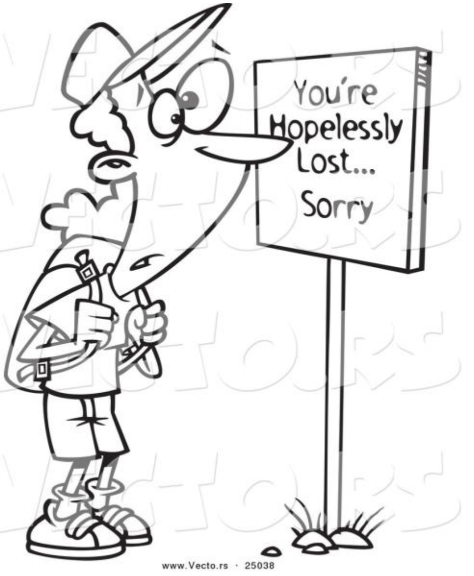
Dave Stevenson

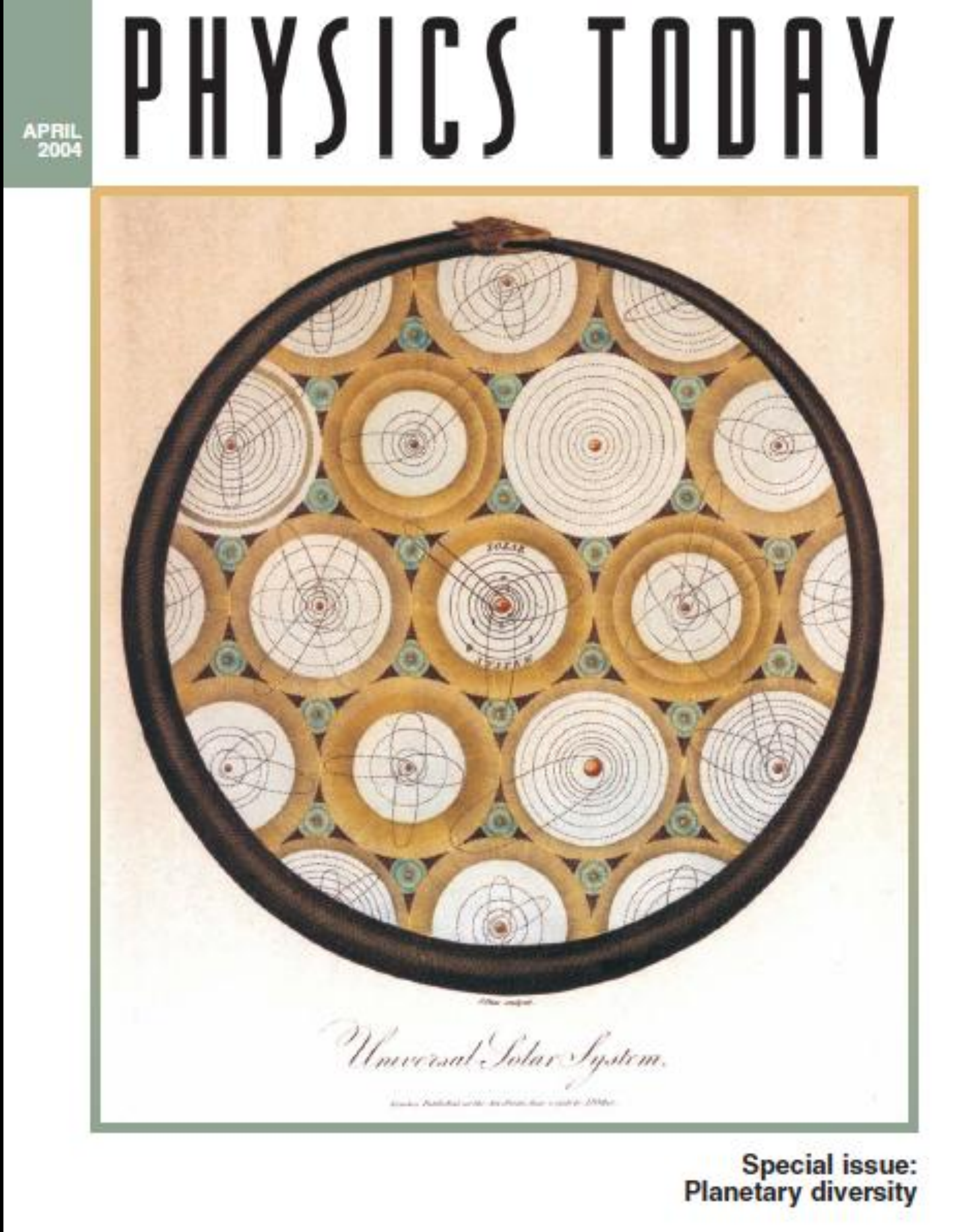
Caltech

KITP Physics of Exoplanets

February 27, 2015



Cover is from an Encyclopedia published in 1794; original is owned by Ewine van Dishoek, Leiden



”Interstellar”

What are we Trying to Do?

- Characterize what's out there
  - Probabilities, range of behaviors, range of environments
- Use what we find to improve our understanding of how planets form & evolve
  - And place our solar system in context (though it may not be typical)
- "Habitability"? Intellectually suspect goal
  - Ill defined
  - Probably unreachable anyway (at least in the near term)…same is true for Mars & Europa
  - But the public love it and they pay

Astronomy /Astrophysics

–Observational techniques, telescopes (including radio, etc)
-History of categorization of bodies & behaviors
-Huge range of physical phenomena but usually with simple materials

Planetary Science

-More emphasis on missions
-More emphasis on the individuality of bodies (resistance to generalization & reductionism is good!)
-Complex materials & systems (e.g., atmosphere must be thought of separate from interior)

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Spectroscopy
Dynamics
Cosmochemistry

High pressure physics

Guidelines for the Diversity of Planets

- **STRONG CONSTRAINT:** Dynamically stable (most of the mass satisfies hydrostatic equilibrium); stable to "evaporation" for ~10^9 yrs.
- **MODERATE CONSTRAINT:** Consistent with cosmic abundances.
- **WEAK CONSTRAINT:** Conceivable formation scenario. (In practice, theorists are very good at explaining any observation, even when it's wrong!)

What do all (most*) Planets have in Common

*there will always be oddballs, for example pulsar planets, the first found outside our solar system

- Use the same periodic table
  - But not necessarily the same radioactivity!
- Use the same physics (& obey the same rules of chemistry)
- Have a broadly common genesis story?
  - Gravitational collapse; disk because of angular momentum
  - Accretion of solids followed (sometimes) by accretion of gas

Why do Planets of Similar Mass & Composition have different Behaviors?

- Distance from star plays a role (but not necessarily dominant)
- Environment of formation plays a role
  - Water
  - Carbon dioxide, or…
- Planets (unlike stars) are made of thermodynamically complex materials
  - Complex melting behavior (volcanism)
  - Effect of alloying (e.g., sulfur in iron)
  - Effect of water on rock rheology
- Role of chance in formation
  - Major aspect of Earth-Venus difference?
- Life

THE ASTROPHYSICAL JOURNAL, Vol. 158, November 1969

THE MASS-RADIUS RELATION FOR COLD SPHERES OF LOW MASS*

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University of Maryland, College Park, and Center for Theoretical Physics
AND
E. E. SALPETER
Laboratory of Nuclear Studies, Physics Department, and Center for Radiophysics and Space Research, Cornell University, Ithaca, New York
Received 1969 March 14

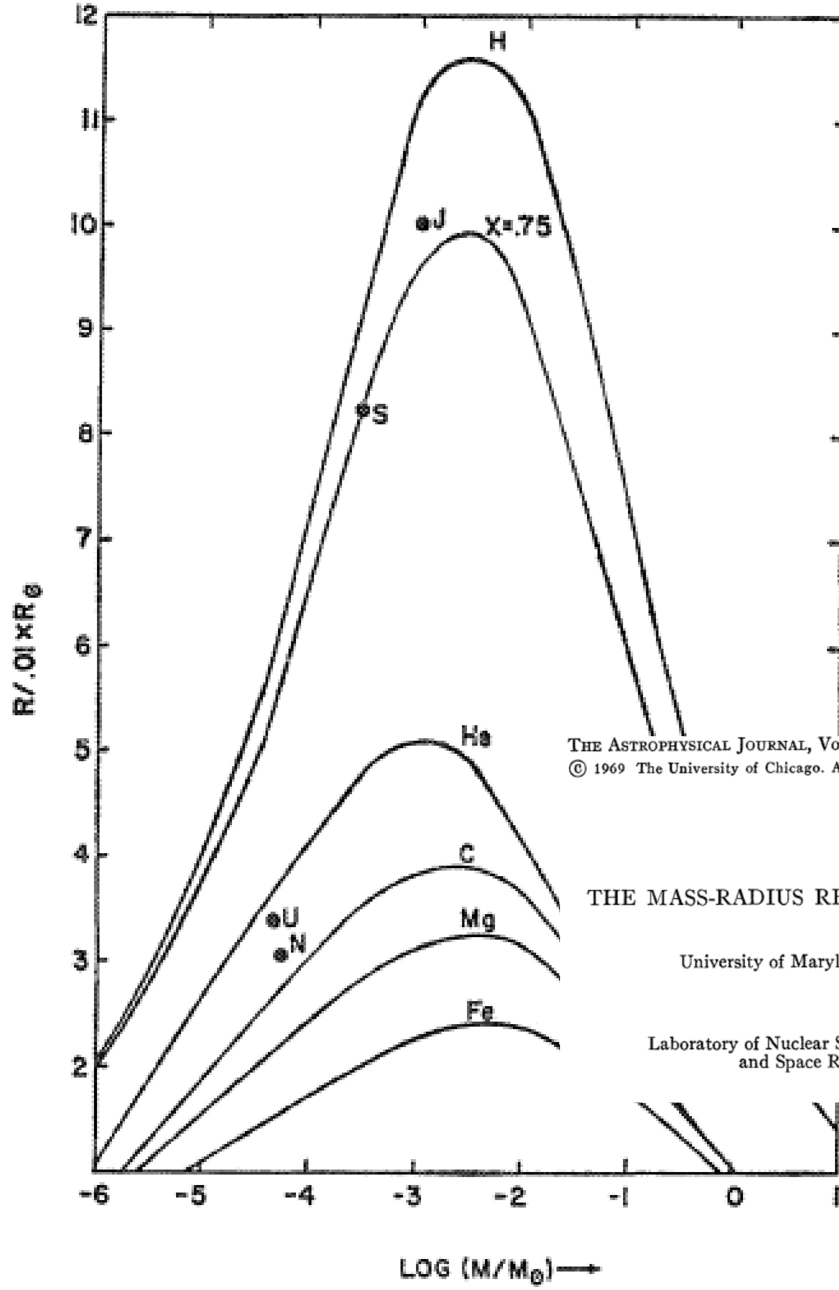
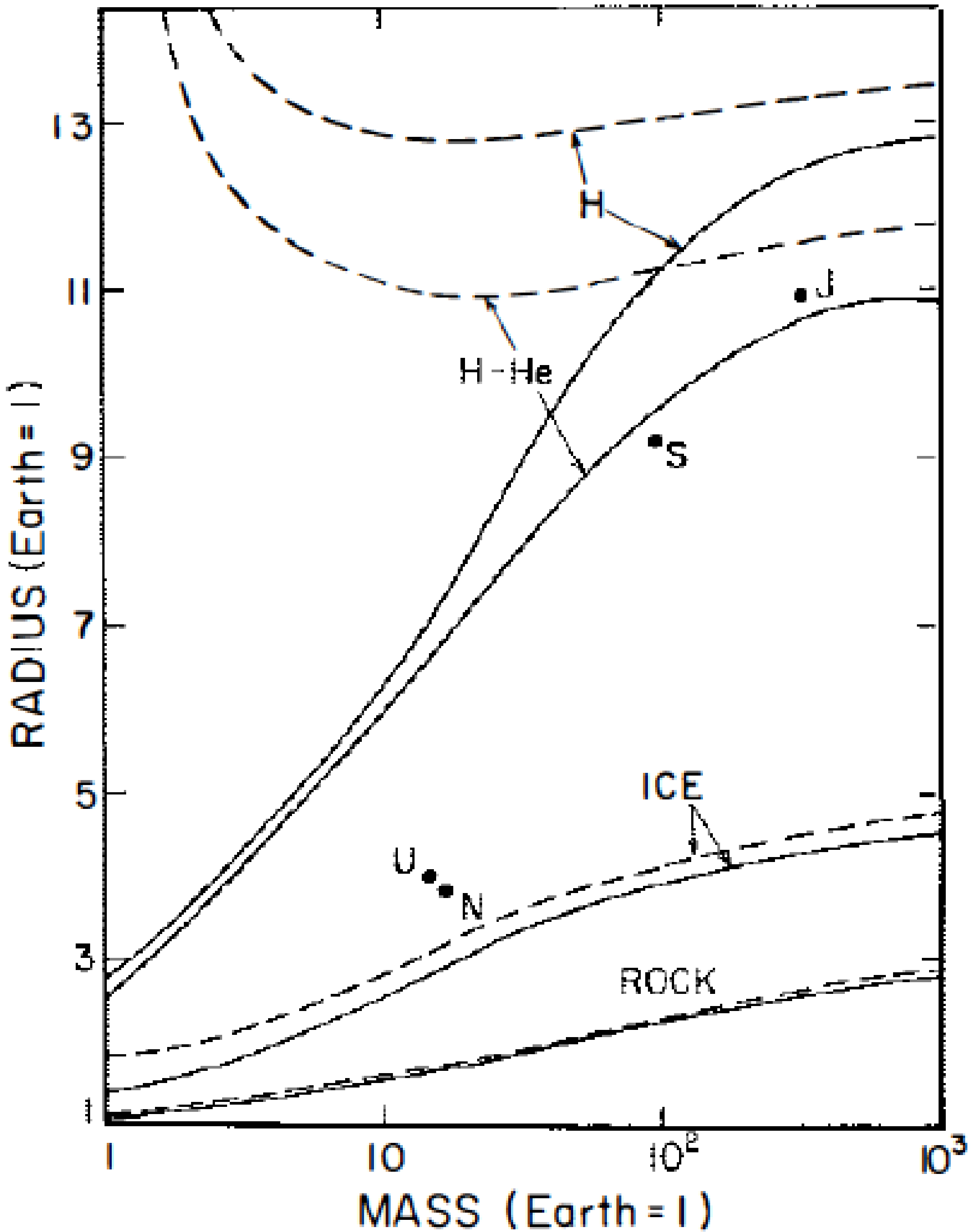
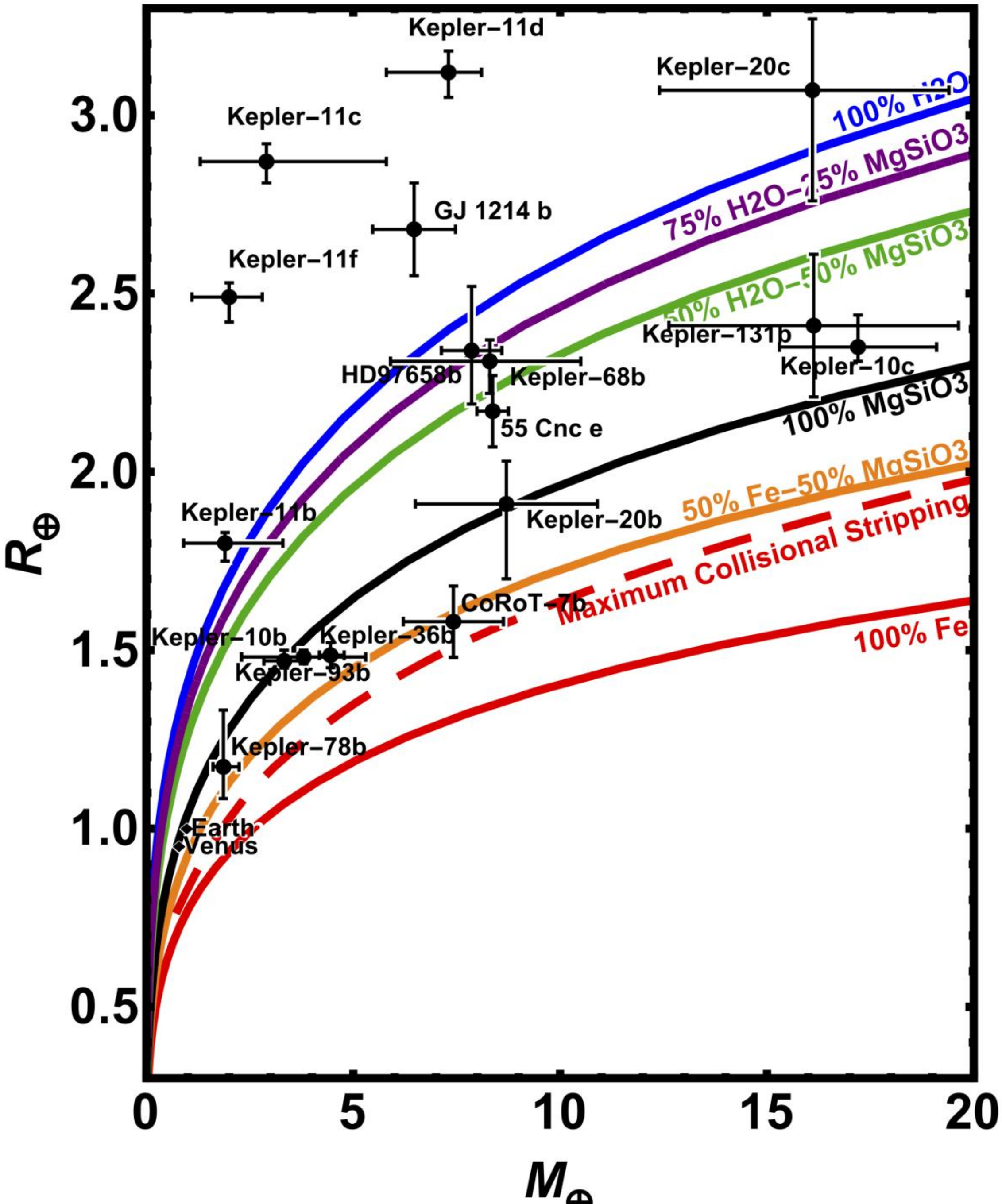


FIG. 1.—Mass-radius plot for homogeneous spheres of various chemical compositions. The points J, S, U, N are the observed values for the Jovian planets.



Stevenson, 1982

Dashed lines are isentropes



Zeng & Sasselov, 2014

What does R(M) tell us?

- Clear evidence for hydrogen–rich envelopes , even for some quite low mass bodies (few Earth masses)
  - Relevant to origin stories
- No clear evidence (yet) for water worlds (superGanymedes)
  - Observational bias
- Some bodies that could be Earthlike in bulk composition
  - But small differences in R(M) can hide important differences in the nature of the body
  - Could be bodies stripped of an atmosphere, *in which case they need not be Earthlike (because the pre-stripped core was potentially very hot)*

J. Geomag. Geoelectr., **37**, 781–799, 1985

Structure of the Primordial Atmosphere Surrounding the Early-Earth

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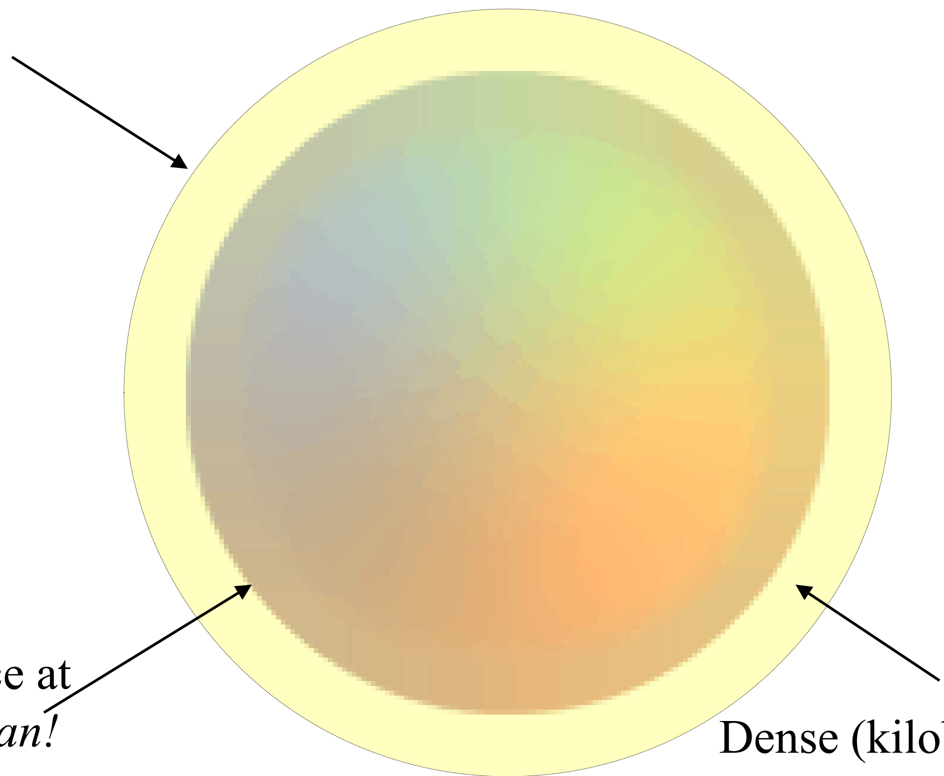
**Max Planck Institut fur Kernphysik, 6900 Heidelberg 1, West Germany*
***Department of Physics, Kyoto University, Kyoto, Japan*

(Received September 4, 1984; Revised March 8, 1985)

We investigate the structure of the primordial atmosphere surrounding the early-Earth under various conditions. We put a special emphasis on stages where the Earth had already grown to the present mass and the gas of the solar nebula was escaping. The atmosphere is assumed to be in hydrostatic equilibrium and spherically symmetric. The structure depends on the energy out flow (i.e., the luminosity) of the Earth, the gas density of the solar nebula, and the abundance of dust grains contained in the atmosphere. Calculations are made for a wide range of these three parameters.

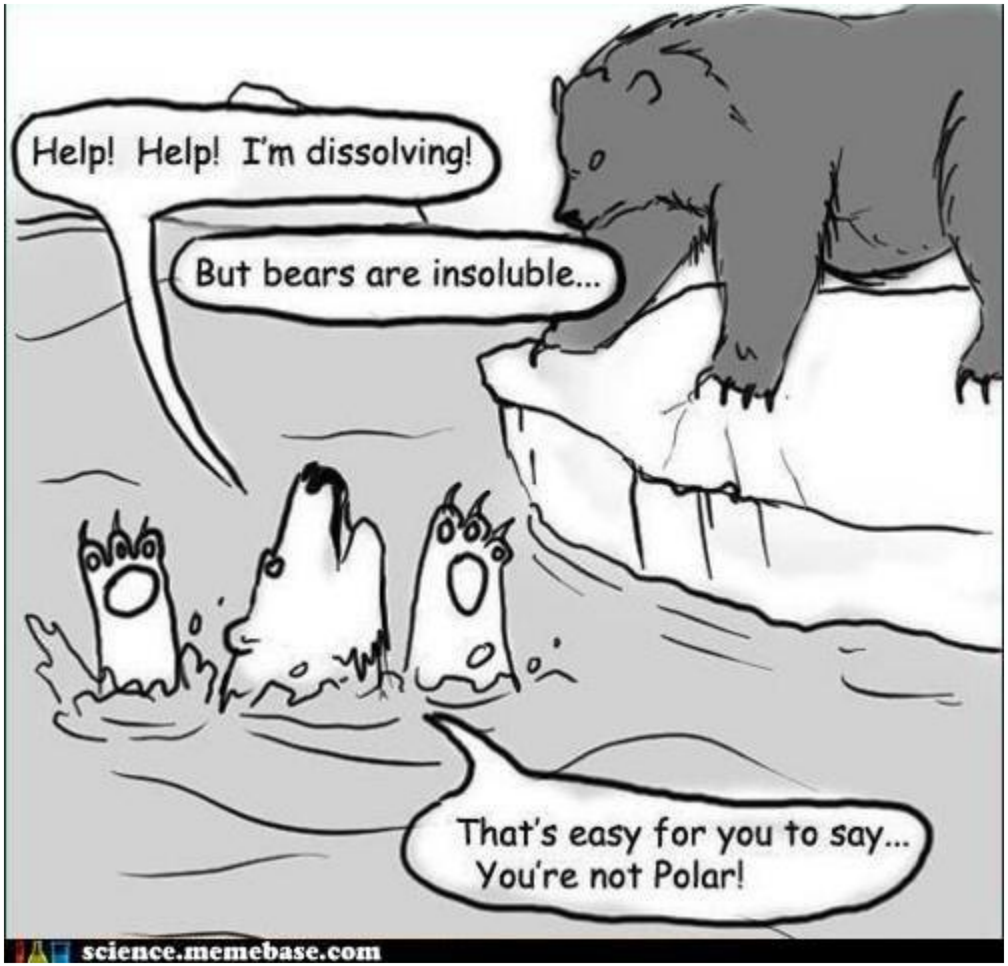
Detailed numerical results for various quantities such as the density and the temperature at the bottom of the atmosphere, the position of the photosphere and the atmospheric mass are tabulated. Distributions of density and temperature are also given. Atmospheric models obtained here will provide basic data for the study of dissipation of the primordial atmosphere and for that of the lunar capture.

An Interstellar Planet



Role of High Pressure Physics

- Not directly very useful for improving R(M)
  - It’s good enough already to use “generic” equations of state
- BUT there are some very interesting and important issues with mixing, liquid vs solid, existence of cores (superEarths need not have iron-rich cores) . These may not affect R(M) directly but affect what happens as material is stripped off & what is left behind
  - Current thinking about this is very primitive

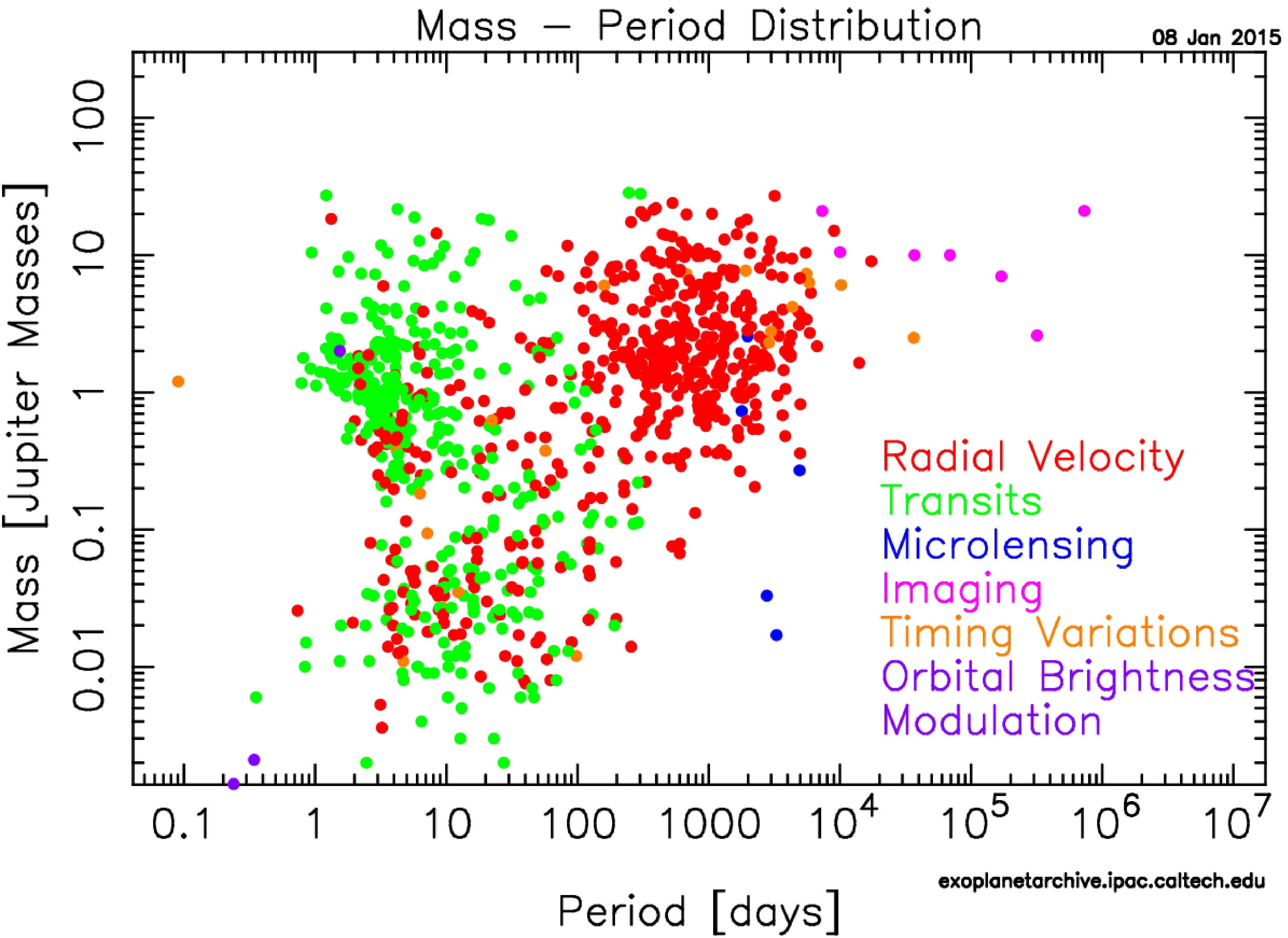

Help! Help! I'm dissolving!
But bears are insoluble...
That's easy for you to say...
You're not Polar!
science.memebase.com

Role of Cosmo/geochemistry

- Two main issues here
  - What are the elemental abundances (not just metallicity but Mg/Si, Fe/Mg; affects the minerals that form
  - What is the oxidation state (for example a system where all the Fe is oxidized and not metallic? There is enough oxygen of course.) This may be determined in the nebula.
    - Claimed metallic core sizes are hugely variable and depend on many different parameters

Role of Atmospheres (Observation & Theory)

- Important!
- The atmosphere should *never* be thought of as something you add on top, even when it is accreted from the nebula
- The distinction between accreted & outgassed is somewhat artificial in many cases
  - The outgassed can be accreted in many different ways
- Atmospheres are potentially diagnostic of interior
  - Requires more work



Mass – Period Distribution
08 Jan 2015
Mass [Jupiter Masses]
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
exoplanetarchive.ipac.caltech.edu

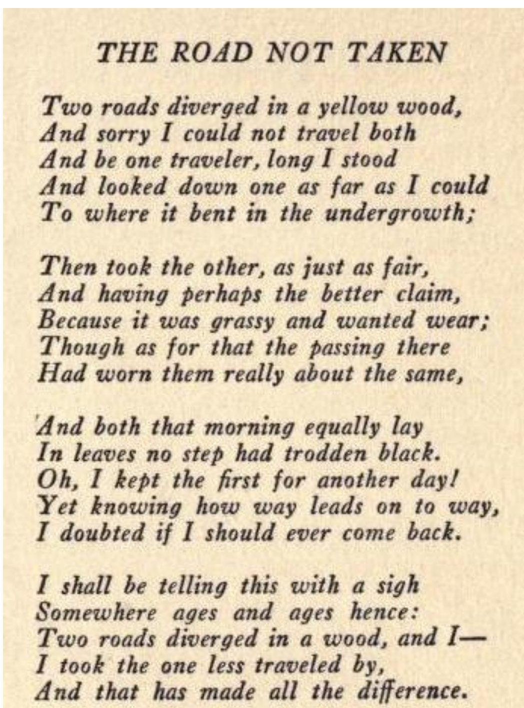
Other Kinds of Measurements?

- Time variability
- Rotation (& obliquity)
  - Can even be interesting in the region of tidal “locking”
  - Diagnostic of origin at larger orbital radius
- Satellites & rings
  - Might even tell us J_2/Love numbers
- Magnetic field (radio)? Microwaves
  - Have not been diagnostic/predictable in our solar system
  - We can always hope!
  - Can have other consequences (e.g., atmospheric loss is modified)
  - Can have dynamo in a very hot magma ocean

Role of other Physical Modeling

- Atmospheric dynamics; coupling with clouds , photochemistry
- Atmospheric escape (all our ignorance is buried in an efficiency factor ~0.1)
- Loss (or not) of water
- Hot Magma oceans
- Better understanding of tidal evolution (the infamous Q)

TESS,…
JWST
Microlensing
Direct imaging
Radio?
Disks..



THE ROAD NOT TAKEN

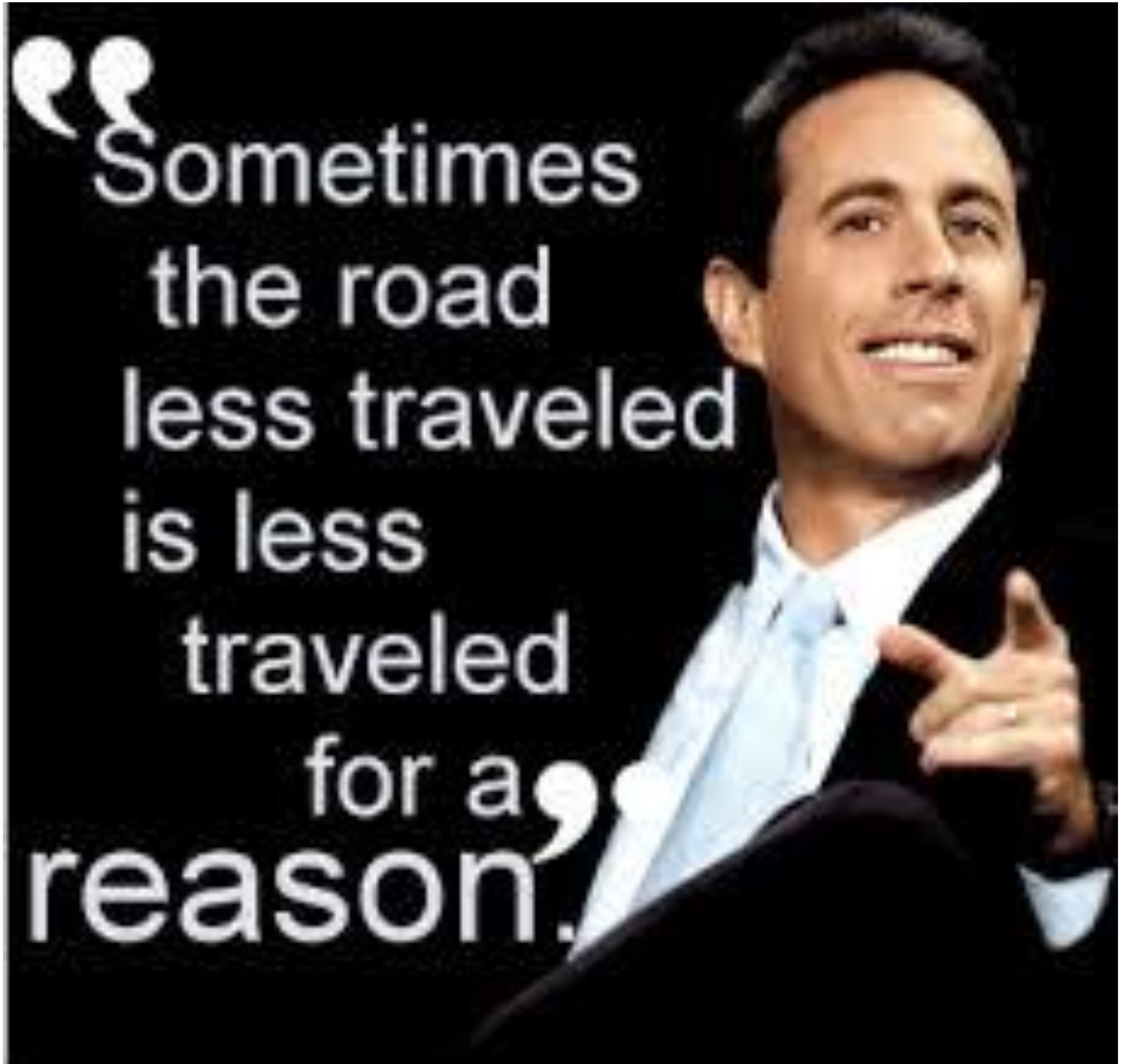
Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,

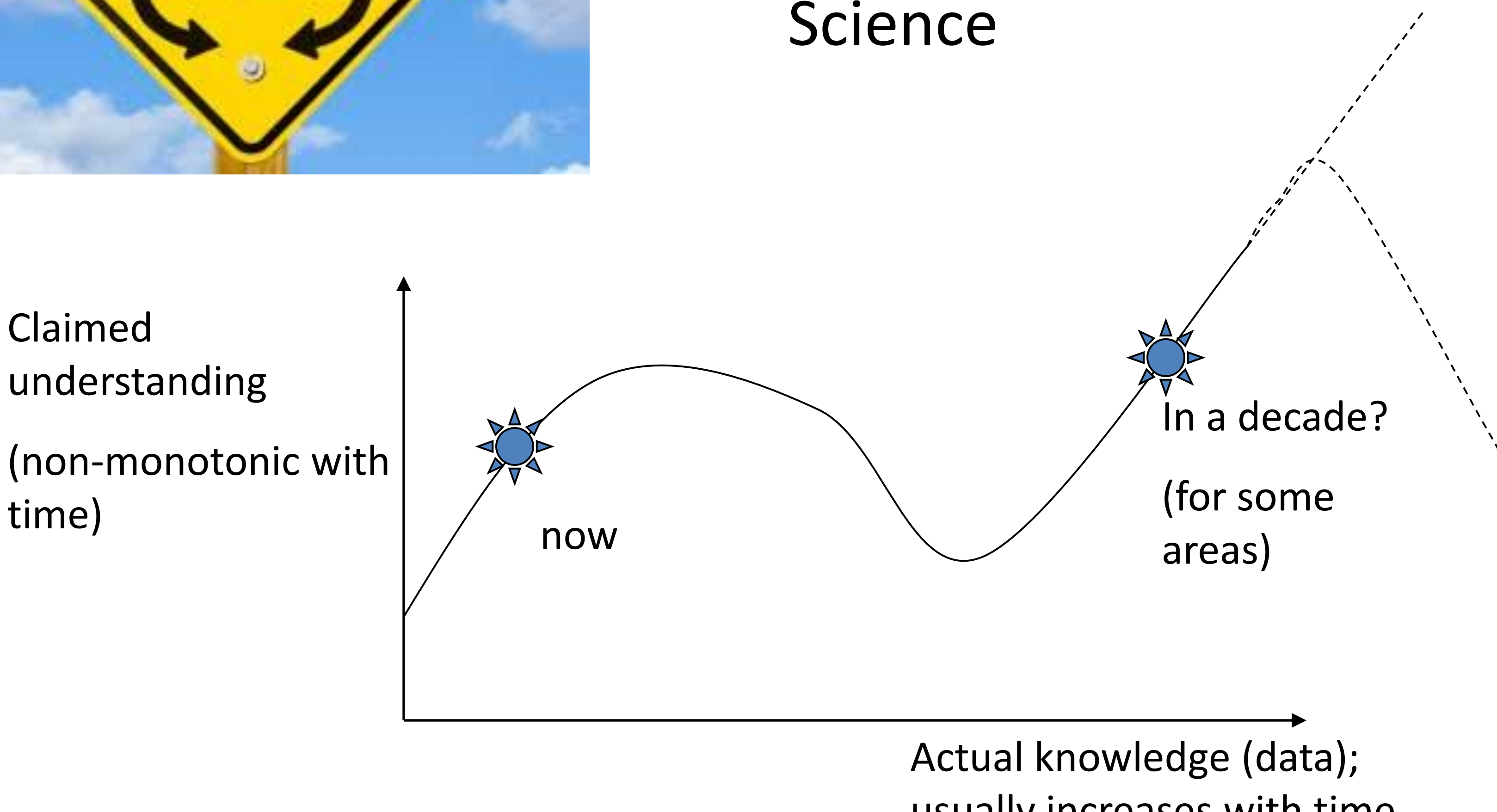
And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.

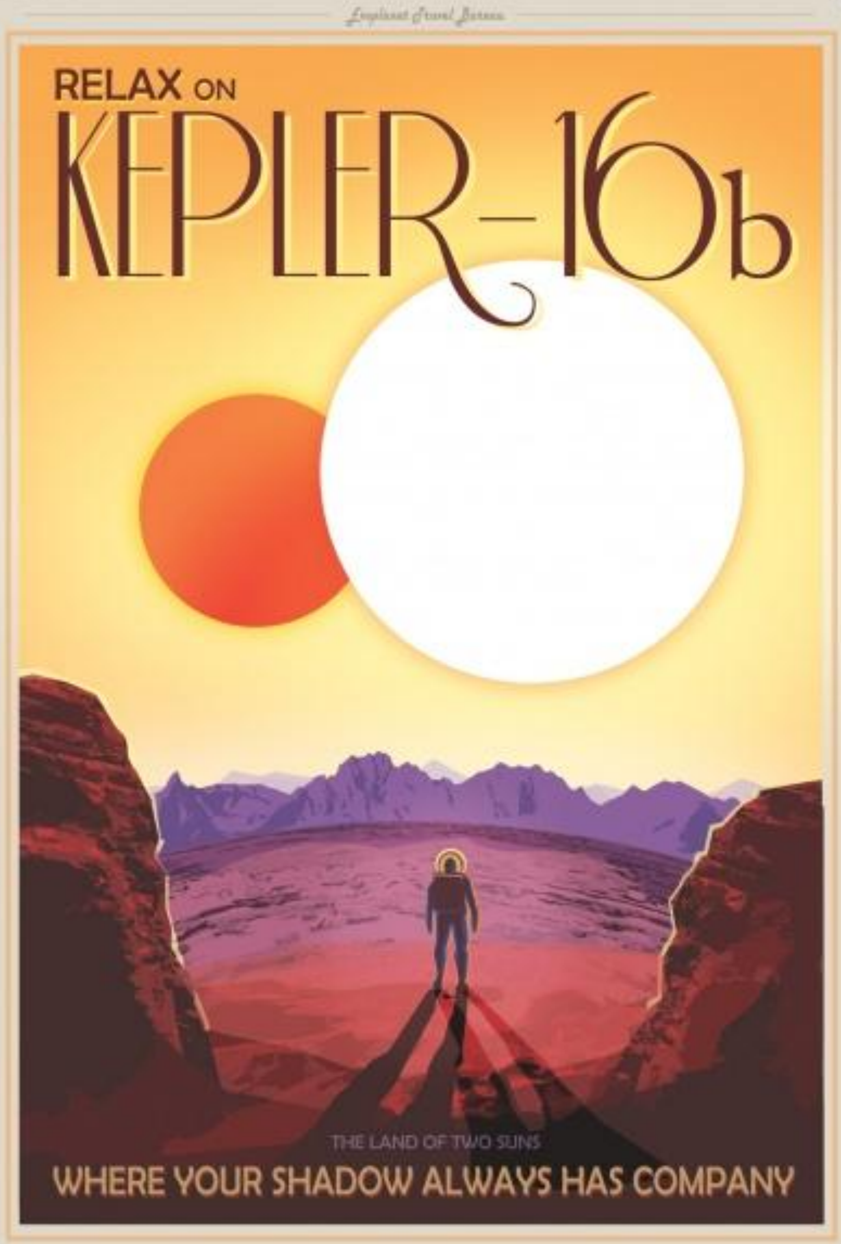
I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

What about the road less traveled?
-Robert Frost


"Sometimes
the road
less traveled
is less
traveled
for a
reason."

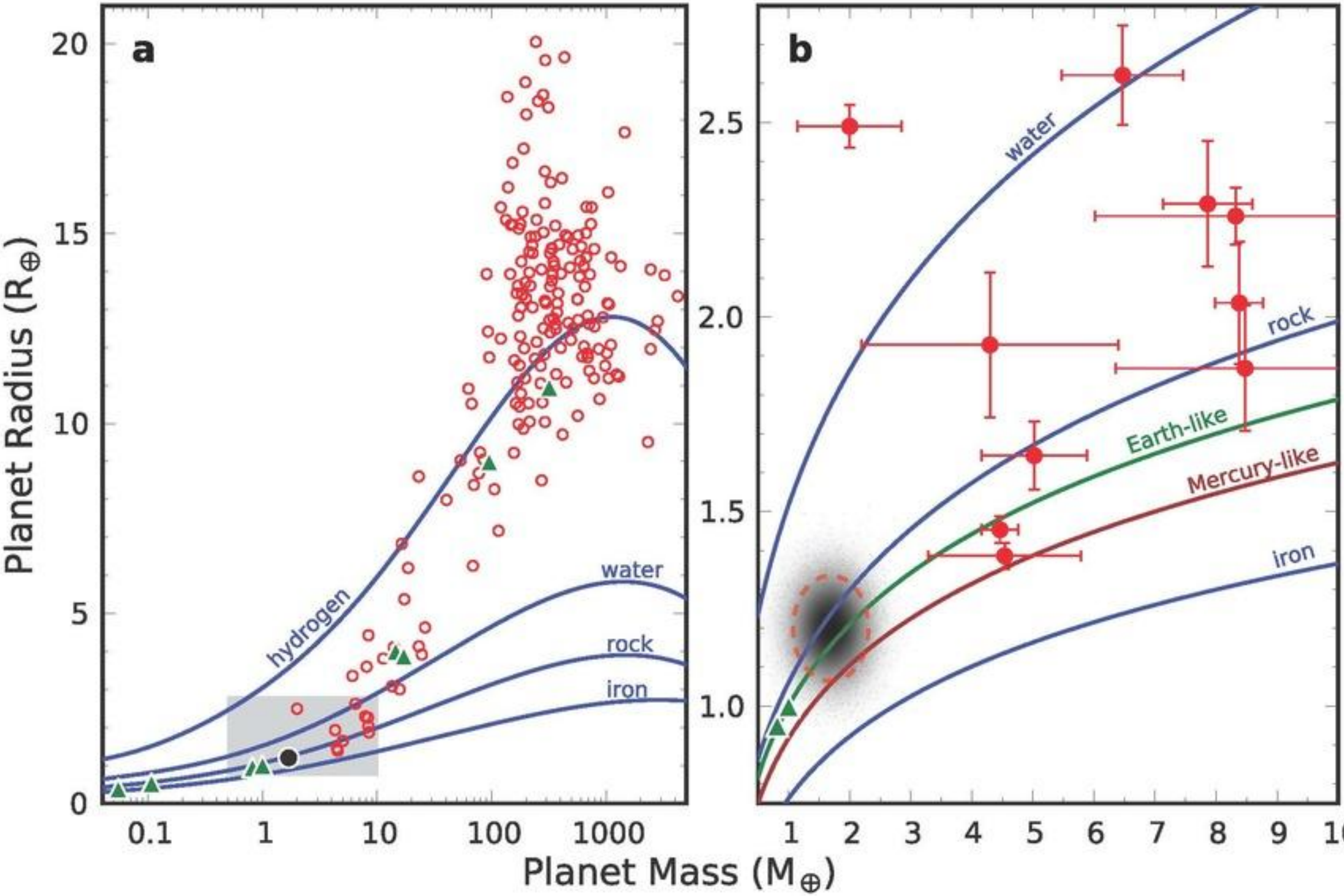
The Usual Pattern in Science




Exoplanet Travel Bureau
RELAX ON
KEPLER-16b
THE LAND OF TWO SUNS
WHERE YOUR SHADOW ALWAYS HAS COMPANY

Back up slides

Known Planets - Masses and Radii



Howard et al. (2013)

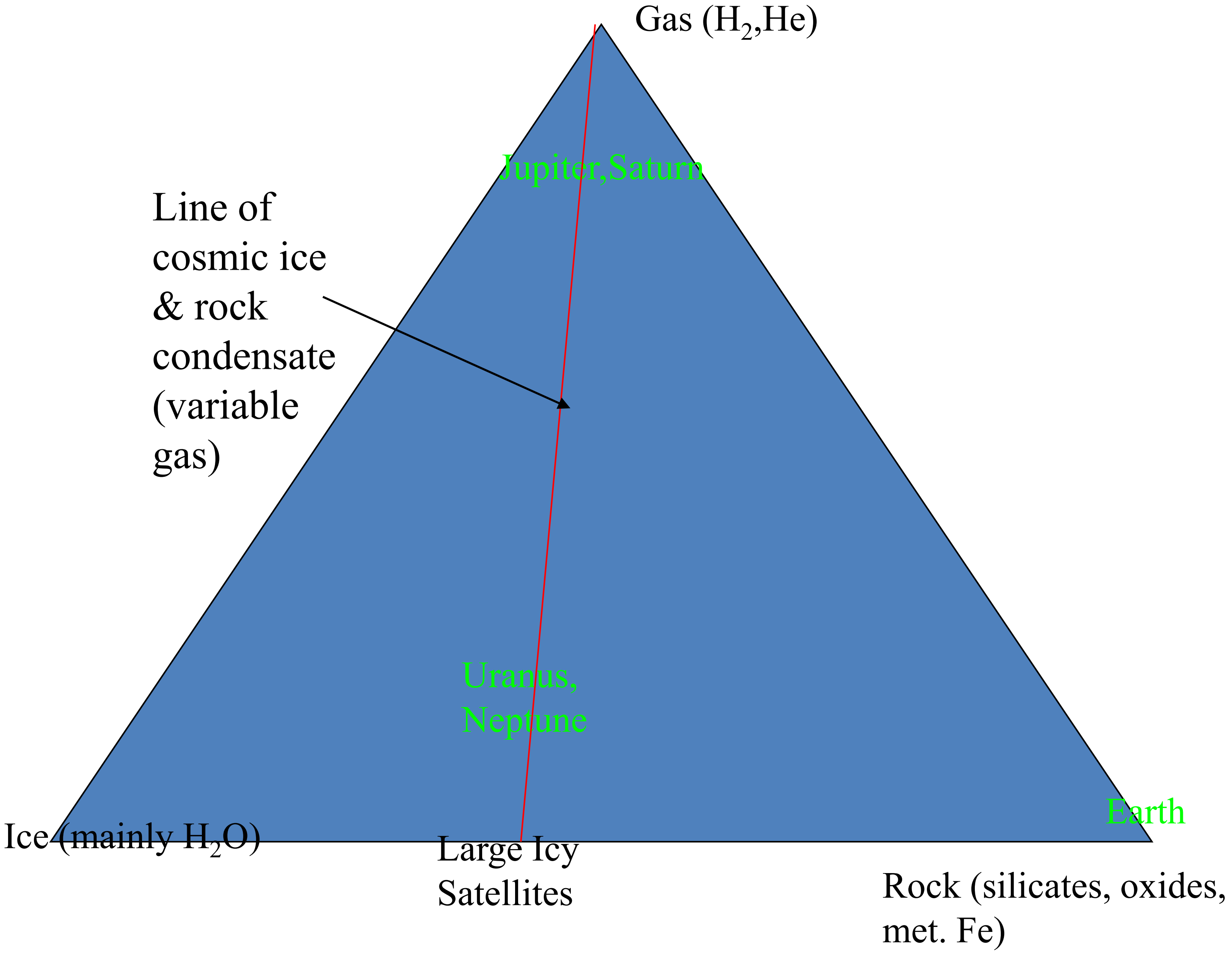
Cosmic (~Solar) Abundances

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

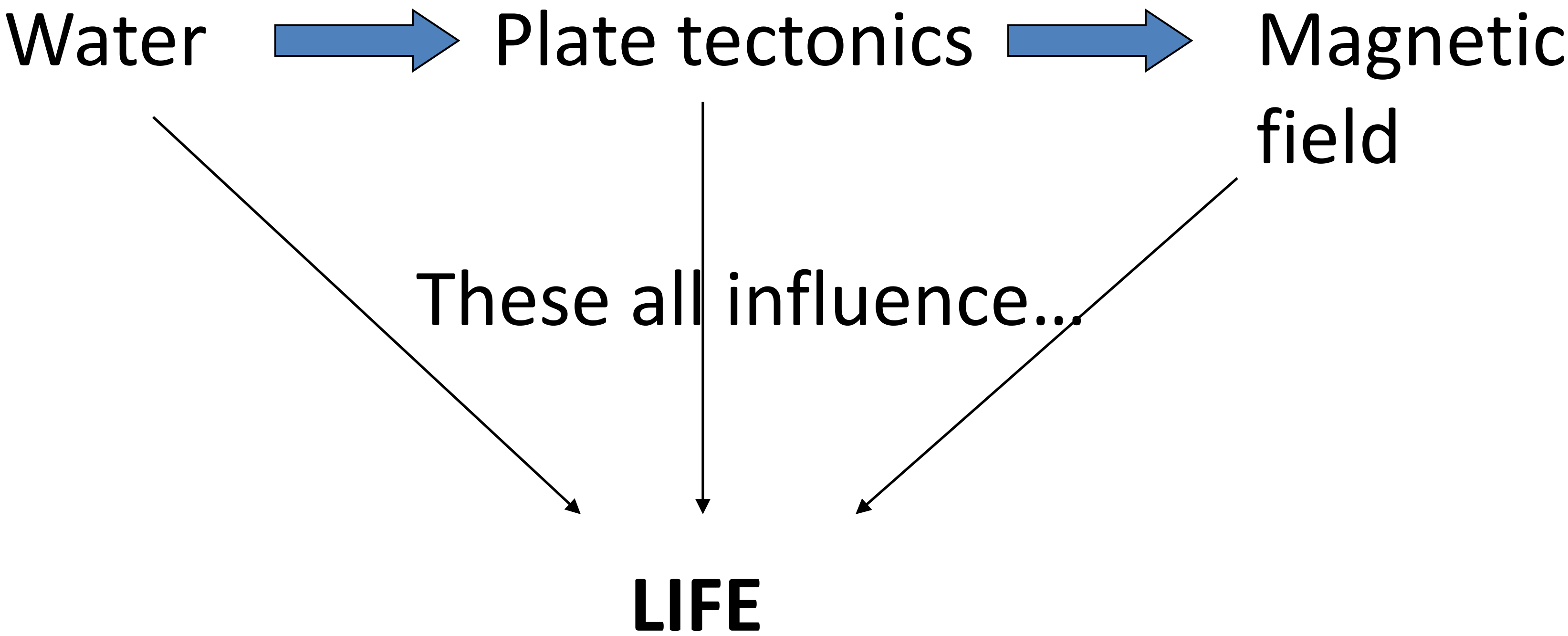
Classes of Planetary Materials

Type of bonding*	Examples	Solid Densities at low P	Bulk modulus of solid	Locations found
Van der Waals	Hydrogen, helium, methane, N_2	e.g hydrogen is ~0.07 g/cc	e.g. hydrogen is a few kilobars	Giant planets (also methane and n itrogen in satellites)
Hydrogen bonding	Water, ammonia	Around unity	Ten kilobar (roughly)	Giant planets, icy satellites
Ionic and covalent (including metallic)	"Rocks", metallic iron	Rocks are around 3g/cc; iron is near 8 g/cc	Typically of order one megabar	Terrestrial planets, cores of giant planets(?), icy satellites

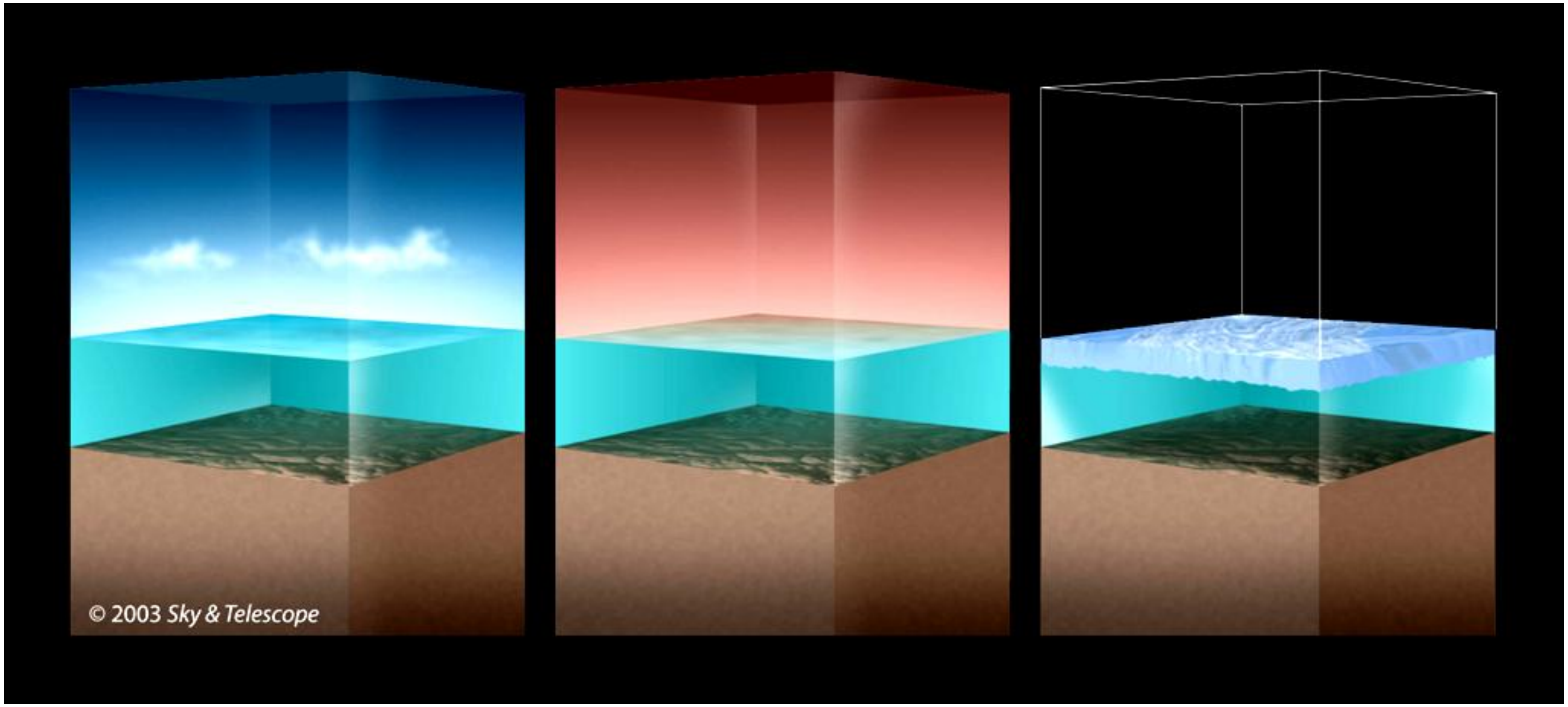
*The type of bonding refers to the low pressure behavior; everything presumably becomes a metal at sufficiently high pressure.



Gas (H2,He)
Jupiter,Saturn
Line of cosmic ice & rock condensate (variable gas)
Uranus, Neptune
Earth
Ice (mainly H2O)
Large Icy Satellites
Rock (silicates, oxides, met. Fe)


Water
Plate tectonics
Magnetic field
These all influence…
LIFE

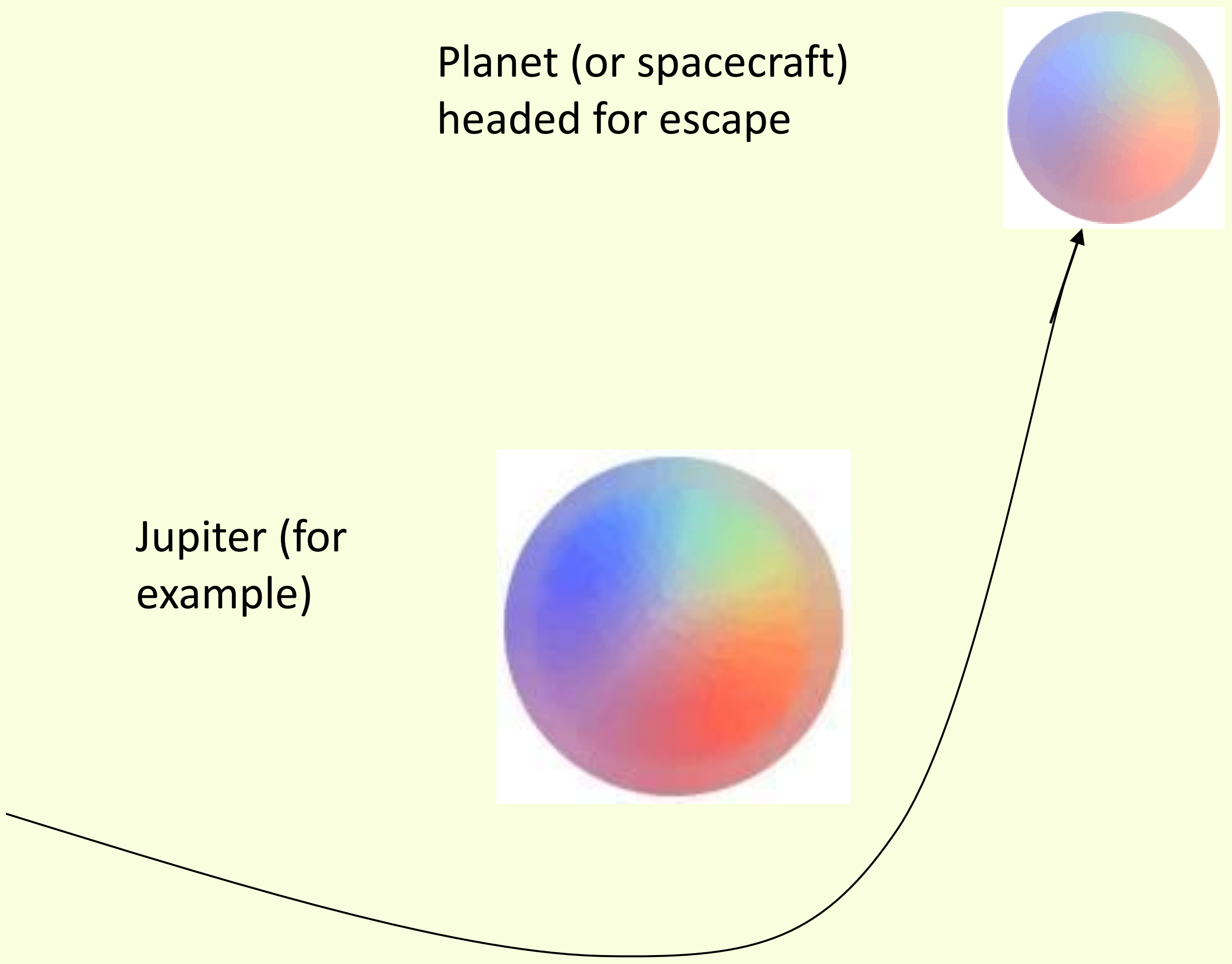
Three Kinds of Oceans



Earthlike

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

Protected by ice



Interstellar Planets?

-they have been observed by gravitational lensing