Uranus & Neptune:
Formation, Evolution, and Interior Structure in Solar and Exrasolar Systems

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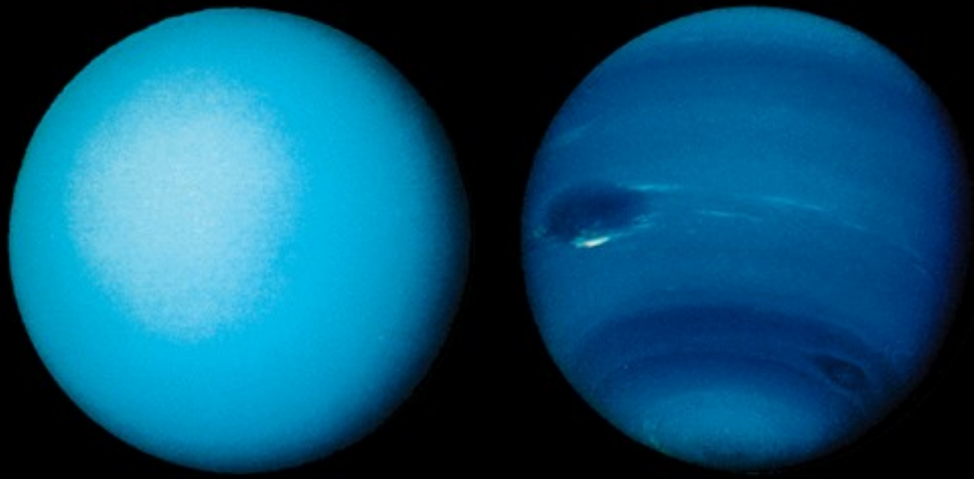
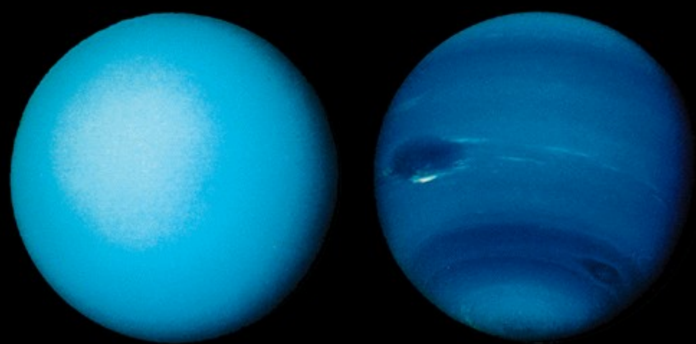
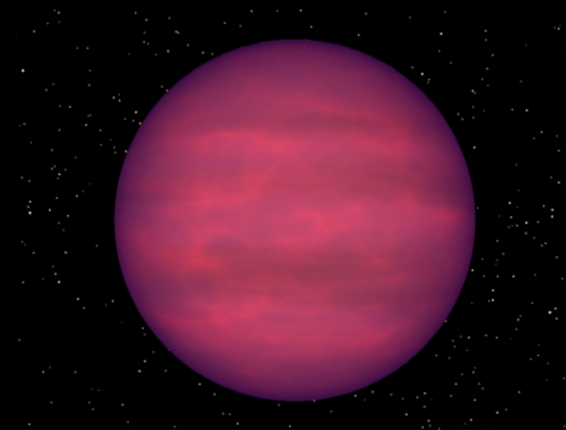


Solar and Extrasolar Planets





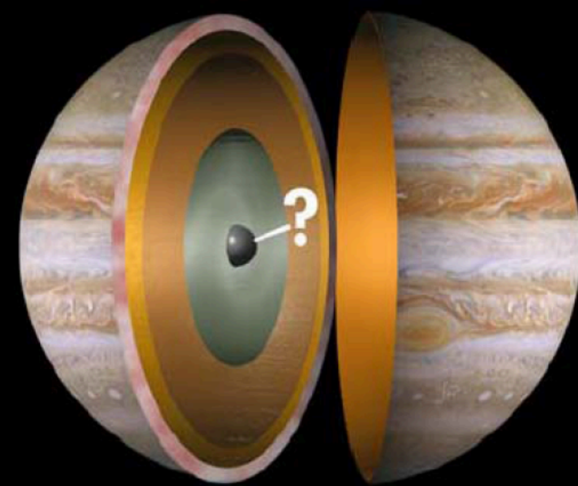
- ***Our goal:*** improve our understanding of low-mass planets
- ***Why?*** (1) Planetary interiors are the key for understanding the formation of planetary systems. (2) Planetary composition teaches us about the physical properties of the solar nebula.

Uranus and Neptune are the

Super-Earths/Mini-Neptunes of the Solar System

Observational Constraints for Interior Modeling:

- Mass
- Radius (usually equatorial)
- Angular velocity ω
- Gravitational Moments (up to J_6)
- 1 bar Temperature
- He/H ratio in the atmosphere



- **What about magnetic field, moment of inertia, shape?**

The external gravitational potential of a planet

$$U = \frac{GM}{r}\left(1 - \sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{2n} \mathrm{J}_{2n}\mathrm{P}_{2n}(\cos\theta)\right) + \frac{1}{2}\omega^2 r^2 \sin^2\theta.$$

with GM and J_{2n} → constrain the interior density:

$$M = \iiint \rho(r,\theta) d^3\tau,$$

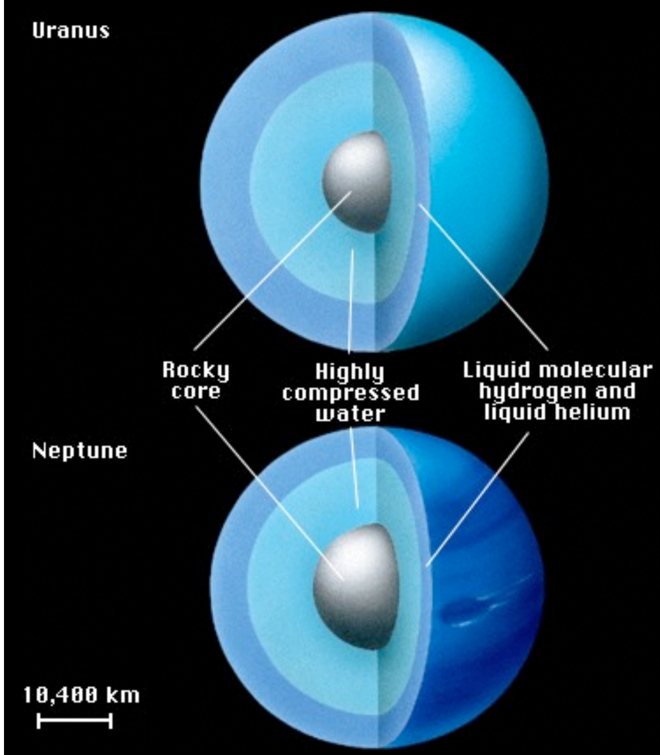
$$J_{2i} = -\frac{1}{MR_{\mathrm{eq}}^{2i}} \iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau.$$

dτ is a volume element - the integrals are performed over the entire planetary volume

Uranus and Neptune
the "Icy (?) Planets"

Uranus: 14.5 $M_{\oplus}$ @ 19.2 AU
Neptune: 17.1 $M_{\oplus}$ @ 30 AU

"Standard" Composition: rocks, ices, and H/He atmosphere



Similarities: Mass, Radius, Rotation, Radial Distance

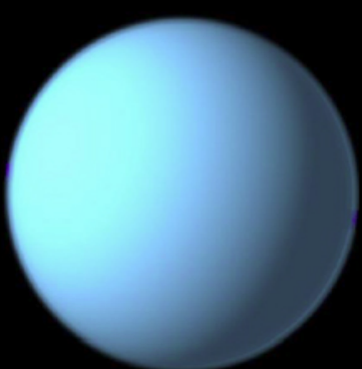
Differences: Heat Flux, Atmospheric Enrichment, Tilt, Satellite System

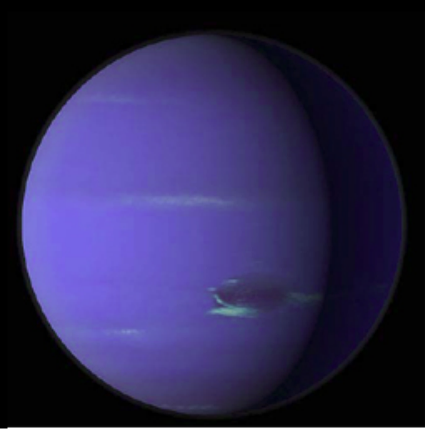
Uranus and Neptune

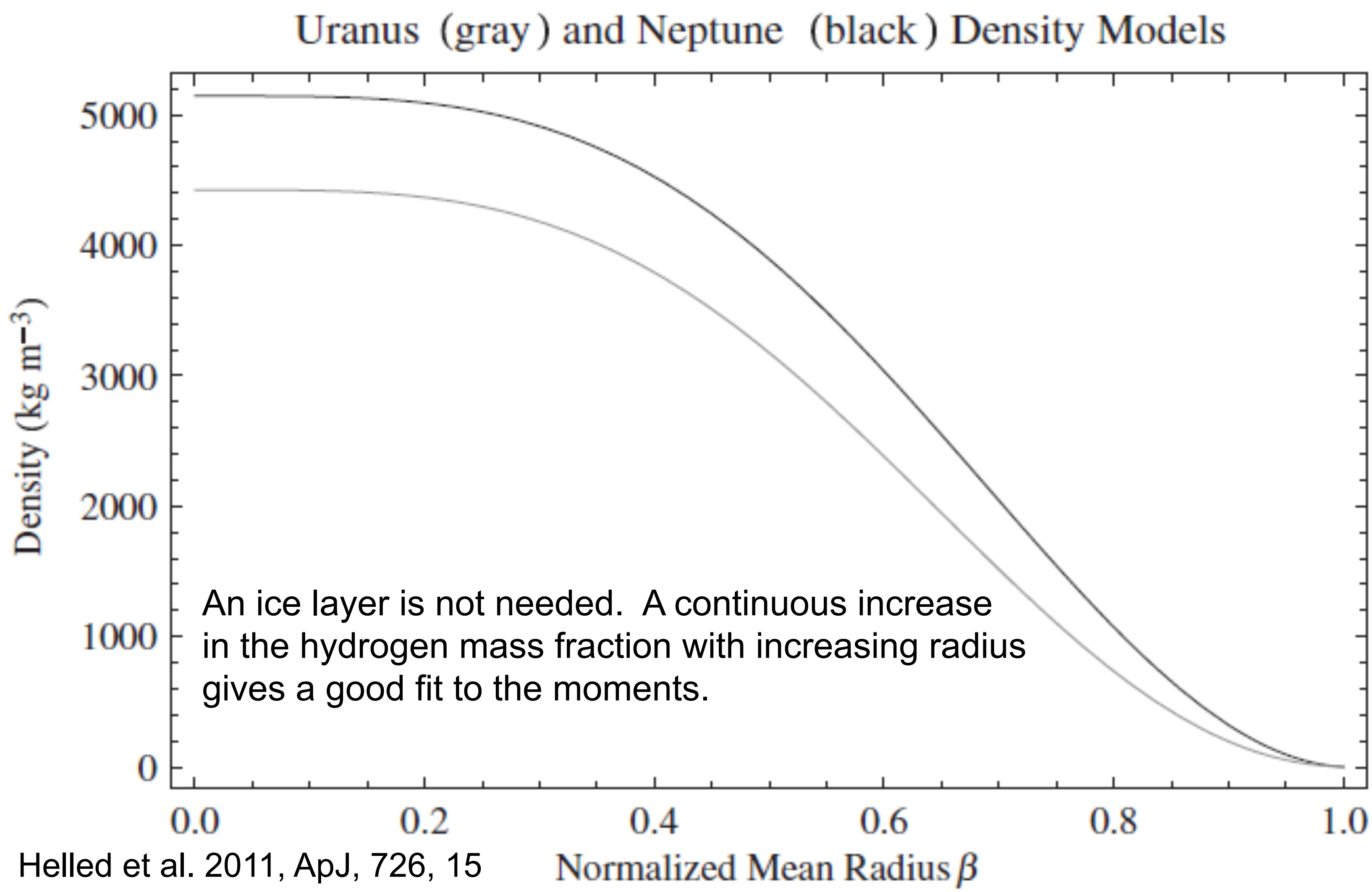
For Uranus and Neptune only J_2 and J_4 are available

- <u>Standard models:</u>
  - Inner region: rocky core ~ 25%
  - Ices (mostly H_2O) ~ 60-70%
  - *H* and *He* atmosphere ~ 5-15%

A large range of possible internal structures ➔ composition is unknown

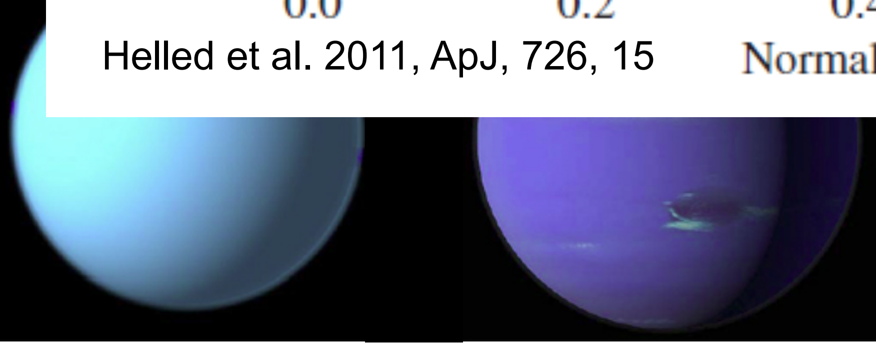






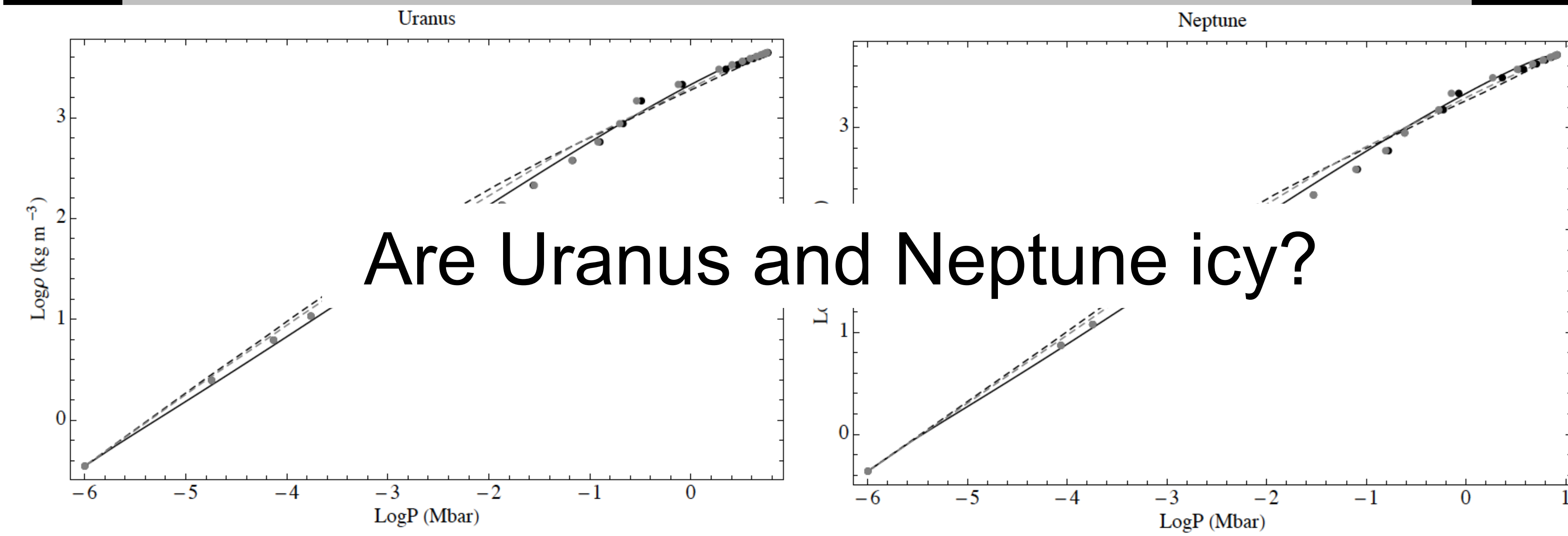
An ice layer is not needed. A continuous increase in the hydrogen mass fraction with increasing radius gives a good fit to the moments.

Helled et al. 2011, ApJ, 726, 15



Uranus and Neptune

The gravity data is ***insufficient*** to constrain the planetary composition



Are Uranus and Neptune icy?

Helled et al., 2011, ApJ, 726, 15

Reasons to believe they have water:

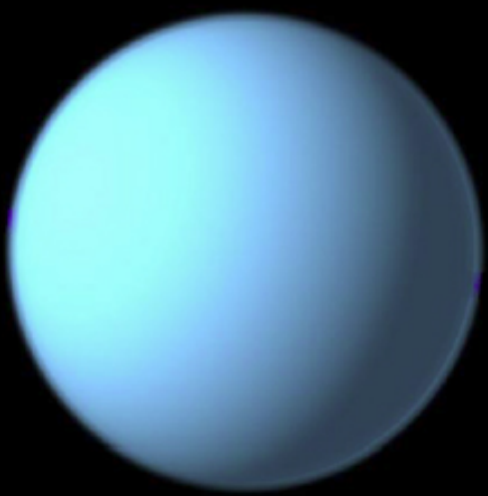
(1) Magnetic fields – ***is it really?***

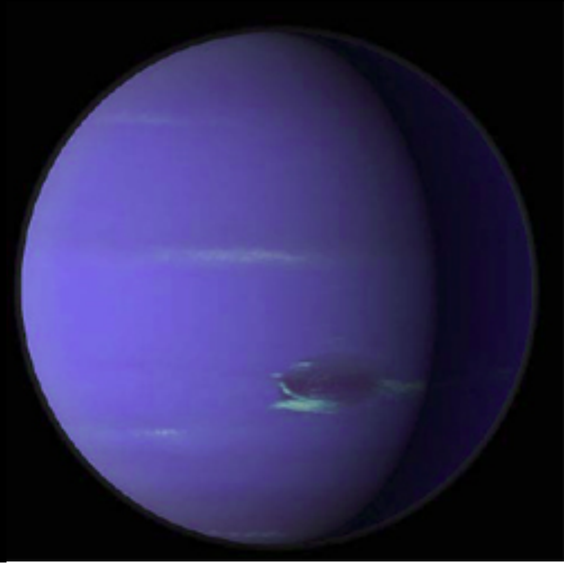
(2) Water is abundant at these distances – ***what about Pluto?***

The Rotation Periods of Uranus and Neptune

- What are the rotation periods of Uranus and Neptune?
  - Complex multipolar nature of magnetic fields
  - Where are the magnetic fields generated?

Rotation period is important because it is used by interior models

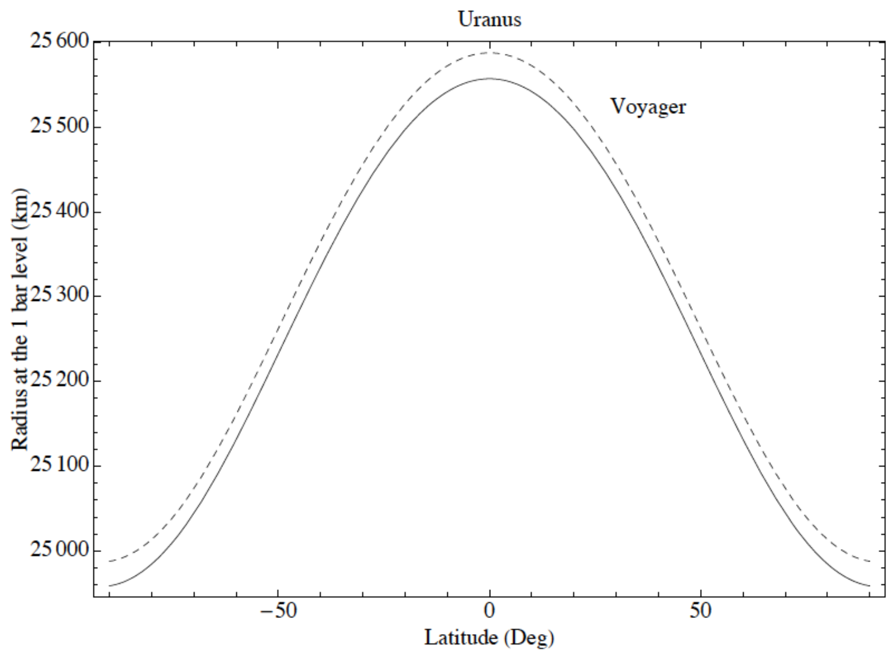


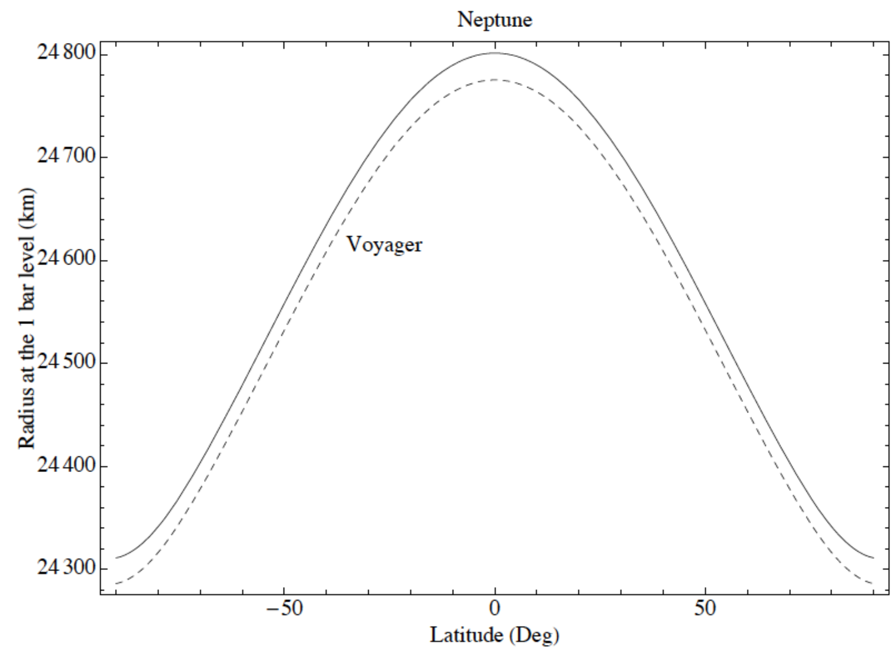


Zonal wind velocities for geoids and solid body rotation rates that minimize the dynamical heights and modified shapes
U: 17.24h ➔ 16.58h; N: 16.11h ➔ 17.46hs

Uranus: **P ~ 16.58h (V: 17.24h)**

Neptune: **P ~ 17.46h (V: 16.11h)**



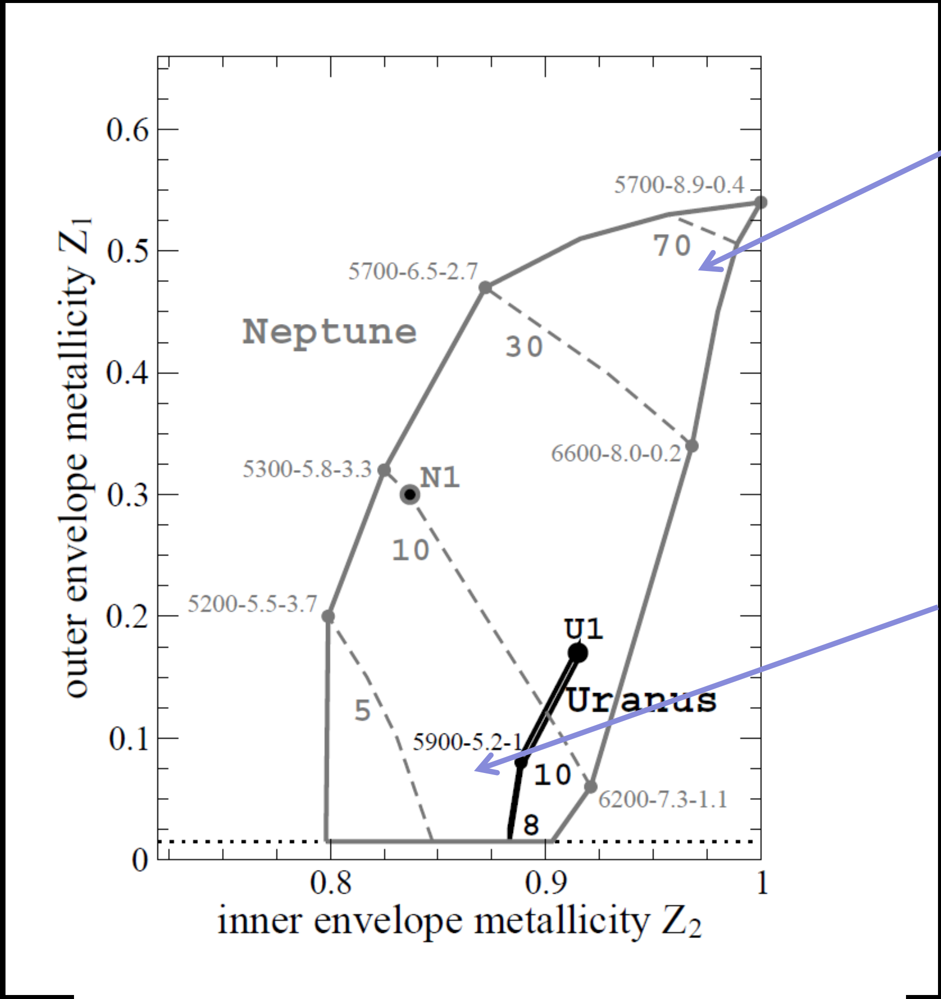


Helled et al., 2010, Icarus, 210, 446

Interior models

black/gray lines - Voyager rotation periods

blue/turquoise lines - modified rotation periods (Helled et al., 2010)



Transition pressure (Gpa)

T_c (K), P_c (Mbar), M_{core} /M_{Earth}

Mass fraction of metals in the outer envelope (Z_1) and in the inner envelope (Z_2) 3-layer models of Uranus and Neptune
Nettelmann, Helled, Fortney, Redmer, PSS, 2012

Interior models with modified rotation

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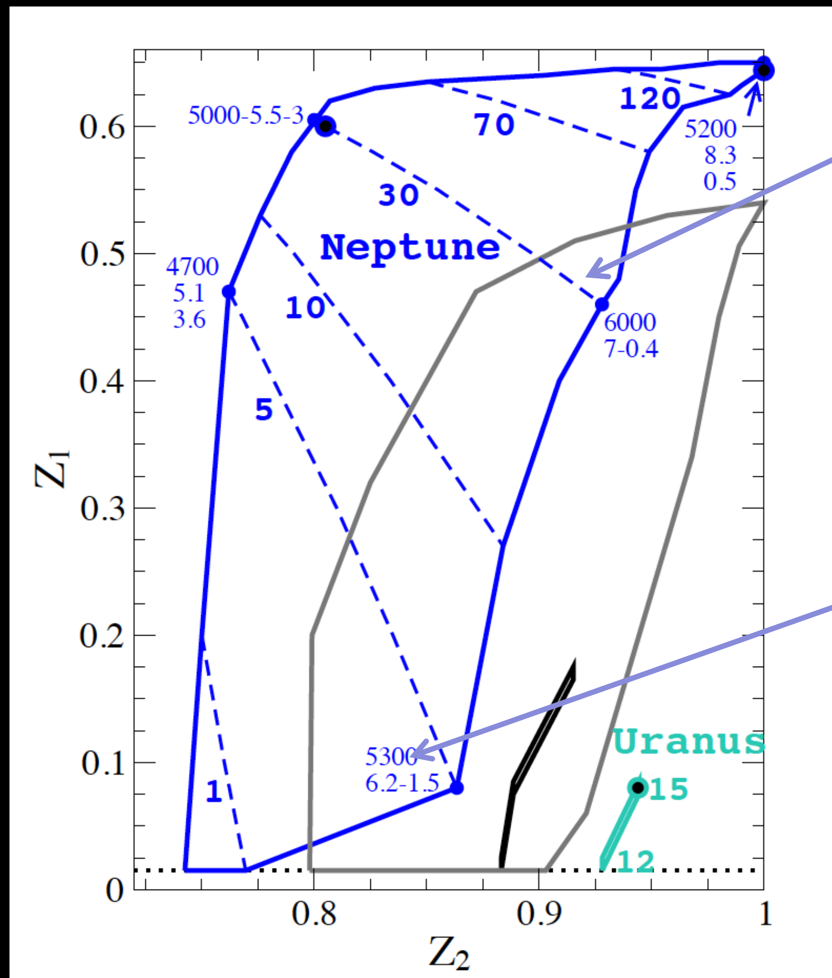

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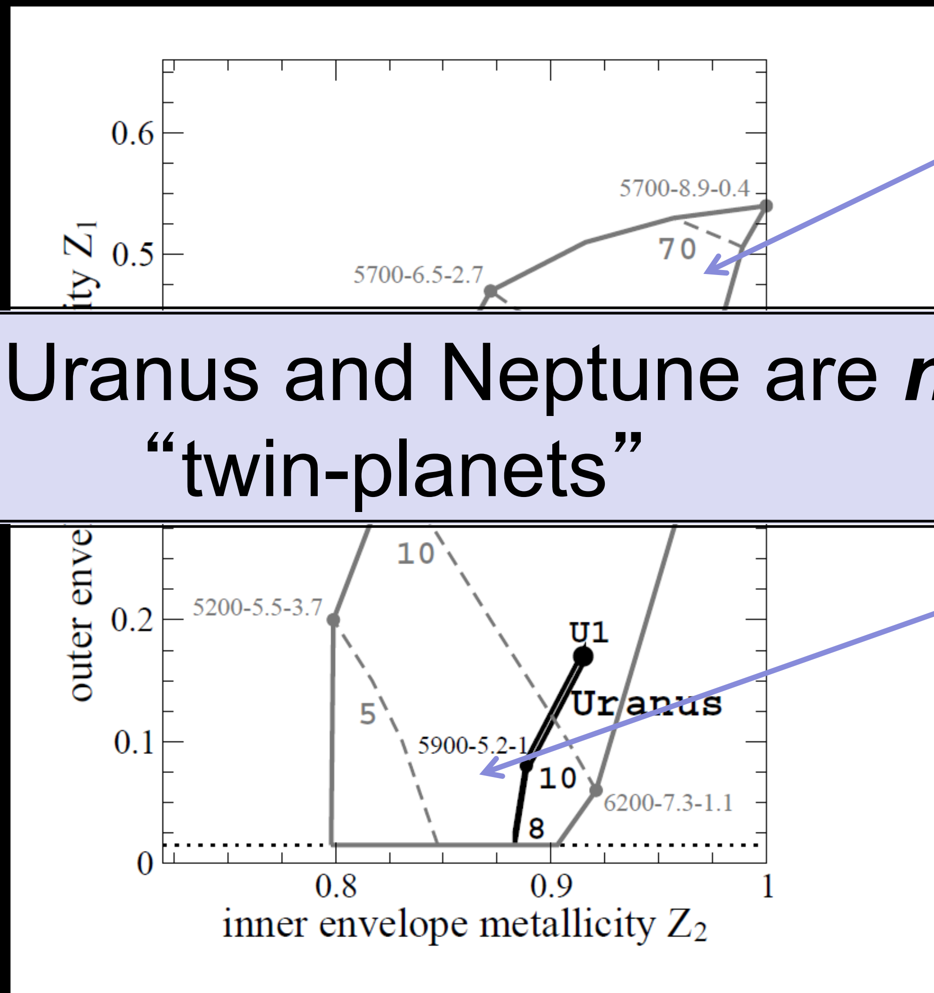

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Maybe Uranus and Neptune are *not* "twin-planets"

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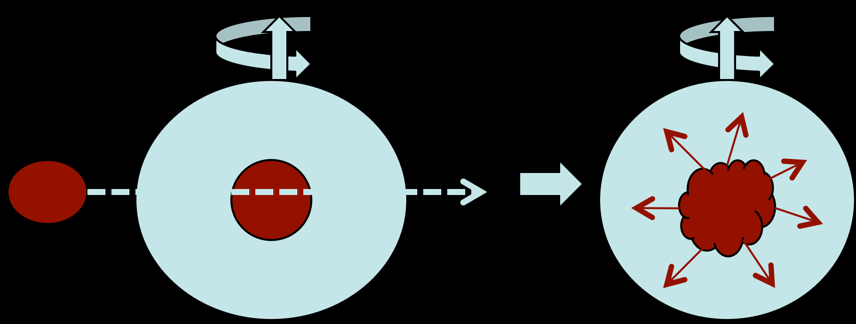
Nettelmann, Helled, Fortney, Redmer, PSS, 2012

Giant impacts: tilt and internal flux

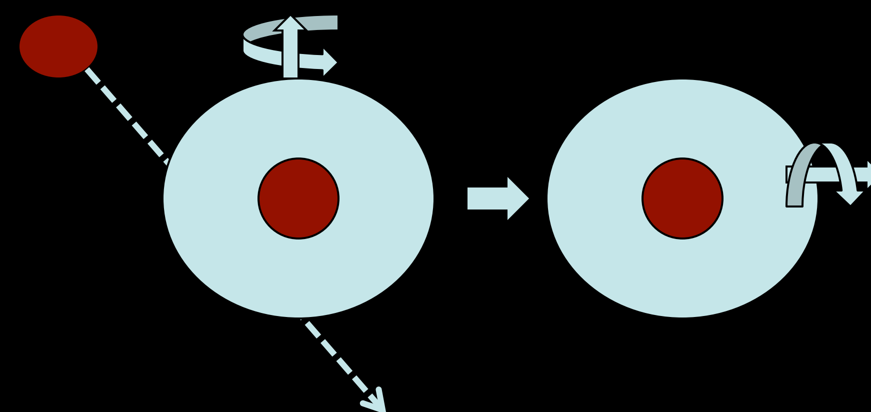
- Uranus is tilted and has very low internal flux – are these two connected??

Neptune: Radial Collision



Enough energy to mix the Core: Mixed and adiabatic interior, efficient cooling

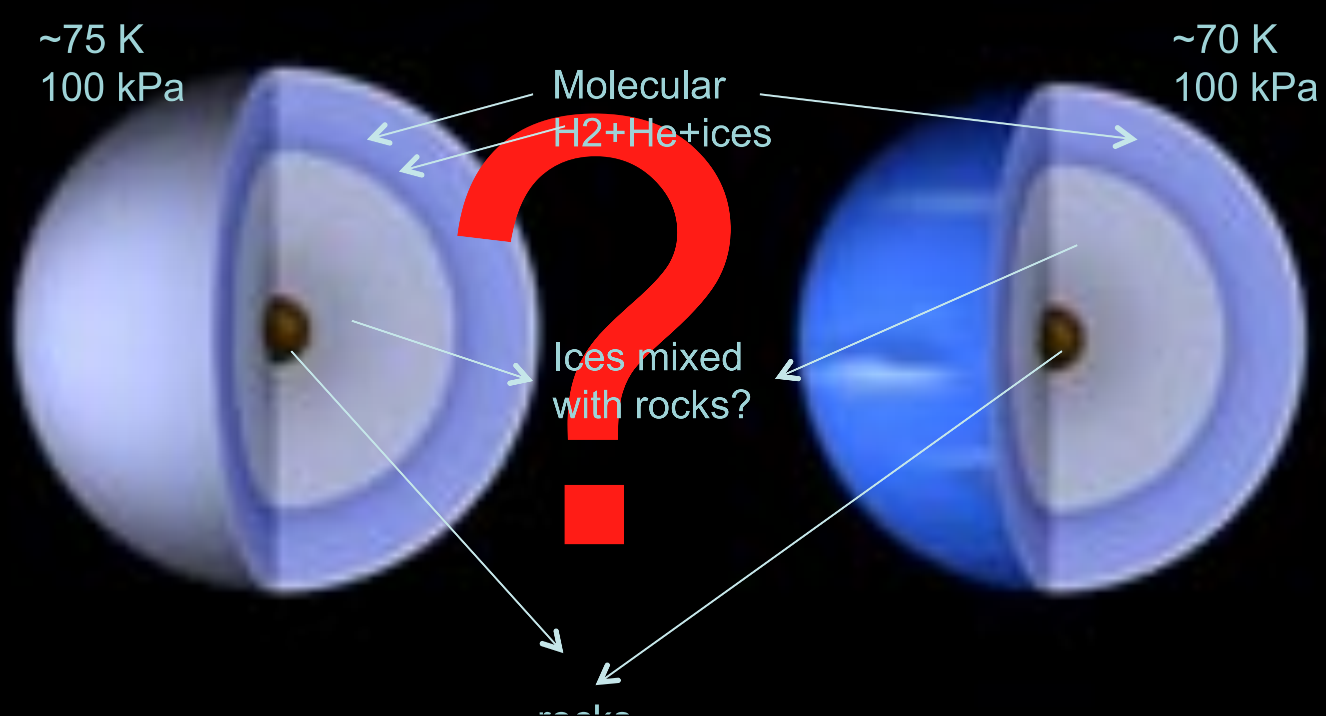
Uranus: Oblique Collision



Angular momentum deposition: Core, convection is inhibited → slow cooling, tilt

Podolak & Helled, 2012, ApJL, in press

Uranus and Neptune



Important for understanding extrasolar planets in this mass regime!

- What are Uranus and Neptune made of? Are they Icy? Can we neglect planetary evolution (e.g., mixing, impacts)?

- What can we really say about low-mass exoplanets? Is it reasonable to assume adiabaticity?

Stop scaling our solar system planets!

Thank you!