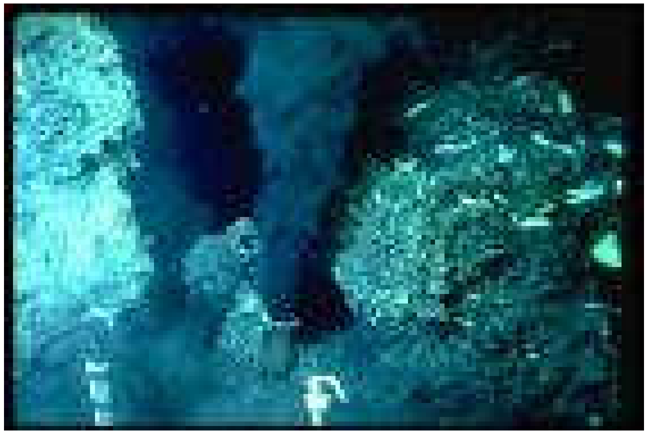
Exploplanets Rising: Astronomy and Planetary Science at the Crossroads

Ocean worlds

C. Sotin, JPL/Caltech



Ocean worlds

Ocean worlds in the solar system

- Water on Earth
- Liquids on Titan
- Ocean within the icy satellites
- Definition of an ocean world among exoplanets?

Modeling the structure of extrasolar ocean worlds

Do they exist?

Conclusions

- References: Leger et al. (2004); Sotin et al. (2007); Grasset et al. (2009); Fu et al. (2010); Rogers and Sieger (2010); …
- Extrapolating the interior structure and dynamics of small bodies to large bodies is “too” simple:
  - The minerals formed at very large pressure and temperature may be quite different from the ‘terrestrial’ silicates – accretion energy must be huge for a 5 Earth-mass planet – what is the core made of?
  - Models of subsolidus terrestrial convection contain approximations which are no more valid at high pressures – (Nu-Ra) relationships may not hold at these pressures.
- How important it is for determining the radius once the mass is known?

H_2O on Earth

Oceans : $1.35\ 10^{21}$ **kg**

Ice : $2.5\ 10^{19}$ **kg**

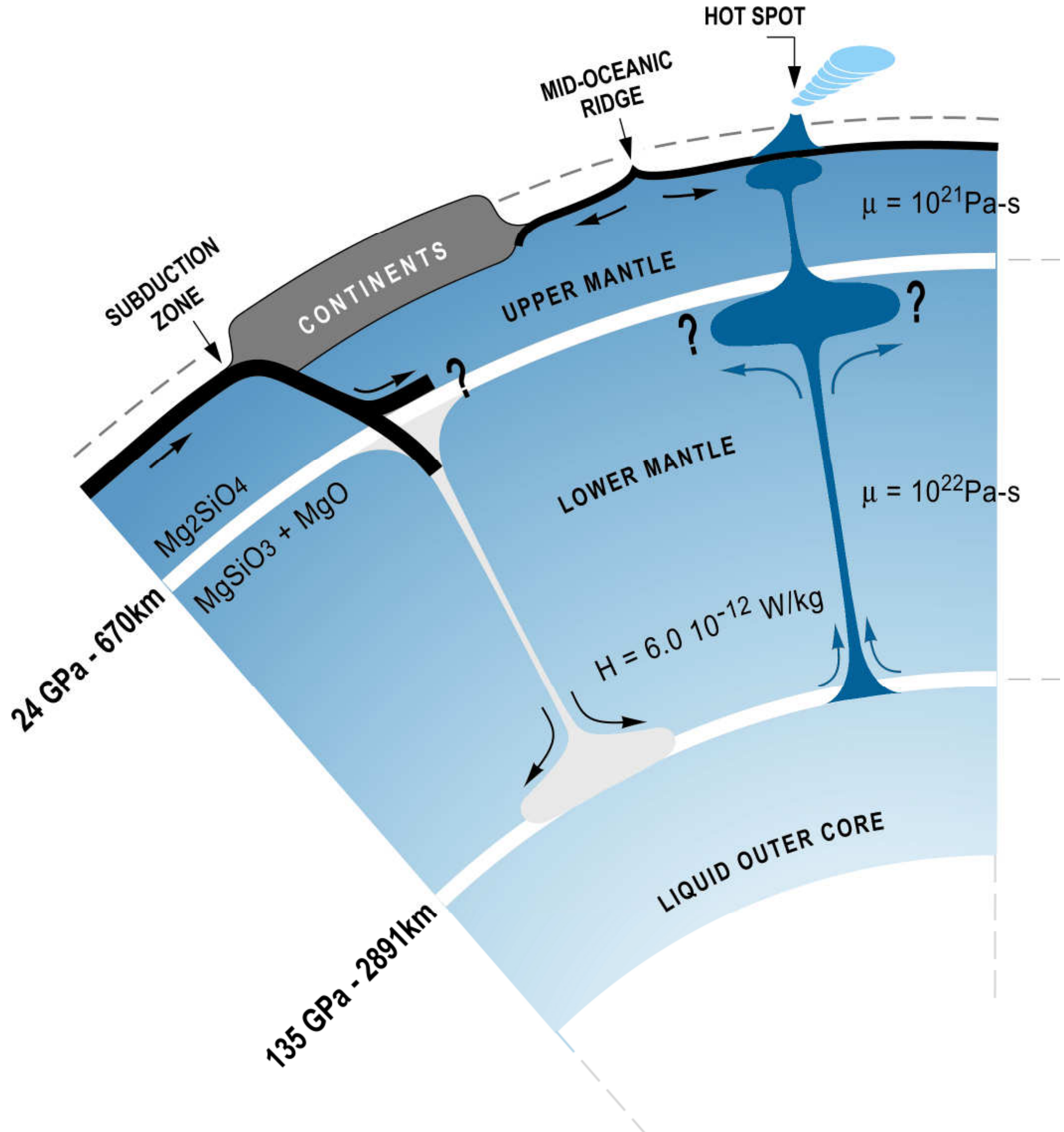
Underground water :
around $0.25\ 10^{21}$ **kg**

H_2O in the mantle :
$0.05\% * 4\ 10^{24}\ kg = 2\ 10^{21}\ kg$

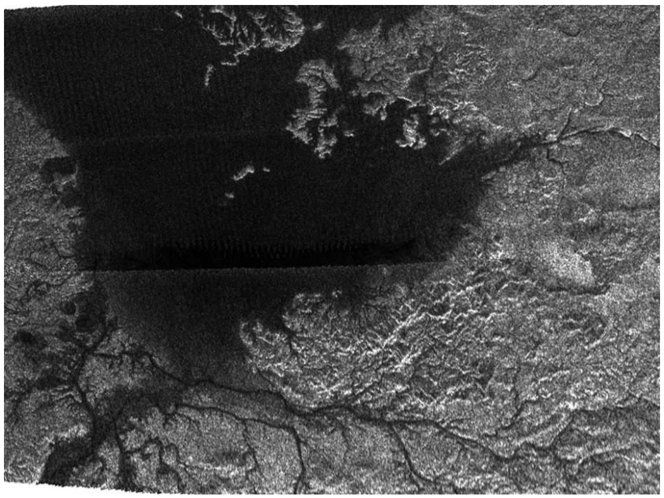
H_2O is about 2.5 **to** $5\ 10^{-4}\ M_T$

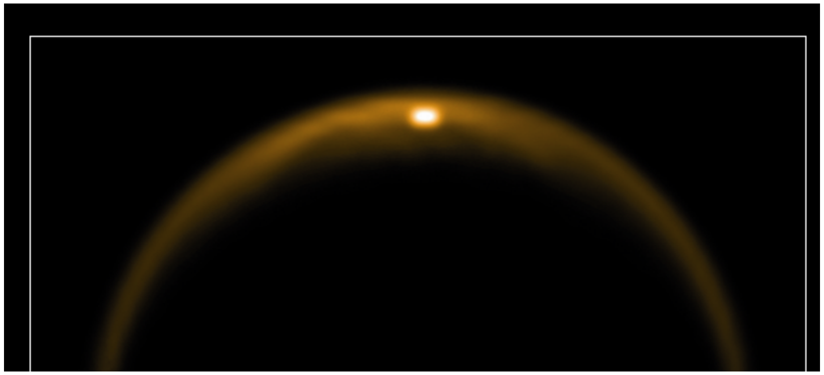
Earth has very little water. Ocean worlds are planets with much more water

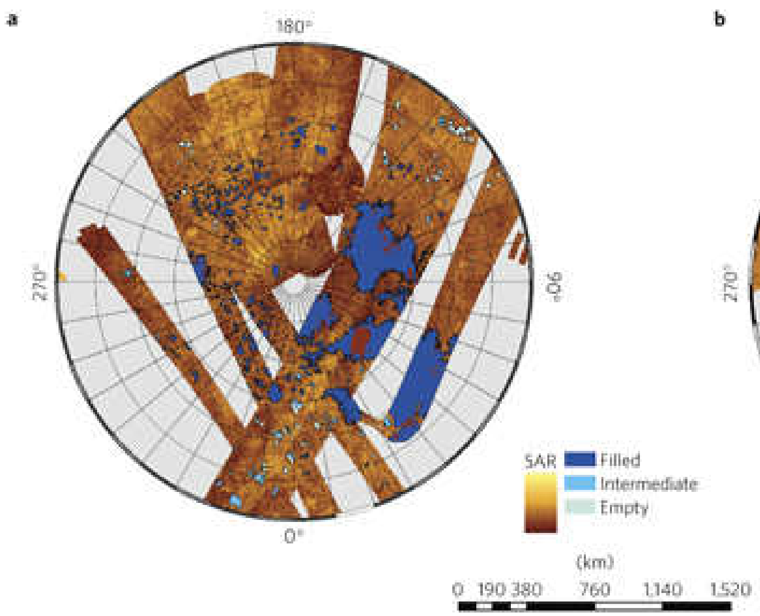
Water cycle on Earth



Liquids on Titan



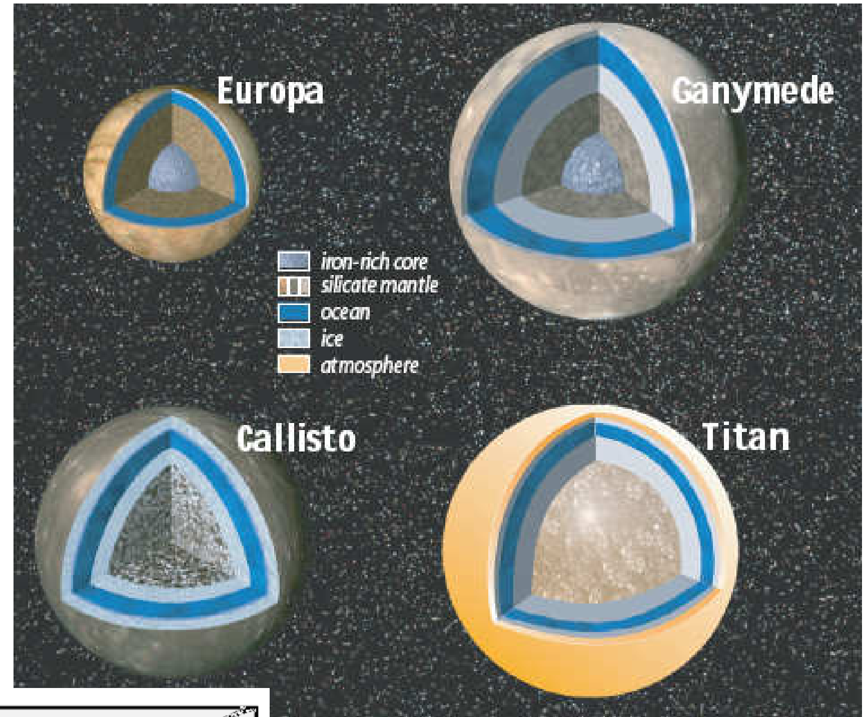


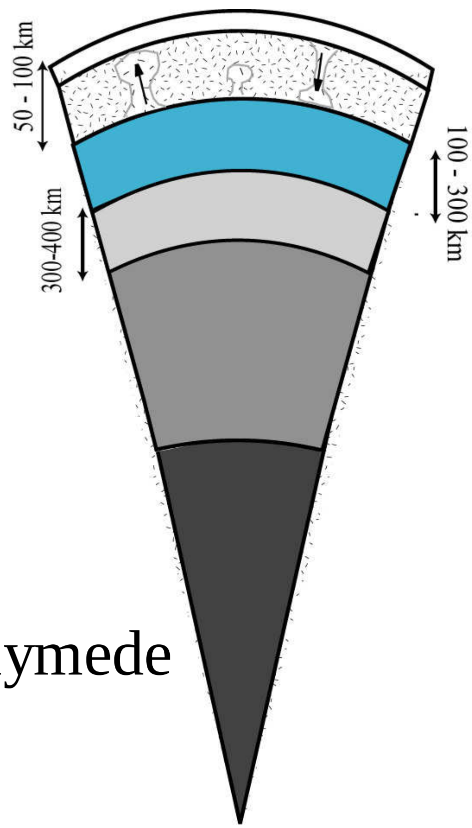


The liquids are hydrocarbons. IR spectra and phase diagram suggest methane and ethane

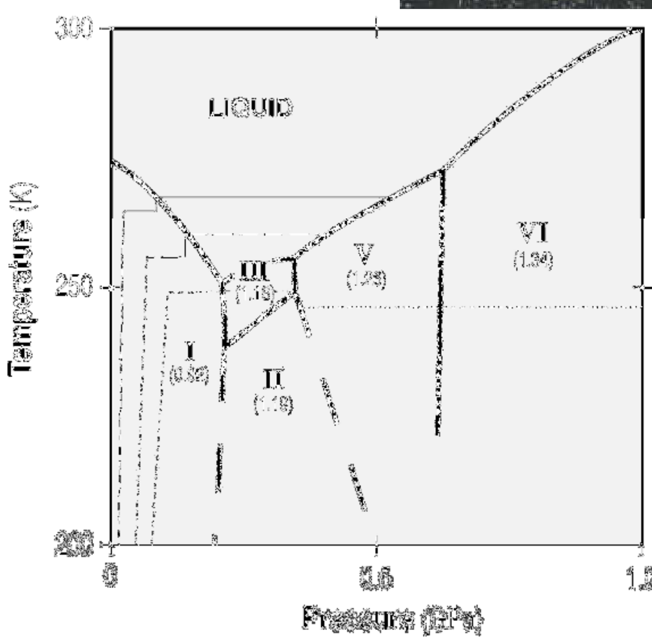
Oceans in icy satellites

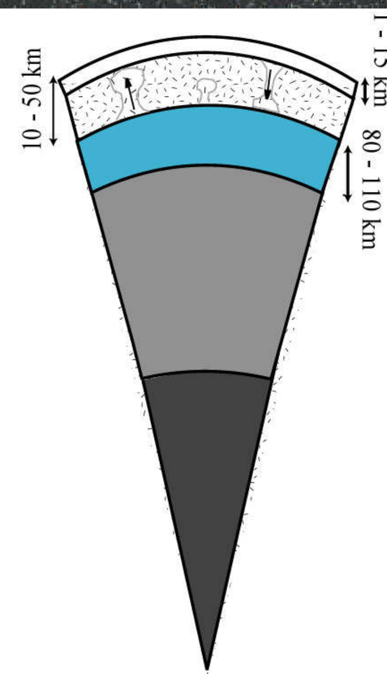
Moments of inertia demonstrate that the galilean satellites are differentiated.
Magnetic data suggest the presence of a liquid layer in the jovian icy satellites





Ganymede

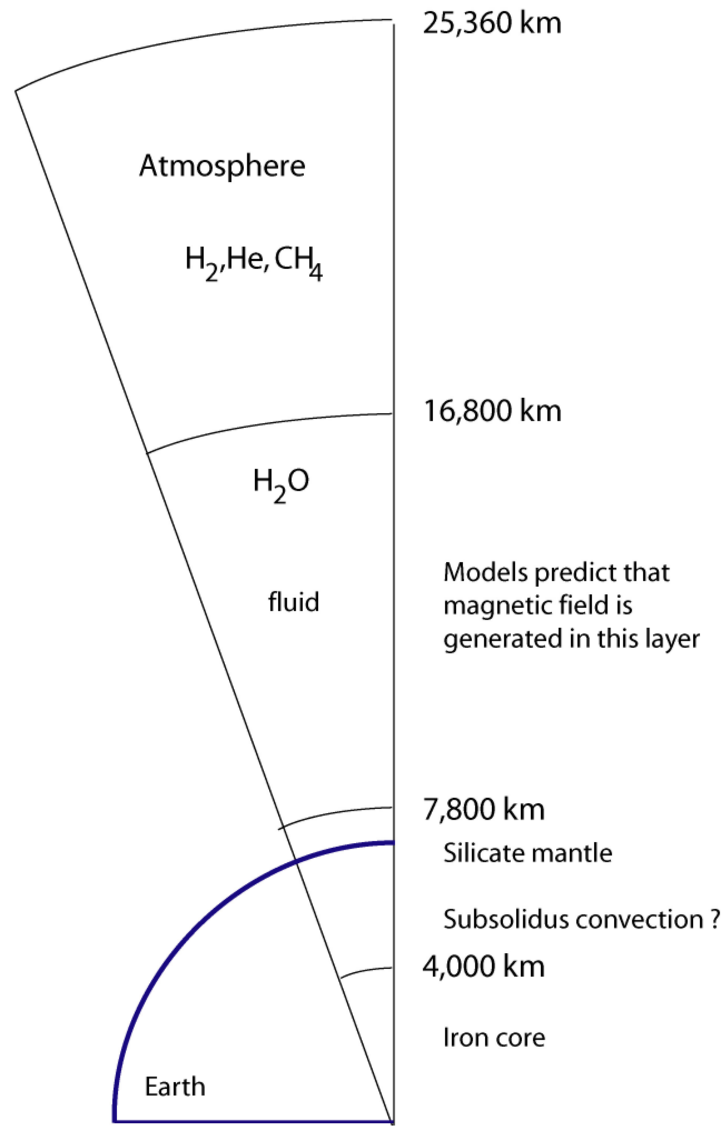




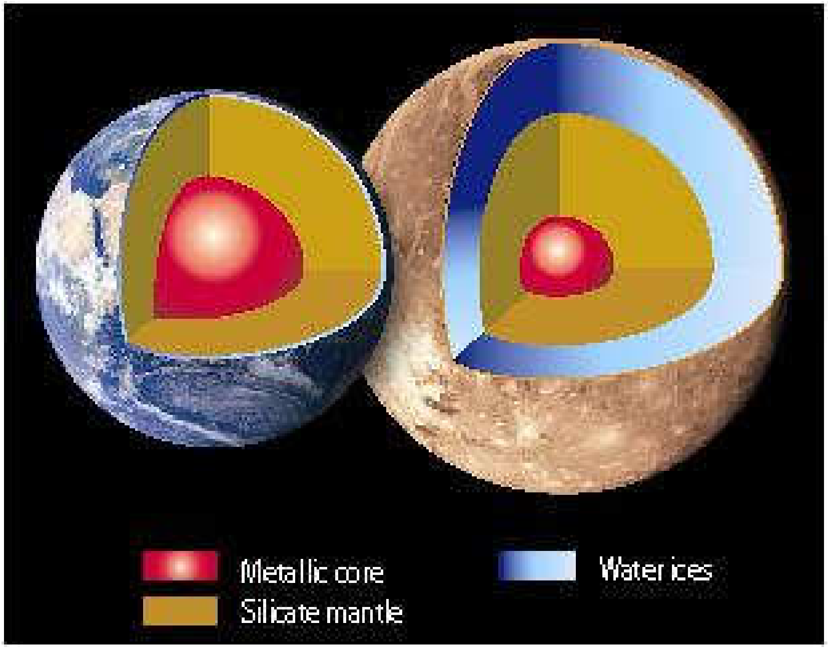
Europa

Uranus and Neptune / Earth

	Uranus	**Neptune**
Mass (10^{24} kg)	86.832 (**14.5**)	102.435 (**17.1**)
Volumetric radius (km)	25,364 (**3.98**)	24,625 (**3.87**)
Mean density (kg/m^3)	1,270 (2)	1,638(4)
Albedo	0.300(49)	0.290(67)
Absorbed power (x 10^{15} W)	5.26(37)	2.04(19)
Emitted power (x 10^{15} W)	5.60(11)	5.34(29)
Intrinsic power (x 10^{15} W)	0.34(38)	3.30(35)
Intrinsic flux (W/m^2)	0.042(47)	0.433(36)
Black-body temperature (K)	59.1	59.3
1-bar temperature[b] (K)	76 (2)	72 (2)
$J_{2,0}$ (x 10^{-6})	3,516(3)	3,539 (10)
$J_{4,0}$ (x10^{-6})	-35.4 (4.1)	-28(22)
$Q=\omega^2R^3/GM$	0.02951 (5)	0.02609(26)
Moment of inertia (I/MR2)	0.230	0.241



What is an ocean world in the family of exoplanets

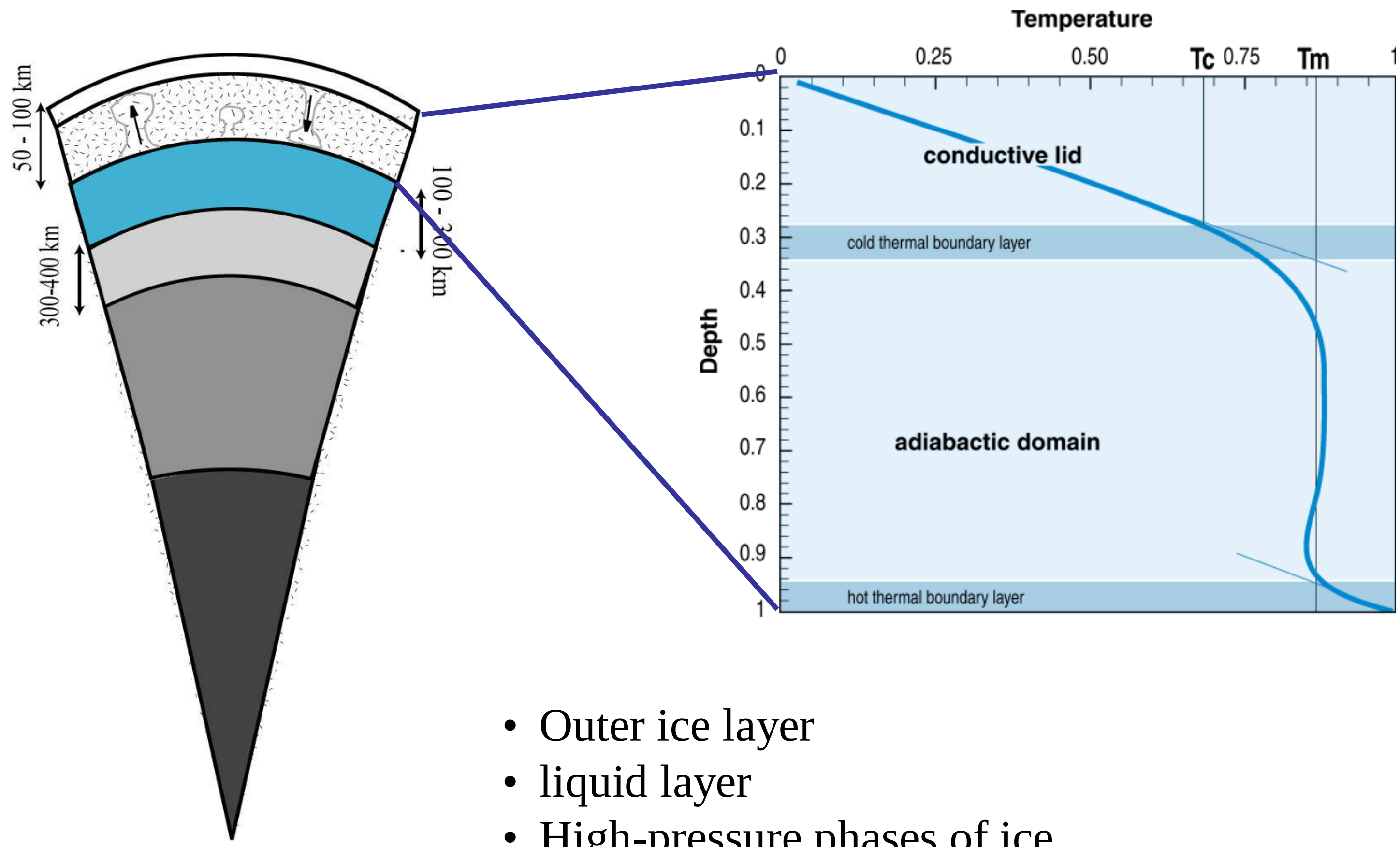


A planet with a small amount of liquid at its surface is an ocean world. But it cannot be differentiated from a dry-rocky planet if only mass and radius are known. Detection of H_2O in the atmosphere is required.

An ocean world is often thought as an H_2O rich planet (> 10%)

Models of the interior structure of icy exoplanets:

extrapolation from models developed for large icy satellites



- Outer ice layer
- liquid layer
- High-pressure phases of ice
- Silicate layer
- Iron core

Relationship between radius and mass

$$M = 4\pi \int_0^R r'^2 \rho(r') dr'$$

$$\frac{dP}{dr} = -\rho(r) g(r)$$

$$g(r) = \frac{4\pi G}{r^2} \int_0^r r'^2 \rho(r') dr'$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \frac{\alpha T}{\rho C p}$$

$$P_{th} = \int_{T0}^{T} \alpha K_T dT$$

Mass and radius are two of the few parameters.
They are related to each other through a simple equation in a 1D model.
Density depends on composition (elementary and molecular), pressure, and temperature
In the calculations, the main parameters are:

- Amount of volatiles H_2O
- The amount of Fe
- Distribution of Fe between iron core and mantle

We need an Equation of State (EoS) which relates density to pressure and temperature.
Example of the Birch-Murnagham EoS :

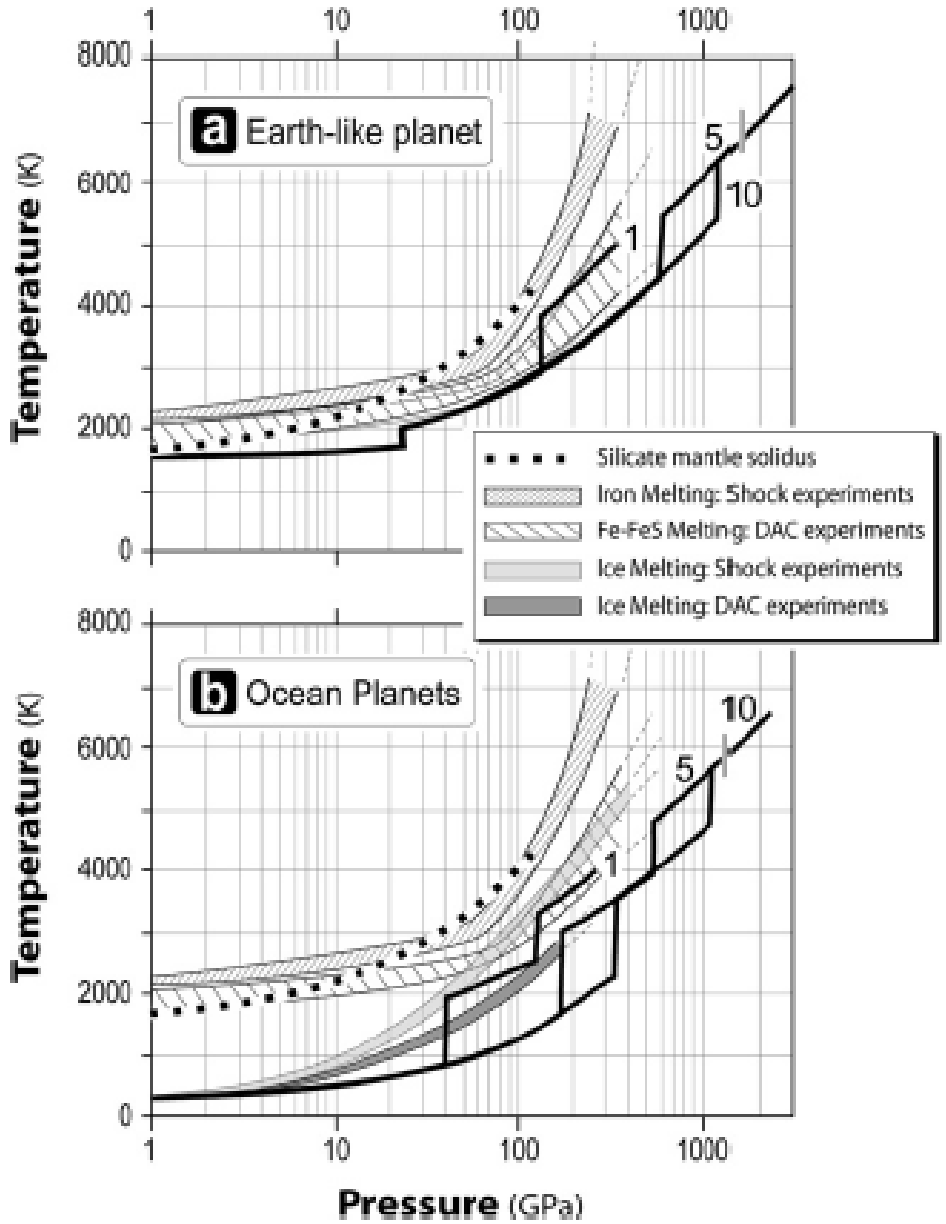
$$P = \frac{3K_{0T}}{2}\left[\left(\frac{\rho}{\rho_0}\right)^{\frac{7}{3}} - \left(\frac{\rho}{\rho_0}\right)^{\frac{5}{3}}\right]\left\{1 + \frac{3}{4}(K'_{0T} - 4)\left[\left(\frac{\rho}{\rho_0}\right)^{\frac{2}{3}} - 1\right]\right\}$$

Temperature profile / melting temperature

Structure:

- Outer ice layer
- liquid layer
- High-pressure phases of ice
- Silicate layer
- Iron core

Temperature profile is controlled by heat transfer process and the efficiency of sub-solidus convection to extract internal heating



Sotin et al., 2007

Different EoS

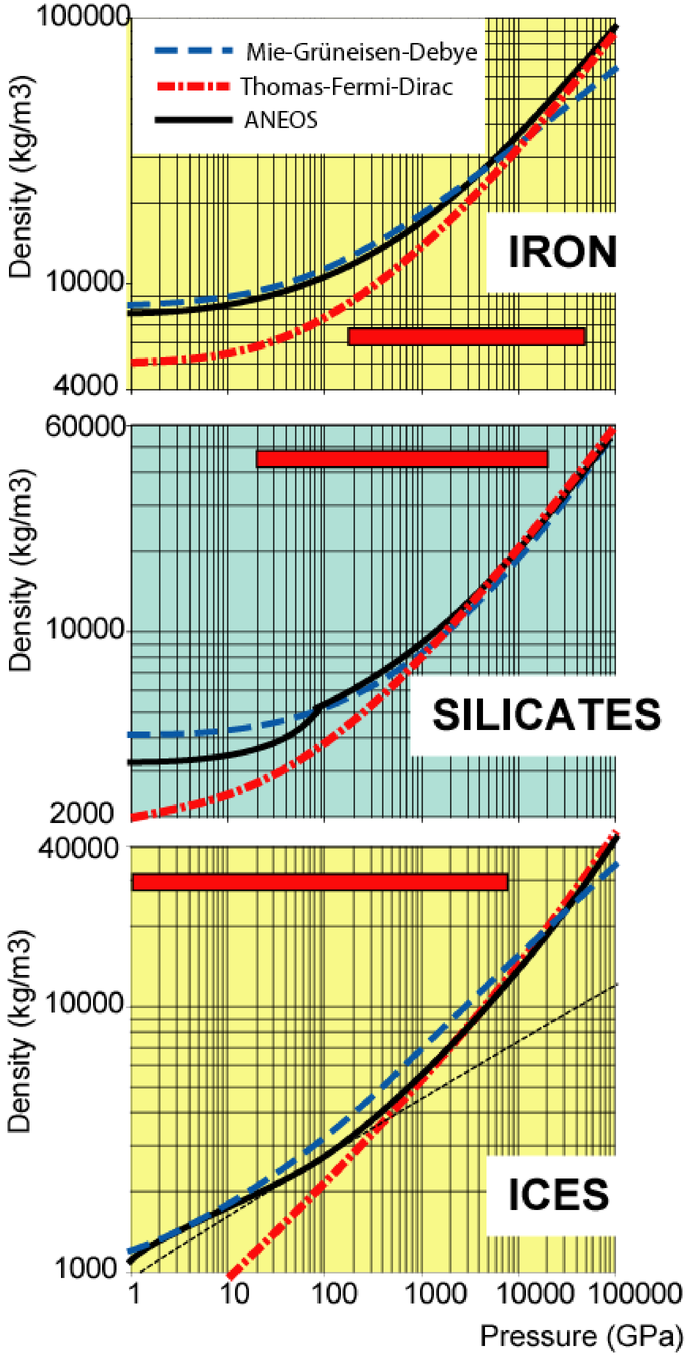
Birch-Mürnhagan EOS
- Liquid layer
- Upper silicate mantle

Mie-Grüneisen-Debye EOS
- Lower silicate mantle

Thomas-Fermi-Dirac
- Icy mantle
- Metallic core (P> 10 TPa)

Vinet EoS

ANEOS (Thompson, 1990)



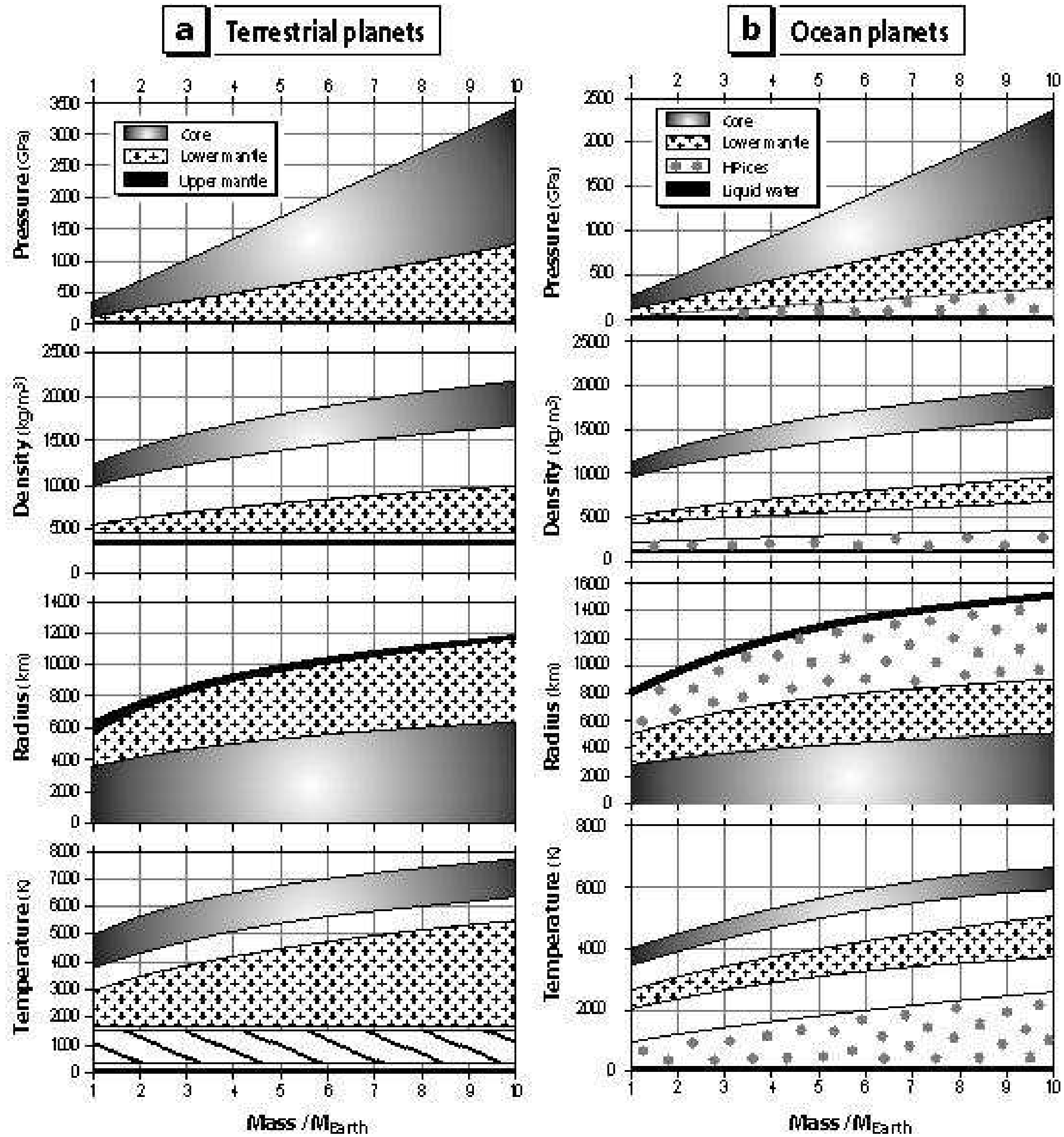
Variations with mass of some parameters

Pressure

Density

Radius

Temperature

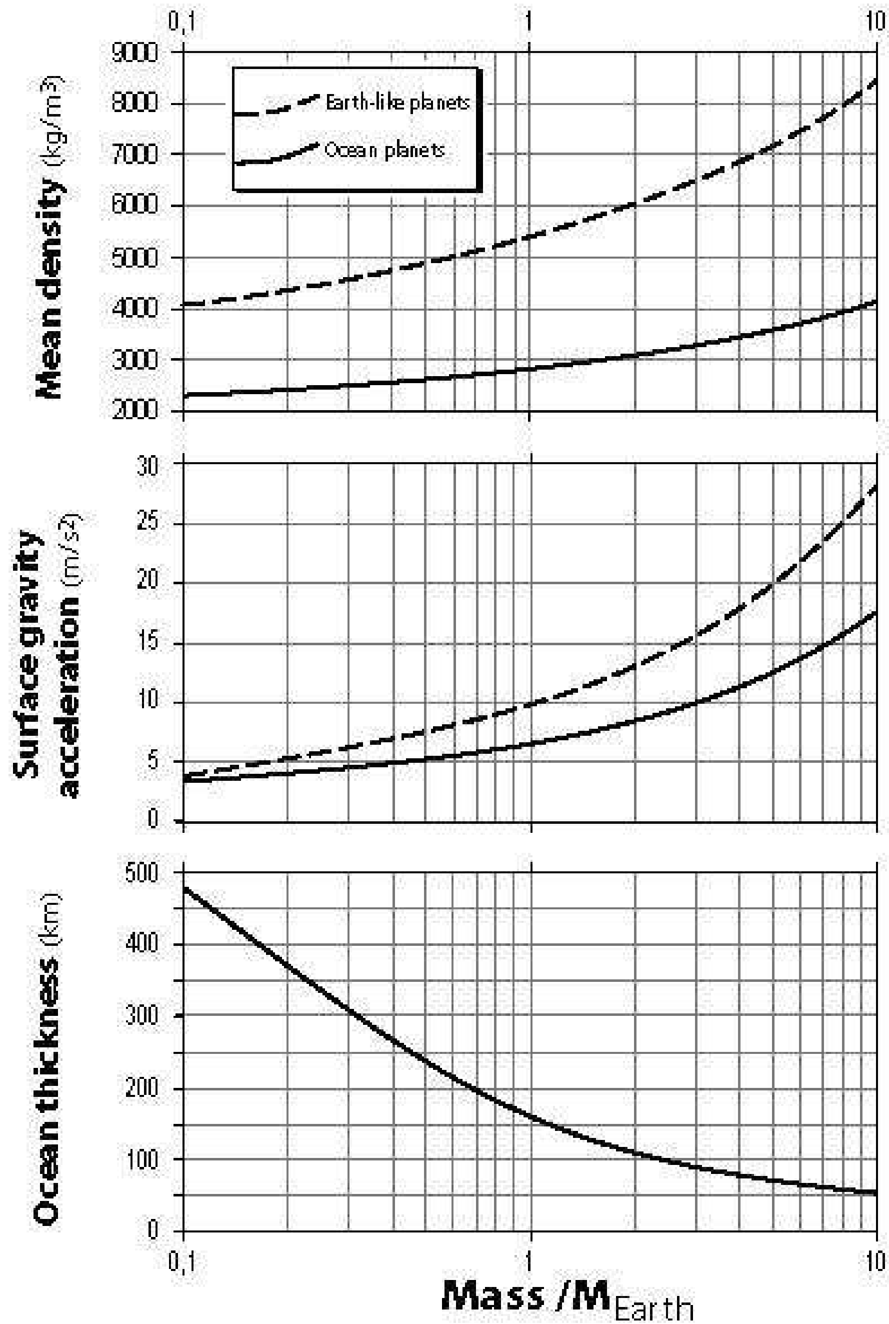


Other parameters

Mean density

Surface gravity

Ocean thickness is controlled by melting curve of ice VI – 50% H_2O. Surface T is 300 K.



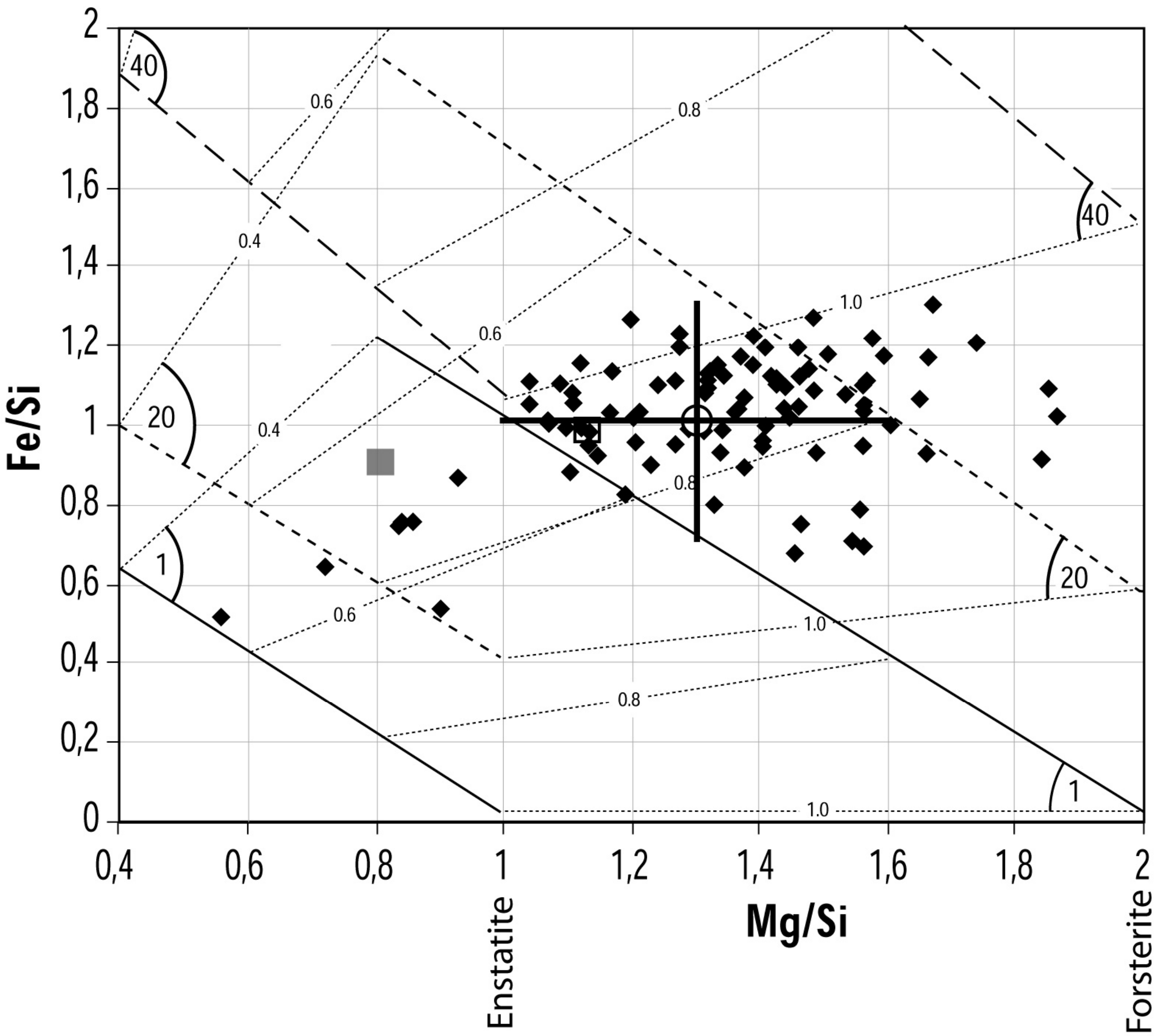
Sotin et al., 2007

Effect of composition

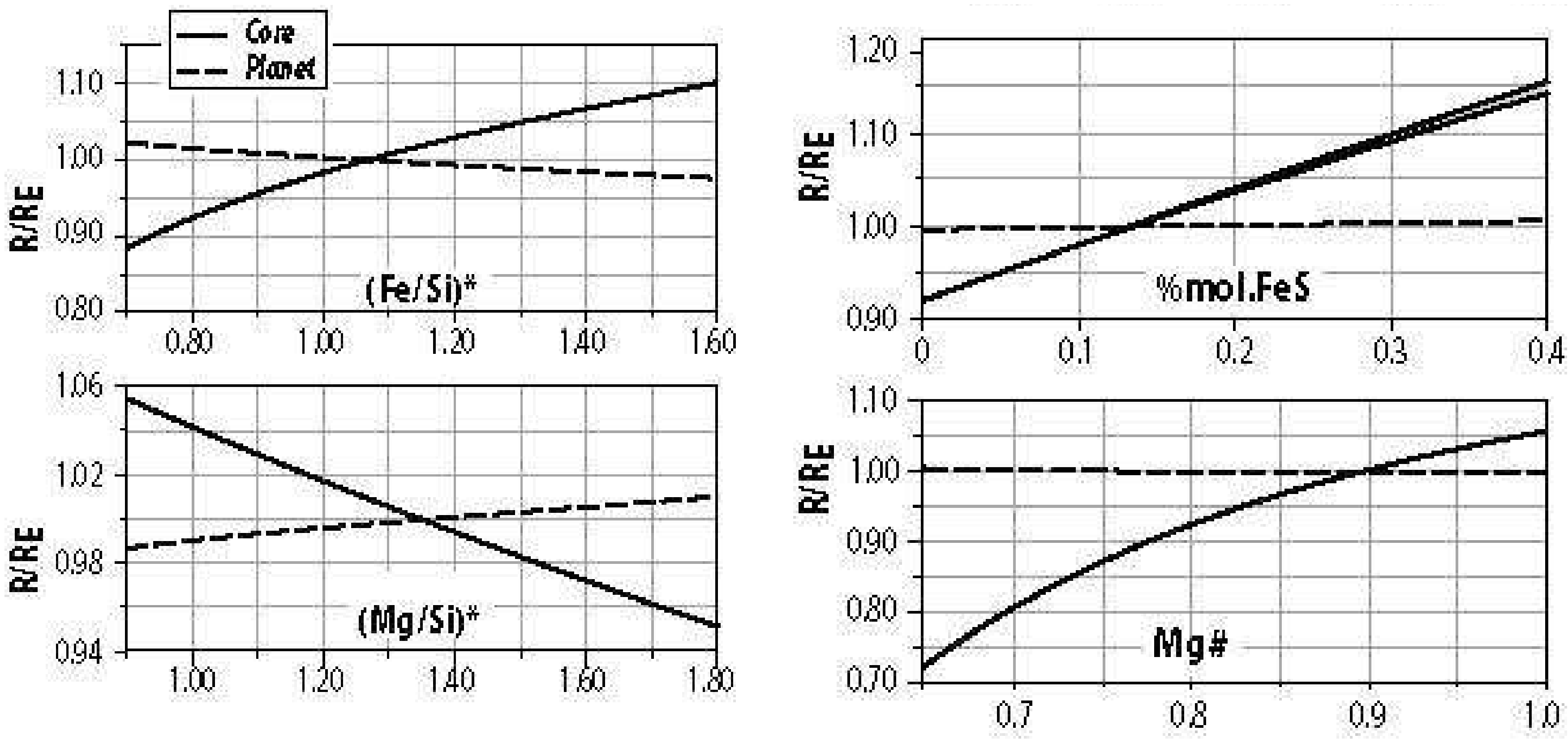
Composition:
Data from Beirao et al. (2006) and Gilli et al. (2006)

Empty square is solar composition.
Filled square is the enstatite end-member composition for the Earth's mantle.
Empty circle is the mean value of all the stellar compositions.
The large cross is typical uncertainties

Lines are values of Mg#
Areas give mass fraction of the core



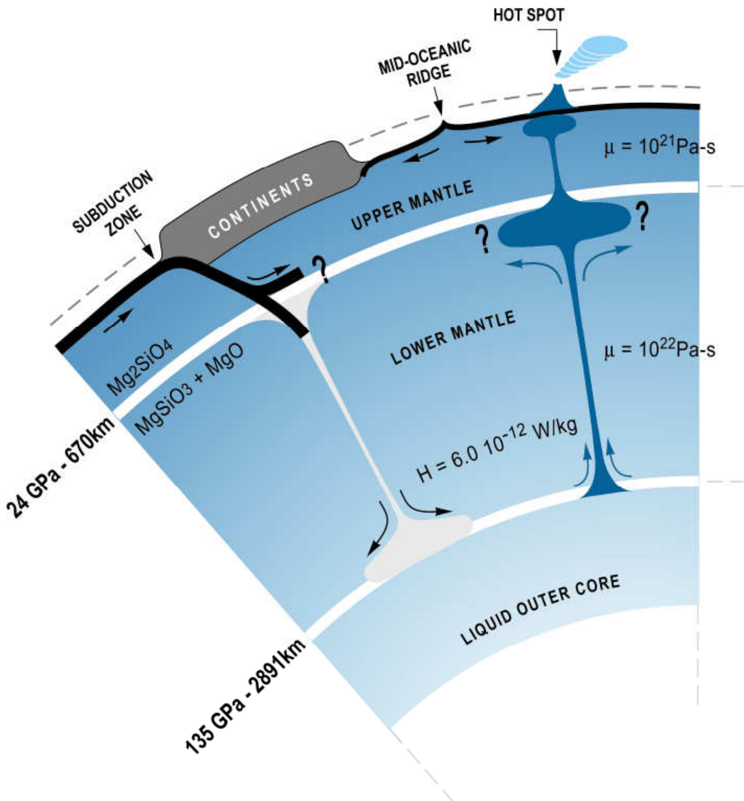
Radius versus composition (1 M_E < M < 10 M_E)



Total radius does not vary significantly with the composition or the partitioning of iron between the core and the mantle

The amount of Fe plays a significant role for the radius of the core which is supposed to be made of Fe/FeS

Abundances of other elements than Fe, Mg, Si, O

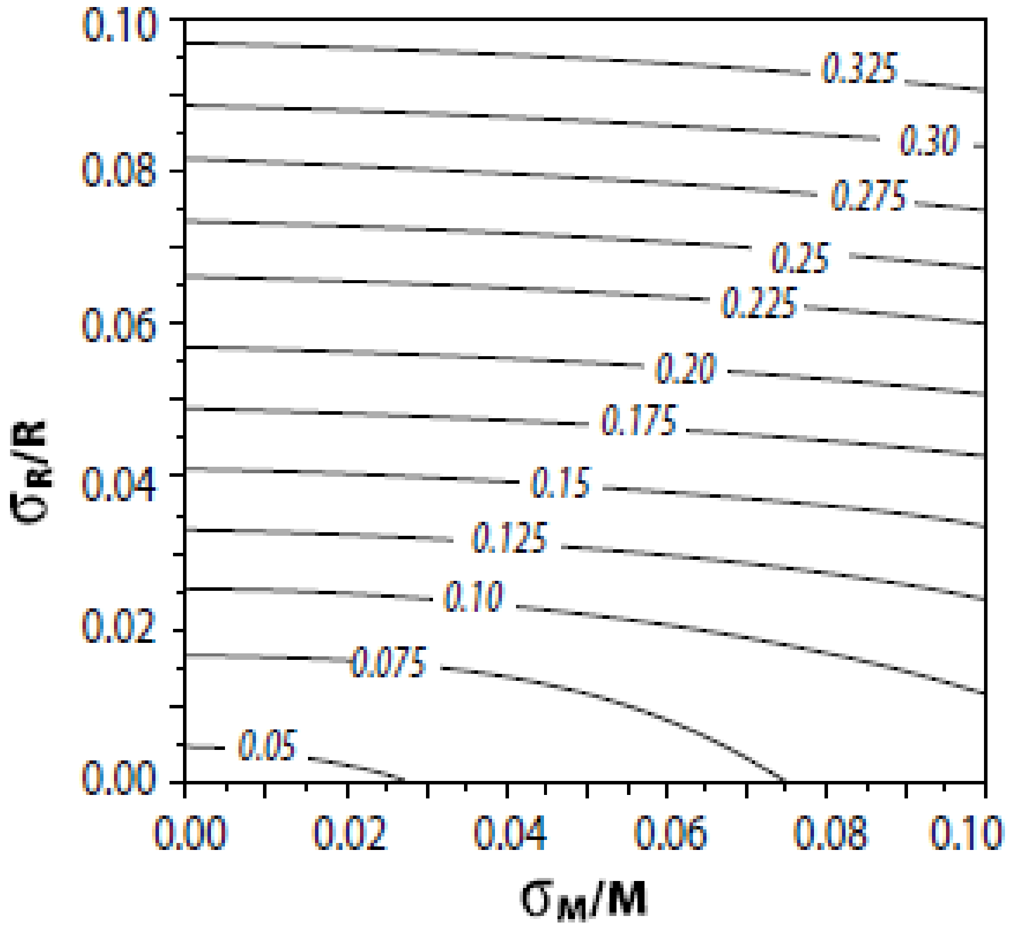


	EEH Earth model	PUM	LM	Core
O	30,28	44,76	43,8	1,61
Fe	33,39	5,89	12,69	80,25
Si	19,23	21,35	24,28	10,34
Mg	12,21	23,21	16,18	0
Total	**95,11**	**95,21**	**96,95**	**92,2**
Ni	2,02	0,25	0,71	4,99
Ca	1,01	2,32	1,2	0
Al	0,93	2,13	1,1	0
S	0,85	0,01	0,01	2,57
Total	**99,92**	**99,92**	**99,97**	**99,76**

O	30,28	44,76	43,8	1,61
Fe	35,41	6,14	13,4	85,24
Si	19,69	22,41	24,83	10,34
Mg	13,68	26,59	17,93	0

Core : Iron + light element (S, O, other).
Mantle : $(Mg,Fe)_2Si_2O_6$, $Ca(Mg,Fe)Si_2O_6$, $(Mg,Fe)_2SiO_4$ and Al phase / $(Mg,Fe)SiO_3$, $(Mg,Fe)O$ and Al phase

Uncertainty on the amount of water



Grasset et al., 2009

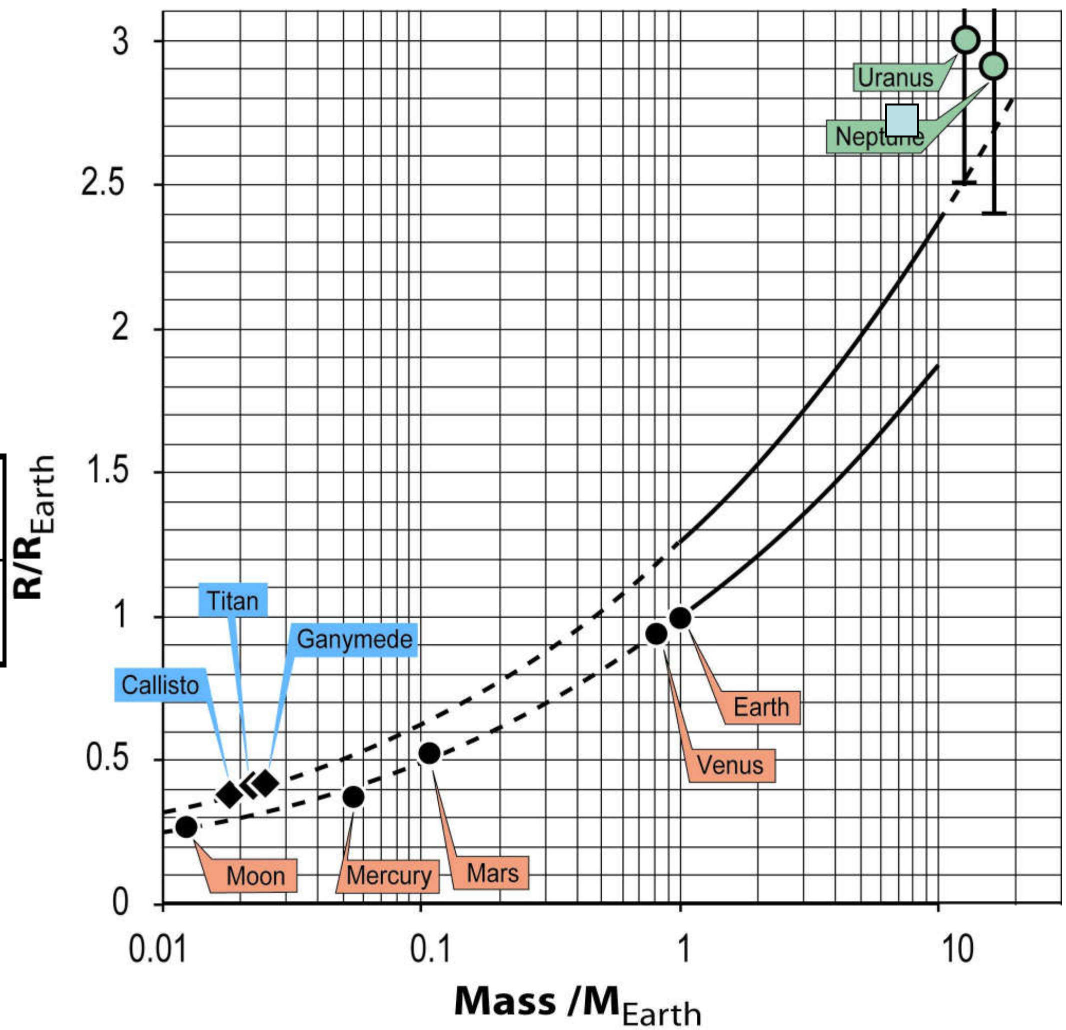
Results : Validation of the model – Solar system

$$\frac{R}{R_{Earth}} = \left(\frac{M}{M_{Earth}}\right)^{0.274}$$

	Earth-like		Ocean/Icy	
0.01-1	1.00	0.306	1.258	0.302
1-10	1.00	0.274	1.262	0.275

A planet with 50% water is 26% larger than a planet without water (for the same total mass)
The points Uranus and Neptune have 1 Earth radius of atmosphere removed.

GJ1214 has more than 50% ice in it



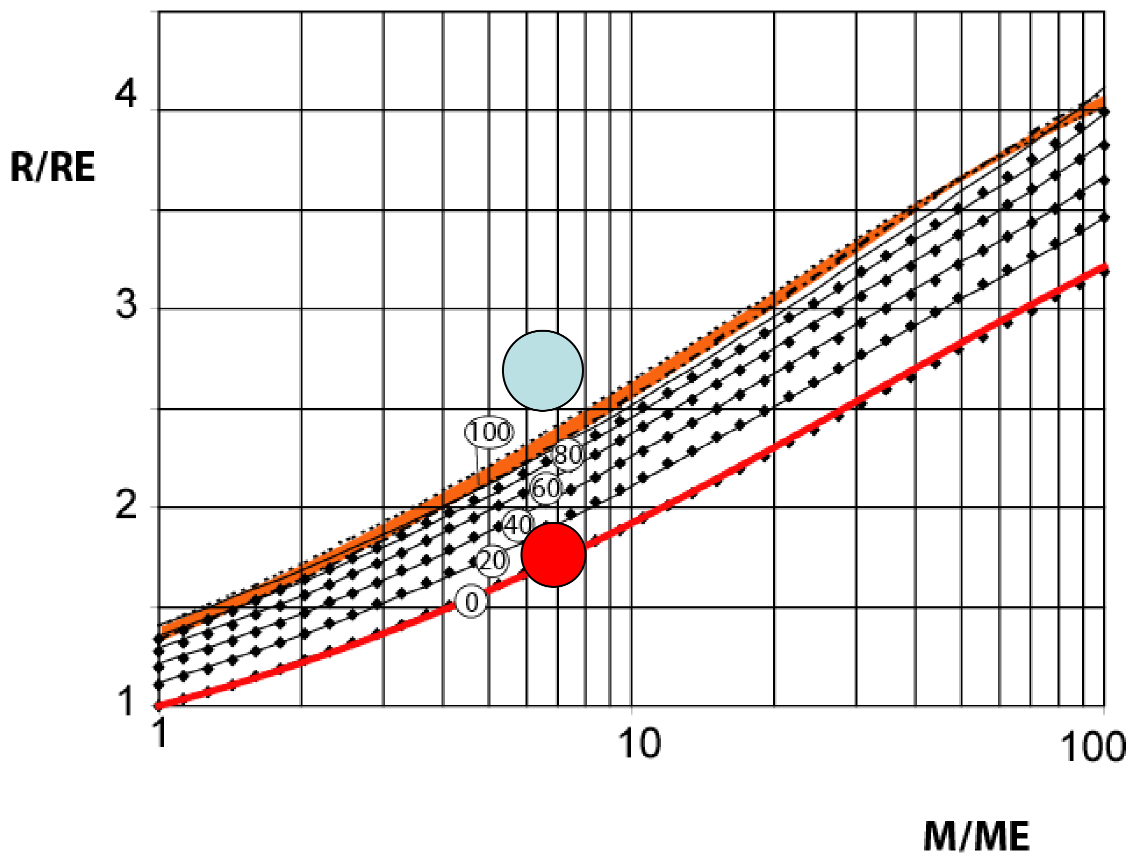
Extrapolation to larger planets with more water

$$\frac{R}{R_{Earth}} = \left(\frac{M}{M_{Earth}}\right)^{0.274}$$

Reference Case :

- **Fe/Si = 1.10 ***
- **Mg/Si = 1.25 ***
- **Mg# = 0.8**
- **H_2O: 0.01 wt %**

* Averaged from Gilli et al., A&A, 2006



$$\log\left(\frac{R}{R_E}\right) = \log(\alpha) + \left(\beta + \gamma \frac{M}{M_E} + \varepsilon \left(\frac{M}{M_E}\right)^2\right) \log\left(\frac{M}{M_E}\right)$$

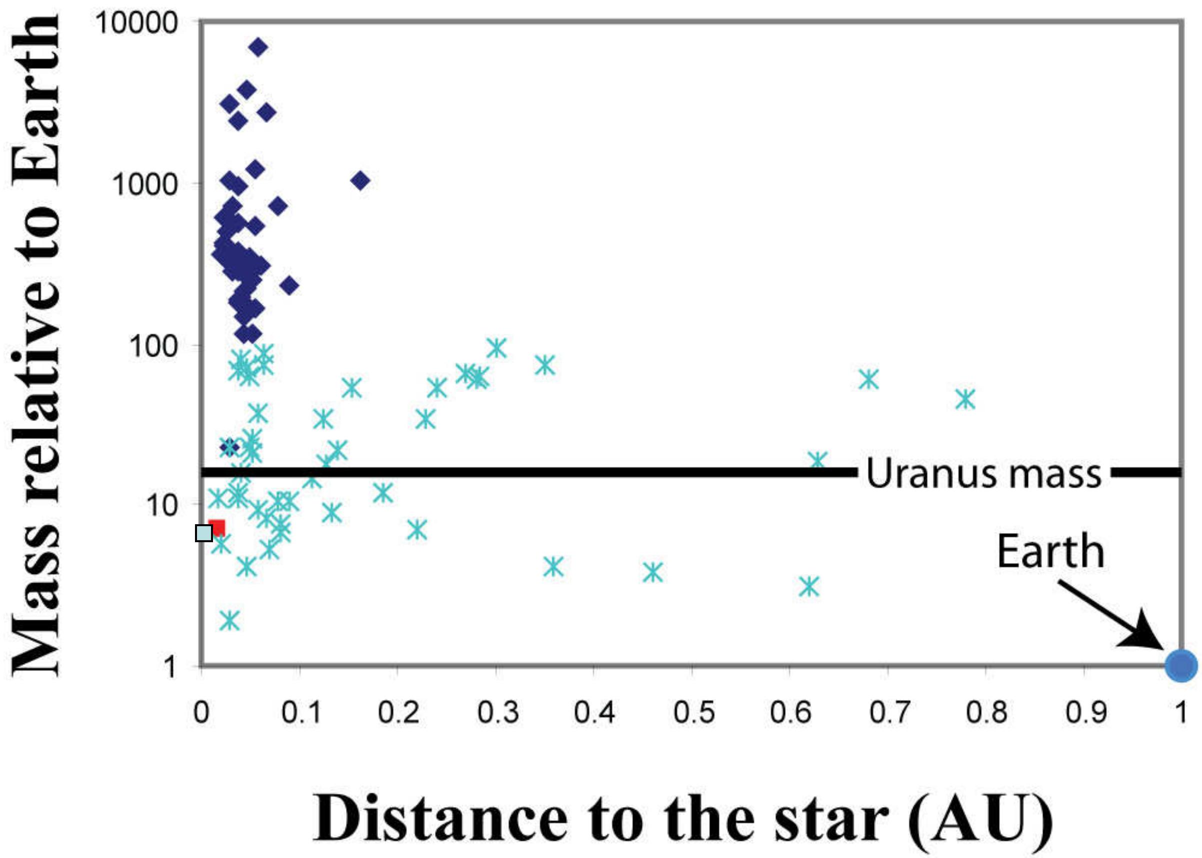
$$\xi = \sum_{i=0}^{2} \xi_i X_w^{i-1}$$

Each coefficient depends on the amount of water (X)

Grasset et al., 2009

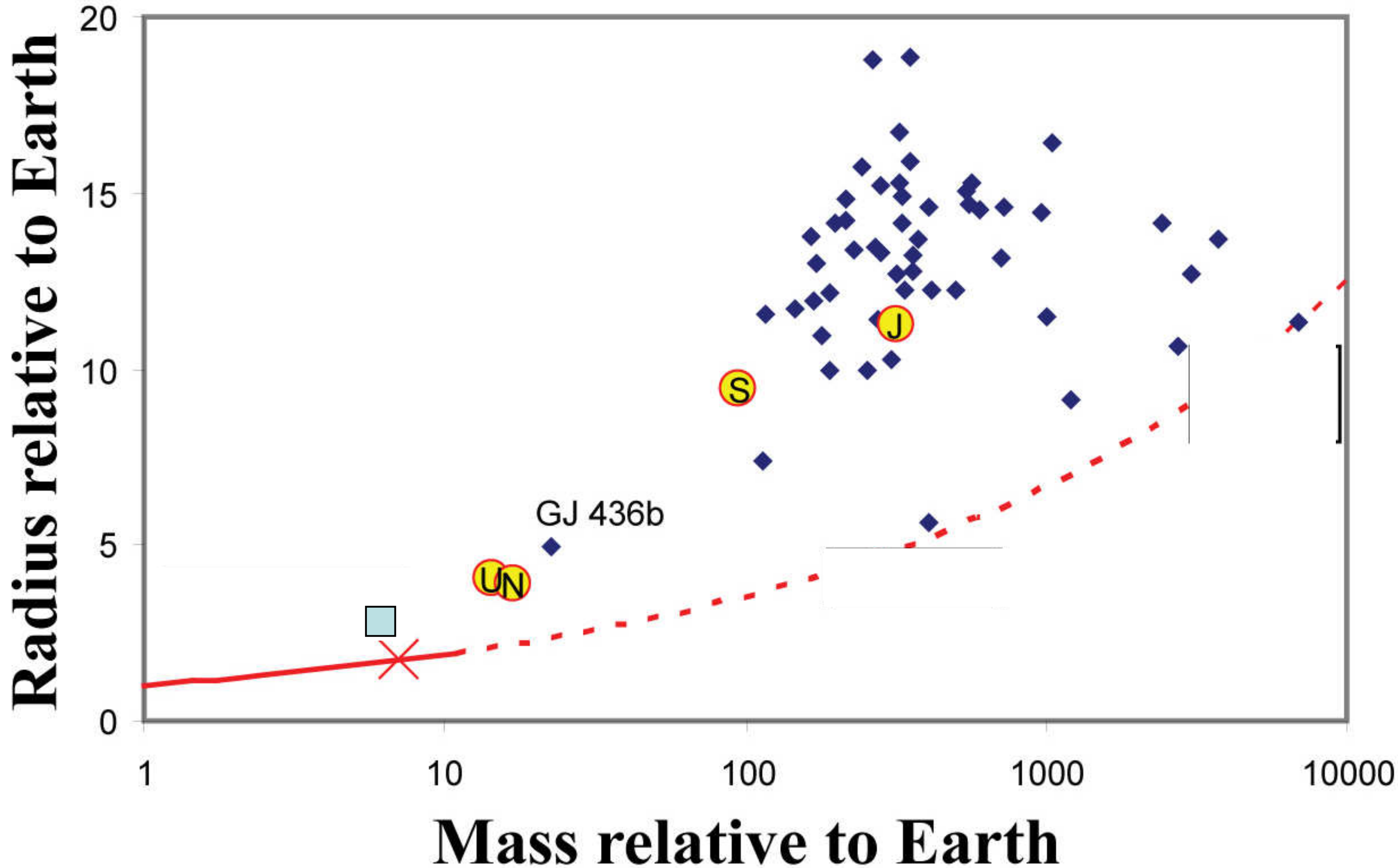
What is known about extra-solar planets?

Star, mass (M.sin(i)), distance to the star, radius, age, atmosphere, ….

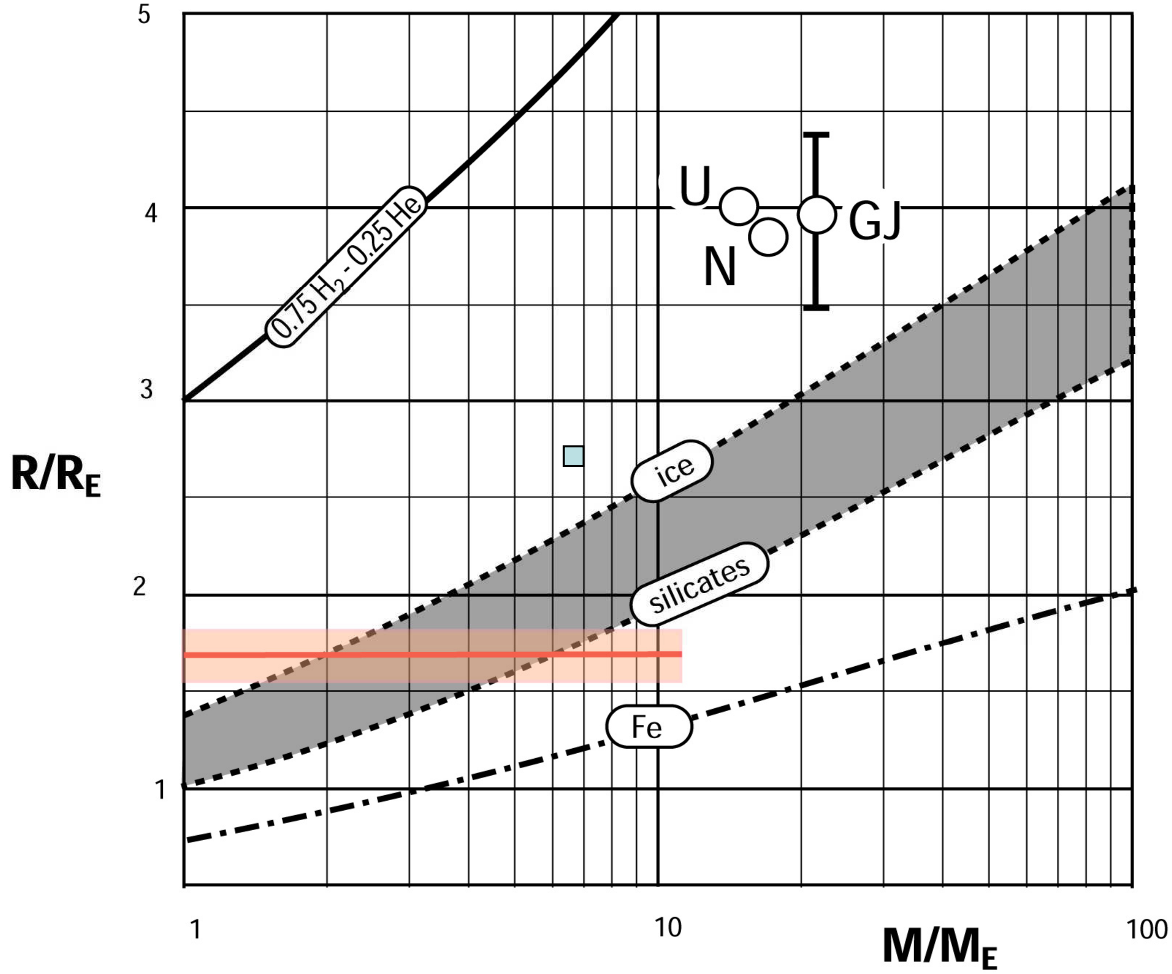


Radius – Mass

Keep track of the evolution on the determination of mass and radius



CoRoT Exo-7b & GJ1214b



Conclusions

- Better knowledge of solar system bodies is very important
  - •Interior structure of icy satellites
  - •Interior structure of icy giants
- For the same mass, the radius of an ocean planet with 50 %wt of ice is 26 % larger than that of a rocky planet.
- If mass and radius are perfectly known, the amount of water can be estimated at ± 4.4 % due to our lack of knowledge of temperature profile and elementary composition.
- If there is a 10% uncertainty on mass and radius, then the amount of water can be known at ± 35 %
- A planet with a large amount of water can be differentiated from a rocky planet in a (M,R) plot. But atmospheric composition (presence of H_2, He) must be known in order to make the difference between mini-Neptune and H_2O rich planets, the so-called ocean worlds.
- Corot7b and GJ1214b are on each side of the ocean worlds (M,R) domain. The discoveries of more exoplanets of those type will tell us whether ocean worlds may exist.