Mass-Radius Relations of Giant Exoplanets

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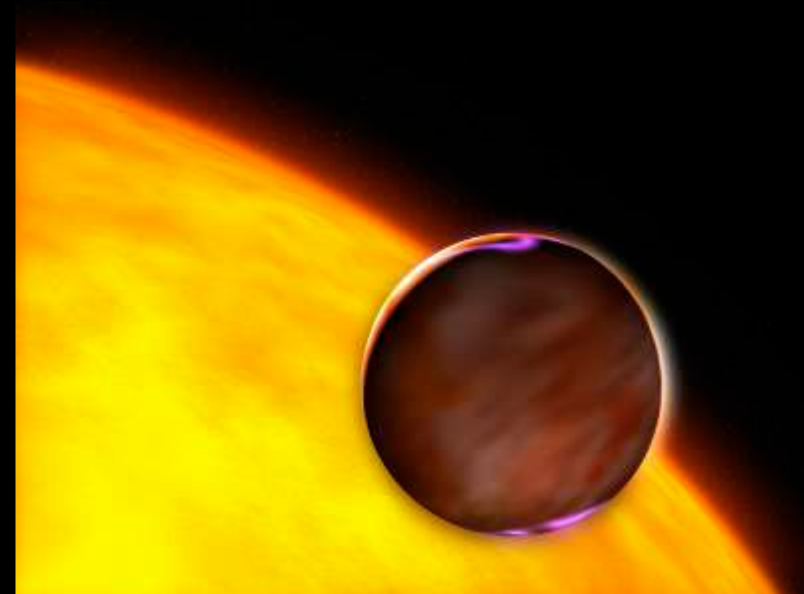
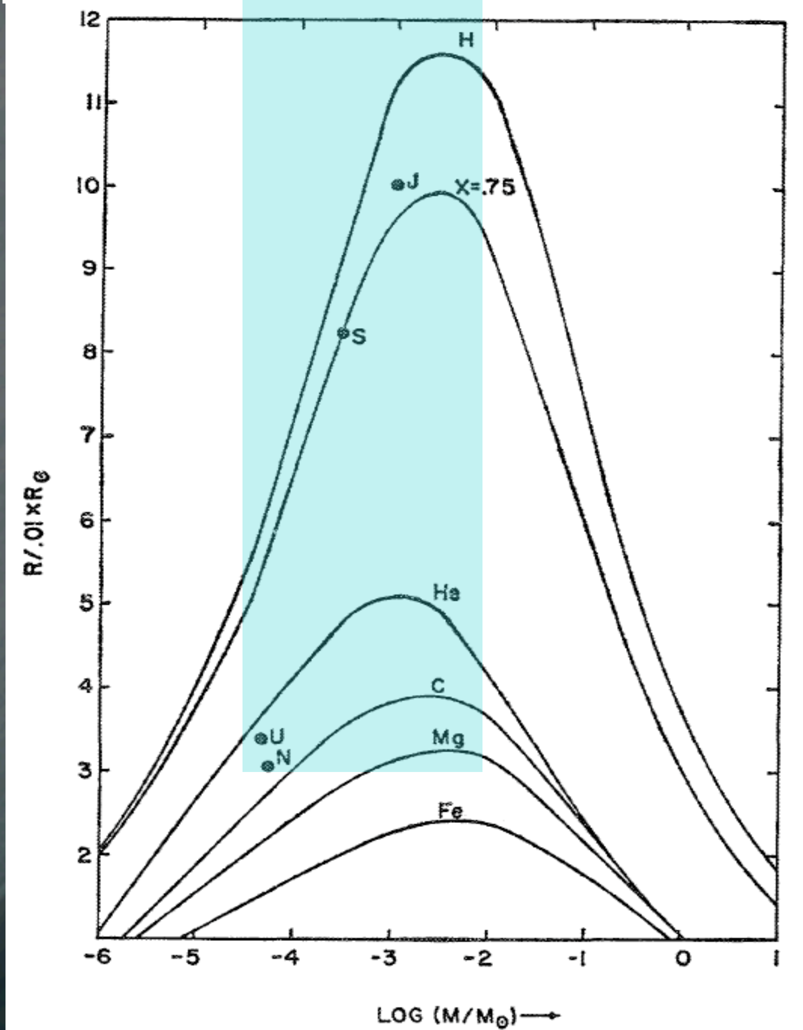
Talk Outline

- Overview of mass-radius
- Lessons from Jupiter and Saturn
- Structure and Radii of Gas Giant Planets
- Lessons from Uranus and Neptune
- Hot Neptune GJ 436b

- We are taking the first steps towards characterizing exoplanets
- These planets receive ~10^4 more stellar flux than Jupiter
- Incident flux is ~10^4 greater than intrinsic flux

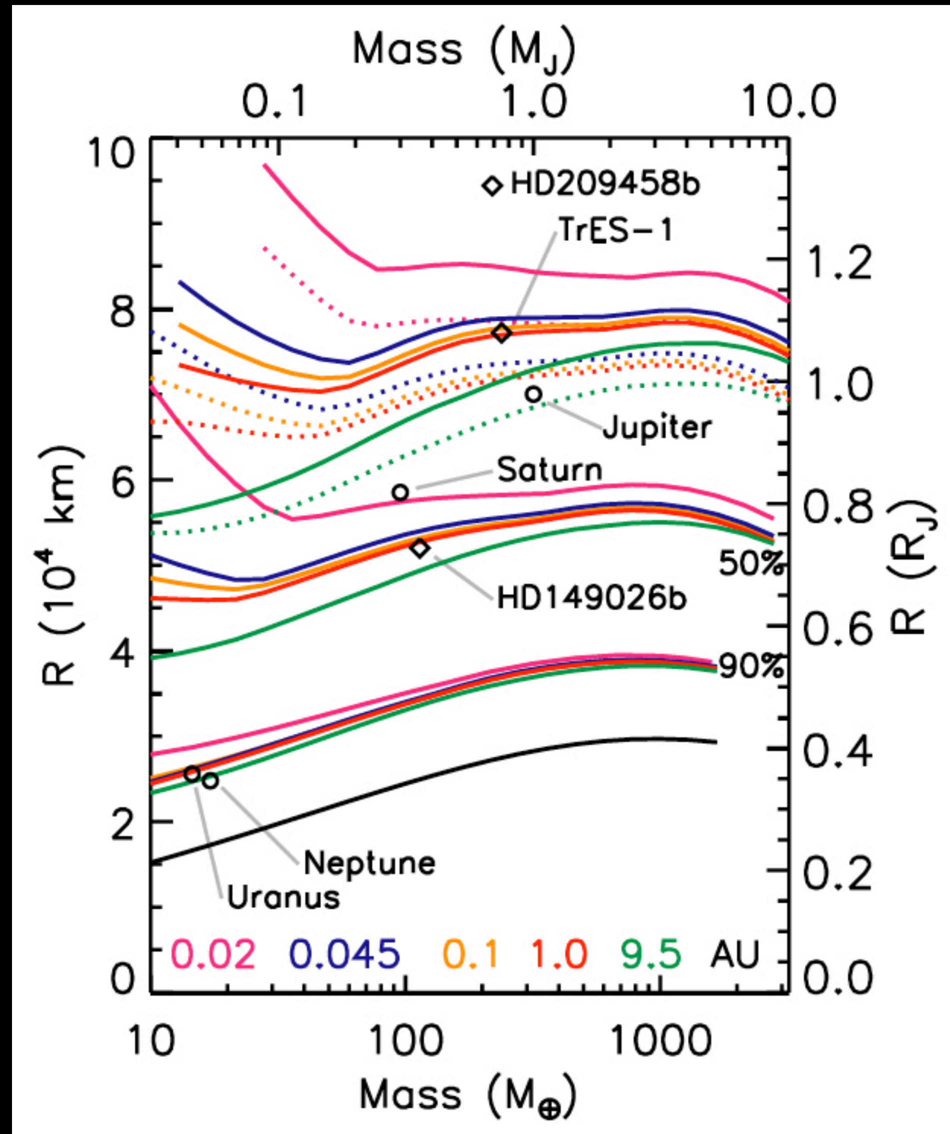


Zero-temperature mass-radius



Zapolsky & Salpeter (1969)

Realistic mass-radius at 4.5 Gyr with cores



Fortney, Marley, & Barnes (2007)

Jupiter and Saturn's Heavy Elements: How much and where are they?

Saumon & Guillot, 2004, have published detailed interior models using various hydrogen equations of state.

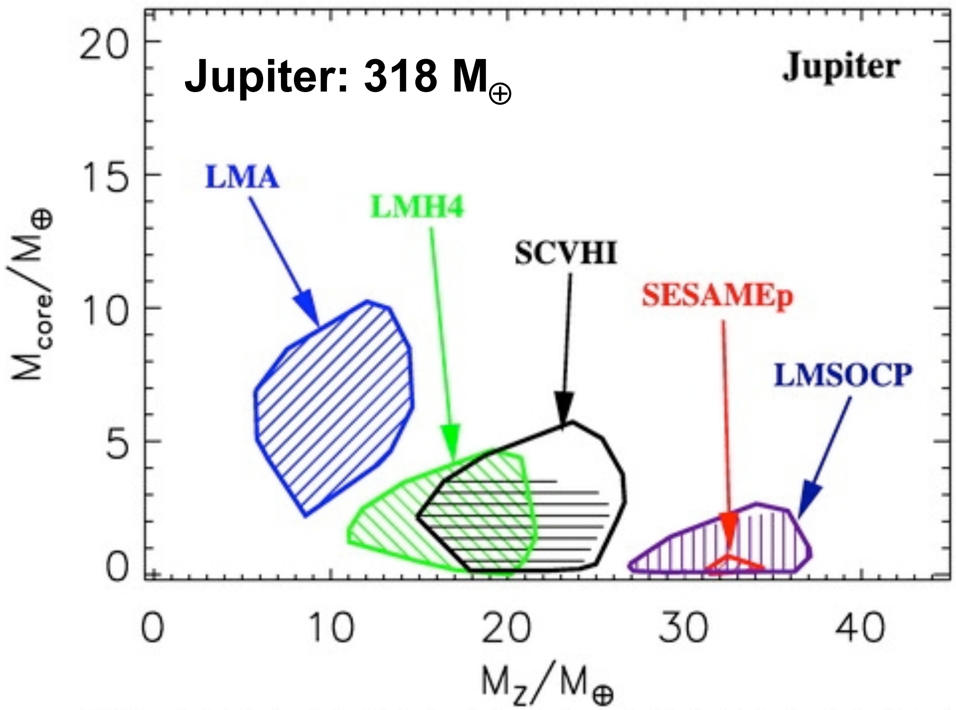
The core masses and total abundances of heavy elements are our main data in understanding the formation of giant planets.

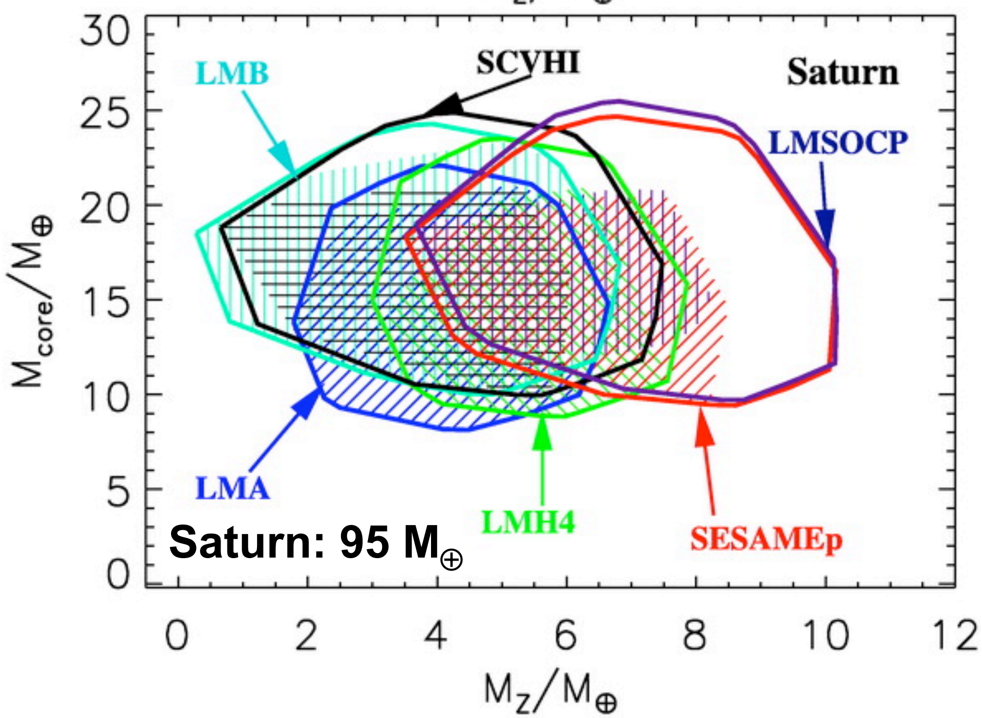
In total…

Saturn: $13<M_Z<28\ M_\oplus$

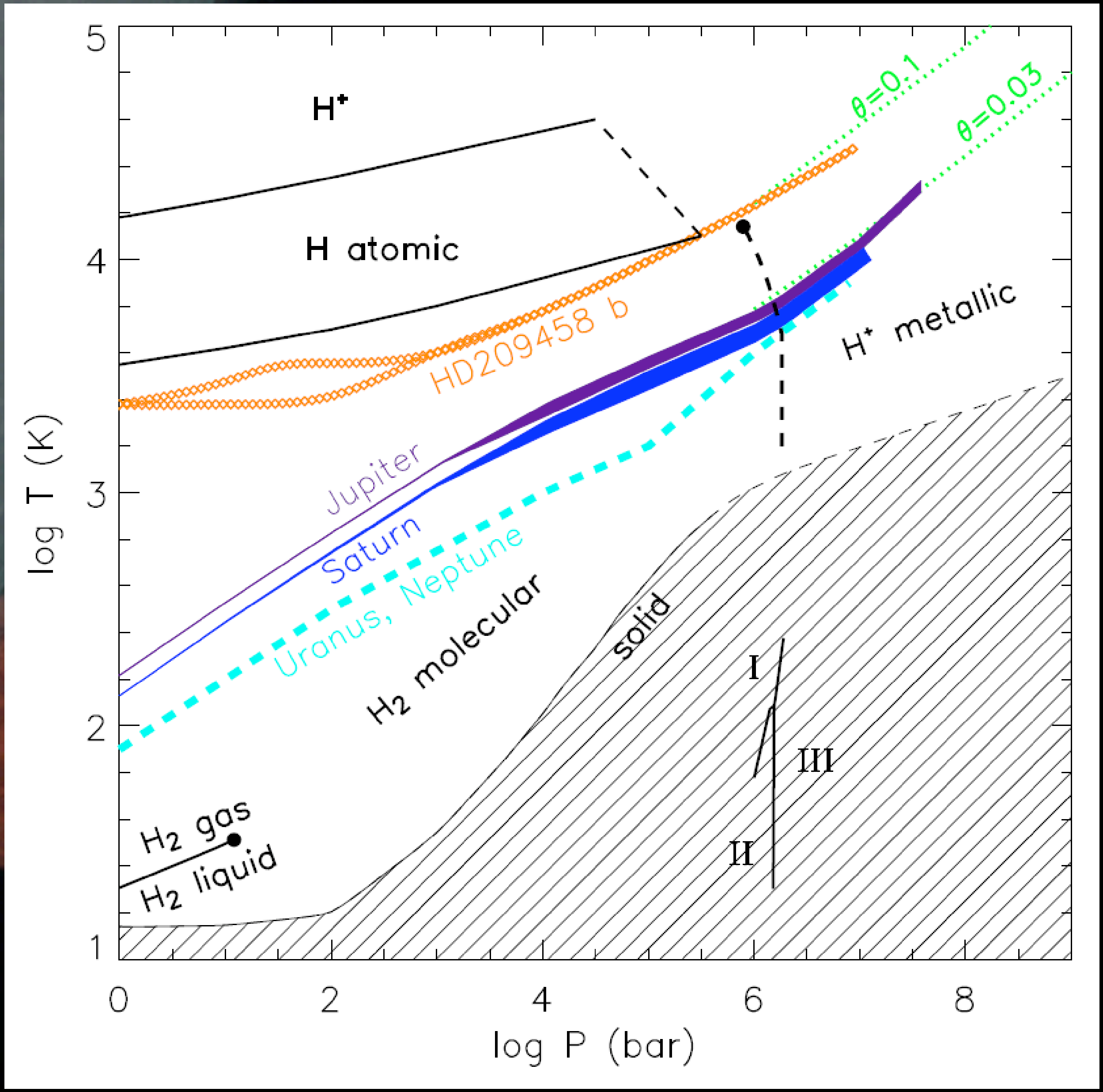
Jupiter: $8<M_Z<38\ M_\oplus$

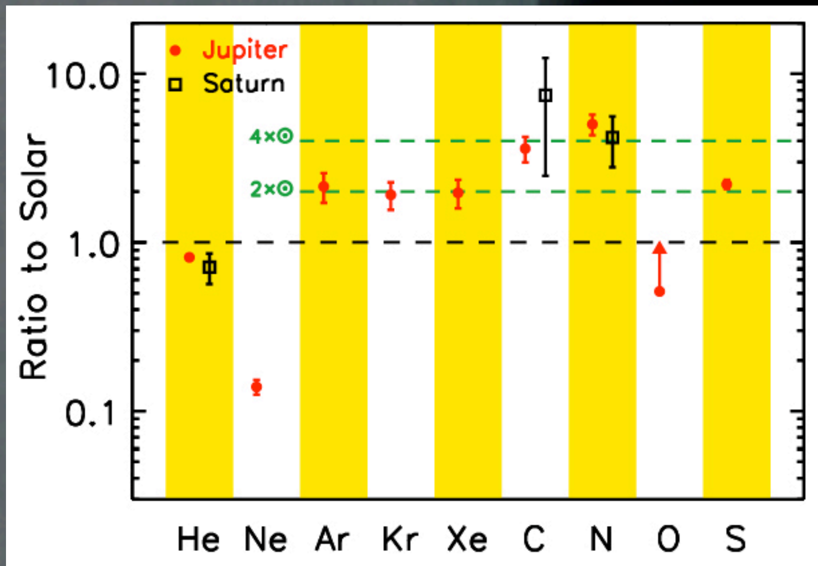
Jupiter and Saturn are not of solar composition. Jupiter is 1.5 – 6X and Saturn 6 – 14 X solar.

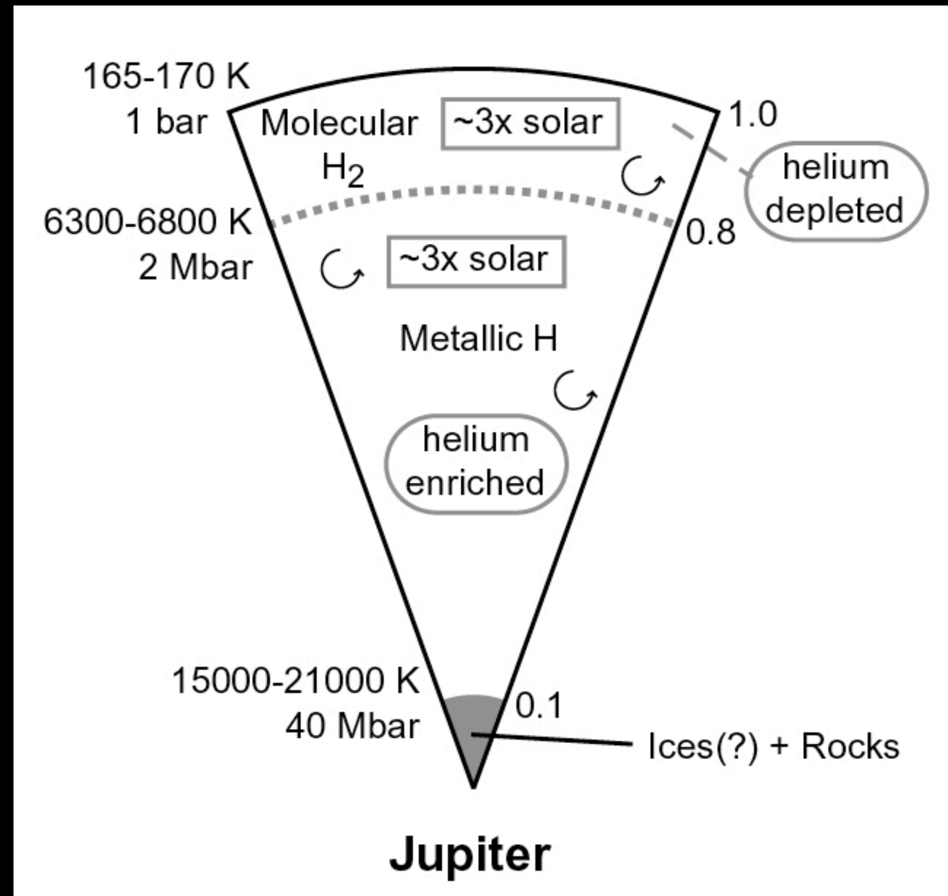




Hydrogen Phase Diagram (from Guillot, 2005)





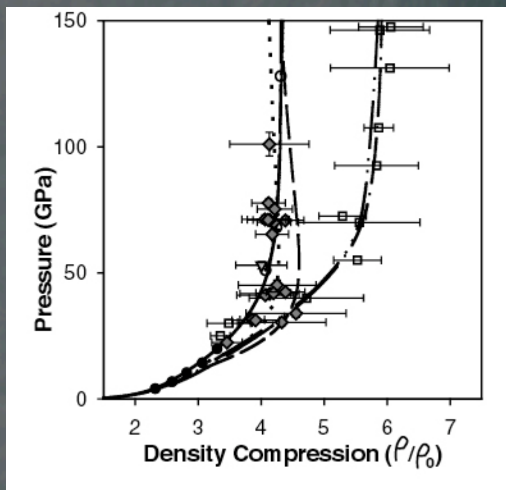


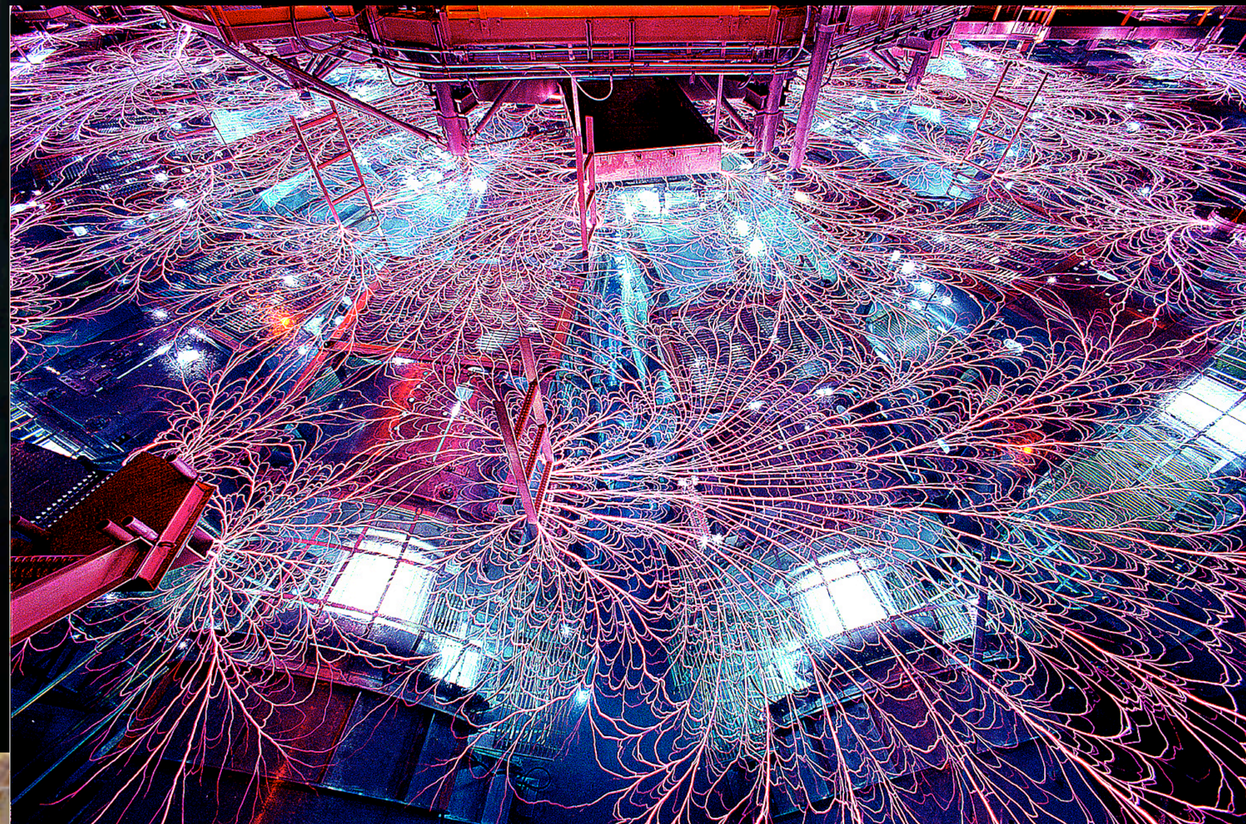
Jupiter as a Model Planet

Interior temperature of ~10^4 K implies that zero temperature treatment is too crude

Jeffries (1924): Jupiter/Saturn mostly ice (with rock) and H envelope in outer 20%
Demarcus (1958): Jupiter/Saturn mostly cold H, with rock cores
Hubbard (1968,1969): Jupiter/Saturn are H/He fluid (not solid), warm, fully convective, likely have cooled to present day by K-H contraction
Podolak & Cameron (1974): Firmly establish heavy element enrichment

H at High Pressure: Obtaining Data

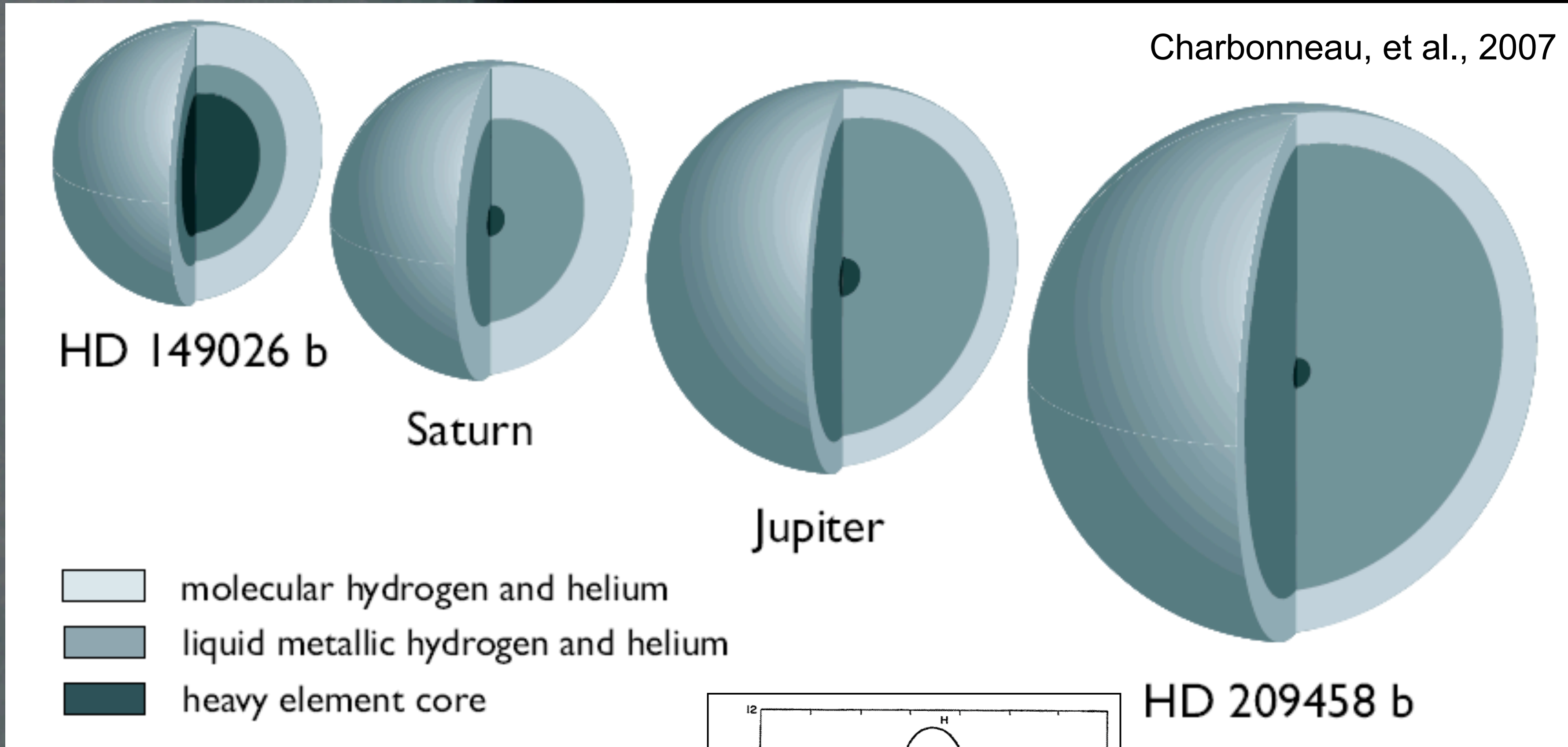




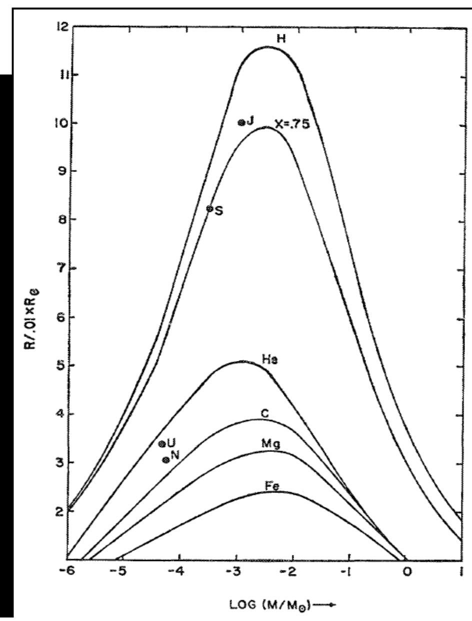
Sandia National Laboratory Z Machine

There is a vast literature of theory and data on H. He has been mostly neglected

Lawrence Livermore National Laboratory Two-Stage Light Gas Gun



- There is considerable diversity amongst the known transiting planets
- Radii for planets of similar masses differ by a factor of two, which cannot happen for pure H/He objects



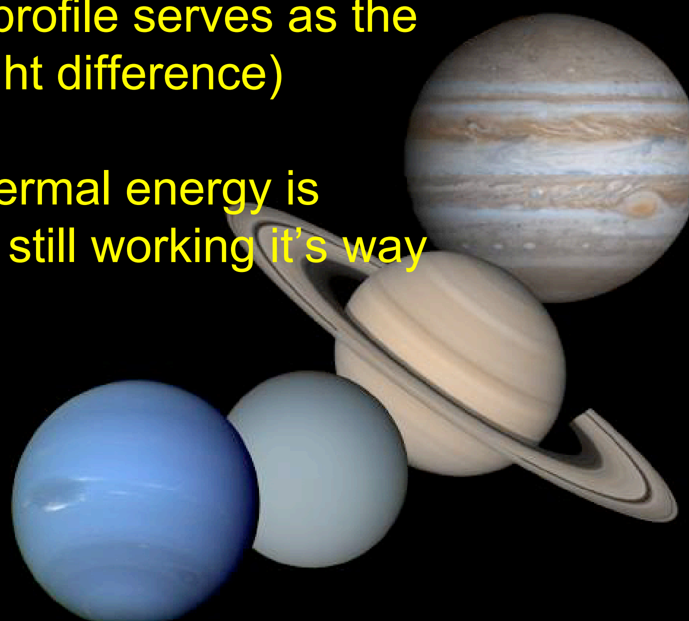
Giant Planet Evolution and Contraction: Key Ideas and Assumptions

- Giant planets are warm, fluid, and fully convective
- Convection is efficient and leads to an essentially adiabatic temperature gradient
    - H/He envelope is homogeneous and well mixed
    - Heavy element core is distinct from H/He envelope

- It is the radiative atmosphere that is the bottleneck for interior cooling and contraction (atmosphere models are much more important here than in stellar evolution)

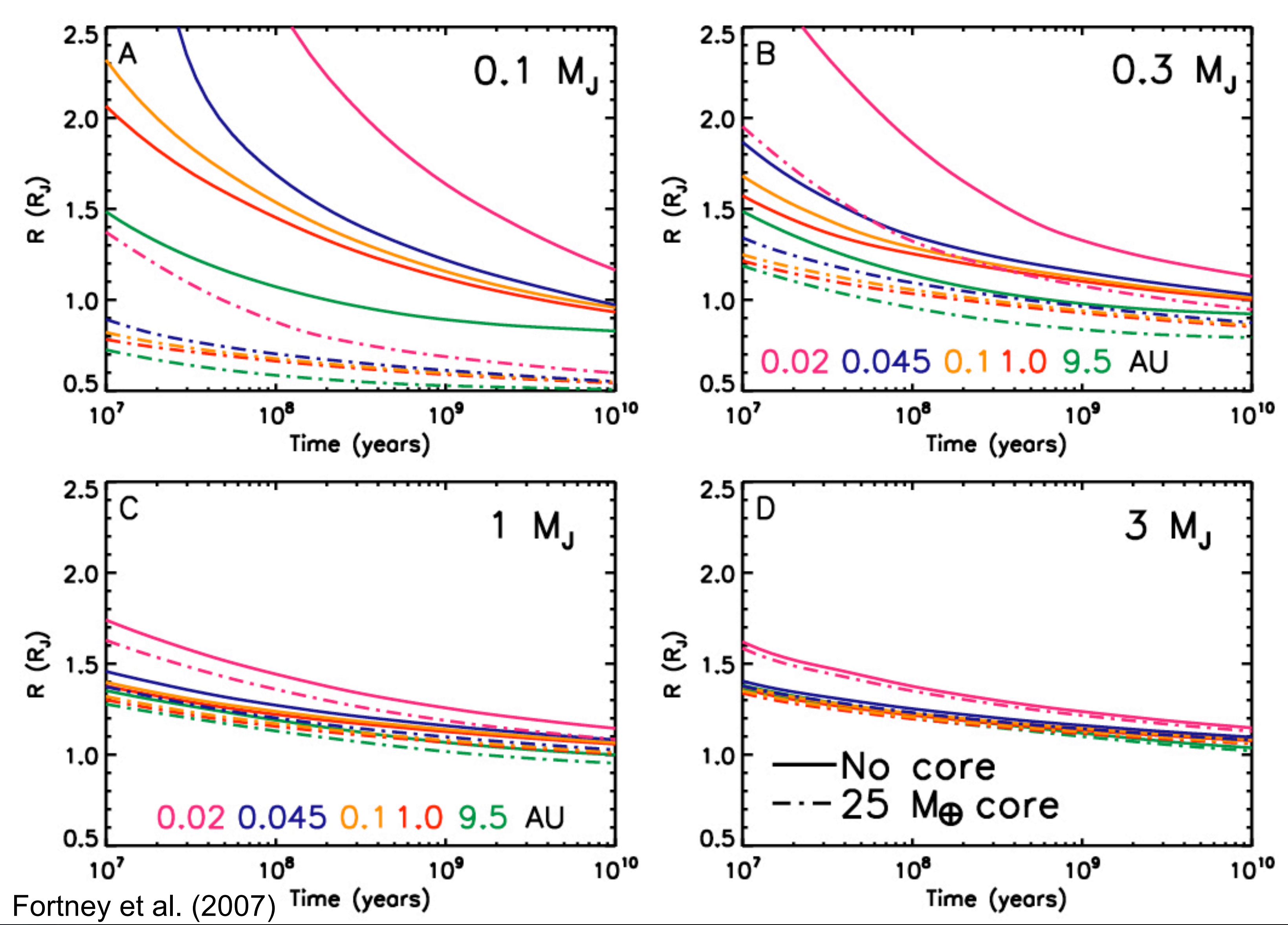
- One "planet-wide average" pressure-temperature profile serves as the upper boundary condition at a given age (no day/night difference)

- A Gyr ages, the vast majority of a giant planet's thermal energy is remnant energy from its formation (the big collapse) still working it's way out. There is little contraction at Gyr ages



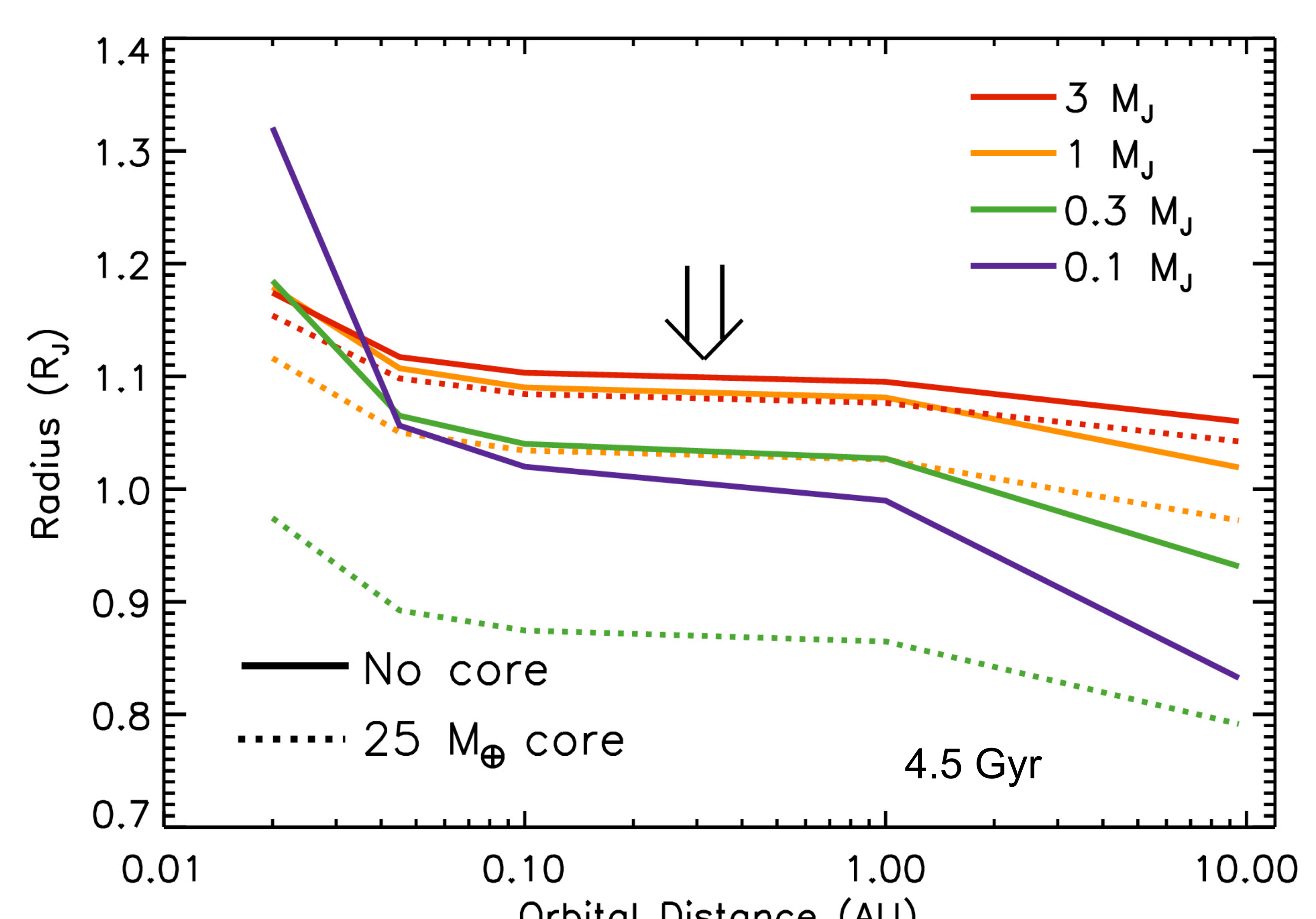
How well does this work in our Solar System?

Contraction with time, with and without cores. A given core mass has a larger effect on a smaller mass planet.



Fortney et al. (2007)

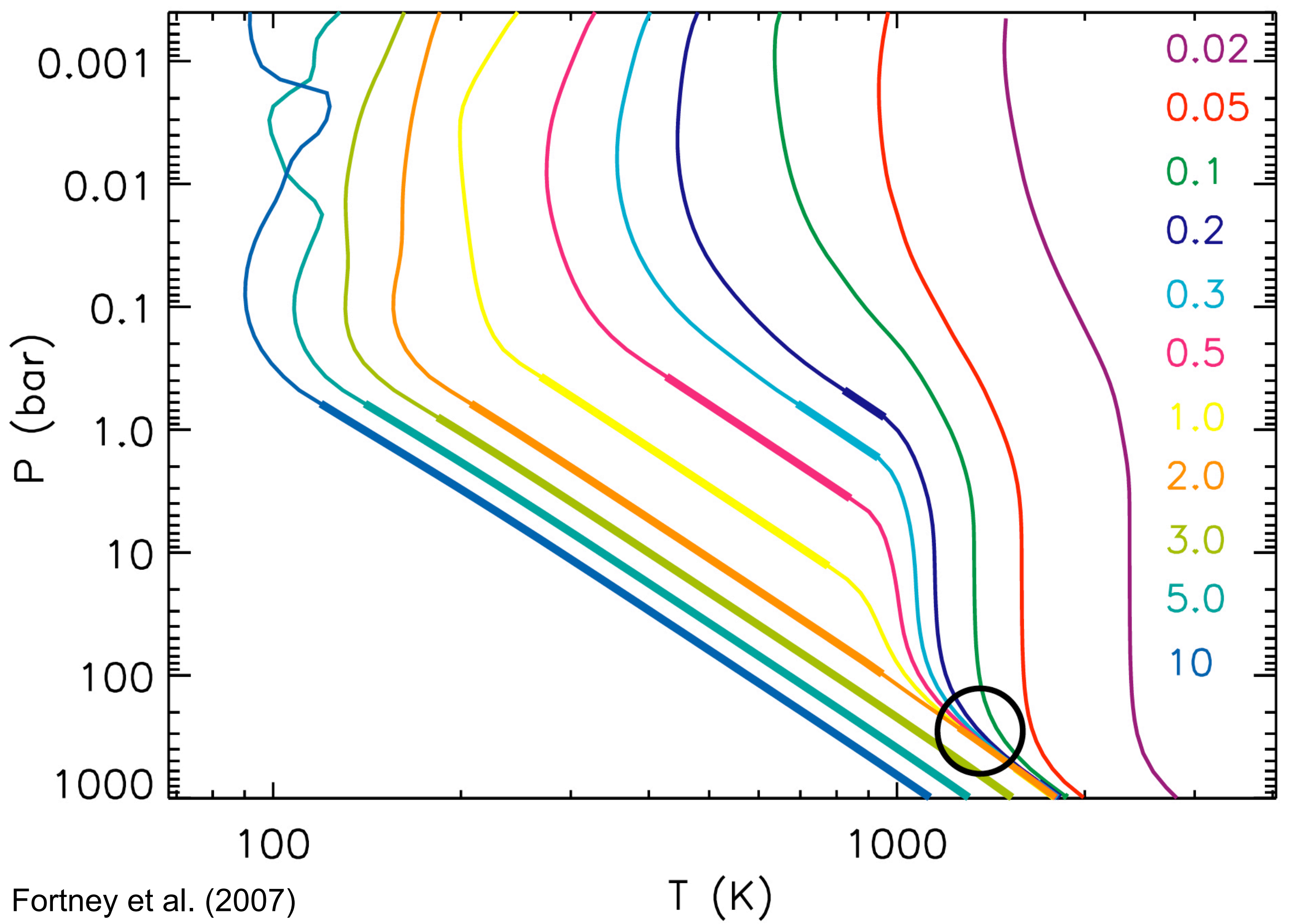
Effects of Incident Flux on Contraction are Complex



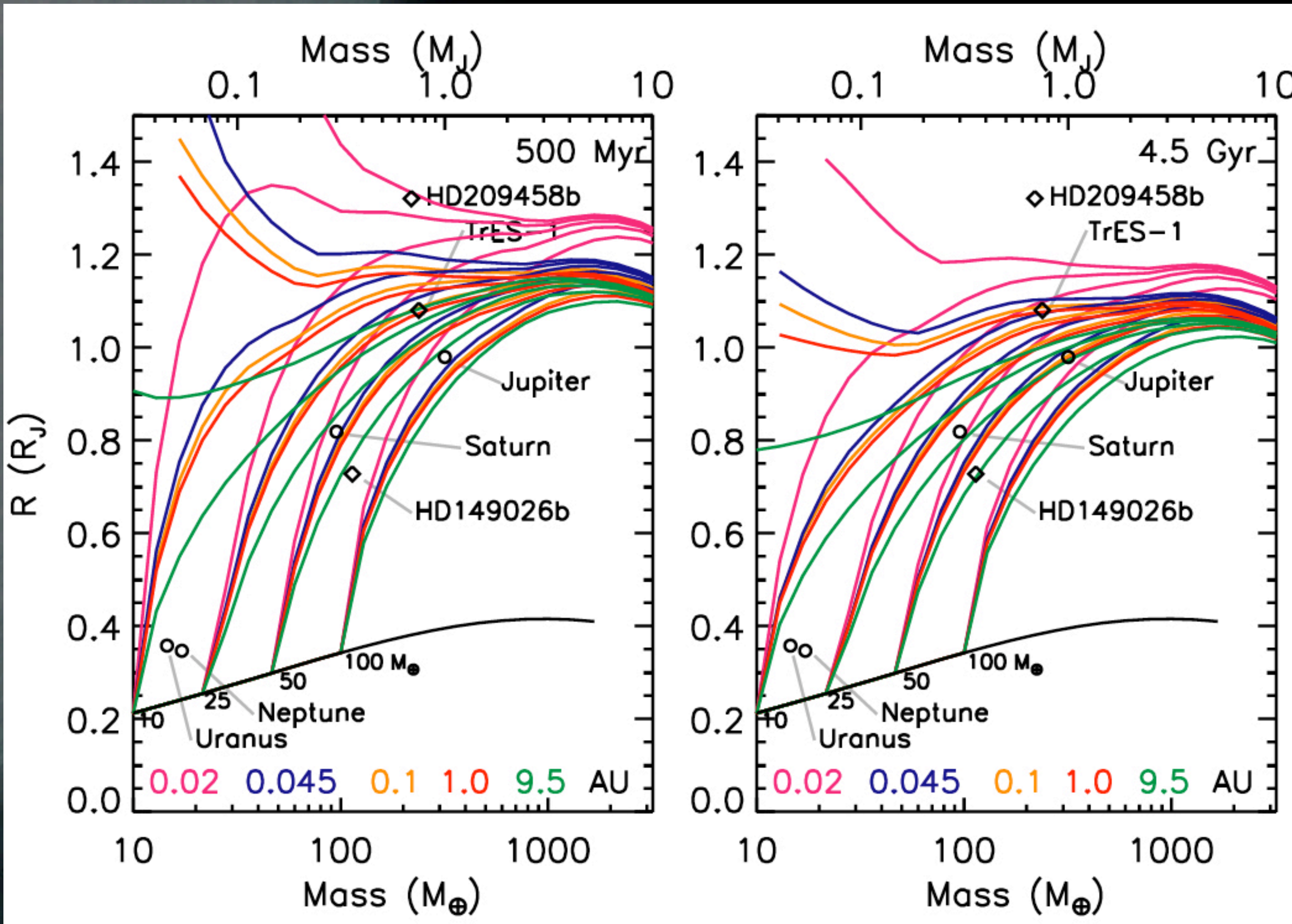
Fortney et al. (2007)

Why do planets under extreme levels of incident radiation contract more slowly that planets far from their parent stars?

A giant planet's atmosphere serves as the bottleneck for interior cooling.

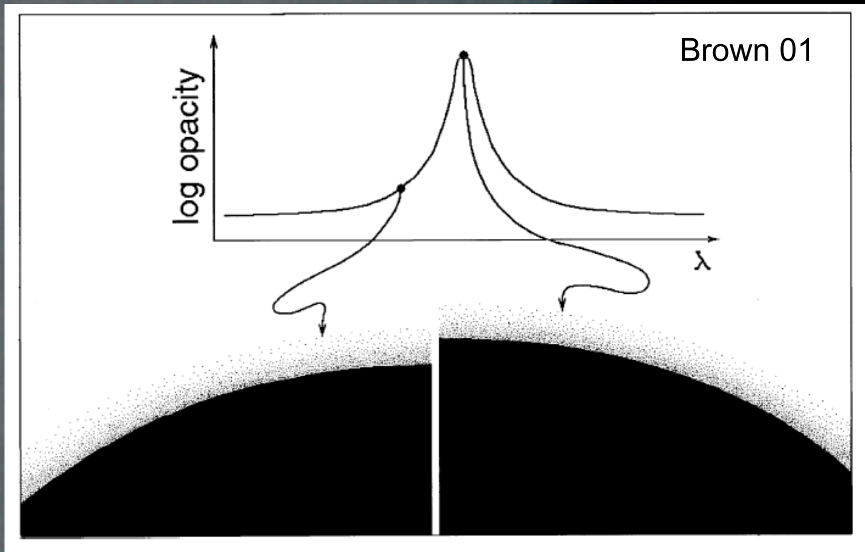


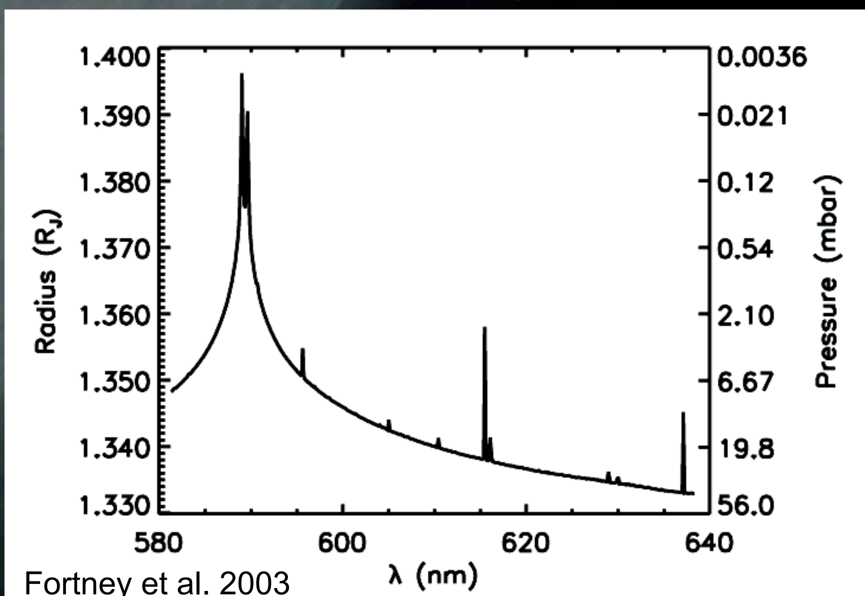
Fortney et al. (2007)



Mass (M_J)
0.1
1.0
10
500 Myr
4.5 Gyr
HD209458b
TrES-1
Jupiter
Saturn
HD149026b
Neptune
Uranus
100 M⊕
50
25
10
R (R_J)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.02 0.045 0.1 1.0 9.5 AU
10
100
1000
Mass (M⊕)

The "Transit Radius"





- The radius that ones measures during a transit is a function of the opacity of the planet's atmosphere (Seager & Sasselov, Brown, Hubbard et al., Fortney et al., Tinnetti et al., etc.)

- At a given wavelength, $R_{transit}$ is larger than R_{normal} by ~5H (Burrows et al. 2007)

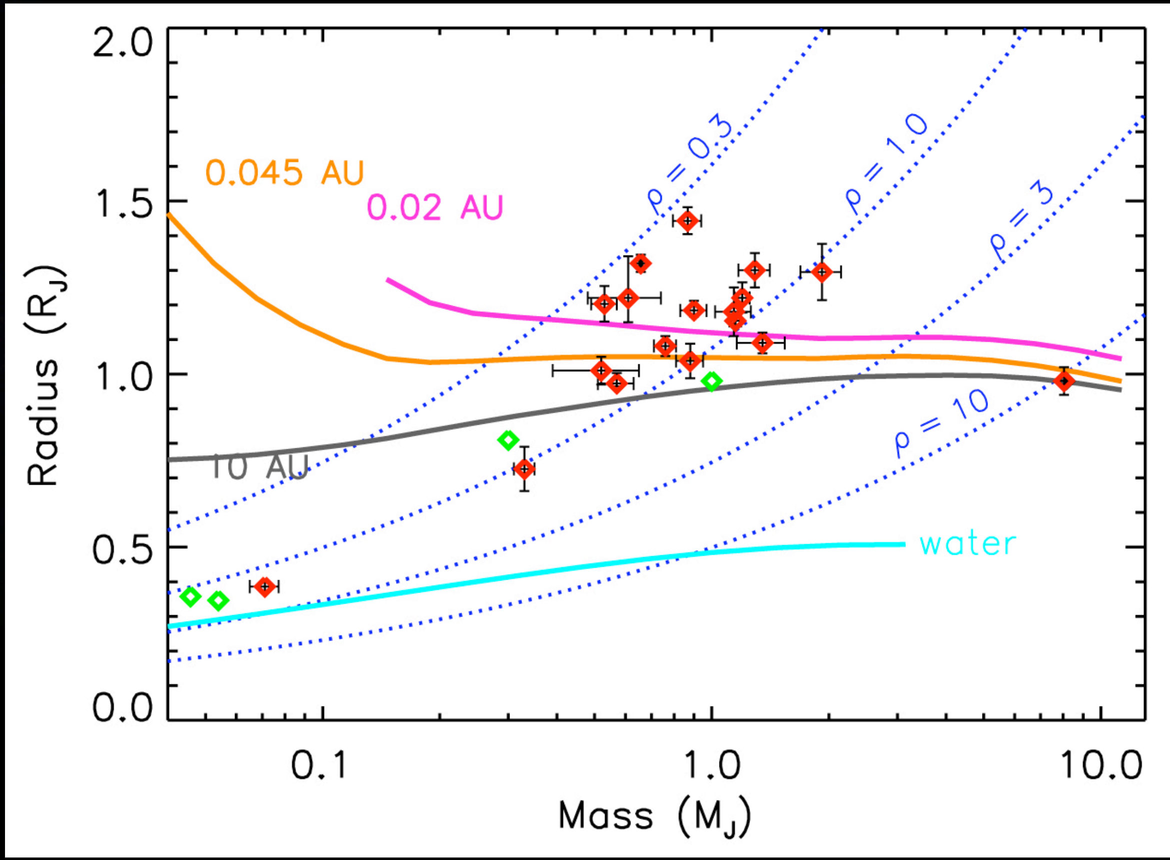
- Scale height H=RT/μg depends on radius, mass, and temperature: ~1 to 4% of R

- Baraffe et al. (2004) were the first to incorporate the effect in models

- In what band are you measuring your radii?

Planets Large and Small

- Some planets are clearly smaller than expected for pure H/He objects. This is not surprising.
- Some planets are clearly larger than expected for pure H/He objects.



- Two classes of explanations for large radii:
  - Those that affect just the 3-4 outliers
  - Those that affect all these planets, but are masked in some by large cores

Explaining Large Radii

Evolution of "51 Pegasus b-like" planets

T. Guillot[1] and A. P. Showman[2]

ON THE TIDAL INFLATION OF SHORT-PERIOD EXTRASOLAR PLANETS[1]

Peter Bodenheimer,[2] D. N. C. Lin,[2] and R. A. Mardling[2,3]

Received 2000 May 17; accepted 2000 October 11

OBLIQUITY TIDES ON HOT JUPITERS

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Received 2005 May 13; accepted 2005 June 20; published 2005 July 15

The effect of evaporation on the evolution of close-in giant planets

I. Baraffe[1], F. Selsis[2], G. Chabrier[1], T. S. Barman[3], F. Allard[1], P. H. Hauschildt[4], and H. Lammer[5]

POSSIBLE SOLUTIONS TO THE RADIUS ANOMALIES OF TRANSITING GIANT PLANETS

A. Burrows,[1] I. Hubeny,[1] J. Budaj,[1,2] and W. B. Hubbard[3]

Received 2006 December 22; accepted 2007 February 9

HEAT TRANSPORT IN GIANT (EXO)PLANETS: A NEW PERSPECTIVE

Gilles Chabrier and Isabelle Baraffe[1,2]

Received 2007 March 6; accepted 2007 March 28; published 2007 May 4

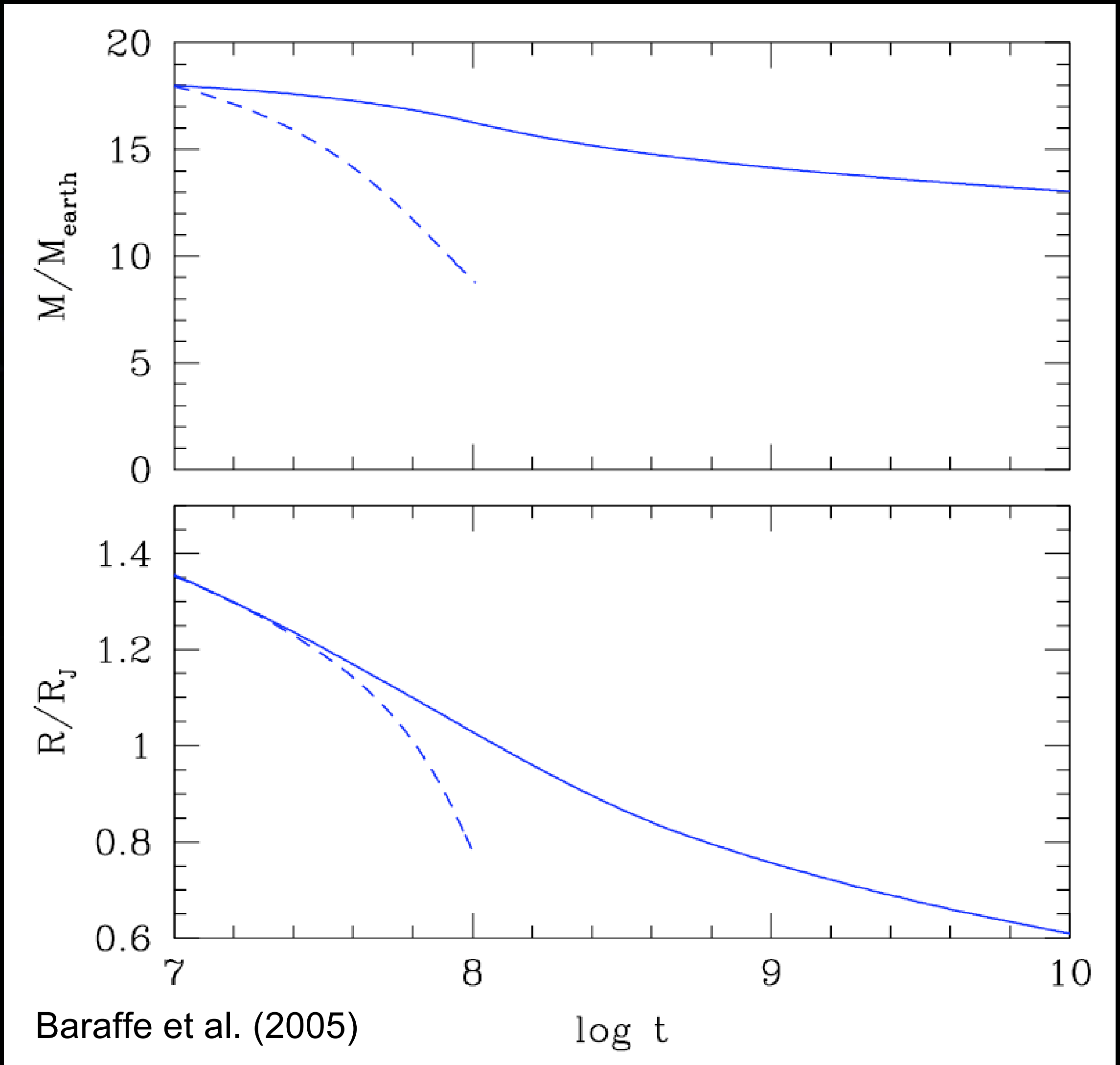
Two Classes of Hot Jupiters

Brad M. S. Hansen[1] & Travis Barman[2]

- The first Hot Neptune does ***not*** appear to be a Hot Jupiter evaporation remnant

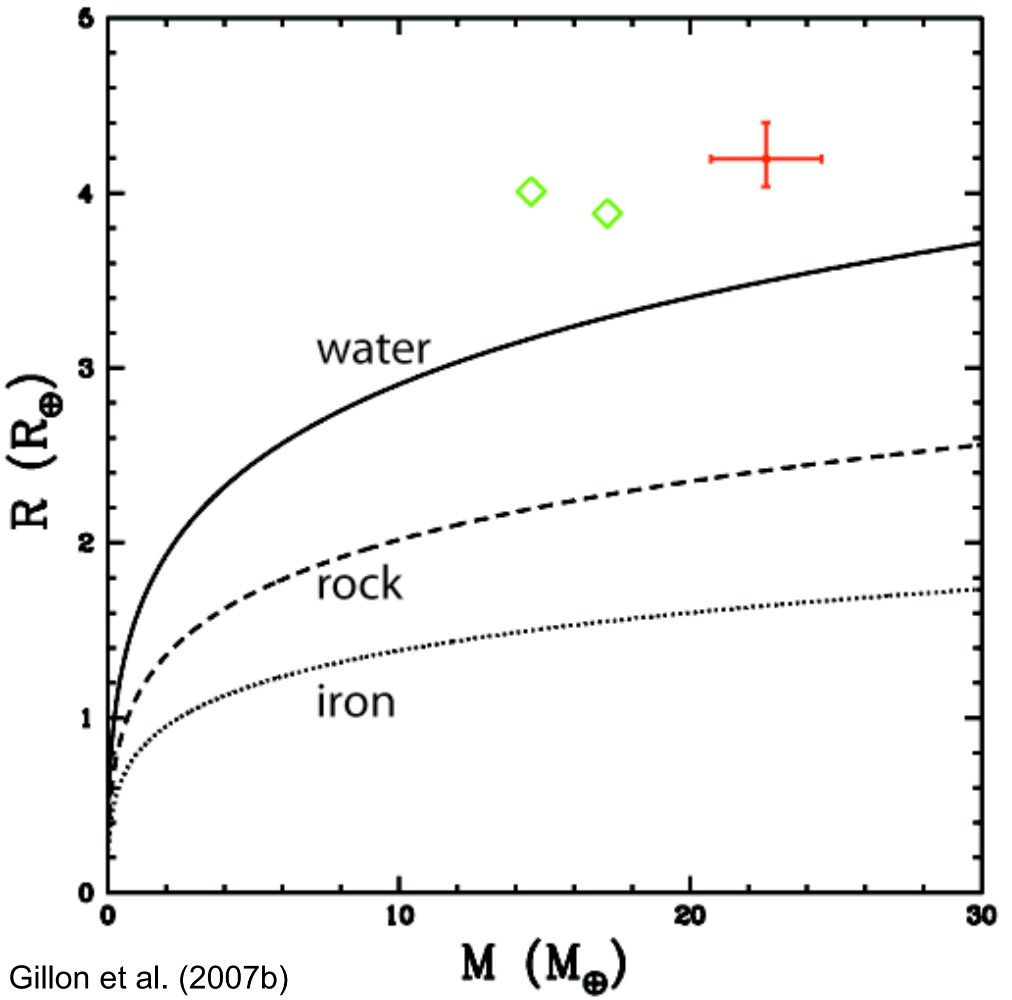
- Baraffe et al. (2004, 2005) models predict remnant Hot Neptune radii of ~0.6 to 1.4 R_J (GJ 436b is ~0.38 R_J)

- Although evaporation certainly occurs, planets perhaps only lose ~1% of mass over Gyr timescales



Baraffe et al. (2005)

Transiting Planet GJ 436b: The Smallest & Coolest Yet



Gillon et al. (2007b)

Mass: 22 M_{Earth}
Radius: 3.8 R_{Earth}
T_{eq} ~ 630 K

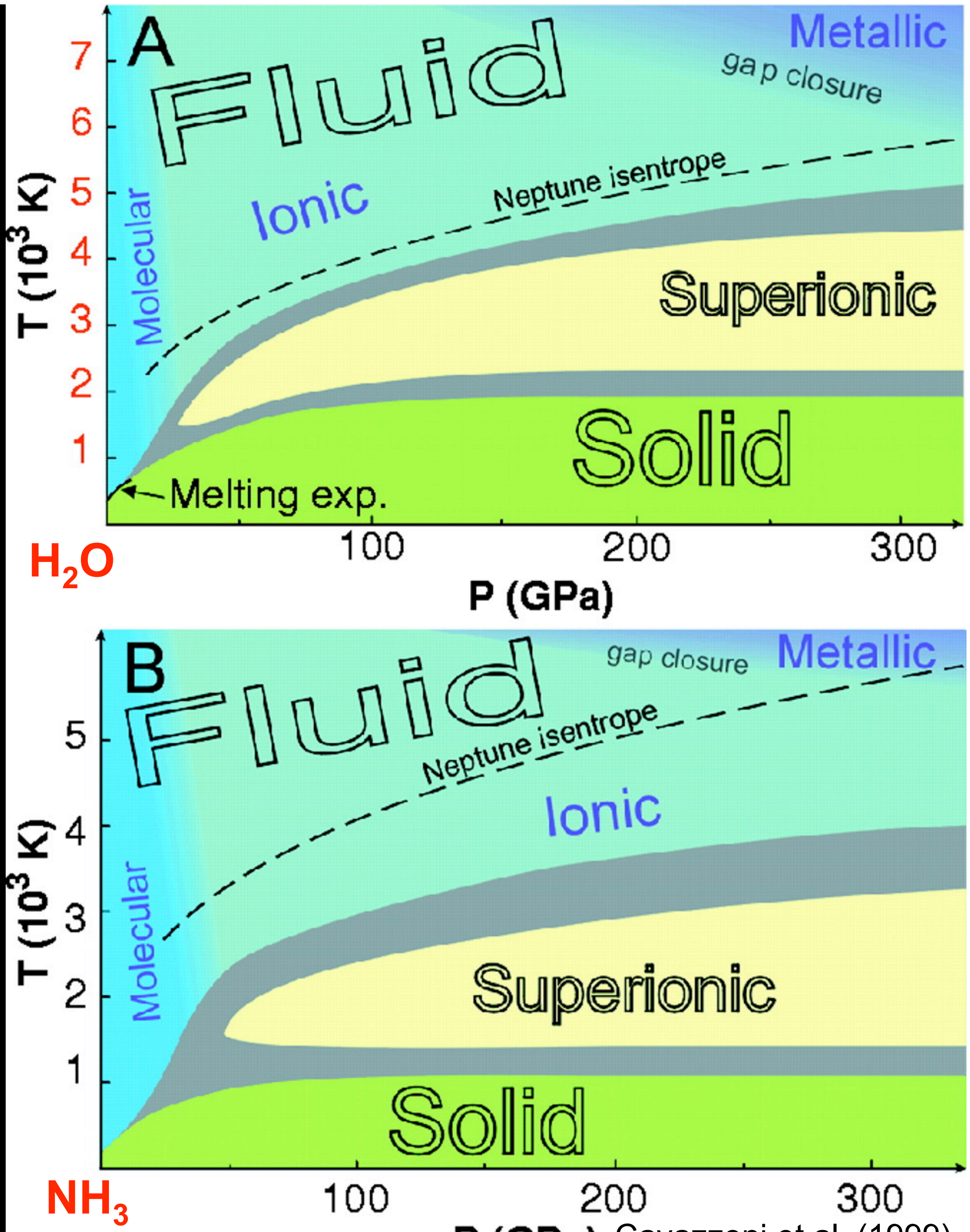
The Uranus/Neptune Paradigm:

- Interior mostly ***FLUID*** H_2O, CH_4, NH_3 (dissociated & ionized)
- A few M_{earth} of rock/iron in core
- A few M_{earth} of H/He atmosphere
- Atmospheric metallicity of 30-40 X solar!

- GJ 436b is by far the coolest transiting planet

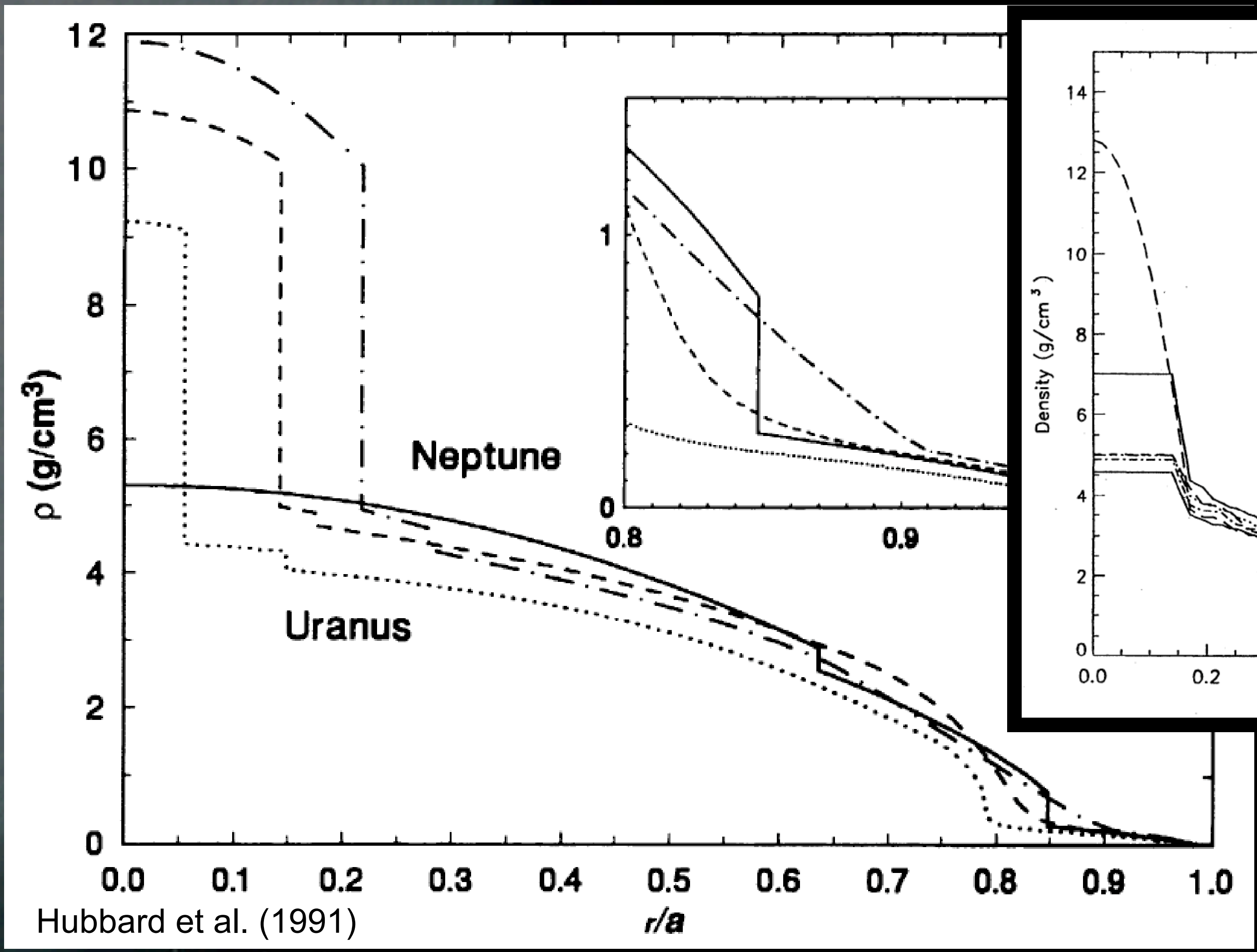
Is the ice in planet GJ 436b solid?

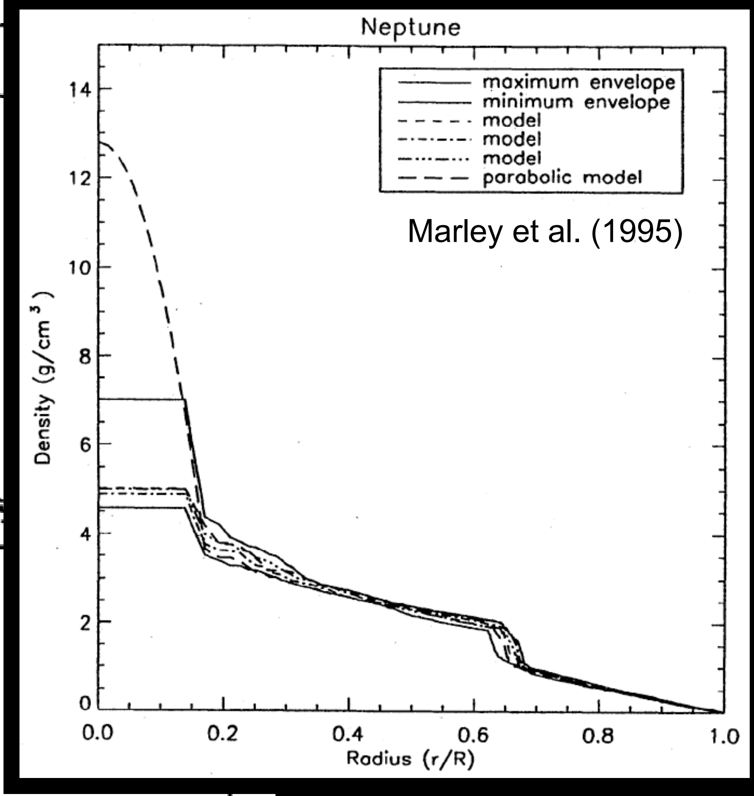
- No.
- All evidence for Uranus/Neptune indicates that their interiors are predominantly fluid
  - A fluid "sea" of partially dissociated fluid H_2O, NH_3, and CH_4
  - This is backed up by models of dynamo-generated magnetic field
  - Experiments by Nellis et al. on water and "synthetic Uranus" mixtures
- GJ 436b is more massive and receives ~10^5 more incident flux, meaning it likely has an even warmer interior than Uran./Nept.



Cavazzoni et al. (1999)

Uncertainties in Understanding the Interiors of Uranus and Neptune

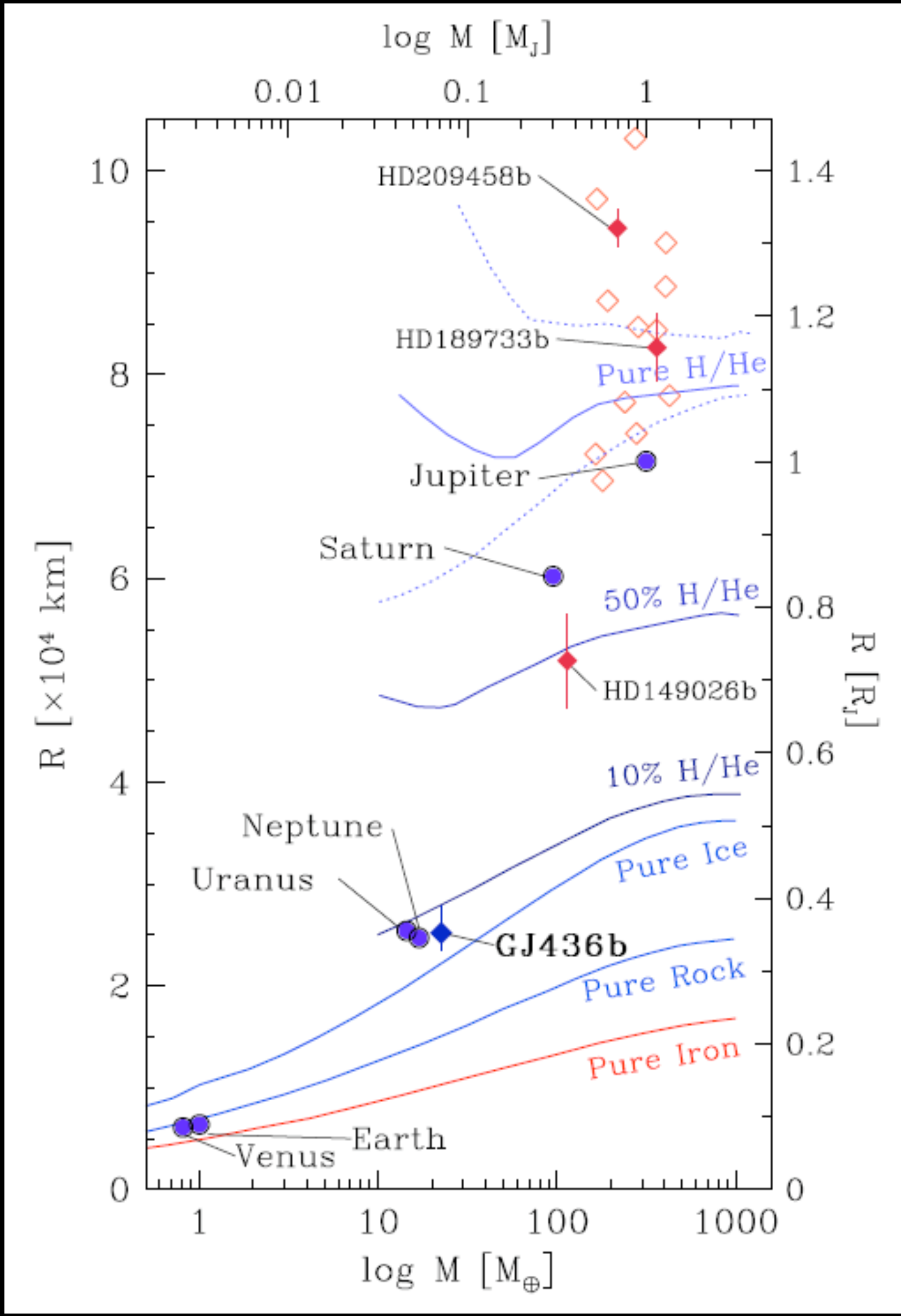




Rock cores of Uranus and Neptune may be quite small

GJ 436b: Structure and Composition

- Uranus/Neptune-like composition appears to be a valid starting point: ~75% ices, ~15% rock, ~10% H/He
- However, there is **significant degeneracy:**
    - Same radius can be achieved with less water (or not water) and more rock and H/He
    - It is not clear how this degeneracy will even be lifted except with a perfect understanding of planet formation
    - Where did the planet form??



Conclusions

- ***Gas Giants:***
  - Current crop of planets likely includes those with larger and smaller amounts of heavy elements than Jupiter and Saturn
  - Work is beginning on linking core masses to stellar metallicity (but is it that simple?)
  - *COROT* and *Kepler* will find planets out to ~0.2 and ~1 AU, respectively, greatly expanding our phase space.

- ***Ice Giants:***
  - One known exo-Neptune-class planet, GJ 436b
  - Relative abundances of H_2O, CH_4, NH_3, silicates, and iron will depend on details of formation, which remain poorly known
  - Considerable degeneracy in mass-radius relation

Nice Review Papers: Stevenson (1982) in AREPS, Chabrier & Baraffe (2000) in ARAA, Hubbard et al. (2002) in ARAA, Guillot (2005) in AREPS