Gaseous and Icy Planets

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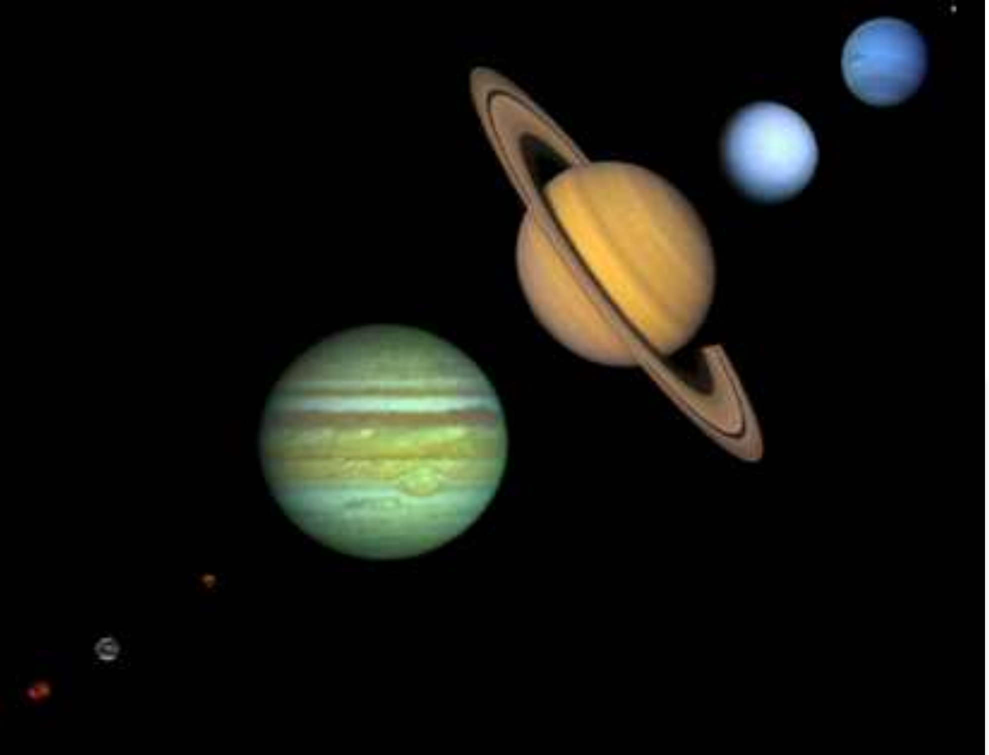
July 2013

PLATO 2.0 workshop

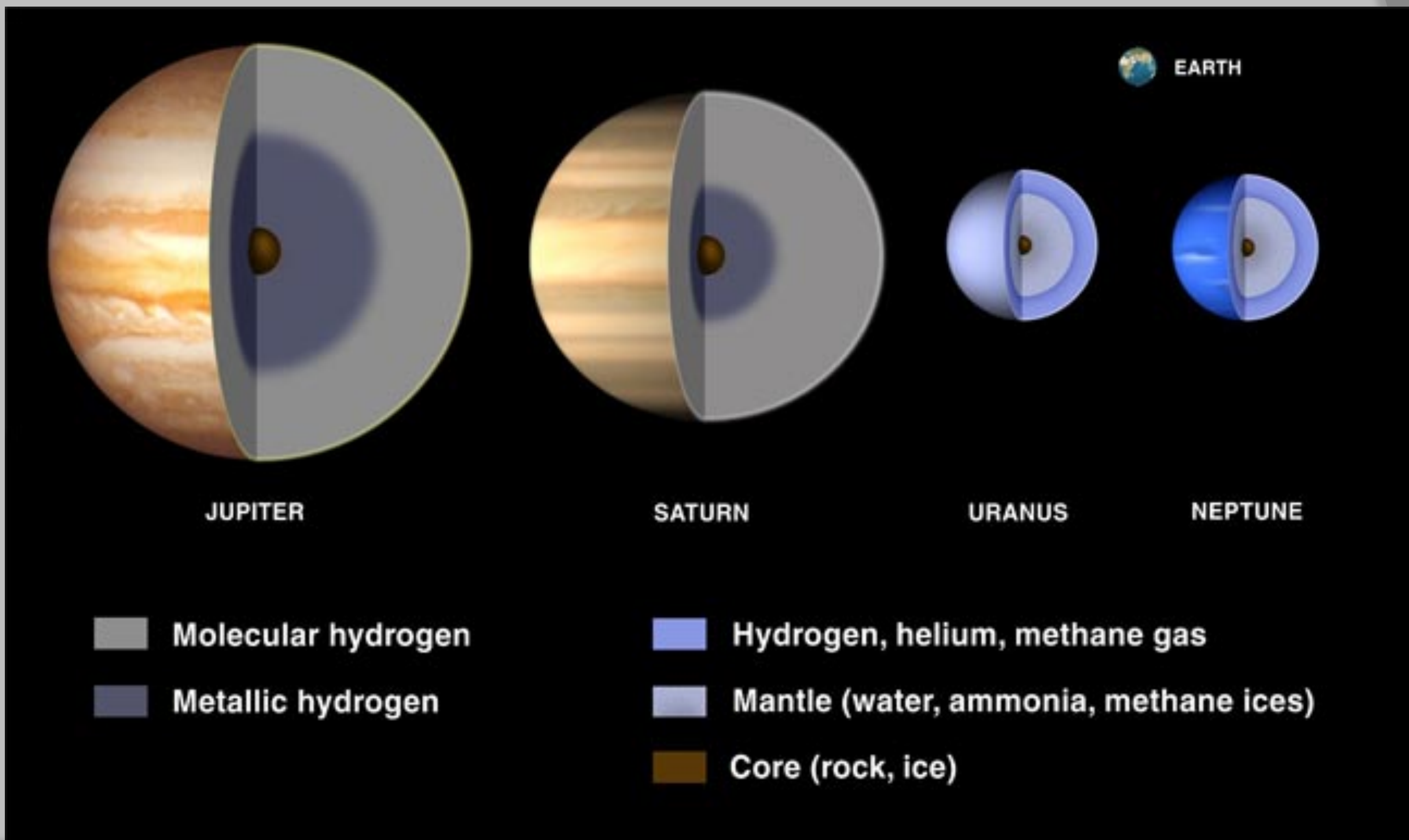


Why study planets (interiors)?

- Uniqueness of the Solar System
- Understand Planet Formation
- Planet Characterization
  - Physics and Chemistry of proto-planetary disks
  - Habitability
  - Planetary Diversity

Solar System Giant Planets

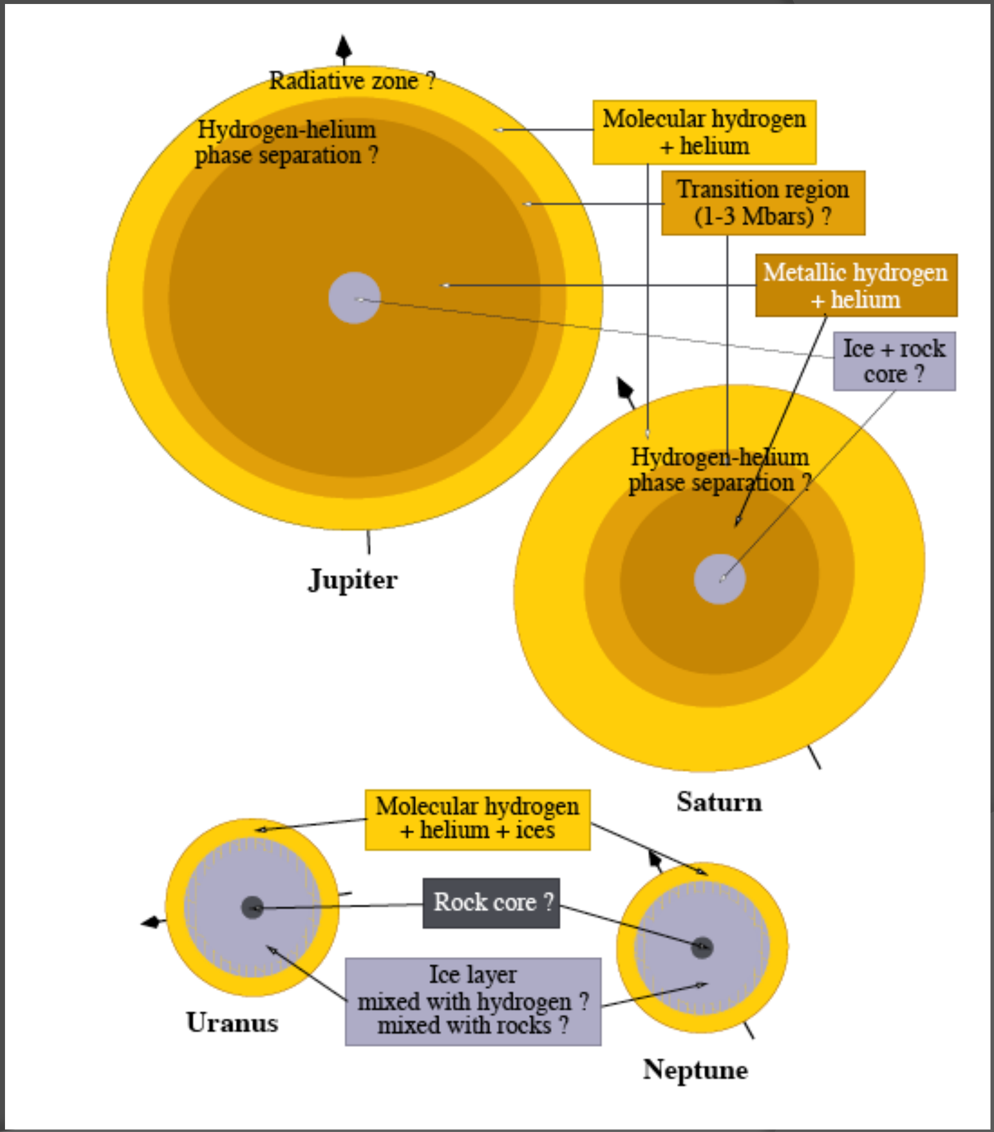
- Outer Planets



In the Solar System

Jupiter, Saturn, Uranus, Neptune

- Giant planets exist at large radial distances (> 5 AU)
- Mass is decreasing with radial distance.
- Metal enrichment is increasing with decreasing mass.



Wuchterl et al., 2000. PPIV.

In the Solar System

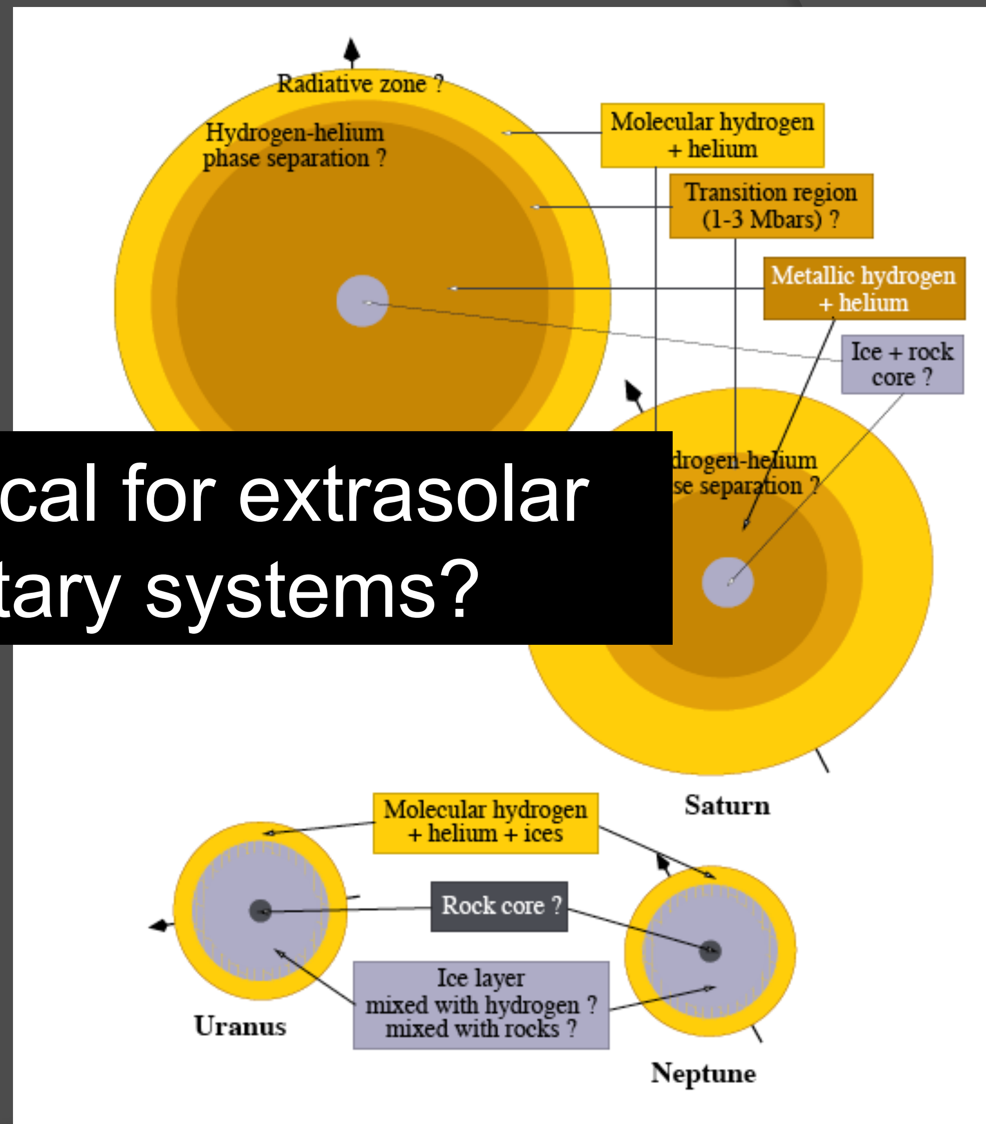
Jupiter, Saturn, Uranus, Neptune

- Giant planets
radial distance

Is this typical for extrasolar planetary systems?

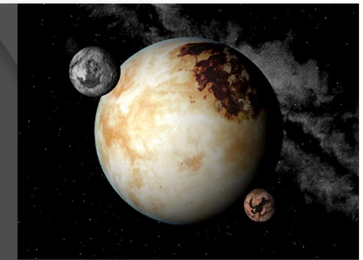
- Mass is decreasing with radial distance.

- Metal enrichment is increasing with decreasing mass.



Wuchterl et al., 2000. PPIV.

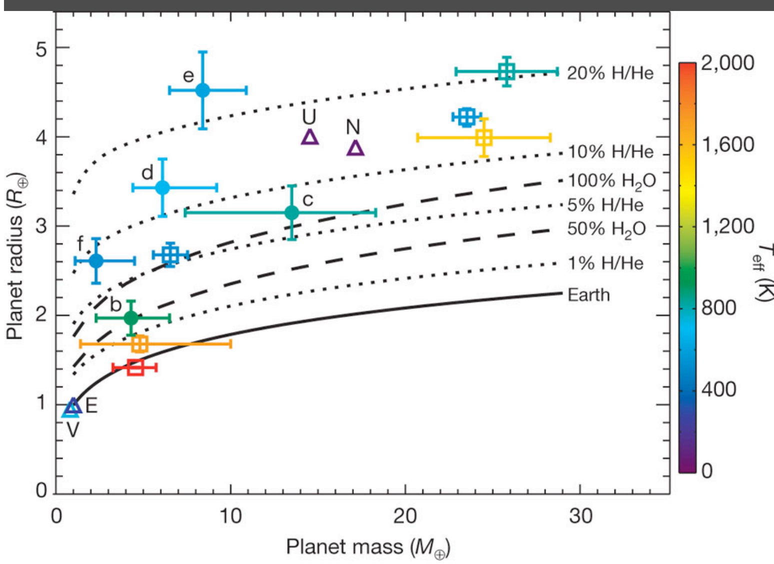
Composition of Extrasolar Planets



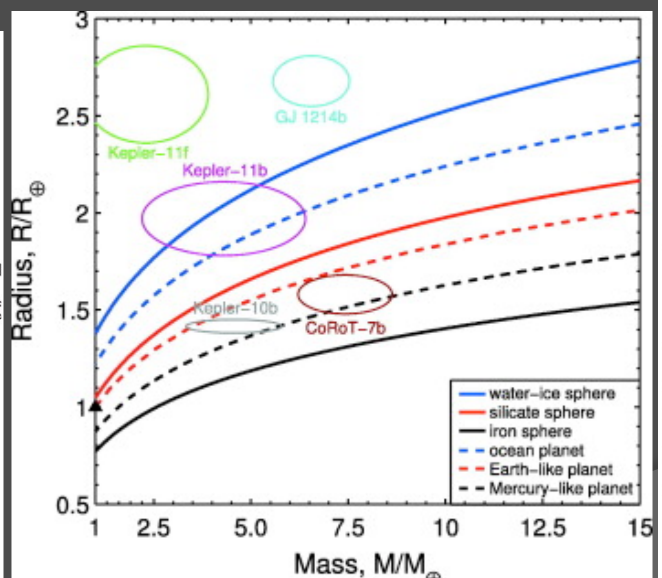
Mean density does NOT give us the distribution of the materials

A very large … mean density

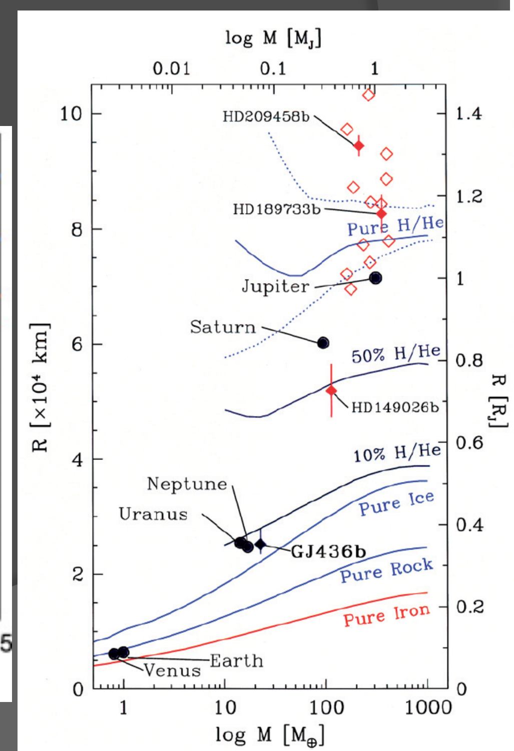
Are there compositions which are impossible? more likely?



Lissauer et al., 2011

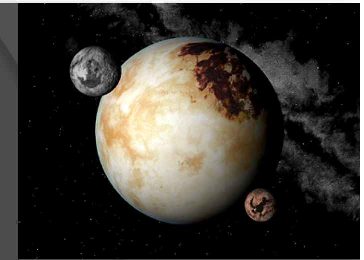


Wagner et al., 2011



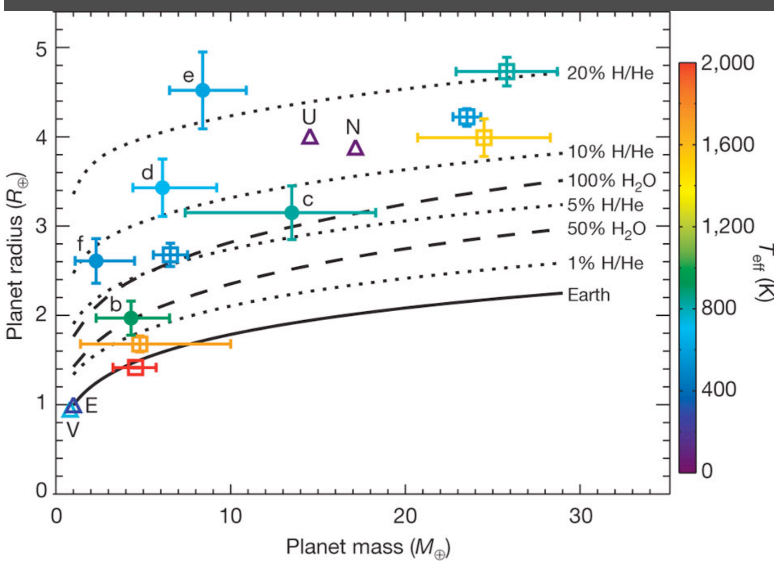
Gillon et al., 2007

Composition of Extrasolar Planets



Mean density does NOT give us the distribution of the materials

A very large range of compositions will provide the ***same*** mean density



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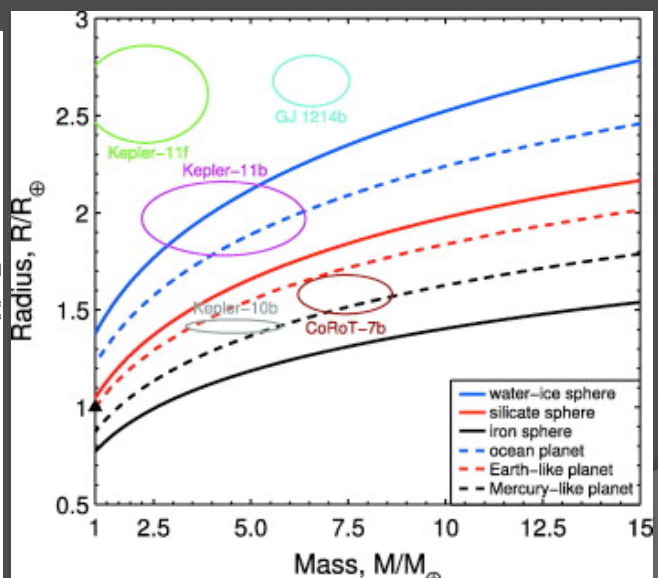

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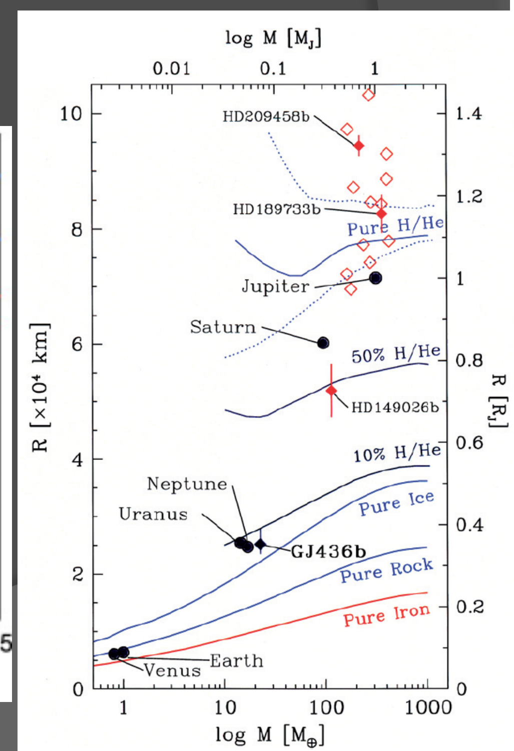


Gillon et al., 2007

Solar System Outer Planets

- Jupiter and Saturn
  - Gas planets (H, He, heavy elements)
- Uranus and Neptune
  - ‘Icy’ planets (ices, rocks, H/He atmospheres)

Modeling planetary interiors

- Basic idea: observations as constraints for interior models
  more accurate measurements → less freedom in modeling

- 'Standard' modeling gas planets: 3 layers
  - Central Core (rock/ice)
  - Inner Envelope: helium rich, metallic hydrogen
  - Outer Envelope ('atmosphere'): helium poor, molecular hydrogen

- 'Standard' modeling icy planets: 3 layers
  - Central Core (rocks)
  - Inner Envelope: ices
  - Outer Envelope ('atmosphere'): molecular hydrogen and helium

Making an interior model

- Assumptions: spherical symmetry & hydrostatic equilibrium
- **<u>Basic equations</u>**: mass conservation, hydrostatic equilibrium, heat transport, energy conservation, EOS: $P(\rho,T)$
- Interior models account for rotation (but usually solid-body!)

Theory of Figures (Zharkov & Trubitsyn, 1978):

The external gravitational potential of the planet

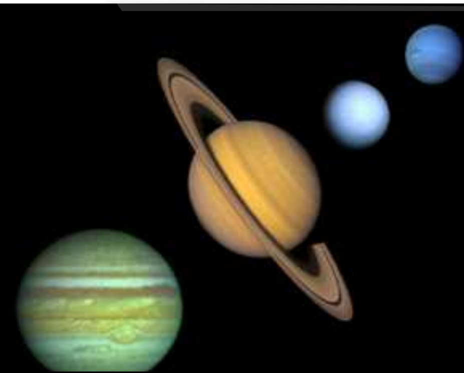
$$V_{\text{ext}}(r, \cos\theta) = \frac{GM}{r}\left[1 - \sum_{n=1}^{\infty}\left(\frac{a}{r}\right)^{2n} J_{2n} P_{2n}(\cos\theta)\right]$$

a is the equatorial radius; J_{2n} gravitational moments

With GM and J_{2n} ➔ constrain the interior density:

$$\begin{aligned} M &= \iiint \rho(r,\theta) d^3\tau, \\ J_{2i} &= -\frac{1}{MR_{\text{eq}}^{2i}} \iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau. \end{aligned}$$

$d\tau$ is a volume element - the integrals are preformed over the entire planetary volume



- J_2, J_4, J_6 are measured from Pioneer, Voyager and Cassini…
- Remember (!):
  - Constraints on the ***density profile*** of the planets
  - High-order harmonics provide information on outer regions

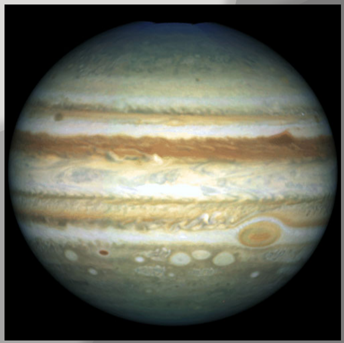
- Presence of a core is inferred ***indirectly*** from the model
- The core properties (composition, physical state) cannot be determined

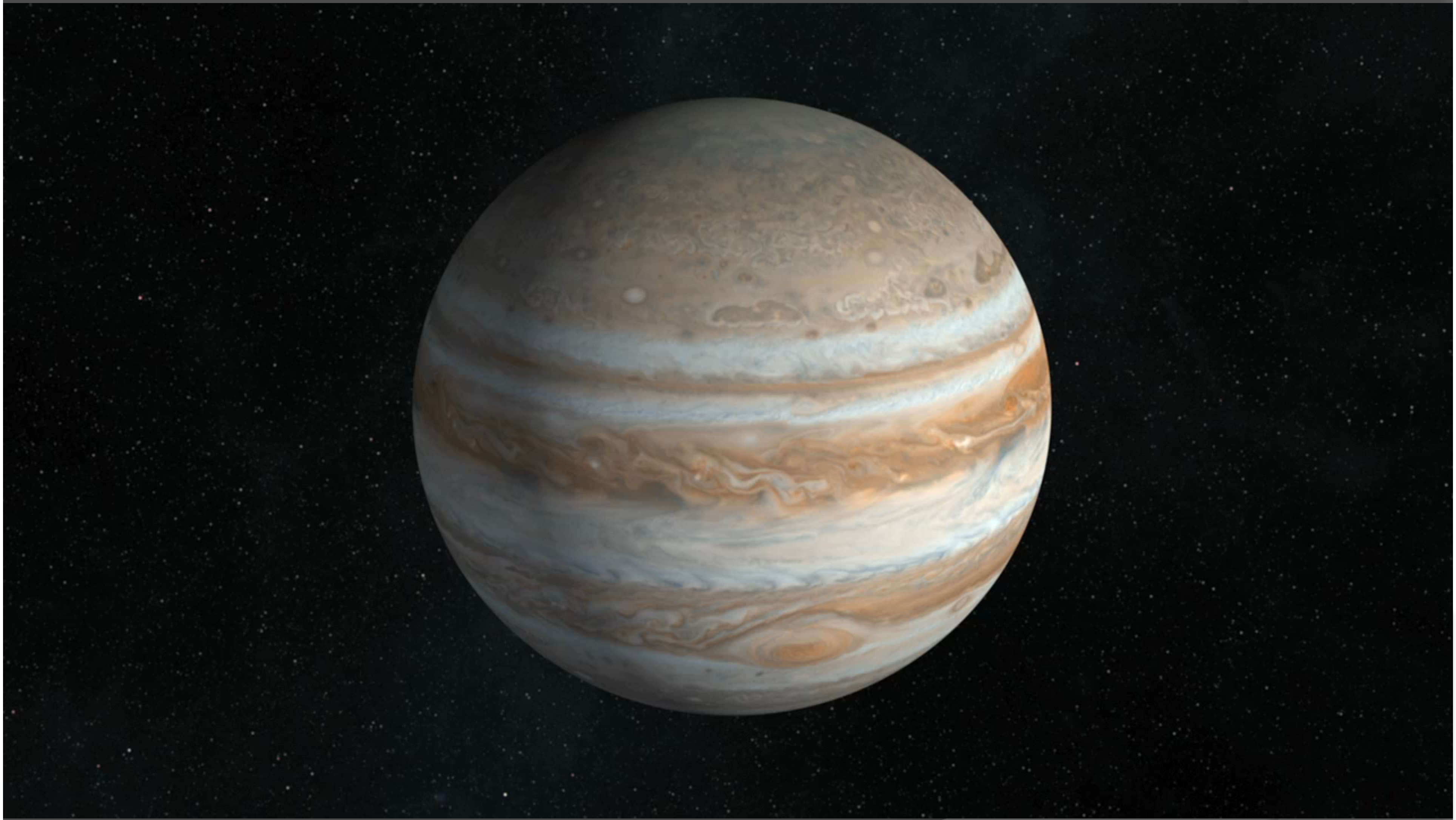
Jupiter: Uncertainties with EOS

- Jupiter’s interior: high P, T
- EOS is difficult to calculate (molecules, atoms, and ions coexist and interact).
- H/He EOS: theory & high pressure experiments

- Hydrogen EOS: deep in the interior metallic hydrogen, molecular to metallic transition (~ Mbar)

- Saumon & Guillot, 2004: Jupiter interior models using a careful study of the uncertainties in EOSs

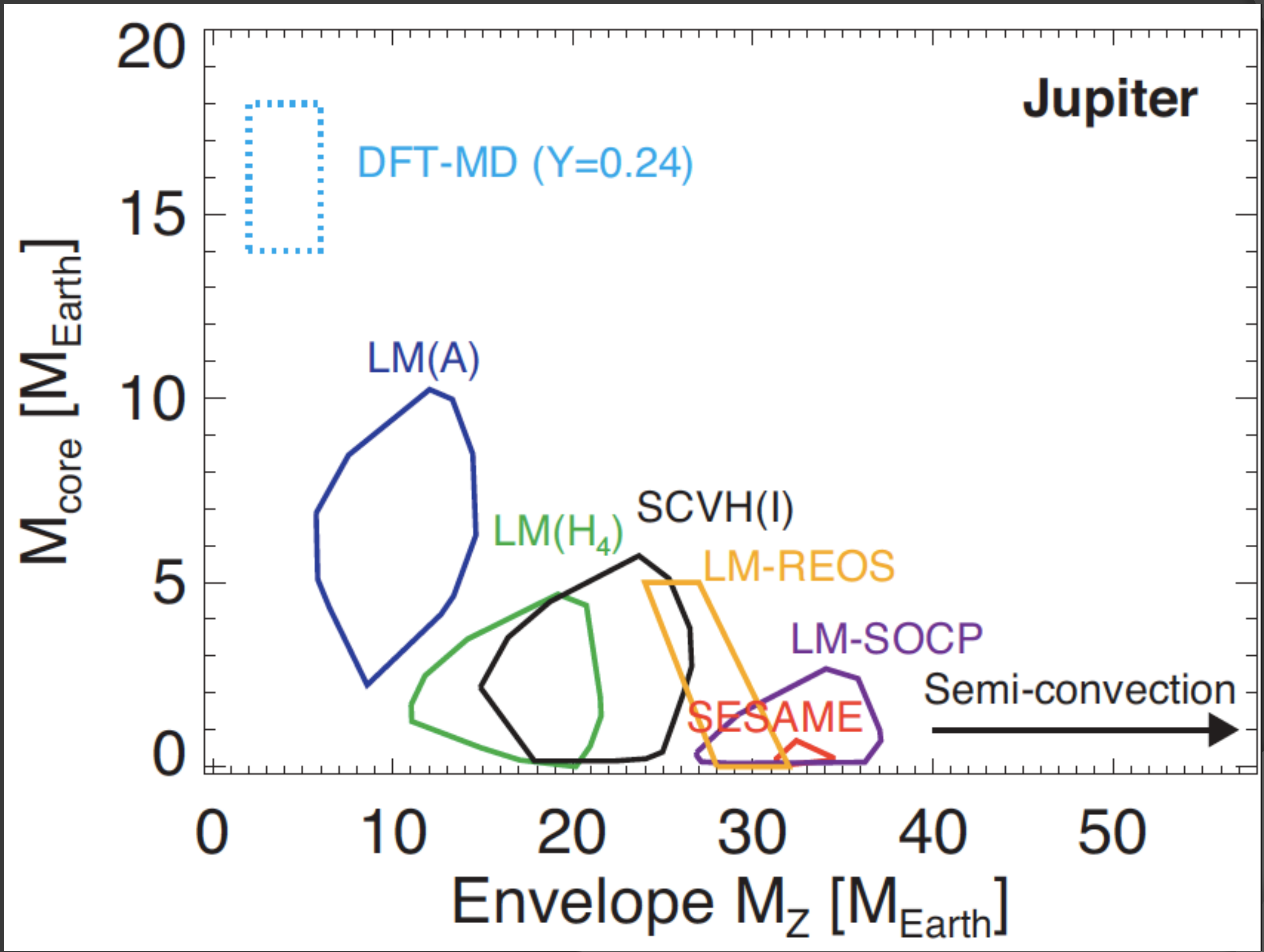




Jupiter - recent models

- Militzer et al., 2008, 2-layer model:
  - Differential rotation is needed to fit J_4 (gravity ⇔ dynamics)
  - Results: $M_{core} \sim 15 - 18\ M_{\oplus}$, $M_Z \sim 0 - 7\ M_{\oplus}$
  - Atmosphere is water-poor - water above the core
- Nettelmann et al., 2008, 3-layer model:
  - Solid-body rotation
  - Results: $M_{core} \sim 0 - 6\ M_{\oplus}$, $M_Z \sim 15 - 32\ M_{\oplus}$
  - Atmosphere is water-rich
- Nettelmann et al., 2011 (various EOS), 3-layer model:
  - Solid-body rotation
  - Results: $M_{core} \sim 0 - 18\ M_{\oplus}$, $M_Z \sim 16 - 30\ M_{\oplus}$
  - Atmosphere is water-rich
- Leconte and Chabrier, 2012, non-adiabtic interior:
  - Solid-body rotation
  - Results: $M_{core} \sim 0\ M_{\oplus}$, $M_Z \sim 40 - 60\ M_{\oplus}$
  - Atmosphere is water-rich

Jupiter: Results with uncertainties due to the hydrogen EOS

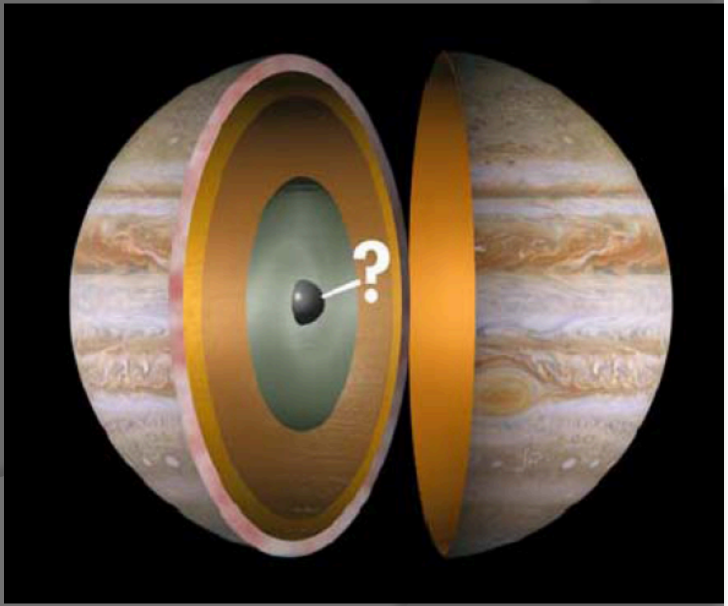


T. Guillot

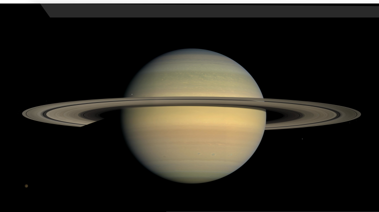
Jupiter's Interior

- Uncertainties:
  - M_{core}, Y, Z, water
  - Core composition
  - H/He EOS

- Results Summary:
  - M_{core}: 0 - 20 $M_{\oplus}$
  - M_Z: 1 - 40 $M_{\oplus}$
  - Total heavy elements mass 8 - 40 $M_{\oplus}$



Saturn

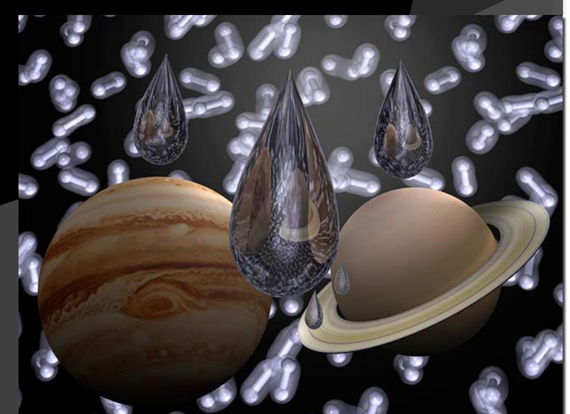


- Less uncertainty in EOS due to the pressure range (smaller mass) - but there are other complications…

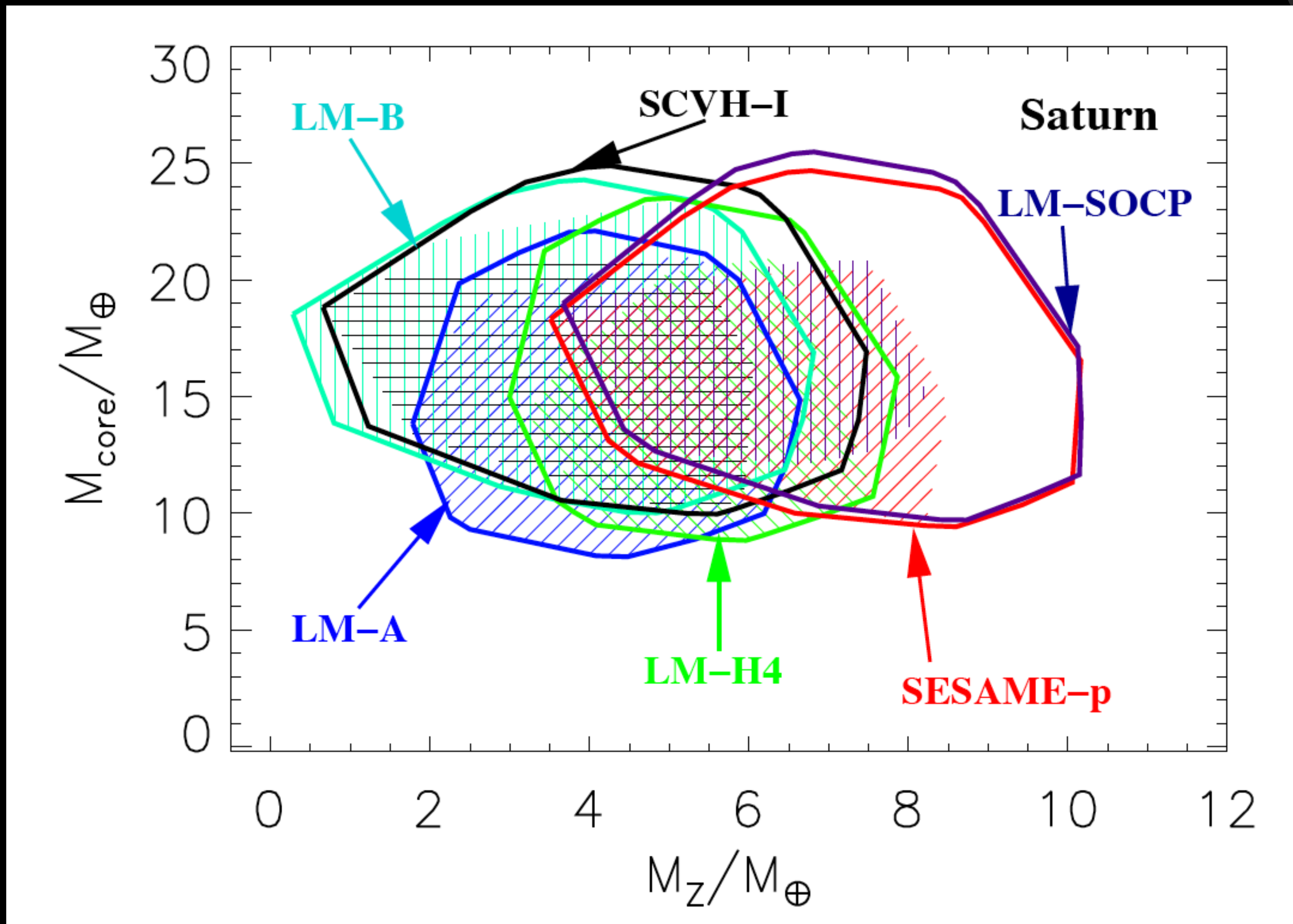
1. Saturn's luminosity is ~ 50% larger than predicted from homogeneous evolution models: helium rain ➔ an energy source (e.g., Stevenson & Salpeter, 1977).

   Indeed Saturn's atmosphere is *He* depleted + evidence from EOS calculations.

2. Saturn's rotation period is unknown within a few minutes

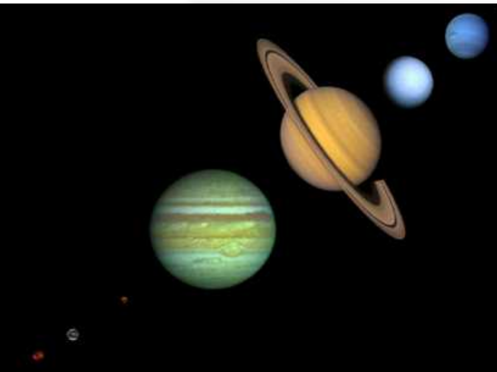


Saturn: Results with uncertainties due to the hydrogen EOS (Voyager rotation period & gravity field)



Saumon & Guillot, 2004

Saturn’s Rotation Period

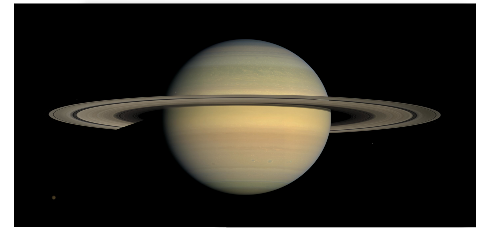


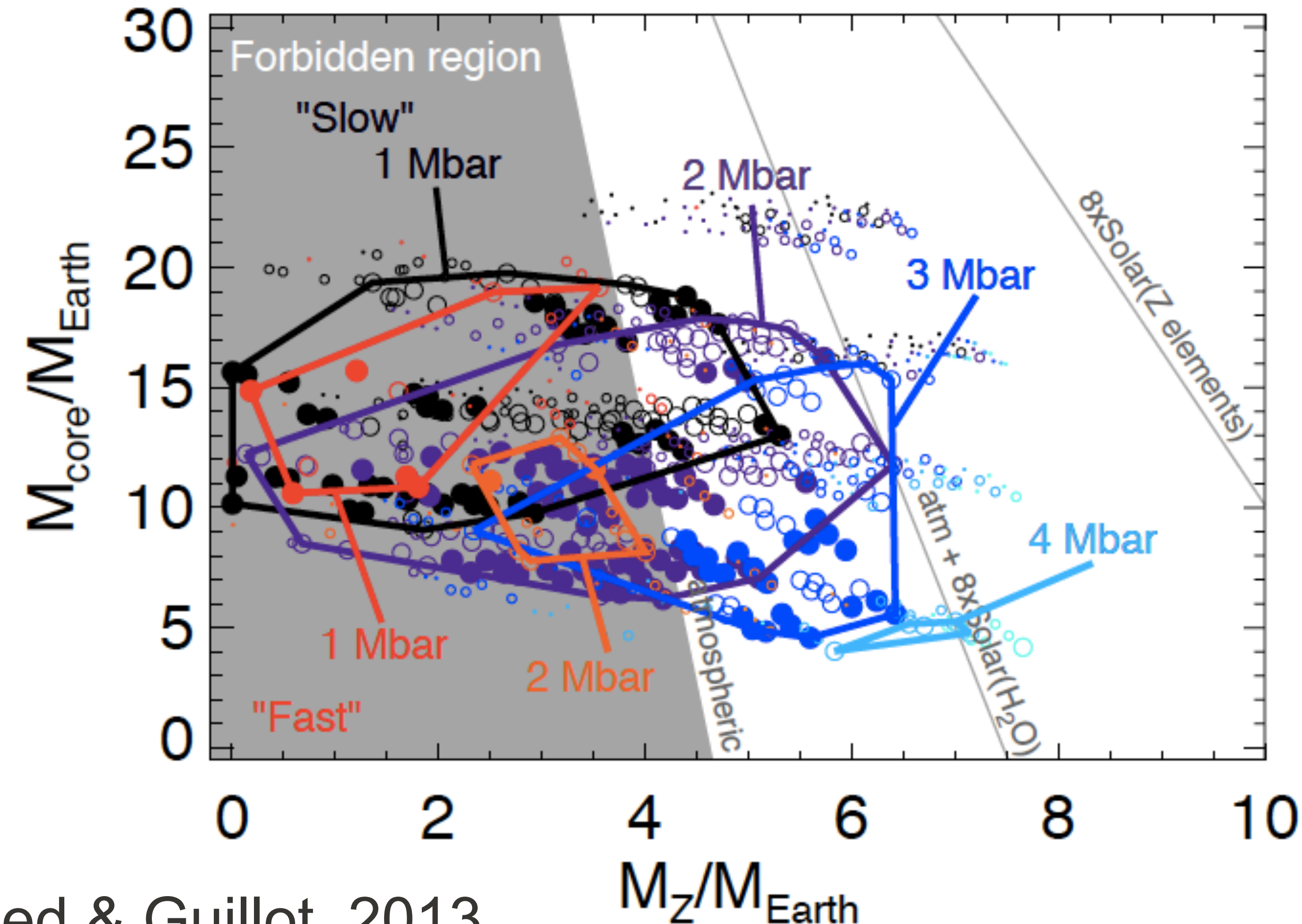
- Saturn’s magnetic field is highly axisymmetric and its dipole is aligned with its rotation axis ➔ magnetic field rotation rate cannot be inferred

- Measured radio periods: Voyager: 10h 39m 22s
  Cassini: 10h 45m 45s

- The radio periods do NOT represent the period of Saturn’s bulk internal rotation ➔ we don’t know Saturn’s rotation period!

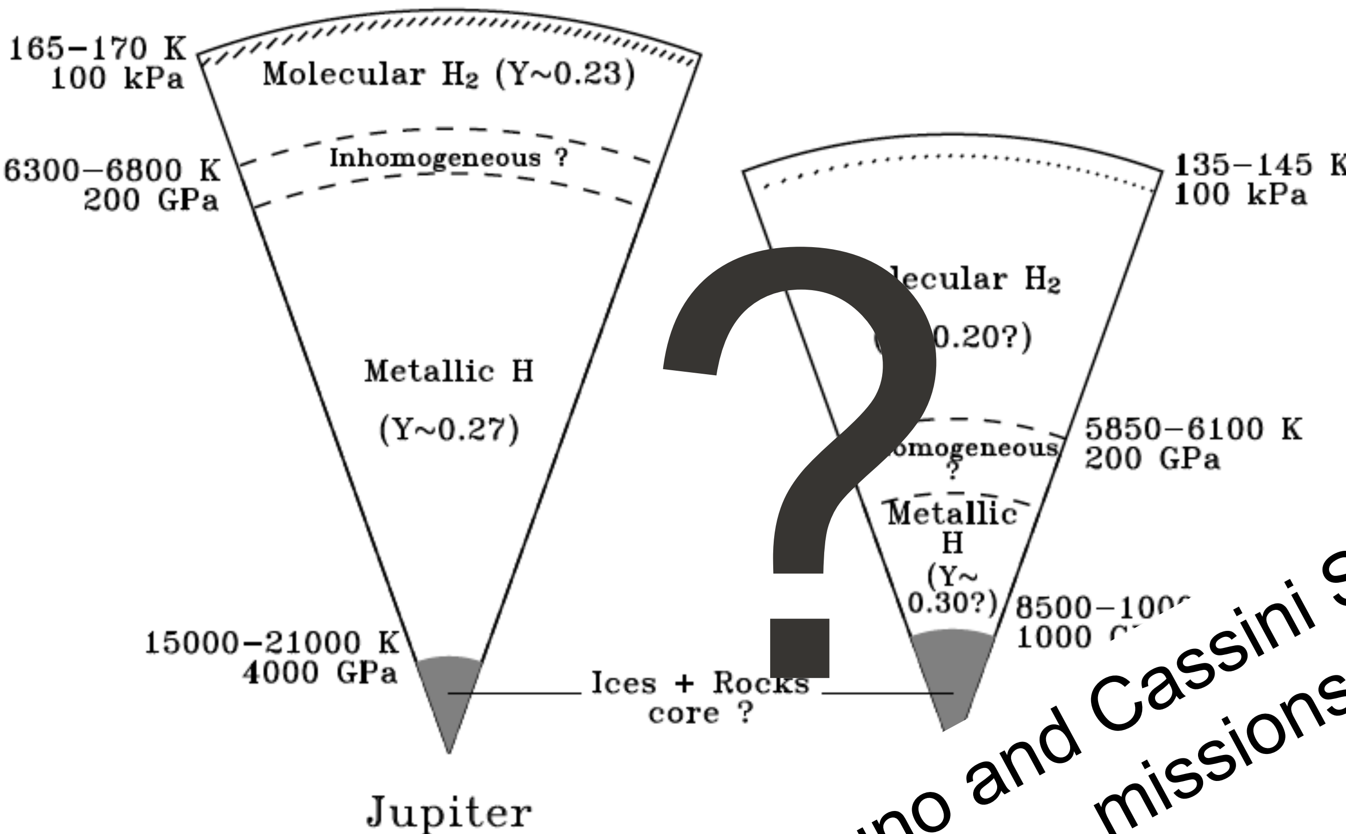
Saturn – updated models





Helled & Guillot, 2013

Jupiter and Saturn



Juno and Cassini Solstice missions

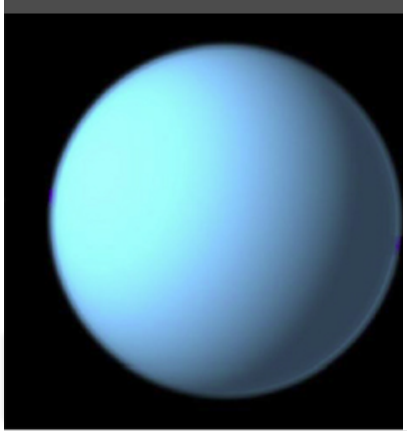
Guillot, 2005

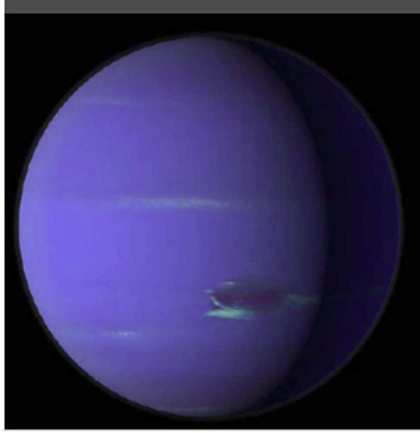
Uranus and Neptune

For Uranus and Neptune only J_2 and J_4 are available

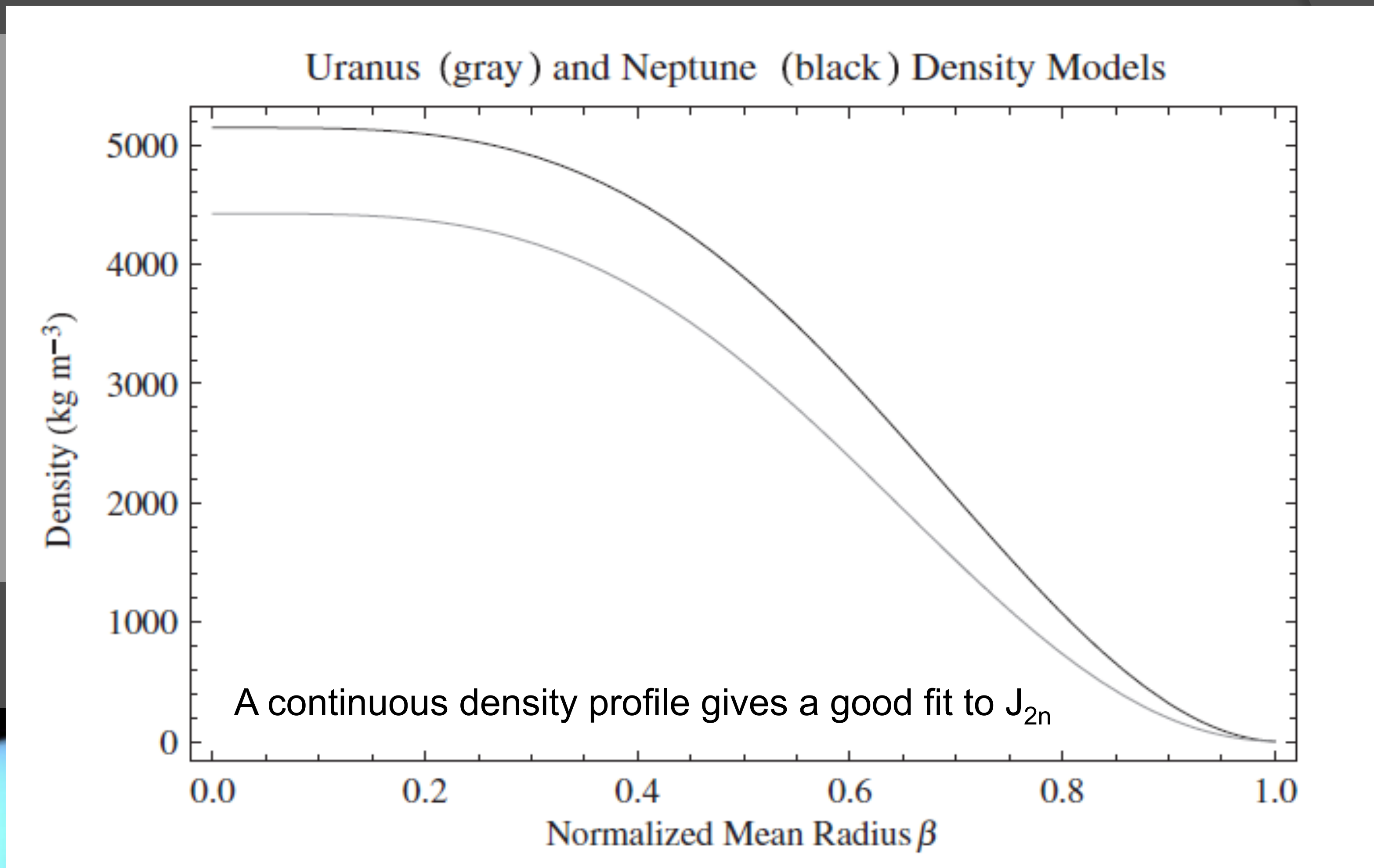
- <u>Standard models:</u>
  - Inner region: rocky core ~ 25%
  - Ices (mostly H_2O) ~ 60-70%
  - *H* and *He* atmosphere ~ 5-15%

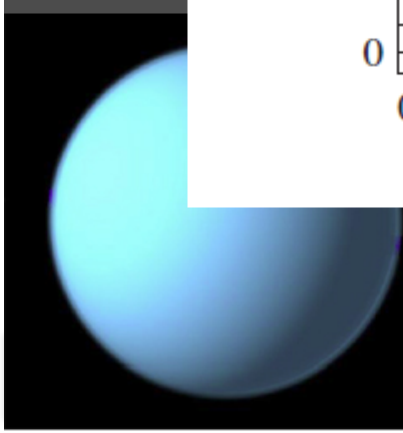
A large range of possible internal structures → composition is unknown

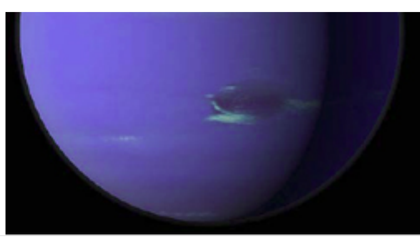




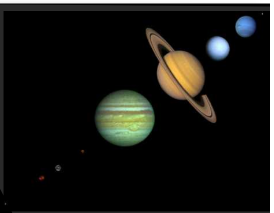
Uranus and Neptune



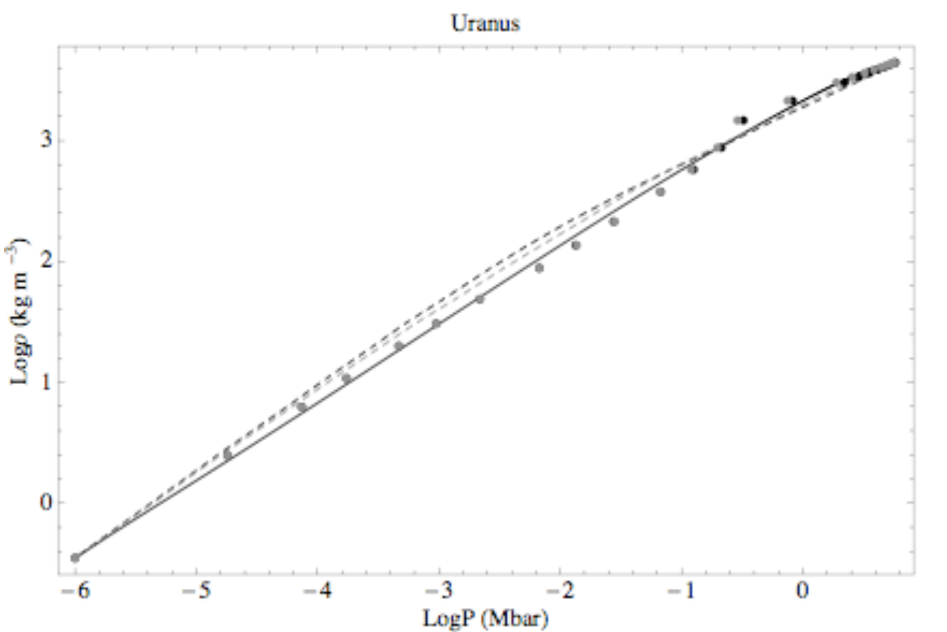


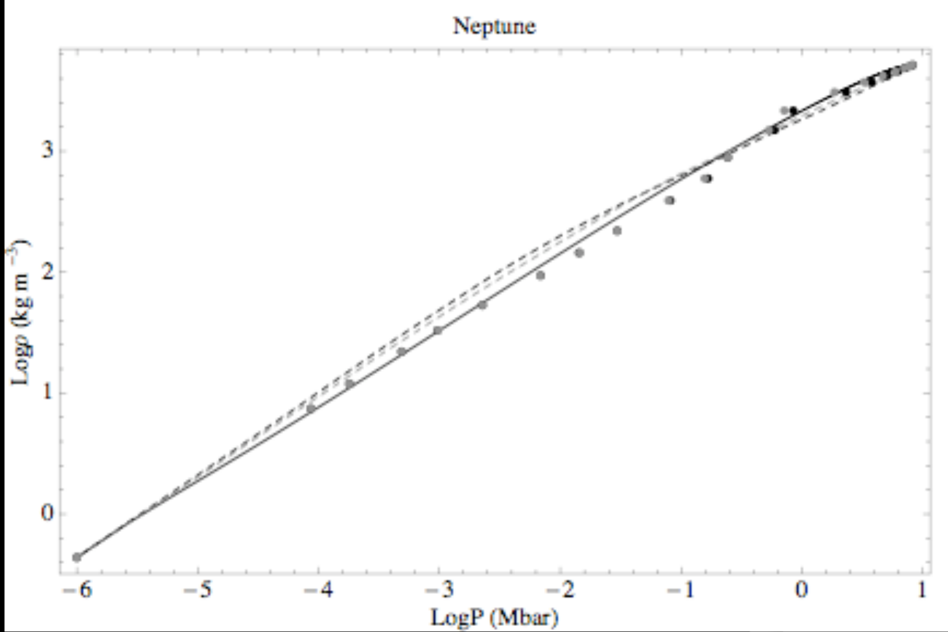


Uranus and Neptune



The gravity data is insufficient to constrain the planetary compositions





Helled et al., 2011

Reasons to believe they have water:

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

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

Uranus & Neptune: Rotation Periods and Shapes

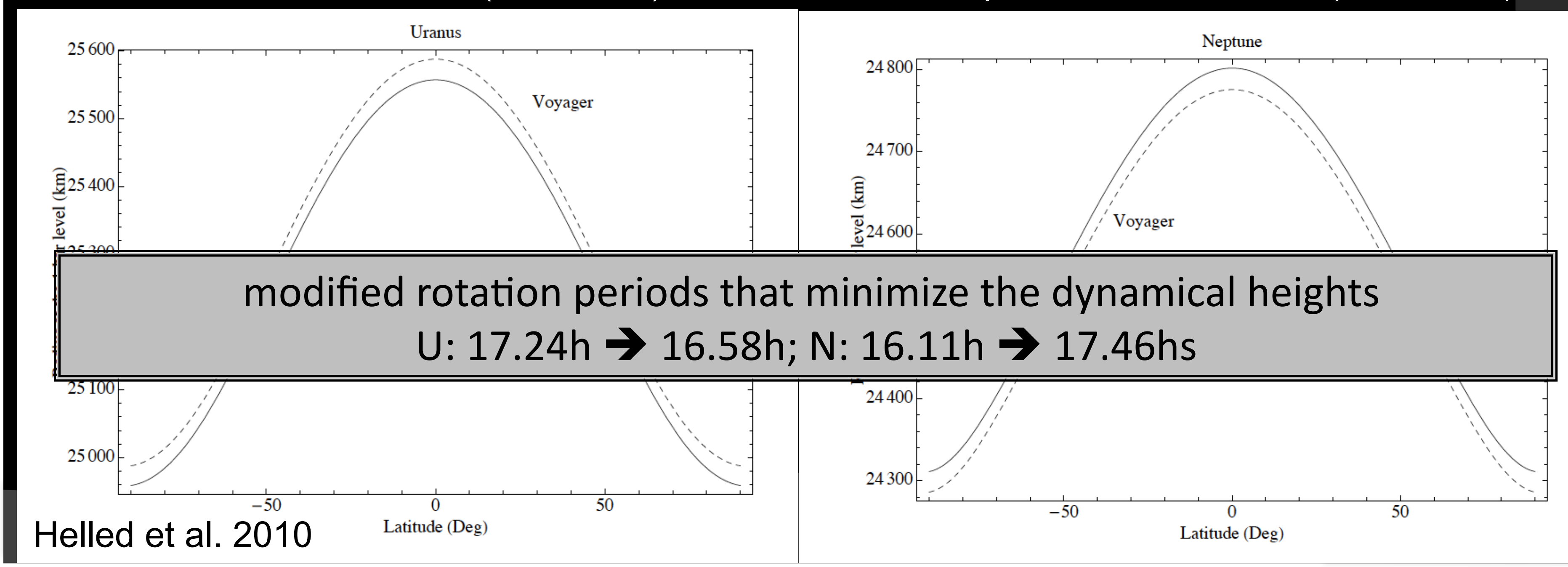
What are the rotation periods of Uranus and Neptune?

- Complex multipolar nature of magnetic fields
- Where are the magnetic fields generated?

Rotation period and share are important because they are used by interior models

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

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



modified rotation periods that minimize the dynamical heights
U: 17.24h ➔ 16.58h; N: 16.11h ➔ 17.46hs

Helled et al. 2010

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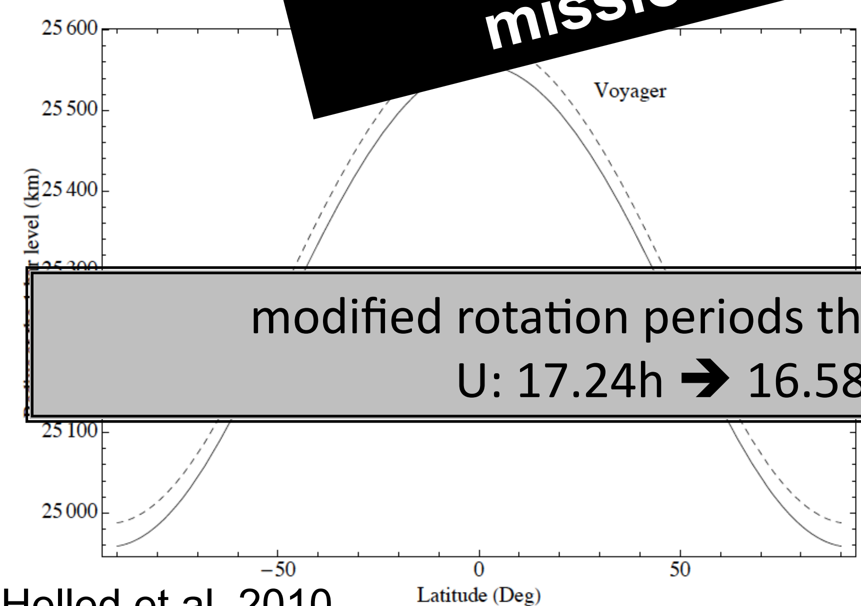
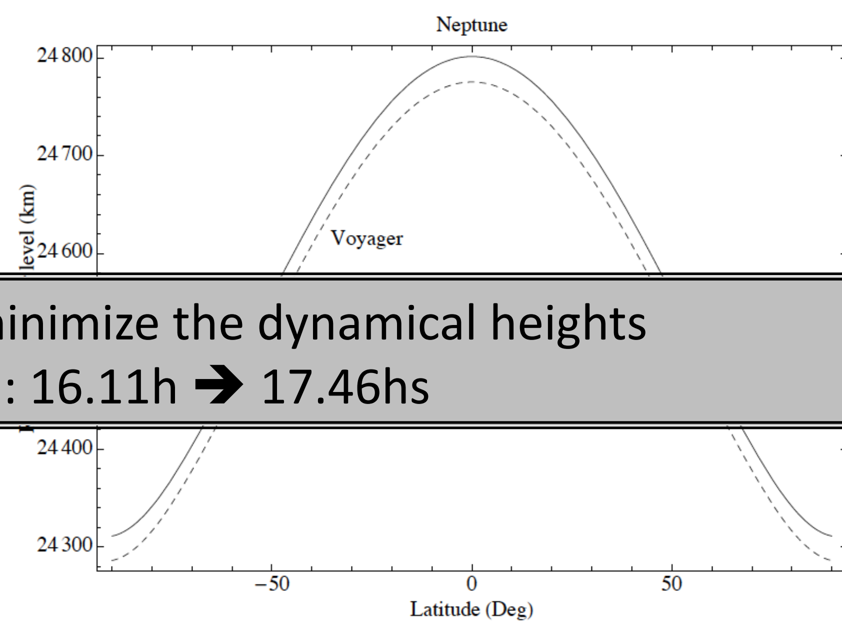
Rotation period and share are important because they are used by interior models

We need a Uranus and/or Neptune mission to improve the data

Uranus: P

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



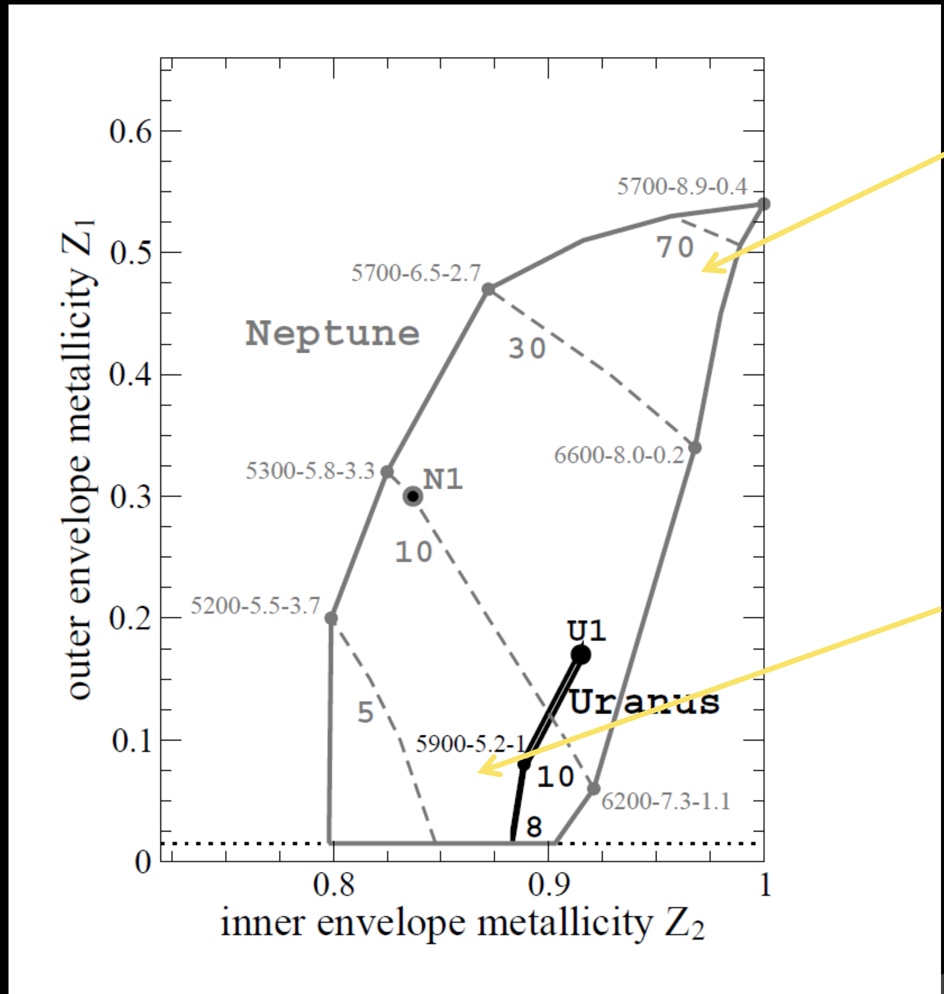


modified rotation periods that minimize the dynamical heights
U: 17.24h ➔ 16.58h; N: 16.11h ➔ 17.46hs

Helled et al. 2010

Interior models with modified rotation

- 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 et al. 2013

Interior models with modified rotation

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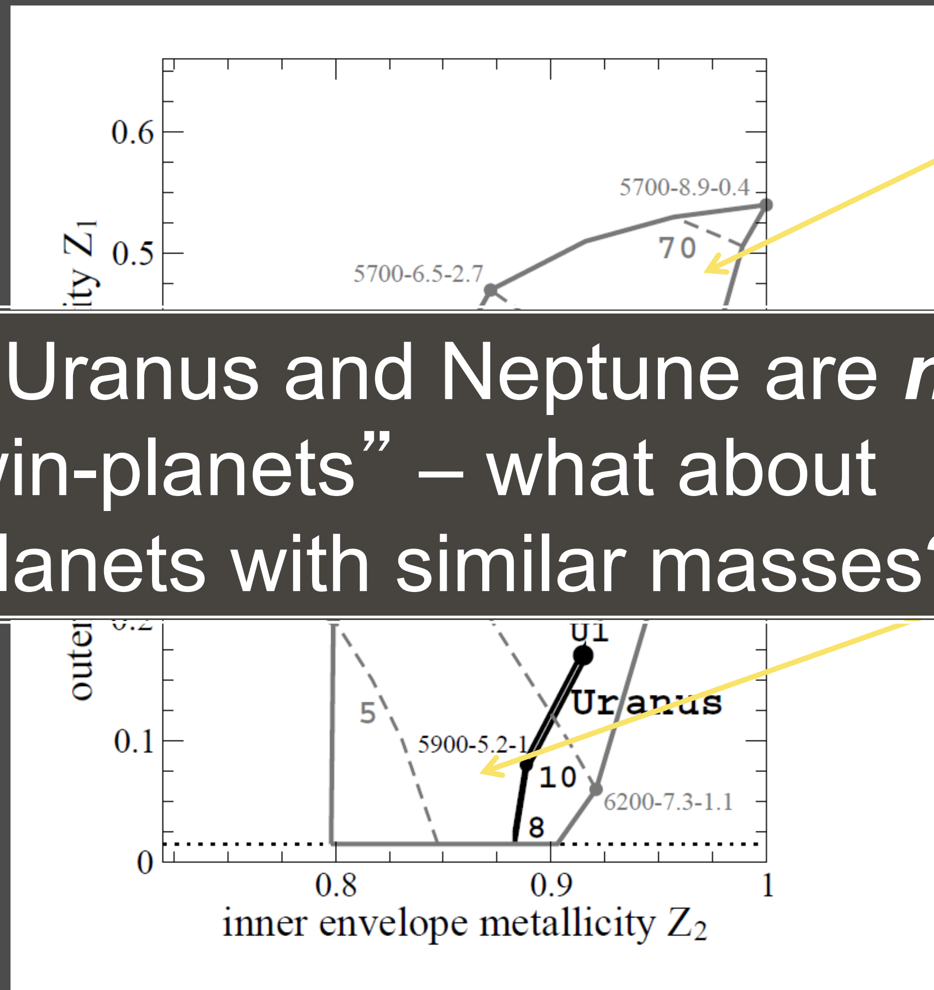


Transition pressure (Gpa)

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

Maybe Uranus and Neptune are *not* "twin-planets" – what about exoplanets with similar masses?

Mass fraction of metals in the outer envelope (Z_1) and in the inner envelope (Z_2) 3-layer models of Uranus and Neptune

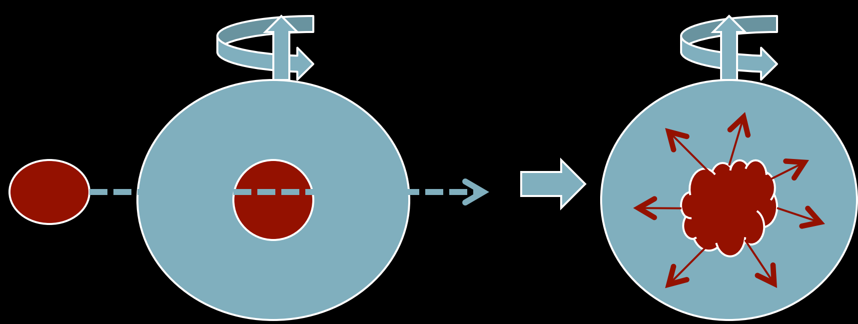
Nettelmann et al. 2013

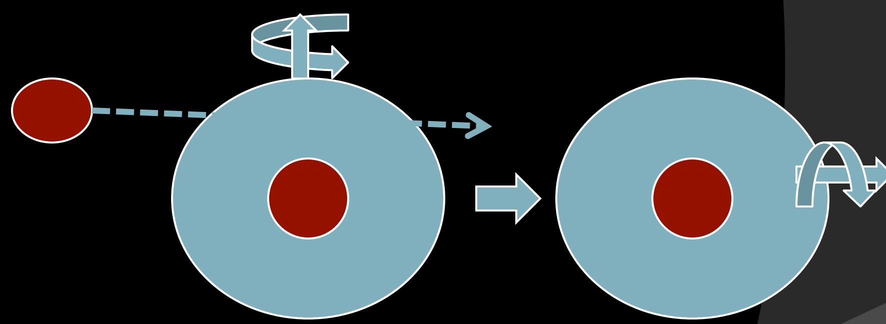
Giant impacts: tilt and internal flux

- Uranus is tilted and has very low internal flux – are these two connected? (D. Stevenson)

Neptune: Radial Collision

Uranus: Oblique Collision





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

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

Podolak & Helled, 2012

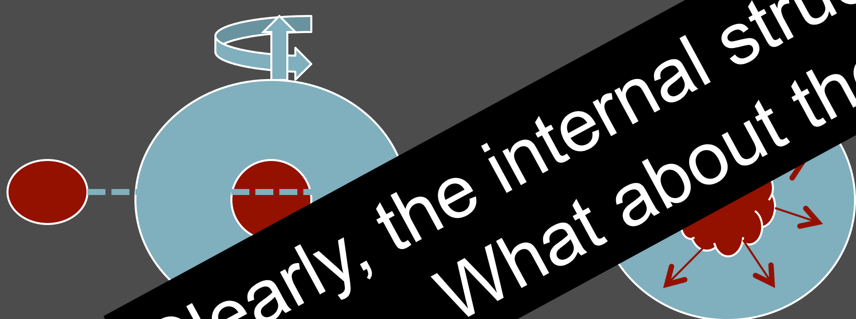
Giant impacts: tilt and internal flux

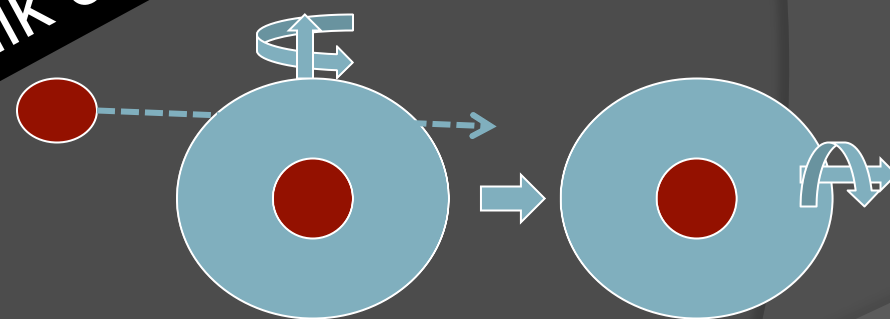
- Uranus is tilted and has very low internal fl… these two connected? (D. Stevenson)

Clearly, the internal structure can change with time. What about the bulk composition?

Neptune: Radial Collision

…: Oblique Collision





Enoug… gy to mix the Core: Mixed and adi…batic interior, efficient cooling

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

Podolak & Helled, 2012

Summary

- A clear difference between gas giants (J&S) and icy giants (U&N)
- Physical processes (helium rain, core erosion, dynamics) add complexity to interior models
- Uranus and Neptune interiors are not well understood

<u>Open Questions:</u>

- Are giant planets adiabatic? homogeneously mixed? Do they have cores?
- What are Uranus and Neptune compositions/structures? How do such planets form?
- How can we connect interior models with planetary formation and evolution models?

- **The PLATO connection:**

  - **Enrichment of giant planets – $Z_{planet}/Z_{\star}$ in exoplanets?**
  - **Architecture of the planetary system: location of terrestrial/icy/giant planets**
  - **Physical properties vs. radial distance & age**
  - **Connect interior models with planet formation and evolution**