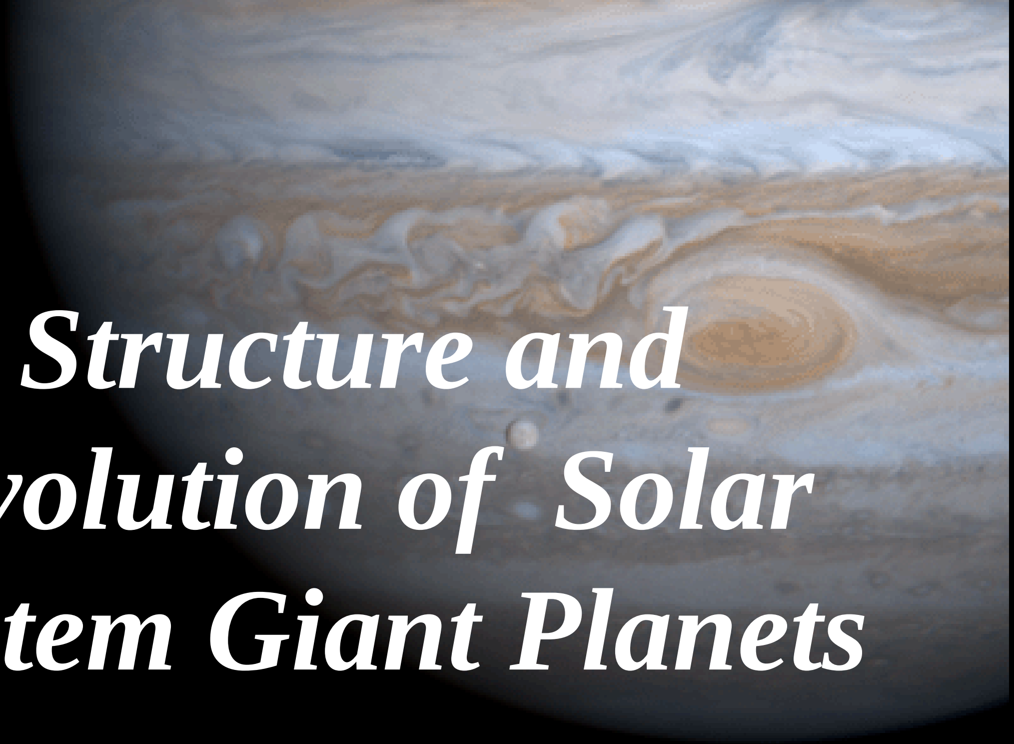


Structure and Evolution of Solar System Giant Planets

Dave Stevenson

Caltech

KITP Exoplanets, March 30, 2010

Why should you Care?
(about a tiny fraction of all planets- the ones in our solar system)

- We have a far greater prospect of understanding them in detail because of better data (including in situ data) - gravity, magnetic field, heat flow, composition (including noble gases and isotopes)
- Some of this better understanding informs us about general processes (not just the vagaries of our solar system) and calibrates our models (e.g. equation of state)
- Our planets teach us humility… our incomplete understanding is in large part because planets are complicated… planetary science will never yield to the astronomical low dimensional representations (such as the H-R diagram).

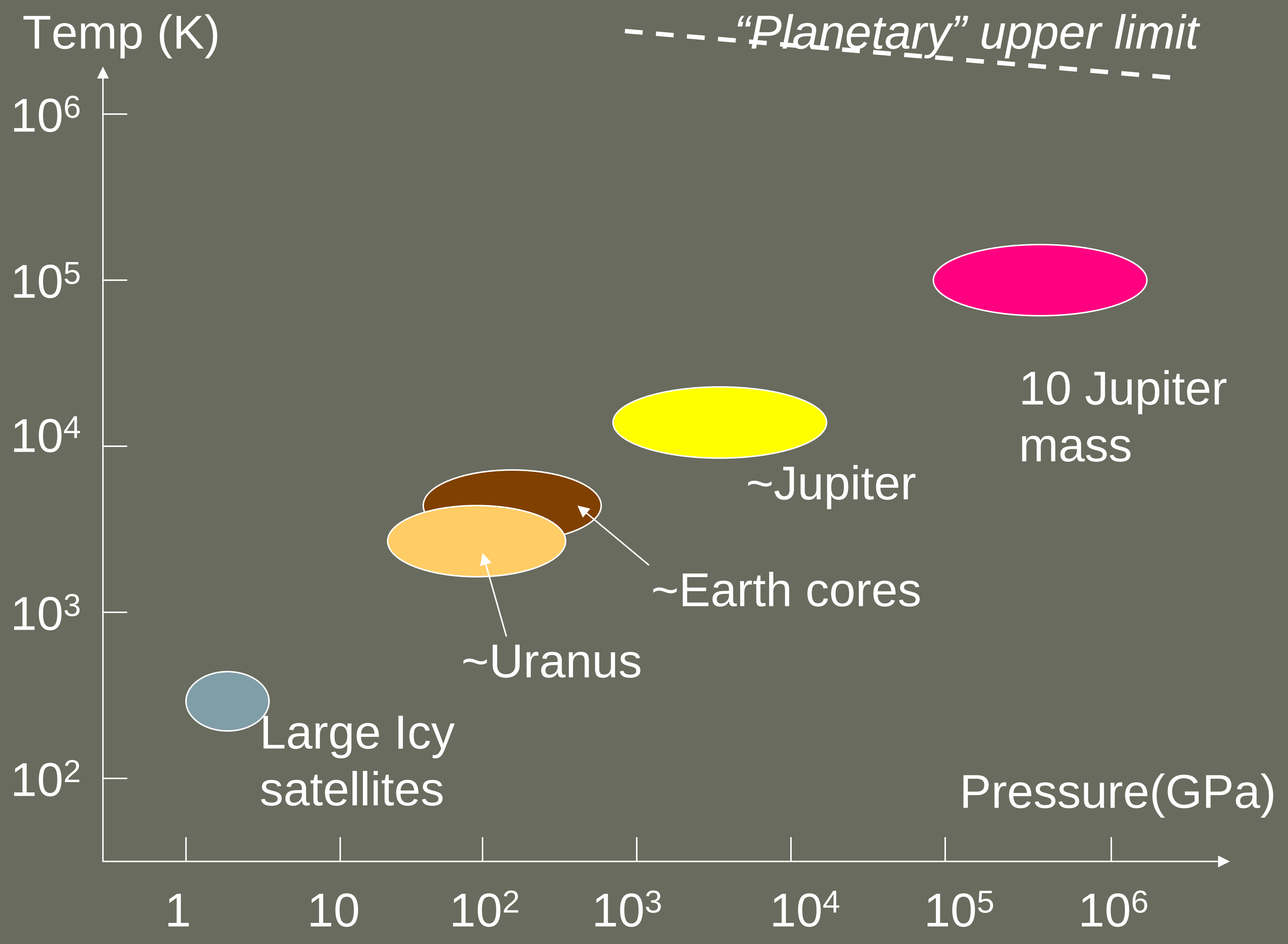
Pressures of Relevance

- At 1 Mbar, $PV_{ion} \sim 1eV$

- $P_{typical} \sim 1Mbar. (M/M_{earth})^2.(R_{earth}/R)^4$

or $P_{typical} \sim 10Mbar. (M/M_{Jupiter})^2.(R_{Jup}/R)^4$

Pressures much higher than 10 Mbar occur in SuperJupiters (common) but hydrogen is "simple" at these extreme pressures (and relevant temperatures)?



Temp (K)
"Planetary" upper limit
10^6
10^5
10^4
10^3
10^2
10 Jupiter mass
~Jupiter
~Earth cores
~Uranus
Large Icy satellites
Pressure(GPa)
1
10
10^2
10^3
10^4
10^5
10^6

Cosmic (~Solar) Abundances

Element	**Number Fraction**	**Mass Fraction**
H	0.92	0.71
He	0.08	0.27
O	7×10^{-4}	0.011
C	4×10^{-4}	0.005
Ne	1.2×10^{-4}	0.002
N	1×10^{-4}	0.0015
Mg	4×10^{-5}	0.001
Si	4×10^{-5}	0.0011
Fe	3×10^{-5}	0.0016

Cosmic (~Solar) Abundances

Element	Number Fraction	Mass Fraction
H (Gas)	0.92	0.71
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Si (Rock)	4×10^{-5}	0.0011
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-But these characterizations are very misleading at high P and T

Mass-Radius Relationships

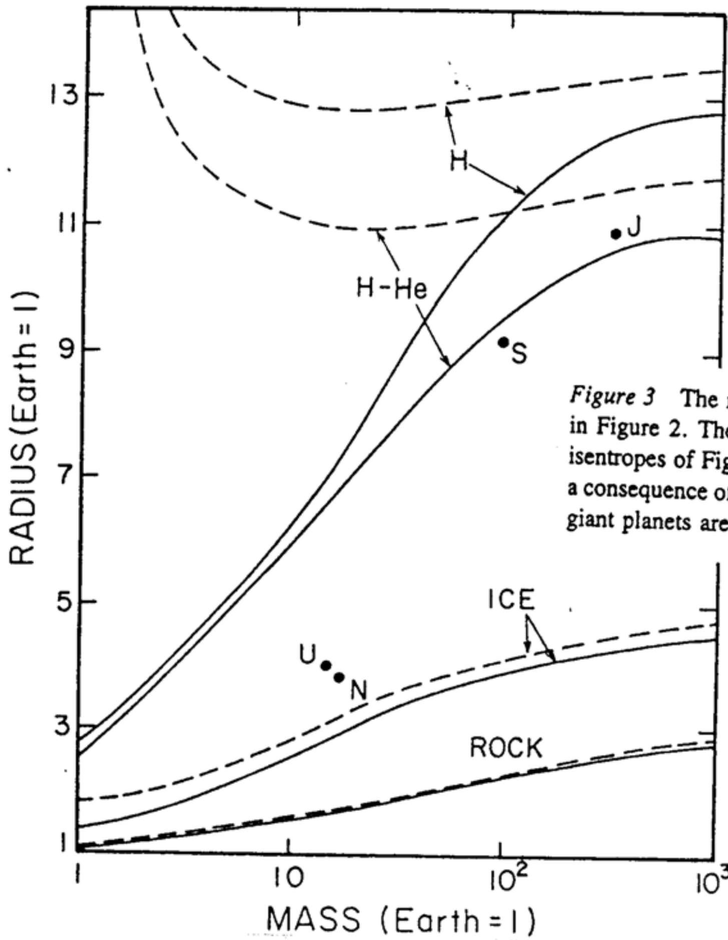


Figure 3 The mass-radius relationship for self-gravitating bodies of the same compositions as in Figure 2. The solid lines are for cold matter ($T = 0$ K); the dashed lines correspond to the isentropes of Figure 2. The insensitivity of radius or mass for hydrogen and hydrogen-helium is a consequence of the approximate validity of $P \propto \rho^2$ (see text for discussion). The positions of the giant planets are labelled by J, S, U, and N.

Stevenson (1982)

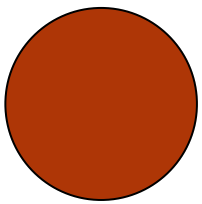
A reworking of Zapolsky & Salpeter (1969), adding isentropic models

Some Significant Facts for Our Solar System

- Jupiter & Saturn are mostly gas. (So they must have formed in the presence of a nebula).
- Jupiter may have a dense core & Saturn almost certainly has a dense core. Both are enriched in heavy elements throughout.
- Jupiter and Saturn release substantially more energy than they receive from the Sun.. Primarily a consequence of steady cooling.
  - Contraction is a consequence of cooling , not an energy source in itself.
  - Possibly also some differentiation.
- Uranus and Neptune resist simple characterization. Contrary to what is sometimes claimed, they are not necessarily ice rich. (You could build them out of Plutos or Tritons plus a modest amount of gas.) Not layercakes!

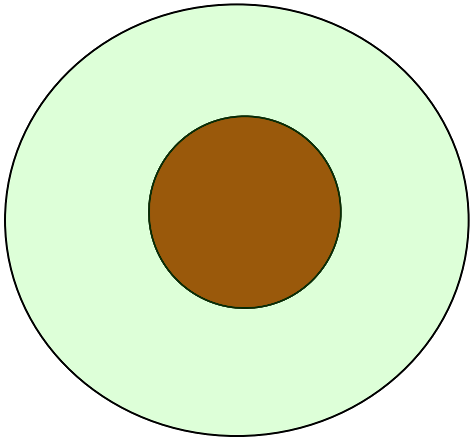
Why might a Planet have a Core?

Bottom Up

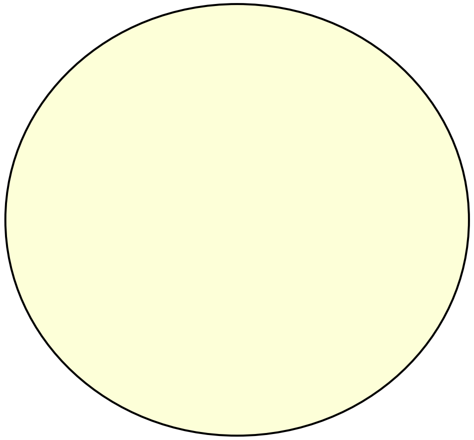


Popular Giant Planet Picture

Accrete gas

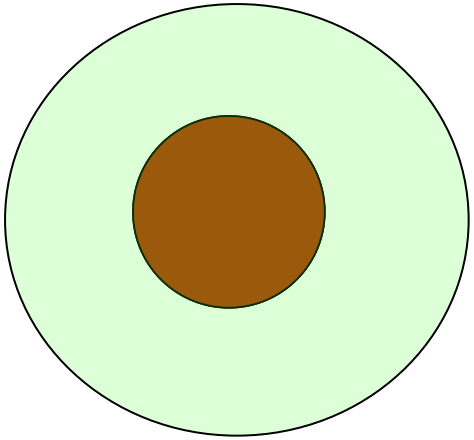


Top Down



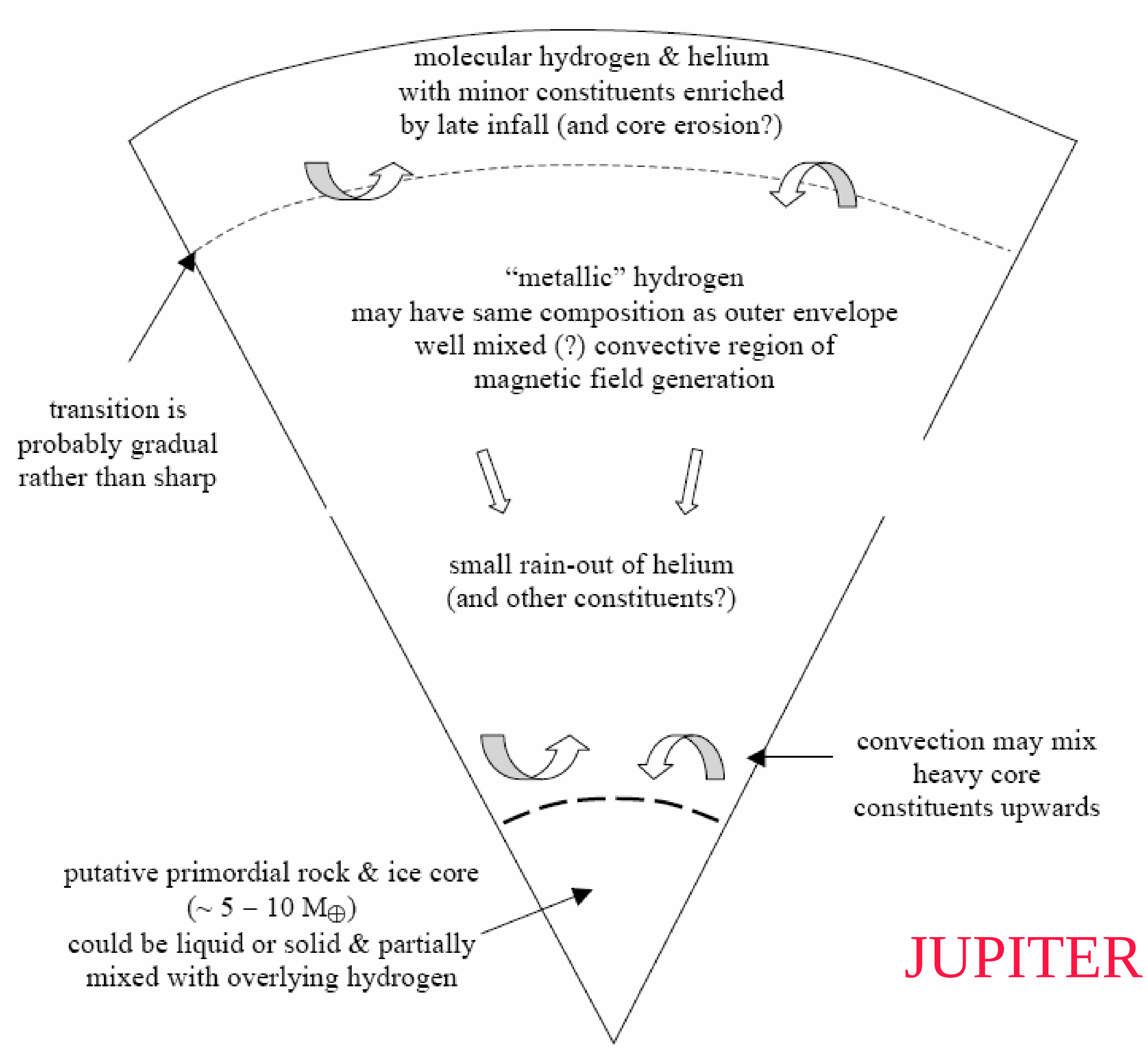
Well established Terrestrial Planet Picture

Differentiate



There are some major problems with giant planet models

- Equation of state uncertainties
  - Theory of pure end-members still not converging with other information
  - Mixtures not well understood. Our usual concepts of relevant materials break down at high P and T.
  - Experiments are difficult
- Unreasonable reliance on parsimony.
  - Concepts of “cores” are based on false analogies (e.g., Earth’s core or behavior of materials at low P and T)
  - Ideas of planet formation do not necessarily lead to simple separation of materials according to density.
- Absence of the most valuable technique: Seismology


molecular hydrogen & helium
with minor constituents enriched
by late infall (and core erosion?)
"metallic" hydrogen
may have same composition as outer envelope
well mixed (?) convective region of
magnetic field generation
transition is
probably gradual
rather than sharp
small rain-out of helium
(and other constituents?)
convection may mix
heavy core
constituents upwards
putative primordial rock & ice core
(~ 5 – 10 M⊕)
could be liquid or solid & partially
mixed with overlying hydrogen
JUPITER

Current State of Jupiter Modeling

- Until a few years ago, the state of the art relied heavily on EOS from Saumon, Chabrier and van Horn (a "chemical approach"). Used extensively by Guillot. But enough uncertainty that one could not say whether Jupiter has a core.
- More recent modeling use density functional approach to the EOS for hydrogen (also some work on mixtures)
- Latest models yield just as much variation in core mass as previous work! (Few to 15 Earth masses).
  - <u>Primary</u> reason is different assumptions about the composition (number of layers)
- Is the molecular to metallic phase transition first order? This may be the wrong thing to focus on since it must be at most a small entropy and density jump.
  - No current evidence of a first order transition.
- Insolubility of helium is now quite well established (this <u>is</u> a first order phase transition).
- Layering, if present, can arise from how the planet was assembled.

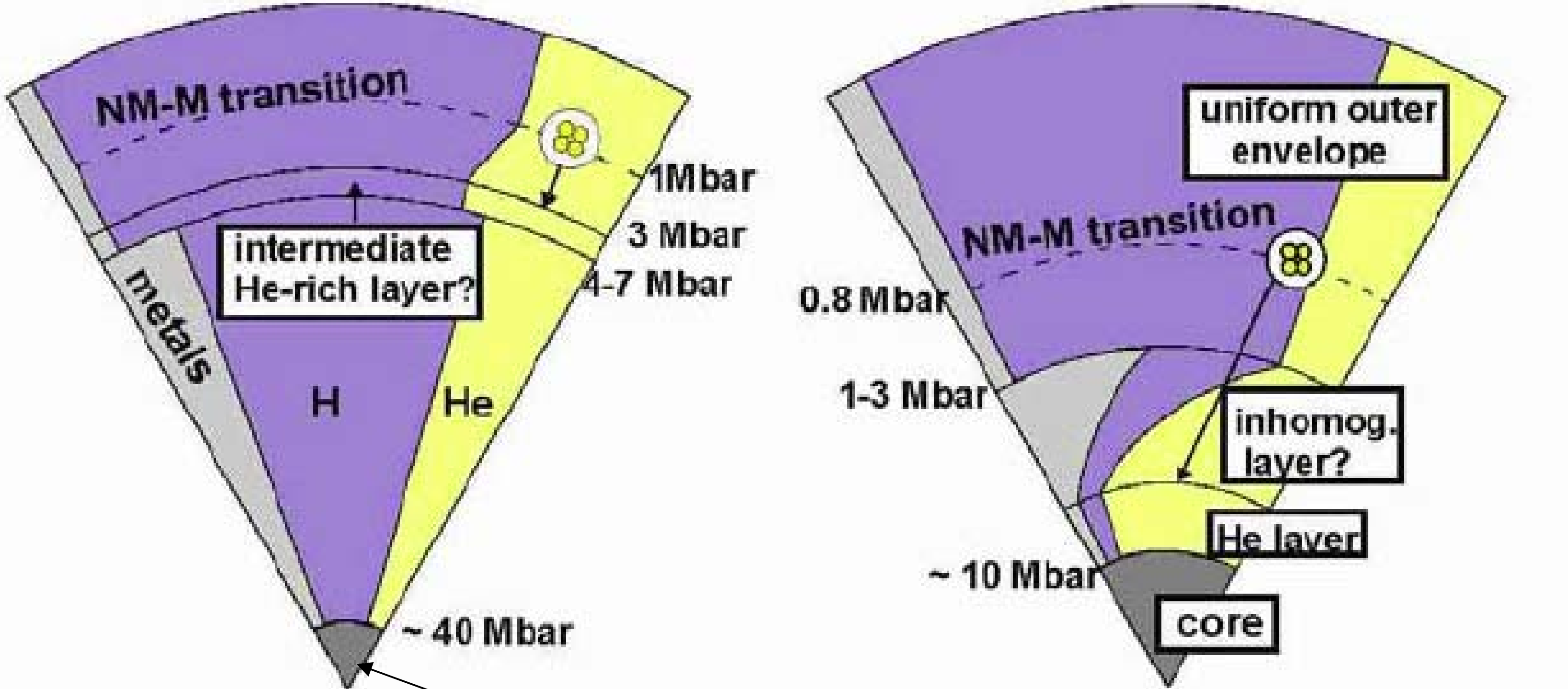


Figure 2: 4-layer interior models of Jupiter (*left*) and Saturn (*right*).

Nettelmann et al,
2008…

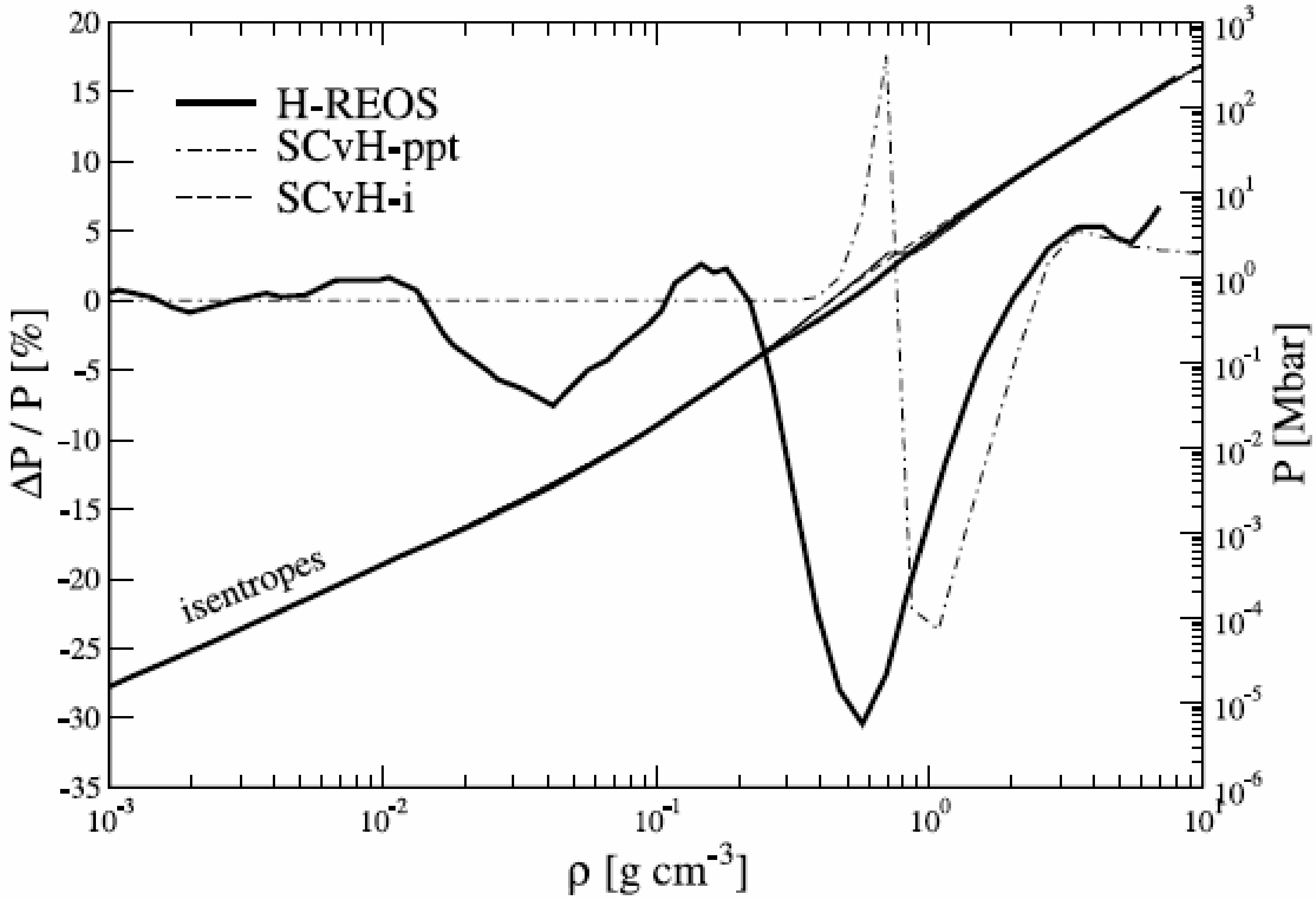


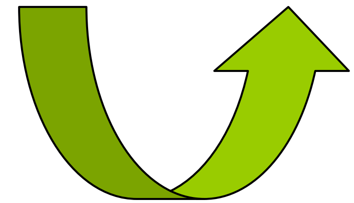
FIG. 6.—Hydrogen adiabats for Jupiter, determined by $T = 165$ K at $P =$ 1 bar, computed with three different hydrogen EOSs: H-REOS, SCvH-i, and SCvH-ppt. The scale on the right shows absolute pressures, and the scale on the left shows relative differences in pressure with respect to the SCvH-i-adiabat.

Nettelmann et al, 2008

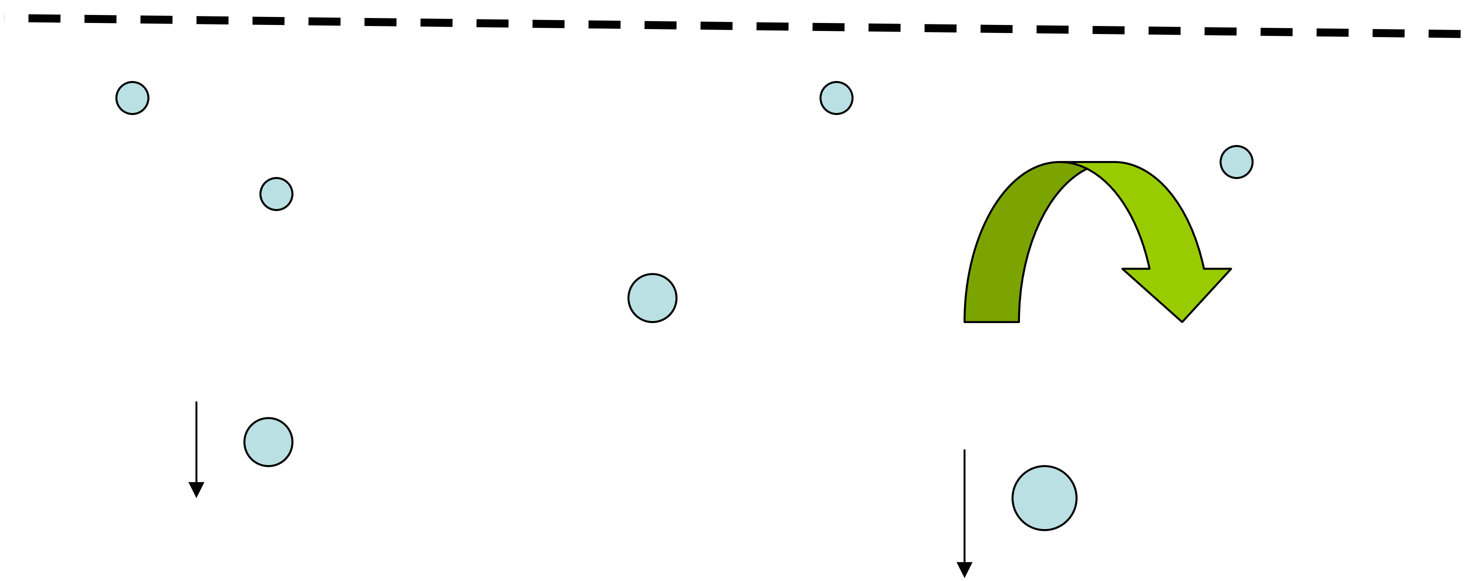
Where do we go with the EOS Issue?

- Experiments at NIF (Livermore) might help
  - Need to use precompressed and cryogenic targets.
- High pressure calibration is a problem!
- The failure of theory at relatively low pressure (~0.5 Mbar) needs to be better understood
- But some reason for optimism on the timescale of the next big influx of information- the Juno mission (launch in 2011, arrival in 2016)

Helium Raindrops form at ~ million atmospheres (15000km depth)….
Neon partitions into the droplets,
Argon does not



Observations now agree with quantum mechanical calculations



Selected for a Viewpoint in *Physics*
PRL **104,** 121101 (2010) PHYSICAL REVIEW LETTERS week ending 26 MARCH 2010

Sequestration of Noble Gases in Giant Planet Interiors

Hugh F. Wilson[1] and Burkhard Militzer[1,2]
[1]*Department of Earth and Planetary Science, University of California Berkeley, Berkeley, California 94720, USA*
[2]*Department of Astronomy, University of California Berkeley, Berkeley, California 94720, USA*
(Received 19 November 2009; published 22 March 2010)

The Galileo probe showed that Jupiter's atmosphere is severely depleted in neon compared to protosolar values. We show via *ab initio* simulations of the partitioning of neon between hydrogen-helium phases that the observed depletion can be explained by the sequestration of neon into helium-rich droplets within the postulated hydrogen-helium immiscibility layer of the planets interior. We also demonstrate that this mechanism will not affect argon explaining the observed lack of depletion of this gas. This provides strong indirect evidence for hydrogen-helium immiscibility in Jupiter.

DOI: 10.1103/PhysRevLett.104.121101 PACS numbers: 96.30.Kf, 31.15.es, 64.75.Bc, 96.15.Kc

NOBLE GASES in JUPITER

Neon is a Jupiter thermometer.. The observed depletion requries a temperature of ~5000K at the raindrop formation location

He	10% depletion	Insolubility
Ne	Factor of ~10 depletion	Partitioning into He raindrops
Ar,Kr, Xe	Factor of ~ 3 enrichment	Sticky

ELECTROMAGNETIC SKIN EFFECT

Field with reduced dipole tilt

Droplet formation

Stable stratification

Wind

This region is thicker for Saturn than for Jupiter , perhaps explaining part of the difference in fields

Field with dipole tilt

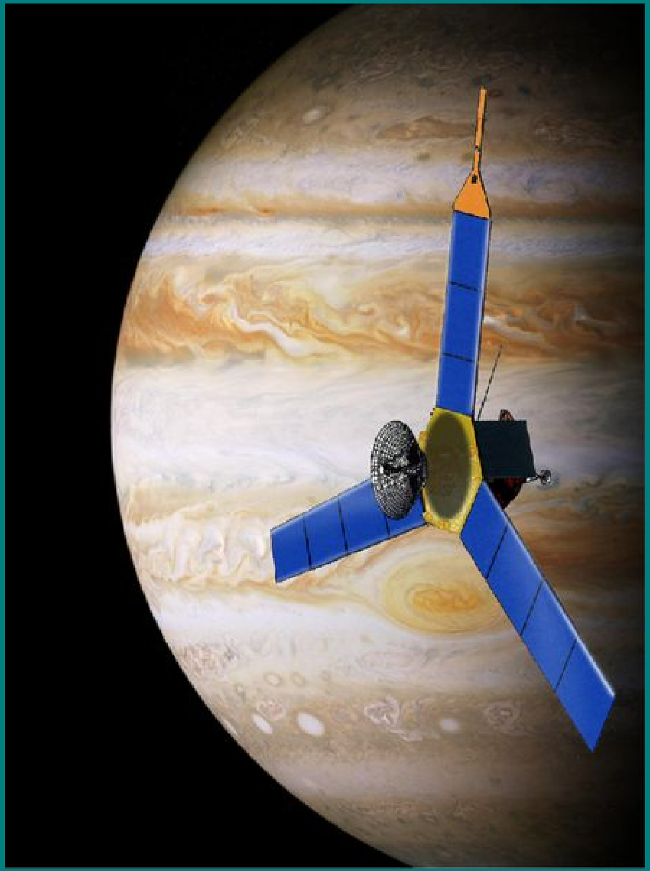
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Spin- axisymmetrization of Saturn’s magnetic field may also be indirectly a consequence of helium rain-out

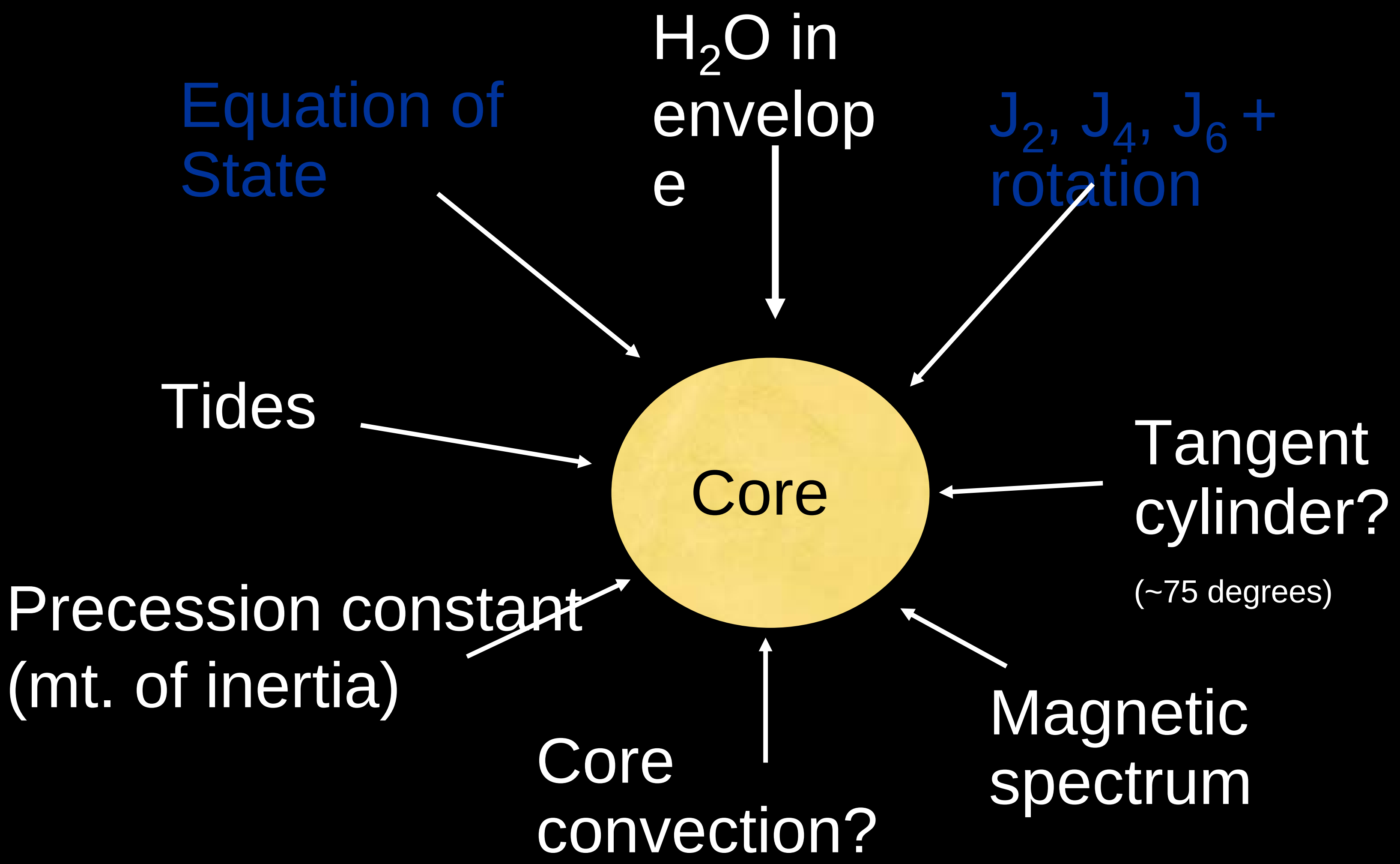
Stanley, GRL, 2010

Juno

- Launch in 2011, arrive in 2016
- Microwave sounding.. Mainly to find water
- Exquisitely accurate determination of gravity and magnetic field



Determination of Core Existence/Mass:
Juno Approach



Why U&N Matter

- Essential part of understanding planetary origin and evolution.
  - “Naked” Jupiter and Saturn cores
  - Formed in presence of nebula (since contain some gas)
  - Exist in other planetary systems

- Distinctively different! Magnetic fields are dominated by $(l,m) = (2,0)$ *and* $(1,1)$
  - Not isentropic? Some stable stratification

ICARUS 24, 280–284 (1975)

Cosmogonical Considerations Regarding Uranus

A. G. W. CAMERON

Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138

Received September 13, 1974

The cosmogony of Uranus is discussed within the context of a picture in which solid condensed materials accumulate to form a large body, which then acquires significant amounts of gas from the primitive solar nebula. Of prime cosmogonical importance is the tilt of the equatorial plane of the planet and of the plane of the satellite orbits by 98° with respect to the plane of the planetary orbit. The tilt of the planet can easily occur as a result of a major collision during the formation process; it seems most likely that the tilt of the satellite orbits requires that they were formed from a gaseous disc rotating about the planet after the tilt of the planetary rotational axis had occurred. Possible methods for tilting this gaseous disc are discussed. A strong early magnetic field may have helped in this and may have played an essential role in slowing down the spin of the planet to the present observed value. These processes may have produced significant compositional differences between the satellites of Uranus and those of Jupiter and Saturn.

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Observed parameters

Parameter	Uranus	Neptune
Mass (10^{29} g)	0.868	1.024
Equatorial radius (km)	25,559 ± 4	24,764 ± 20
Rotation period (hrs)	17.24 ± 0.01	16.11 ± 0.05
$J_2 \times 10^6$	3516 ± 3	3538 ± 9
$J_4 \times 10^6$	−31.9 ± 5	−38 ± 10
Mean density (g/cc)	1.27	1.64

These are uncertain
(especially for Neptune)

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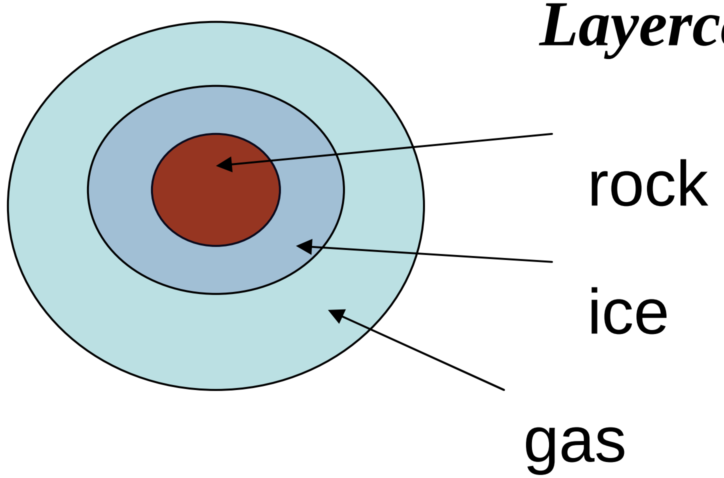
Much higher than Saturn….Sufficient to infer a large amount of elements heavier than H and He

Layercake Model for U or N

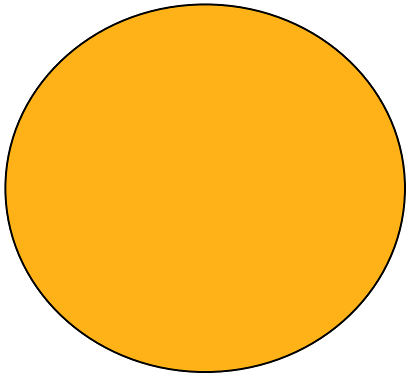


This model fails to give the right J_2 (moment of inertia is too small).

This model also fails to give the right heat flow… too much heat after 4.5 Ga.

May also not give the right magnetic field?

Fully mixed Model for U&N ….Not ridiculous a priori because ice , rock and gas may mix in all proportions at high P and T and the energy of accretion is sufficent to mix it up



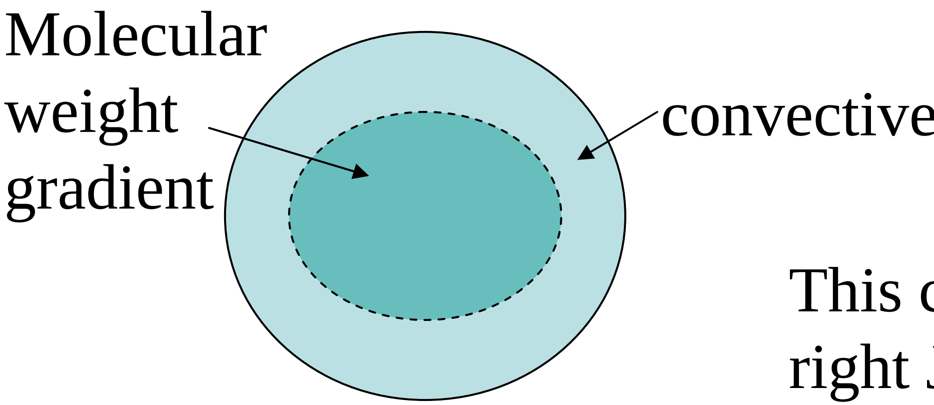
This model fails to give the right J_2 (moment of inertia is too big).

This model <u>also</u> fails to give the right heat flow… too much heat after 4.5 Ga.

This model also gives wrong deep atmosphere (even after allowing for cloud formation).

May also not give the right magnetic field?

The "Correct" Model?



This can be adjusted to get the right J_2 . It has a gravitational energy ~-0.79GM^2/R

This can also be adjusted to get the right heat flow (assuming the heat from the deeper region is unable to escape.. Deep U & N are very hot!…..over 10,000K)

This may also give an distinctive environment for the dynamo.. a shell bounded below by a non-convecting but fluid, convective deeper region.

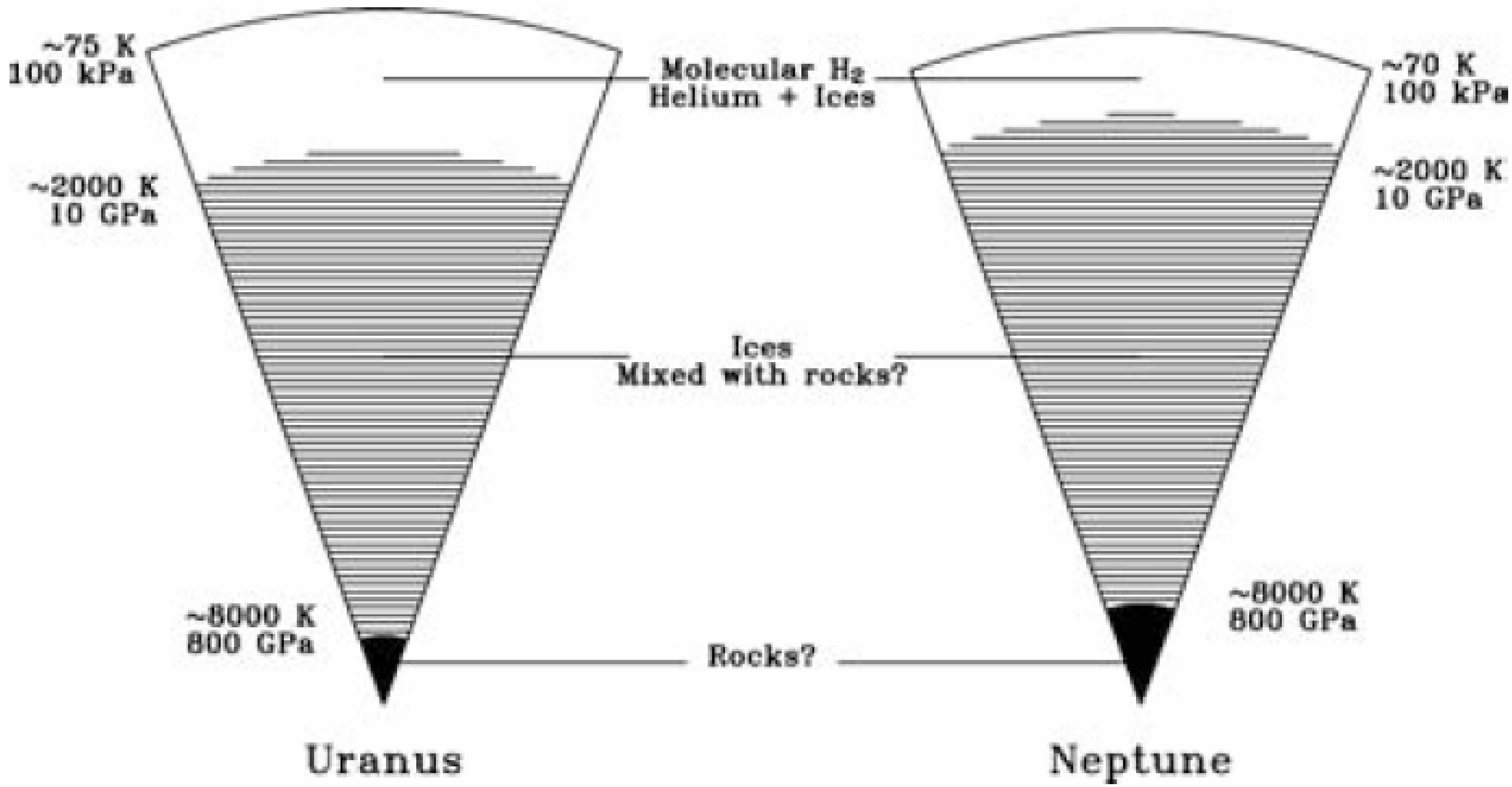
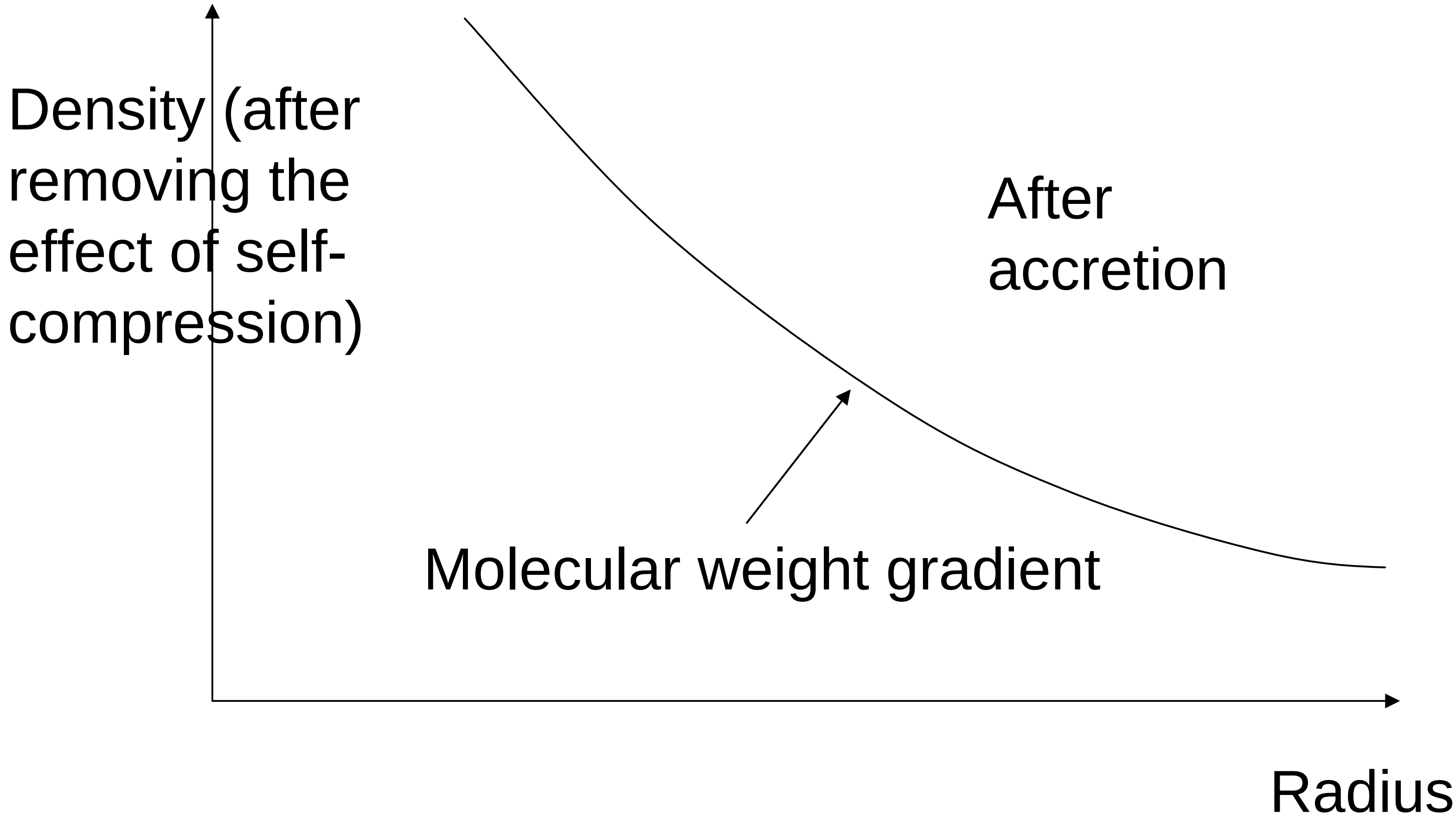


Figure 9 Schematic representation of the interiors of Uranus and Neptune. Adapted from Guillot 1999b.

What is a plausible scenario?



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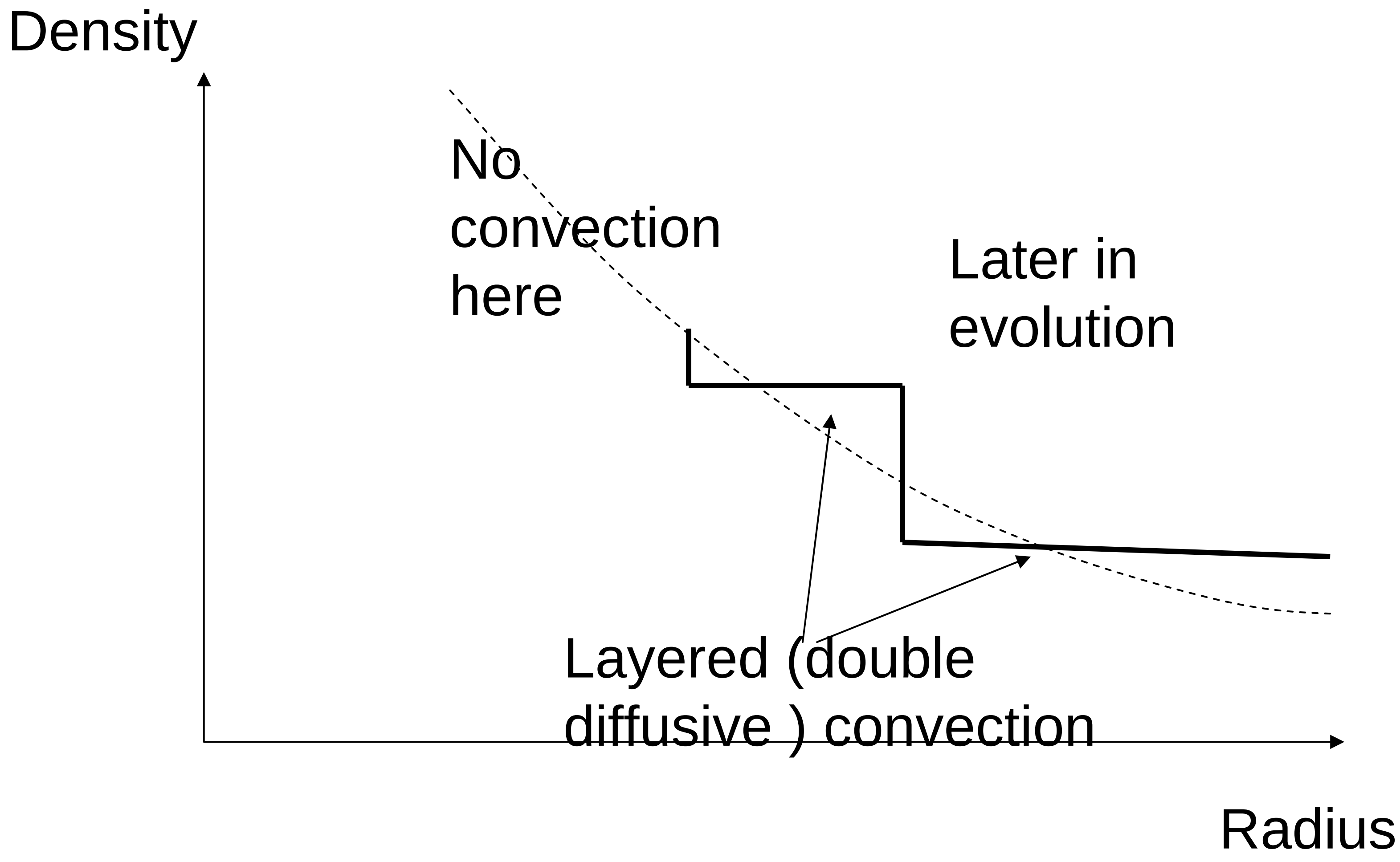

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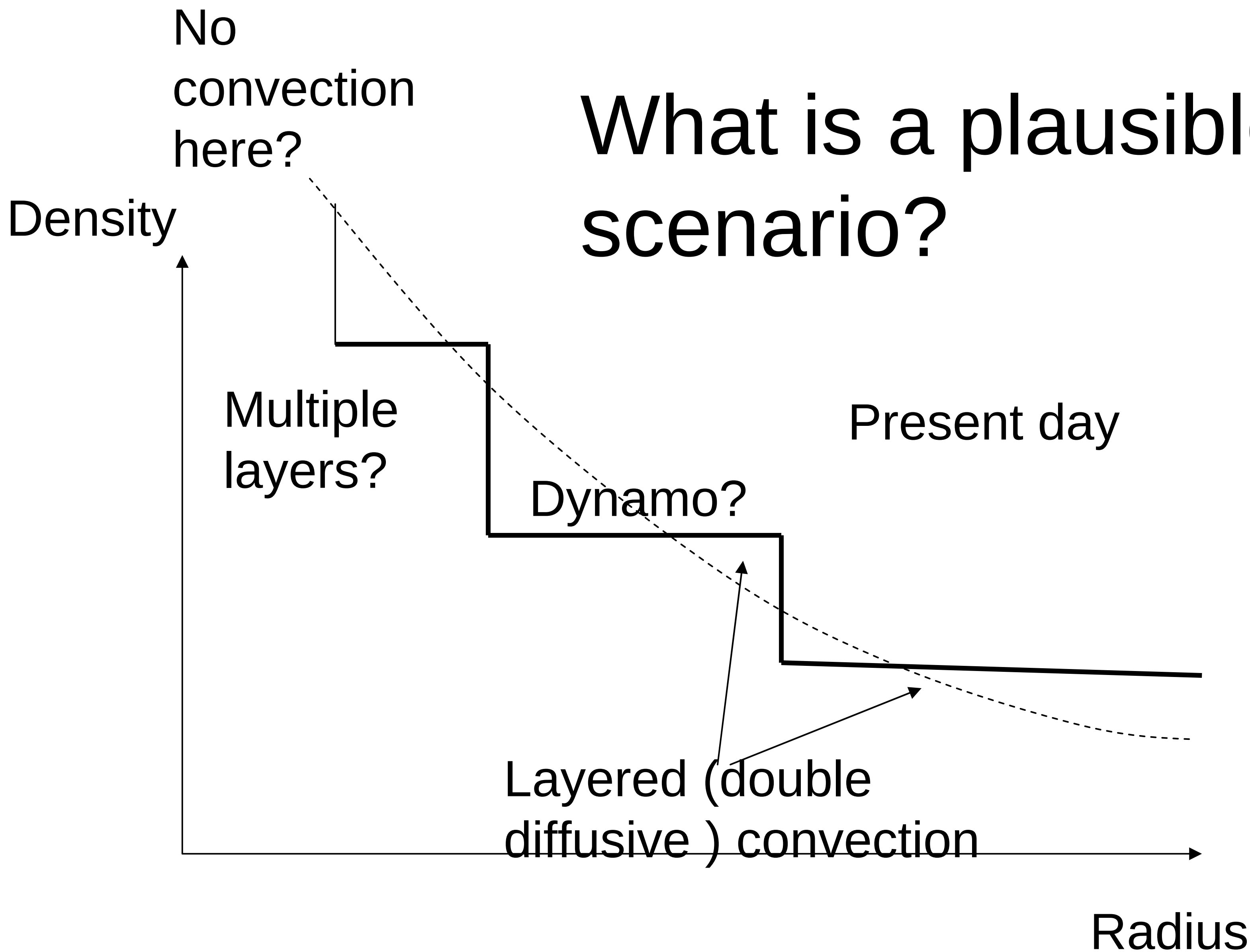

Main Conclusions

- Our planets can tells us about things that are beyond anything you could hope to learn outside our solar system
- Jupiter and Saturn have cores
- But the picture is not a simple one. The “core” is messy. Uranus and Neptune indicate this.
- Role for traumatic events? (giant impacts, embryo merging)

Future Work

- Hydrogen Equation of state.
- Thermodynamics of mixtures
- Juno & Probes.
- More realistic accretion models including orbital migration (the argon problem), etc.
- Uranus and Neptune!

“Measure what is measurable, and make measurable what is not so.”

-Galileo Galilei

The End