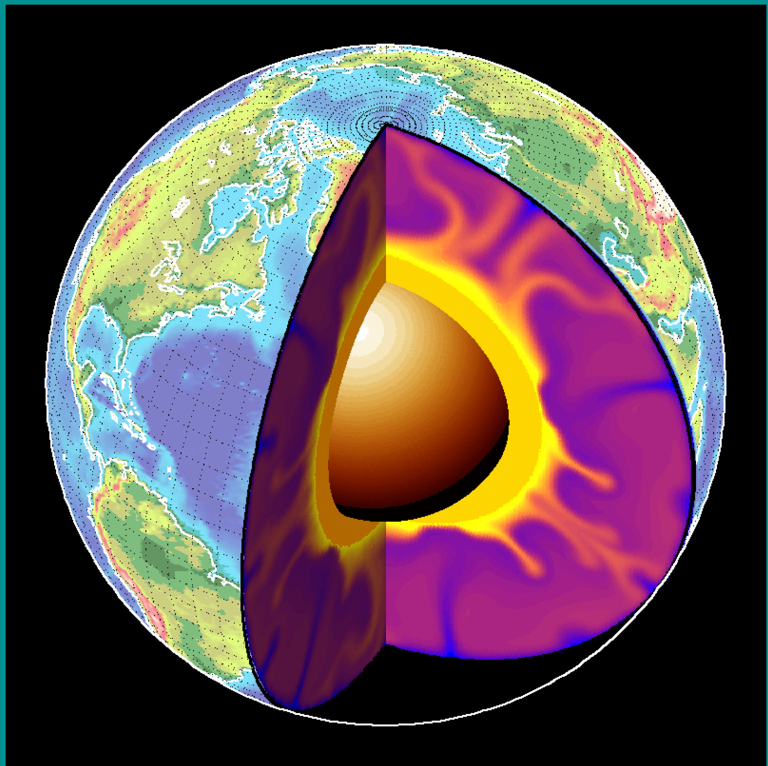
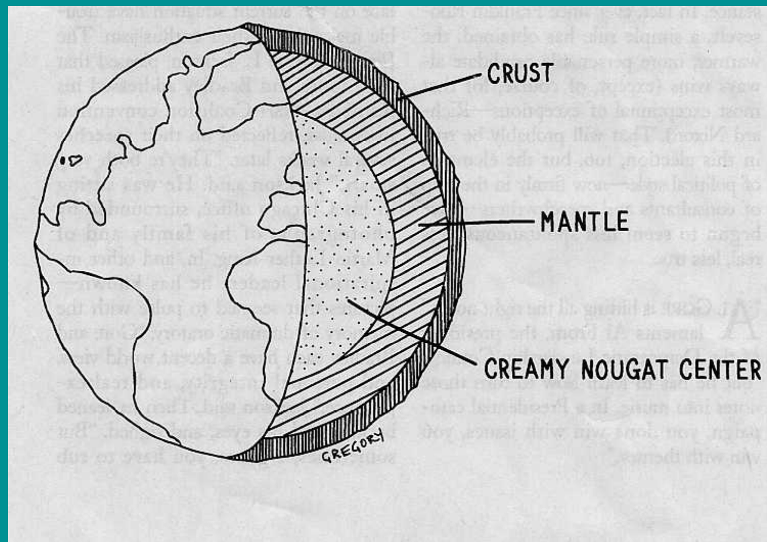
Earth Structure & Dynamics

What is Universal? What is Special?

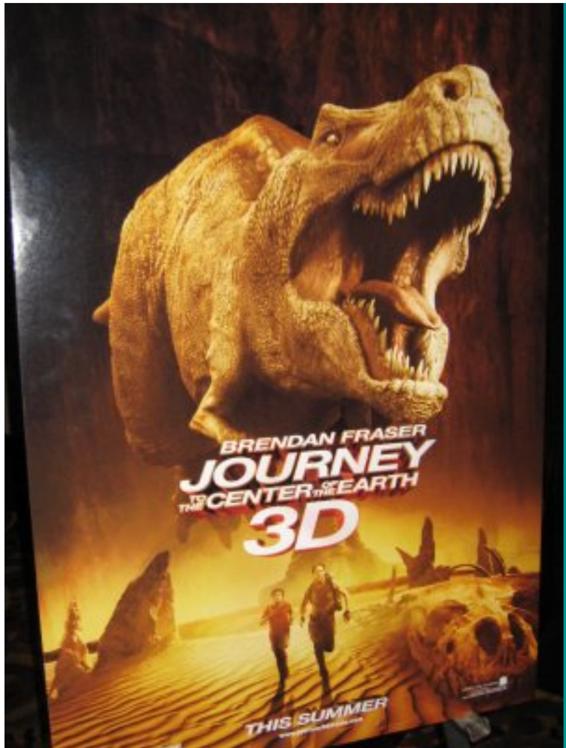


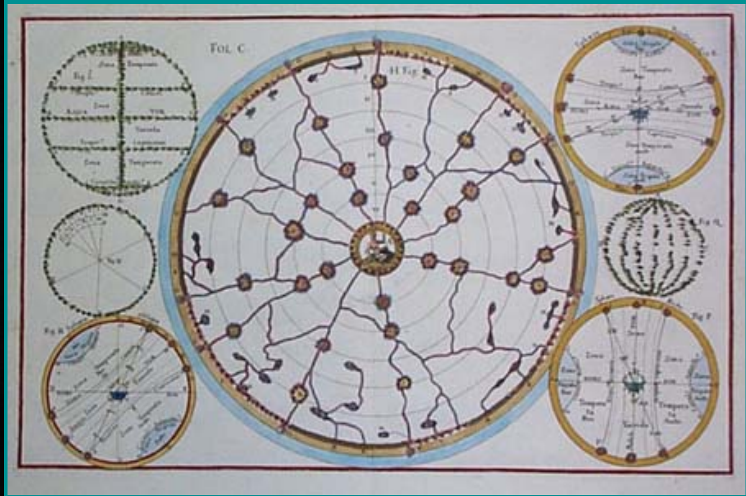


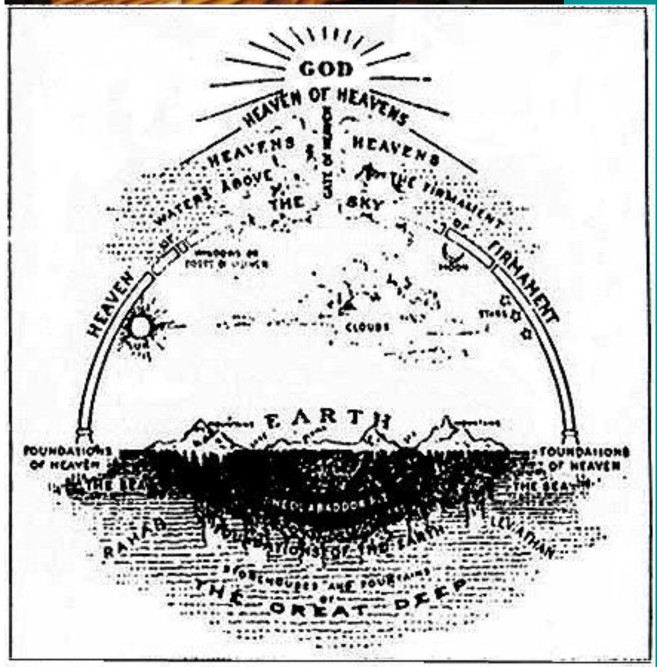
Dave Stevenson

CPS 9th International School, Kobe

June 25, 2012





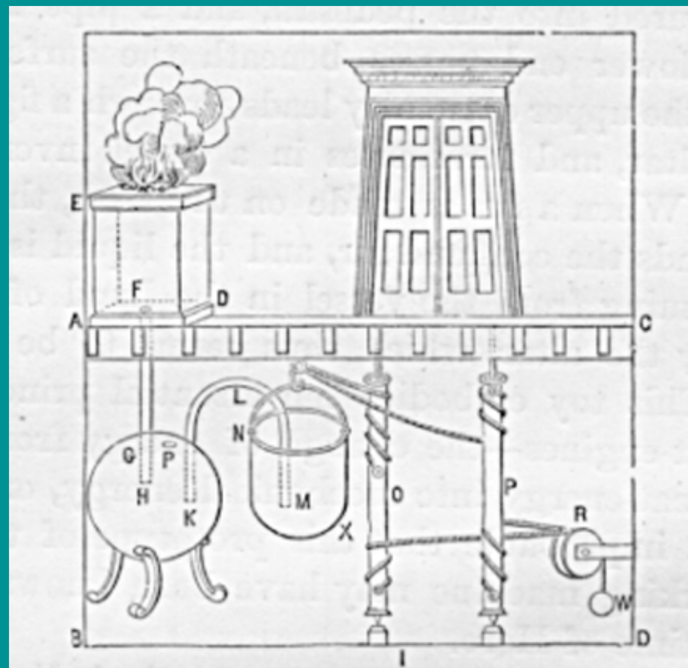


The Ancient Hebrew Conception of the Universe
(from Robinson 1913, p. 13)

Most realistic (drawn by a 6 year old child)

How to think about a Planet?

- Could discuss provenance- the properties of an apple depend on the environment in which the tree grows
- Or could discuss it as a machine (cf. Hero [n], 1st century AD)
- ***We will do both***



Here are the Questions

- What are we made of (and why)?
- Why do we have a mantle and core?
- Why do we have mantle convection?
- Why do we have Crust (Basaltic & Continental)
- Why do we have an atmosphere?
- Why do we have an ocean?
- Why do we have plate tectonics?
- Why do we have a magnetic field?
- Why do we have a moon? (Why a 24 hour day?)
- Why do we have life?

What determines planetary materials?

- Nuclear physics determines the elemental abundances
  - Big bang
  - Stellar nucleosynthesis
- Low pressure, low temperature physical chemistry determines the form in which these elements are delivered.
- The actual conditions inside the planet are high P, high T, sometimes invalidating our usual ideas of material behaviors.

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

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Rock Si	4×10^{-5}	0.0011
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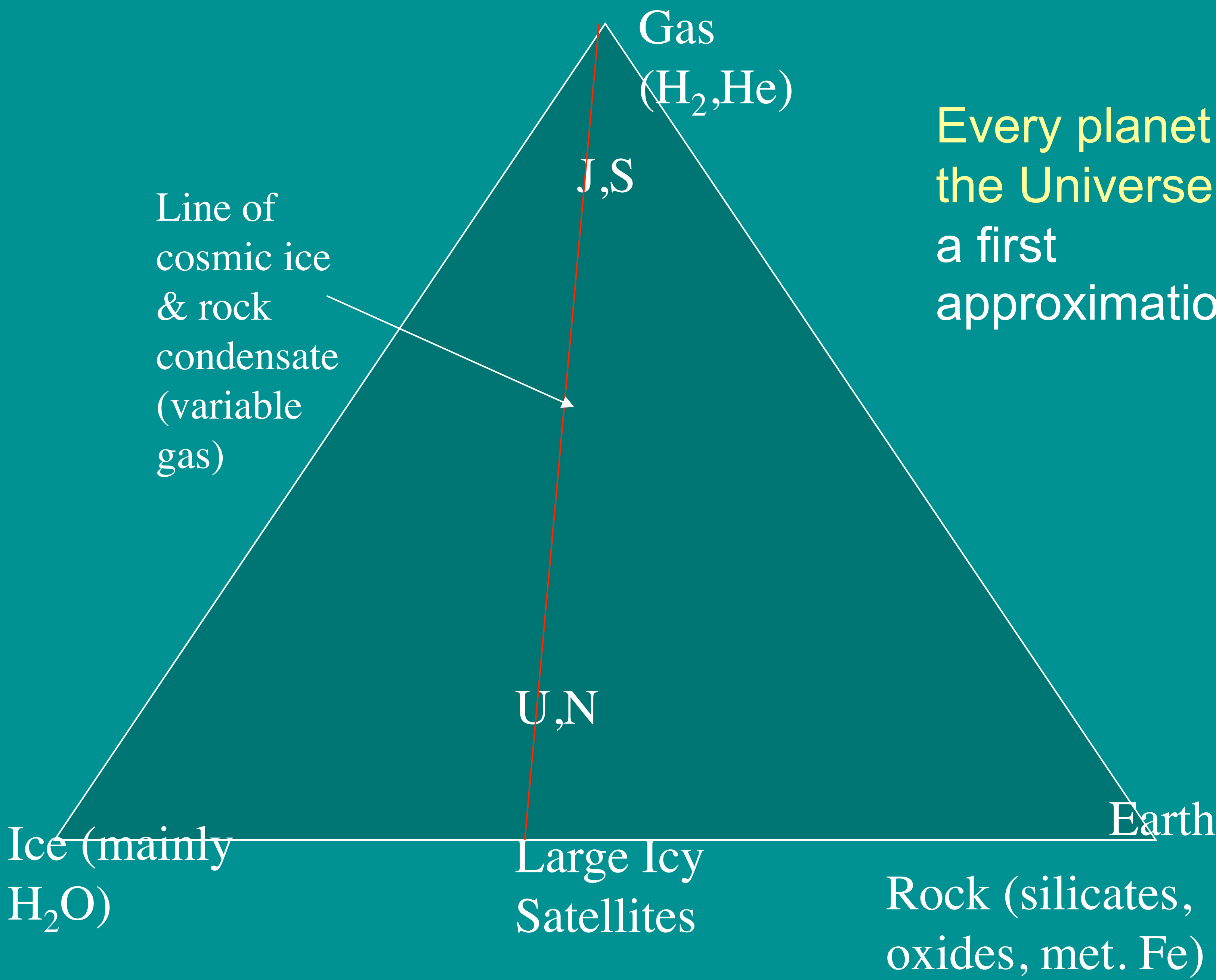
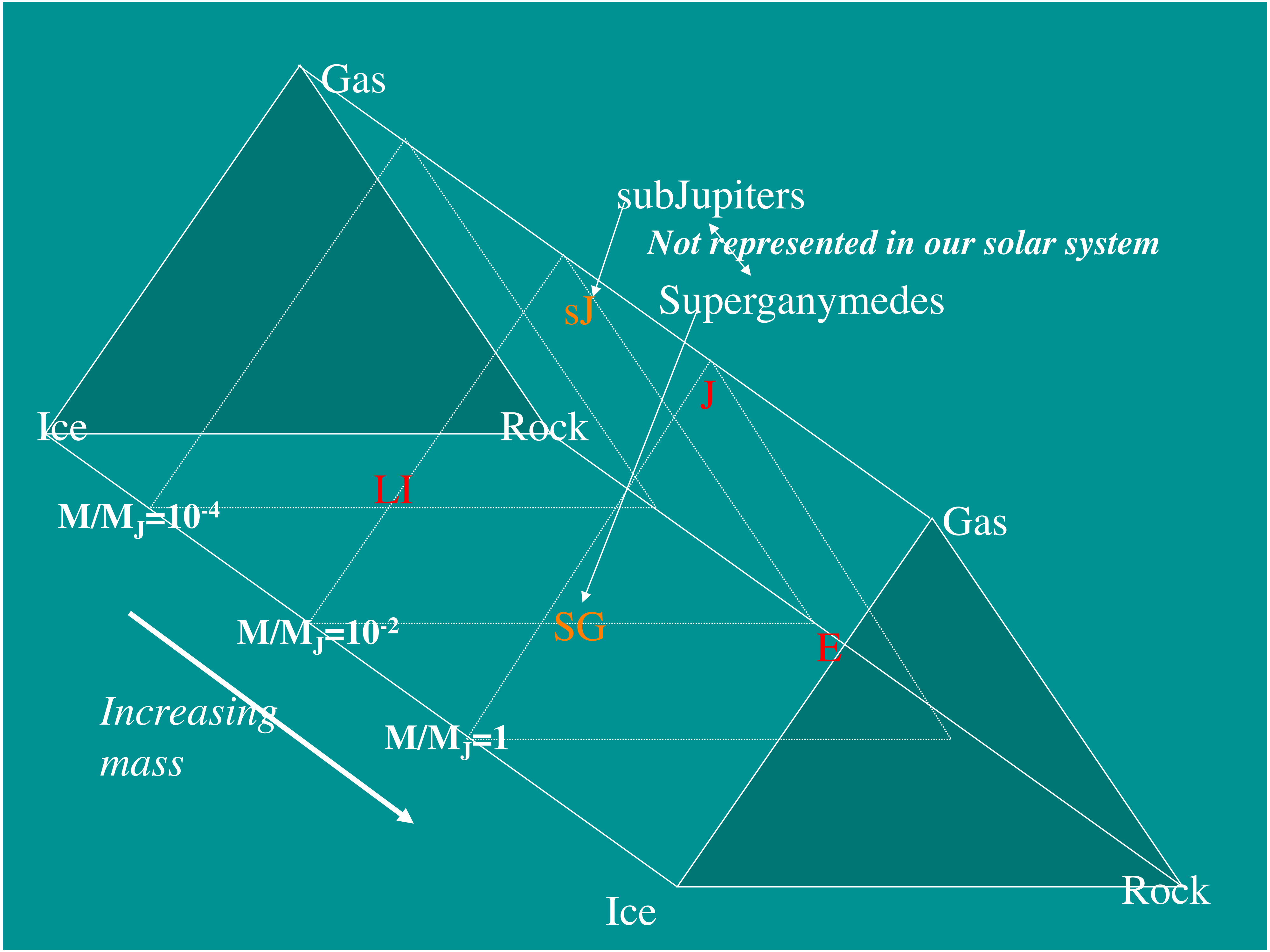
-But these characterizations are very misleading at high P and T

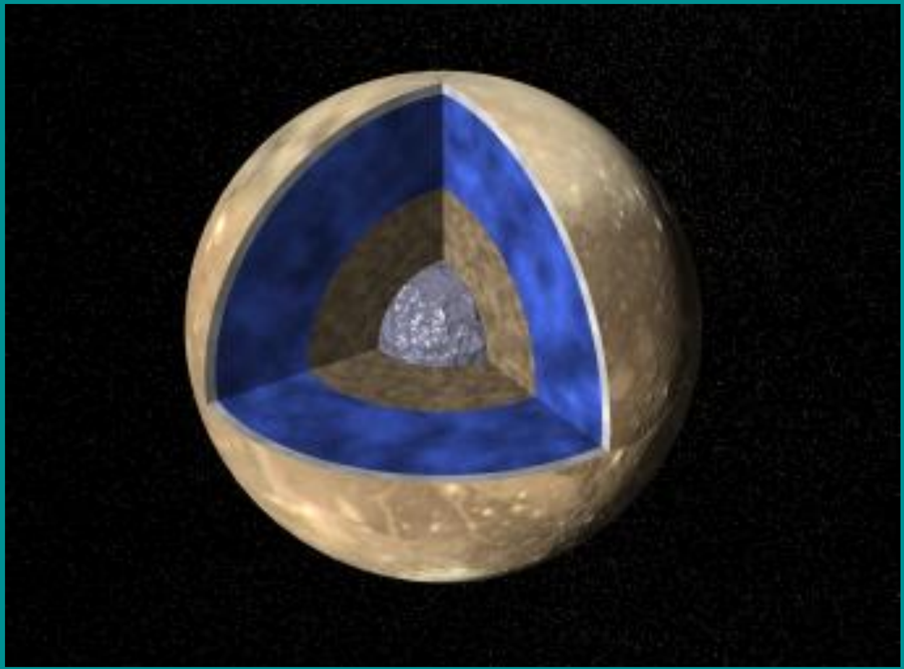
Every planet in the Universe (to a first approximation)




Gas
subJupiters
Not represented in our solar system
Superganymedes
sJ
J
Ice
Rock
LI
M/M$_J$=10^{-4}
Gas
SG
M/M$_J$=10^{-2}
E
Increasing mass
M/M$_J$=1
Ice
Rock

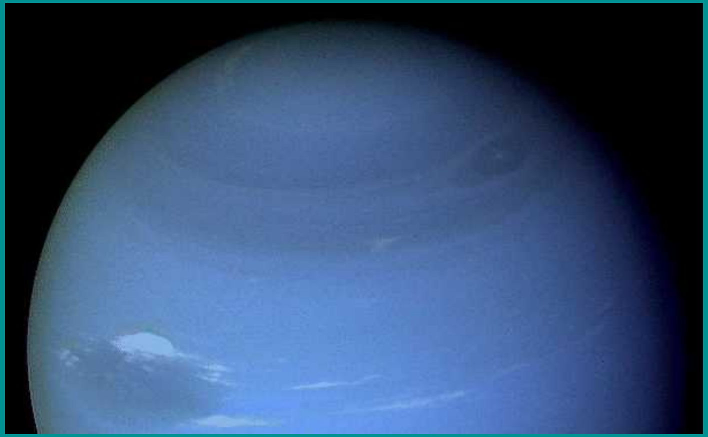
Solid Planets

- *Terrestrial (silicates, oxides and iron alloy)-* Mercury, Venus, Earth, Moon, Mars, Io
- *Large icy satellites (terrestrial +ice)* Europa, Ganymede, Callisto, Titan, Triton, Pluto…



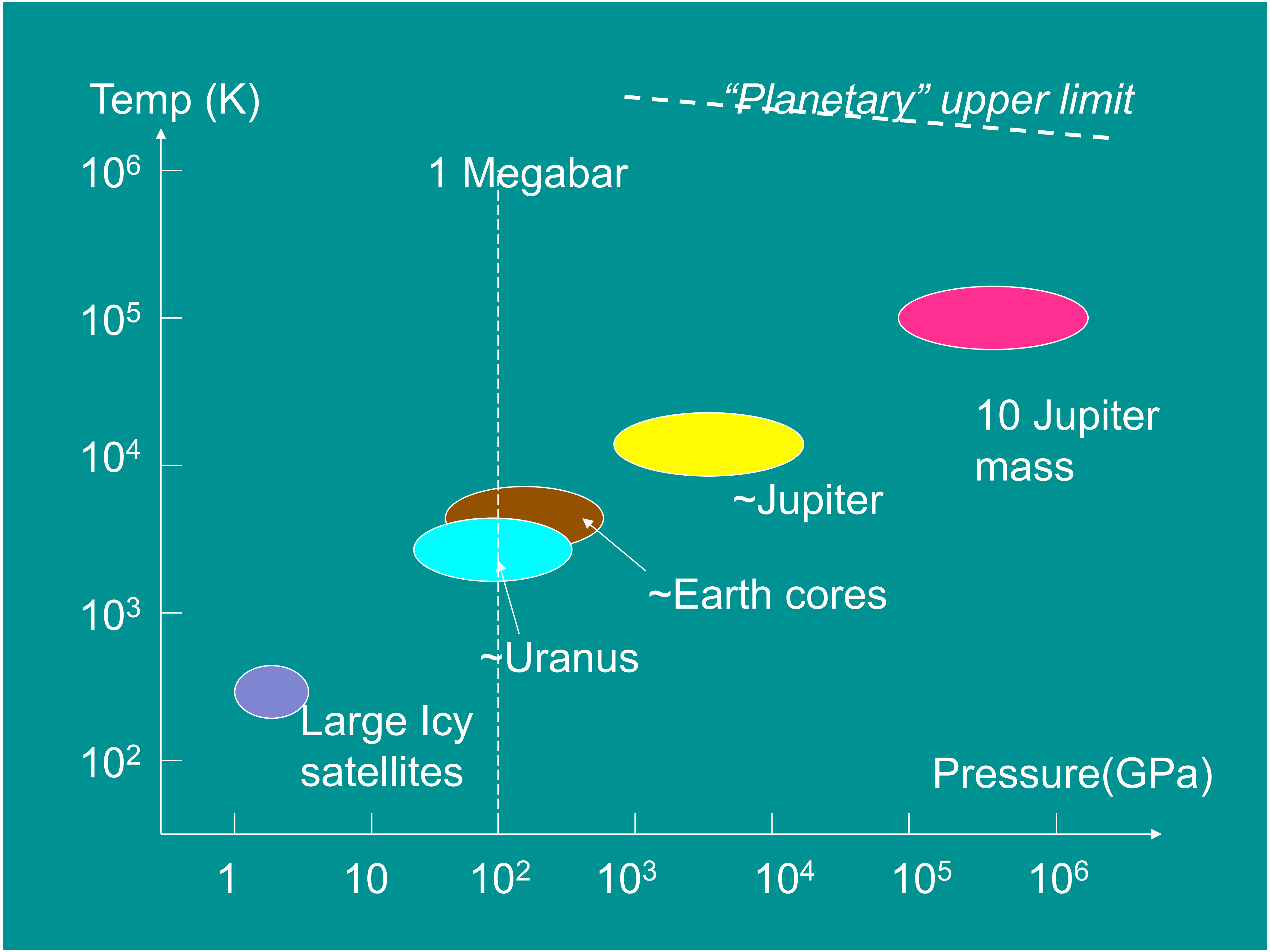
Fluid Planets

- *Gas Giants (primarily hydrogen and helium)*- Jupiter and Saturn
- *Ice Giants (everything, but including large amounts of H_2O at high P,T)* Uranus and Neptune



Pressures of Relevance

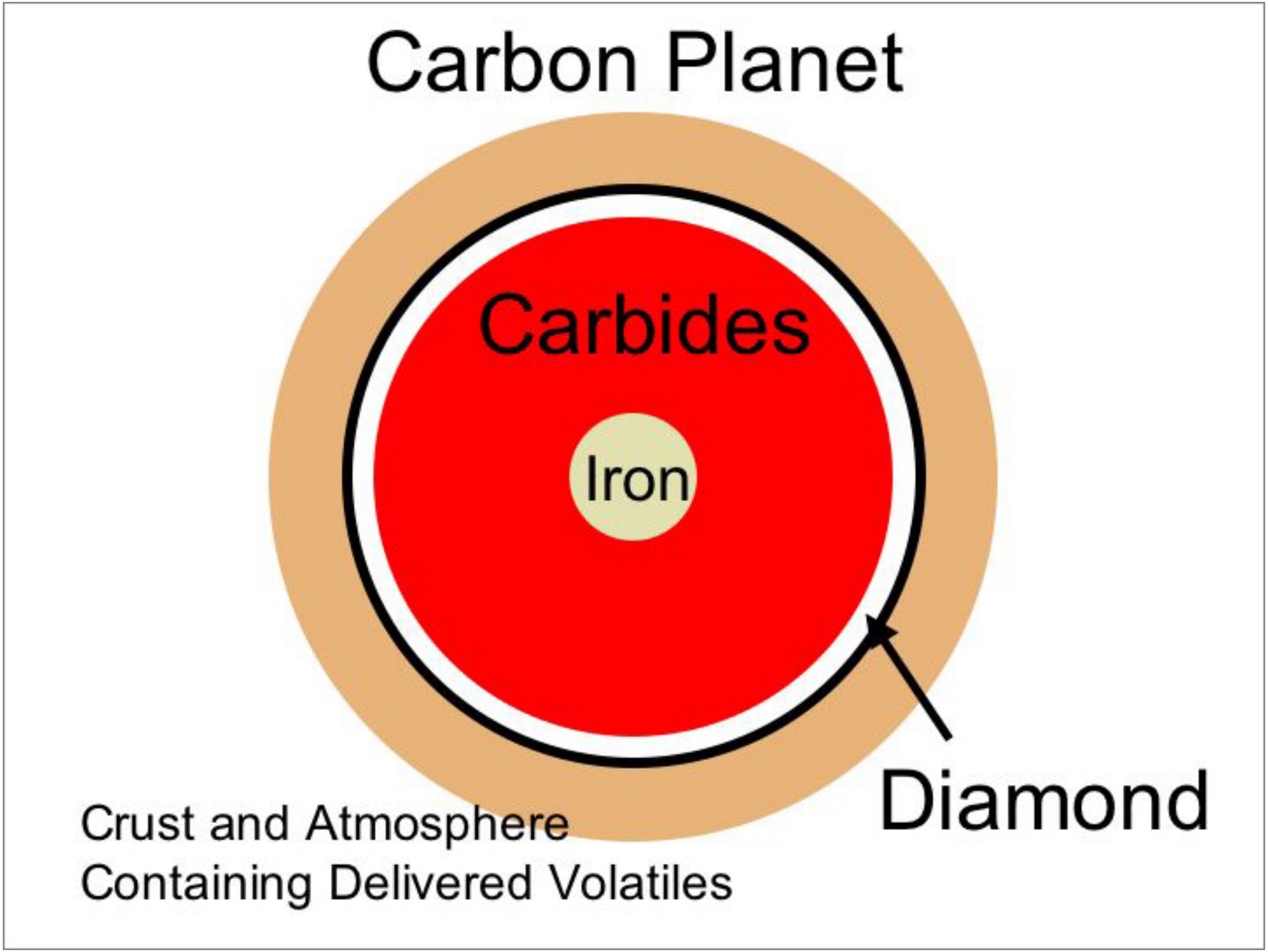
- At 1 Mbar, $PV_{ion} \sim 1eV$
- $P_{typical} \sim 1Mbar. (M/M_{earth})^2.(R_{earth}/R)^4$
- Earth mass planets are at the size for which electronic and gravitational energies are comparable.
- Thermal energies are always relatively small inside planets.

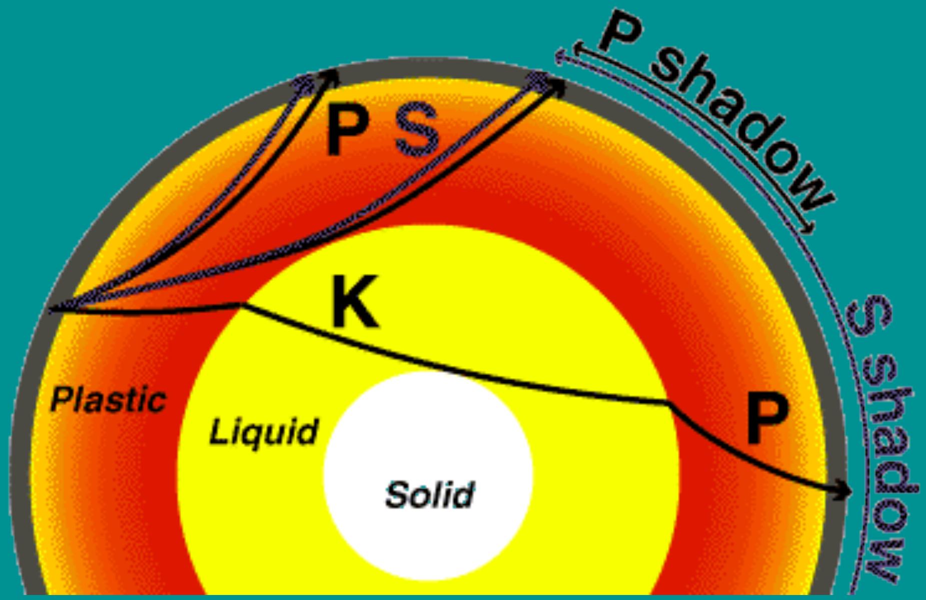


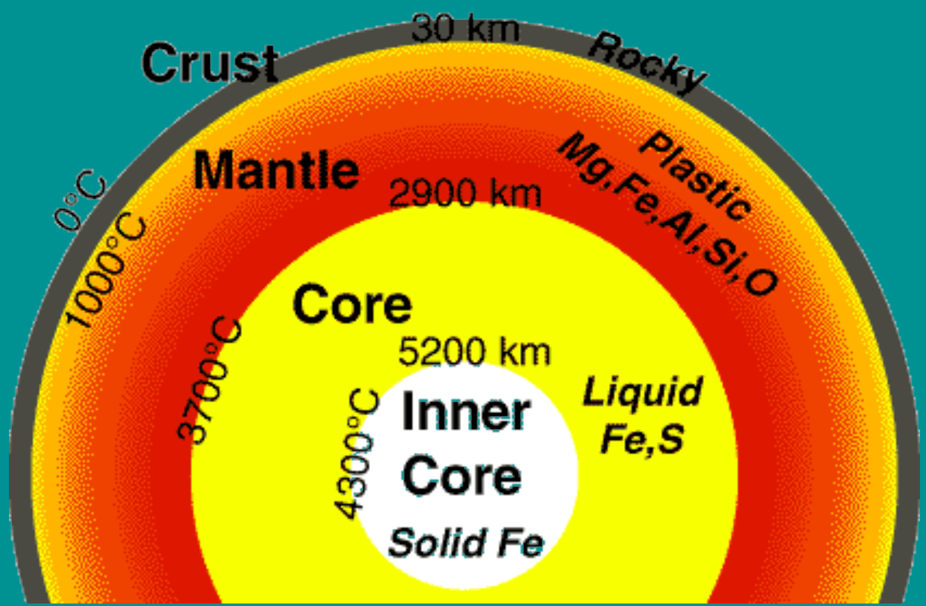
Temp (K)
"Planetary" upper limit
1 Megabar
10^6
10^5
10^4
10^3
10^2
10 Jupiter mass
~Jupiter
~Earth cores
~Uranus
Large Icy satellites
Pressure(GPa)
1
10
10^2
10^3
10^4
10^5
10^6

What are we made of (and why)

- To a first approximation, we are made of the materials that condense at around 500K or higher, But the condensates may not fully equilibrate at the lowest T. This will give an Earth composition consistent with data.
- But some materials are clearly lower T (e.g., water)
- And the oxidation state matters. (It is not obvious that you will get metallic Fe!)
- Mg/Si ratio matters for the silicate and core composition
- C/O matters (for our solar system it is ~0.6, mildly less than unity)


Carbon Planet
Carbides
Iron
Diamond
Crust and Atmosphere
Containing Delivered Volatiles





- Main source of information about Earth is seismic data
- Solid (plastic) mantle for outermost ~3000km; liquid core except for innermost solid core
- Mantle is mainly silicates & oxides (Mg, Si, O,Fe)
- Core is mainly Fe (but we have no samples!)

Why do we have a mantle and a core?

- NAÏVE ANSWER: We have metallic iron (more dense) settling from silicates/oxides (less dense)
- CORRECT ANSWER:
  - Iron and silicates are immiscible
  - One or both phases is at least partly liquid when Earth formed, allowing macrosegregation
  - You need both of these
  - This is not trivial! Even when satisfied, nearly complete separation is not necessarily achieved

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CORELESS TERRESTRIAL EXOPLANETS

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ABSTRACT

Differentiation in terrestrial planets is expected to include the formation of a metallic iron core. We predict the existence of terrestrial planets that have differentiated but have no metallic core, planets that are effectively a giant silicate mantle. We discuss two paths to forming a coreless terrestrial planet, whereby the oxidation state during planetary accretion and solidification will determine the size or existence of any metallic core. Under this hypothesis, any metallic iron in the bulk accreting material is oxidized by water, binding the iron in the form of iron oxide into the silicate minerals of the planetary mantle. The existence of such silicate planets has consequences for interpreting the compositions and interior density structures of exoplanets based on their mass and radius measurements.

Subject headings: accretion, accretion disks — planets and satellites: formation — solar system: formation

Online material: color figure

In the beginning….

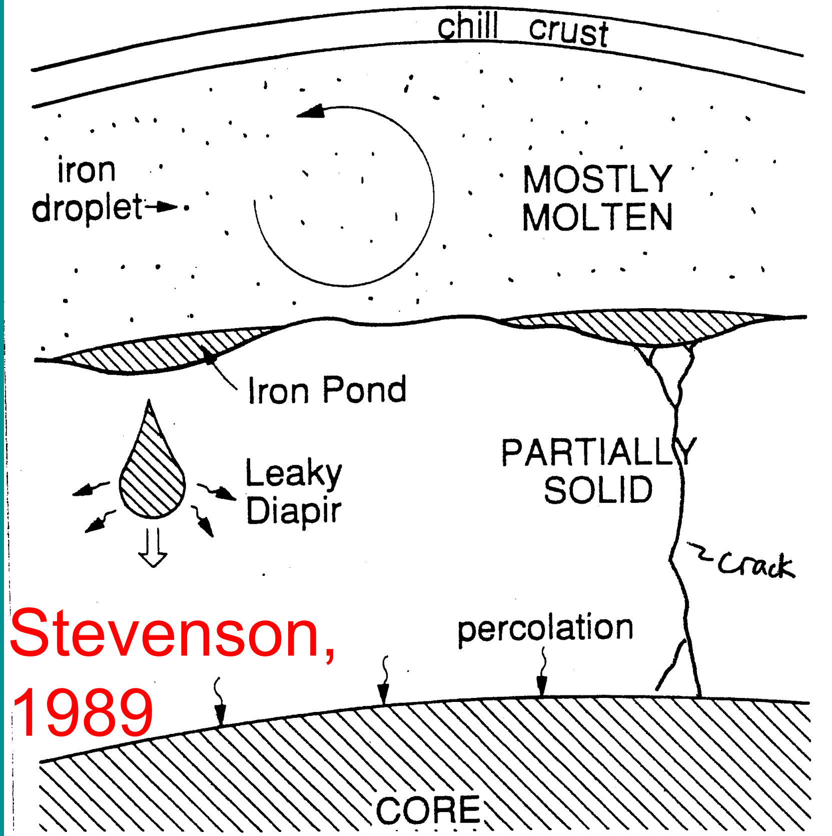
“Leibnitz, the great mathematician, published his *Protogæa* in 1680. He imagined this planet to have originally been a burning luminous mass, and that ever since its creation it has been undergoing gradual refrigeration. Nearly all of the matter of the earth was at first encompassed by fire. when the outer crust had at length cooled down sufficiently to allow the vapours to condense, they fell and formed a universal ocean, investing the globe, and covering the loftiest mountains…..”

Charles Lyell, *Principles of Geology* (1830), p40 [First edition]

Some Important Numbers

- $GM/RC_p \sim 4 \times 10^4 K$ *where M is Earth mass, R is Earth radius, C_p is specific heat*
- $GM/RL \sim 1$ *where L is the latent heat of vaporization of rock*
- Equilibrium temp. to eliminate accretional heat ~400K *(but misleading because of infrequent large impacts and steam atmosphere)*
- $E_{grav} \sim 10\ E_{radio}$ *where E_{grav} is the energy released by Earth formation and E_{radio} is the total radioactive heat release over geologic time*

Core Formation



Stevenson, 1989

Wood et al, 2006

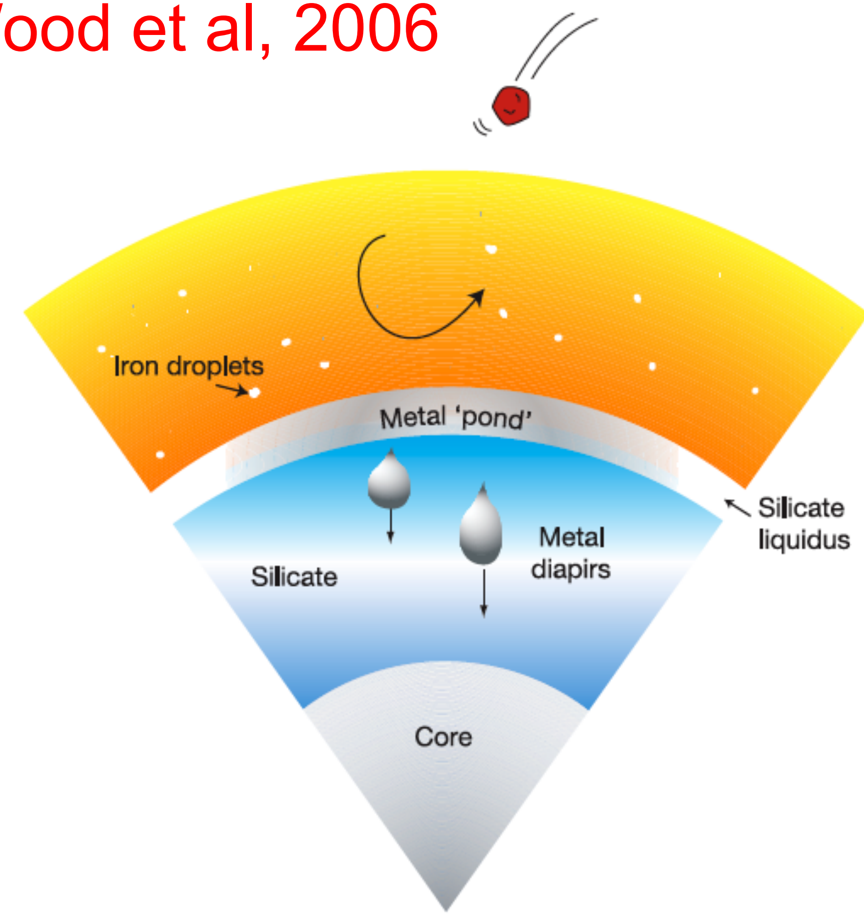
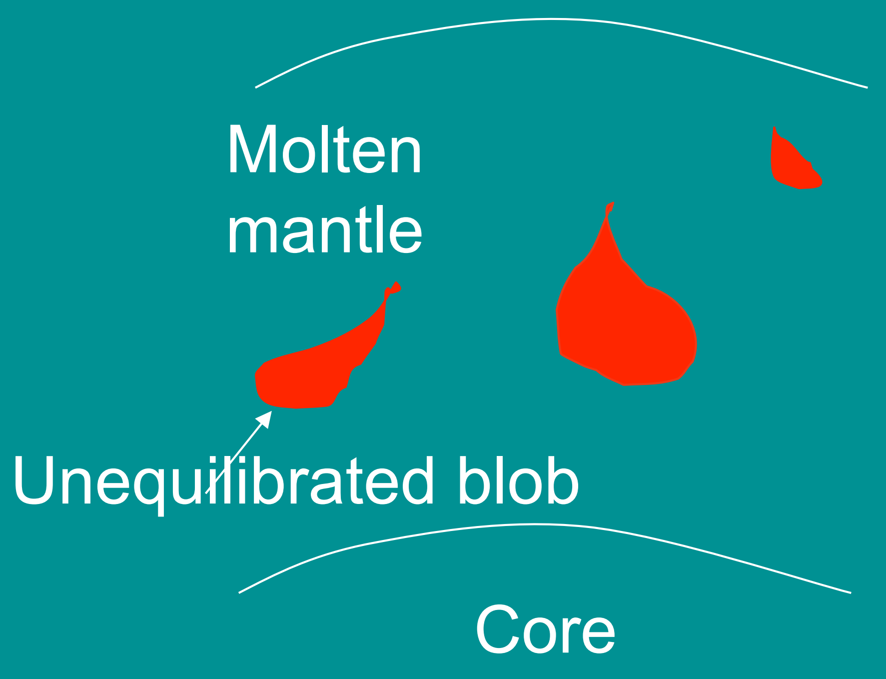


Figure 3 | The deep magma ocean model. Impacting planetesimals disaggregate and their metallic cores break up into small droplets in the liquid silicate owing to Rayleigh–Taylor instabilities. These droplets descend slowly, re-equilibrating with the silicate until they reach a region of high viscosity (solid), where they pond in a layer. The growing dense metal layer eventually becomes unstable and breaks into large blobs (diapirs), which descend rapidly to the core without further interaction with the silicate. Note that the liquidus temperature of the silicate mantle should correspond to pressure and temperature conditions at a depth above the lower solid layer and plausibly within the metal layer as indicated.

Core Formation with Giant Impacts

- Imperfect equilibration $\Rightarrow$ no simple connection between the timing of core formation and the timing of last equilibration
- No simple connection between composition and a particular T and P.



Some Important Scalings

- Energy/mass from gravity $GM/R \propto M^{3/4}$ so $\Delta T \sim (3 \times 10^4 K).(M/M_E)^{3/4}$
  - Gravity/Radiogenic $\sim 10(M/M_E)^{3/4}$
- Core formation $\Delta T \sim (5 \times 10^3 K).(M/M_E)^{3/4}$
  - Core Differentiation/Radiogenic $\sim 1.5(M/M_E)^{3/4}$
- Current day Core differentiation at the rate of $(2\%).(M_E/M)^{3/4}$ per Ga will balance current radiogenic heat flow .
  - Assumes $\sim 3 \times 10^{-8}$ erg/g.sec radiogenic
- Note: $P \sim GM^2/R^4 \propto M$ so $T \propto P^{3/4}$, steeper than most melting curves

A Reminder about Fundamental Thermodynamics & Statistical Physics

- Everything mixes with everything* at sufficiently high T… even things that are electronically incompatible (such as metals and insulators or ionic and non-ionic materials)
- <u>Reason</u>: The energy differences that inhibit mixing are bounded. The free energy difference that favors mixing (~-kT*ln*2) is unbounded as T increases

*By "mixing" I do not mean as in an emulsion, I mean down to the atomic level. In this context, Earth's upper mantle for example is an emulsion (a phase assemblage).

Temperature Matters!

…More than you might have supposed

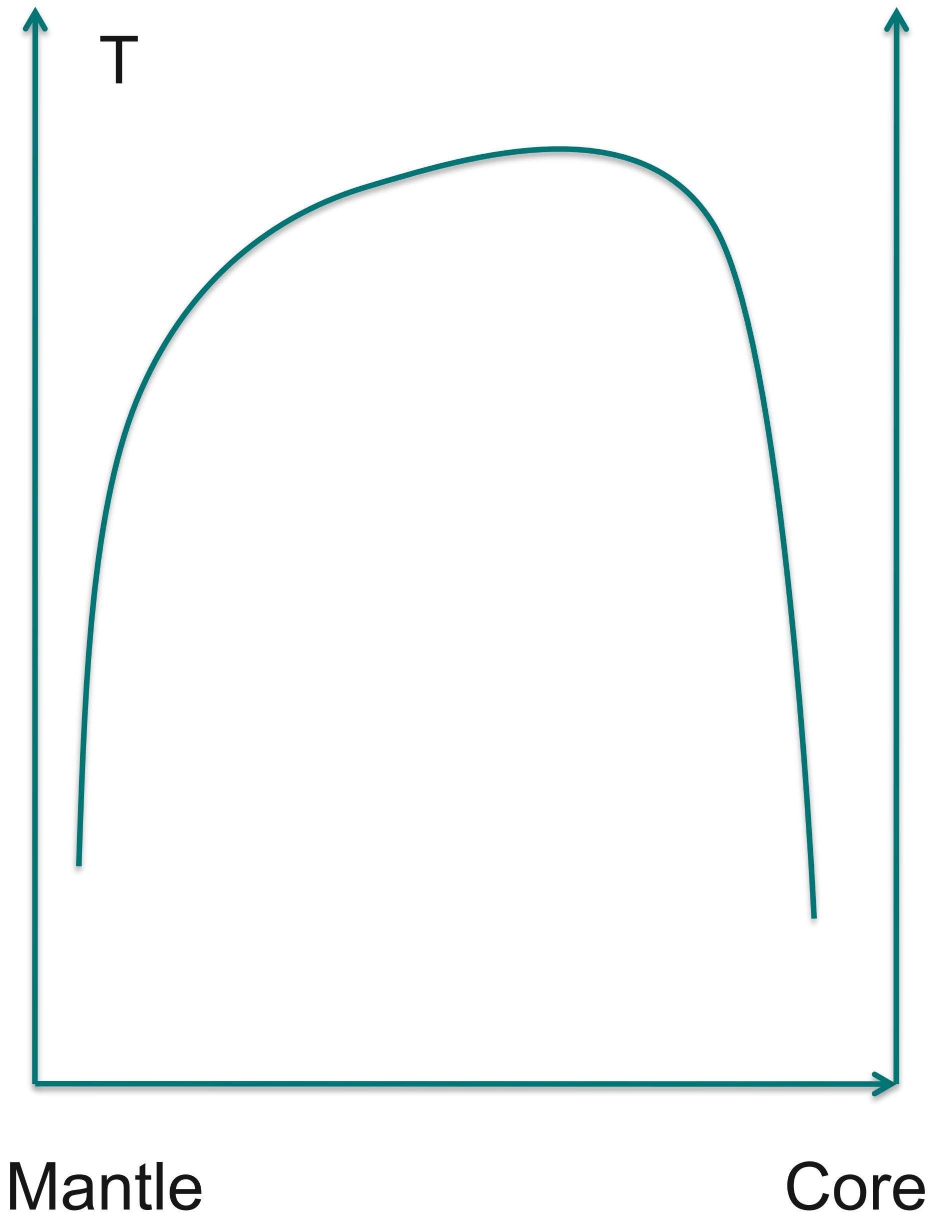
- Not because of thermal expansion
  - $\alpha\Delta T$ ~10% or less even in these more massive bodies
- T reduces mobility gaps and favors mixing *in addition to the effect of entropy of mixing.*
- There is evidence for this in existing calculations for hydrogen/helium, for water, and perhaps for iron/silicates & oxides.

Planets too hot to form a core

Planets with core & mantle

Increasing mass

Planets too cold to form a core (solid emulsion like ice cream)



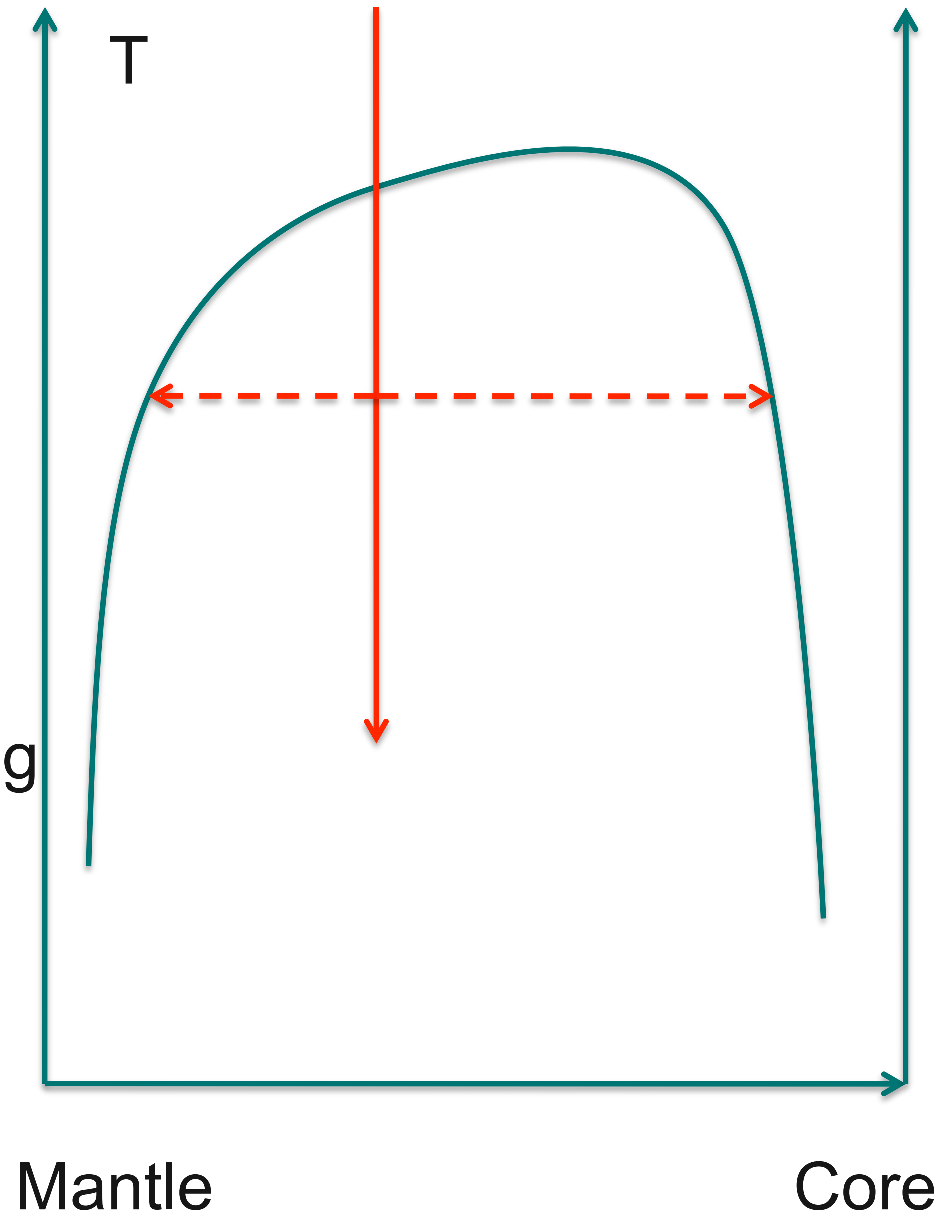
A conceptual phase diagram

Planets too hot to form a core

Planets with core & mantle

Increasing mass

Planets too cold to form a core (solid emulsion like ice cream)



A conceptual phase diagram

Dense steam
atmosphere
(greenhouse effect)

“mantle”

Compositional
gradient (convection
inhibited)

“core”

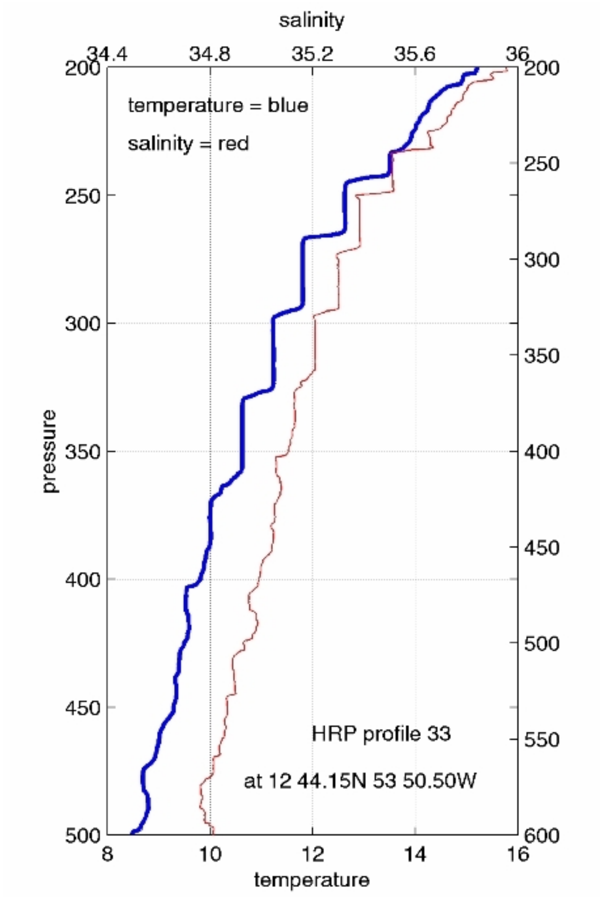
Why do we have mantle convection?

- NAÏVE ANSWER: To get the heat out (conduction & radiation are not adequate). Earth is a heat engine
- CORRECT ANSWER:
  - You could get the heat out by magma delivery to surface (Io)
  - Rocks are able to flow efficiently when near solidus. (Their ability to do so is quite sensitive to composition.. But a wide range of viscosity laws will do it)
  - Mantles tend to start out well mixed? But this is not obvious!
  - Convective process prevails independent of the top boundary condition (stagnant or mobile)

Double-Diffusive Staircase

An example of thermohaline convection in Earth's oceans

The steps develop naturally and evolve over time so that transport of both heat and composition are much enhanced over pure molecular diffusion.

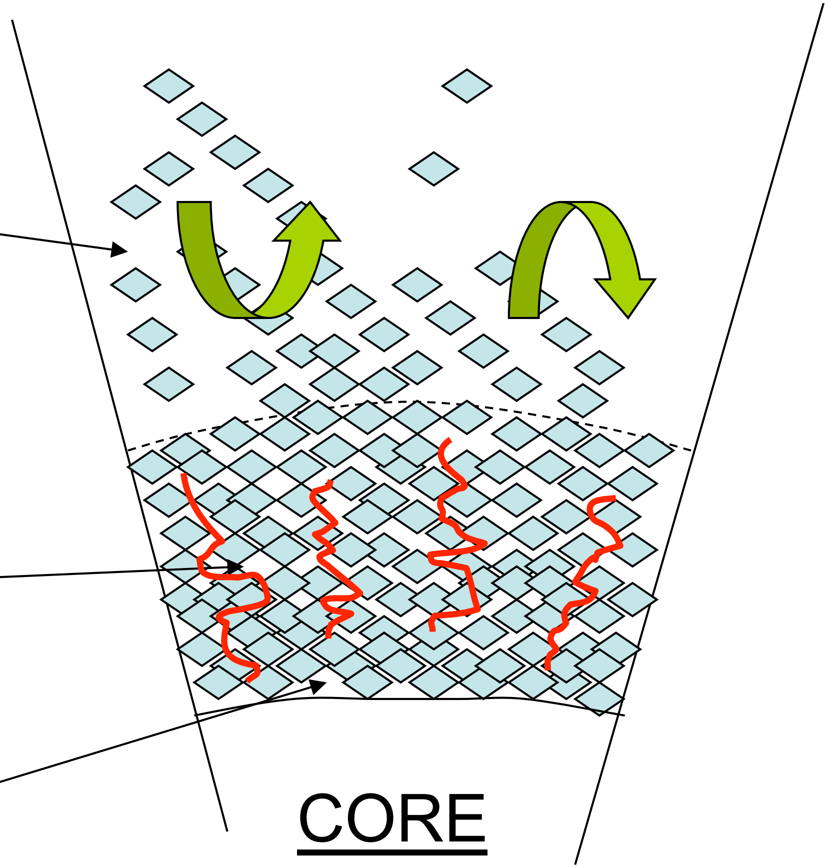


Differentiation in the Mantle?

Dense suspension,
vigorously convecting.
May be well mixed
Solomatov & Stevenson (1993)

Much higher viscosity, melt percolative regime. Melt/ solid differentiation?

High density material may accumulate at the base. Iron-rich melt may descend?



Why do we have a Crust

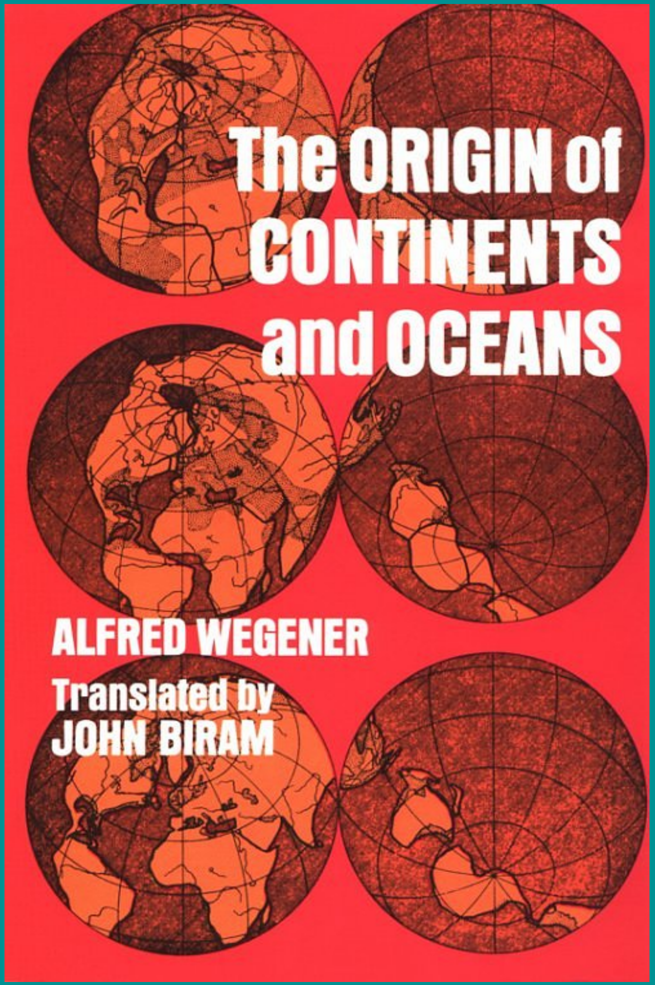
Basaltic? Continental?

- Basaltic crust arises primarily by pressure release of mantle material…the mantle potential T is above the solidus (potential T = T of the adiabatically decompressed mantle)
- Evidently the amount depends on the amount of decompression permitted (greater when there is plate tectonics or rifting) and also on the vigor of convection
  - Crustal production = (convective mass flux) x (degree of melting)
  - Plume volcanism smaller if there is surface rifting (as in plate tectonics)
  - Does not have a major role to play in heat flow!

Why do we have a Crust
Basaltic? Continental?

- Continental crust appears to have an intimate relation to plate tectonics and to water ("No oceans, no continents…")
- Arc volcanism is an important contribution
- History and role of continent formation remains controversial
  - Does it affect mantle convection & plate tectonics in a major way? (By redistribution of heat sources, by changing the boundary condition)

Origin of Continents



- Wegener was basically right, but….
- Continents are still not understood
- And the continents are merely along for the ride; most of the action is in the ocean basins.

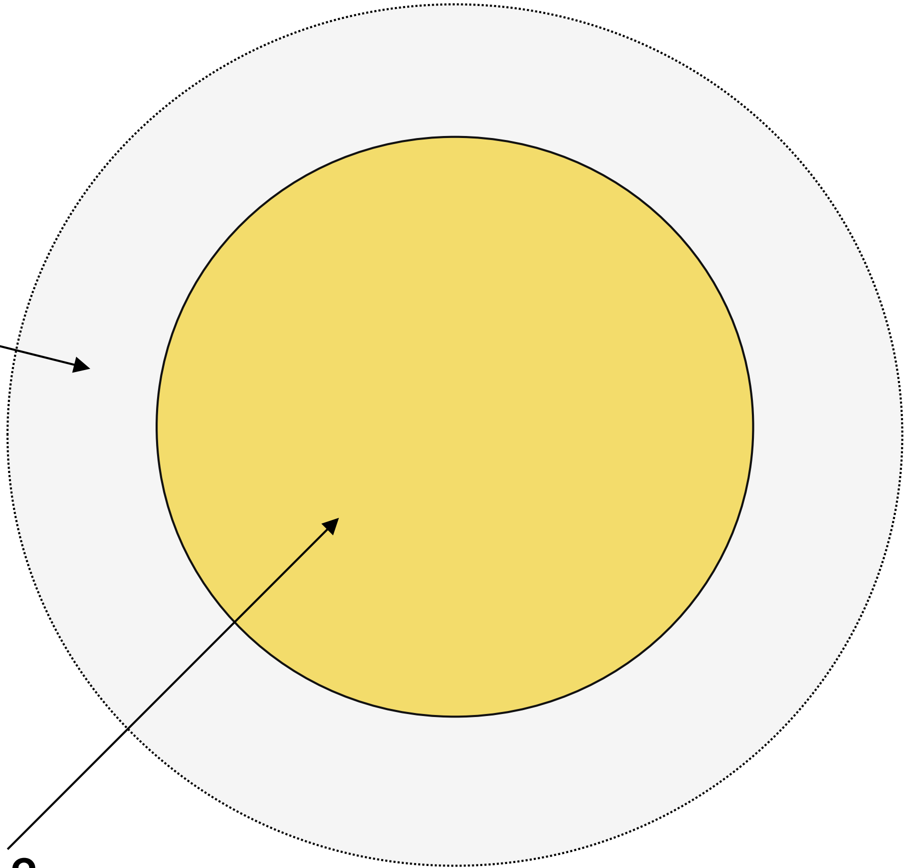
Why do we have an atmosphere?

- NAÏVE ANSWER: We accreted material that wants to be in vapor form
- CORRECT ANSWER:
  - Gas forming constituents partition between interior and exterior in a way that depends on a cycle, not just on thermodynamics. But the answer depends on which volatile you are thinking about.
  - It is possible that earth's core is the biggest reservoir of all volatiles, so its isolation from the mantle & convective cycle may be crucial.

Solar
nebula

Gas density
enhancement

$\sim \exp[GM/Rc^2]$



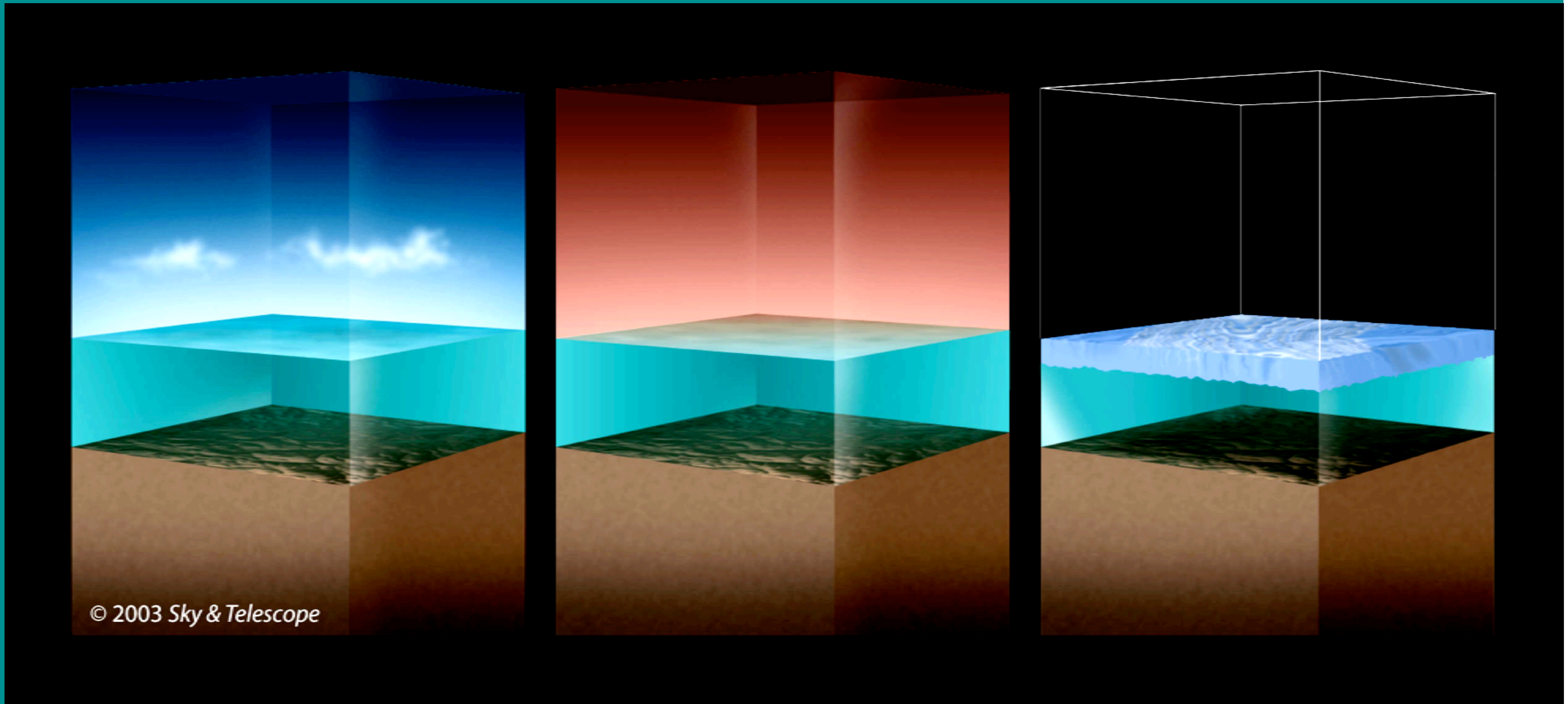
Mars mass
embryo -hot &
differentiated

This predicts some ingassing (assuming the embryo has an accessible magma ocean)

Volcanism & Volatile Release

- Earth's atmosphere & ocean came in part through outgassing
- But volatiles are recycled on Earth- the inside of Earth is "wet"

Three Kinds of Water Oceans



Earthlike (Naked)

Protected by a dense atmosphere (e.g.,greenhouse)

Protected by ice

Why do we have an ocean?

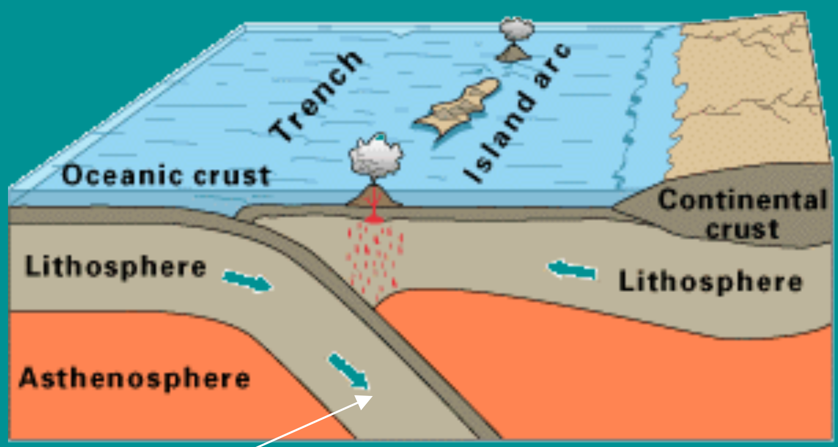
- Earth's water cycle is imperfectly understood!
  - Water certainly comes out in volcanism
  - Water certainly goes down in subduction zones.
  - Deep earth reservoir poorly constrained but likely to be at least as important as the oceans
  - Wide variation in other planets likely because of wide variation in water delivery

Why do we have Plate Tectonics?

- It doe not follow from any straightforward stability analysis
- It is not mandatory for removing heat.
- It is “more efficient” in removing heat (but there is no variational principle that optimized heat delivery)
- We don’t even know if it is deterministic or contingent behavior.
  - Mantle convection is determinstic
  - Climate change, dynamos.. Are somewhat contingent.
- Since we don’t understand why earth does it, talking about superearths or other earthlike planets is highly speculative

Earth's Engine

- Plate tectonics is not at all obvious! But once in motion, it is a heat engine.
- But why do plates happen? Mantle convection does not require plates!



Oceanic-oceanic convergence

Cold slab sinks under the action of gravity

Nature of Plate Tectonics

- Expression of mantle convection -how Earth loses heat
- Dictated by the brittle nature of near surface rocks and the ductile nature at depth

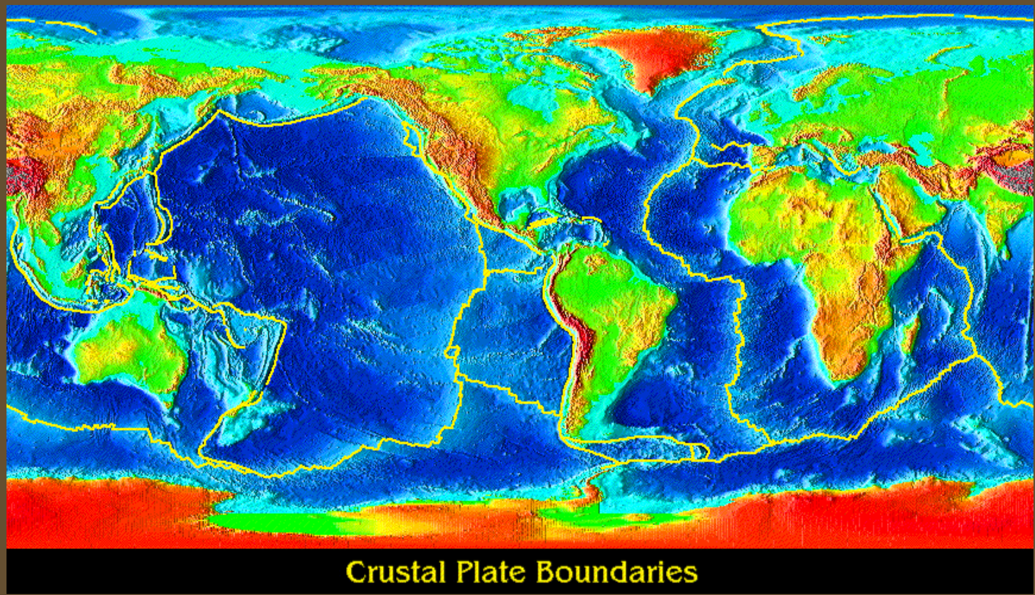
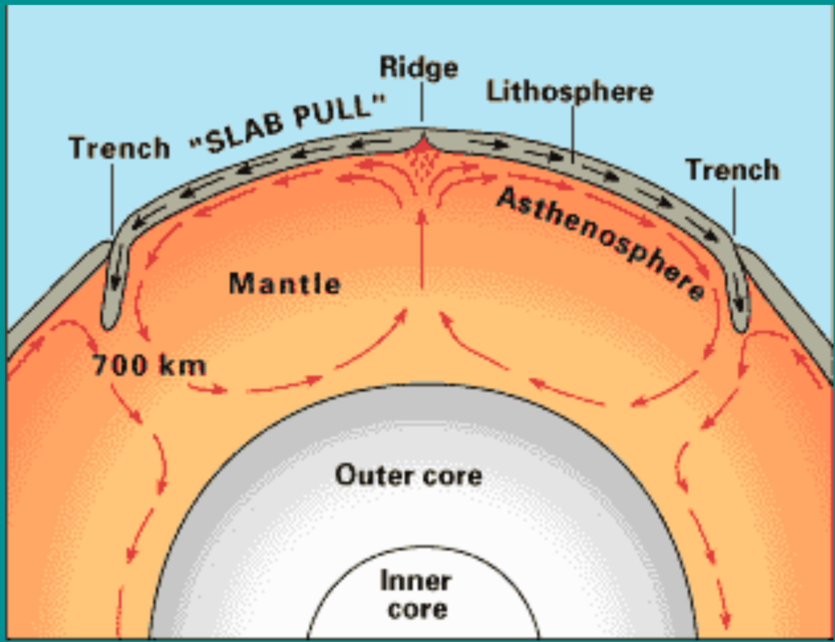


Plate Tectonics & the Role of Water

- Water lubricates the asthenosphere
- Water ***defines*** the plates
- Maintenance of water in the mantle depends on subduction; this may not have been possible in our solar system except on Earth



Why do we have a magnetic field?

- Core is metallic
- Core is (partly) liquid
  - This is not obvious , but seems universal because of presence of alloying constituents
- Core is convective
  - This is a close call! High electrical conductivity means high thermal conductivity (Wiedemann-Franz relationship)
- A convective core probably sustains a dynamo for most realistic parameters.

Essential Features of a Dynamo

Relevant equation for magnetic field **B** is

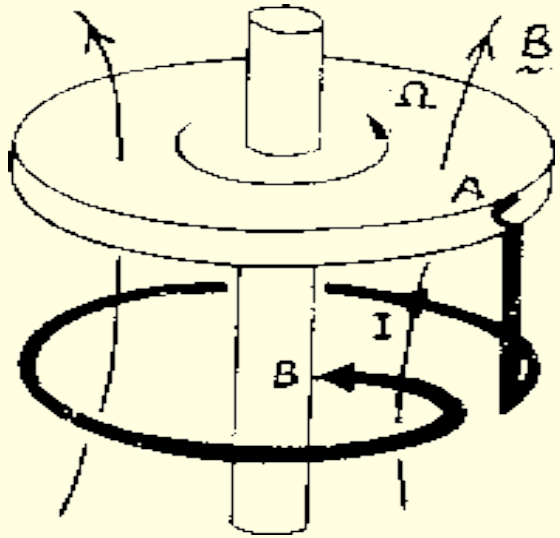
$\partial \mathbf{B}/\partial t = \lambda \nabla^2 \mathbf{B} + \nabla \times (\mathbf{v} \times \mathbf{B})$

λ=magnetic diffusivity = $1/\mu_o\sigma$

v = fluid motion relative to rigid rotation

Fluid motion is important provided $R_m \equiv vL/\lambda >\sim 10$

Then *perhaps* a field is sustained.



In this mechanical analog (the disk dynamo) the emf created by disk rotation creates a current that produces the field repsonsible for the emf.

Large, Global Fields, Predominantly Dipolar

"Large" means ~1Gauss typically, at the inferred conducting region

	B (Gauss)	Dipole Tilt(°)	Quad/Dipole
Earth	0.5 (surface)	~10°	~0.2 (core)
Jupiter	4.2 (surface)	~10°	~0.2 (core)
Saturn	0.2 (surface) ~2 (core)	~0°	~0.2 (core)
Ganymede	0.02 (surface), ~1 (core)	~10°?	Not known
(Mercury)	0.002 (surface)	~3°?	~0.4

Large, Global Fields, Predominantly Dipolar

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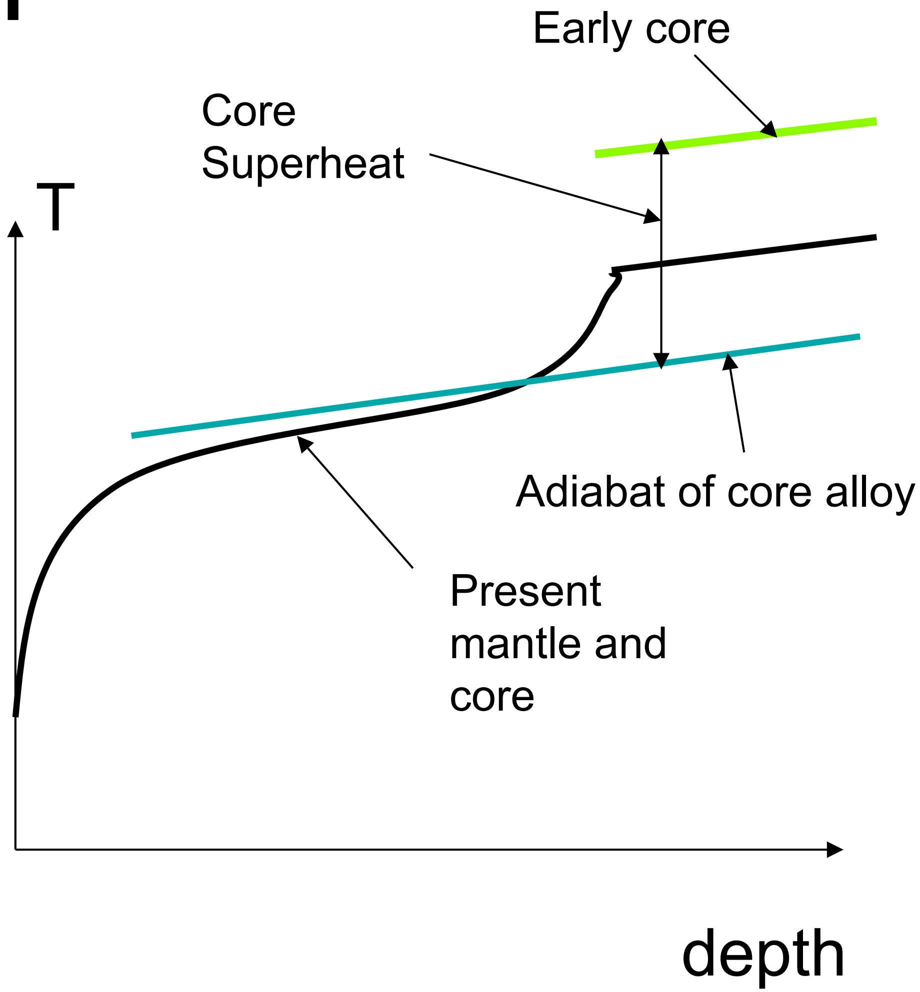
Ganymede	0.02 (surface), ~1 (core)	~10°?	Not known
(Mercury)	0.002 (surface)	~3°?	~0.4

But Venus & Mars are absent from the list

Core Superheat

- This is the excess entropy of the core relative to the entropy of the same liquid material at melting point & and 1 bar.
- Corresponds to about 1000K for present Earth, may have been as much as 2000K for early Earth.
- *It is diagnostic of core formation process*...it argues against percolation and small diapirs.



Criterion for Thermal Convection

Need nearly neutral stability for large scale vertical motions

$\Rightarrow$ $dT/dr = -\alpha Tg/C_p$ *Adiabatic lapse rate*

$\therefore$ Need heat flow $F > F_{cond,ad} = -k(dT/dr)_{ad}$

But $k/\sigma T = \mathcal{L} = 2 \times 10^{-8}$ SI *Wiedemann-Franz law*

↑ ***Lorenz number***

$\therefore$ $\sigma < F_{cond,ad} C_p / \mathcal{L} \alpha T^2 g$ *Upper bound for electrical conductivity for a dynamo*

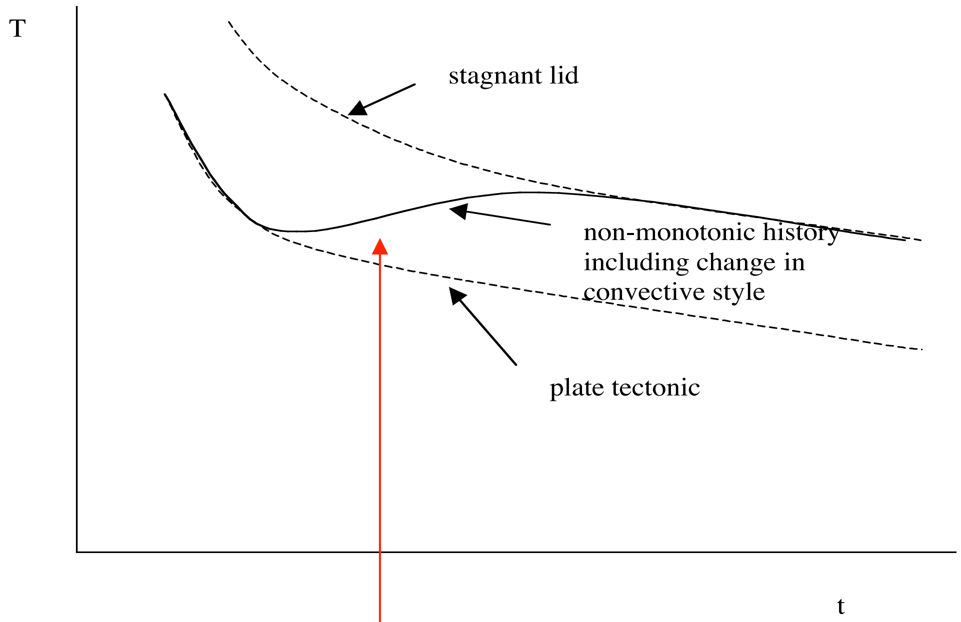
Note that F and g are linear in planet radius so this criterion is roughly independent of planet size.

$\sigma_{crit} \sim \sigma_{iron}$

Inner core helps… compositional convection

How Plate Tectonics can control a Dynamo

- Planets with plate tectonics cool more efficiently
- If plate tectonics ceases, the planet must shift to the less efficient stagnant lid regime. This requires mantle heating.
- When the mantle heats up, the core convection turns off.



This may have happened to Venus & Mars

Formation of the Moon

- Impact “splashes” material into Earth orbit
- The Moon forms from a disk in perhaps a few 100 years
- One Moon, nearly equatorial orbit, near Roche limit- tidally evolves outward

Universality of Moons?

- Evidently not…Venus does not have one (and being closer to the sun is not relevant!)
- Bu giant impacts are common…moon forming events should be common; absence of Venus' moon is the puzzle, not the presence of Earth's moon
- Moon causes 24hr day, affecting weather & climate. It may be relevant to development of life?

Other Consequences of Large Impacts

- Delivery of volatiles- perhaps from Jupiter zone (our water did not come primarily from comets)
- Impact frustration of the origin of life? Or seeding the origin of life? Maybe both!

Earth Habitability

Our planetary habitat has **all** of the following:

(a) Physical and chemical conditions suitable for liquid H_2O.

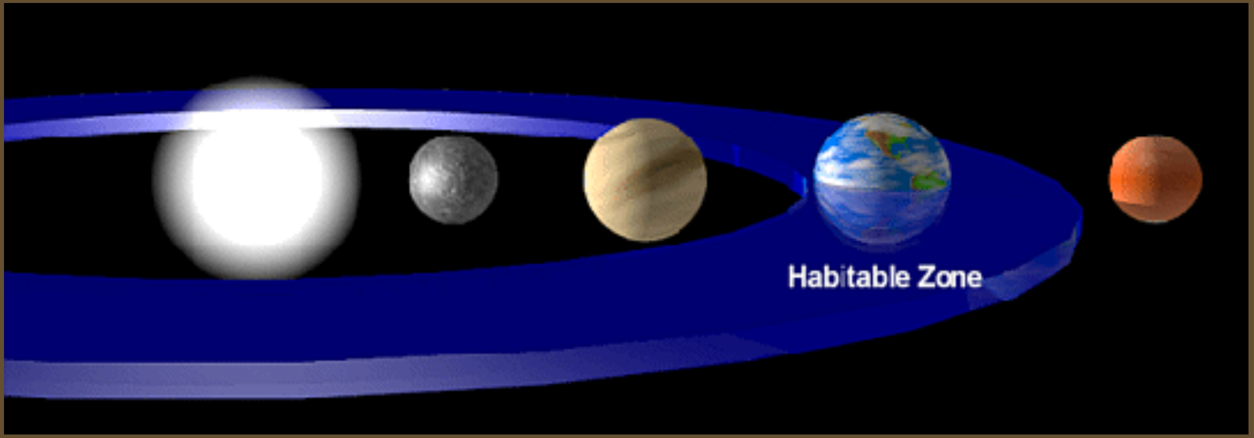
(b) Possibility of sustained thermodynamic disequilibrium.

(c) A very long ("geological") period during which these conditions existed. (Infrequent "killing" events.)

(d) Plate tectonics to provide a driver for change and diversity

Popular Concept of a Habitable Zone

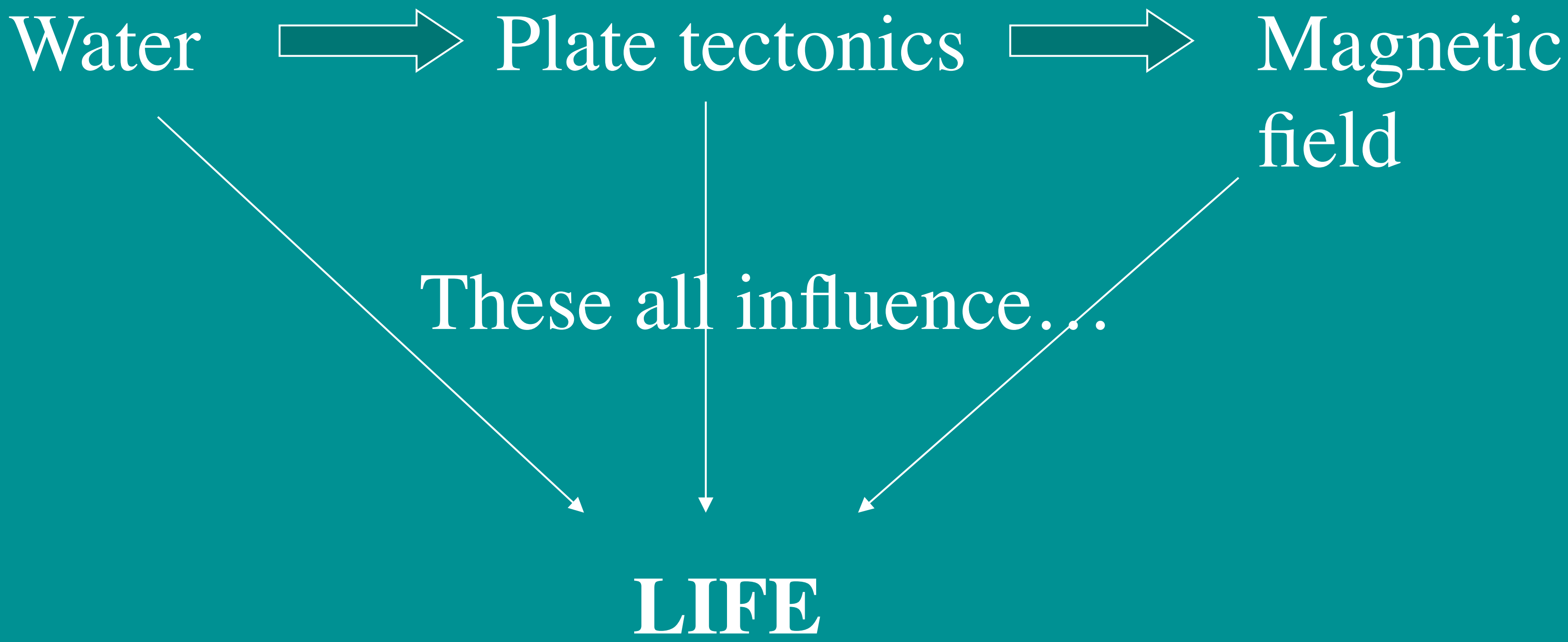
Goldilocks scenario



- Location, location, location!
- Size matters
- Also depends on availability of H_2O. Very abundant in the Universe… very under-abundant on Earth

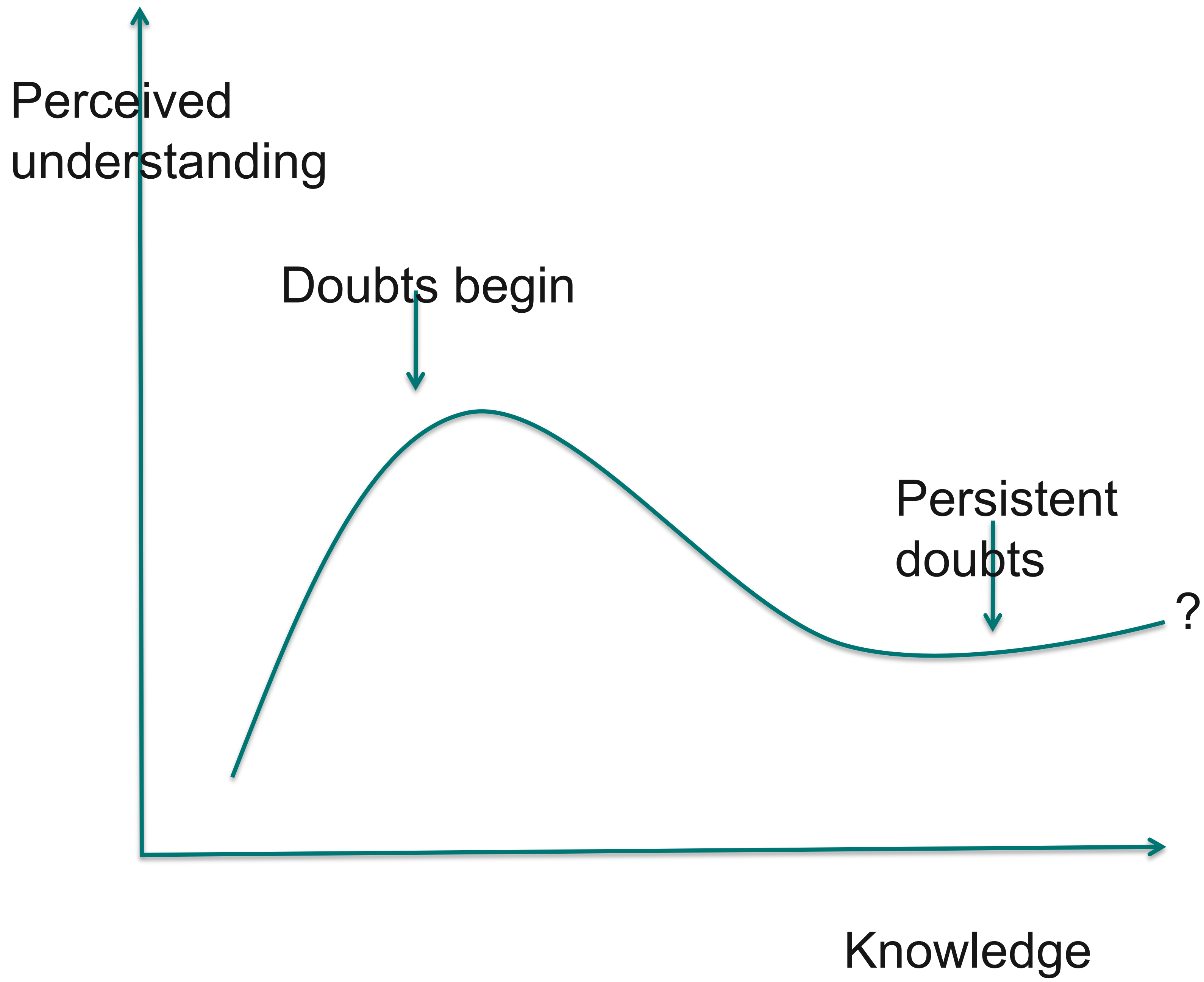
Anthropocentrism?

- The planets in our solar system are a small, unrepresentative sample of all planets. A planet at Venus location is habitable if it lacks large carbon dioxide reservoir.
- Most notions of the habitable zone are anthropocentric. The habitable zone may be almost everywhere in the Universe if we include all places with energy sources & liquid water.


Water
Plate tectonics
Magnetic field
These all influence…
LIFE

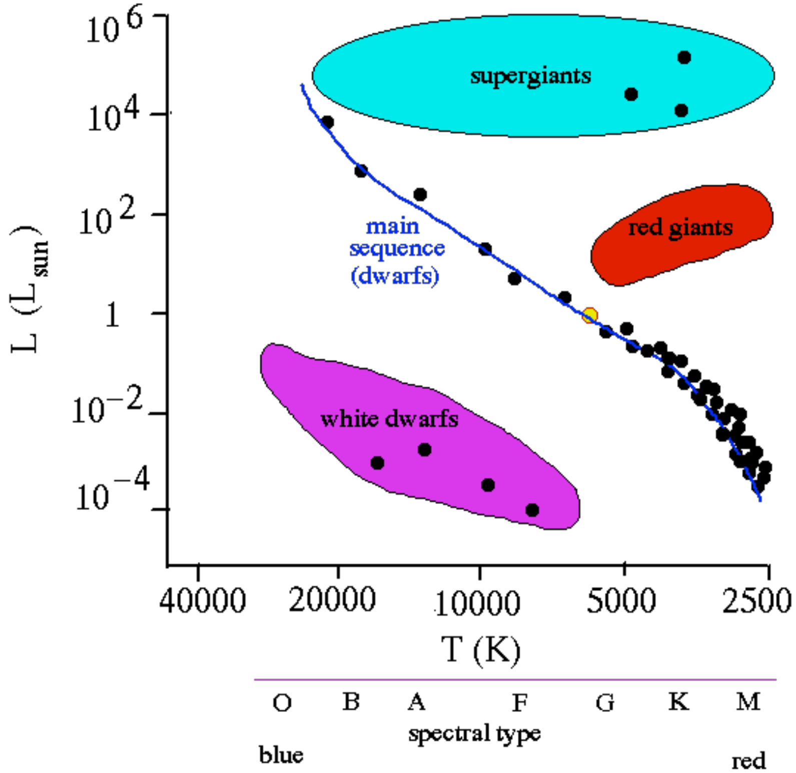
Supposing that the human race endured long enough, the time would necessarily come when nothing could be said which has not been said before. However it is not certain that a time would come when nothing can be said which has not been said before. For it could happen that certain things are never said, even if all eternity were used up, and therefore there will always remain things which could be said and were not yet said. There are no perfect returns as in circles or ellipses, nor can it happen that one place or one time in the universe be perfectly alike another; they only appear so to the senses….

LEIBNIZ (1701): DEMONSTRATIONS CONCERNING THE IMMENSE AND ETERNAL UNIVERSE; ON THE WORLD AND ITS AGES, DOWN TO THE STATE OF REMOTE AND FUTURE THINGS


Perceived understanding
Doubts begin
Persistent doubts
?
Knowledge

Is there a Planetary Equivalent of the HR Diagram?

- HR diagram is a 2D representation of much of stellar physics
- Diversity of planet composition makes it difficult to construct a planetary equivalent
- *But it's even worse…*



Universe above

10^{57} larger by volume

Mostly unknown

Mostly empty

Earth below

Mostly unknown

But crammed with interesting stuff

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

-Galileo Galilei

Conclusion

- Universality of process; diversity of outcome
- Many aspects of Earth are still not well understood; this implies humility when making claims of what to expect elsewhere
- There is much to be gained by understanding Earth better, but exoplanets will surprise anyway

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