Introduction to exoplanetology

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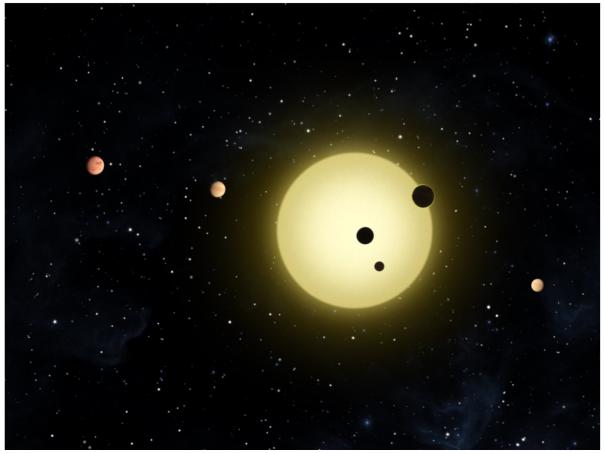
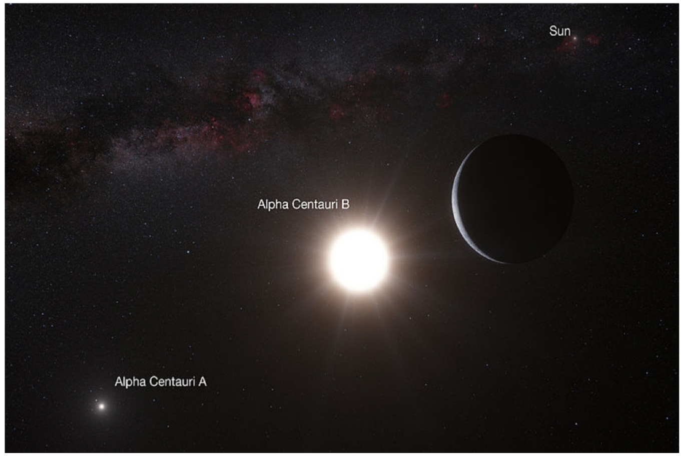
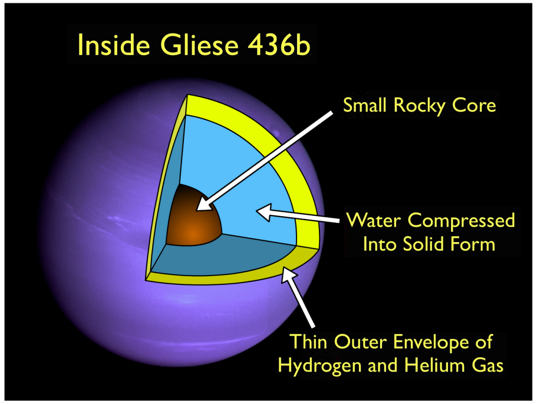
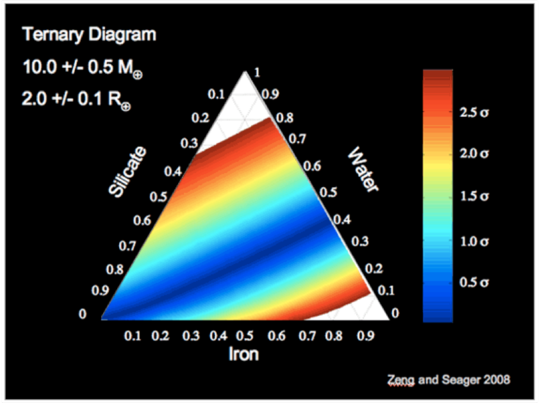


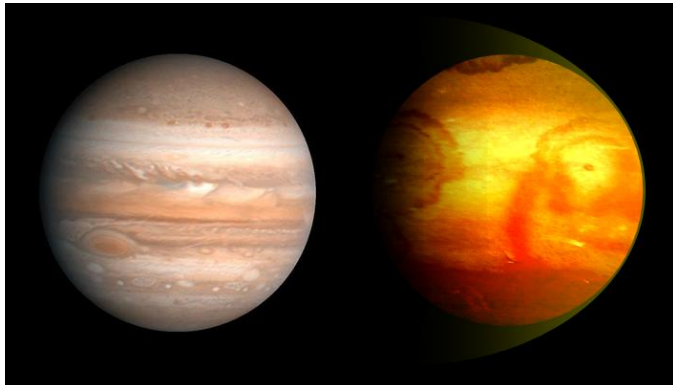


Introduction to exoplanetology. IX.

Structure and atmosphere of exoplanets







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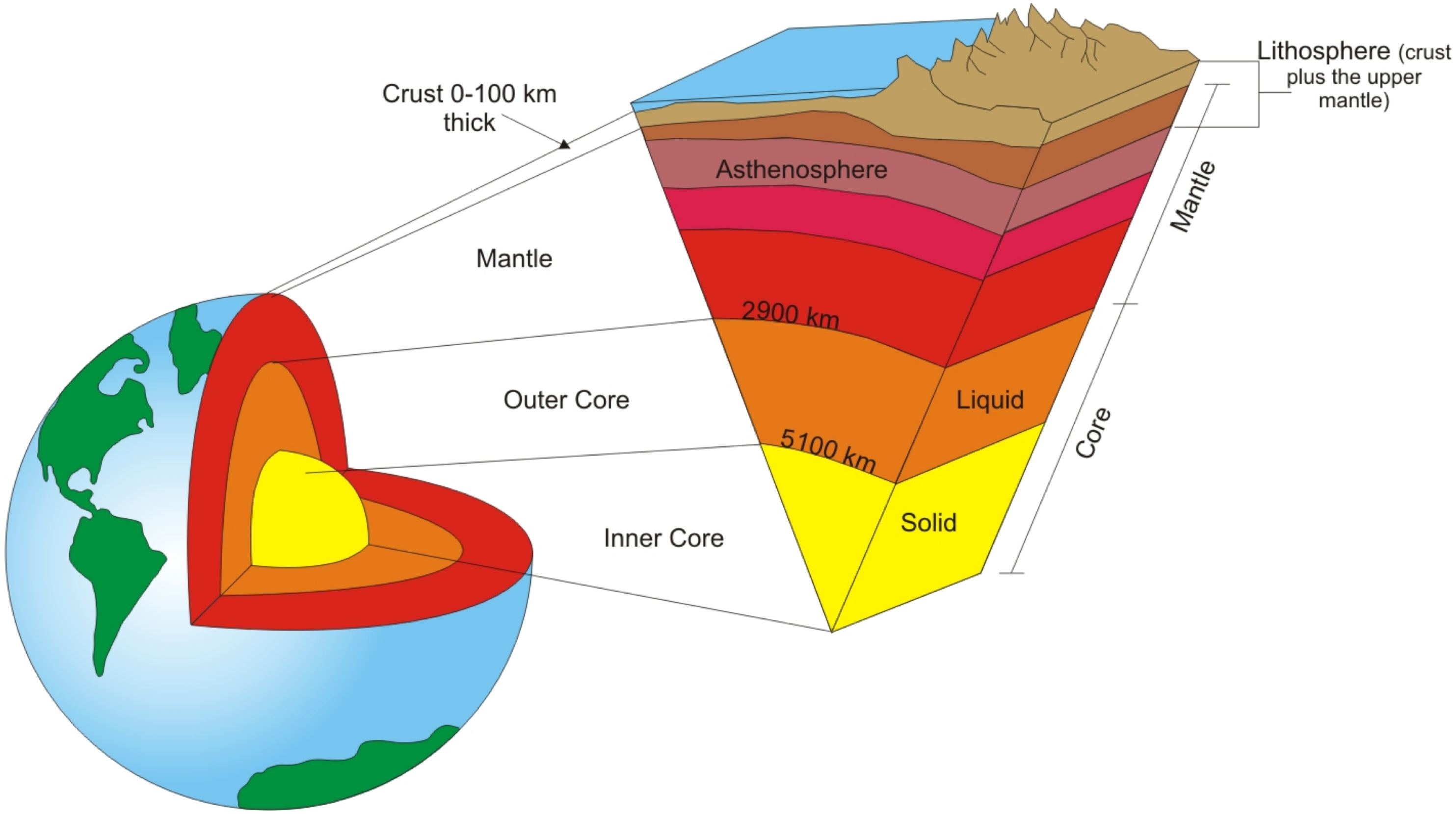
Internal structure of terrestrial planets

1. Earth

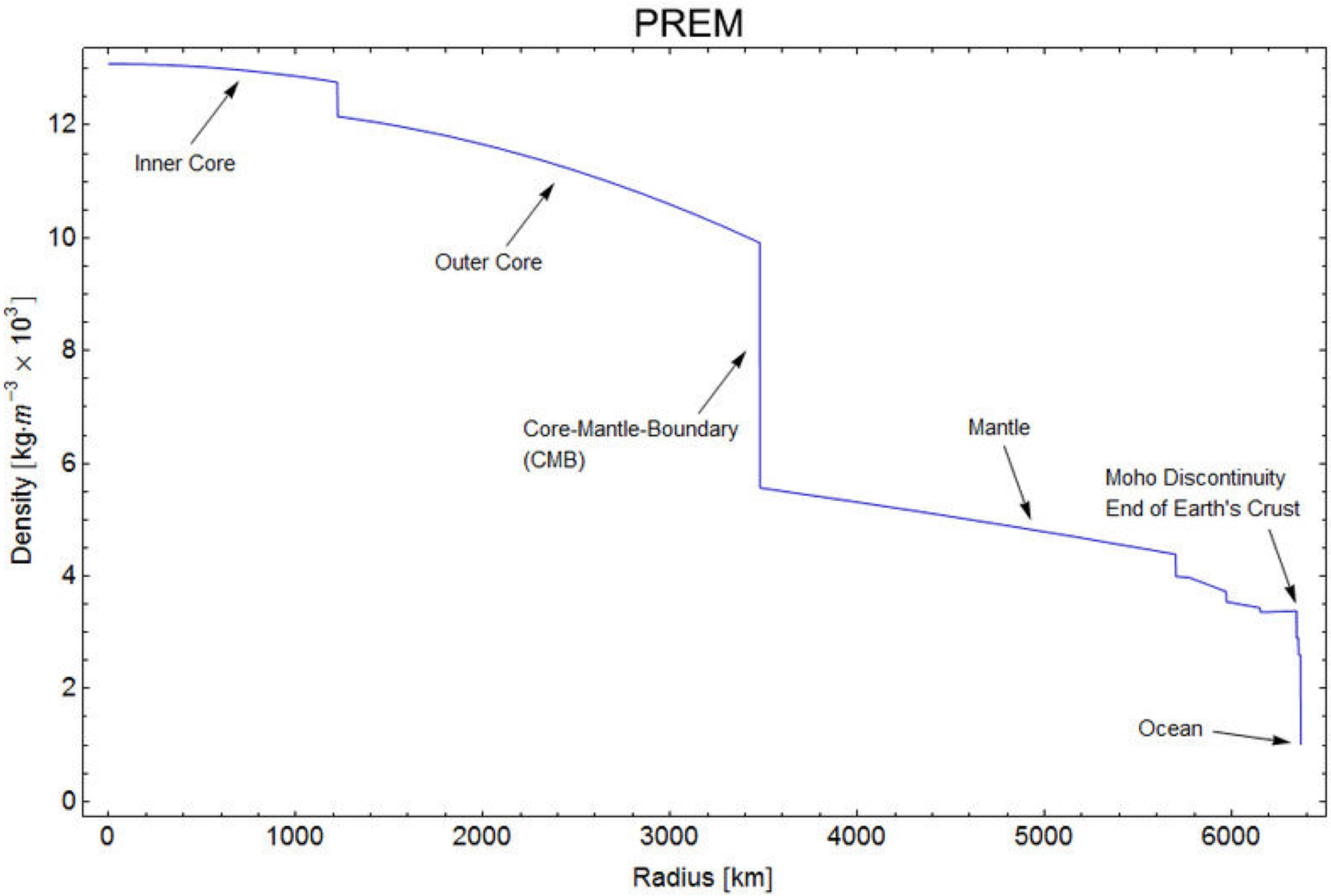
Differentiated structure:

Crust of silicates, viscous mantle of silicates enriched with Fe, outer + inner core of Fe



Internal structure of terrestrial planets

1. Earth

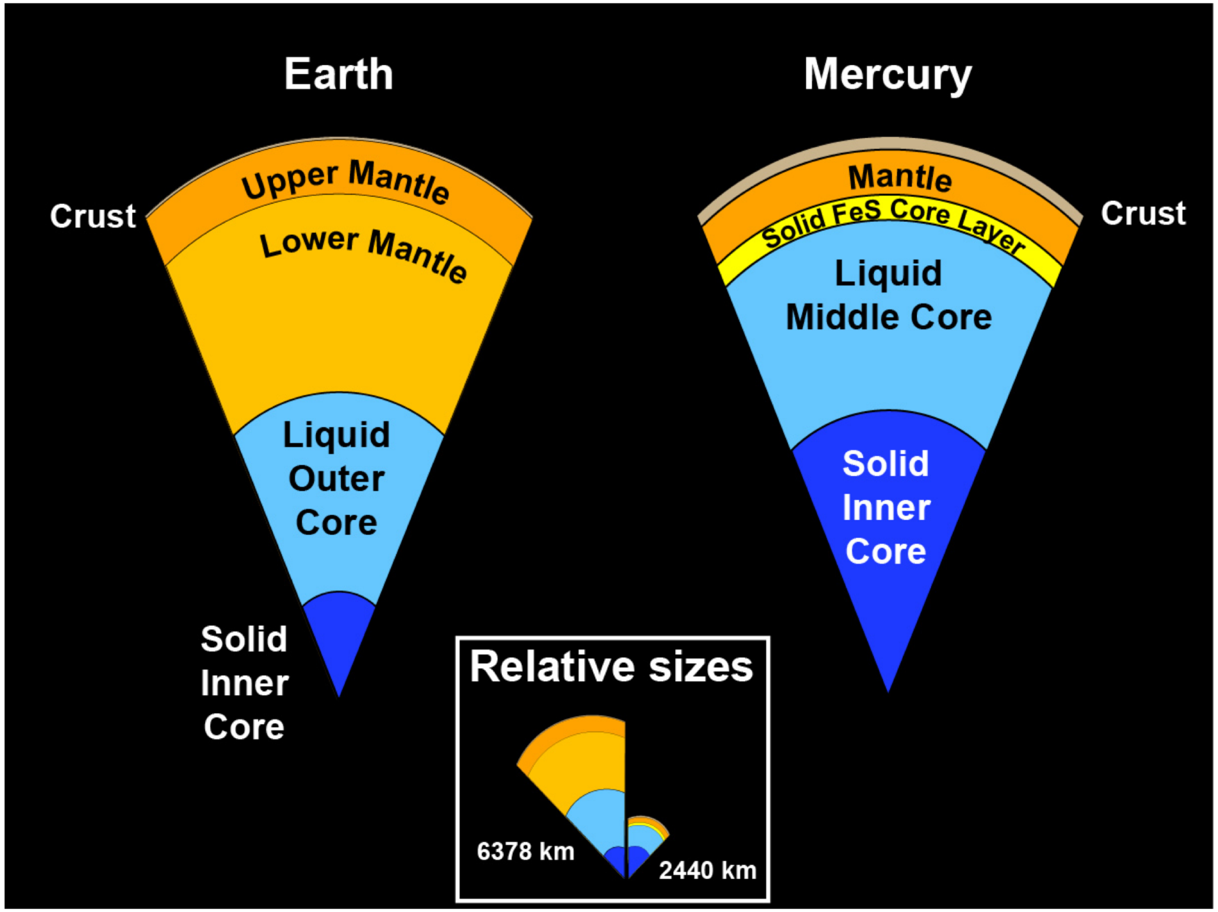


Internal structure of terrestrial planets

2. Mercury

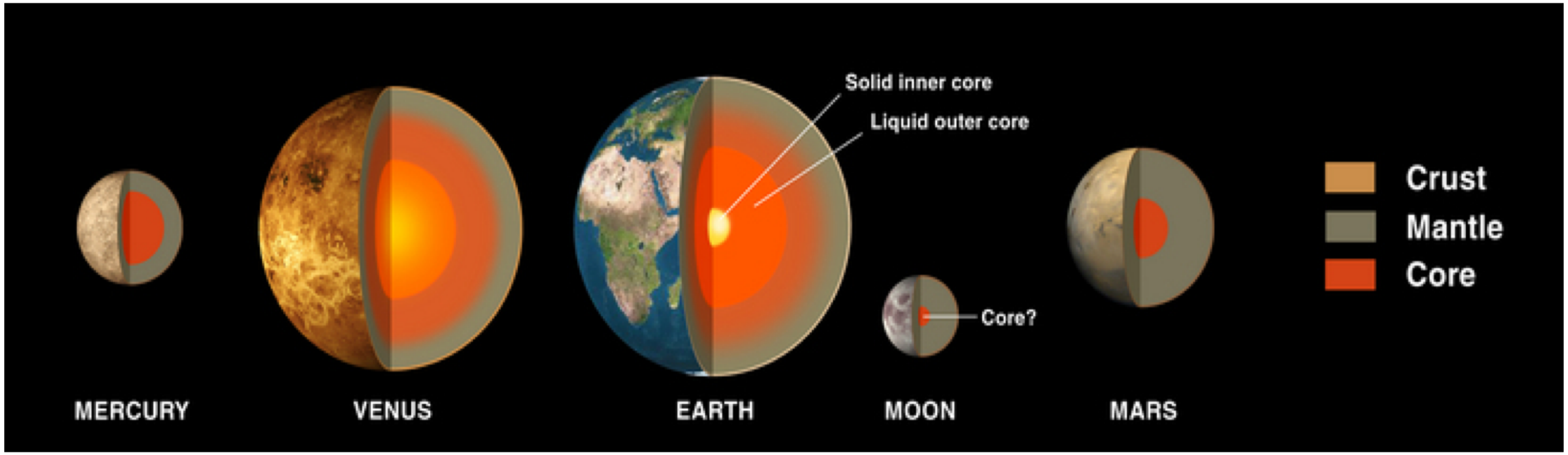
Significantly enriched in Fe compared to Earth

Origins? Maybe a giant impact having stripped out the planet of its outer shells *(Benz et al. 1988)*



Internal structure of terrestrial planets

3. Mars, Venus, and the Moon



Differentiated structure: core – mantle - crust

Plate tectonics	no	no	yes	no	no
Volcanism	no	yes?	yes	no	no
Magneto-sphere	yes	no	yes	no	no

Internal structure of terrestrial planets

Elementary composition of the Earth

O: 30.3%
Fe: 33.4%
Si: 19.2%
Mg: 12.2%
Total: 95.1%

+

Ni: 2.0%
Ca: 1.0%
Al: 0.9%
S: 0.9%
Total = 4.8%

+

rest… 0.1%

Including other elements than **O, Fe, Si, Mg** changes the results of the models at a level <1%

Basic assumptions of terrestrial planet models
Planet composed of 2 basic components: Fe and silicates
Differentiated structure, with different elementary compositions for each layer

Earth: core, lower and upper mantle
crust? Negligeable. Same for *hydrosphere* and *atmosphere*

Internal structure of terrestrial planets

General structure equations of a planetary model

$$\frac{\partial P}{\partial r} = -\rho g$$

Hydrostatic equilibrium

$$\frac{\partial T}{\partial r} = \frac{\partial P}{\partial r}\frac{T}{P}\frac{dlnT}{dlnP}$$

Thermodynamic equilibrium

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

Mass conservation

$$\frac{\partial L}{\partial r} = 4\pi r^2 \rho \left(\dot{\epsilon} - T\frac{\partial S}{\partial t}\right)$$

Energy conversation

$$\rho_i = f_i(P,T)$$

Equation of state (1 per layer)

+ boundary conditions

Internal structure of terrestrial planets

Modeling

Are assumed a planetary mass
O/Si, Fe/Si, Mg/Si, and Mg# = (Mg/Mg+Fe)$_{\text{silicates}}$
N layers
an elementary division for each layer (core: only Fe)

Elementary composition -> mineralogical composition

Structure equations

1. Mass conversation

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

with ρ(r) depends on the local composition, T and P

Internal structure of terrestrial planets

2. Thermodynamic equilibrium (energy transfert)

Planetary interiors: transfer dominated by convection

$$\frac{\partial T}{\partial r} = \frac{\partial P}{\partial r}\frac{T}{P}\frac{d\ln T}{d\ln P} \quad \text{with} \quad \frac{dT}{dP} = \frac{\alpha T}{\rho C_p}$$

For each layer, allowing for discontinuities at the junctions

with α the thermal expansion coefficient (K^{-1}) and C_p is the thermal capacity (J/K)

3. Hydrostatic equilibrium

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

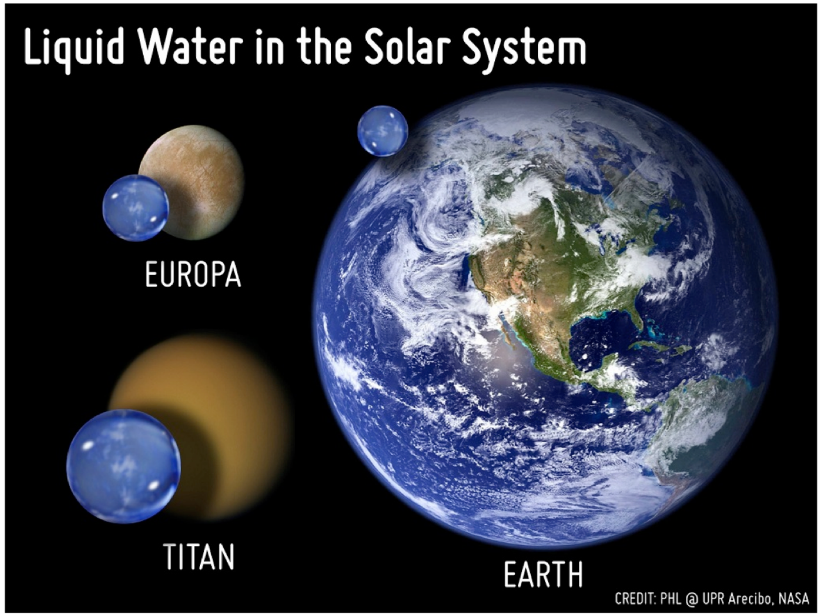
4. Equation of state (EOS)

$$\rho_i = f_i(P,T)$$

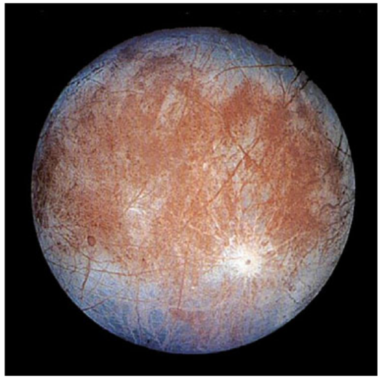
Well calibrated for Earth-mass planets, but not so much for super-Earths, for which pressures can be > TPa

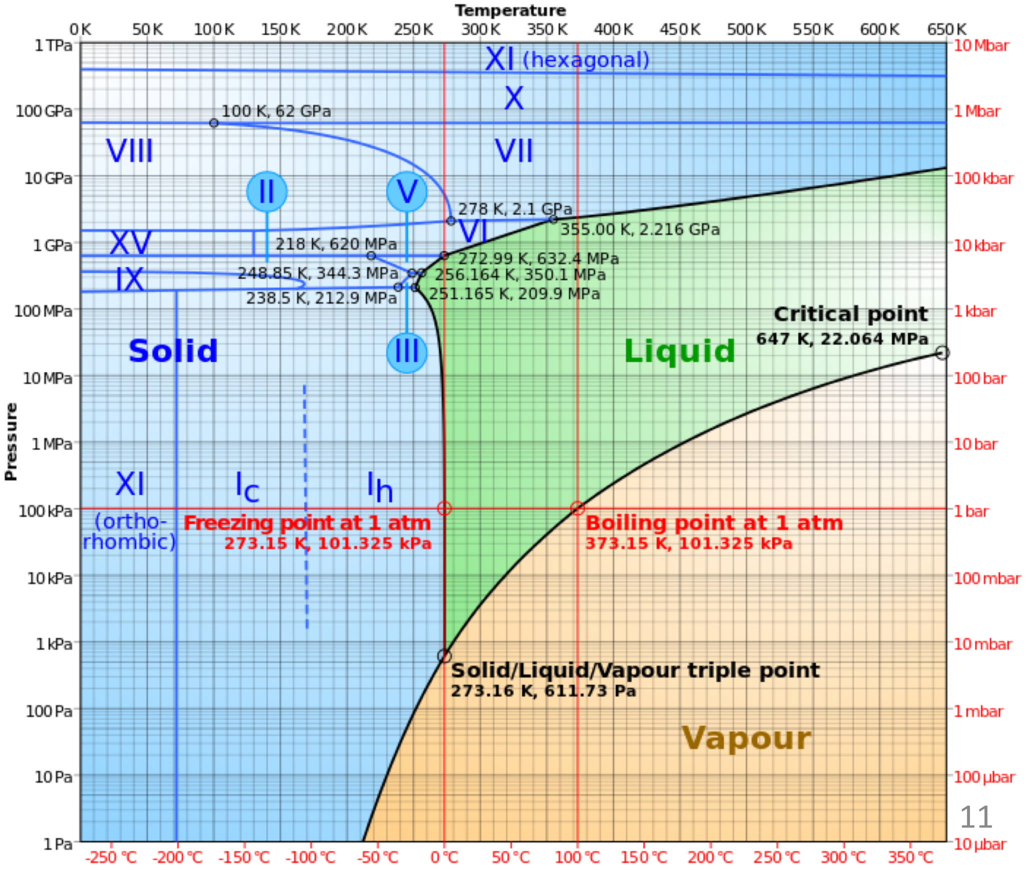
Internal structure of terrestrial planets

Ocean planet: external layer of water



CREDIT: PHL @ UPR Arecibo, NASA





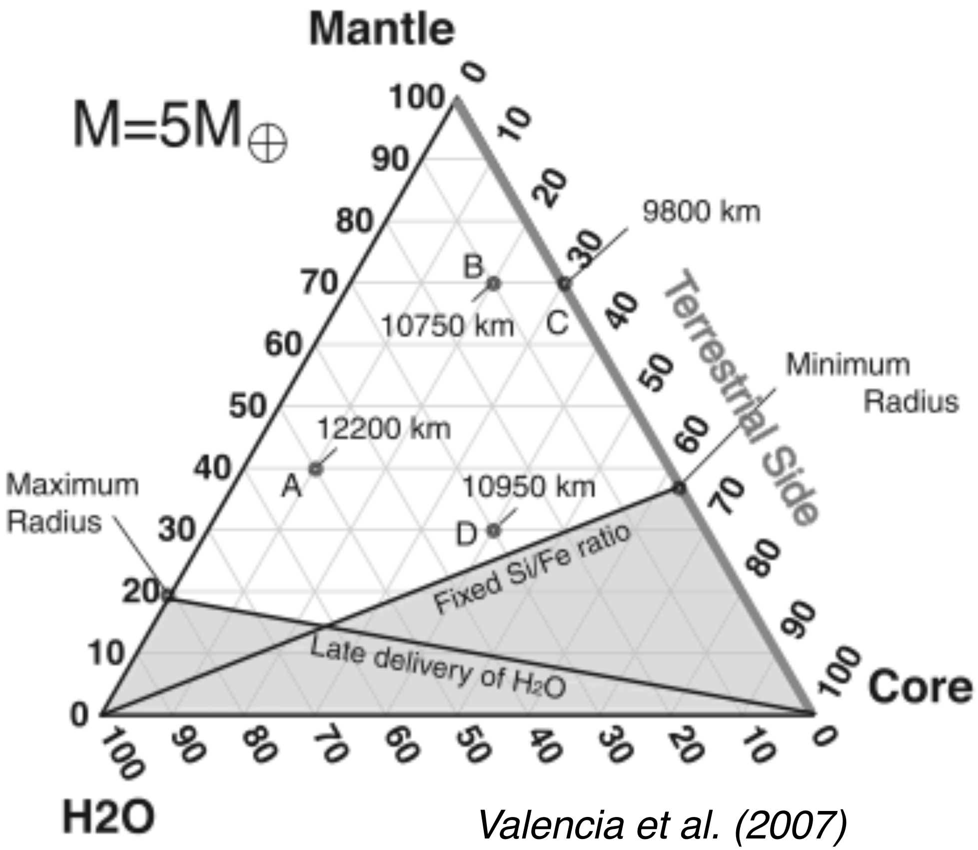
Water ice of type VII and X

Liquid water layer?

External thin layer of water ice of type I? (cold enough planet)

Internal structure of terrestrial planets

Ternary diagram



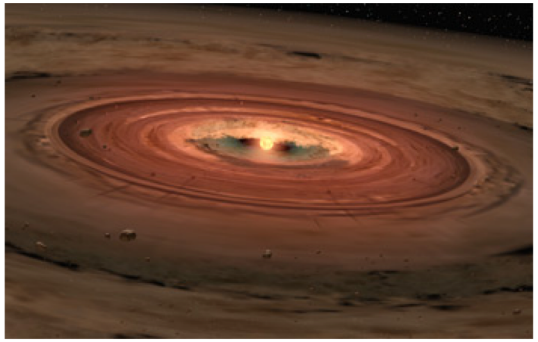
Valencia et al. (2007)

With M_p and R_p, the structure of the planet can't be unambiguously determined

Assume initial conditions: **combining planetary and disk models?**

Internal structure of terrestrial planets

Good idea a priori, but….



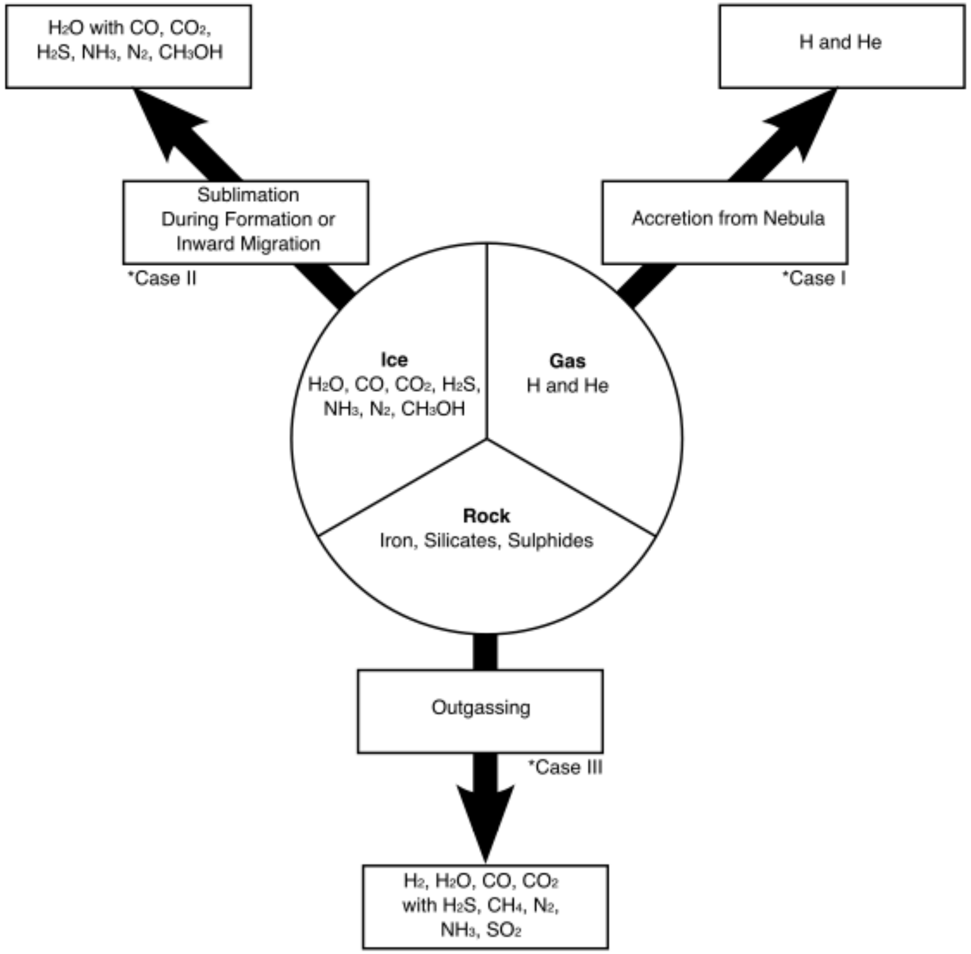
Planets can migrate by planet-disk, planet-planet, and planet/star interactions

Collisions can significantly alter the planetary compositions (Mercury, Moon + Earth)

The evaporation of the external layers des should be significant for close-in planets

Internal structure of super-Earths

Additional degeneracy: possible massive gas envelope



H_2O with CO, CO_2, H_2S, NH_3, N_2, CH_3OH

H and He

Sublimation During Formation or Inward Migration

*Case II

Accretion from Nebula

*Case I

Ice
H_2O, CO, CO_2, H_2S, NH_3, N_2, CH_3OH

Gas
H and He

Rock
Iron, Silicates, Sulphides

Outgassing

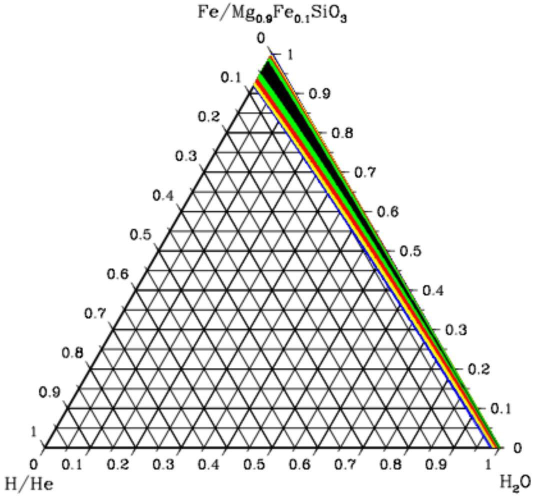
*Case III

H_2, H_2O, CO, CO_2 with H_2S, CH_4, N_2, NH_3, SO_2

Rogers & Seager (2010)

Origins ?

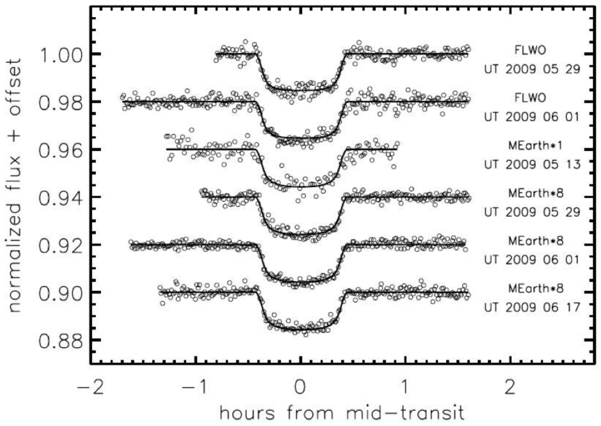
❑Outgassing during formation
❑Volcanism
❑Sublimation of surface layers (ices, rocks for very irradiated planets)
❑Accretion of H/He
❑Impacts



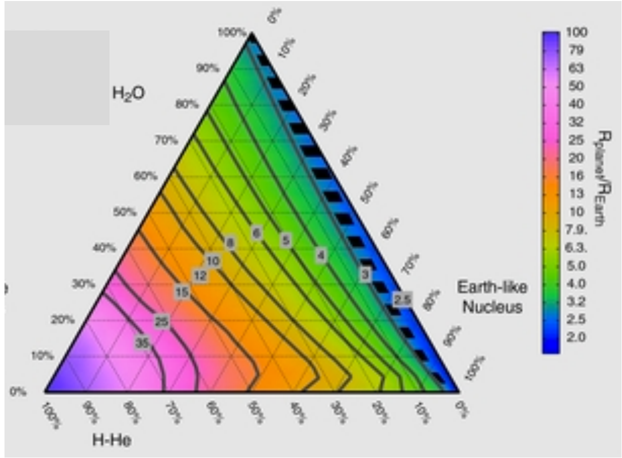
Internal structrure of terrestrial and super-Earth planets

Solution: precise measurement of M_p and R_p AND study of the atmosphere

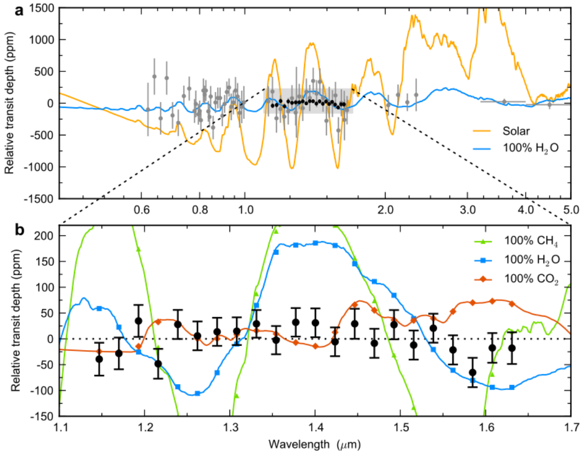
Ex: GJ1214b



Charbonneau et al. (2009)

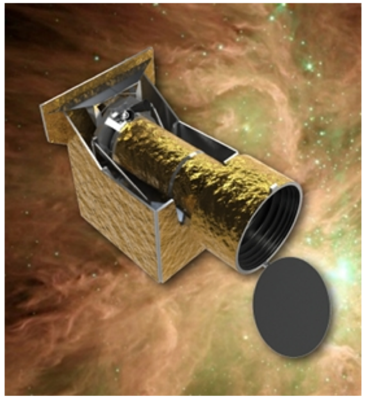


Valencia et al. (2013)



Kreidberg et al. (2014)

Target nearby stars!



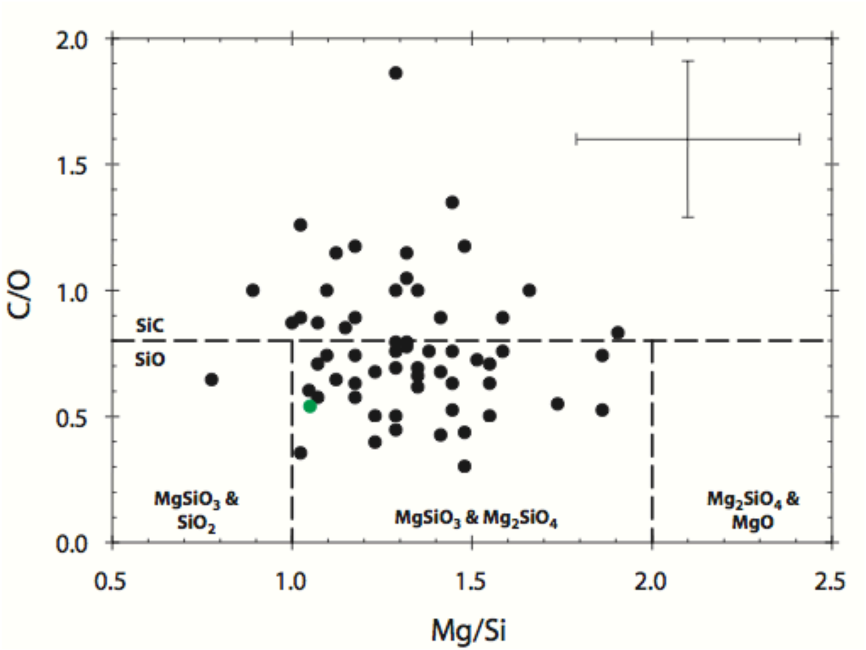
CHEOPS

TESS

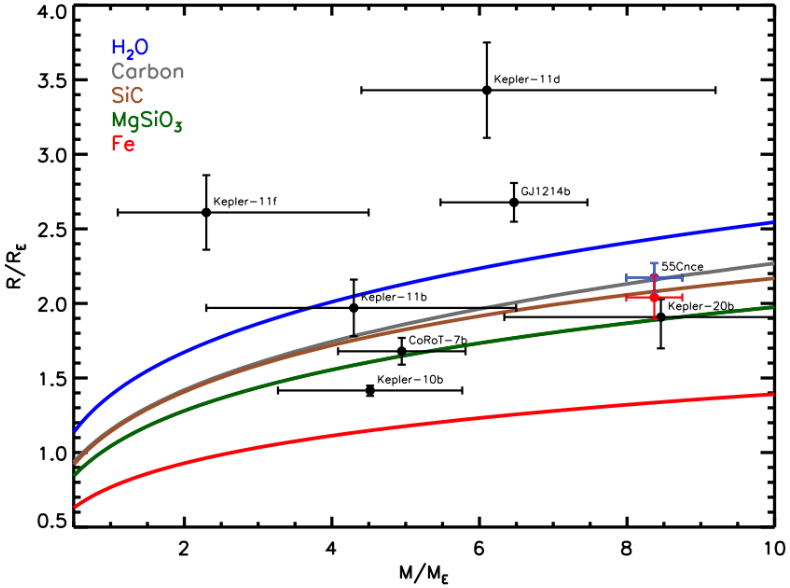
SPECULOOS

Carbon planets

If C/O doubled compared to solar value in the protoplanetary disk, most silicates would be replaced par silicon carbides and other carbon components *Kuchner & Seager (2007)*



Bond et al. (2010)

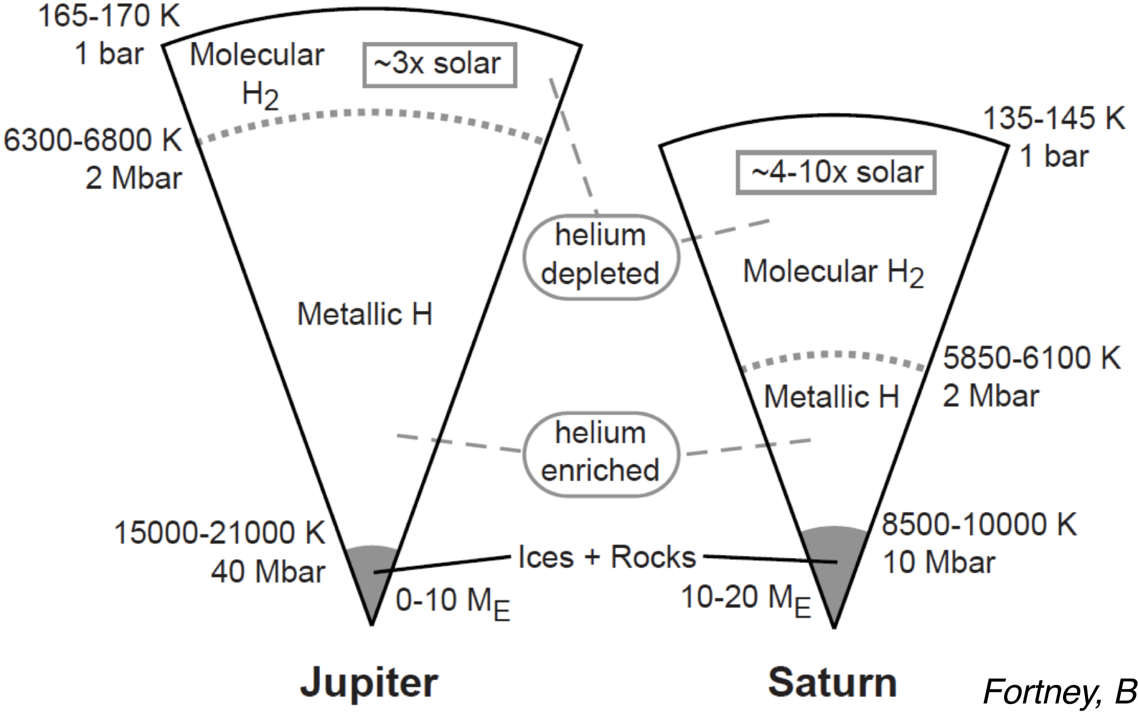


Madhusudhan et al. (2012)

C/O increases with Fe/H and towards the center of the Galaxy

Internal structure of giant planets

Jupiter and Saturn

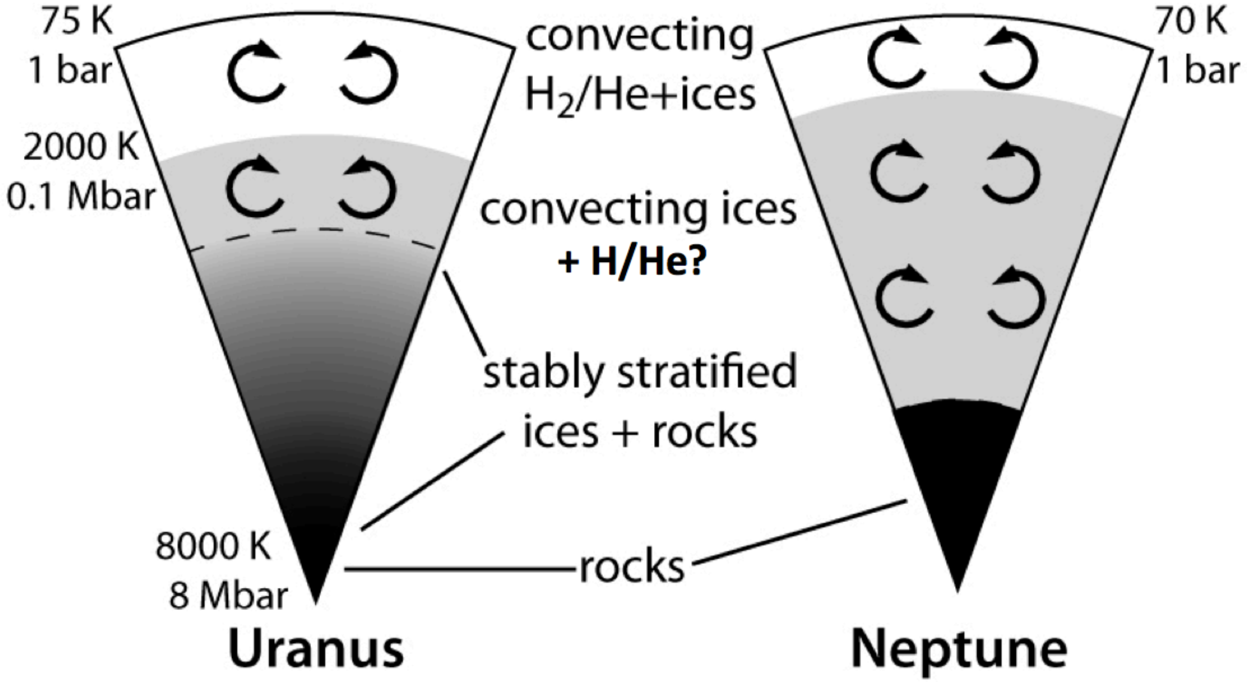


Fortney, Baraffe, & Militzer (2010)

Metallic hydrogen: trellis of protons with a spacing << Bohr radius (degenerate matter), uncoupled of the electrons ➔ highly conductor (heat and electricity). Required pressure: ~2 MBar
Coupled to Jupiter's rotation ➔ strong magnetic field

Internal structure of giant planets

Uranus and Neptune



Fortney, Baraffe, & Militzer (2010)
“Exoplanets” book, Arizona Space Science Series

External H-He envelope = 5-10% of the mass of the planet, 10–20% of the radius

Internal structure of giant planets

Giant planet model

First approximation : are neglected the magnetic field, the rotation, and the radiative pressure ➔ fluid object supported by gravity and gas pressure

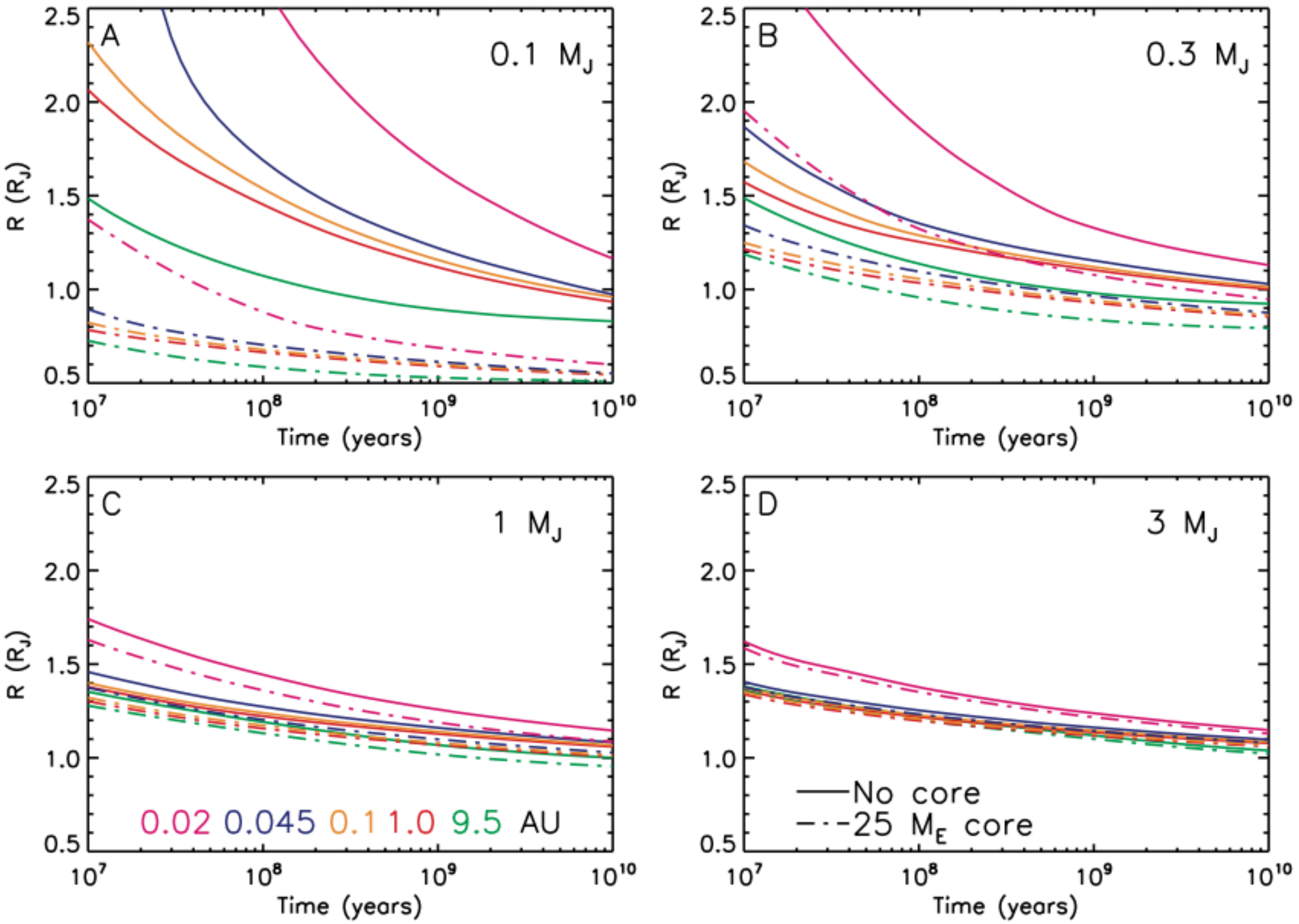
Equations

Same as for a terrestrial planet **+ energy conservation equation**

$$\frac{\partial L}{\partial r} = 4\pi r^2 \rho \left(\underbrace{\dot{\epsilon}}_{\text{Energy source (planetesimal accretion + host star irradiation + tidal heating)}} - \underbrace{T \frac{\partial S}{\partial t}}_{\text{Energy loss (emission)}} \right)$$

Internal structure of giant planets

Evolution of the radius of an irradiated giant planet



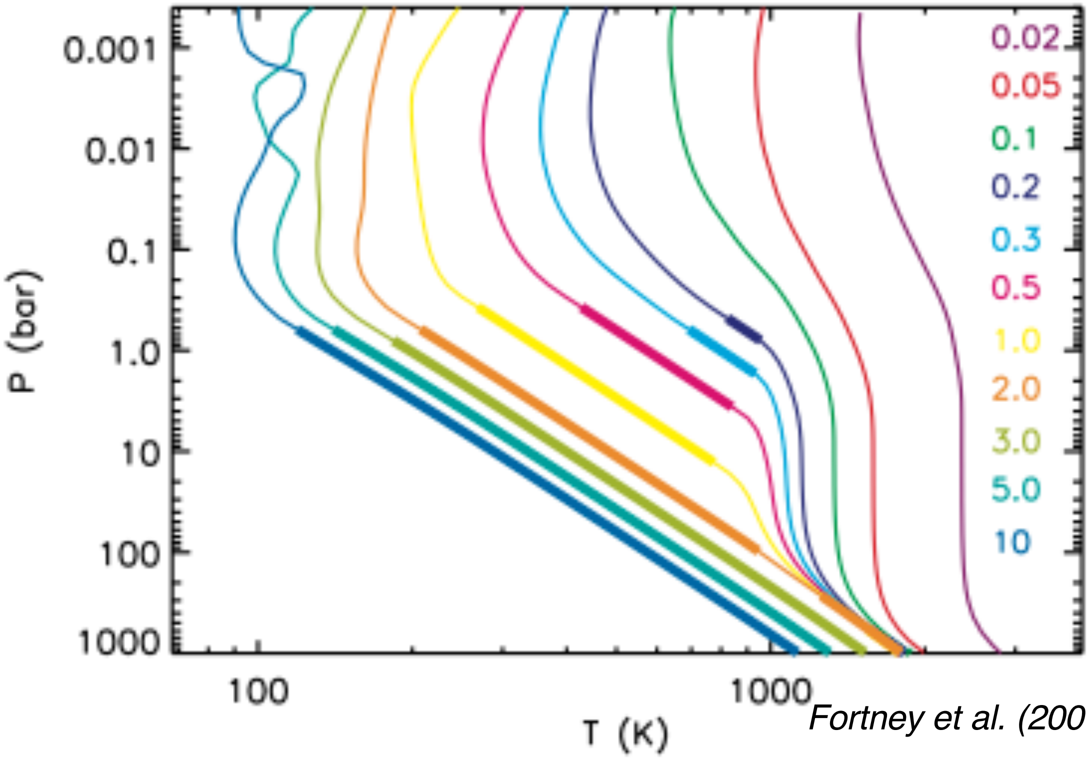
Fortney et al. (2007)

Internal structure of giant planets

Thermal evolution and connection interior-atmosphere

The atmosphere is the bottleneck that controls the deposit (irradiation) and the release of the energy.

The structure model must be coupled to an atmospheric model



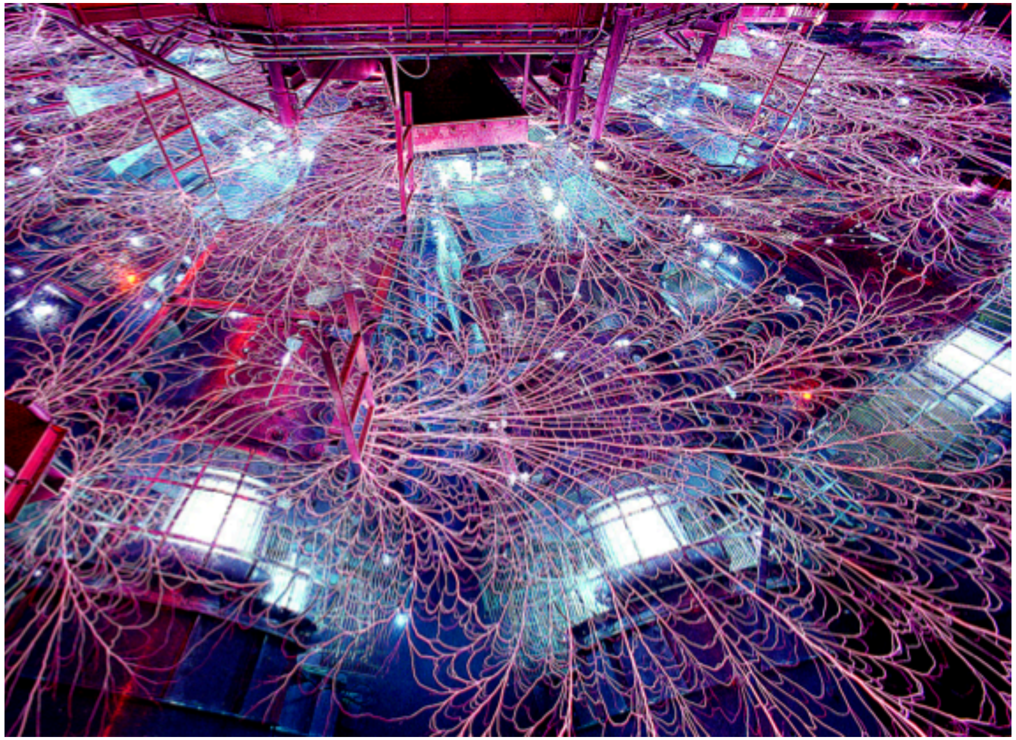
Fortney et al. (2007)

P-T profiles for 4.5 Gy Jupiter-like planets

Thick line = convective regions

Internal structure of giant planets

Equation of state at very high pressure and temperature



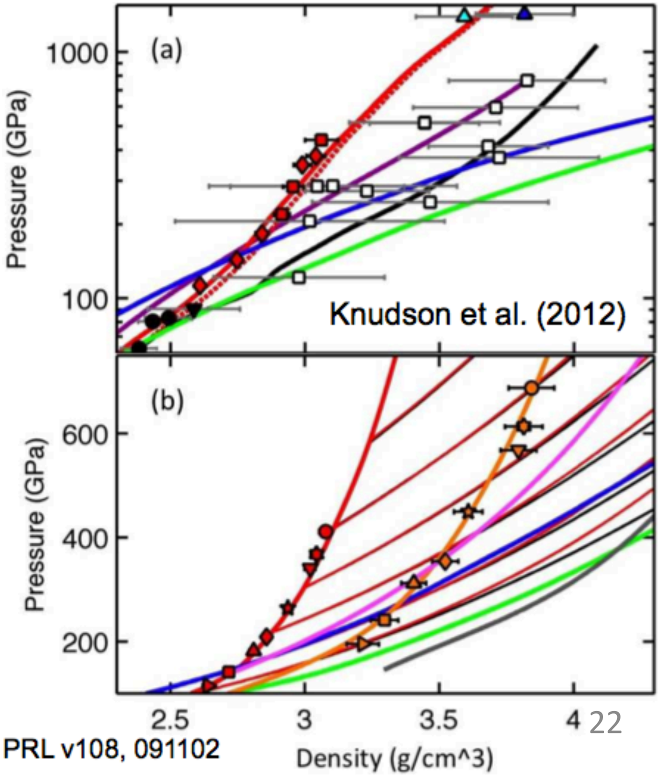
Sandia National Laboratory Z Machine
High P (>1TPa) and T (>2GK) reached
through high electromagnetic fields

Recent significant advances via

Ab initio computations

Precise measurements

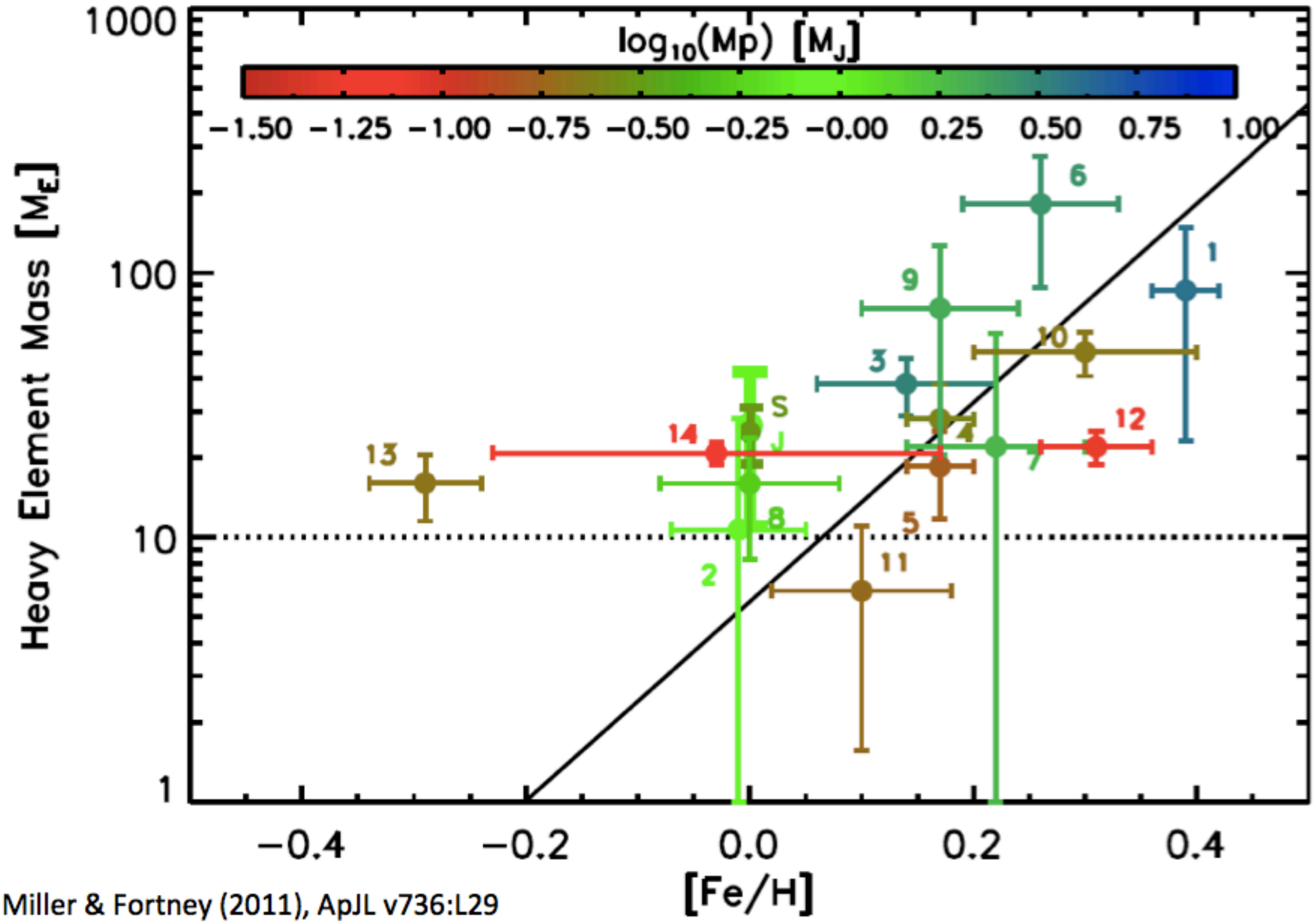
H_2O



PRL v108, 091102

Internal structure of giant planets: results

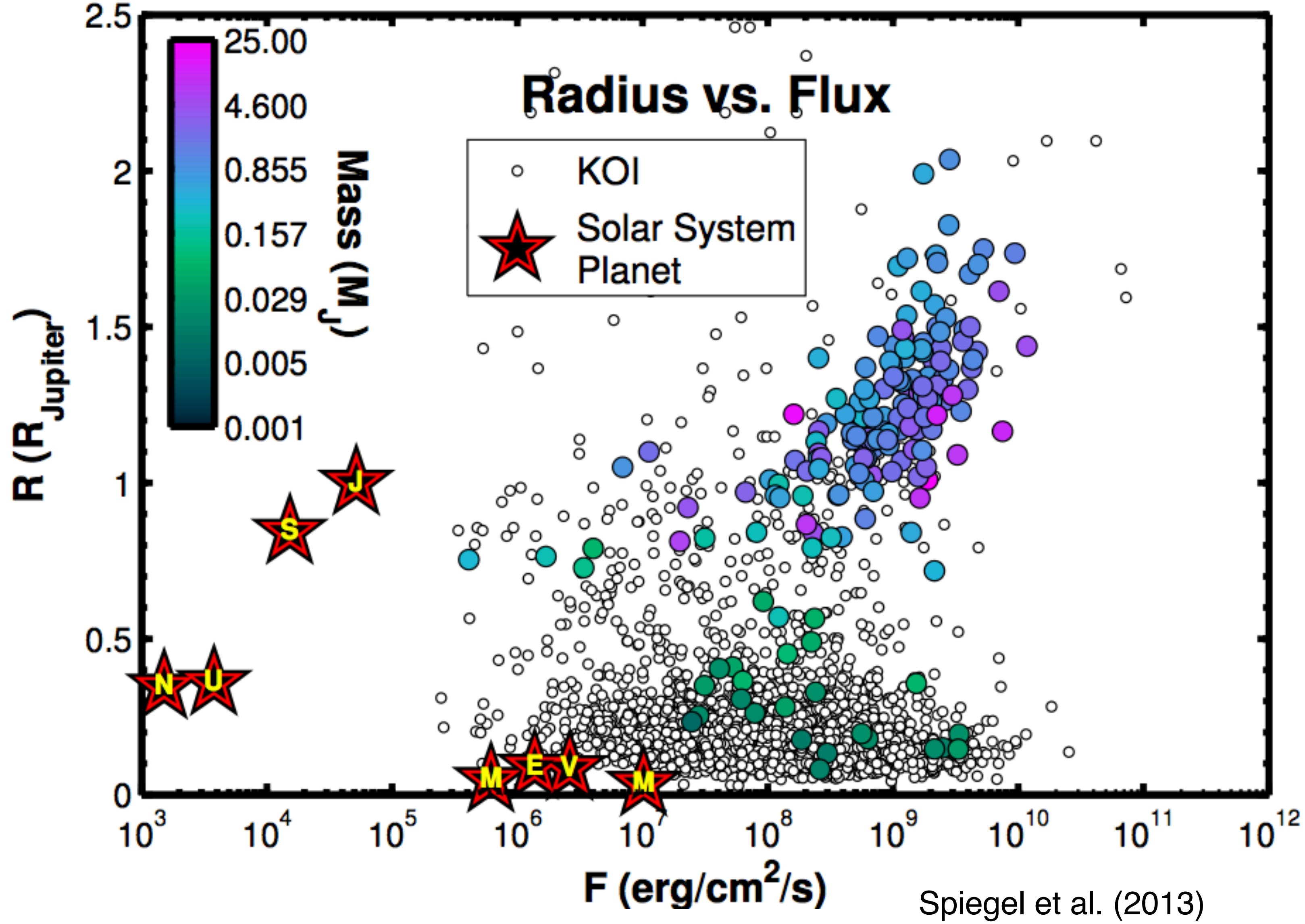
Correlation between stellar and planetary abundances?



Miller & Fortney (2011), ApJL v736:L29

Internal structure of giant planets: results

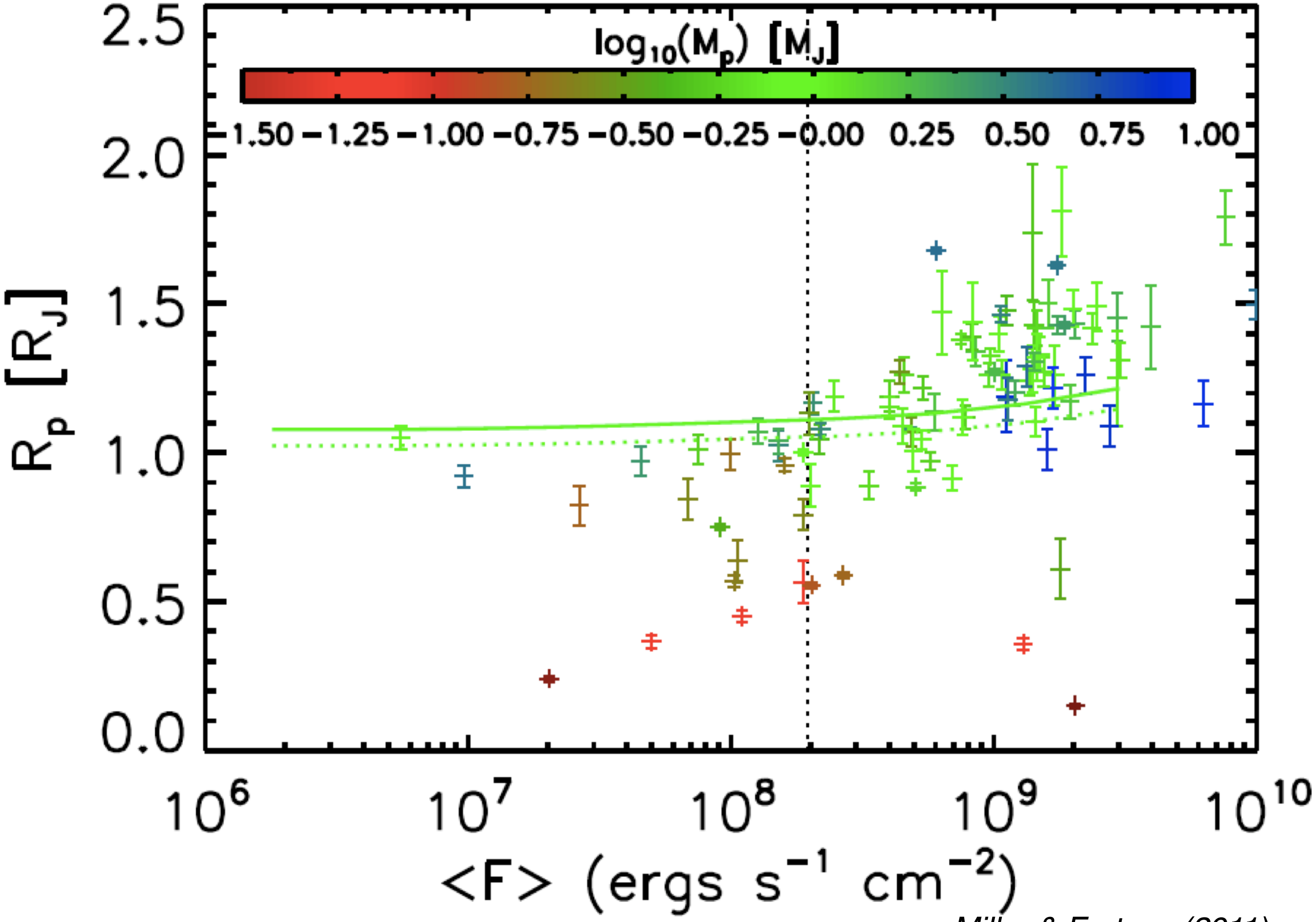
Relationship radius – irradiation for giant planets



Spiegel et al. (2013)

Internal structure of giant planets: resqults

The most irradiated giant planets are often ‘too’ big



Miller & Fortney (2011)

Internal structure of giant planets

Origins of that "radius anomaly" ?

1/ Deep deposit (at the radiative-convective limit, or lower) of 0.1 to 1% of incident irradiation

Mechanism? Day-night winds *(Guillot & Showman 2002)*; ohmic dissipation *(Batygin & Stevenson 2010)*

2/ Slowed down contraction

Current theories predict contractions too fast to explain radius anomalies.

Additional mechanism? Larger opacities *(Burrows et al. 2007);* convection in layer due to composition gradient *(Chabrier & Baraffe 2007)*

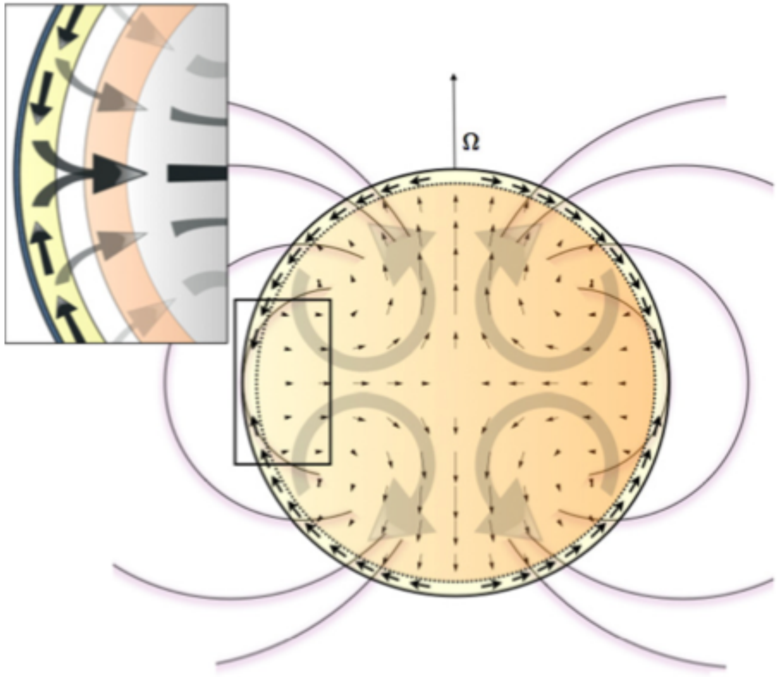
3/ Tidal dissipation

Stellar tides: strong effect but drops to zero once the orbit is fully circularized *(Bodenheimer et al. 2001)*

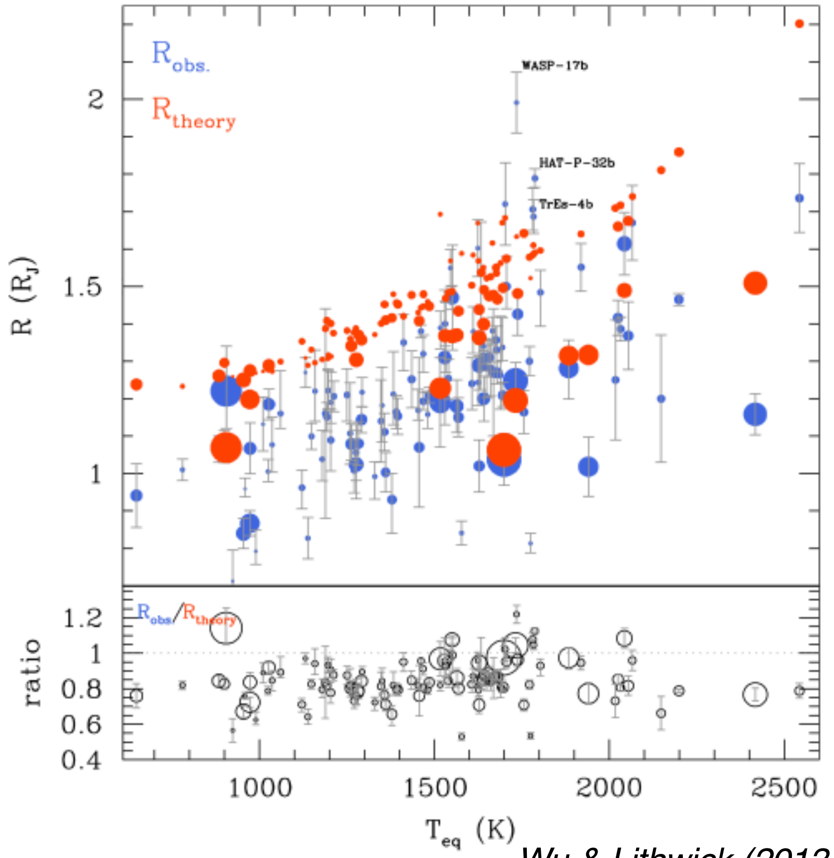
Thermal tides? *Arras & Socrates (2010)*

Internal structure of giant planets

Ohmic dissipation



Batygin & Stevenson (2010)



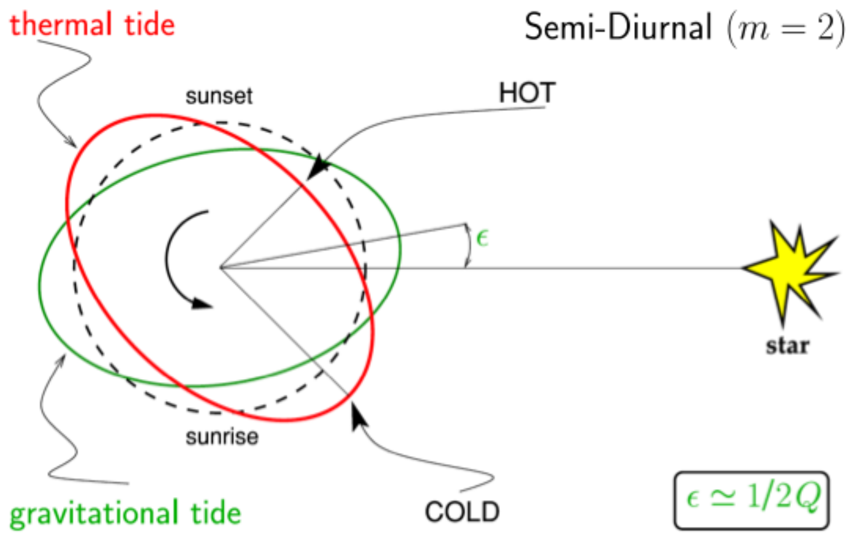
Wu & Lithwick (2013)

- Alkaline metals (Li, Na, K,…) thermally ionized and carried by advection in the strong winds of the external layer.
- Creation of a magnetic field distinct from the inner magnetic field (dynamo)
- Induced current deposits its energy by ohmic dissipation in the internal layers

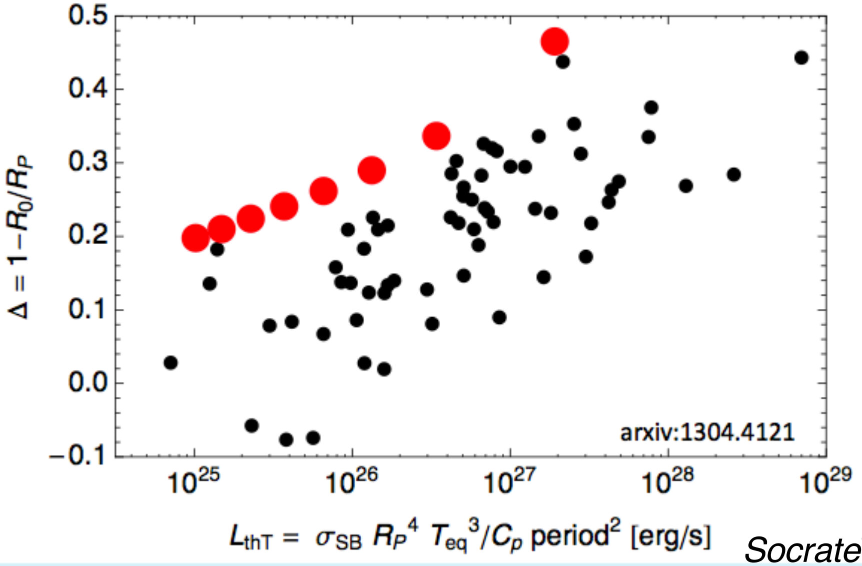
Internal structure of giant planets

Thermal tides

- The thermal inertia of the atmosphere is generally not negligible
- The peak of T (afternoon) happens later than the irradiation peak (noon)
- The attraction of the star on the thermal bulge tends to make the planet spin faster
- Opposition between gravitational and thermal tides ➔ constant energy source
- Outcome: a tidal mechanism with irradiation as energy source



Arras & Socrates (2010)



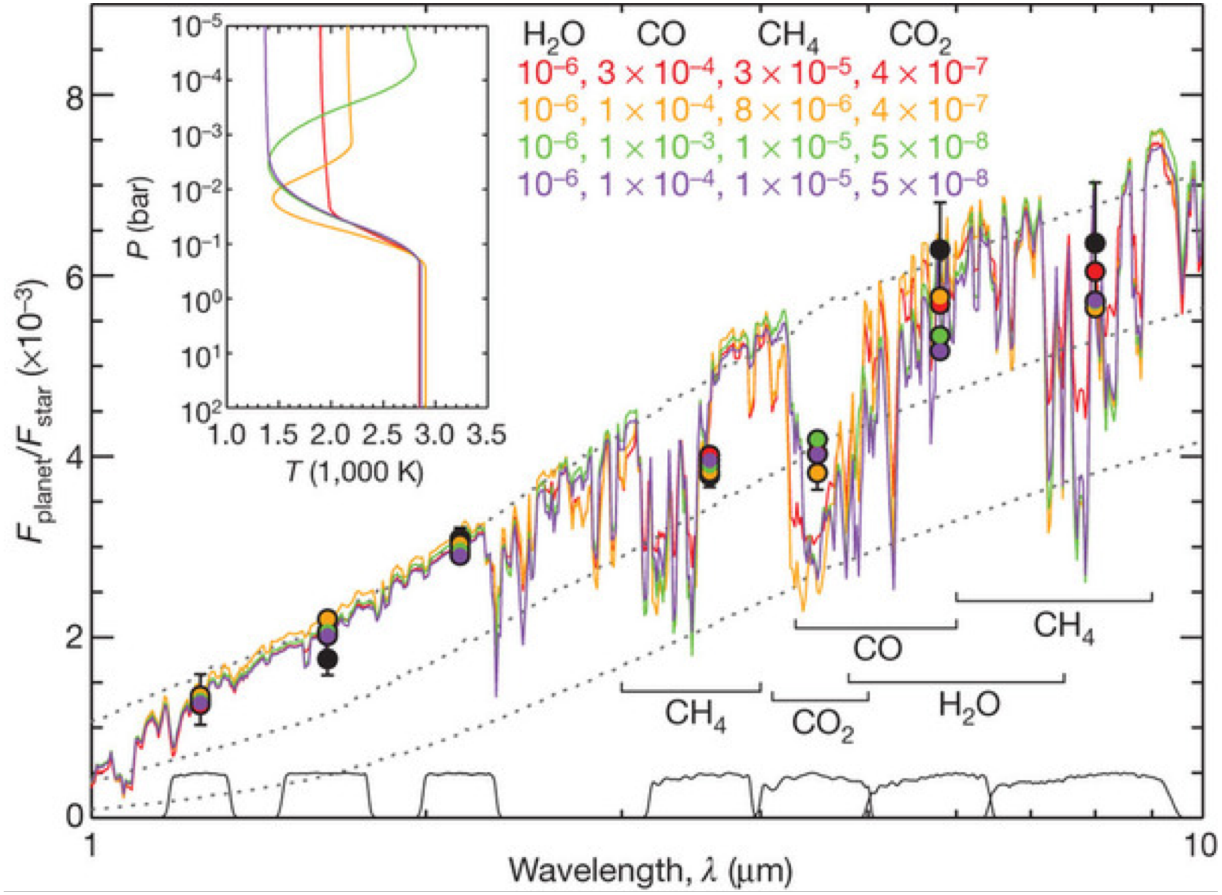
Socrates (2013)

Planetary atmosphere

Study of exoplanet atmospheres

Composition, circulation, clouds, thermal structure, etc.

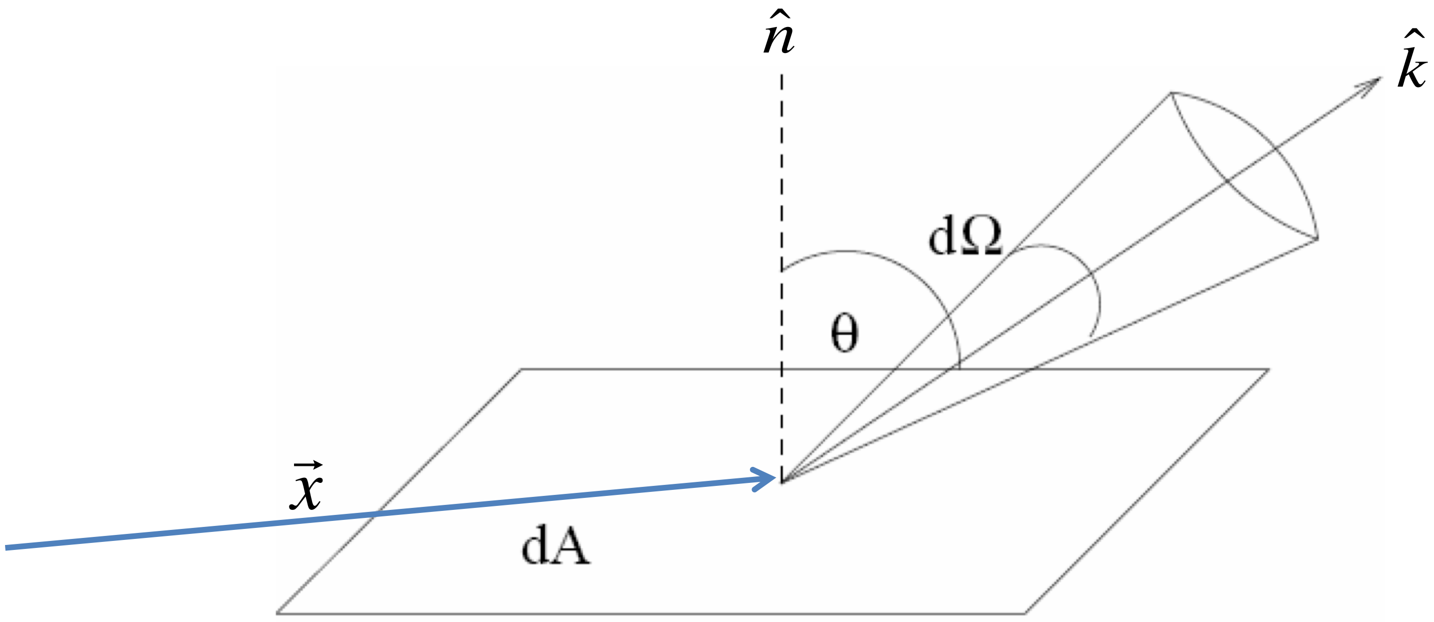
➔ spectroscopy then inferences based on the comparison with radiative transfer models



Madhusudhan et al. (2011)

Planetary atmosphere

Spectral radiance (a.k.a. specific intensity)



$$dE_\nu = I_\nu \cos\theta \, dA \, d\Omega \, dt \, d\nu$$

Spectral radiance $I_\nu = I(\nu, t, \vec{x}, \hat{k})$

Units: W m^{-2} sr^{-1} Hz^{-1}

Planetary atmosphere

Flux

$$\vec{F}_\nu(\vec{x},\nu,t) = \int_{4\pi} I_\nu(\vec{x},\nu,t,\hat{n})\hat{n}d\Omega$$

Measurement of the quantity of energy crossing dA at a given time t and at a frequency v

We are generally interested in the flux **in our direction**

$$F_\nu = \int_{4\pi} I_\nu \hat{n}.\hat{k}d\Omega$$

$$F_\nu = \int_{4\pi} I_\nu \cos\theta d\Omega$$

Planetary atmosphere

We have thus $dE_\nu = I_\nu \cos\theta dA d\Omega d\nu dt$

Spectral radiance = the energy in a beam at a given time

The equation of radiative transfer describes how this energy varies due to the interactions between light and matter ➔ variations of I_ν as a function of the length of the path travelled in the medium

$$dI_\nu = -\kappa_\nu \rho I_\nu ds + j_\nu \rho ds$$

Absorption cross section

Emission cross section

ds = infinitesimal distance travelled
ρ = density of the crossed medium

Planetary atmosphere

The equation of radiative transfer

$$\frac{dI_\nu}{\kappa_\nu \rho ds} = -I_\nu + S_\nu$$

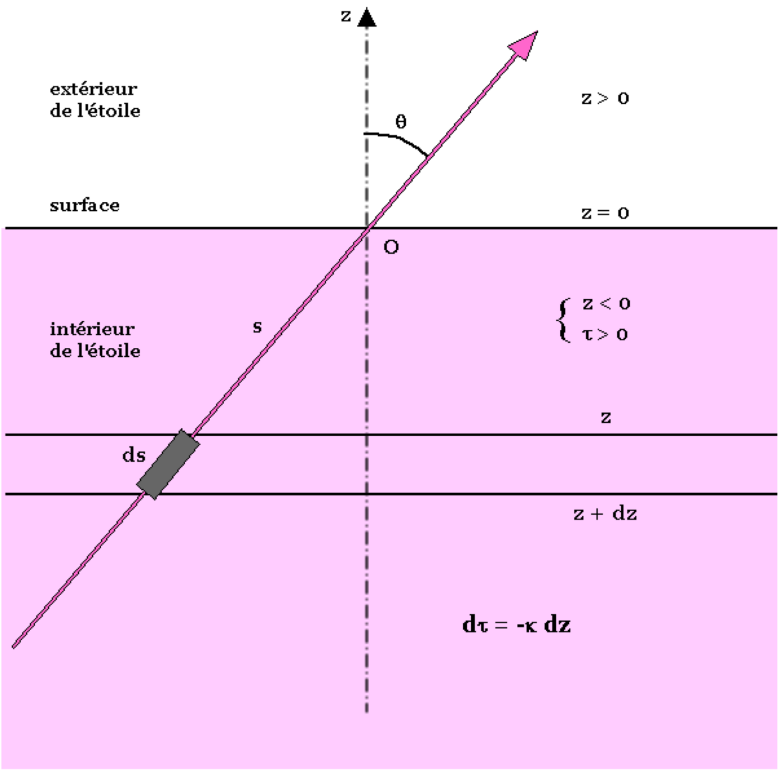
With $S_\nu = \frac{j_\nu}{k_\nu}$ the source function

Apparently simple equation, but

- Not linear: I_v depends on j_v, but j_v depends also on I_v
- Opacities behind k_v and j_v depend on millions of atomic and molecular lines, and in the case of opacity due to clouds, include many free parameters.

Planetary atmosphere

Plane-parallel atmosphere



The curvature of the atmospheric layers is neglected

If $\mu = \cos\theta$

Then $dz = cos\theta ds$

Is then defined the optical depth τ_ν, measured from the top of the atmosphere, as:

$$\tau_\nu(z) = -\int_z \kappa_\nu(z)\rho(z)dz$$

➔ Equation of radiative transfer becomes $\boxed{\mu\frac{dI_\nu}{d\tau} = I_\nu - S_\nu}$

Planetary atmosphere

Analytical solutions. **I. Transmission in the optical**

Thermal emission of the atmosphere negligible: $S_\nu = 0$

$$\mu \frac{dI_\nu}{d\tau} = I_\nu \quad \Longrightarrow \quad I_\nu = I_\nu(0) e^{-\tau_\nu / \mu}$$

Beer-Lambert law

II. Thermal emission without scattering, local thermodynamical equilibrium (LTE)

$S_\nu = B_\nu$ Source function = Planck function

$$\mu \frac{dI_\nu}{d\tau} = I_\nu - B_\nu \quad \Longrightarrow \quad I_\nu(z) = \int_0^\pi \frac{1}{\mu} \int_0^\infty B_\nu(\tau) e^{-\tau_\nu(z)/\mu} d\tau d\mu$$

Planetary atmosphere

Chemical composition

An elementary composition is adopted (e.g. solar)
Assumed network of chemical reactions
The chemical equilibrium is assumed (no change of abundances)
The abundance of a given molecule in a given layer depends on P and T (in first approach).

Computation of abundances through **minimization of Gibbs free energy G**

First law of thermodynamic: $dU = dQ - dW = TdS - PdV$

Definition of G: $G = U + PV - TS$

$$dG = dU + PdV + VdP - SdT - TdS$$

$$dG = VdP - SdT$$

dG ≤0 until equilibrium for which dG=0

Planetary atmosphere

Chemical composition

Determination of the minimum of

$$G/RT = \sum_i n_i \left[\left(g_i^0(T)/RT \right) + \ln P + \ln\left(n_i/N \right) \right]$$

with

$$\sum_i a_{ij} n_i = b_j$$

n_i =number of moles of molecule *i*

g_i^0 = Gibbs energy of molecule *i* at standard pressure ***(Tables)***

N = total number of moles of the system

b_j = number of moles of element *j*

a_{ij} = number of atoms of element *j* in molecule *i*

A charge constraint can also be used to take into account ions

Solid particules? Same but no pressure term

Planetary atmosphere

Departure from chemical equilibrium

If P and T are high, chemical reactions are fast and equilibrium is quickly reached.
But in the cold low-density layers, it can never be reached…

e.g. T-type brown dwarfs (T_{eff} < 1300K)

CO is the dominant form of carbon-bearing in the deep layers, and CH_4 should totally dominate the upper colder layers. Still, they also contain CO.

It is due to this following reaction which is there very slow:

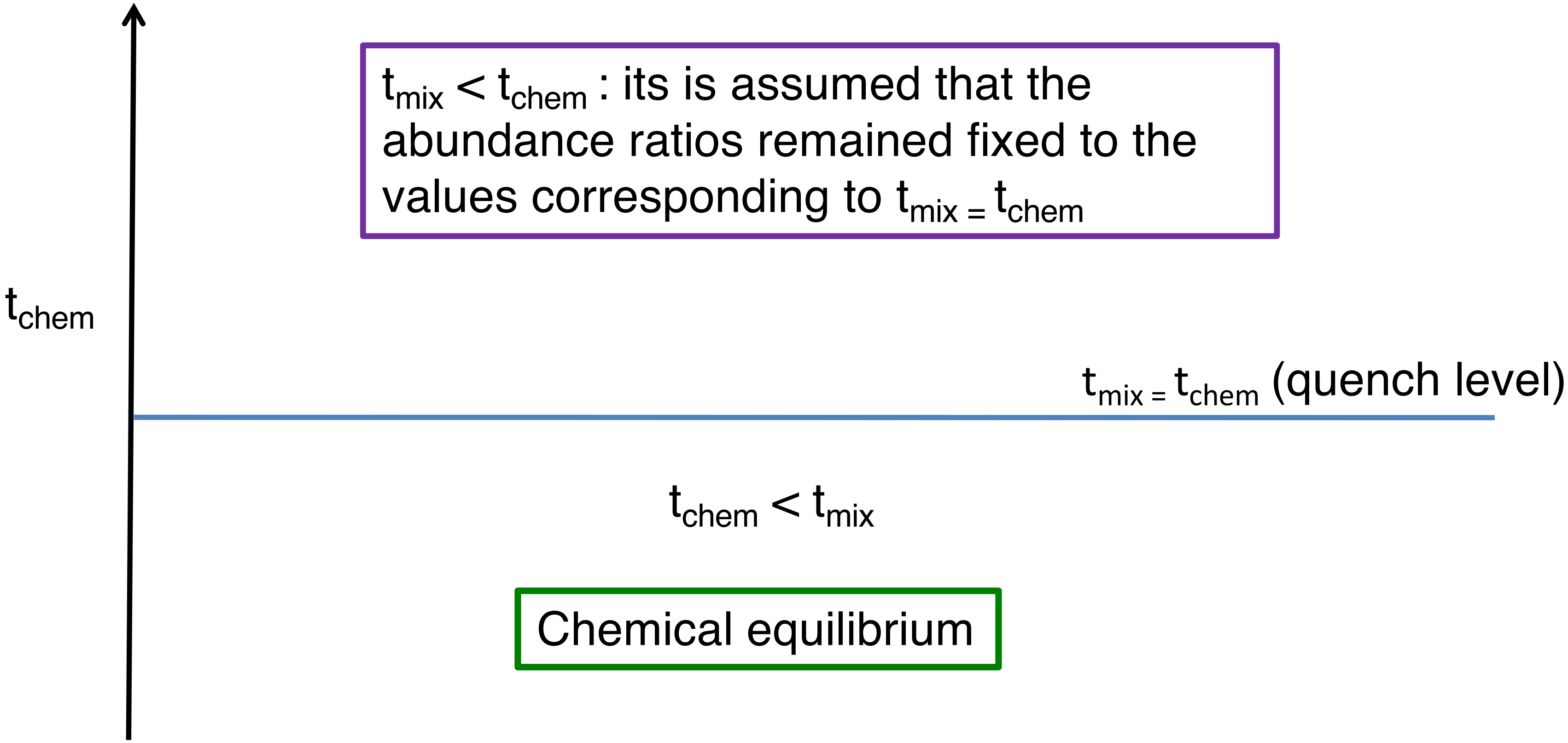
$$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$$

The vertical mixing rate of CO is much superior to its rate of transformation into CH_4, so CO accumulates in the upper layers.

Same thing happens in Jupiter's atmosphere.

Planetary atmosphere

Departure from chemical equilibrium: modeling



$t_{mix} < t_{chem}$: its is assumed that the abundance ratios remained fixed to the values corresponding to $t_{mix} = t_{chem}$

t_{chem}

$t_{mix} = t_{chem}$ (quench level)

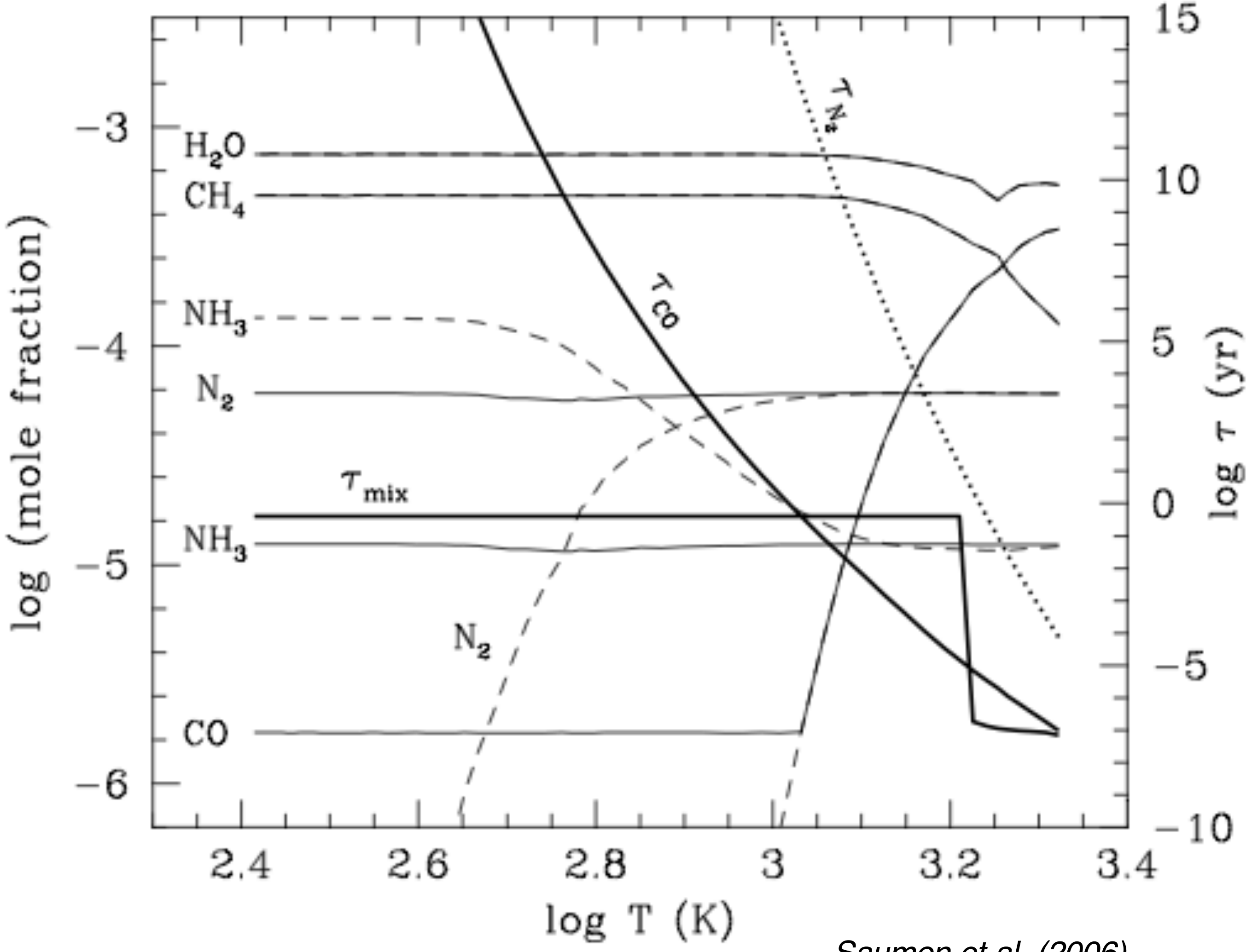
$t_{chem} < t_{mix}$

Chemical equilibrium

t_{mix} is generally poorly constrained…

Planetary atmosphere

Departure from chemical equilibrium



Saumon et al. (2006)

Planetary atmosphere

Atmospheric model (simplest version)

Code of radiative transfer (1D plane-parallel + LTE).
Resolution for each layer of the equation of radiative transfer + thermodynamic equilibrium (radiation or convection-dominated heat transfert) + hydrostatic equilibrium, so to obtain P(z), T(z), and I(z,v) = **atmospheric profile**

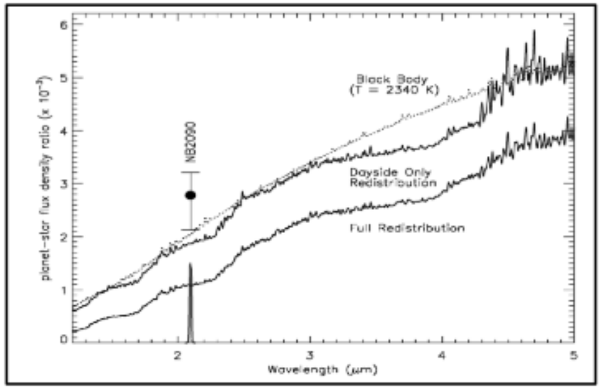
Limit conditions: stellar irradiation and internal entropy

Parameters:

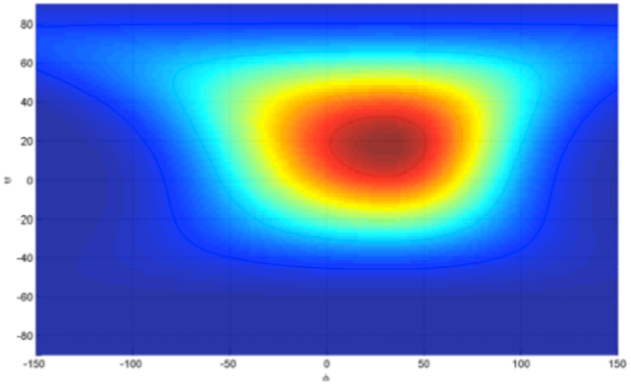
- **Internal entropy**
- **Irradiation**
- **Opacities**
- **Choice of atomic and molecular species**
- **Elementary composition**
- **Chemical equilibrium or not (vertical mixing)**
- **Clouds (opacities)**
- **Efficiency of the day-night heat transfer**

Planetary atmosphere

1D vs CGM 3D models



Gillon et al. (2010)



de Witt et al. (2012)

Habitability

Habitability criteria (NASA)

1. *Extended areas of liquid water*
2. *Conditions suitable to the assembly of complex organic molecules*
3. *Sources of energy available to sustain metabolisms*

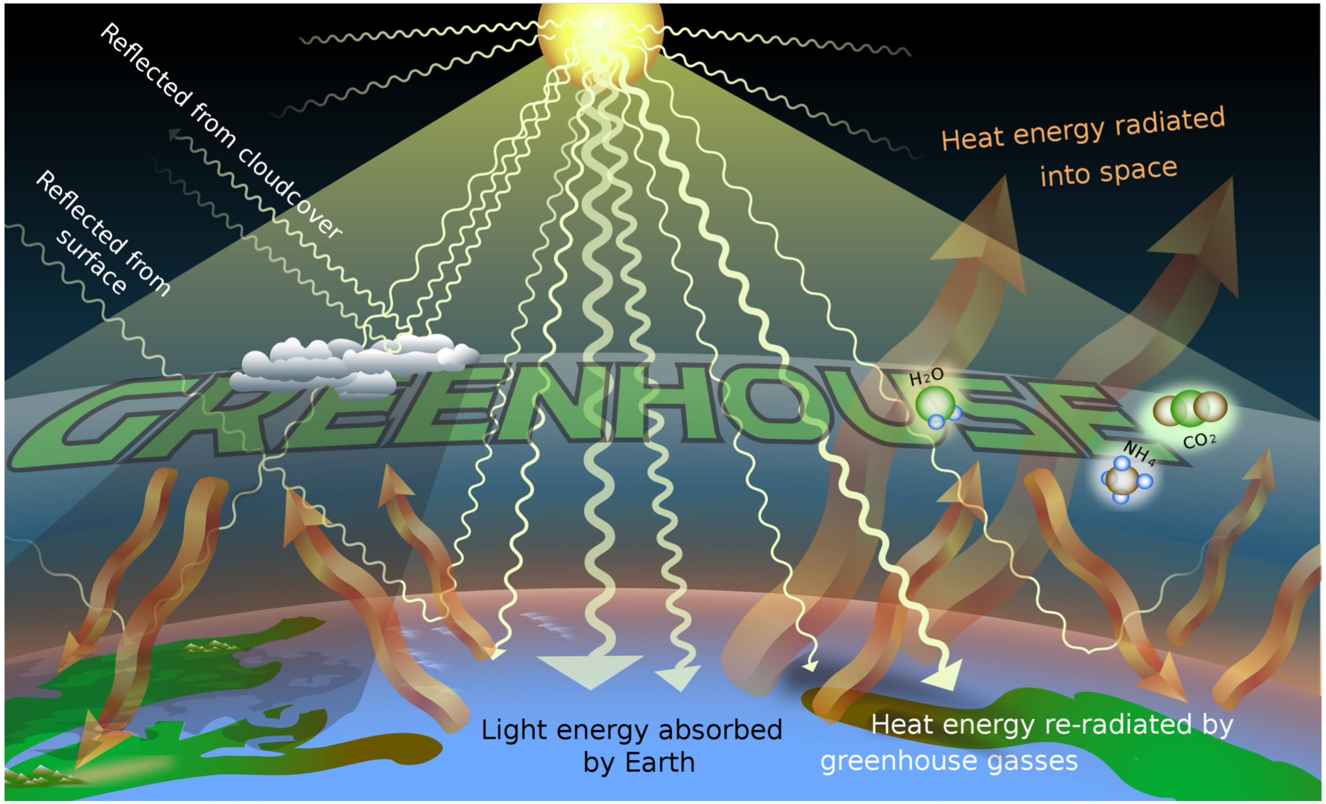
Exoplanets
Focus is on terrestrial planets that could harbor liquid water on their surface

↓

Notion of Habitable Zone (HZ)

The greenhouse effect

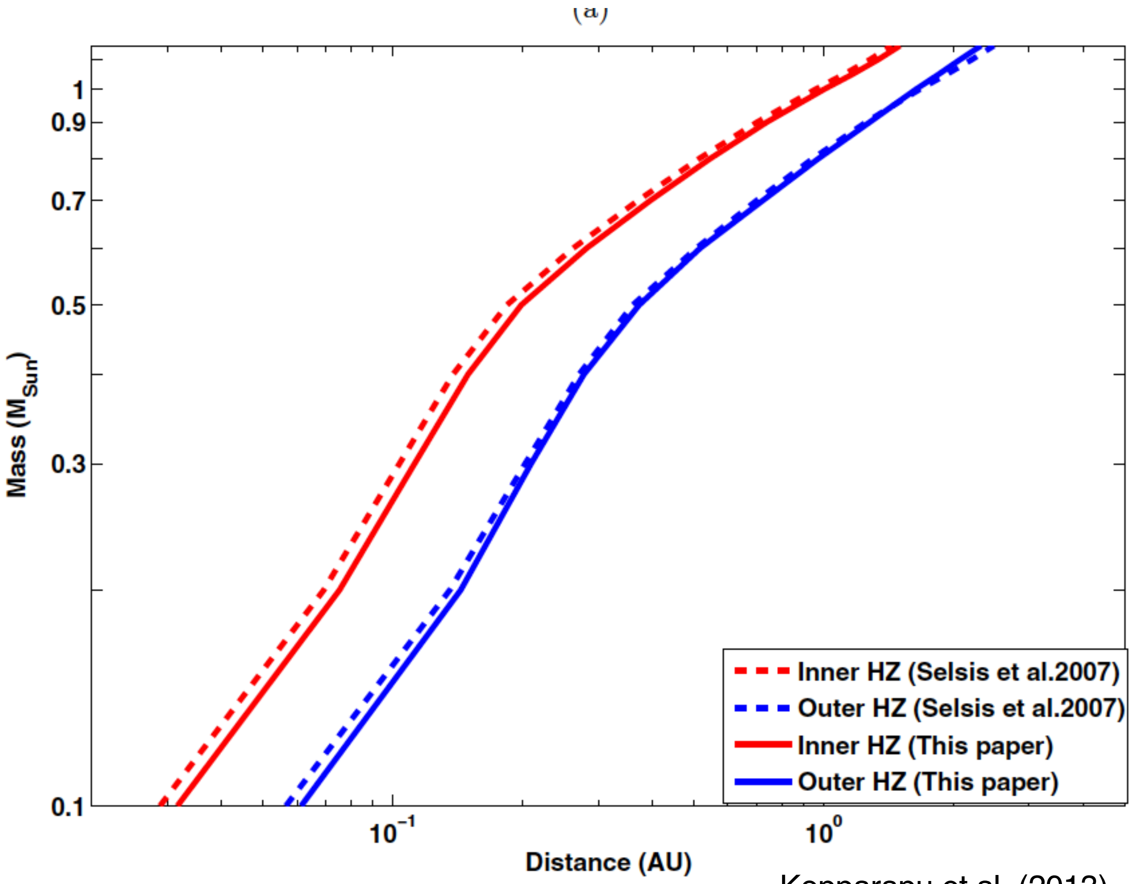
Trapping of radiation within the atmosphere by absorption & isotropic reemission of the infrared emission from the surface or lower atmospheric layers



Earth’s greenhouse gases: $H_2O > CO_2 > CH_4 > N_2O > O_3 >$ CFCs

The habitable zone

Distance range to a star in which a terrestrial planet with suitable atmospheric features could sustain liquid water on its surface (Huang 1959)



Kopparapu et al. (2013)

Inner limit:
Runaway greenhouse state -> water loss by photolysis and hydrogen loss

Outer limit:
Formation of CO_2 clouds that cool down the surface by increasing the albedo and decreasing the greenhouse effect

Solar system: from 0.99 AU to 1.7 AU (Kopparapu et al. 2013)

The greenhouse effect: importance of CO_2

Main CO_2 sources:

1) **Decarbonation of carbon-containing rocks in subduction zones**:

silicates + $CaCO_3$ -> other silicates + $\boxed{CO_2}$ → Outgassed by volcanoes, hot springs, etc.

2) **Uplifting of carbon-rich sediments** (mostly of biological source) during mountain building (or by human intervention), **which are oxidized and release CO_2.**

3) **Decomposition/respiration**: $(CH_2O)n + nO_2$ -> $CO_2 + H_2O$

CO_2 sinks:

1) **Chemical weathering** $CO_2 + H_2O$ (rain water) : H_2CO_3

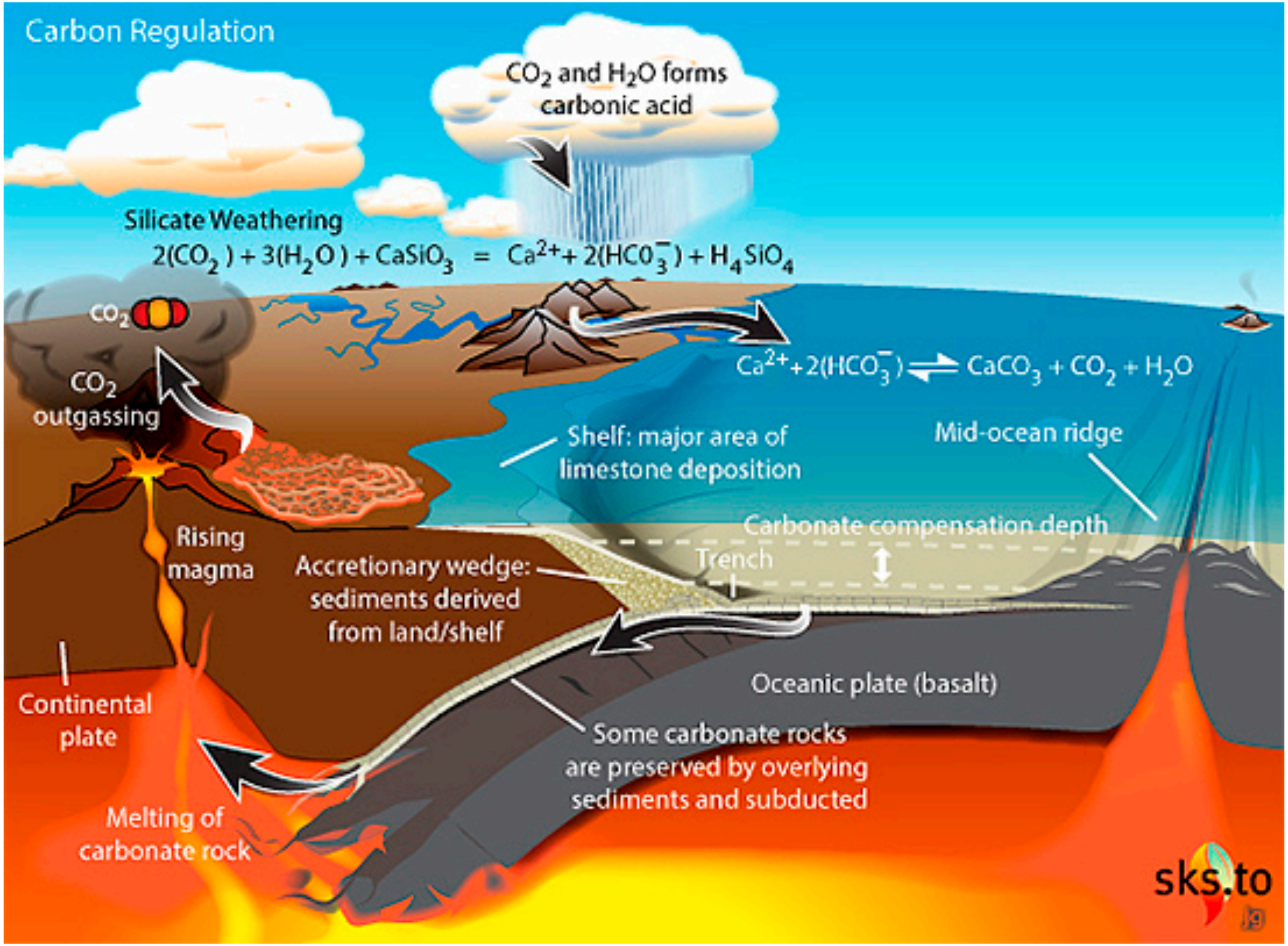
$2H_2CO_3 + H_2O + CaSiO_3$ -> $Ca^{2+} + 2HCO_3^- + H_4SiO_4$ (chemical weathering of silicates)

$Ca^{2+} + 2HCO_3^-$ -> $\boxed{CaCO_3} + CO_2 + H_2O$

2) **Burial of carbon-rich sediments** (e.g. late Carboniferous Period)

3) **Photosynthesis**: $nCO_2 + nH_2O$ –> $(CH_2O)n + nO_2$

The greenhouse effect: importance of CO_2



Source: wikipedia

CO_2 and H_2O: climate feedbacks

CO_2:

If T increases -> more evaporated water -> more chemical weathering
-> less CO_2 in the atmosphere
-> smaller greenhouse effect -> **T decreases**

Negative feedback loop (stabilizing)

H_2O:

If T increases -> more evaporated water -> larger greenhouse effect -> **T increases**
-> More clouds -> **T increases or decreases**

-> less ice -> lower albedo -> **T increases**

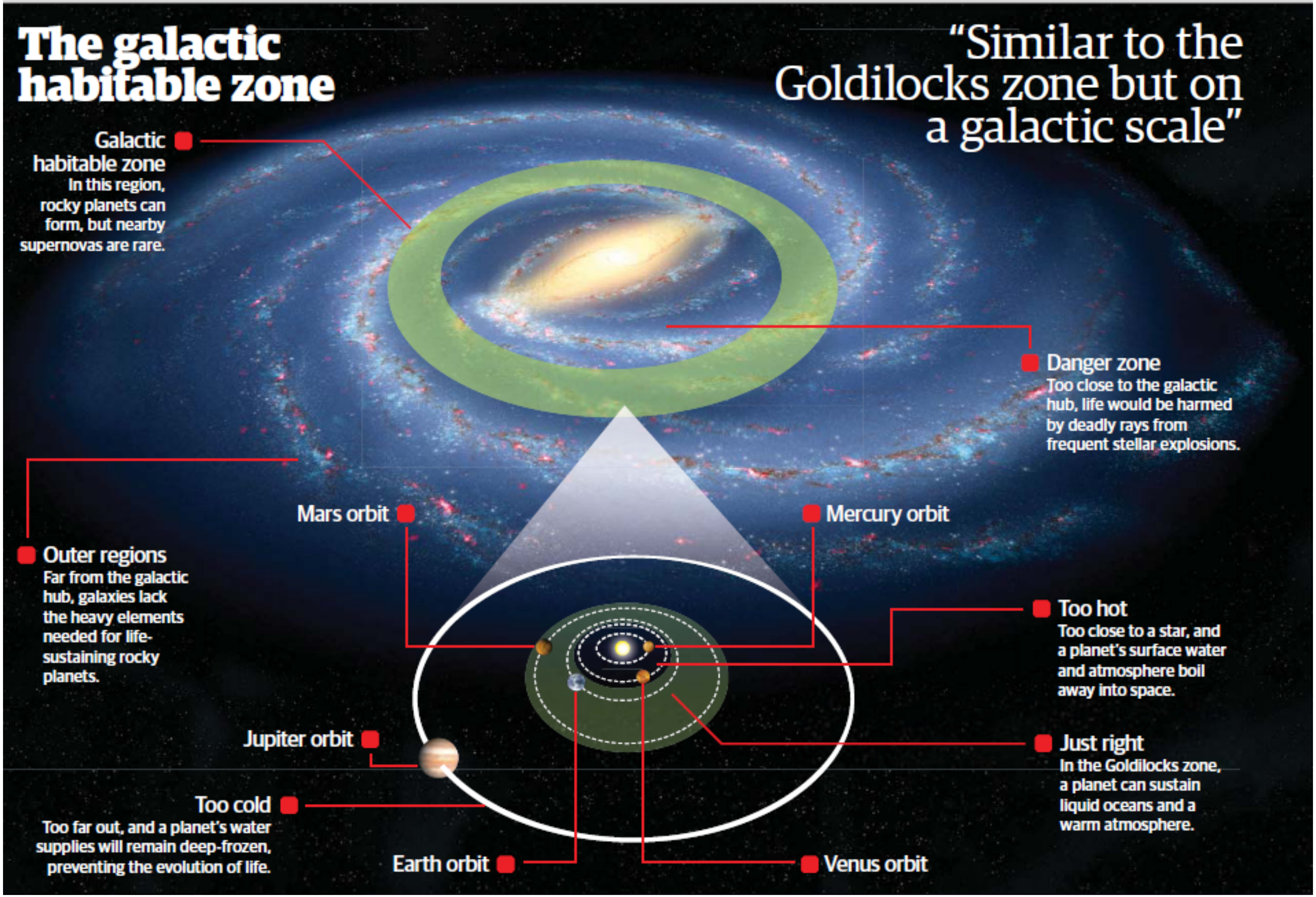
Positive feedback loop (destabilizing)

Habitability: a complex multi-factors problem

Parameters

- Axial tilt (importance of the Moon)
- Orbital eccentricity
- Continents' position
- Tides (heating, orbital evolution, tidal locking)
- Atmospheric composition (e.g. H_2 is a strong greenhouse gas)
- Life itself!
- Surface gravity
- Plate tectonism (could be more or less likely for super-Earths)
- Radioactive decay
- Atmospheric erosion
- Volcanism
- Impact rate
- Magnetosphere
- Heat redistribution: oceanic and atmospheric currents, rotation period
- Low insolation regime: regular snowball states
- Spectral type
- Etc…

The galactic habitable zone

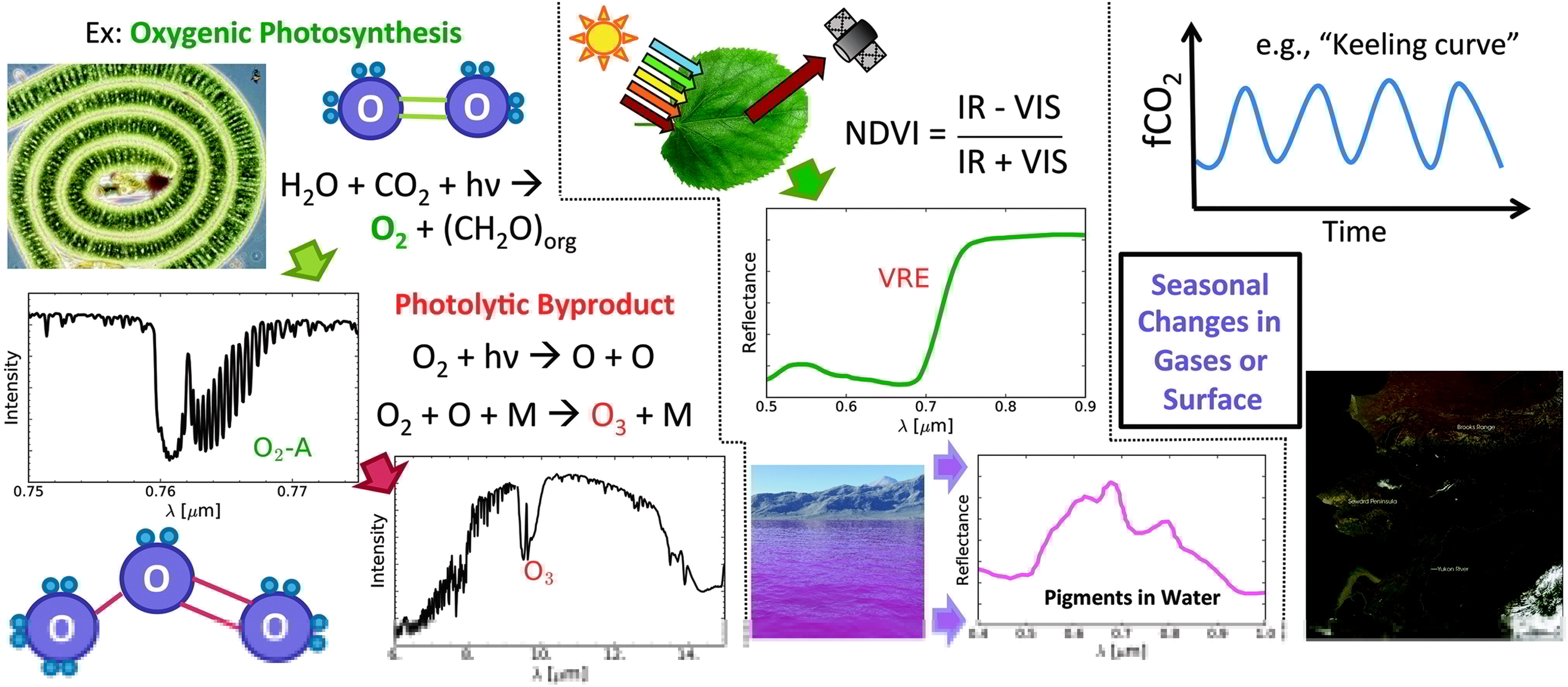


Biosignatures: detecting life elsewhere

Gaseous

Surface

Temporal



Ex: **Oxygenic Photosynthesis**

$H_2O + CO_2 + h\nu \rightarrow O_2 + (CH_2O)_{org}$

Photolytic Byproduct

$O_2 + h\nu \rightarrow O + O$

$O_2 + O + M \rightarrow O_3 + M$

$$\text{NDVI} = \frac{\text{IR - VIS}}{\text{IR + VIS}}$$

e.g., “Keeling curve”

Seasonal Changes in Gases or Surface

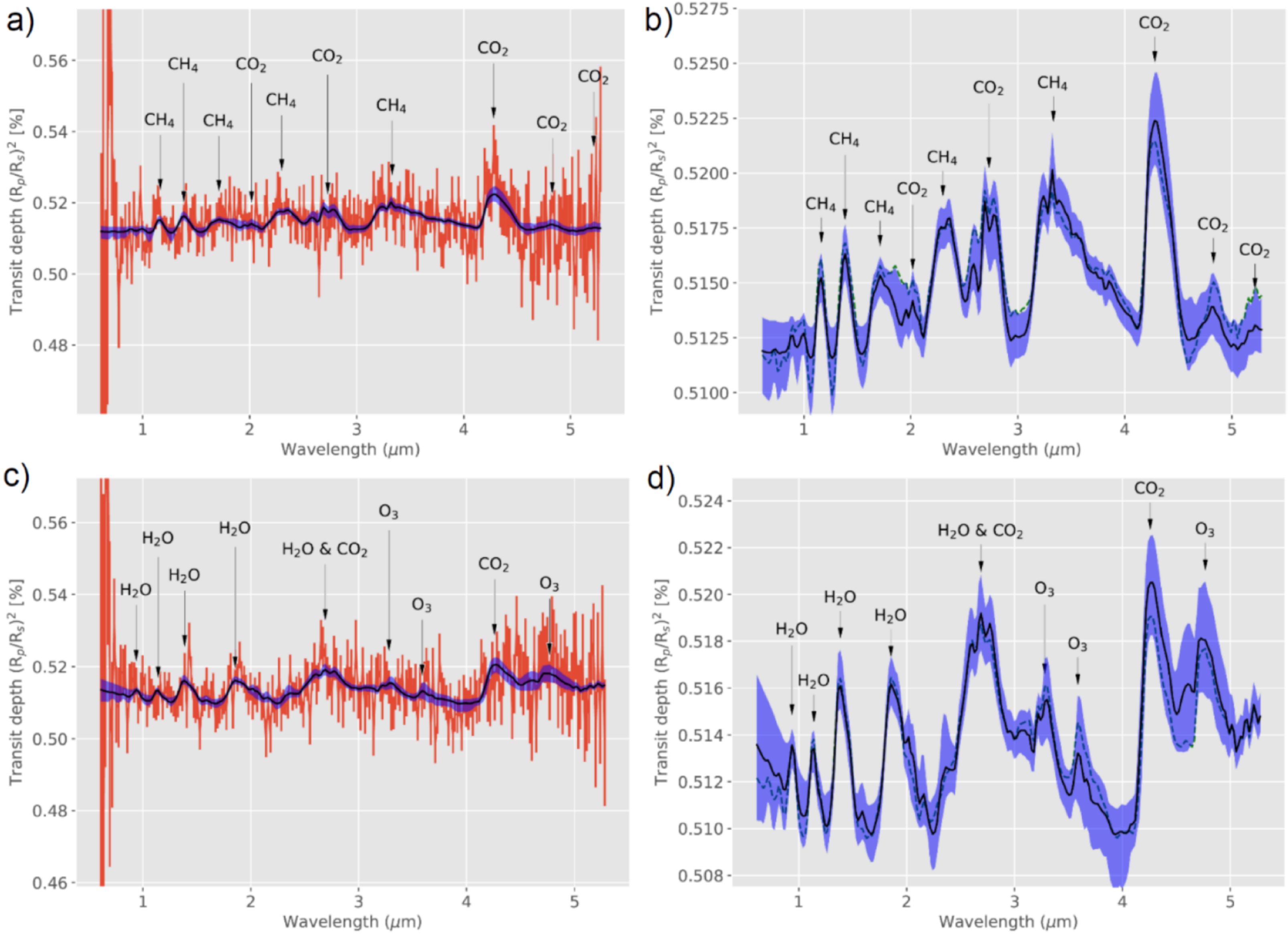
Best prospect for exoplanets: strong chemical disequilibrium detected by spectroscopy

Best shot: O_2 / CH_4 . Together, these gazes form quickly CO_2 and H_2O

Case study: TRAPPIST-1e in transmission

Archean Earth

Modern Earth



Krissansen-Totton et al. 2018

No life around M dwarfs?

Tidal locking

The planets always shows the same face to the star.

➔ The atmosphere freezes gradually on the night side (atmospheric collapsus)(Haberle et al. 1996)

➔ **3D climate modeling show that 0.1bar is enough to avoid this collapsus (Joshi et al. 1997)**

No flux in the visible

So no photosynthesis possible?

Chlorophyll f absorbs light at 706nm (Chen et al. 2010)

Some bacterioclorophylls absorbs up to 1.2 microns

M-dwarfs are magnetically actives (flares + spots)

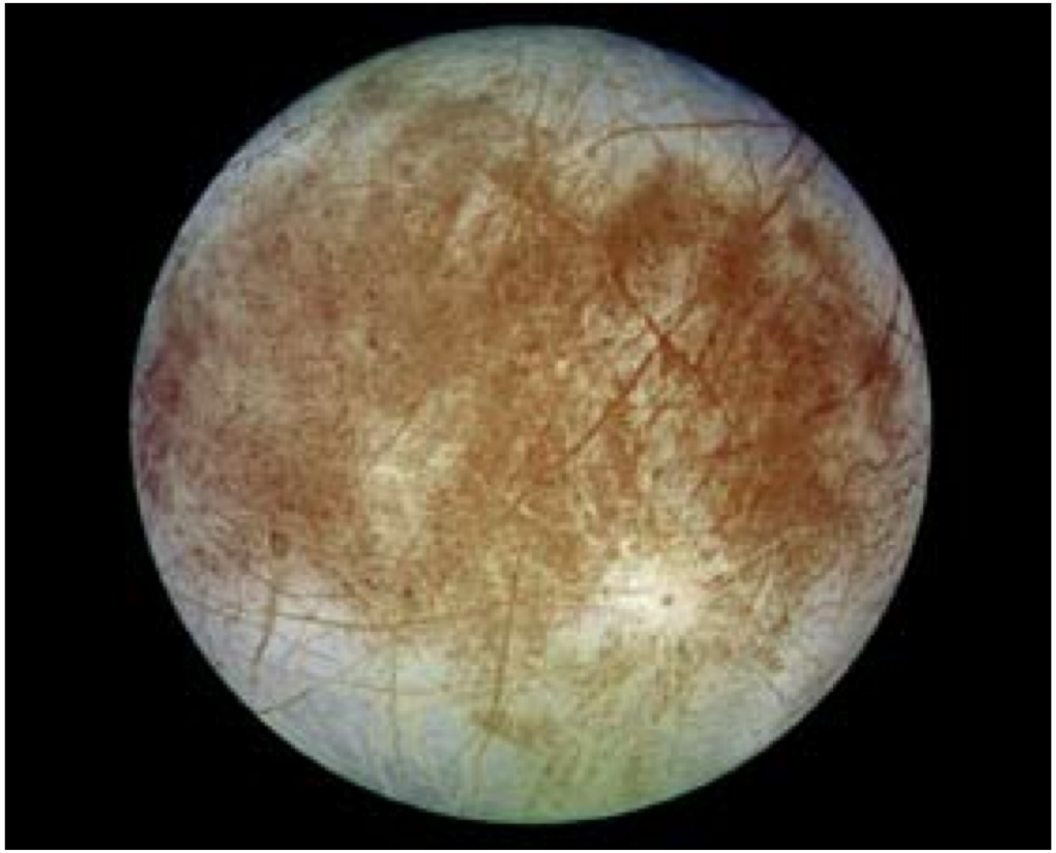
Spots ➔ **effects similar to seasons on Earth (Joshi et al. 1997)**

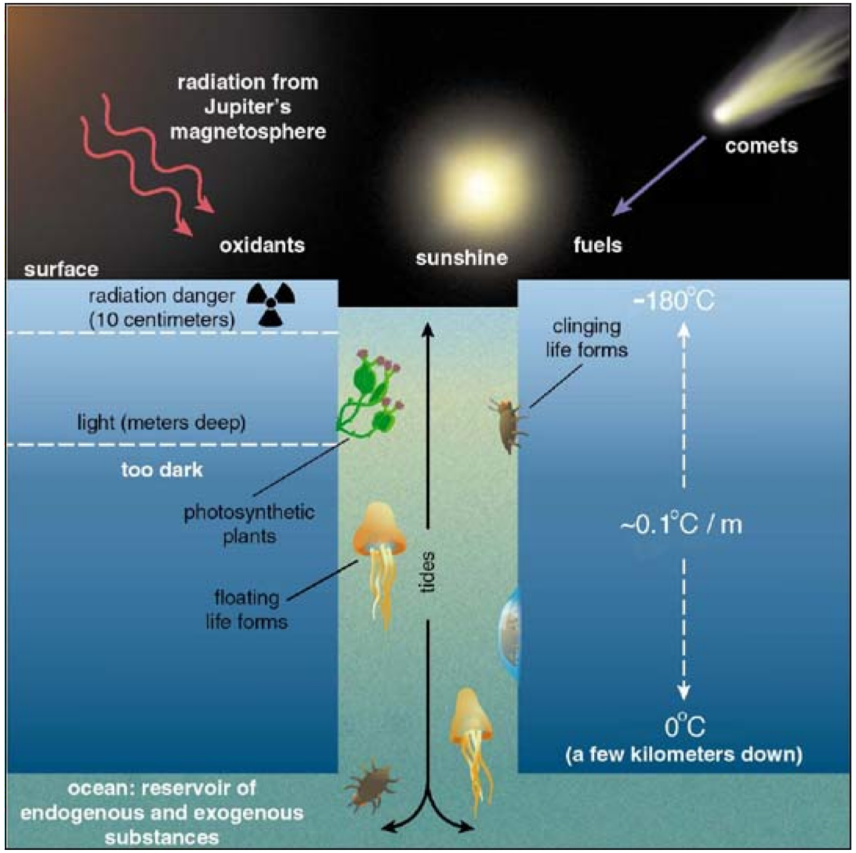
Flares ➔ **emission in UV and X very strong but sporadic. The cumulated impact on the ground could be similar in amplitude to Earth (Heath et al. 1999)**

➔ strong emission of charged particules, so erosion of the atmosphere and harsh biological damages. A magnetosphere is required, but tidal locking could inhibate it (slow rotation).

But Mercury has a 59 days rotation and it has a significant magnetosphere…

No life outside the HZ?



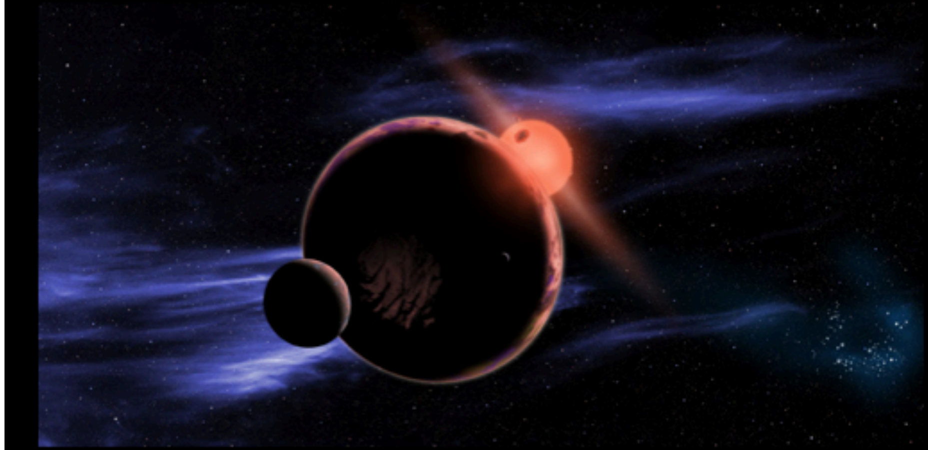


Richard Greenberg

Why not? But for exoplanets, we are forced to focus on biospheres giving rise to strong atmospherical signatures (biosignatures) -> **we focus on HZ**

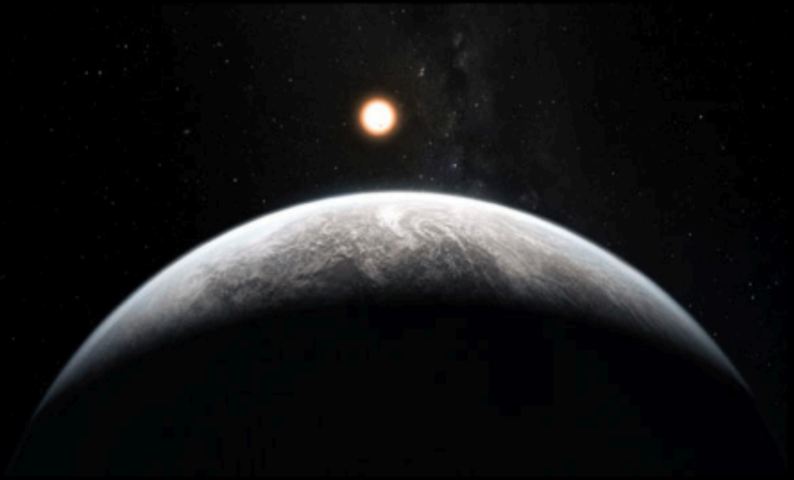
How many potentially habitable planets in the Galaxy?

Dressing & Charbonneau (2013)



Red dwarfs: 1/6 to 1/7
20 billions

Petigura et al. (2013)



Solar-type stars: 1/5
8 billions

At least 25 billions of potentially habitable planets!

Next step: study the atmospheres of some of the nearest

Exoplanets and Fermi's paradox


Enrico Fermi
(1901-1954)

Summer 1950, Los Alamos: « Where is everybody? »

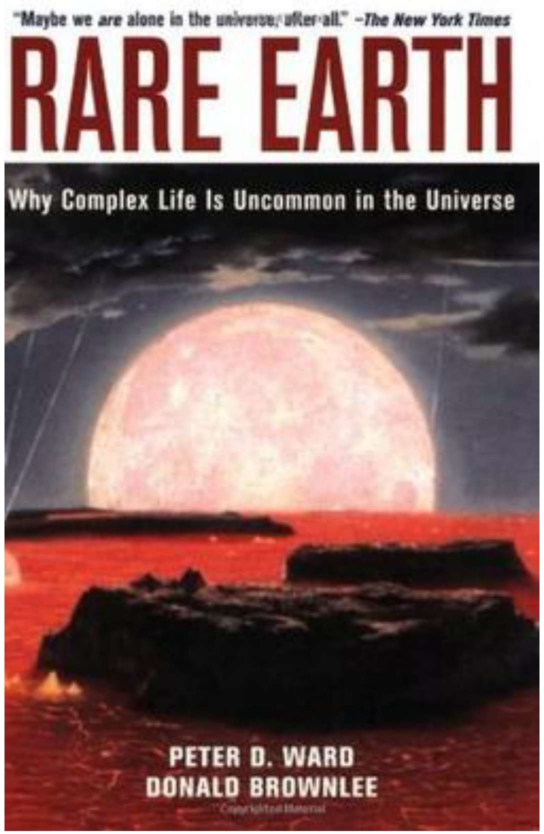
No trace of alien technology in any of our observations of the Universe

2019: Milky way hosts ~300 billions stars, and billions of potentially habitable planets. The Universe contains hundreds of billions of galaxies.

Several classes of solution (Cirkovic 2018):

- *Logistic*: They have not been able to come yet (interstellar travel is really hard)
- *Catastrophist:* They have been destroyed (SN, gamma-ray burst, self-destruction…)
- *Rare Earth:* they do not exist (early great filter, consciousness is ephemeral)
- *Solypsist:* they are here, or we live in a simulation
- *The Great Old Ones:* they have been there for long and do not like the competition

The Rare Earth – Great Filter Hypotheses



Peter D. Ward – paleontologist
Donal Brownlee – astrophysicist

Habitable planets are frequent in the Universe
Chemical elements required by life are frequent in the Universe
Microbial life is probably frequent

BUT

The apparition of multicellular complex organisms –and especially technologicaly advanced species- requires so many special conditions and unlikely events that the odds for our galaxy to host another civilization are close to zero

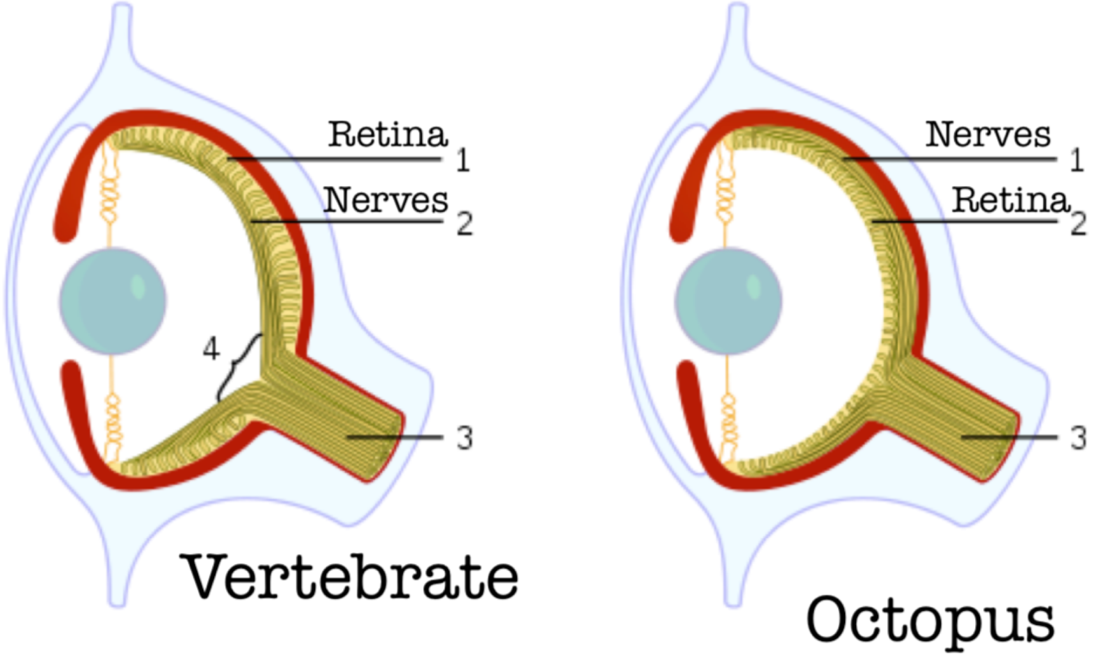
Only one low-probability event (**Great Filter**) in the chain of events that led to the apparition of life and its evolution to complex organisms and humans could explain the Fermi's paradox.

Critics against the Rare Earth – Great Filter Hypotheses

Misconception: « *evolution building an intelligent being from microbes is as unlikely as a tornado in a junkyard assembling a 747* ».

BUT: evolution is not a random process, nor is it a process with a « goal » . It is based on the selection of traits produced by mutations that enable a species to survive under the pressure of the environnement, including the competition from other species.
-> global tendency towards complexity.

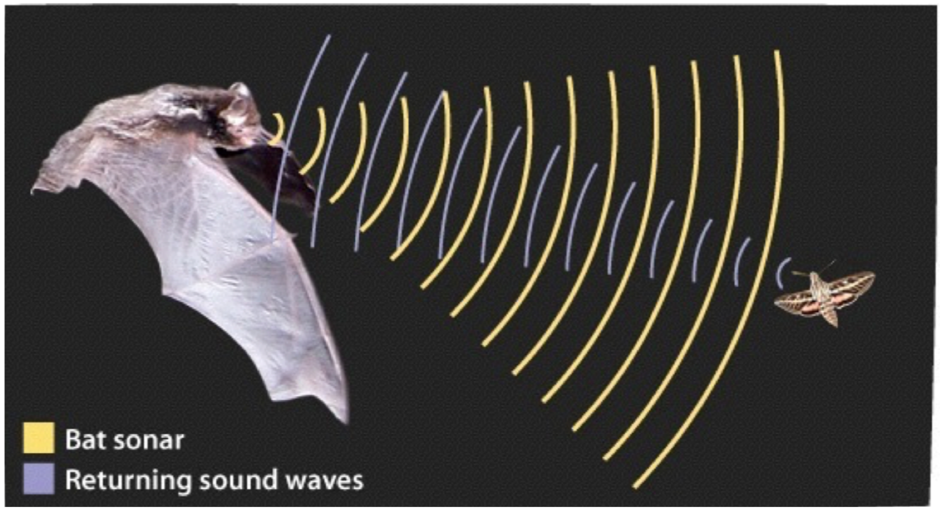
Convergence: there are only a limited number of evolutionary solutions that work



Critics against the Rare Earth – Great Filter Hypotheses

Intelligence is clearly a solution that works (for a time, at least…)

The diversity of the evolutionary « solutions » is much larger than generally thought

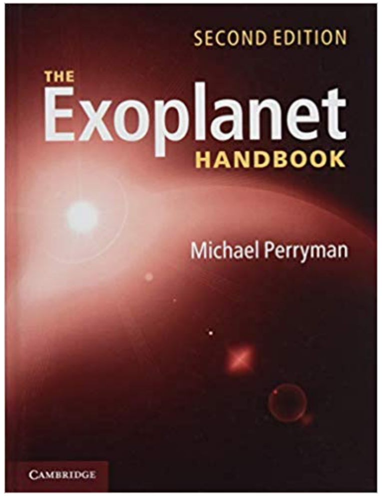


Mantis Shrim: 16 kinds of
photoreceptors from UV to deep-red
and polarized light

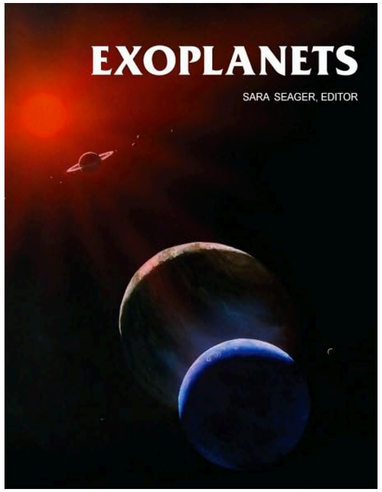
The Great Old Ones

http://shop.alexanderjansson.com/product/the-great-old-ones

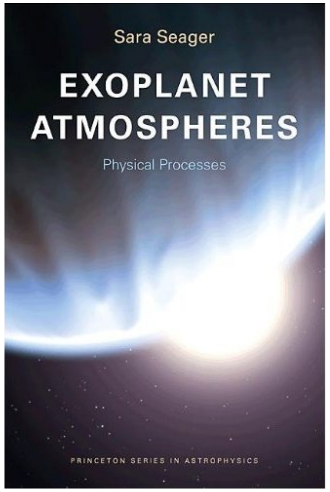
References



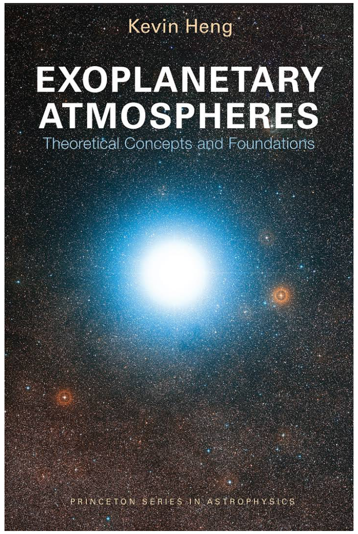
M. Perryman
Cambridge University Press
Chapter 11



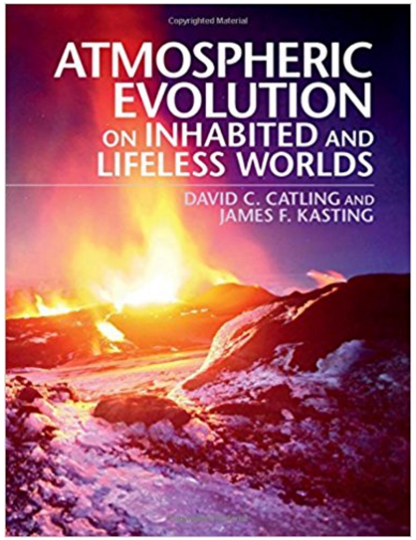
S. Seager
University of Arizona Press
Chapters 16 to 19



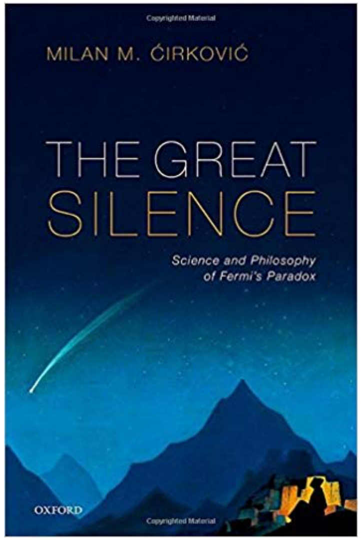
S. Seager
Princeton Series in
Astrophysics



K. Heng
Princeton Series in
Astrophysics



D. Catling & J. Kasting
Cambridge University Press



M. M. Cirkovic
Oxford University Press