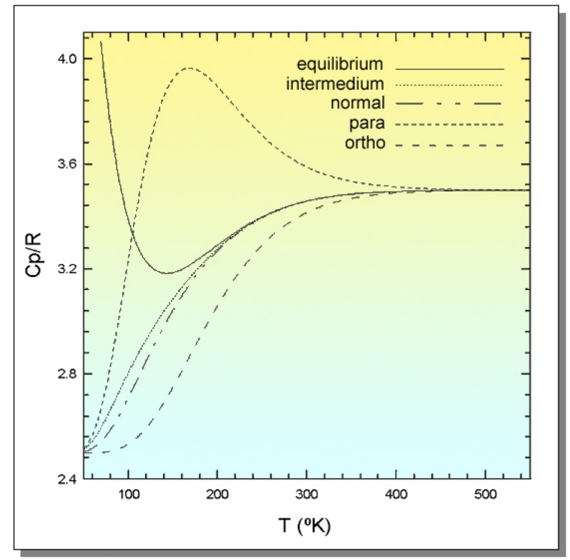


$$\boxed{\frac{dT}{T} = \frac{R^*/\mu}{C_P}\frac{dP}{P}}$$

$$\Gamma_m = \frac{d\ln T}{d\ln P} = \frac{1 + \sum_i \eta_i \beta_i}{\frac{\hat{c}_p}{R} + \frac{\sum_i \eta_i \beta_i^2 + \left(\sum_i \eta_i \beta_i\right)^2}{1 + \sum_i \eta_i}}, \qquad \beta_i = L_i/(RT)$$

Additional Physics

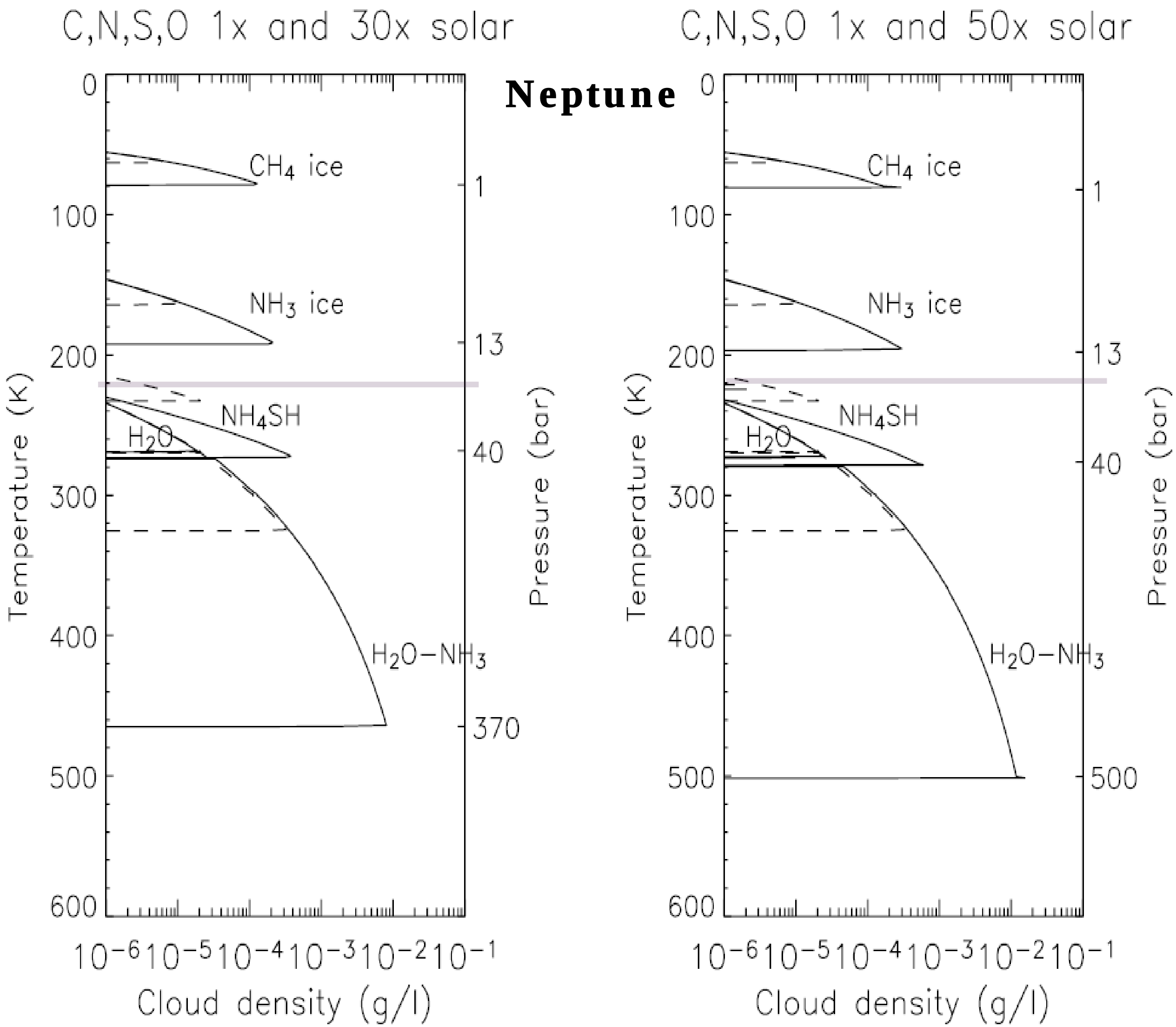
Latent heat (wet adiabat or pseudoadiabats)

+ SH2 and NH3 molecules locked in the NH4SH cloud

U&N:
+ non ideal gas equation at high pressures
+ stabilization effects of the vertical gradient of molecular weight

First thermochemical models of clouds in Uranus & Neptune

Weidenschilling and Lewis seminal paper in 1973



NH4SH locks the minor constituent: NH3 or H2S (at the time of these models H2S was supposed to be fully locked in this ammonia hydrosulfide cloud, this is now known to be wrong)

NH3 disolved in the H2O water cloud

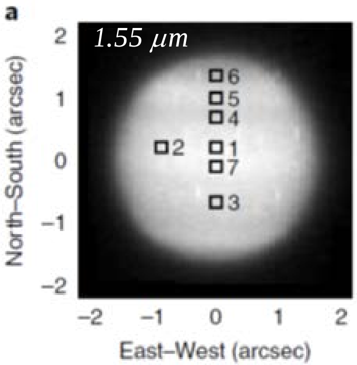
Modern reevaluations:

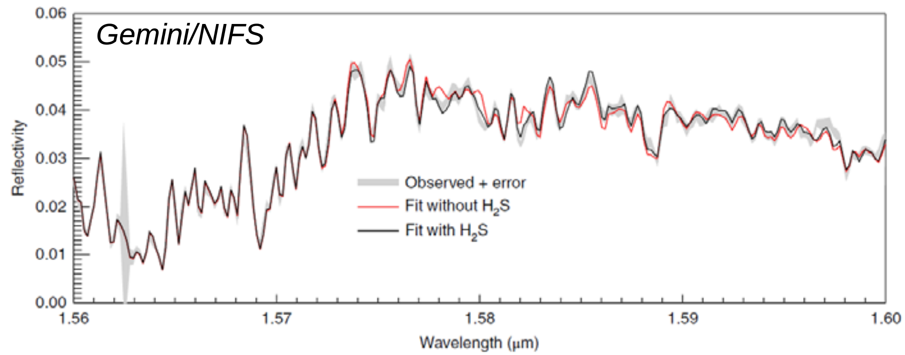
Atreya and Wong, 2005

Importance of non-ideal gas law lowering deep clouds 10s of bars

Note the water cloud condensation level at 300-500 bar

H2S clouds (spectroscopic evidence on Uranus and Neptune)



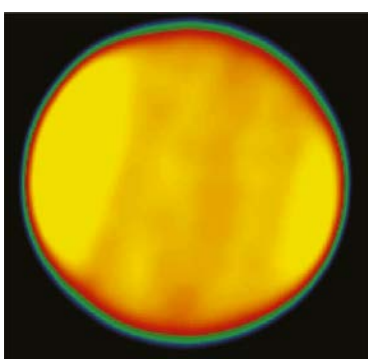


Uranus: *Irwin et al., Nat. Astron. 2018*
Neptune: *Irwin et al., Icarus, 2019*

At solar abundances (or with same enrichments) N/S ≈ 4.6 –> All H_2S should be stored in the the NH_4SH cloud and no H2S should be detected
S/N > 1 in Uranus and Neptune requiring N being sequestered in the interior or different formation scenarios.

Radio observations pointed to this result in the late 80s

At radio wavelengths the main absorbing gas is NH3 but both Uranus and Neptune are too bright for NH3 solar composition

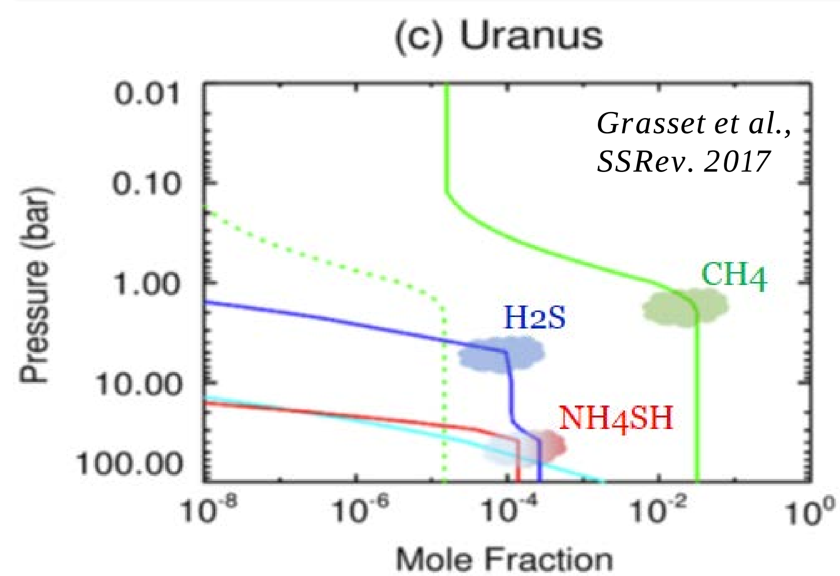


Uranus at 1.3 cm (VLA)

de Pater et al., Icarus, 1991
de Pater, Nat. Astron. 2018
“Selective enrichment of volatiles”

Abundances of H2S varying at different latitudes. Similar for CH4 in both planets

No ammonia cloud expected in Uranus and Neptune
Deep “ubiquitous” H2S cloud



Thermal & humidity winds

Thermal winds

$$\frac{\partial u_g}{\partial p} = \frac{1}{f}\frac{\partial}{\partial y}\left(\frac{1}{\rho}\right)$$

$$\frac{\partial u_g}{\partial p} = \frac{R_d}{fp}\frac{\partial T_v}{\partial y}$$

The vertical structure of geostrophic winds depend on the meridional gradient of density "Thermal wind"

Geostrophic winds modified by gradients in volatiles abundance

Sun, Stoker & Schubert, Icarus, 1991

$$\frac{\partial u_g}{\partial p} \cong \frac{R_d}{fp}\left(\frac{\partial T}{\partial y} + CT\frac{\partial q}{\partial y}\right)$$

$C = (1 - \varepsilon)/\varepsilon$

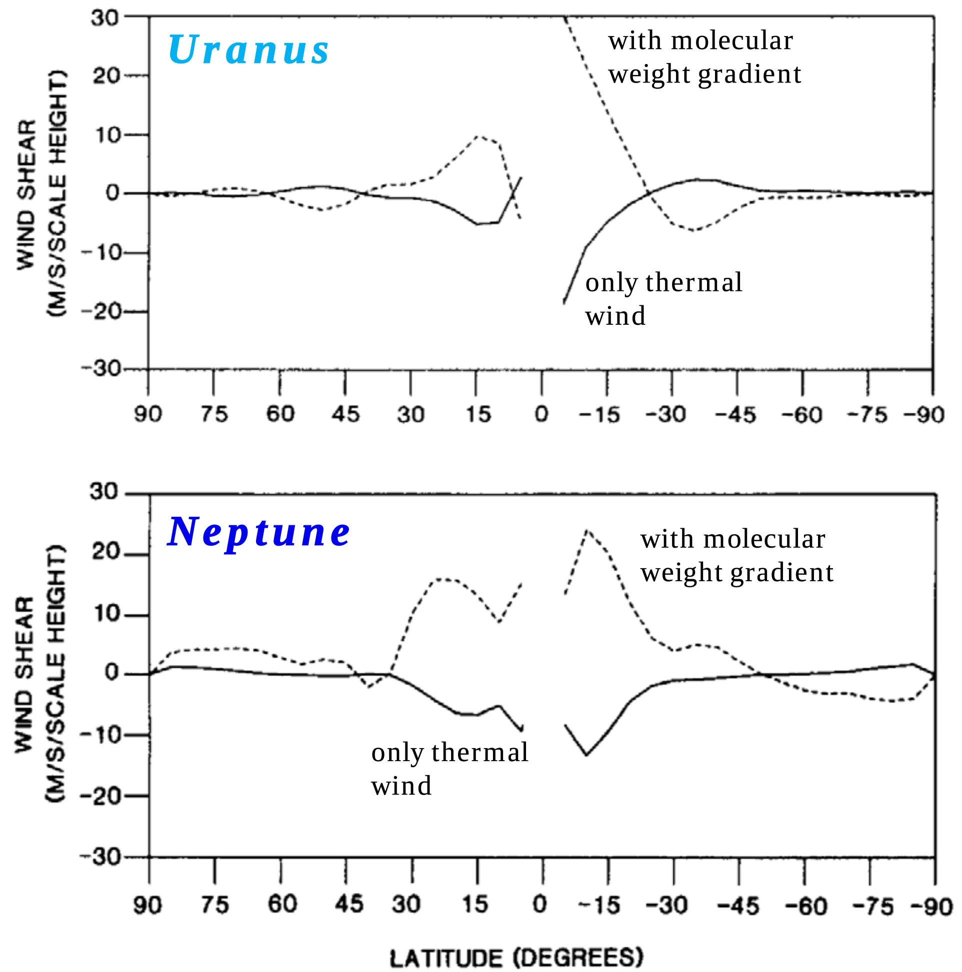
ε =ratio of molecular weights

Thermal wind component

Humidity wind component

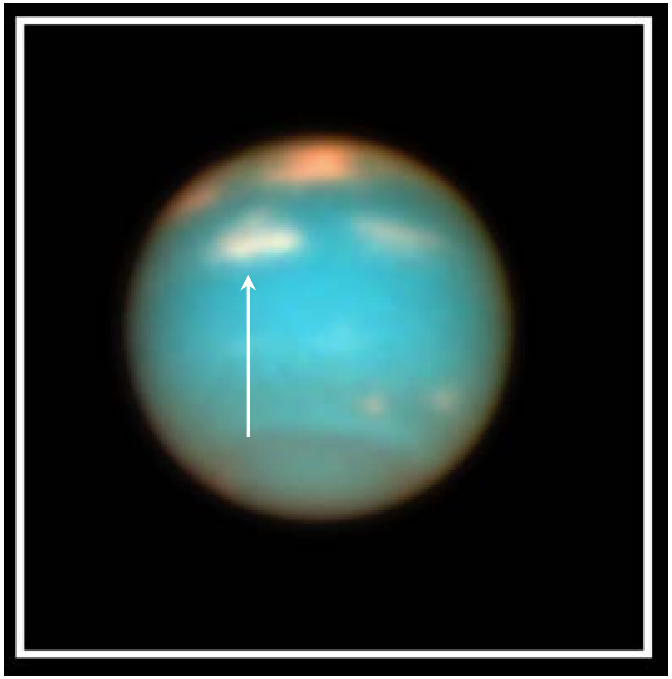
Unique to Uranus and Neptune

Estimated effects on the vertical wind shear at the time of the Voyagers

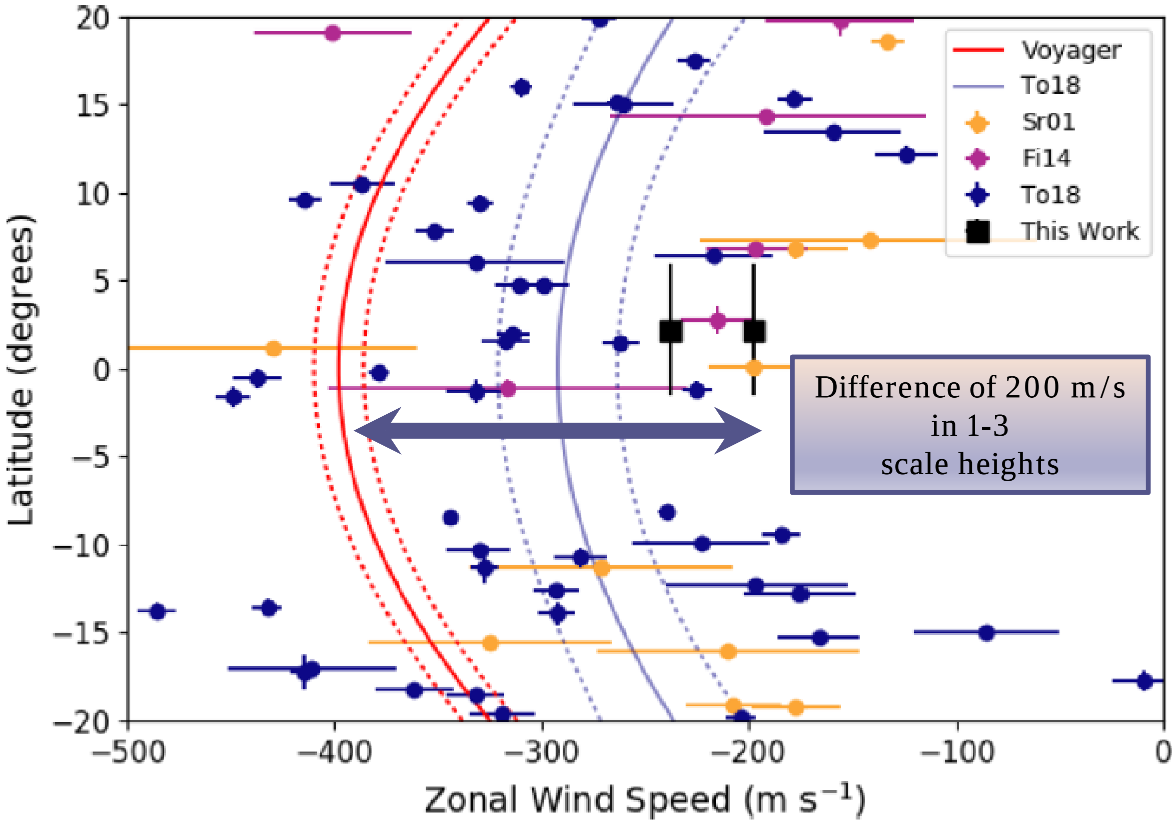


Vertical shears are specially strong at Neptune's Equator

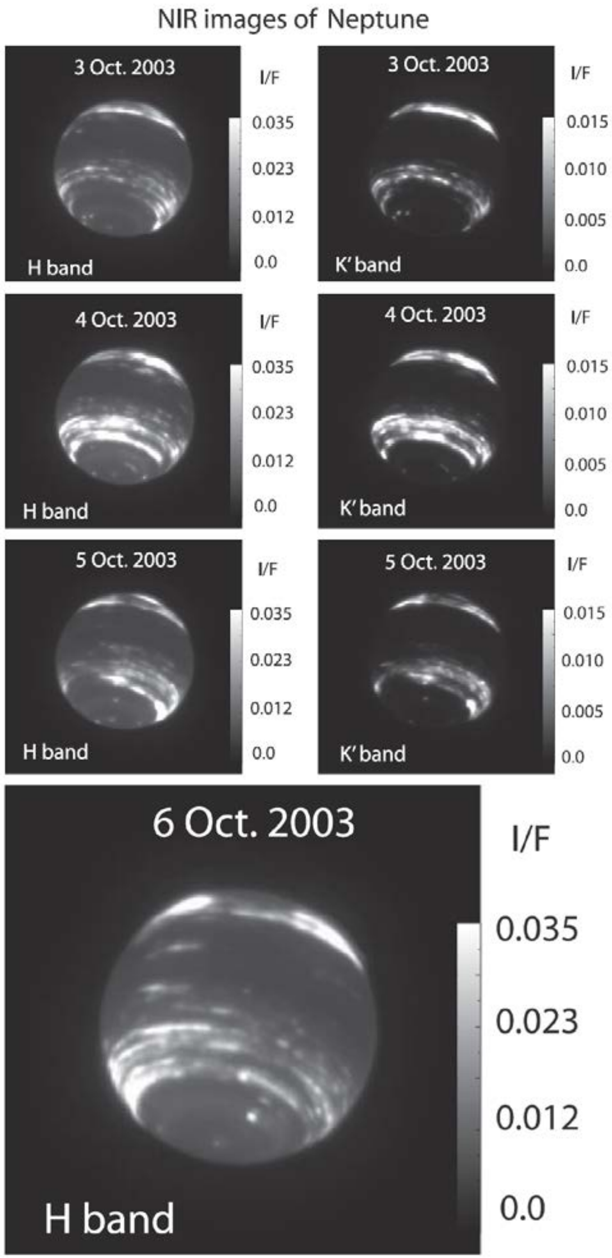
In agreement with "humidity winds"
But at latitudes where geostrophic equilibrium is not valid anymore

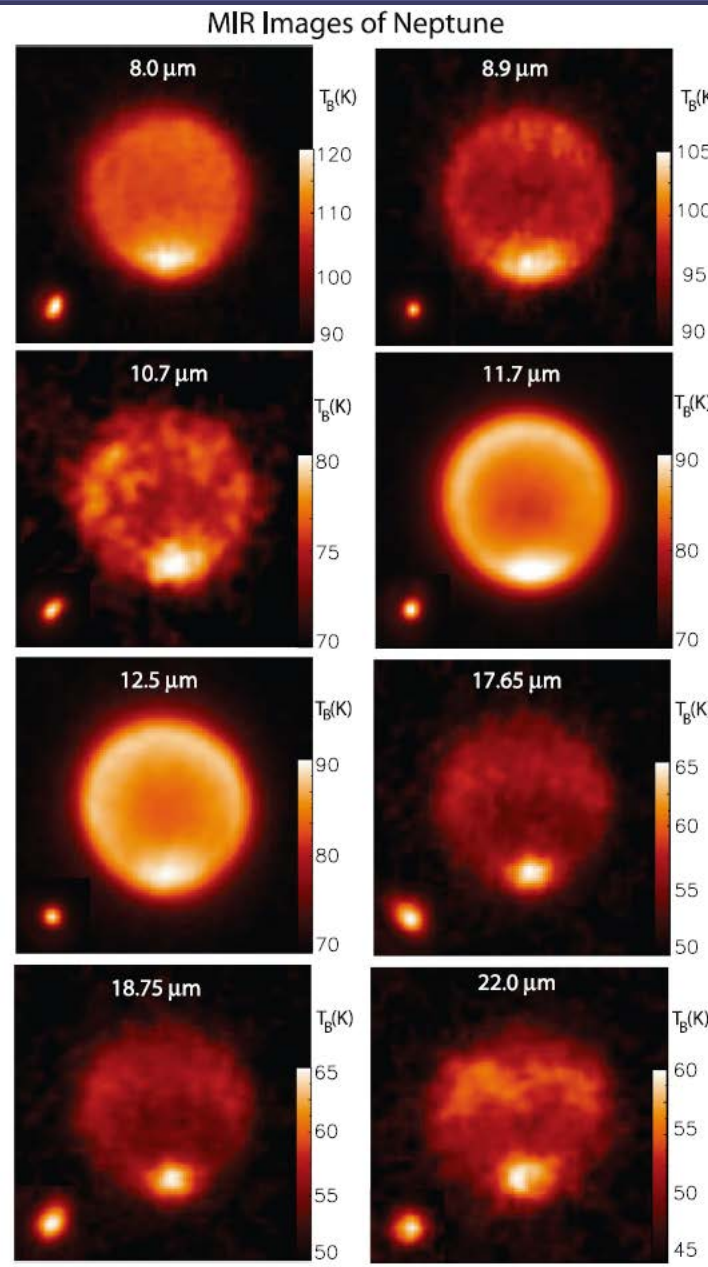


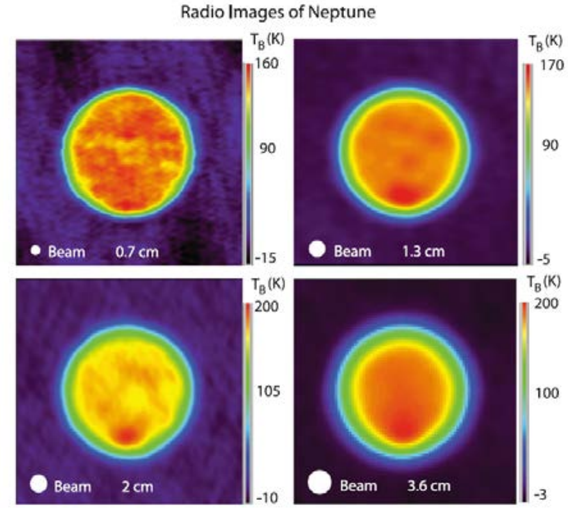
Molter et al. Icarus (2019)



Towards understanding the General Circulation



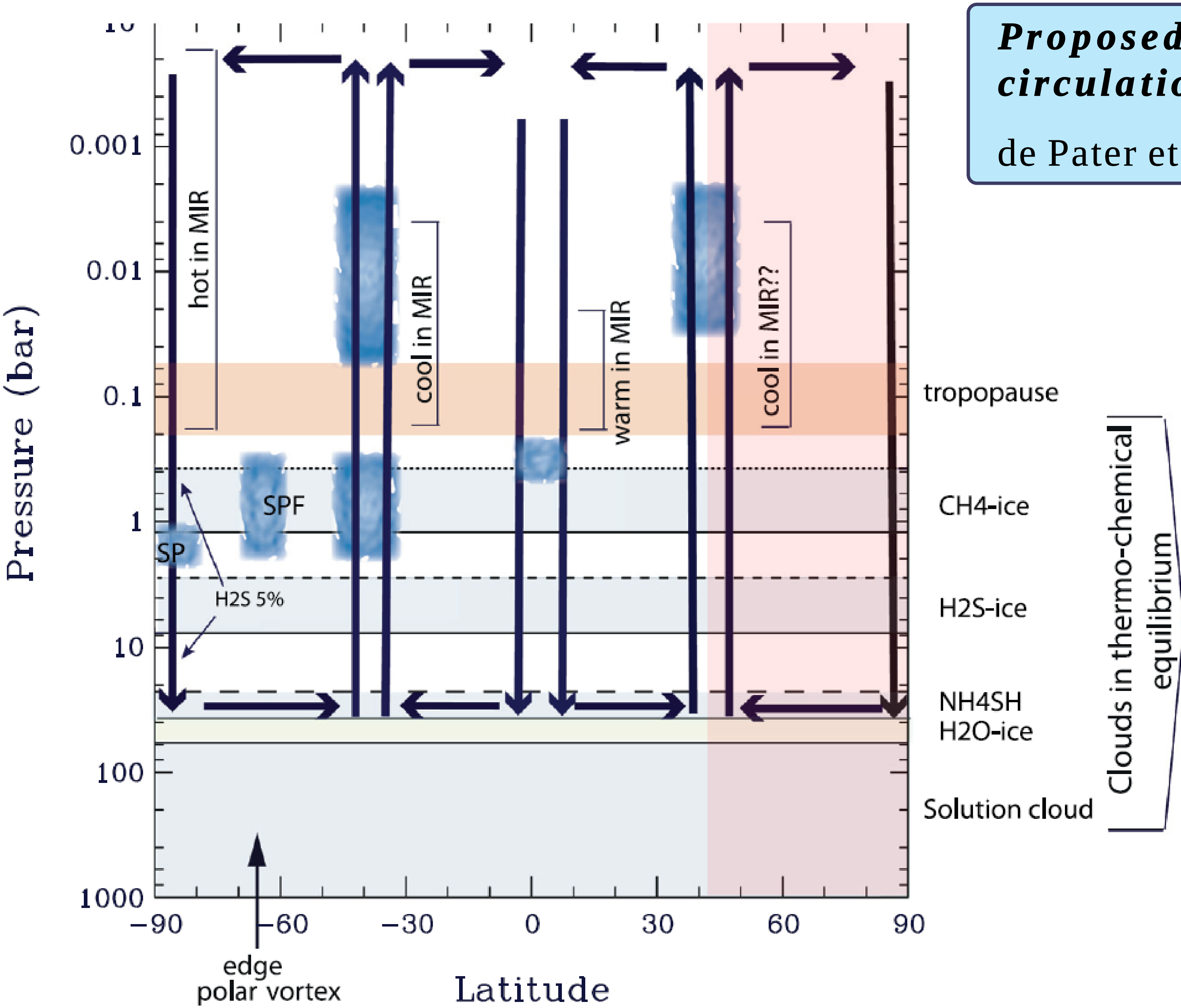




Nearly simultaneous observations of Neptune in the **NIR**, **MIR** and **Radio (cm)** wavelength ranges

+ Radiative transfer analysis of the observations in each wavelength range

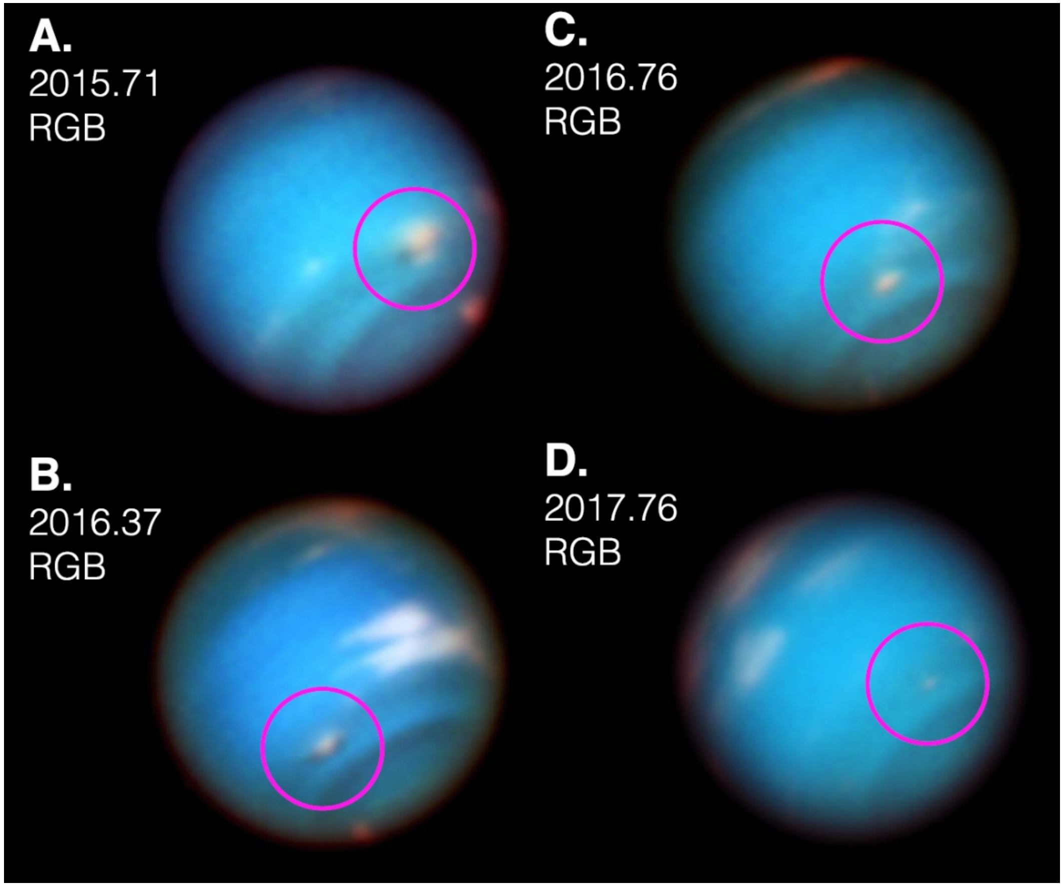
de Pater et al. Icarus, 2014



Proposed global circulation in Neptune

de Pater et al. Icarus, 2014

Double Hadley-cell with updrafts in the mid-latitudes



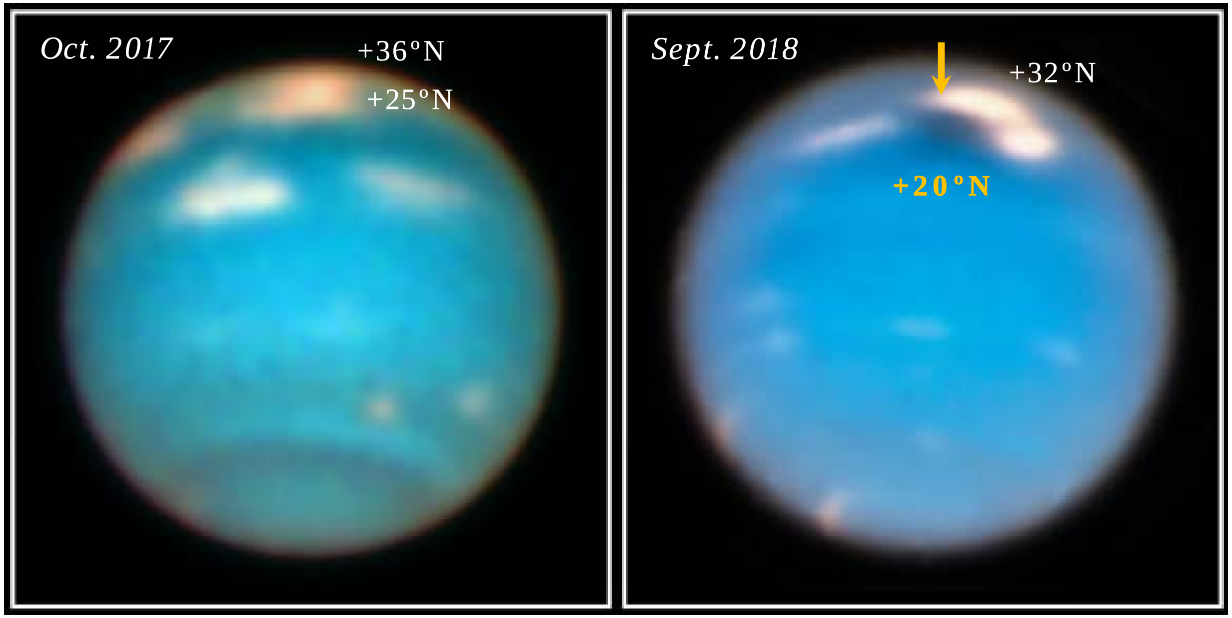
Dark spots, Bright companion clouds and bands evolving over years

Dark spots are an observational door to lower atmospheric levels (possibly the H2S cloud)

Wong et al., AJ, 2018

Name	Discovery	Demise	Latitude*	Size Lon.×Lat.	Meridional drift	References
GDS	1989	1990	−20°	38°× 15°	+0.11°/day equatorward	Smith et al. (1989)
DS2	1989	<1994	−55°	39°× 6°	±2.4° oscillation	Sromovsky et al. (1993)
NDS-1994	1994	1998–2000	+32°	35°× 10°	0°/day	Hammel et al. (1995); Sromovsky et al. (2001)
NDS-1996	1996	1997–1998	+15°	22°× 12°	0°/day	Sromovsky et al. (2001)
SDS-2015	2015	>2017	−49°	15°× 5°	−2.5°/year poleward	Wong et al. (2016)

A 6th Dark-spot in Neptune in 2018 (+20°)

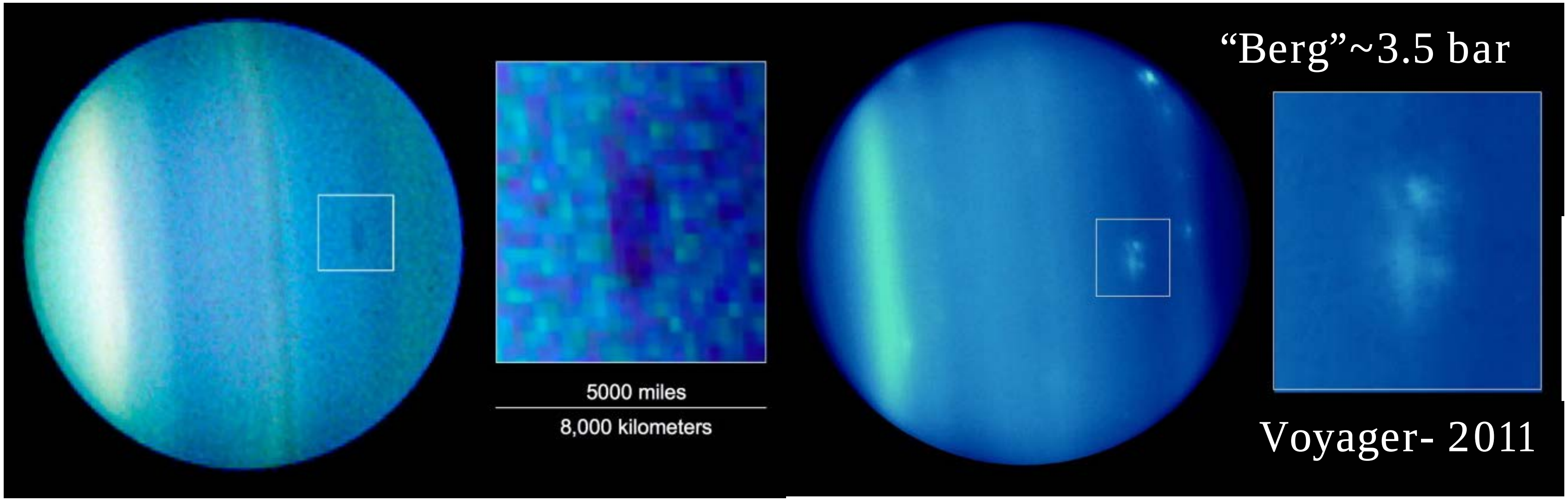


Changing views of the North-tropical band & changing seasons

Sub-Earth and Sub-Sun latitude on Saturn moved 2° northwards

HST/OPAL observations

A single dark spot in Uranus (2006) & a long-lived oscilating feature "Berg"

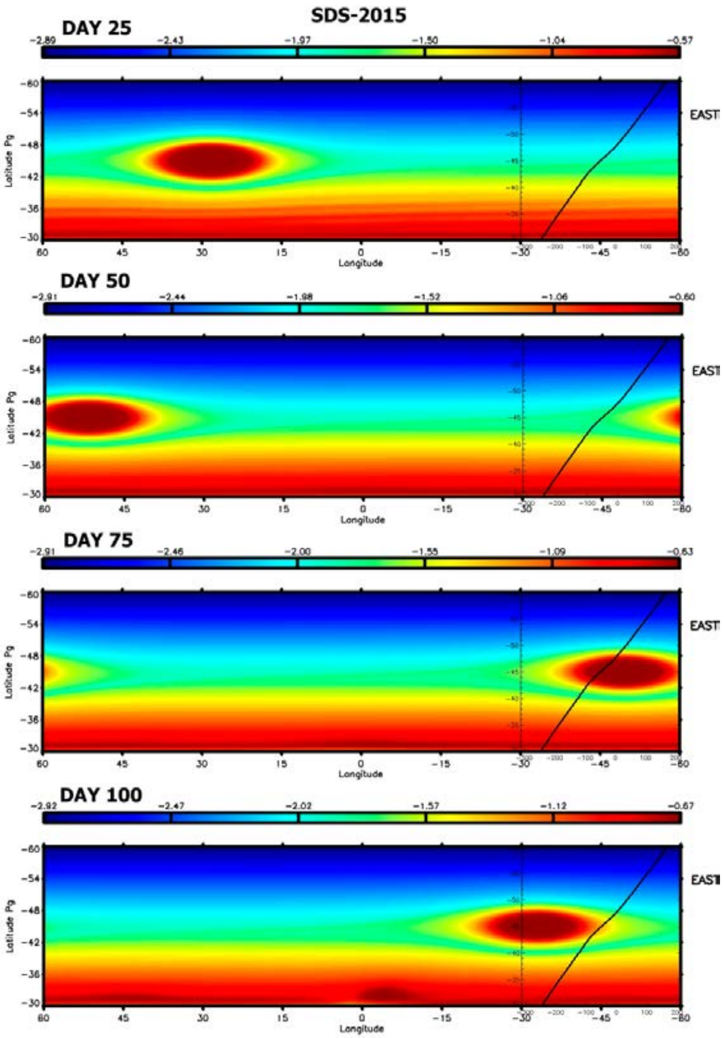


Hammel et al., Icarus, (2009)

de Pater et al., Icarus, (2011)

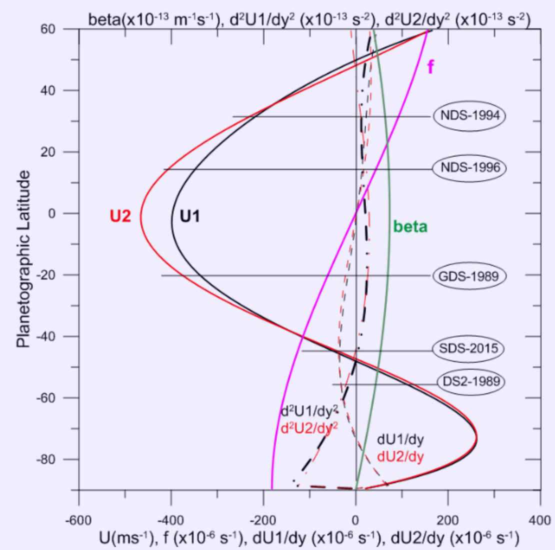
Neptune's dark spots numerical models

EPIC model (Dowling et al., 1998)

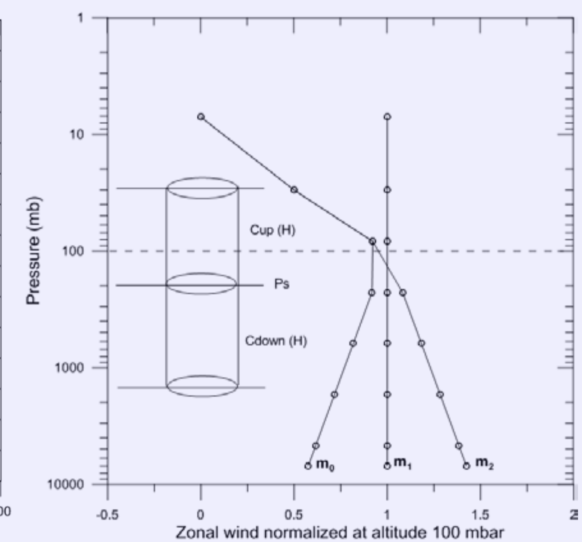


Stability and zonal drift require wind profile modification at depth

Zonal winds structure



& Vertical profiles

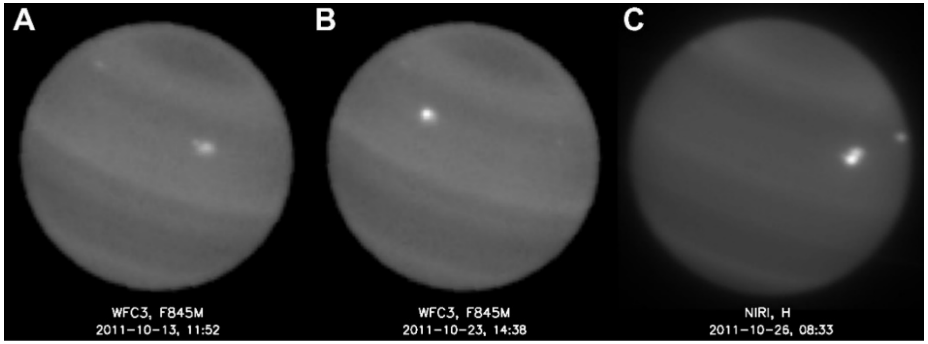


Legarreta & Sánchez-Lavega (in preparation)

It is possible to test deep winds and static stability profiles at least down to 2 bar from the behavior of these dark spots (stability, latitudinal migration & dissipation time-scales)

Several GDS simulations: Polvani et al., Science, (1990); LeBeau and Dowling, Icarus, (1998); Stratman et al., Icarus, (2001)

Moist convection in Uranus?

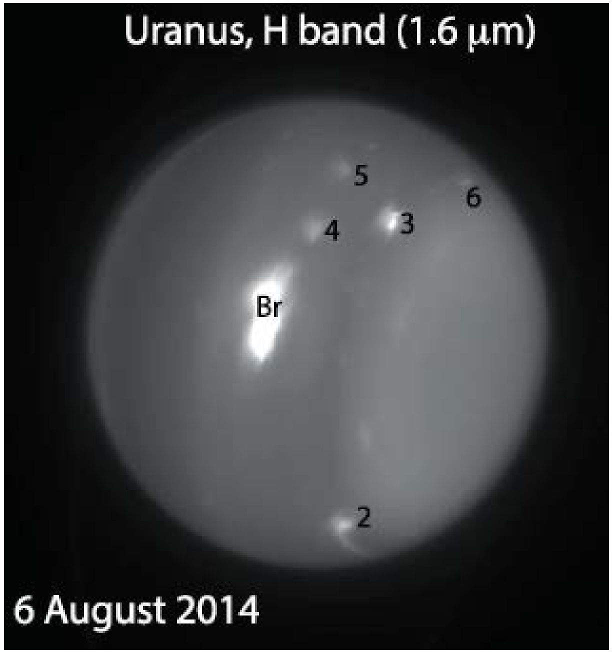


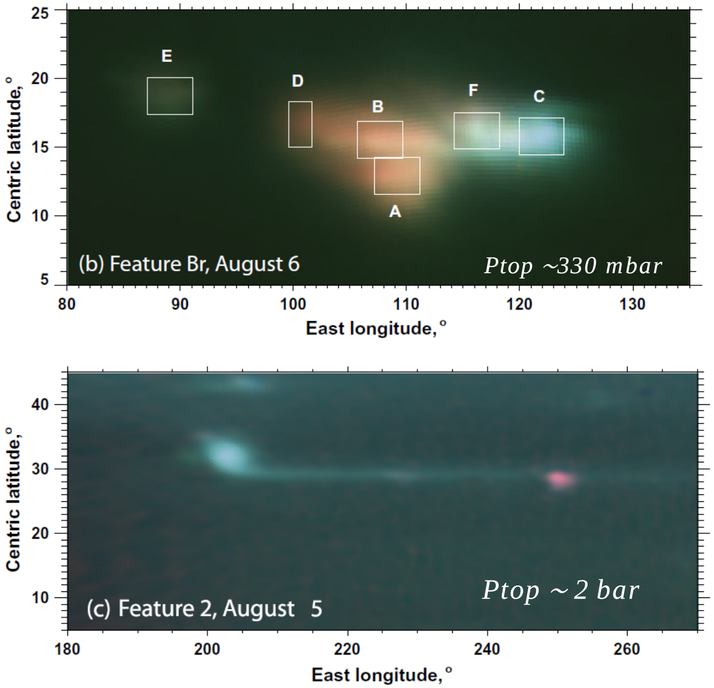
Sromovsky et al. Icarus, 2012

Storm-like events in 1999, 2004 (“Berg”), 2005 and 2011.

The two events in 2011 had cloud tops at 350–600 mb and 1–1.3 bar but time-evolution and scale do not require the clouds to be convective

2014 Storm: brightest and longest-lived in Uranus





de Pater et al. Icarus, 2015

Irwin et al. Icarus, 2017

Non convective origin of these features

Moist convection in Neptune?

Stoker and Toon, GRL, 1989

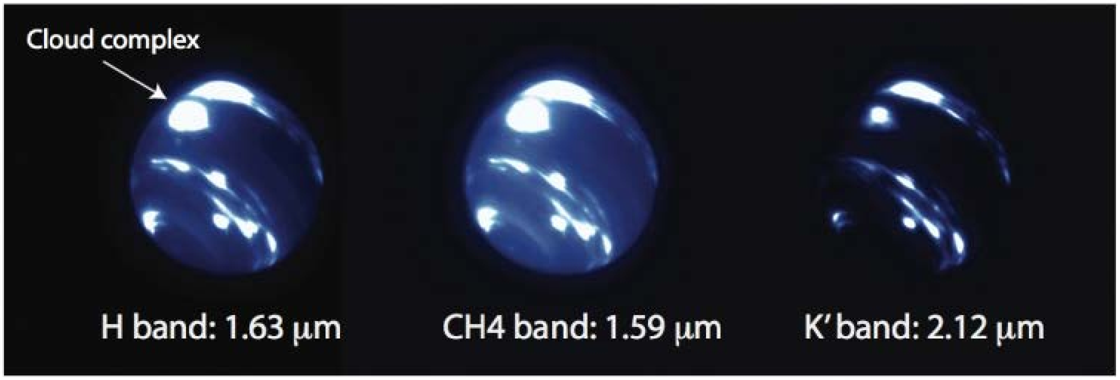
Pre-Voyager expectations of strong methane powered moist convection.

No evidence of moist convective storms found observationally

$$CAPE = \frac{w_{max}^2}{2} = \int_{Z_f}^{z_n} g\left(\frac{\Delta T}{T}\right)dz \approx \frac{g\Delta T}{\langle T\rangle}\Delta z$$

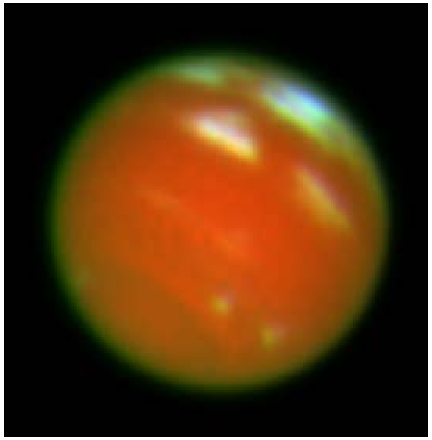
$$w_{\max} \sim 260 - 370 \text{ m s}^{-1}$$

An Equatorial storm in Neptune (2017)



Molter et al. Icarus 2019

Contradictory evidence in favor and against moist convection for this storm



R: F547M (deep cloud)
G: F763M
B: F845M (upper hazes)

Different drift rate with respect to theVoyager winds,
Different drift rates in different epochs,

↓

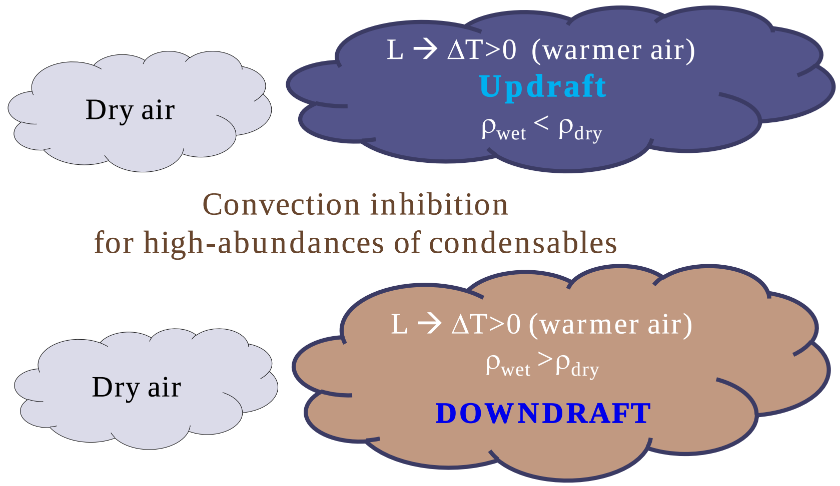
Deep origin of the equatorial and northern clouds

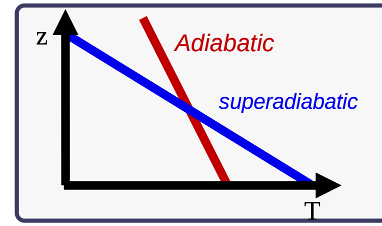
Non-conclusive evidence in favor of moist convection

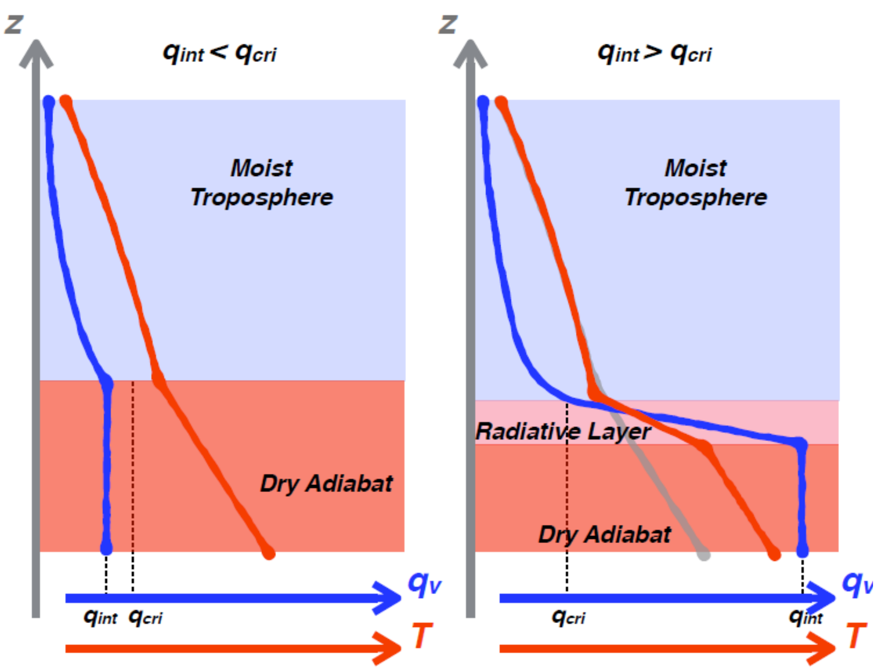
Inhibition of “deep” water convection

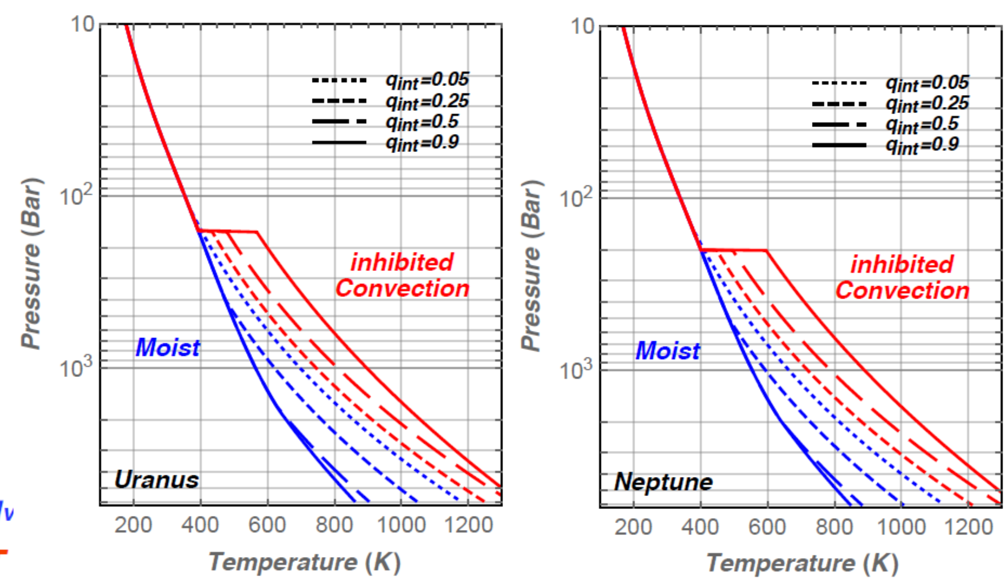
Guillot, Science, 1995

Thermal gradient could be significantly superadiabatic modifying the lower atmosphere cloud structure and condensation levels, critical abundances are needed (most efficient in Uranus & Neptune).









Leconte et al., A&A, 2017. See also Cavalié et al., Icarus, 2017

Efficiency of convection in different clouds

Latent heat	Molec. weight ratio	X_{Solar}	$20X_{Solar}$	Latent x X_{total}
L_{CH4}=511 KJ/kg L_{H2S}=549 KJ/kg	CH4/H2= 10 H2S/H2= 17	CH4/H2=3.62×10^{-4} H2S/H2=8.1×10^{-6}	CH4/H2=7.2×10^{-3} H2S/H2=1.6×10^{-4}	59 Joules/mol atm 3 Joules/mol atm
L_{NH3}=1369 KJ/kg (but no NH3 cloud in Uranus or Neptune)	NH3/H2= 8.5	NH3/H2=5.6×10^{-5}	NH3/H2=1.1×10^{-3}	26 Joules/mol atm
L_{H2O}=2265 KJ/kg	H2O/H2= 9	H2O/H2=4.26×10^{-4}	H2O/H2=8.5×10^{-3}	346 Joules /mol atm

H2S is extremely poor as a condensable that could power moist convection.

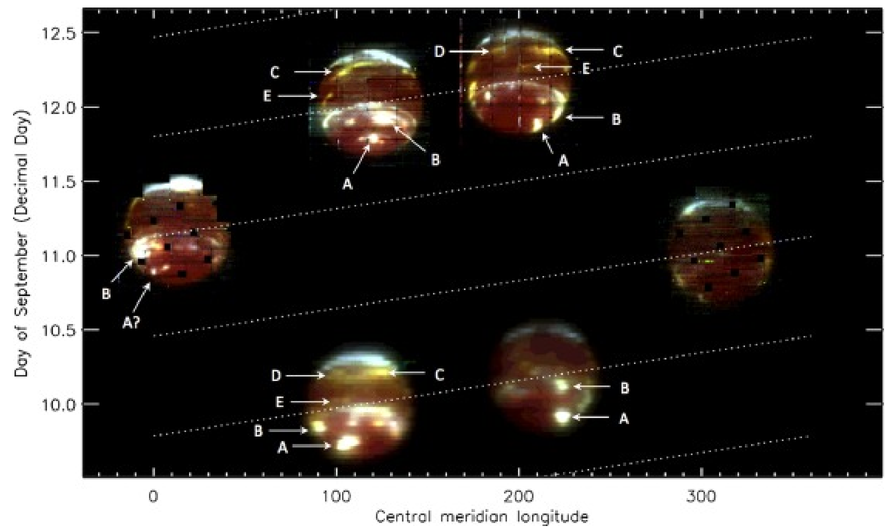
Methane should be ok but convection can be inhibited by the gradient of molecular weight and the ortho-para hydrogen conversion effects

Water is "deeply buried" in the atmosphere

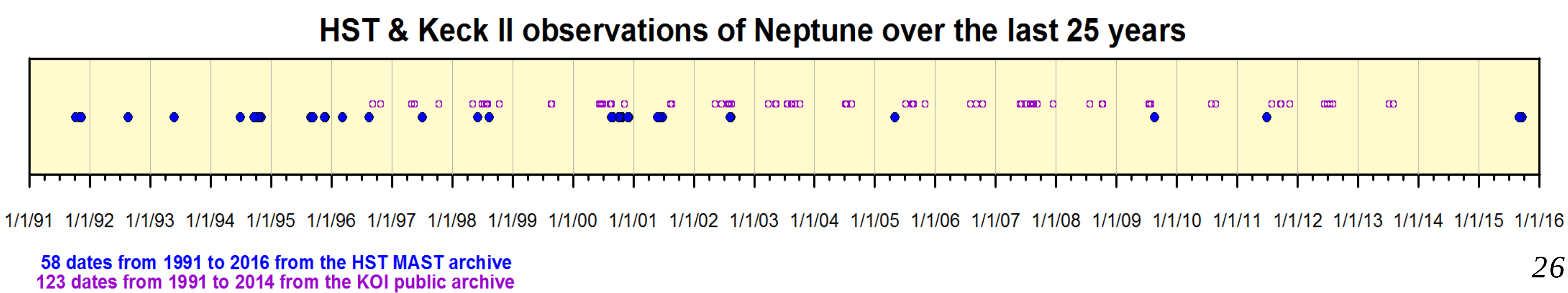
Challenges in observations of Uranus & Neptune

Neptune: small size (2.31-2.35 ")
Low brightness (Magnitude = 7.85; about 6,000 darker than Jupiter)
Low contrast of atmospheric features in the visible range.
Atmospheric features are contrasted in the near infrared where the planet is >10 times darker.

Only highly competitive telescopes have been able to advance our knowledge in this field until very recently and with limited time sampling

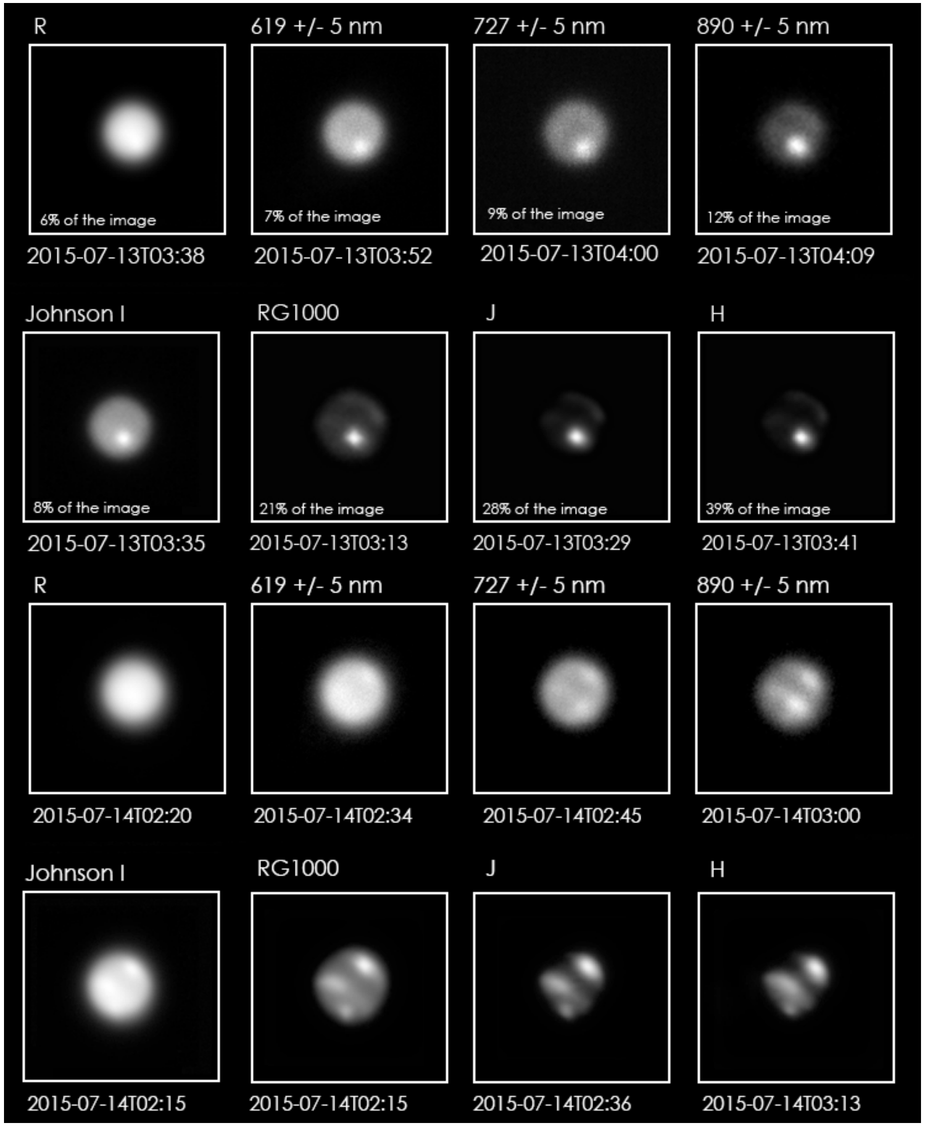


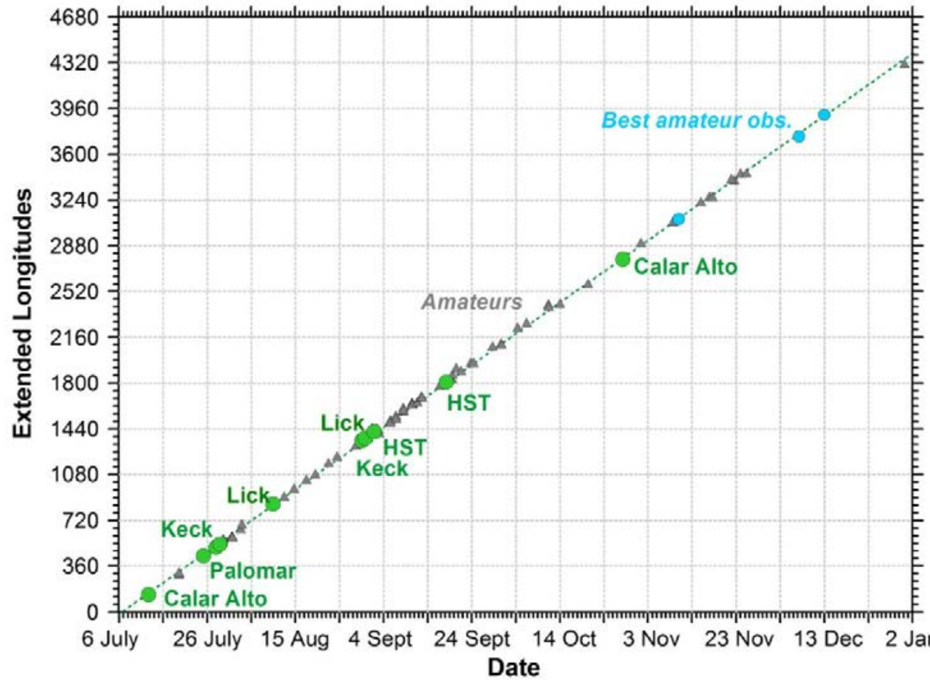
Exploring archives: About 240 dates of Keck or HST observations over the last 25 years. + Observations by many other telescopes (VLT, IRTF…) with lower image resolution.

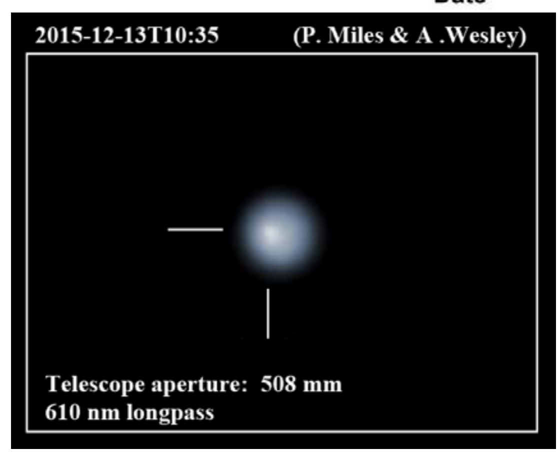


Observations of Neptune from small & large telescopes

PlanetCam observations in 2015 of a particularly bright feature in Neptune



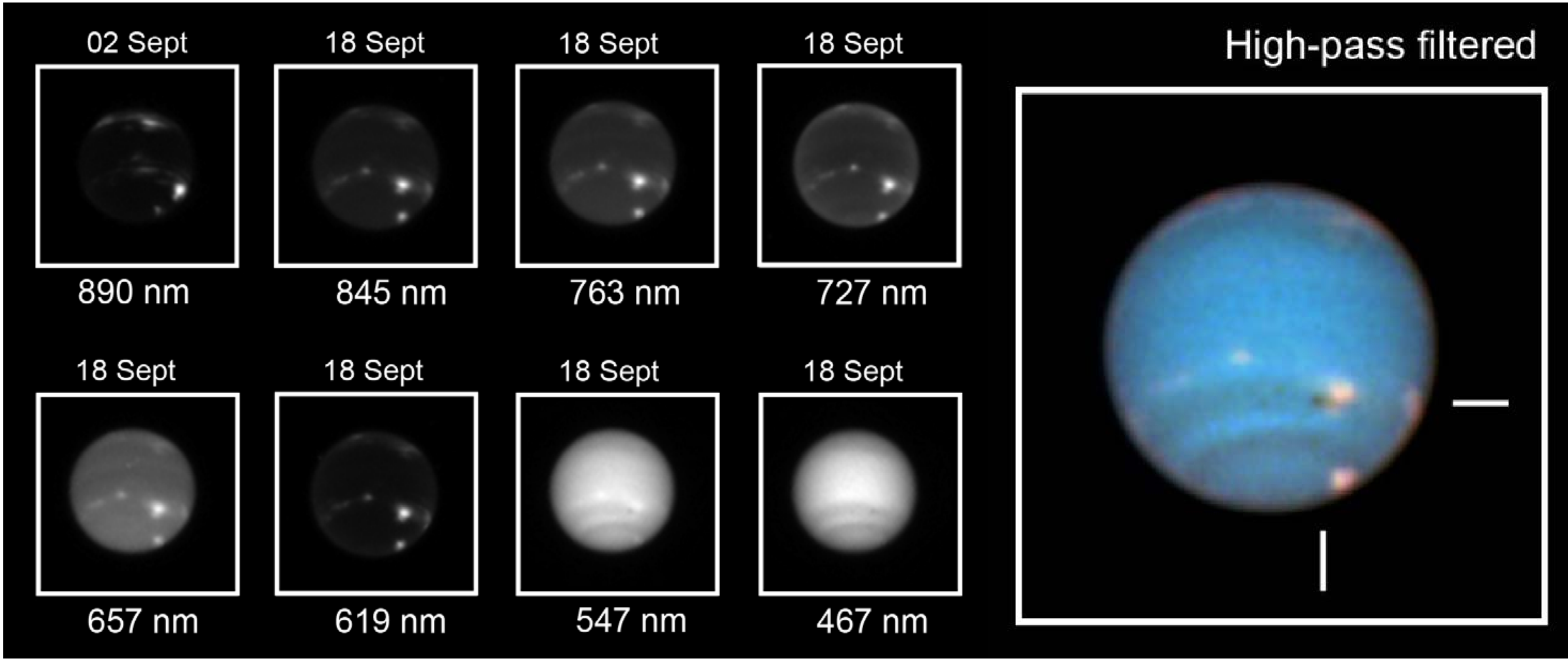




Extended study of 2013-2015: Major changes in the brightest features in the planet

Hueso et al. Icarus, 2017

Observations of Neptune from small & large telescopes



Hueso et al. Icarus, 2017 (28-cm to HST and 10-m telescopes

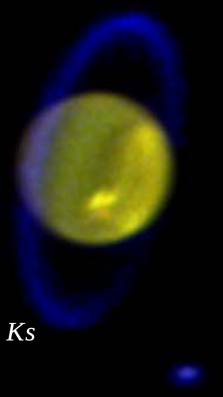
Wong et al. AJ, 2018 (HST only)

Molter et al. AJ, 2018 (again with a large amateur collaboration)

Survey of atmospheric activity in U&N from Spanish Telescopes

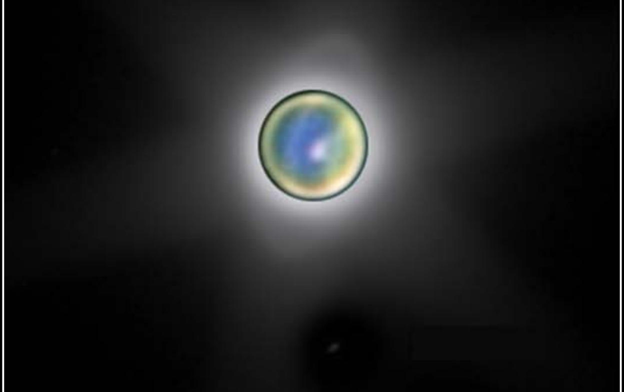
Uranus storm in 2014

Urano (3.7")
NAOMI/INGRID@WHT *(decomisionned)*
15-Oct-2014



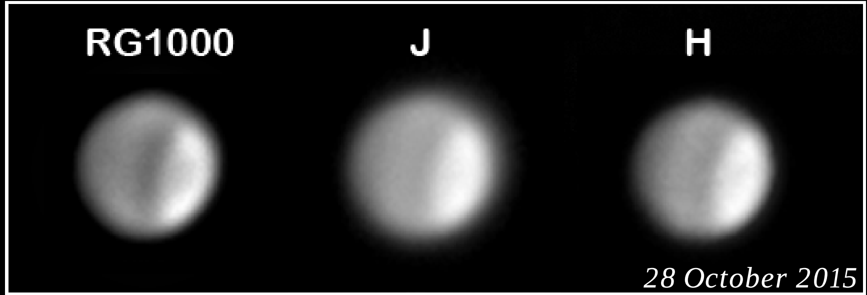
Hcont, Hclear, Ks

GTC/OSIRIS *"fast-read-out"*
15-Oct-2014

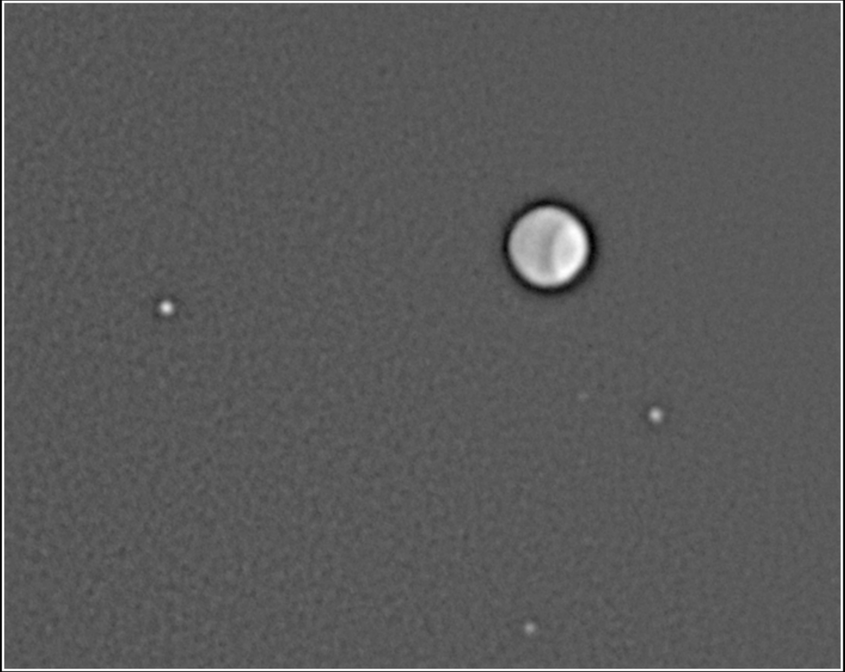


r' (640 nm), I' (771 nm) y z' (970 nm).

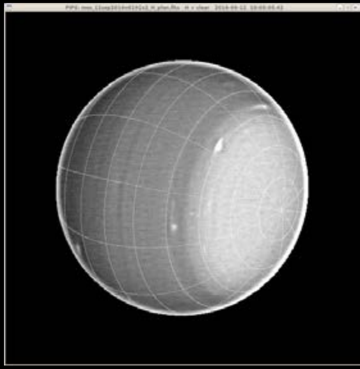
PlanetCam @ Calar Alto (2.2m)



2016-09-18 00:36 UT

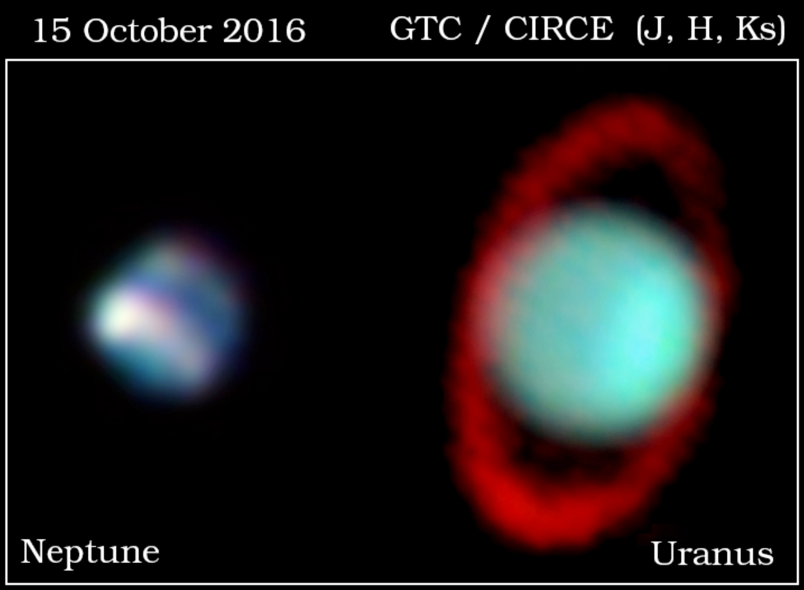


High-pass filtered (5-10% best frames) RG1000



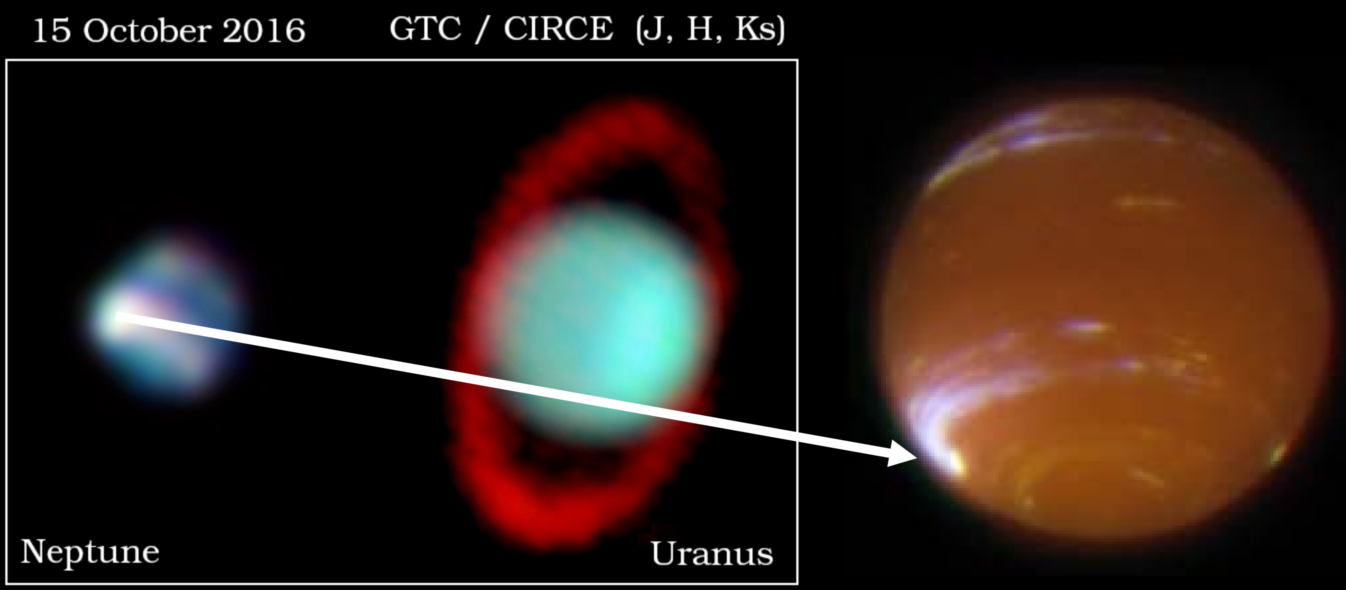
2016-09-12
10:05UT

Survey of atmospheric activity in U&N from Spanish Telescopes



CanariCam & HiPerCam observations in Sept.-Oct. 2019
(3 observing programs approved)

Survey of atmospheric activity in U&N from Spanish Telescopes

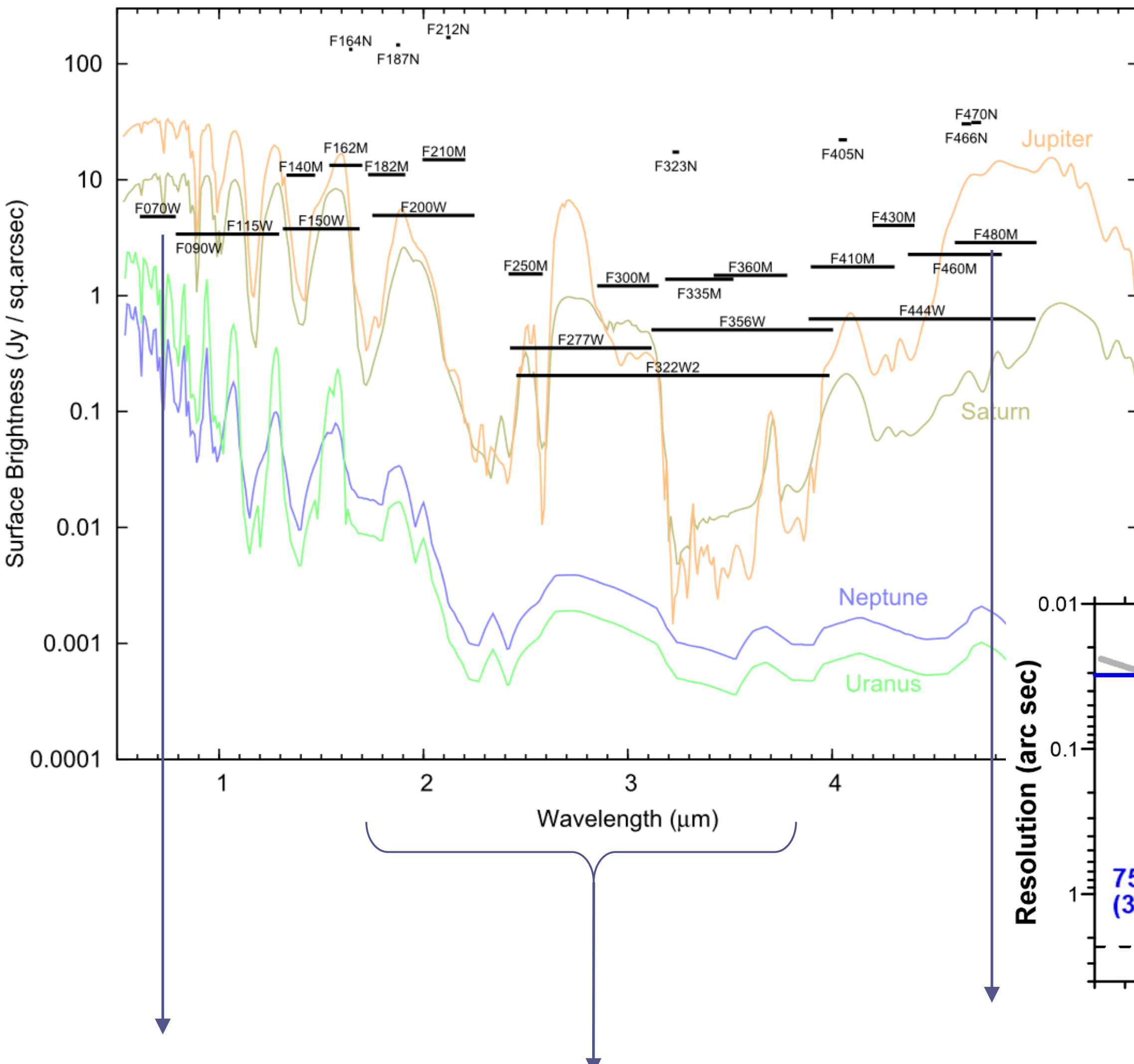


CanariCam & HiPerCam observations in Sept.-Oct. 2019
(3 observing programs approved)

+

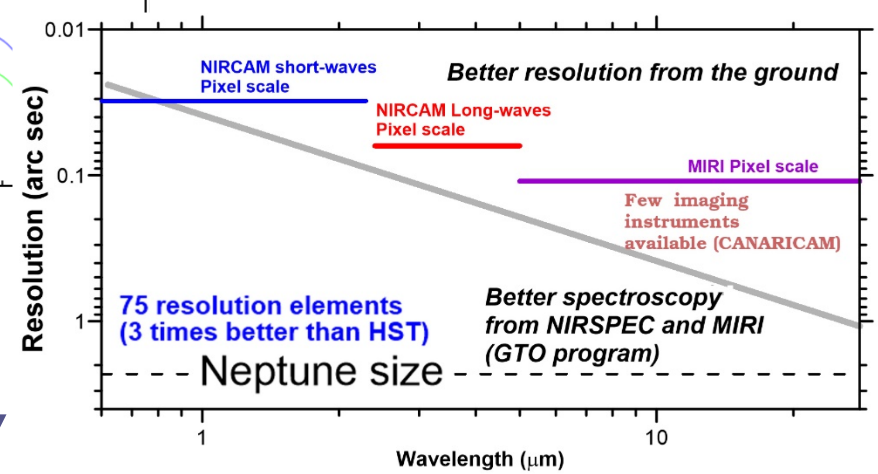
Yearly observations with PlanetCam (twice per year, one run at opositions)
Yearly survey of major features since 2015 + collaborations with some Keck, VLT, Lick and HST/OPAL observing programs

JWST (current launch date: 30-March 2021)



NIRCAM observations in:
0.6–2.3 µm (0.031"/pix) &
2.4–5.0 µm (0.063"/pix)

MIRI observations
5-28 µm
Images with pixel size: 0.11''

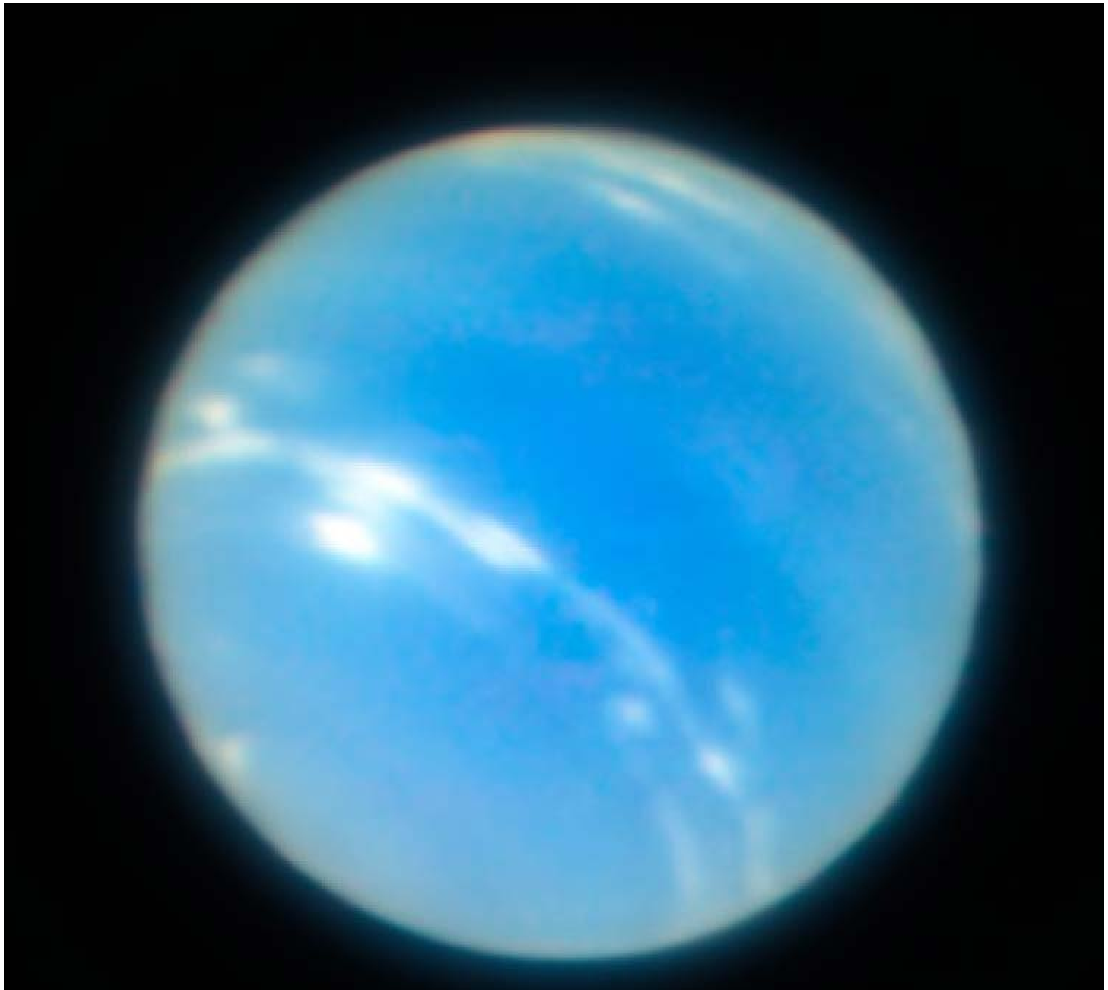


Clouds

Hazes

Hazes+
Thermal

GALACSI AO System (4 lasers) in VLT UT4
MUSE, HAWK-1 (0.9-2.5 μm) and ERIS (successor of NACO and SINFONI)


Test image from ESO Press release

VLT: Better than JWST in terms of spatial res.

Unique current capability to observe in **short wavelengths (better than HST)**

ELT could be the most useful facility to understand varying meteorologies in these worlds in the future unless a dedicated space mission is selected by ESA or NASA.