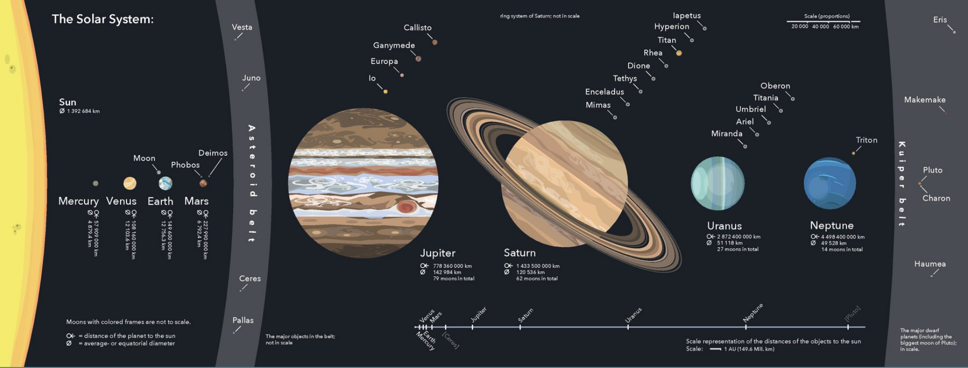
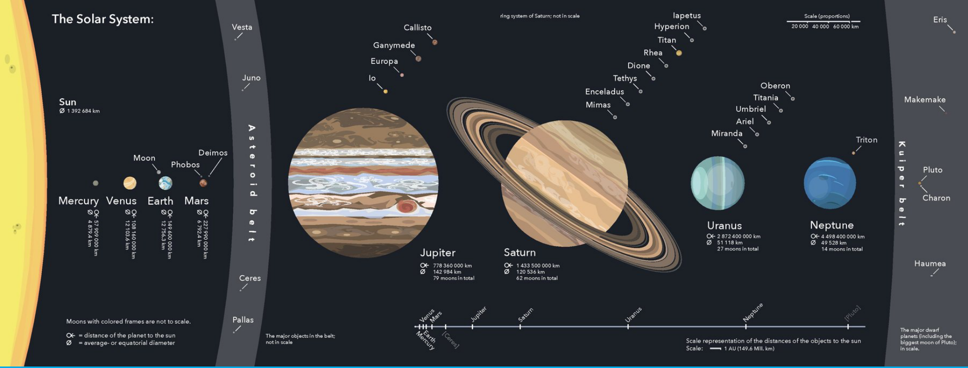


Planets (for internal Earth scientists), an introduction

Gaël Choblet
Laboratoire de planétologie et géodynamique, Nantes



Definition of a planet?

- probably not a primordial question,
- let us ask this question again at the end of the class.

JUPITER System

0

Io

1.77 days • 422 thousand km

Europa

3.55 days • 671 thousand km

Ganymede

7.15 days • 1.07 million km

Callisto

16.69 days • 1.88 million km

ORBITAL PERIOD

TRAPPIST-1 System

0

1b

1.51 days • 1.66 million km

1c

2.42 days • 2.28 million km

1d

4.05 days • 3.21 million km

1e

6.10 days • 4.21 million km

1f

9.21 days • 5.55 million km

1g

12.35 days • 6.75 million km

1h

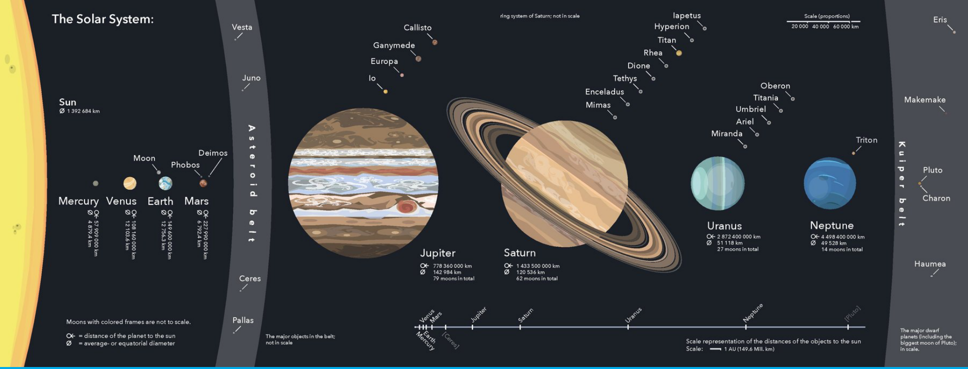
~20 days • ~9.42 million km

TRAPPIST-1

Comparing sizes and orbital periods.

All sizes scaled to Jupiter.

TRAPPIST-1 is a system containing seven planets comparable to Earth. They orbit a small star called an ultra-cool dwarf. The distance of the planets to the star means that liquid water could likely persist on their surfaces. The system was found when the planets passed in front of the star, casting a shadow called a transit. This property means that we will be capable to investigate their climate and chemical composition, an essential step ahead of finding-out whether life has emerged there.



At first order, three primordial aspects seem to possibly affect the history and internal structure of planets

- the distance to “their” star,
- the composition,
- the size.

The role of distance to the Sun: where would be an Earth whose internal heat budget matches the solar heat flux?

Heat flux received by the Earth from the Sun:

- solar constant $s = 1.361$ kW m^{-2},
  flux density measuring the mean solar electromagnetic radiation (solar irradiance) per unit area at one astronomical unit (au),
- heat received by the Earth: $\pi R_\oplus^2 s$ on a $4\pi R_\oplus^2$ surface, i.e. 340 W m^{-2},
- slightly smaller at Earth's surface. . .

Heat flux from Earth's interior: 90 mW m^{-2}

Pluto's distance: 30-50 au. But Puto is not 100% rocks (ices/organic matter). And might have retained less heat at present.

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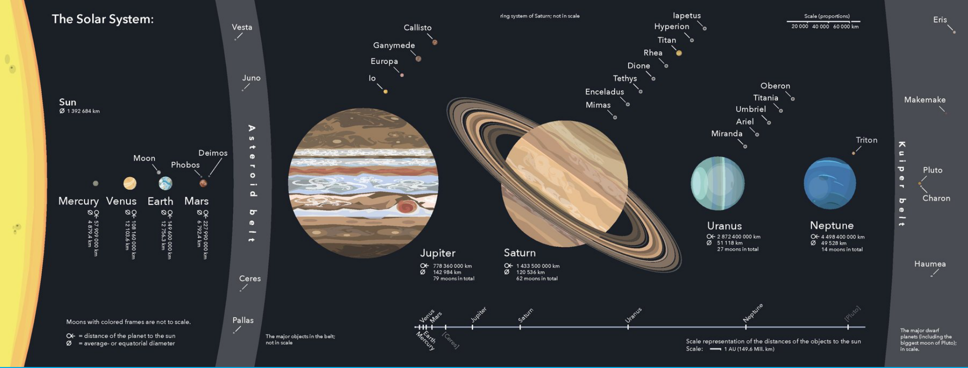

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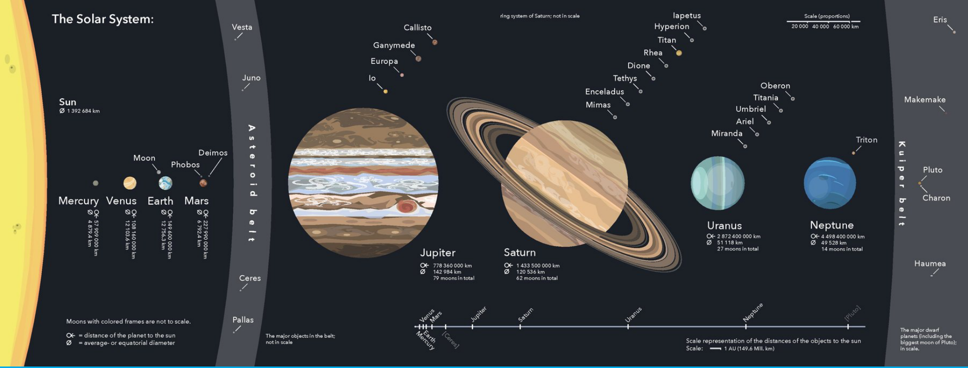

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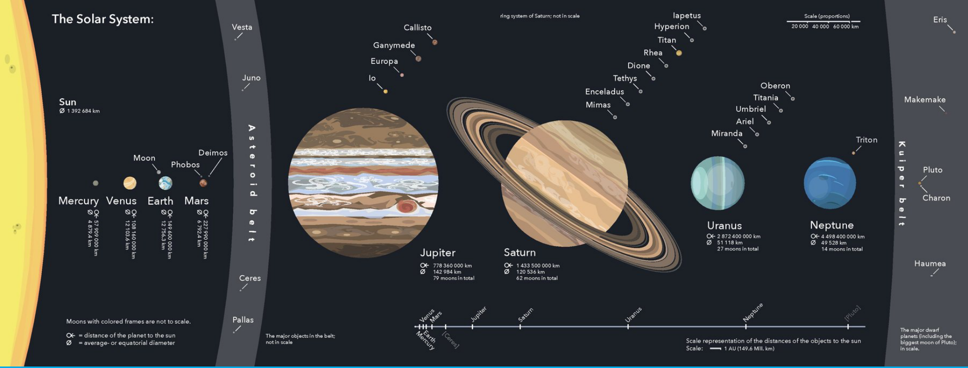
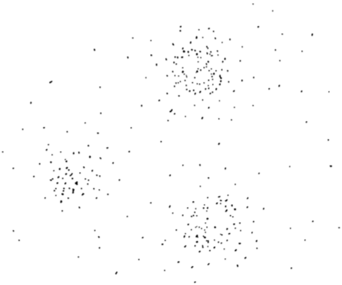
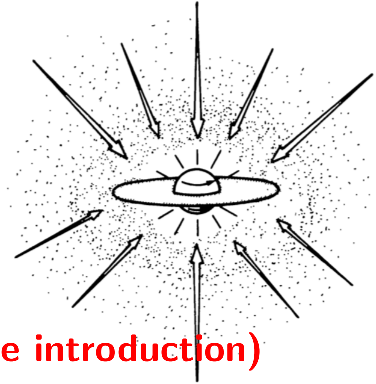


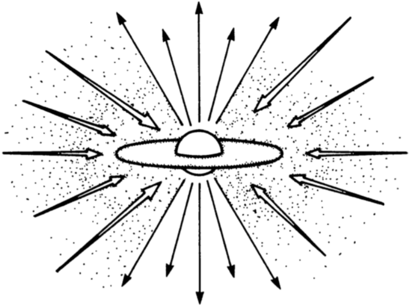
Outline

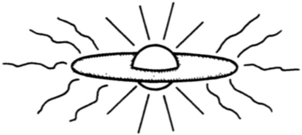
- 1. introduction (of the introduction)
- 2. Venus and the Earth
- 3. the role of size x on the (simplified) thermal history of a terrestrial planet

1. Introduction (of the introduction)



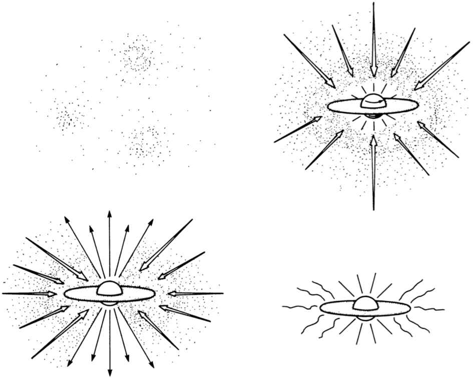






Formation of the solar system

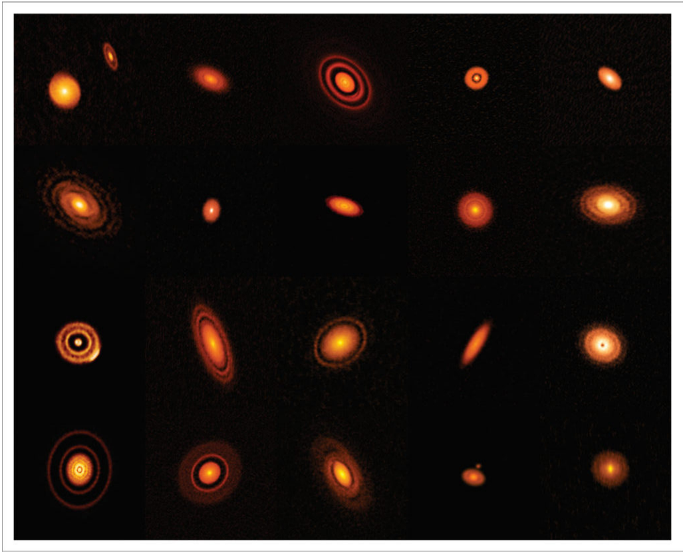
P.-S. Laplace noticed that all the planets and moons known to him rotated in the same direction which is very unlikely (he used a bayesian interpretation of probability). This gave observational root to the *nebular hypothesis*.



Tielens (1988)

- 1. formation of dense clumps of dust and gas in molecular clouds,
- 2. rotating clumps undergo gravitational collapse (triggered by supernova?) and form a heated central object surrounded by a disk (conservation of angular momentum),
- 3. powerful stellar wind reverses flow of incoming material,
- 4. protostar and surrounding disk (embryonic solar system of planet-sized bodies resulting from repeated collisions, i.e. accretion) become visible.

Observed protoplanetary disks!!

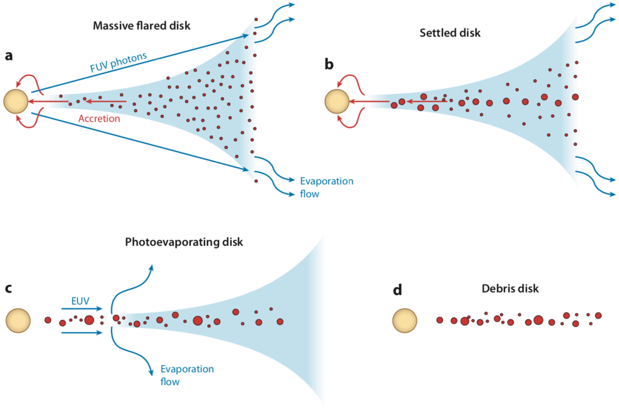


Disk Substructures at High Angular Resolution Project (DSHARP)

at Atacama Large Millimeter/submillimeter Array (ALMA) (2018)

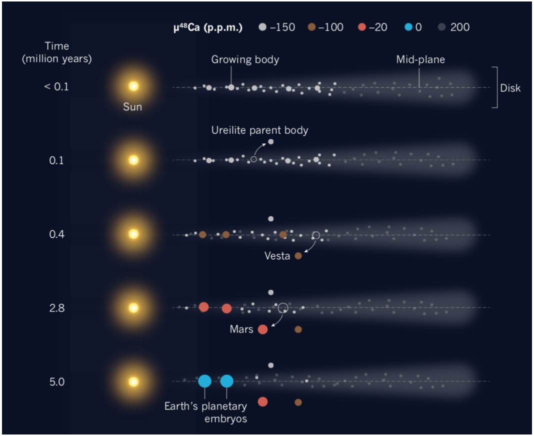
Evolution of the disk, planetary accretion

Williams et al. (2011)



although the large picture is relatively clear, key aspects of the scenario remain enigmatic with competing models. . .

Evolution of the disk, planetary formation



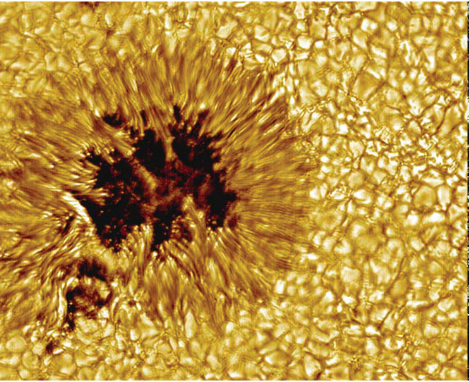
Schiller et al., 2018:

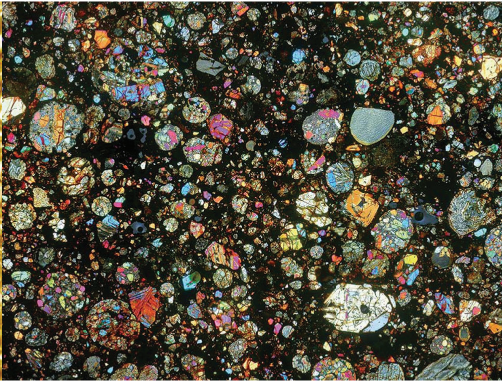
- the calcium-isotope composition of planetary bodies in the inner Solar System correlates with their masses,
- this suggests that all bodies grew at the same time but stopped accreting at different times (unconventional view).

"The authors' work adds a missing piece to the jigsaw puzzle of planet formation that will need to be connected with the other pieces provided by isotopic, chemical, chronological and dynamical constraints. Although the puzzle seems more complete than before, perhaps some other key pieces are still missing."
Morbidelli, in the "news and views" section

Composition of the nebula

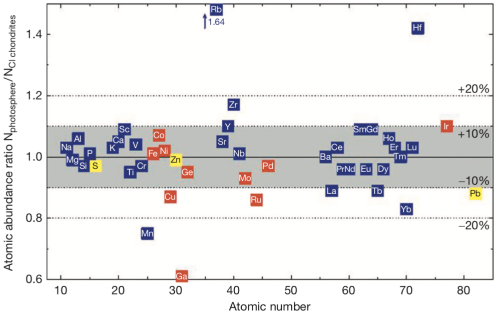
- the nebula/protoplanetary disk model suggests the planets and the Sun should have a similar composition
- access to this nebular composition: solar composition (photosphere), primitive meteorites,





Composition of the nebula

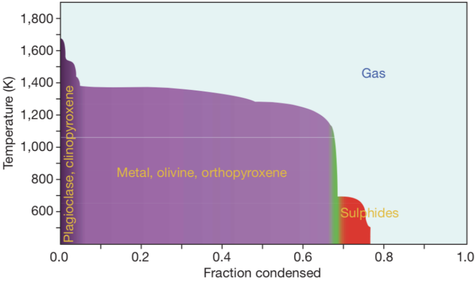
- the nebula/protoplanetary disk model suggests the planets and the Sun should have a similar composition
- access to this nebular composition: solar composition (photosphere), primitive meteorites,
- both are very similar (except for the most volatile elements)!

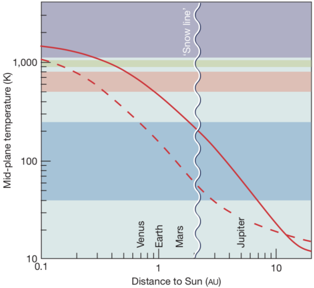


lithophile, siderophile, chalcophile, *Treatise on geochemistry, Palme et al., (2014)*

Composition of planets

Albarède (2009)

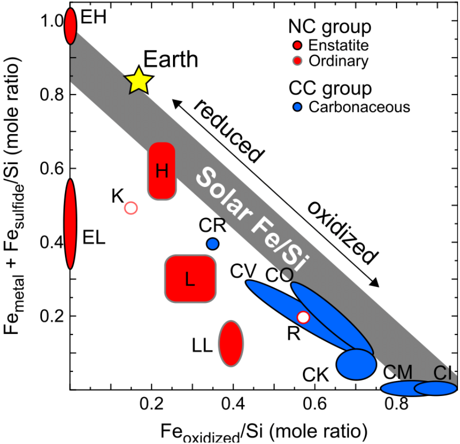




- upon cooling, elements are accreted according to a specific sequence of condensation (see example on the left),
- the modeled thermal structure of the nebula involves a *snow line* located around the asteroid belt (see example on the right),
- volatiles depleted in inner solar system owing to powerful solar wind, and small terrestrial planets do not accrete H from nebula.

But the solids (from agregates to large planetesimals and even planets) migrate: this is certainly true for some exoplanetary systems and probably also in our solar system.

Subsequent chemical evolution, the example of Fe



the Urey-Craig diagram: oxidation state of iron relative to silicon among chondrite groups,

- no Fe metal (or sulfide) in the most primitive (carbonaceous) chondrites,
- ordinary chondrites involve various amount of Fe metal, and some enstatite chondrite may contain no iron oxide,
- the Earth and its core is considered to host a large fraction of Fe metal: specific planetary events (e.g. magma oceans) are expected to affect the redox state of planets...

Other constraints on the composition of planets

surface/subsurface:

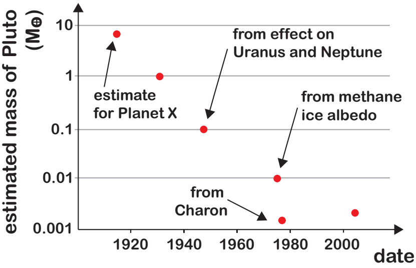
- samples exist from planets (Earth, Moon, Mars, Vesta),
- in situ analysis of some planets composition (Mars, Venus, Enceladus),
- remote sensing of planetary surfaces.

differentiated bodies

- most planets are at least partially differentiated with denser materials at depth,
- most often, only superficial layers are accessed - even on Earth (bridgemanite was observed in a meteortie, no rocks from the Earth's core),
- terrestrial planets start hot and form a buoyant crust (basalts), icy bodies have hydrospheres enveloping denser materials.

Constraints on the deeper layers, interior structure

- mass and density from the orbit of a natural satellite or the effect on another planet (harder, see left),



- moment of inertia estimated from the low degrees of gravity estimated from flybys (under specific assumptions such as hydrostastic equilibrium).
- combining topography and gravity retrieved from spacecraft measurements provides indirect constraints on interior (again this involves assumptions on some form of relaxation).

Key properties of planets (akin to a definition)

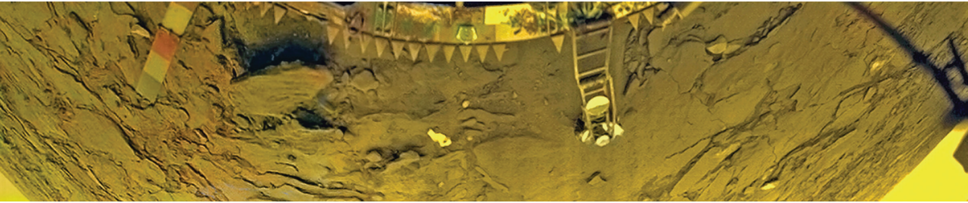
self-gravity:

- exceeds electronic energy of atoms for a large enough body,
- causes differentiation, allows convection.

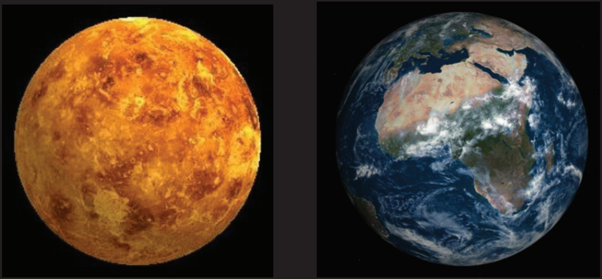
heat:

- hot start for terrestrial/large planets, cold start for icy/smaller moons,
- radiogenic decay up to geological time scales,
- difficult to extract: materials are heated, they flow, they melt which gives rise to most phenomena observed at the planet's surface (volcanism, magnetism, etc.).

2. Venus and the Earth

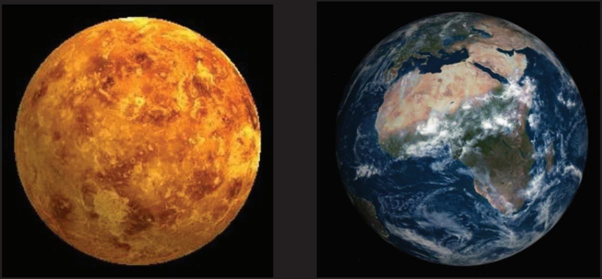


Venus and the Earth are alike



distance to sun (au)	0.72	1
radius (km)	6052	6371
mass ($M_\oplus$)	0.8	1
density (kg m^{-3})	5.24	5.51
gravity (m s^{-2})	8.87	9.81
MoI	*0.33*	0.3308
composition	rocks + metal	rocks + metal

Venus and the Earth are not alike



rotation (days)	243	1
revolution (days)	224.67	365.25
obliquity (°)	-2.9	23.45
J_2 coefficient (/Earth)	0.001	1
atmos. compo. (%)	96 CO_2, 3.5 N_2, SO_2...	78 N_2, 21 O_2, H_2O...
atmos. pressure (bars)	90	1
surface temp. (°C)	460	15
albedo	0.78	0.30
present dynamo, moon	no	yes

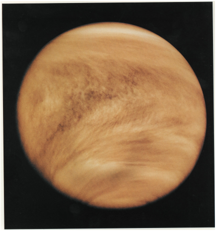
the Les Houches (2021) curriculum with a Venus focus

A pass to the Deep Earth (H-C. Nataf)

$\sim$

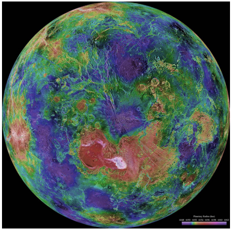
my parents/me:

visible
(Pioneer orbiter, 1979)



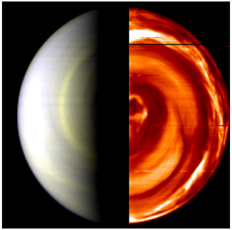
solar wind/ionosphere
upper atmosphere
first glance at surface

radar
(Magellan, 1990)



global topography
surface geology

infrared
(Venus Express, 2006)



atmosphere
recent volcanism?

+ soviet Venera program (1960s-1980s, including 1st landing on other planet)
+ japanese Akatsuki mission (2010-present with failed orbital insertion)

A pass to the Deep Earth (H-C. Nataf)

$\sim$

my children/you:

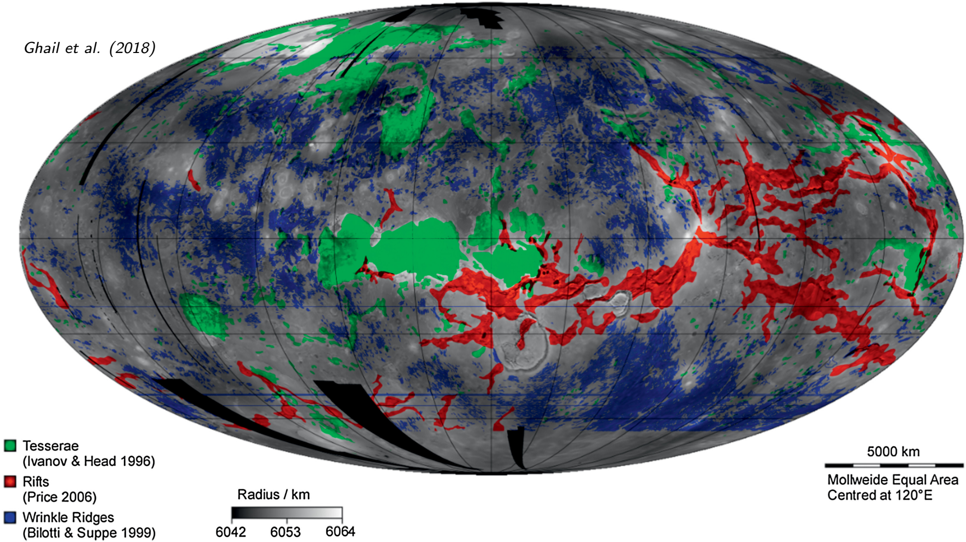
2031- 2033- 2035-

in-situ entry probe in atmosphere:
- atm. composition/structure
- noble gases isotopes during descent
- imaging of tesserae

complementary global surveys:
- topography and imagery from SAR
- gravity
- near-IR emissivity

formation/early evolution scenarios
geodynamics

internal structure
(crust/lithosphere/mantle/core)



tesserae are highly tectonically deformed, often ancient, regions on Venus - sometimes interpreted as buoyant continents.

other global scale tectonic features: relatively quiescent basins (with possibly wrinkle ridges denoting cooling of basaltic lava), bounded by high strain rifts.

Introduction to body and surface waves (B. Romanowicz)
Seismic anisotropy (J.-P. Montagner)
Introduction to normal modes (S. Rosat)
Inverse problem (B. Romanowicz)
Diffusion of seismic waves in the Earth (L. Margerin)

∼

the material in all these classes is also valid and pertinent for Venus.
⇒ obviously the data we miss most: imagine the knowledge on Earth interior without seismology. . .

Venera 14 landing (1981), life expectancy on venusian soil: 57 minutes.

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Introduction to geodesy (I. Panet)

∼

probably the best bet in the coming years!

Introduction to rheology (F. Garel)
Introduction to core mineral physics (G. Morard)
Mineral physics : rock deformation and anisotropy (A. Tommasi)
Mineral physics for magneto-tellurics and seismology (B. Reynard)
Experimental petrology and water in the mantle (S. Demouchy)

$\sim$

all this is also valid and readily available for Venus! probably a key for lithosphere/mantle/core dynamics:

- what is the role of a hot surface?
- what role do volatiles (including water) play on the global geodynamics?
- can we envision a different core composition? or has the absence of dynamo a purely thermal origin?

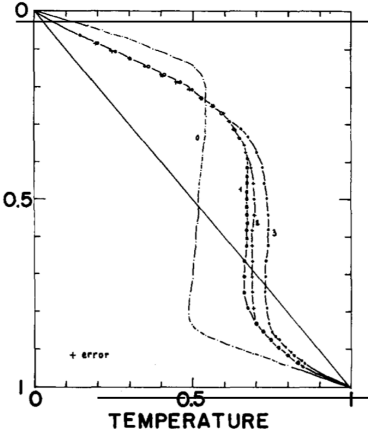
Introduction to geodynamics (S. Labrosse)
What is a plate ? (F. Garel)
Lithosphere and mantle dynamics (M. Arnould)
Grain dynamics and mantle convection (Y. Ricard)

$\sim$

- here is the reign of models (numerical, experiments),
- because of the lack of data, Venus is paradise,
- some failed Earth-like models were considered Venus-like (stagnant-lid regime),
- some propose a more convincing pathway to Earth/Venus dichotomy (e.g. limited lithospheric damage and inheritance for hot surface conditions, Ricard and Bercovici, 2014, cf. Jean's presentation yesterday).

the stagnant-lid regime

for strongly temperature-dependent viscosity, the asymptotic regime for thermal convection involves a cold and viscous lid atop a quasi-isoviscous convecting layer

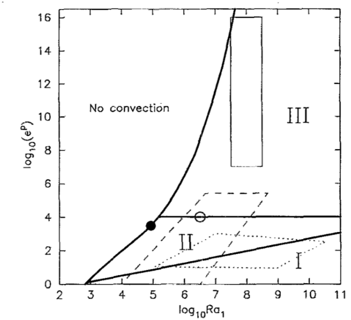


Nataf and Richter (1982)

- temperature-dependence of viscosity breaks the symmetry between the hot and cold boundary layers (BL) - the latter grows (vertical advection is less efficient), and eventually becomes stagnant,
- an exemple of epistemological paradox for geodynamics: adding an ingredient that is attested and expected to play a key role makes the model less realistic when compared to models that neglect it.

the stagnant-lid regime

$\eta = \eta_0 \exp(-\gamma T)$ (non-dimensional viscosity parameter $p = \gamma \Delta T$)



Solomatov (1995)

I: low viscosity regime, II: mobile-lid regime, III: stagnant-lid regime.

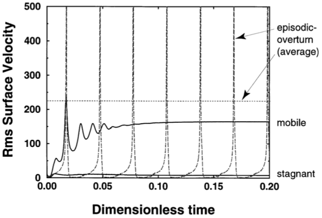
- the lid thickness (δ_0) is
  $\delta_0 \sim dp^{4/3} Ra_i^{-1/3}$
  with Ra_i defined with interior viscosity
  (this translates the classical balance between mechanical work of buoyancy and viscous dissipation)
- only a small part of the lid participates to convection, with a thickness
  $\delta_{rh} \sim \delta_0/p$
  also equal to the thickness of the hot boundary layer as convection is isoviscous beneath the lid,
- the corresponding temperature difference is
  $\Delta T_{rh} \sim p^{-1} \Delta T$,

catasrophic resurfacing of Venus and the episodic overturn

spatial distribution of impact craters on Venus:

- seems random (while all other aspects do not),
- consistent with a uniform age of 500-750 Myr
- considered as evidence for a global/catastrophic resurfacing event (i.e. where a one-plate lithosphere subducts within the planet),
- note this is also consistent with the end of global magmatism. . .

this led to the notion of an episodic regime alternating stagnant- and mobile-lid periods (Moresi and Solomatov, 1998):

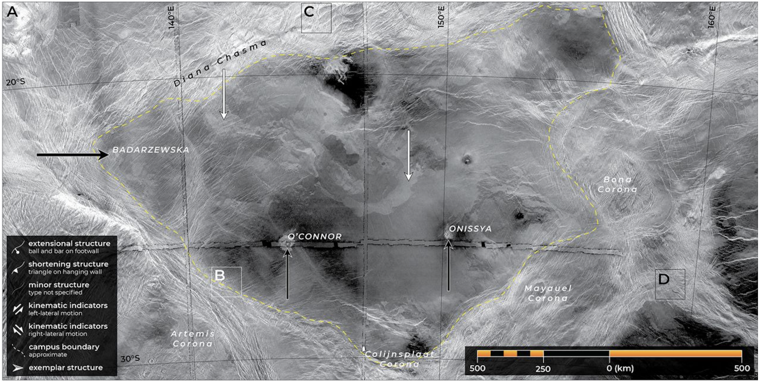


- such a behavior is obtained for a temperature-dependent fluid when brittle failure is mimicked by the use of Byerlee's law to limit the maximum stress in the lithosphere,
- the dichotomy between Earth and Venus is attributed to the friction coefficient (a higher value on Venus, owing to dry conditions, enables the intermittent regime).

towards more complex interpretations

a reappraisal may be required:

- evidence for ongoing deformation within the lowlands (i.e. that postdates the emplacement of magmatic material),
- fragmentation into crustal blocks with apparent motion, possibly driven by deeper mantle dynamics.



Byrne et al., (2021)

Introduction to core convection (T. Alboussière)
Introduction to the geodynamo (N. Schaeffer)

$\sim$

- slow rotation does not seem sufficient to explain the absence of a dynamo,
- no knowledge of possible extinct dynamo preserved in the Venusian crust,
- is this simply caused by a different thermal history (e.g. no inner core)?
- is a planetary dynamo the rule or the exception?

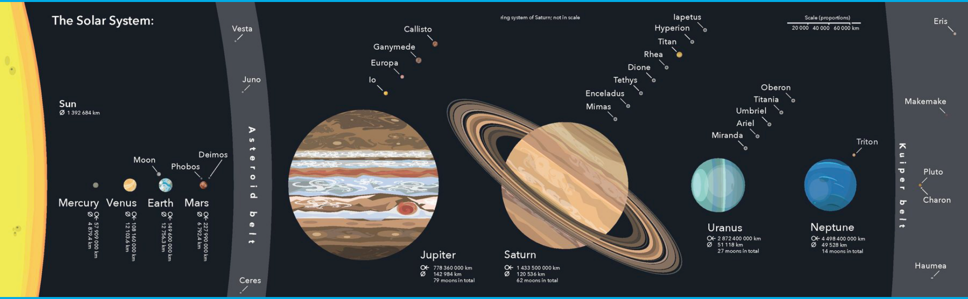
Formation and differentiation of the Earth (M. Landeau)
Magma oceans (S. Labrosse)

∼

H.-C.'s question "back to the future": how was Venus 4 Ga ago? the most fascinating aspects when declined for Venus, essentially two scenarios:

- Venus and the Earth once were twins (plate tectonics? oceans?) but became evil sisters (coupled interior-climate models, runaway greenhouse?),
- Venus and the Earth were initially shaped as distinct worlds - not satisfactory for Earth interior scientists but what about the Moon formation event. . .

when attending these two classes, please keep Venus in mind and ask questions to Maylis and Stéphane.


The Solar System:
Sun
Ø 1 392 684 km
Mercury
○← 57 909 000 km
Ø 4 879.4 km
Venus
○← 108 160 000 km
Ø 12 103.6 km
Earth
○← 149 600 000 km
Ø 12 756.3 km
Moon
Mars
○← 227 990 000 km
Ø 6 792.4 km
Phobos
Deimos
Vesta
Juno
Asteroid belt
Ceres
Callisto
Ganymede
Europa
Io
Jupiter
○← 778 360 000 km
Ø 142 984 km
79 moons in total
ring system of Saturn; not in scale
Iapetus
Hyperion
Titan
Rhea
Dione
Tethys
Enceladus
Mimas
Saturn
○← 1 433 500 000 km
Ø 120 536 km
62 moons in total
Oberon
Titania
Umbriel
Ariel
Miranda
Uranus
○← 2 872 400 000 km
Ø 51 118 km
27 moons in total
Triton
Neptune
○← 4 498 400 000 km
Ø 49 528 km
14 moons in total
Scale (proportions)
20 000
40 000
60 000 km
Eris
Makemake
Kuiper belt
Pluto
Charon
Haumea

The Solar System:

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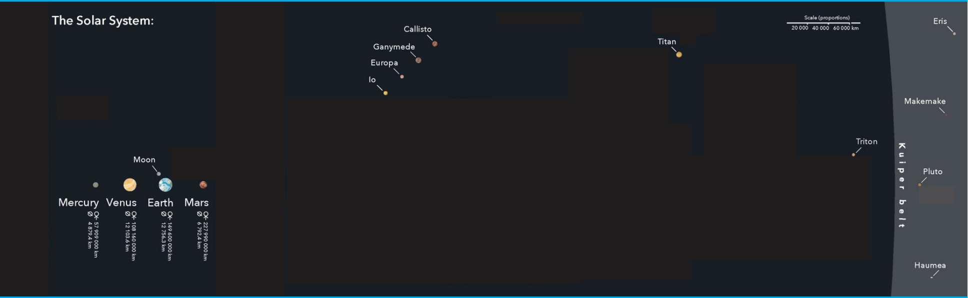

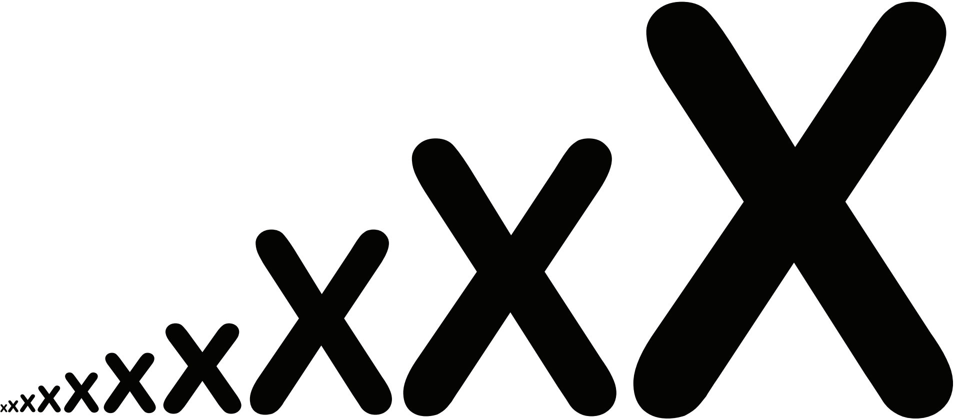

3. the role of size x on the (simplified) thermal history of a terrestrial planet

Accretional heat

Let us assume a planet (planet x) with a radius $R_x = xR_\oplus$, with a bulk density ρ equal (?) to Earth's.

Its gravity is $g_x = \frac{GM_x}{R_x^2} = xg_\oplus$.

The potential energy to accrete a unit mass on this planet is $\frac{GM_x}{R_x}$ (also the kinetic energy of an impact at escape velocity) and its accretion involves building shells from 0 to R_x:

$E_x = \int_{r=0}^{r=R_x} dE(r)$ with $dE(r) = \frac{GM(r)}{r}\rho S(r)dr$.

$E_x = \frac{3}{5}\frac{GM_x^2}{R_x}$.

If all heat is retained in the planet (?), the average temperature increase associated to accretion within planet x is

$\Delta T_x^a = \frac{E_x}{c_p M_x} = \frac{3}{5}\frac{GM_x}{c_p R_x}$.

This constitutes the following fraction of the temperature increase of an Earth-sized planet:

$$\boxed{\Delta T_x^a = x^2 \Delta T_\oplus^a}$$

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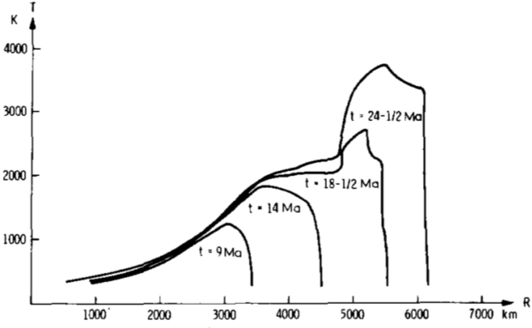
Accretional heat

The above derivation is not realistic as it neglects surface cooling: $\Delta T_{\oplus}^{a} = 30000$ K...

Interior convection could be accounted for as well, Kaula (1979) did that for the accretion of the Earth (with possibly a problem with the numerical integration):



Melting/vaporization could be added.

Heating from core formation

The potential gravitational energy of planet x, once formed but not differentiated (?), is
$U_x^h = -\frac{16}{15}\pi^2 G R_x^5 \rho^2$

Once a metallic core of density ρ_c has been formed leaving a rock mantle of density ρ_m (both densities equal to Earth's core and mantle, respectively (?)), the new potential energy is smaller:
$$U_x^d = -\frac{16}{15}\pi^2 G R_x^5 \left[\rho_m^2 + \frac{5}{2}\rho_m\left(\rho - \rho_m\right) + \left(\frac{3}{2}\rho_m - \rho_c\right)\left(\rho_m - \rho_c\right)\left(\frac{\rho-\rho_m}{\rho_m-\rho_c}\right)\right]$$

The loss in gravitational energy is dissipated in the interior. If this occurs uniformly (?), the associated temperature increase scales as follows with regard to an Earth-sized planet:
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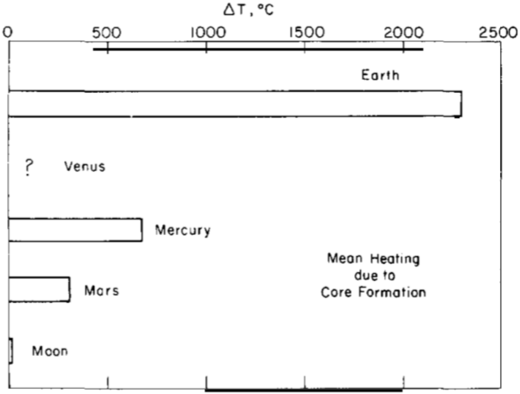
Heating from core formation

Solomon (1979) performed this sort of calculation for terrestrial planets:



In practice, the partition of the differenciation heat into mantle and core depends on the formation process. A fast or even catastrophic event will tend to locate heating in the core.

Summary of primordial heat sources

In the case of Mars, the following heat contributions have been reported:

accretion	(Wetherill, 1990)	4×10^{30} J
differenciation	(Solomon, 1979)	2×10^{30} J
short-lived radiogenic*	(Elkins-Tanton, 2005)	2×10^{30} J

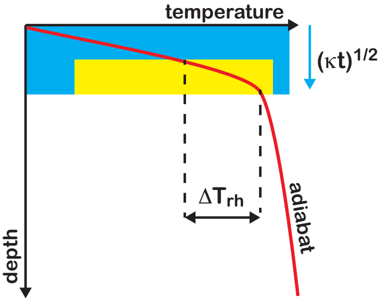
*: *integrated decay of* ^{26}*Al.*

More than sufficient to induce large scale melting.

Accretion and differenciation heating are expected to strongly increase with planet size x ; radiogenic is not.

Onset of convection (after Stevenson, 2003)

Once the surficial magma ocean has solidified, after time t, a cold front will propagate downward, conductively, up to a depth $\delta \sim \sqrt{\kappa t}$. As in the stagnant lid regime formalism, $\eta = \eta_0 \exp(-\gamma T)$.



after Stevenson (2003)

- owing to the temperature-dependence of viscosity, the temperature difference driving the first convective instability ΔT_{rh} is only a fraction of the difference across the cold boundary layer,

- the relevant Rayleigh number for the onset of convection for planet x is $Ra = \frac{\alpha \rho g_x \Delta T_{rh} \delta^3}{\kappa \eta_i}$ the latter reaching a critical value of $\sim 10^3$ in about 100 Myr$/x^{2/3}$.

Subsequent cooling in the stagnant lid regime (after Stevenson, 2003)

The heat flux is related to the rheological sublayer

$F_x \sim k\Delta T_{rh}/\delta$

with

$\frac{\alpha\rho g_x \Delta T_{rh}\delta^3}{\kappa\eta_i} \simeq 10^3$ (critical Ra_x)

and

$\Delta T_{rh} \simeq 5/\gamma$ (stagnant lid experiments).

so that

$F_x \simeq k\left(\alpha\rho g_x/\kappa\eta_i\right)^{1/3}\gamma^{-4/3}$

In terms of size x, the heat flux scales as heat produced in the planet ($\propto x^3$) divided by the planet's surface area ($\propto x^2$), so that

$F_x \propto x$

which implies

$\eta_i \propto g_x/F_x^3 \propto x^{-2}$

It comes that the internal temperature difference between planet x and the Earth-size planet is

$\boxed{T_x^i - T_\oplus^i = 2\ln x/\gamma}$

with smaller planets (negative $\ln x$) being colder and more viscous.

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$$F_x \simeq k\left(\alpha\rho g_x/\kappa\eta_i\right)^{1/3}\gamma^{-4/3}$$

While the global Rayleigh number (based on d) will strongly vary with x (and so will the flow amplitude), the heat flux F_x is almost independent of the size (except through g_x).

Of equal importance is the fact that the thickness of the unstable layer δ is independent of the actual thickness of the mantle d. More, the stagnant lid thickness $\delta_0 \sim dp^{4/3} Ra_i^{-1/3}$ is also independent of d (1/3?). As a conclusion, the thickness of the lithosphere is the same for all values of the planet's size x, all other things being equal.

In the above relationship for heat flow, most variables are constant or do not vary much, besides viscosity η_i. As a consequence, the time evolution of F_x is that of η_i:
$d \ln F_x/dt = -\left(d \ln /\eta_i/dt\right)/3$

Further, assuming that $F_x(t)$ is equal to the radiogenic heat produced at time t, $Q_x(t) = Q_x 0 \exp\left(-\lambda t\right)$ (?), it follows that

$$\boxed{dT_x^i/dt = -3\lambda/\gamma}$$

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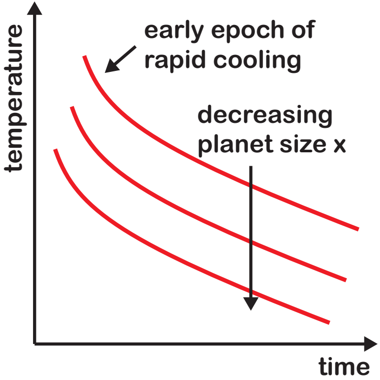
Thermal history in the stagnant lid regime (after Stevenson, 2003)

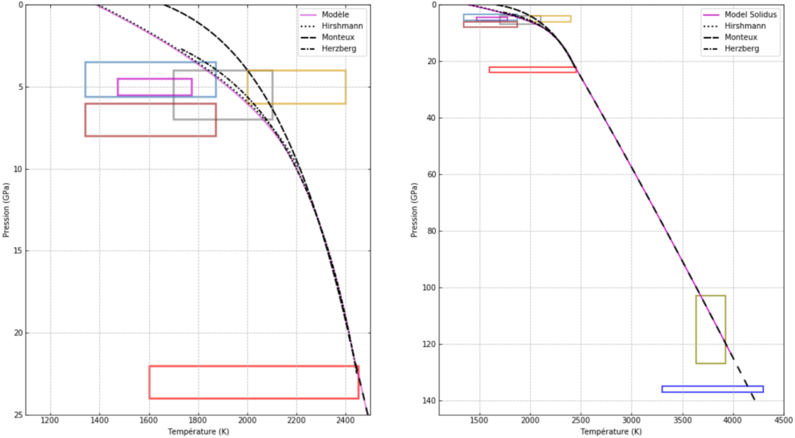
In summary, larger planets start hotter. The initially high temperatures are soon forgotten as a result of temperature-dependence of viscosity.



after Stevenson (2003)

- the offset between curves is $\boxed{T_x^i - T_\oplus^i = 2\ln x/\gamma}$
- the slope of the curves is $\boxed{dT_x^i/dt = -3\lambda/\gamma}$
- while γ varies little (50-100 K) and remains constant through time, λ is strongly time-dependent, which results in cooling rates in the range $[10, 150]$ K Gyr^{-1}.

Planet size x and melting effects



Earth Venus Mars Mercury Moon Io Europa Ganymede

pressure at the CMB

pressure P_x inside the mantle is related to the gravity (assumed uniform): $P_x(r) = x\rho_m g_\oplus \int_{r'=r}^{r'=R_x} r' dr' = x\rho_m g_\oplus \frac{{R_x}^2 - r^2}{2}$. Notably, at the CMB,

$$\boxed{P_x^{cmb} = x\rho_m g_\oplus \frac{{R_x}^2 - {R_x^{cmb}}^2}{2} = x^3 P_\oplus^{cmb}}$$

adiabatic temperature increase

A convenient estimate can be derived assuming a reference temperature, identical for all planets, T_0:

$$\boxed{\Delta T_x^a = \frac{\alpha g_x^s T_0 P_x^{cmb}}{c} = x^4 \Delta T_\oplus^a}$$

solidus temperature

Considering a solidus temperature of the form $T' = T_s'\left(1 + \frac{P}{P_0}\right)^\beta$ in the [0,20] GPa range. The solidus temperature at the CMB for planet x is

$$\boxed{T_x'^{cmb} = x^{3\beta} T_\oplus'^{cmb}}$$

Given the value of β, this induces a value of about 2400 K for a Mars-sized planet ($x \simeq 0.6$) and 1950 K for a Europa-sized planet ($x \simeq 0.3$).

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Final remarks

planetary sciences: data-driven sciences

- e.g. Stéphane's seminar on Pluto would not have existed without the New Horizons flyby,
- e.g. the chapter of this course on Venus,
- something you could forget when studying the Earth on the modeling side. . .
- in absence of seismology, use of topography and gravity of planets to constrain their interior,
- data that may seem antagonistic on Earth and left apart for the sake of progress, have to be complementary in the context of planets,
- an important note: planetary data exist (e.g. from the Cassini mission), and its analysis is far from exhausted. . .

Final remarks

mineral physics: despite a wealth of existing data already applicable (except for extremely HT/HP exoplanets), specific simple investigations still (maybe) required (a wish list)

- melting behavior of the Fe-FeS-Si-O system,
- more on serpentine's (or hydrated rocks) rheology,
- alteration of rocks in unusual conditions,
- how do slight compositional changes affect the mantle phase transitions of Mars or Venus? (cf. Paul's PhD project)
- how do compositional changes inherited from different histories affect the core compositions of Mars or Venus and their evolution?
- carbonaceous matter. . .

Final remarks

the scarceness of data, an opportunity for models:

- adjust models to available informations and consider their uncertainties,
- models for the interior of other planets cannot ressemble sophisticated models for Earth's interior,
- reductionist models that address a comparison between various planets are key to progress, even if they may be incomplete and thus lack pertinence.

Final remarks

when doing research on the Earth

- do not hesitate to project your ideas/questions/results on other planets, e.g. Venus.

when doing research on other planets

- check whether your ideas/techniques/assumptions would make sense for the Earth.