Atmospheric dynamics and cloud structure of the ice giants

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Universidad del País Vasco
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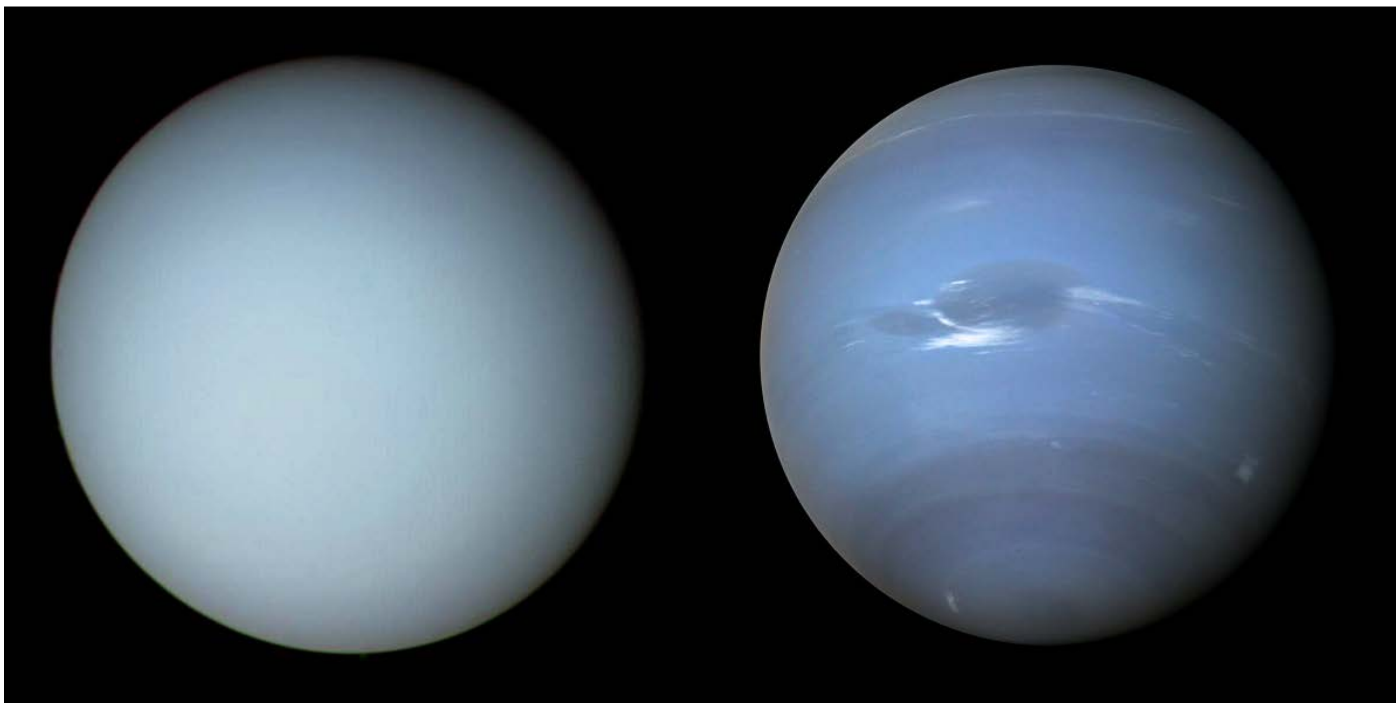
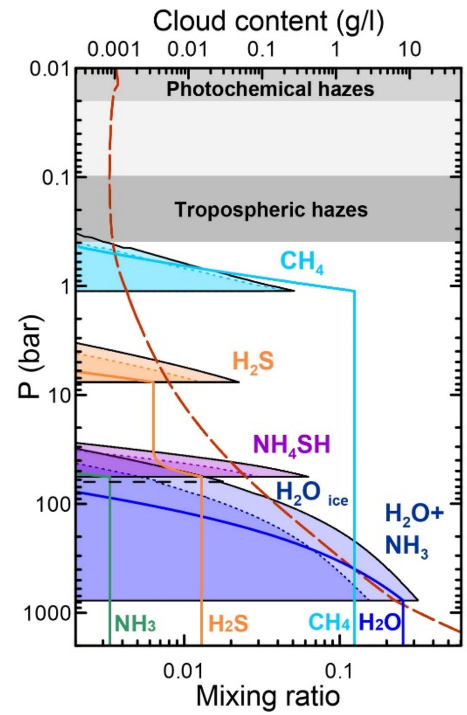
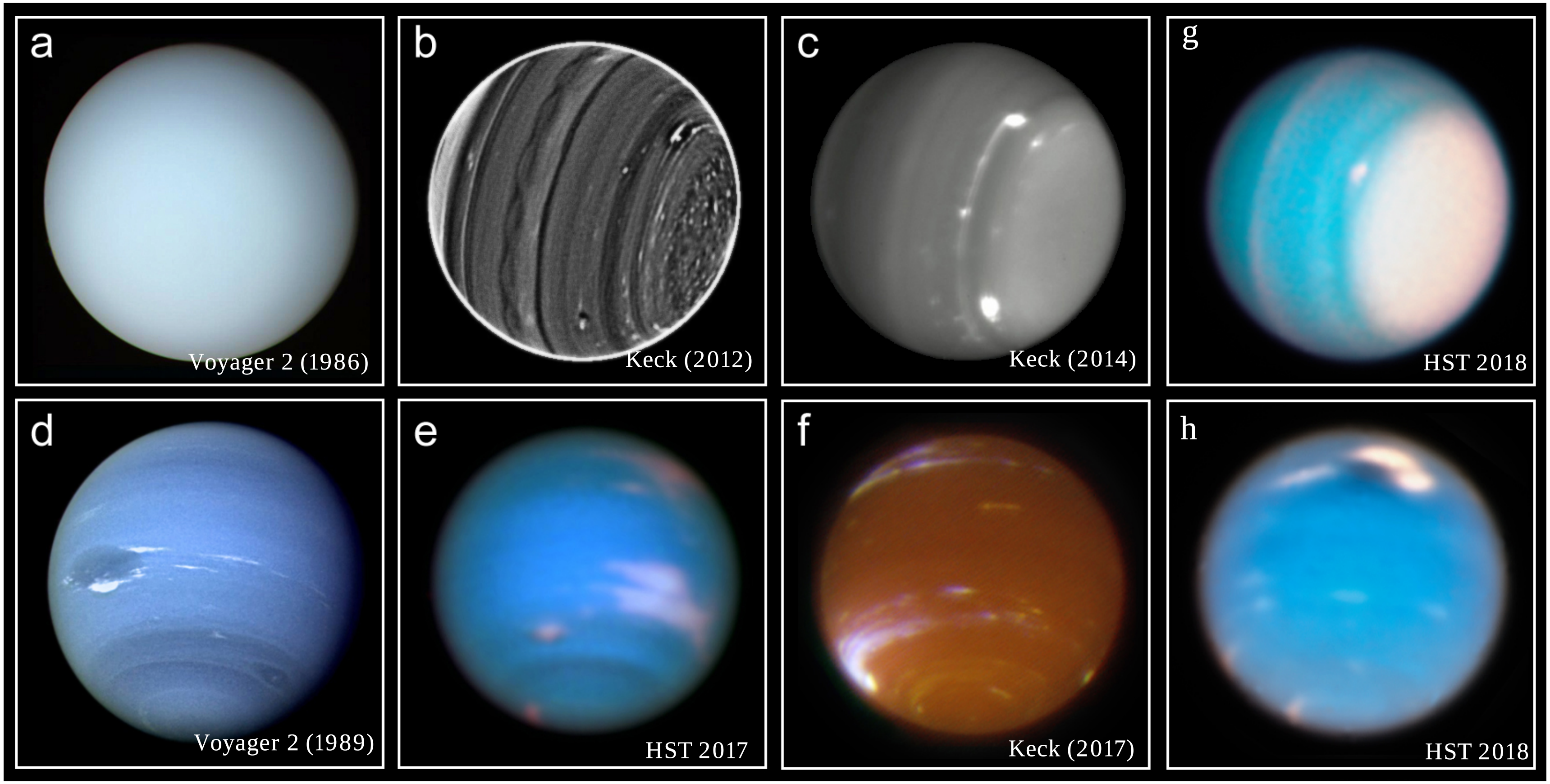




Outline

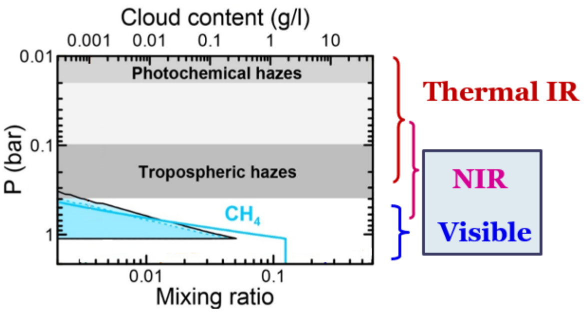
- Atmospheric dynamics
  - Visible levels in the atmospheres of the Icy Giants
  - Winds and their variability
  - Uranus and Neptune discrete cloud systems
  - Long-term variability, seasons and thermal structure
- The Deep Weather Layer beneath the observations
  - Thermochemical models of the atmosphere
  - Moist convection

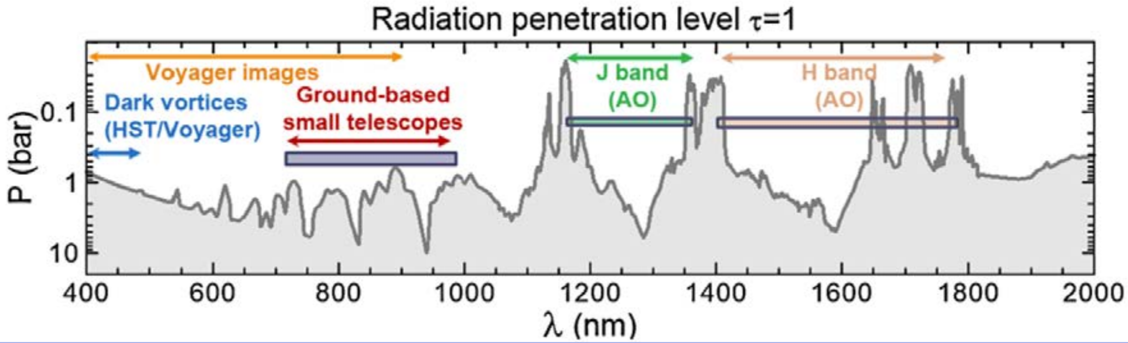
Dynamic atmospheres in visible and NIR wavelengths



Gallery of Uranus and Neptune clouds & hazes

Hueso & Sánchez-Lavega, SSR, 2020

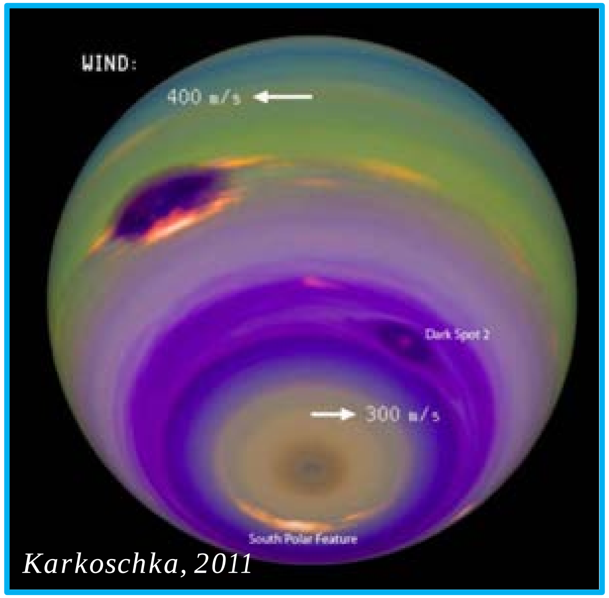




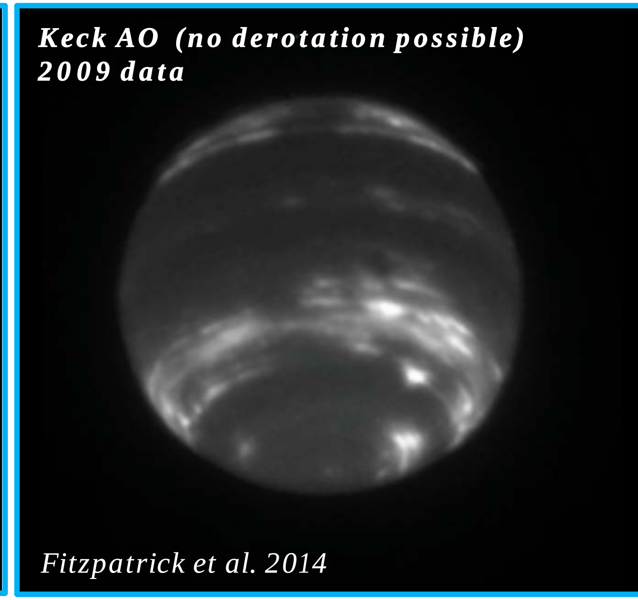
Winds: Reanalysis of Voyager data, modern AO data & HST

Voyager ***(modern reprocessed images)***

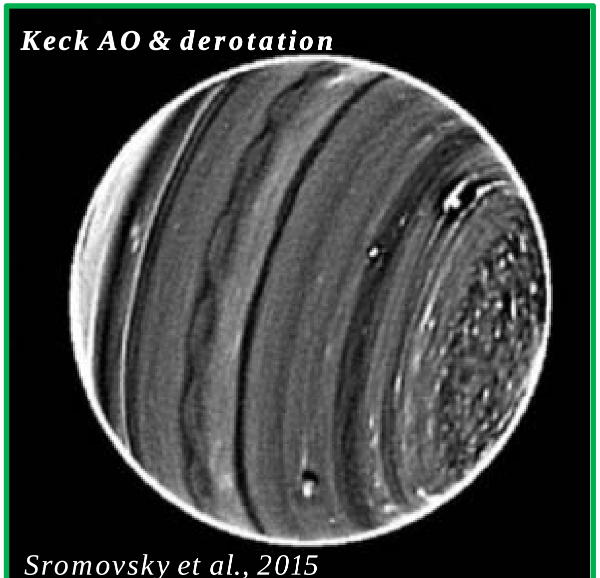
Karkoschka, 2015



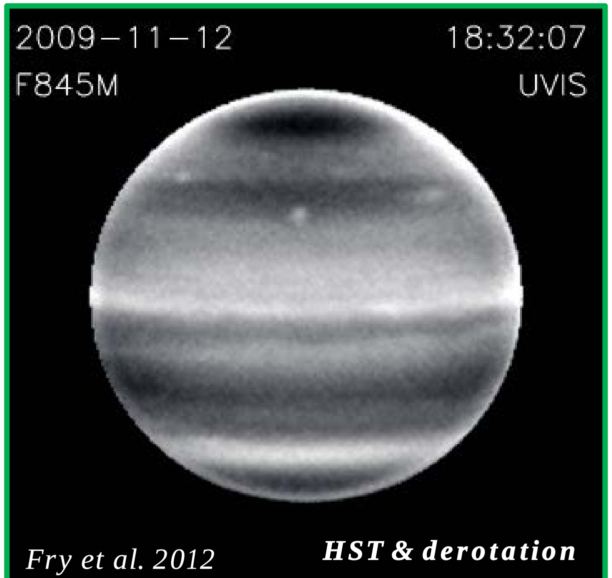
Karkoschka, 2011



Fitzpatrick et al. 2014



Sromovsky et al., 2015

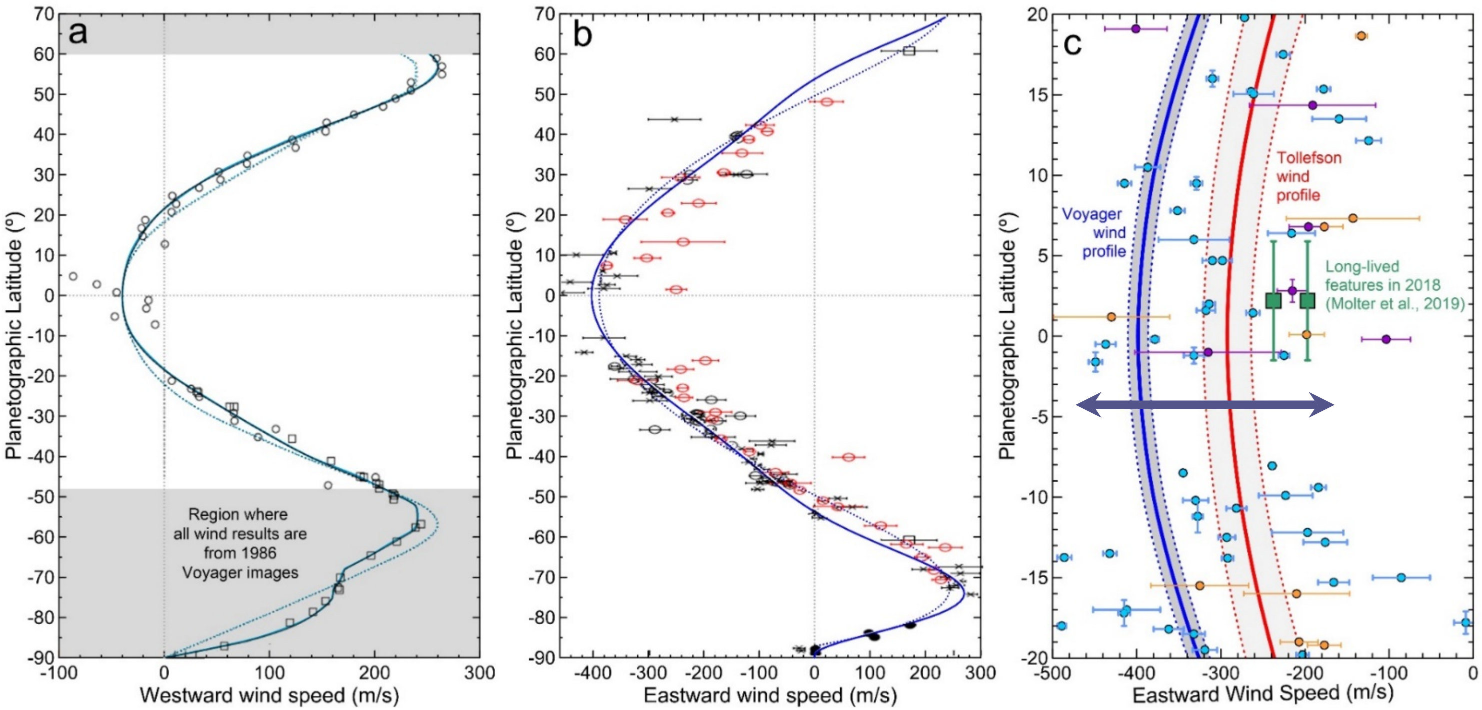


Fry et al. 2012

Wong et al. 2018

Intense zonal winds, low irradiation and shallow winds

Figures from Hueso & Sánchez-Lavega, SSR (2019) and Sánchez-Lavega et al. in “Zonal jets” (2016) based in data mainly compiled by Larry Sromovsky



1. Intense winds in spite of small energy sources

Solar constant:

Uranus: ~3.5-3.9 /m²

Neptune: ~1.5 W/m² + Inner heat source 0.3 W/m²

2. Variability & vertical wind shear

Difference of 200 m/s in 1-3 scale heights

Humidity winds Sun, Stoker & Schubert, Icarus, 1991

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

Thermal wind component

Humidity wind component

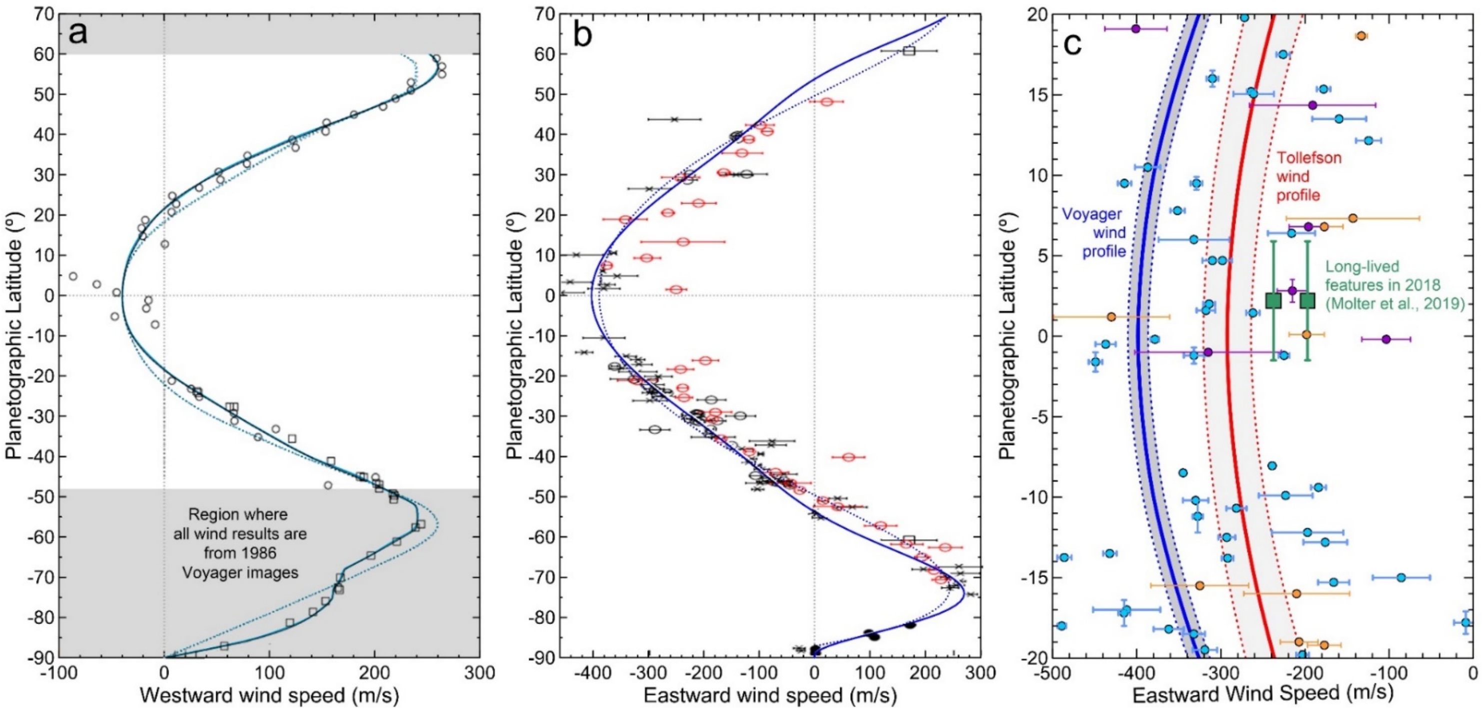
Equatorial corrections to the thermal & humidity winds

$$2\Omega \sin\theta \frac{\partial u}{\partial r} = -\frac{g}{r_0 T}\frac{\partial T}{\partial \theta}\bigg|_p - \frac{g}{r_0}\frac{C}{1+Cq}\frac{\partial q}{\partial \theta}\bigg|_p,$$

Tollefson et al. Icarus, 2018; Marcus et al. Icarus, 2019

Intense zonal winds, low irradiation and shallow winds

Figures from Hueso & Sánchez-Lavega, SSR (2019) and Sánchez-Lavega et al. in "Zonal jets" (2016) based in data mainly compiled by Larry Sromovsky



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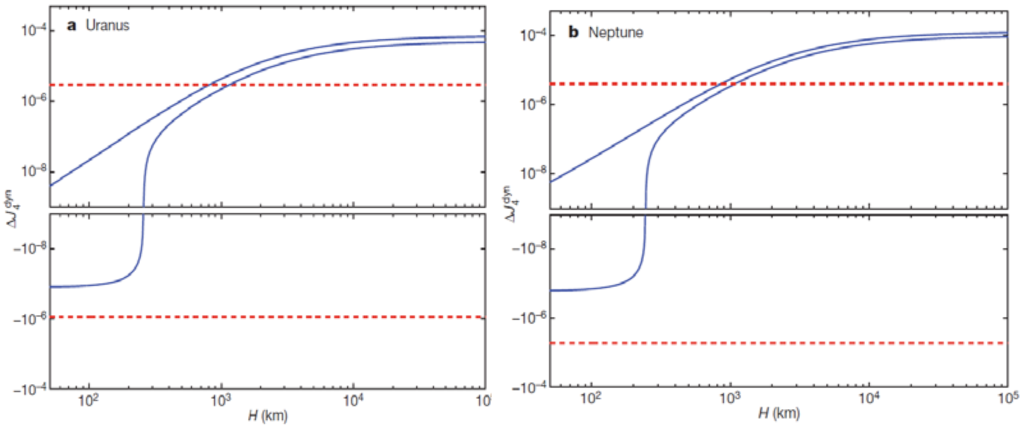
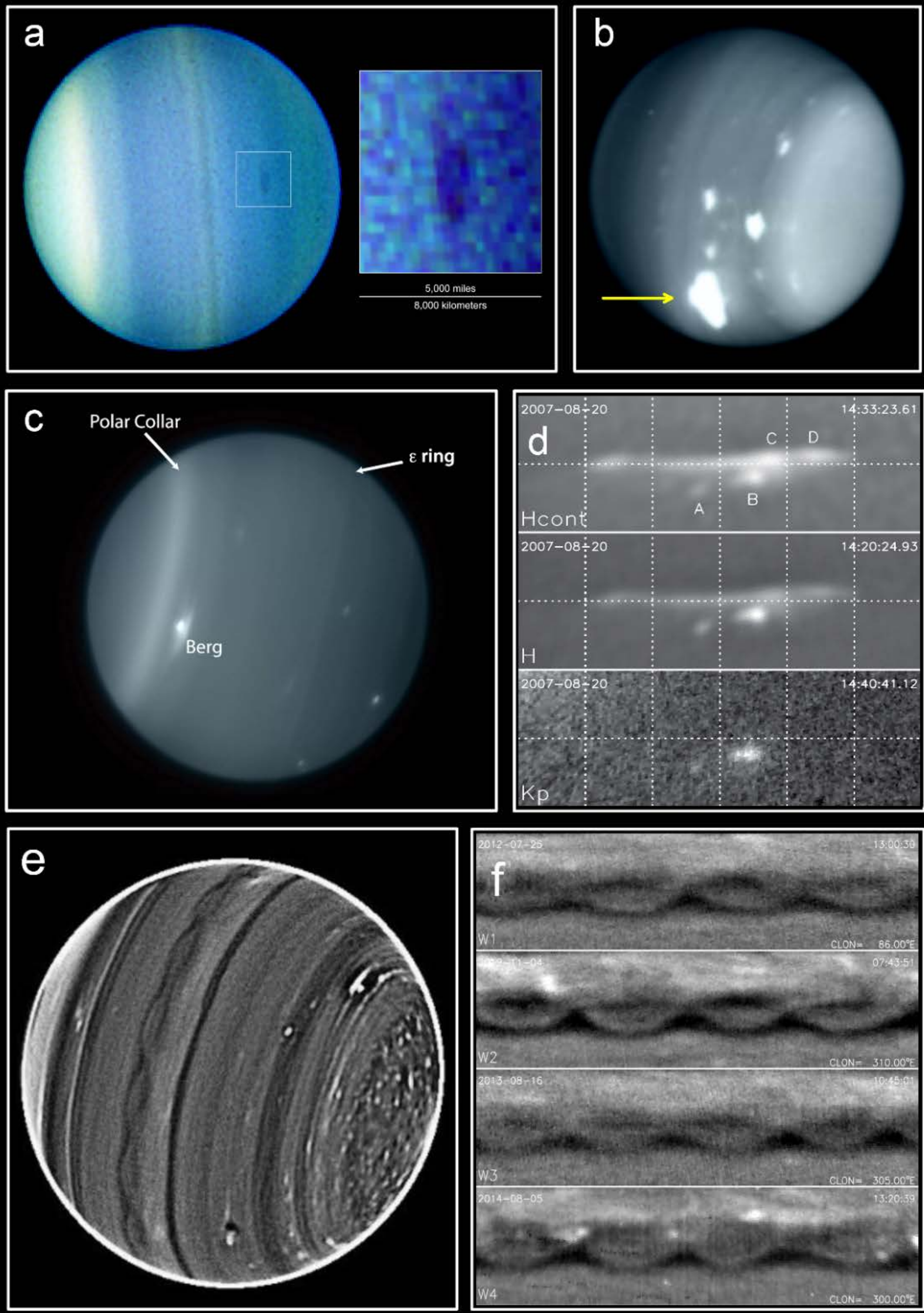


Kaspi et al., Nature, 2013

Depth of the winds from gravity measurements of gravitational moments (J4) and interior models < 1,000 km

Note that this limit is ~150 km below the hypothetical water cloud base and close to the water critical point.



Uranus cloud systems

Two only Dark Spots

a: **Uranus Dark Spot 2006**
(Hammel et al. 2009)
Another dark spot in 2011 *(Sromovsky et al. 2012)*

Several systems of bright spots in different years

(enhanced activity after equinox, more calm since 2014)

b: **Uranus in 2014 (outburst of activity)**

(de Pater et al. 2014)

c: **de Berg "feature" (2004)**

d: **de Berg "feature" (2007)**

(de Pater et al. 2011)

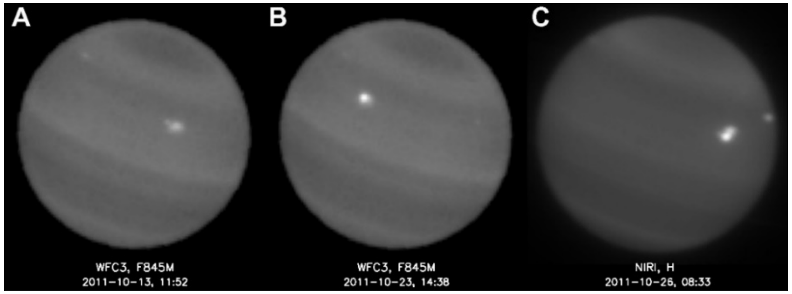
Equatorial waves

e: **Equatorial waves & discrete puffy clouds in the south pole**

f: **Equatorial waves**

(Sromovsky et al. 2015)

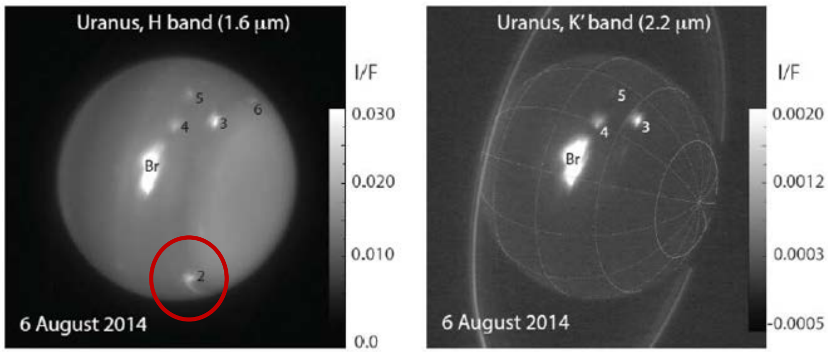
Uranus posible moist convective systems



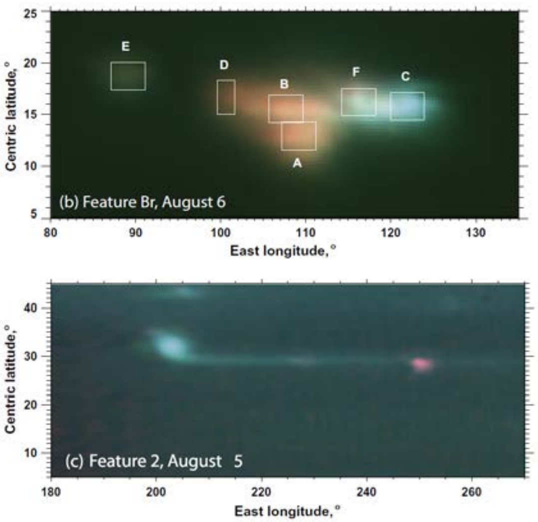
Sromovsky et al. *Icarus*, 2012

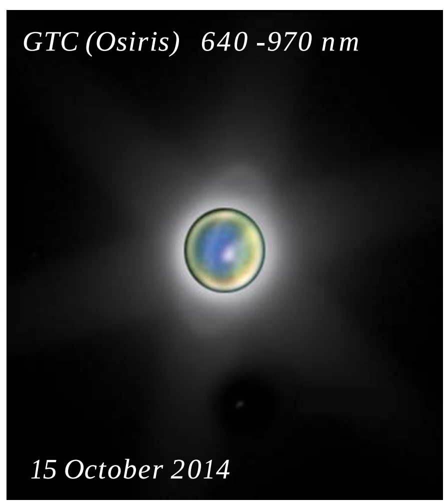
Storm-like events in 1999, 2004 (“Berg”), 2005 & 2011.

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



de Pater et al. *Icarus*, 2015

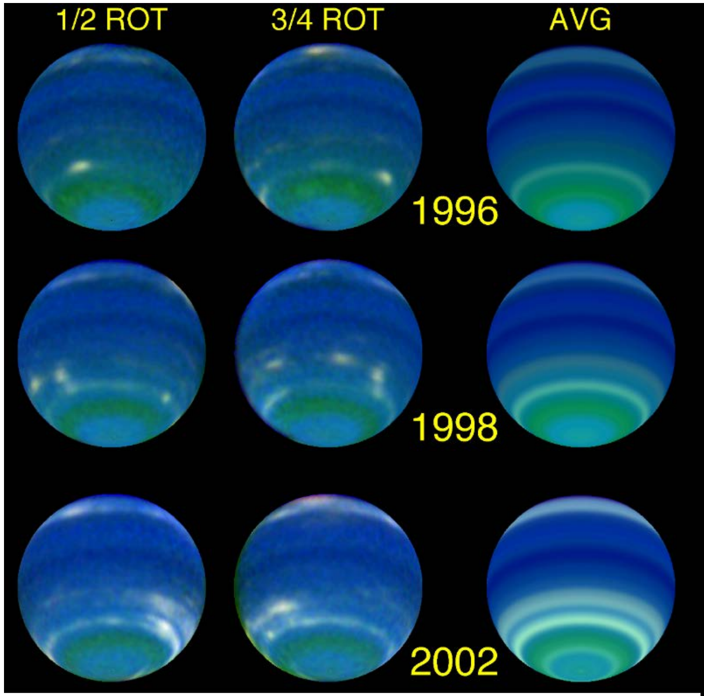


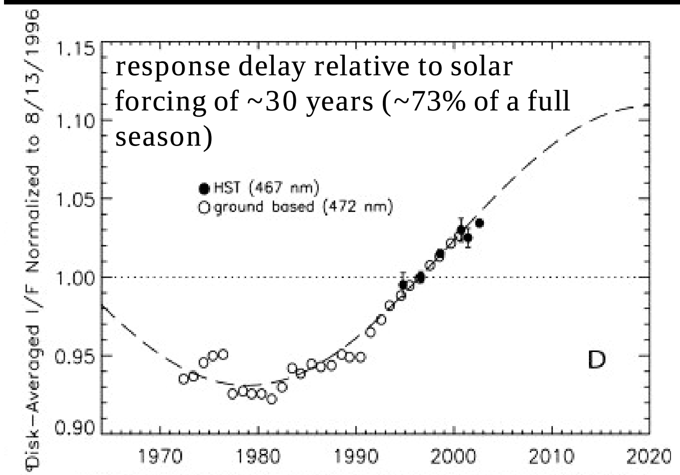


Irwin et al. *Icarus*, 2017
HST & Keck radiative-transfer analysis
P_{top}~2 bar

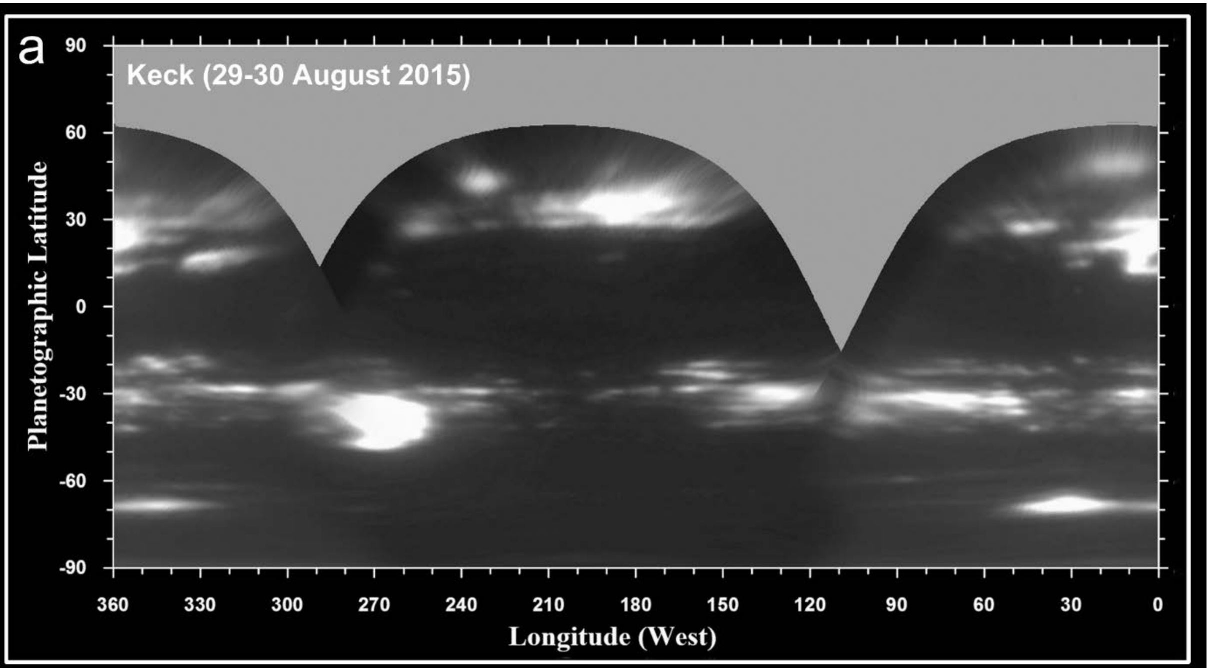
Convection is possible but it’s not the only possible cloud structure compatible with the observations

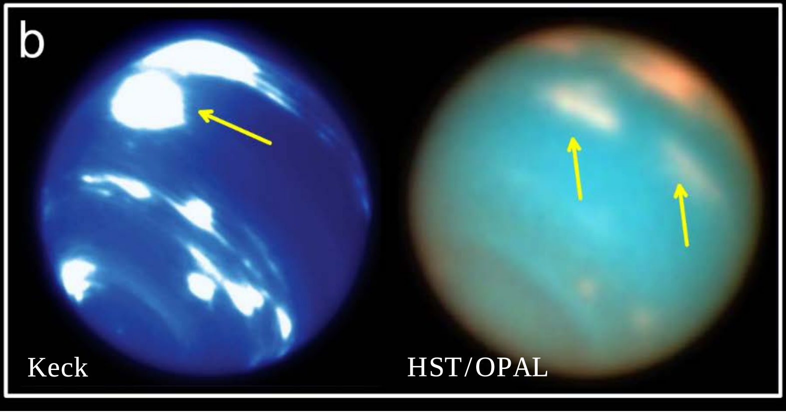
Neptune cloud systems: Bands and discrete cloud features that change in time

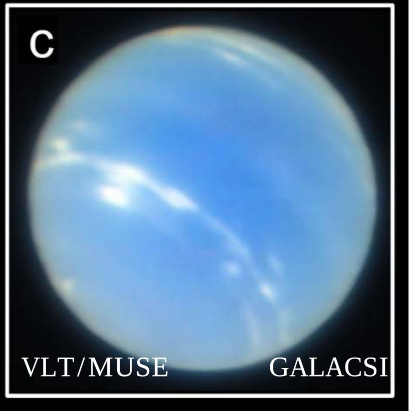




Sromovsky et al., Icarus, 2003



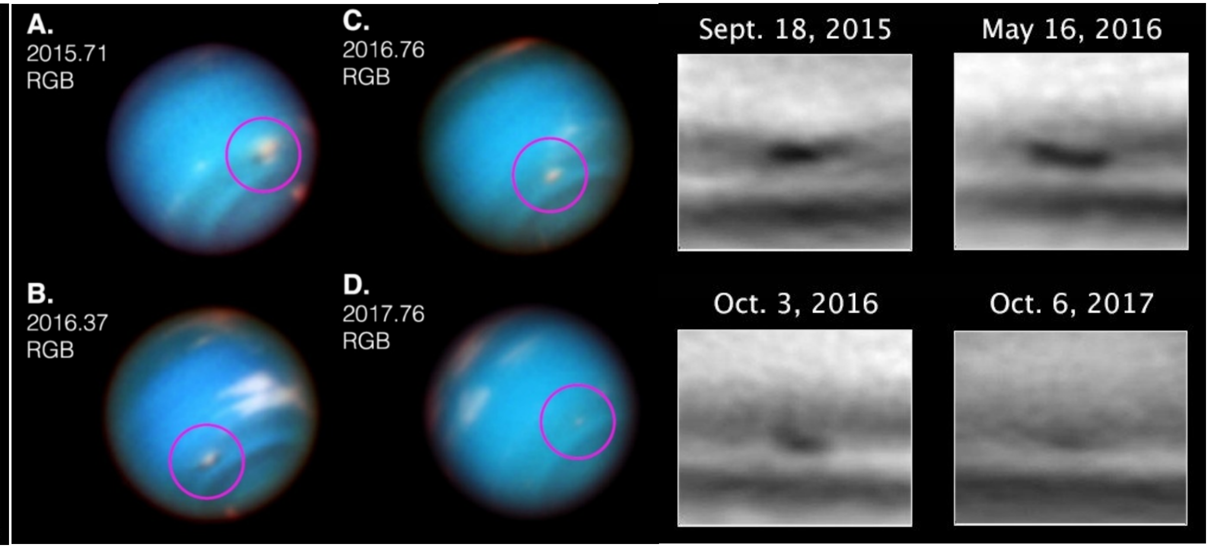




a: **Neptune in 2015**; Hueso et al. 2017
b: **Neptune in 2018**; Molter et al. 2019
c: **Neptune in 2018**; Irwin et al. 2019

Dark spots in Neptune

Smith et al. (1989)



Wong et al., AJ, 2018

Summary of Darks Spots in Neptune

From Wong et al. AJ, 2018 and Hueso & Sánchez-Lavega, SSR, 2019

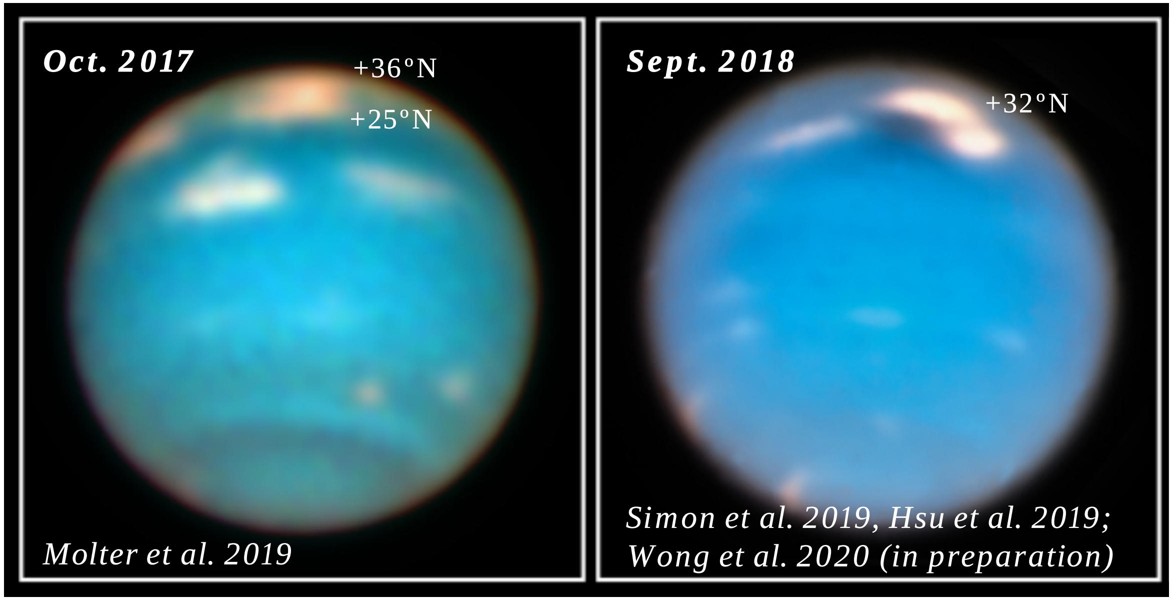
Table 3 Neptune dark spots

Name	Life-time (yrs)	Lat. (pg)	Shape $a \times b$ (km)	Zonal velocity (ms^{-1})	Amb. flow (ms^{-1})	Meridional drift	Meridional motion & oscillations (ms^{-1})	du/dy ($\times 10^{-5}$ s^{-1})	Coriolis f ($\times 10^{-5}$ s^{-1})	Tangent. velocity (ms^{-1})	Ref.
GDS-1989	∼ 7	−20°	15300 × 6500 (b)	Variable (c)	−325	+0.11°/day equatorward	-0.5 (d)	−1.4	−7.4	89	(2–3)
DS2-1989	> 5	−55°	9500 × 2500	+14	+87	±2.4°oscillation	Oscillations(e)	−3.6	−17.7	88	(3)
NDS-1994	4–6	+32°	12700 × 4300	(f)	−222	0°/day	0	2.2	11.5	94	(4–5)
NDS-1996	1–2	+15°	9100 × 5100	−322 (f)	−355	0°/day	0	1.1	5.6	52	(5)
SDS-2015	> 2	−49°	4200 × 2100	Variable (g)	−8	−2.5°/year poleward	+0.034	−2.8	−16.3	62	(6)
NDS-2018	∼ 4	+23°	10600 × 5100	−269	−306		0	1.8	8.5	81	(7)

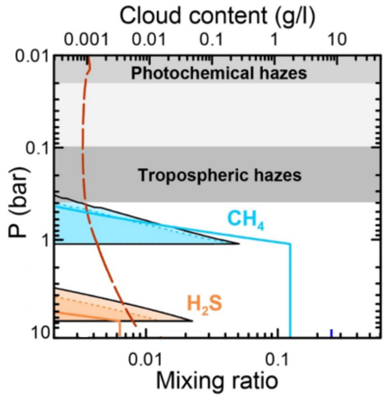
References: (2) Smith et al. (1989), Ingersoll et al. (1995); (3) Sromovsky et al. (1993); (4) Hammel et al. (1995), Sromovsky et al. (2001b,c); (5) Sromovsky et al. (2001c); (6) Wong et al. (2018); (7) Simon et al. (2019)

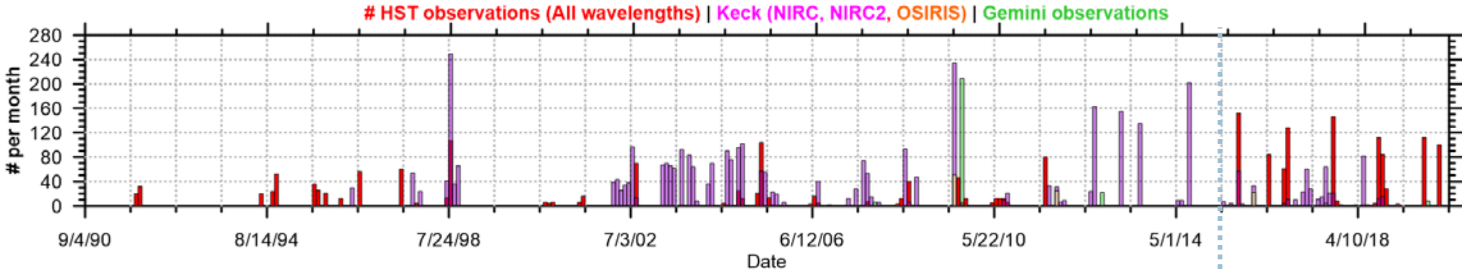
Hsu et al., AJ, 2019 Survey of all HST Blue images of Neptune
~ Approximately one dark spot every four to six year

Equatorial activity in 2017-2020

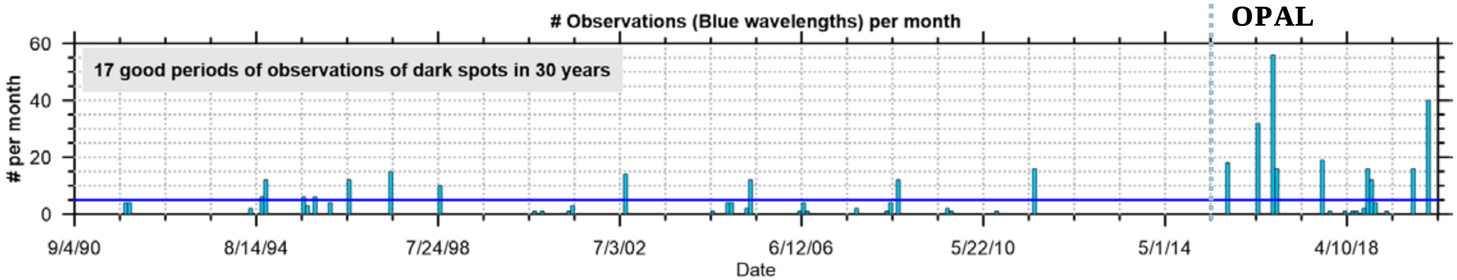


Dark spots are deeper than the environment and they might be updrafted "companion clouds" to deep H2S clouds
Tollefson et al. (2017)





Not enough observational data to constrain the temporal evolution of most large-scale features in Neptune



Very limited observations in blue wavelengths (improved since OPAL program)

Moist convection in Neptune? More active than Uranus!

Stoker and Toon, GRL, 1989

Pre-Voyager expectations of strong methane powered moist convection.

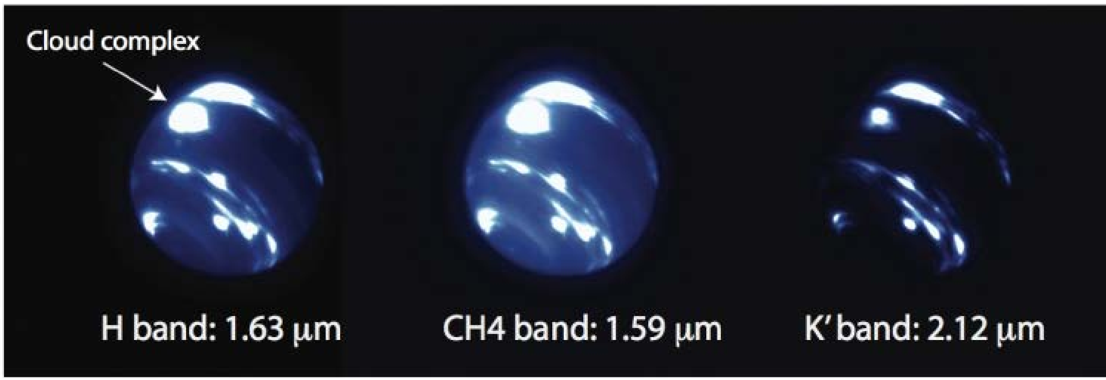
No evidence of strong moist convective storms found observationally

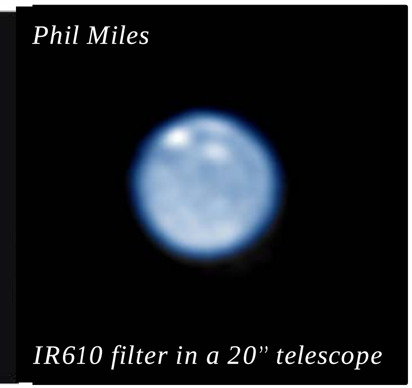
$$CAPE = \frac{w_{max}^2}{2} = \int_{Z_f}^{z_n} g\left(\frac{\Delta T}{T}\right)dz \approx \frac{g\Delta T}{\langle T\rangle}\Delta z$$

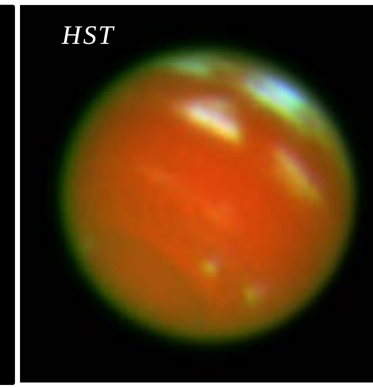
$$w_{\max} \sim 260 - 370 \text{ m s}^{-1}$$

Valid for an extremely wet atmosphere (not realistic)

An Equatorial storm in Neptune in 2017?







Molter et al. Icarus 2019

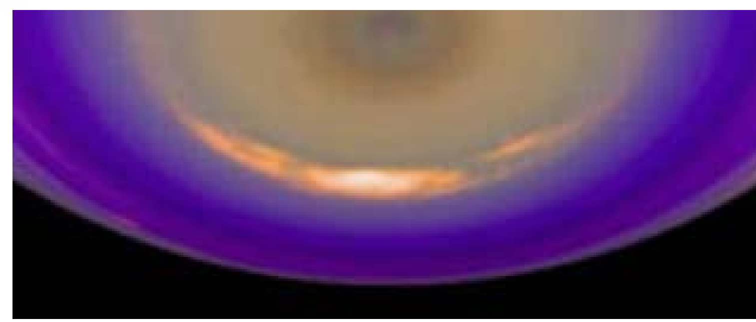
Contradictory evidence ***in favor*** *and against moist convection for this storm*

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

↓

Deep origin of the equatorial and northern clouds

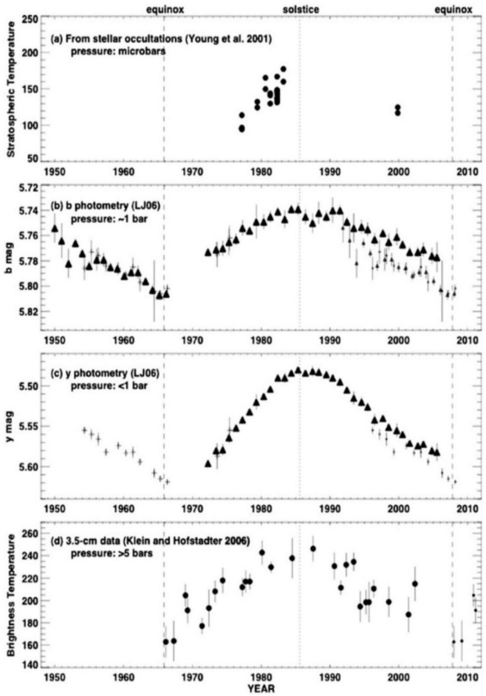
However, non-conclusive evidence in favor of moist convection from rad-transfer analysis



Other locations:
Bright & Variable system active since 1989
Hammel et al. Sci. 1989
Karkoschka, 2011

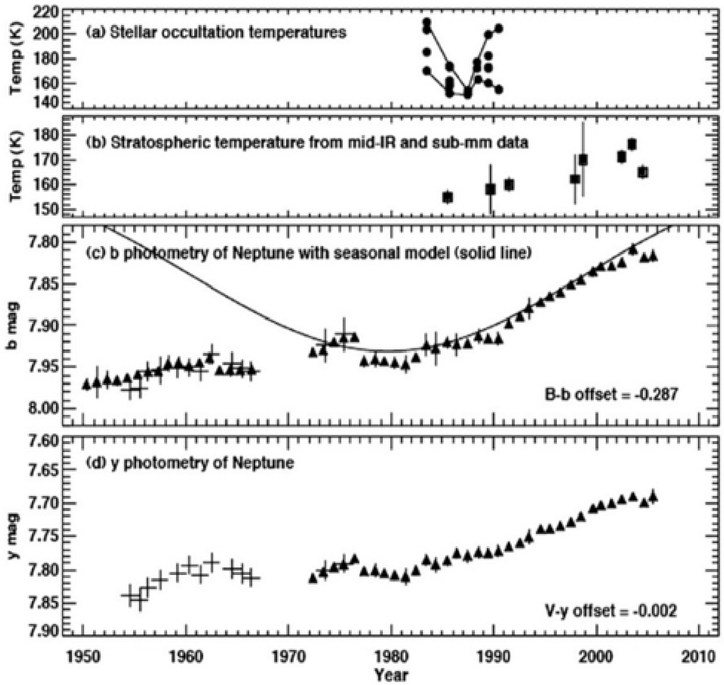
Global albedo variability: Seasonal in Uranus & non-seasonal in Neptune

Uranus



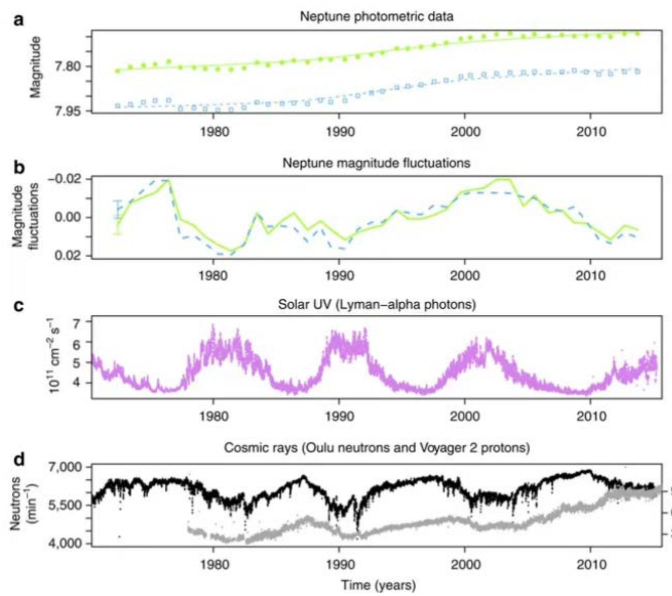
Lockwood, G.W., Jerzykewicz, Icarus, 2006

Neptune

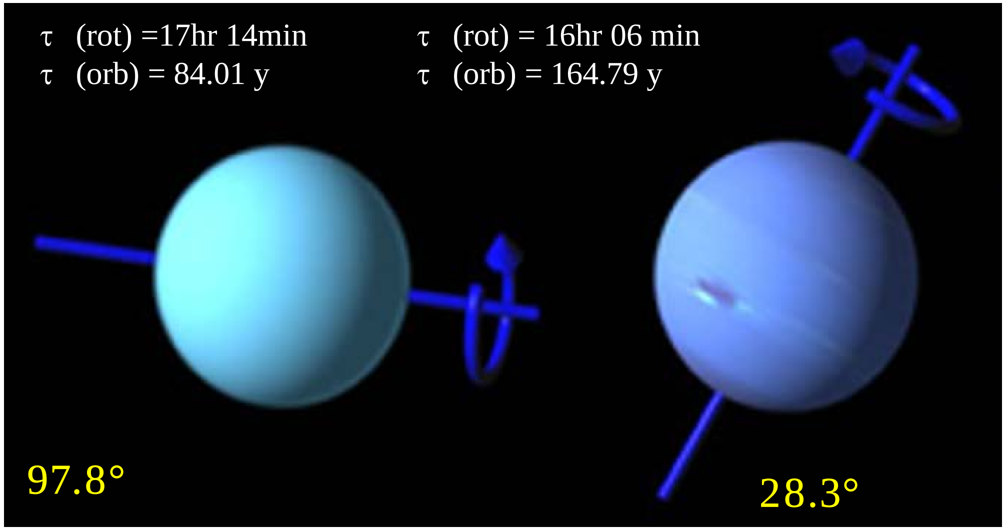


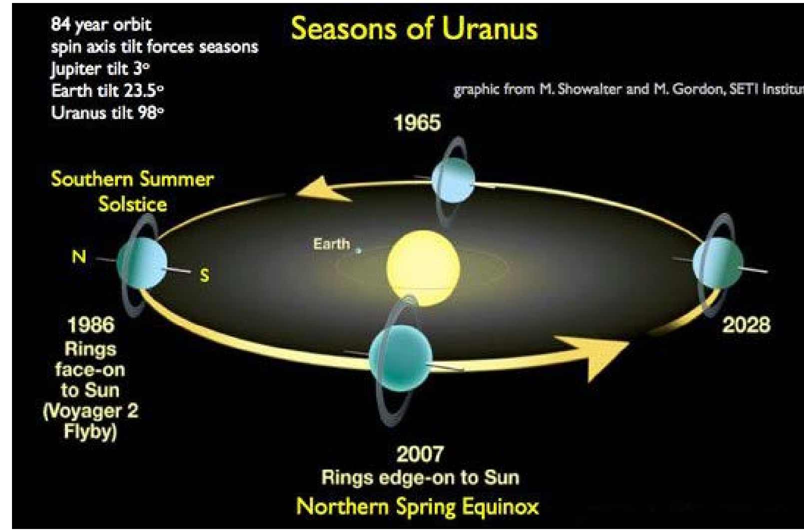
Hammel and Lockwood, Icarus, 2007

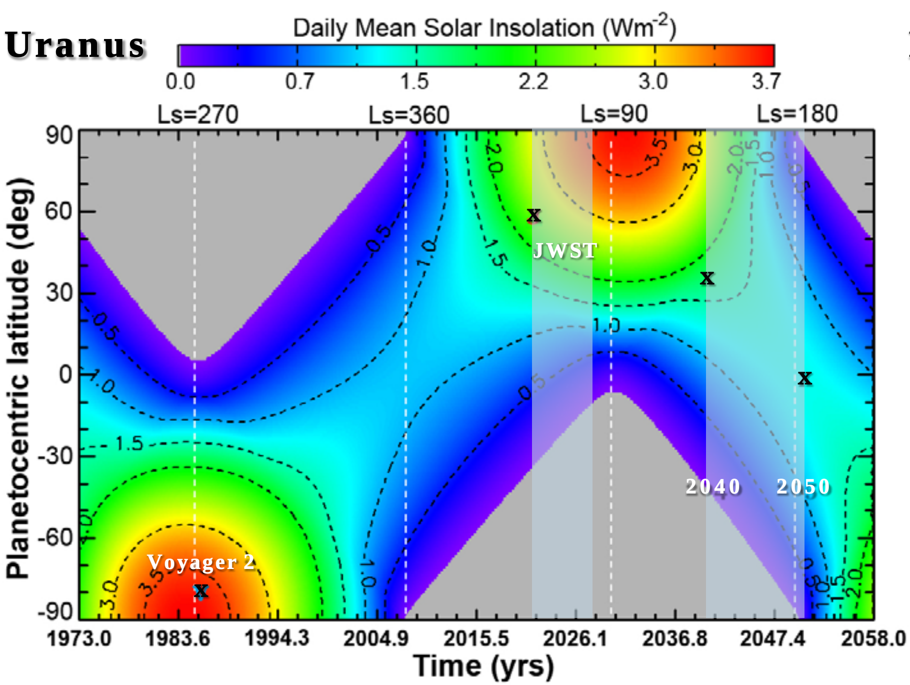
Aplin and Harrison, Nat. Comm. 2016

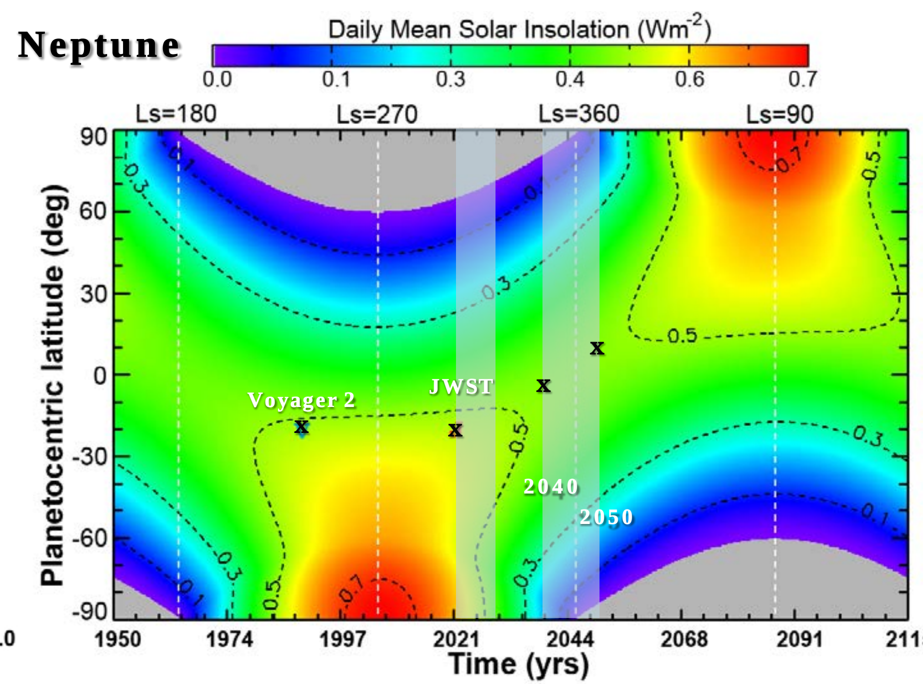


Geostrophic atmospheres under strong seasonal effects



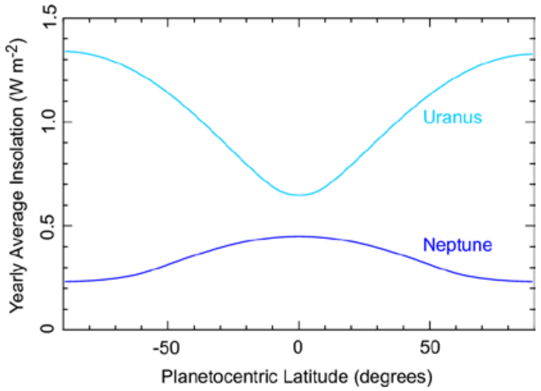






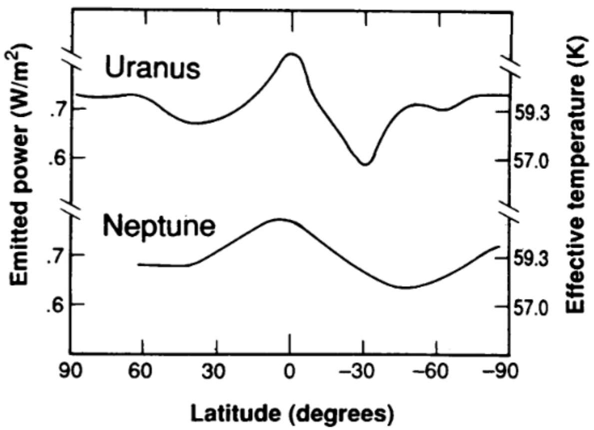
Internal heat source and inner distribution of heat

Yearly average insolation



Moses et al. 2018

Emitted infrared flux and Brigthness temperature from Voyager data



Ingersoll et al. 1990

Radiative Balance

Uranus

$$T_{eq} = 58.2 \pm 1.0 \text{ K}$$

$$T_{eff} = 59.1 \pm 0.3 \text{ K}$$

$$E = \left(T_{eff} / T_{eq}\right)^4 = 1.06 \pm 0.08$$

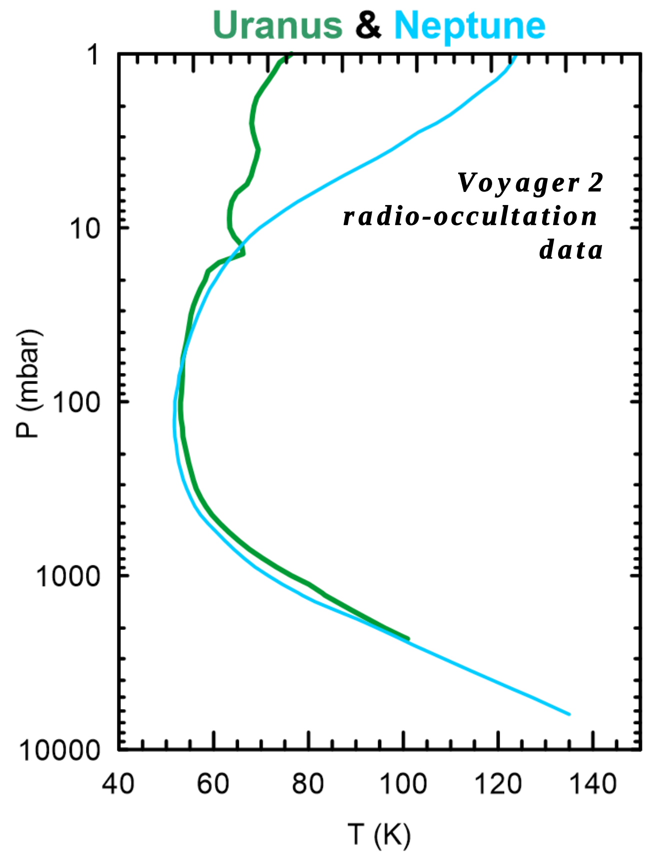
Neptune

$$T_{eq} = 46.6 \pm 1.1 \text{ K}$$

$$T_{eff} = 59.3 \pm 0.08 \text{ K}$$

$$E = \left(T_{eff} / T_{eq}\right)^4 = 2.61 \pm 0.28$$

Pollack et al., 1986 (bolometric albedos)
Pearl et al., 1990 & 1991 (global spectra)

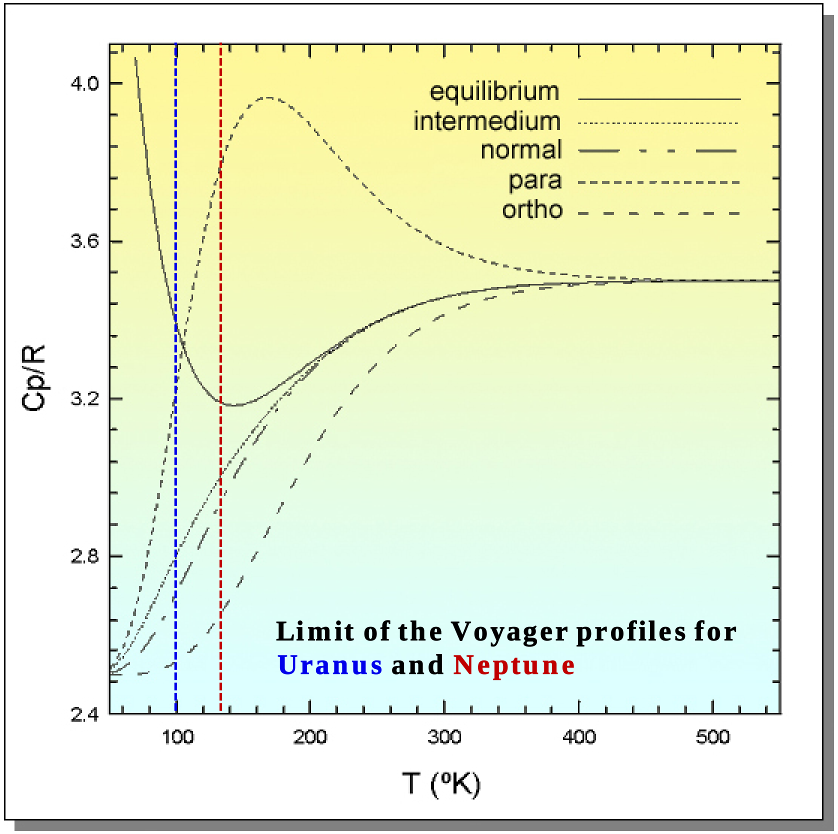


Lindal et al. (1991, 1992)

$$\textit{Uranus}: \quad T_{eq}(1 \text{ bar}) = 76.4 \text{ K}$$

$$\textit{Neptune}: \quad T_{eq}(1 \text{ bar}) = 71.5 \text{ K}$$

Internal heat source and inner distribution of heat



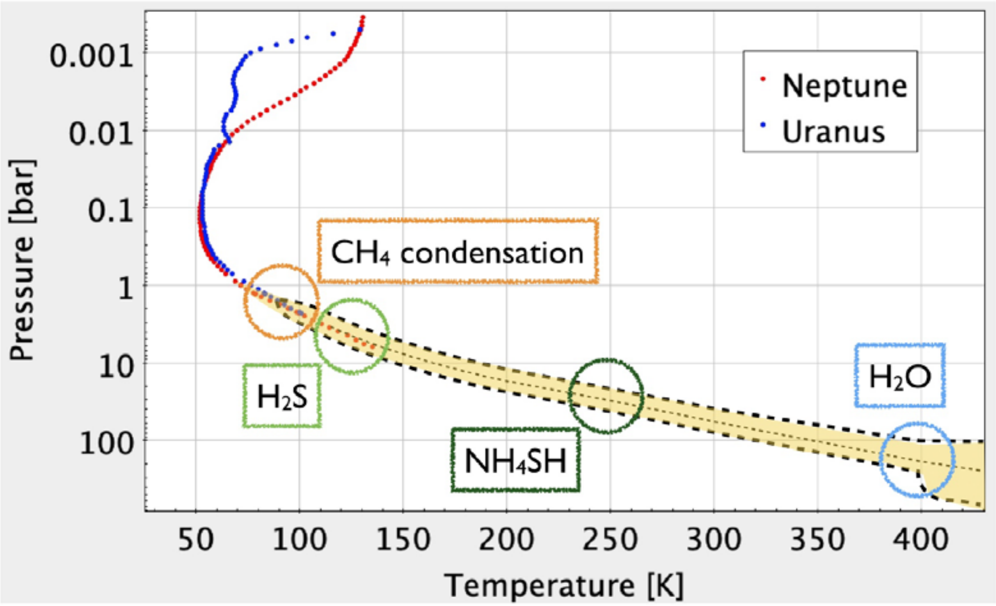


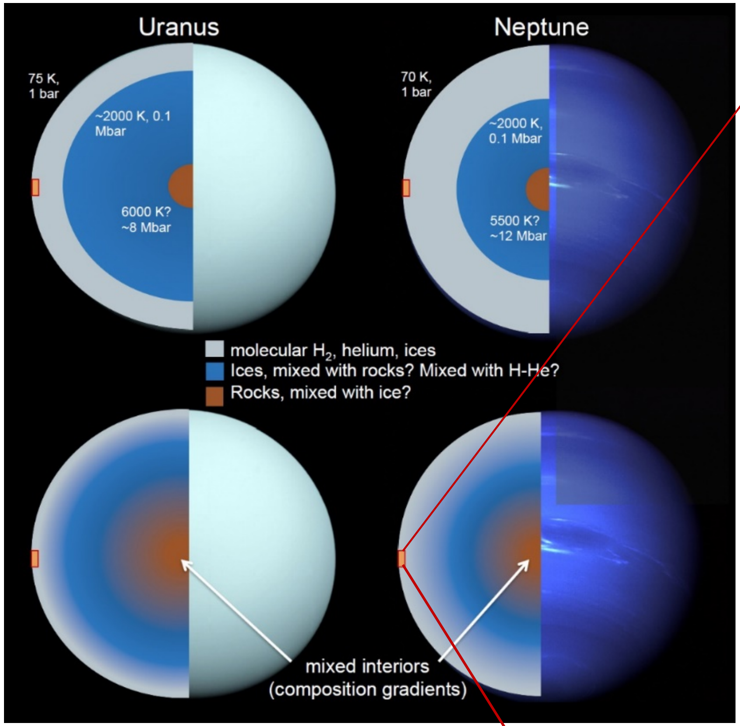
Figure from Guillot, White Paper *to* ESA Voyage 2050

$$\frac{dT}{T} = \frac{R_{dry}}{C_P(T)}\frac{dP}{P}\left(\frac{1+\dfrac{L_i\left(\mu_{vi}/\mu_d\right)f_i}{R_iT_v}}{1+\dfrac{L_i^2\left(\mu_{vi}/\mu_d\right)f_i}{C_pR_cT^2}}\right)$$

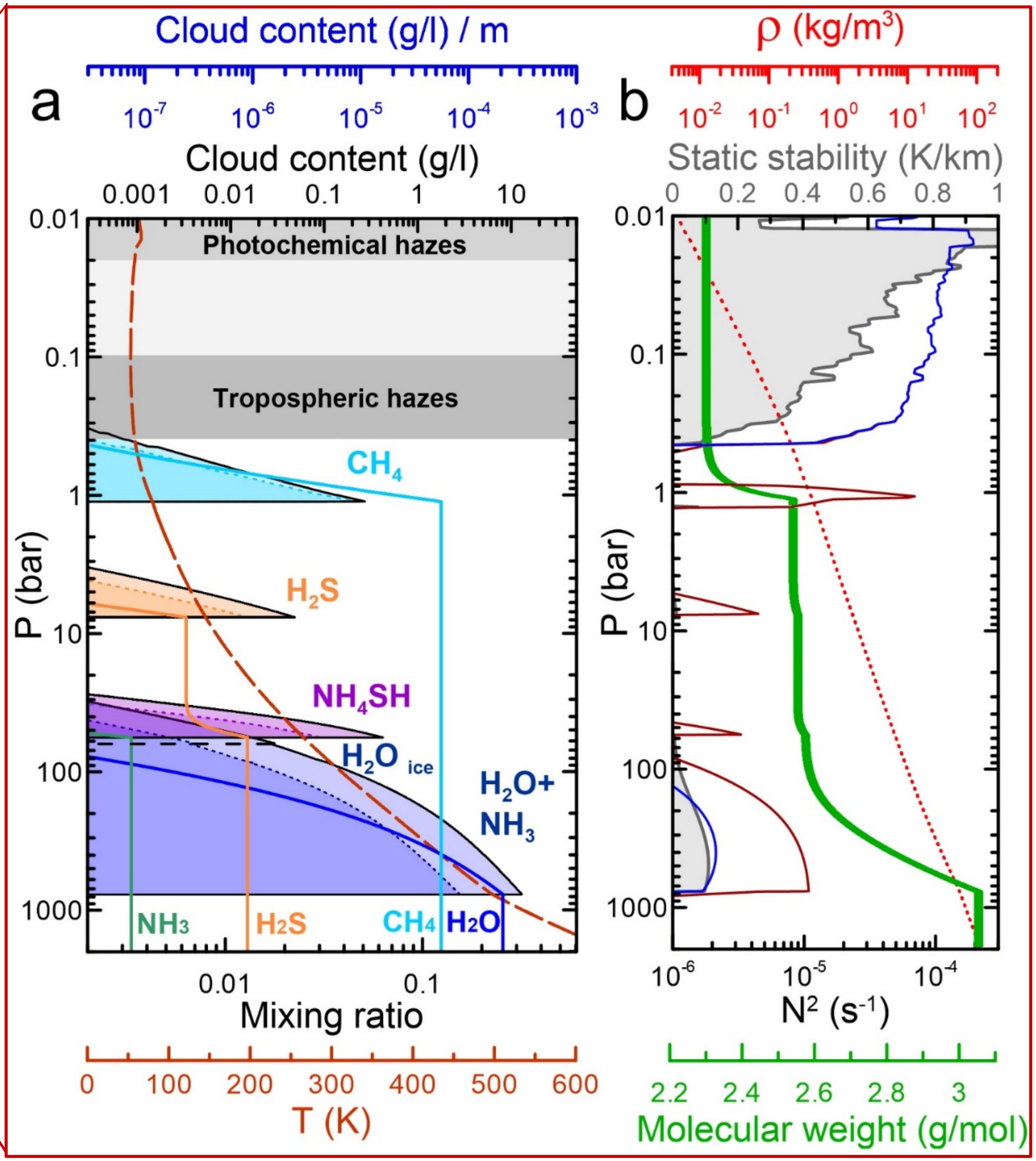
μ = molecular weight of the atmosphere
μ_d = molecular weight of the dry air
μ_{vi} = molecular weight of the vapor i

f_i = mixing ratio of vapor i

Observations of the atmosphere: The tip of extended weather layers

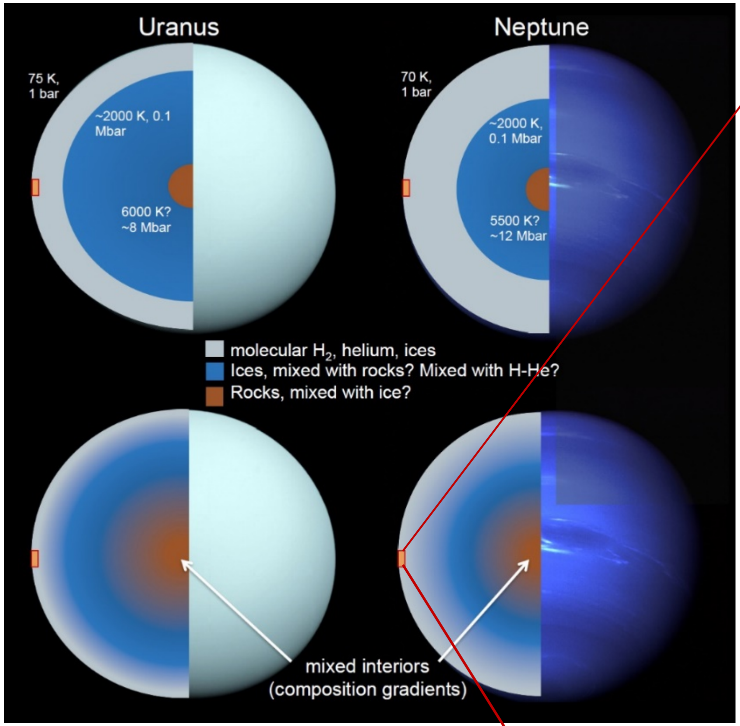


Helled et al. SSR, 2020



Hueso & Sánchez-Lavega, SSR, 2020

Observations of the atmosphere: The tip of extended weather layers



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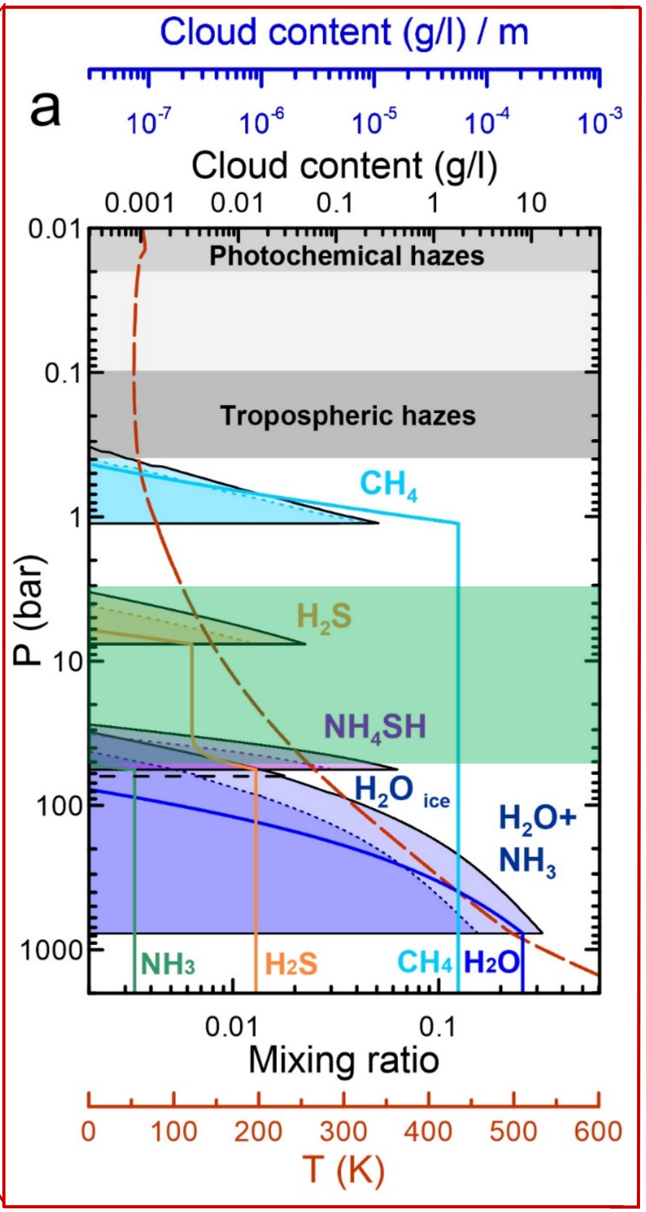


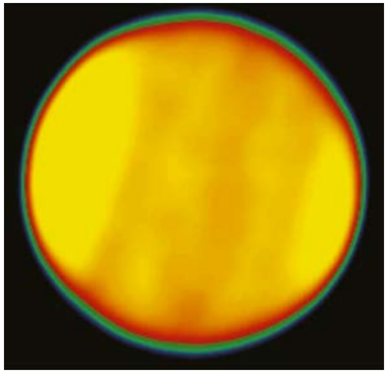
Hueso & Sánchez-Lavega, SSR, 2020

Thermal IR

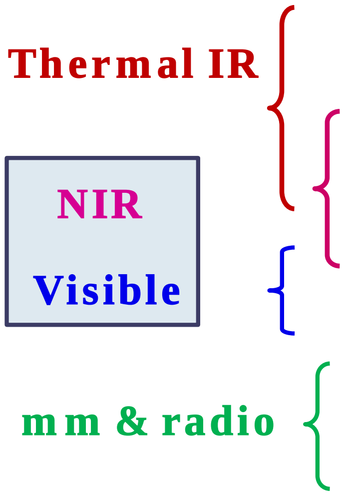
NIR

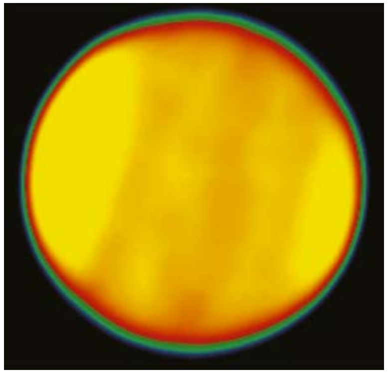
Visible

mm & radio



de Pater, Nat. Astron.2018 from data by Mark Hofstadter and Bryan Butler





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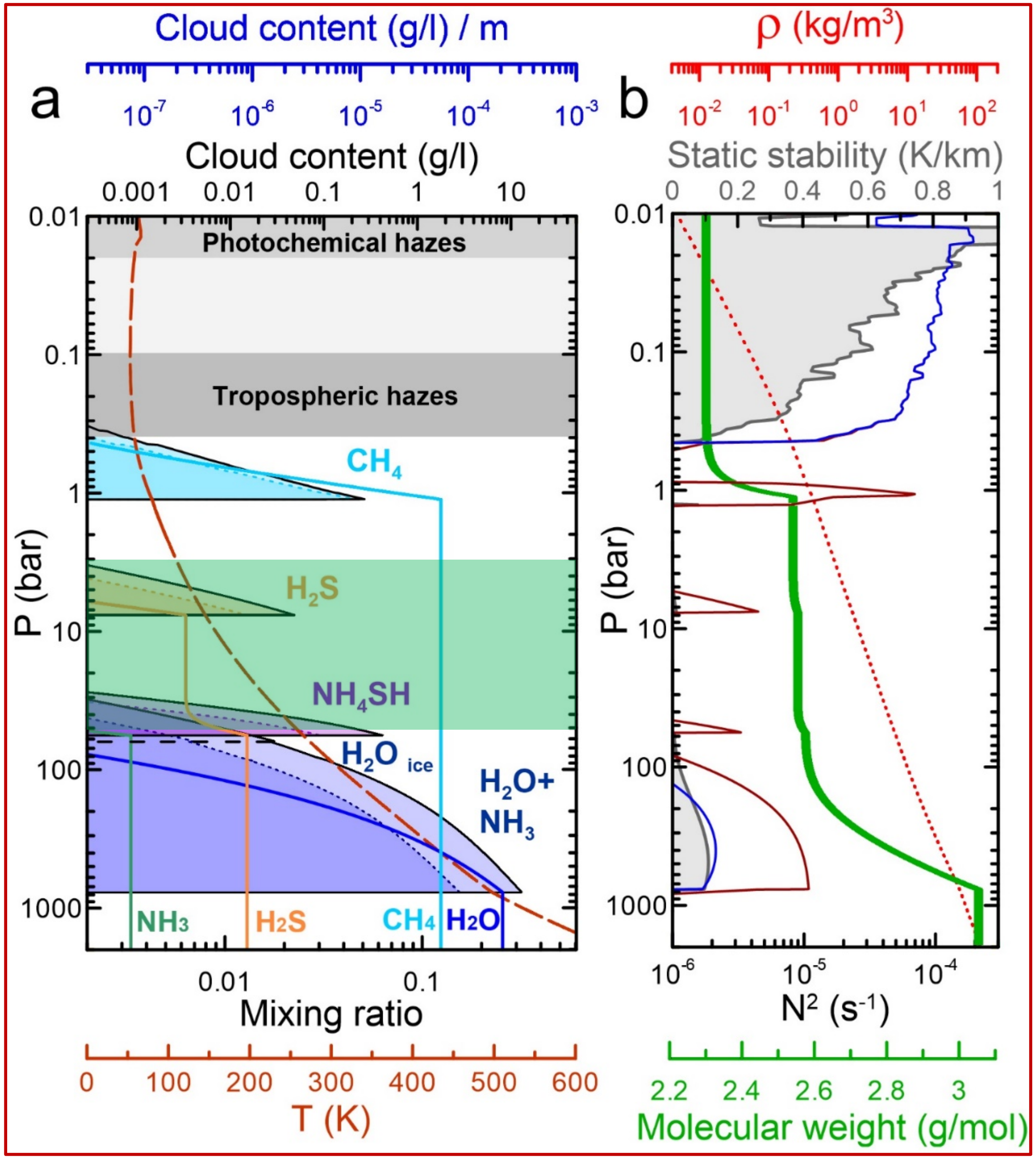
from data by Mark Hofstadter
and Bryan Butler

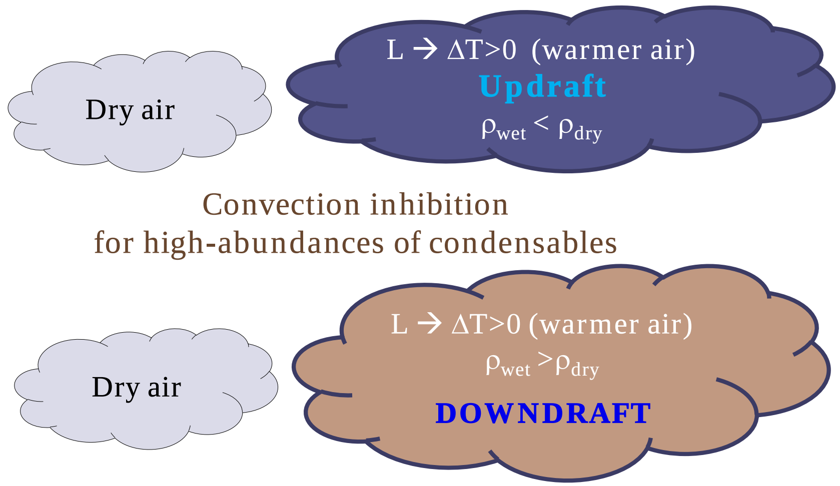


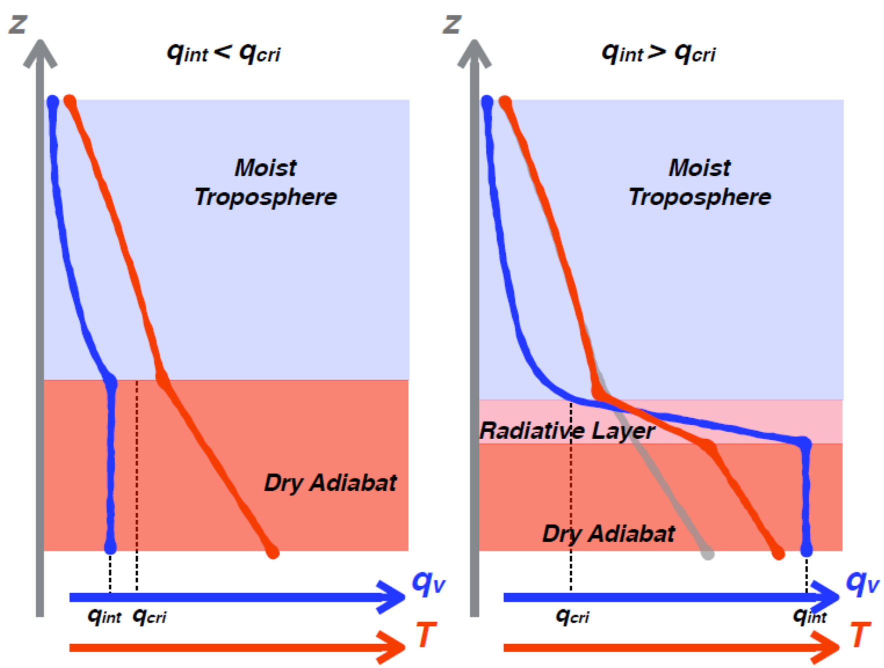
Inhibition of methane and “deep” water convection

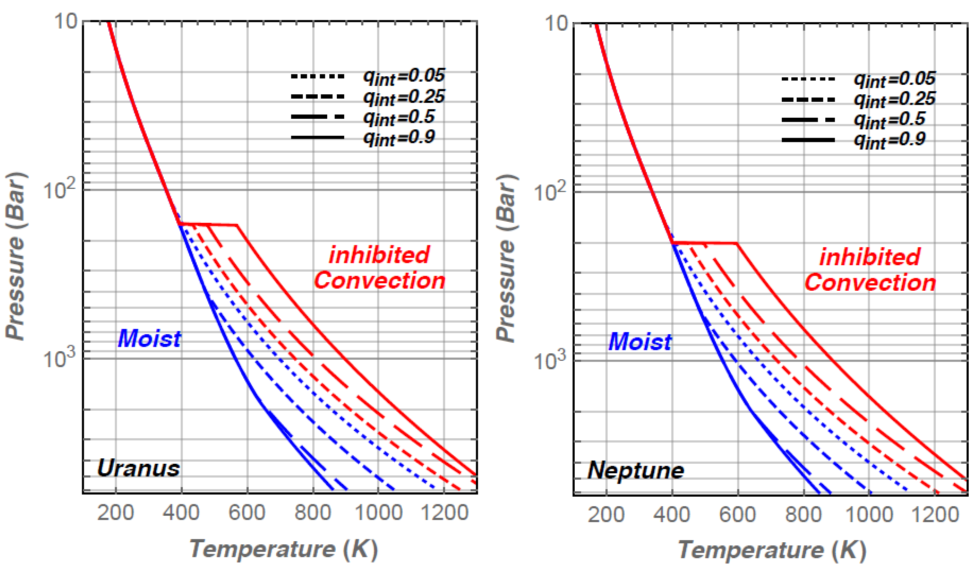
Guillot, Science, 1995

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

2 Mechanisms for convection

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

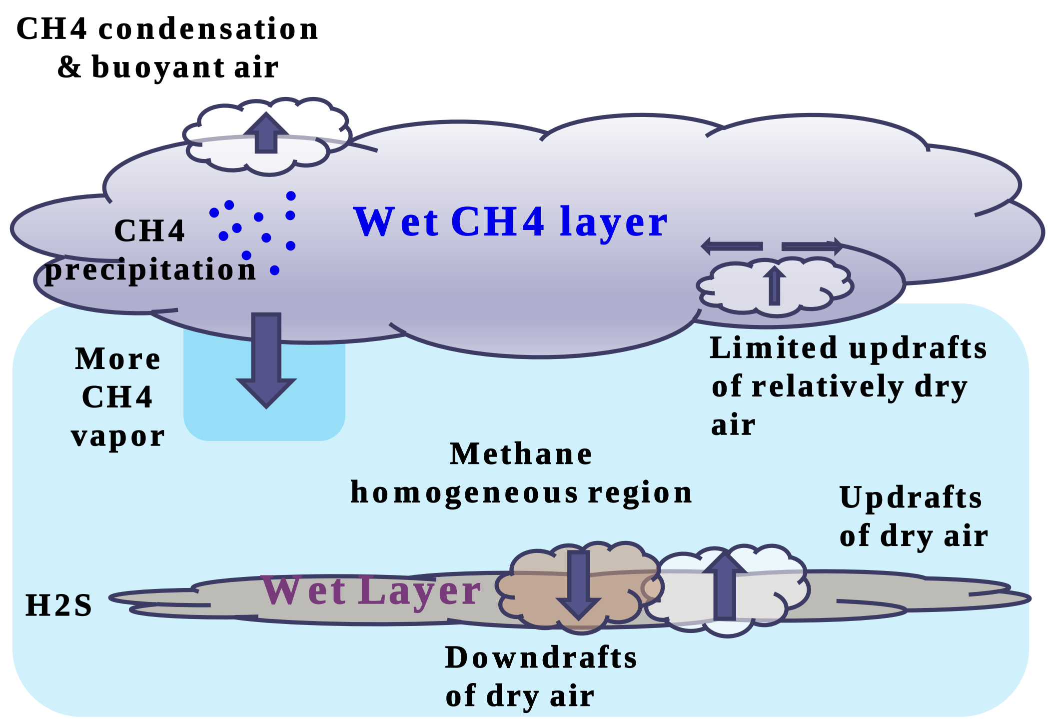
Methane could have both:

i) conventional moist convection through condensation

ii) non-conventional drier air convection (weak shallow convection)

H2S could power dry convection in updrafts

(critically depends on the deep abundance of H2S and also on NH3 since it desiccates H2S)



Some relevant and unanswered questions

- **How is the vertical wind shear at depth?**

- **What's the vertical extension of the "weather layer"?**

  What are the abundances of condensables at depth?

  Probably this requires a combination of a probe and Juno-like radio measurements

- **What are the effects of seasons?**

  Flux of internal heat, cycles of convection at the deep water cloud)

- **How strong is methane convection in Uranus and Neptune? Are there evidences of H2S-related meteorology?**

  More rad-transfer analysis of existing observations

  More theoretical work needs to be made on moist convection

In situ measurements of abundances and Juno-MWR like maps are needed and could produce substantial surprises.