Terrestrial Planets

Week 6

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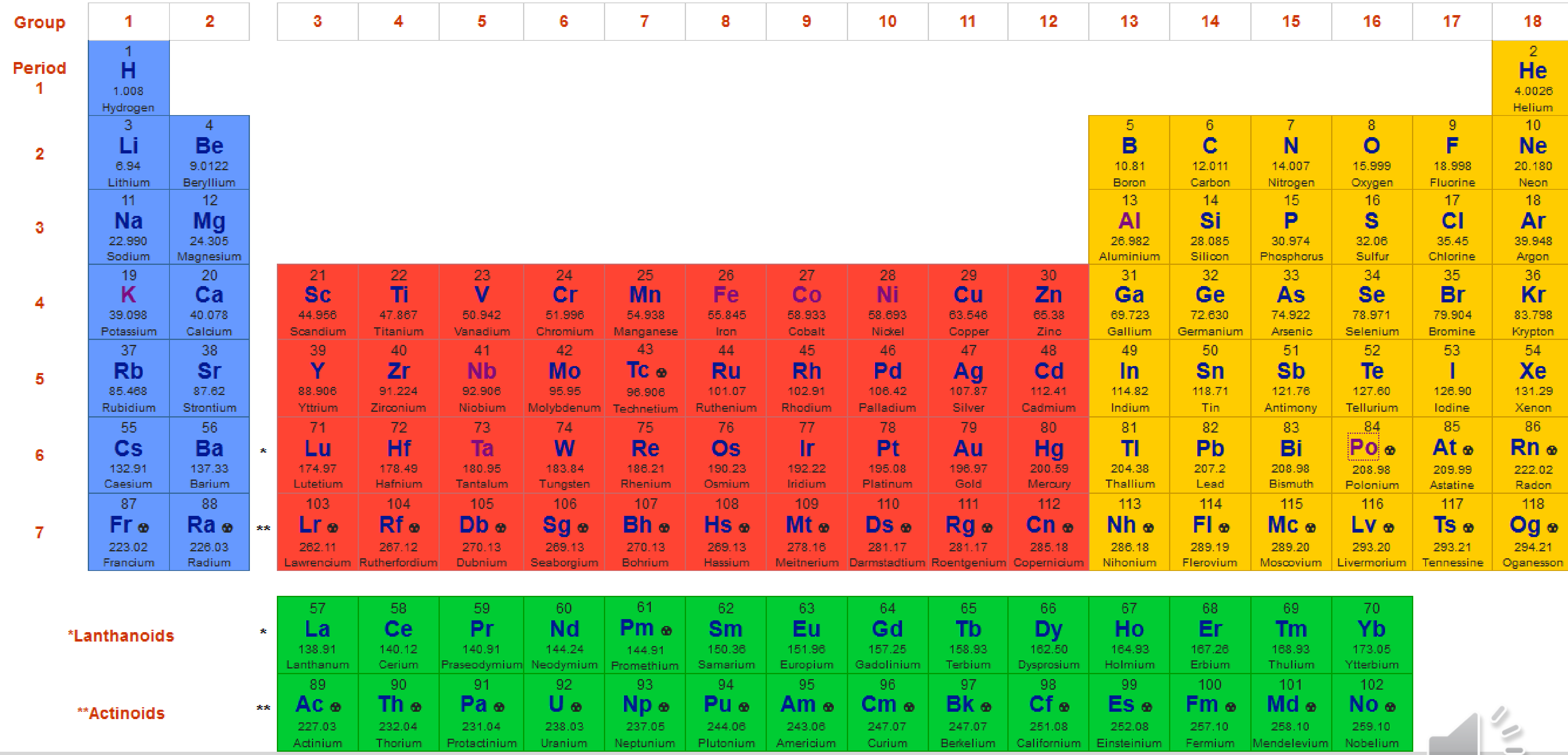
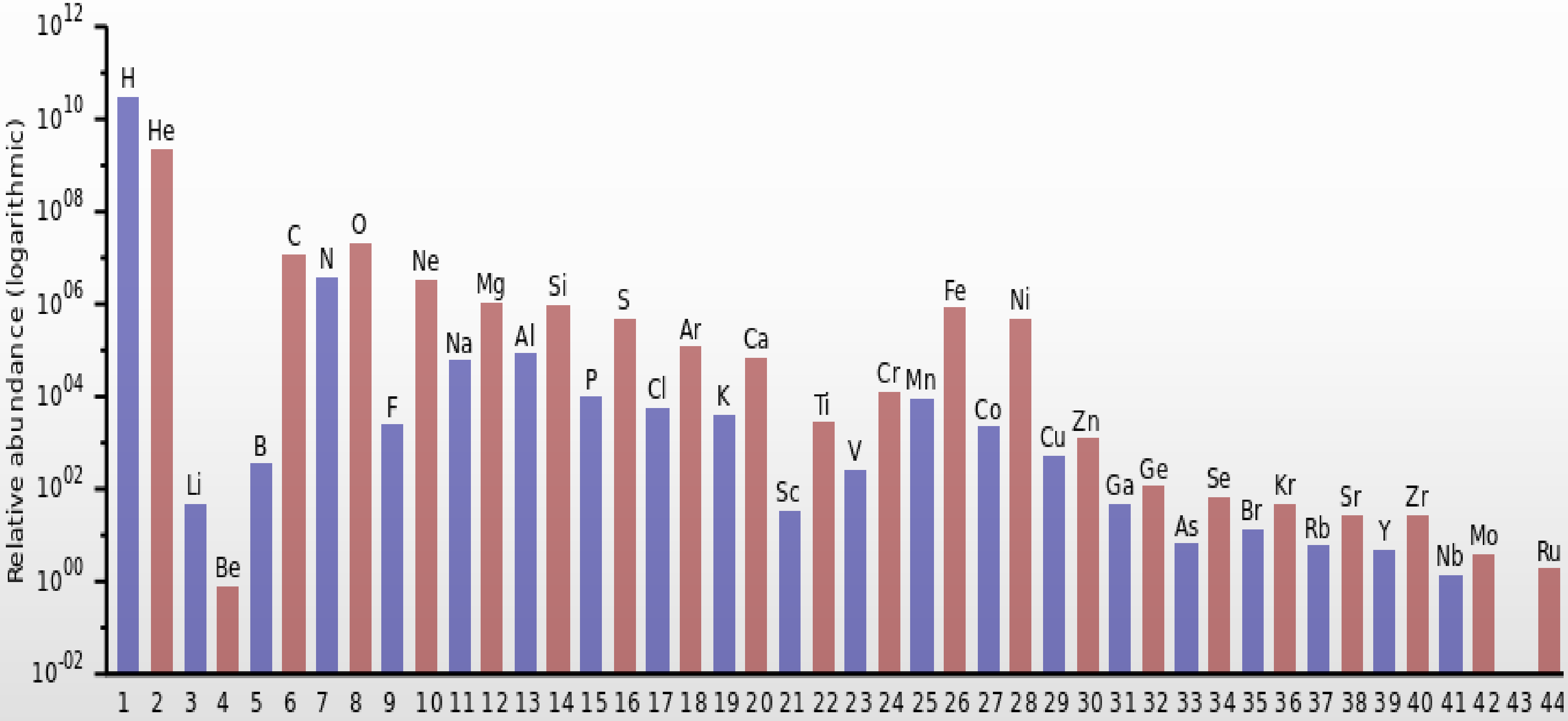
Earth and Planetary Sciences
FD Adams 131C

Solar system elemental abundances



Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H 1.008 Hydrogen																		2 He 4.0026 Helium
2	3 Li 6.94 Lithium	4 Be 9.0122 Beryllium												5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.999 Oxygen	9 F 18.998 Fluorine	10 Ne 20.180 Neon
3	11 Na 22.990 Sodium	12 Mg 24.305 Magnesium												13 Al 26.982 Aluminium	14 Si 28.085 Silicon	15 P 30.974 Phosphorus	16 S 32.06 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.948 Argon
4	19 K 39.098 Potassium	20 Ca 40.078 Calcium		21 Sc 44.956 Scandium	22 Ti 47.867 Titanium	23 V 50.942 Vanadium	24 Cr 51.996 Chromium	25 Mn 54.938 Manganese	26 Fe 55.845 Iron	27 Co 58.933 Cobalt	28 Ni 58.693 Nickel	29 Cu 63.546 Copper	30 Zn 65.38 Zinc	31 Ga 69.723 Gallium	32 Ge 72.630 Germanium	33 As 74.922 Arsenic	34 Se 78.971 Selenium	35 Br 79.904 Bromine	36 Kr 83.798 Krypton
5	37 Rb 85.468 Rubidium	38 Sr 87.62 Strontium		39 Y 88.906 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.906 Niobium	42 Mo 95.95 Molybdenum	43 Tc ☢ 96.906 Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
6	55 Cs 132.91 Caesium	56 Ba 137.33 Barium	*	71 Lu 174.97 Lutetium	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.84 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po ☢ 208.98 Polonium	85 At ☢ 209.99 Astatine	86 Rn ☢ 222.02 Radon
7	87 Fr ☢ 223.02 Francium	88 Ra ☢ 226.03 Radium	**	103 Lr ☢ 262.11 Lawrencium	104 Rf ☢ 267.12 Rutherfordium	105 Db ☢ 270.13 Dubnium	106 Sg ☢ 269.13 Seaborgium	107 Bh ☢ 270.13 Bohrium	108 Hs ☢ 269.13 Hassium	109 Mt ☢ 278.16 Meitnerium	110 Ds ☢ 281.17 Darmstadtium	111 Rg ☢ 281.17 Roentgenium	112 Cn ☢ 285.18 Copernicium	113 Nh ☢ 286.18 Nihonium	114 Fl ☢ 289.19 Flerovium	115 Mc ☢ 289.20 Moscovium	116 Lv ☢ 293.20 Livermorium	117 Ts ☢ 293.21 Tennessine	118 Og ☢ 294.21 Oganesson
*Lanthanoids			*	57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm ☢ 144.91 Promethium	62 Sm 150.36 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.05 Ytterbium		
**Actinoids			**	89 Ac ☢ 227.03 Actinium	90 Th ☢ 232.04 Thorium	91 Pa ☢ 231.04 Protactinium	92 U ☢ 238.03 Uranium	93 Np ☢ 237.05 Neptunium	94 Pu ☢ 244.06 Plutonium	95 Am ☢ 243.06 Americium	96 Cm ☢ 247.07 Curium	97 Bk ☢ 247.07 Berkelium	98 Cf ☢ 251.08 Californium	99 Es ☢ 252.08 Einsteinium	100 Fm ☢ 257.10 Fermium	101 Md ☢ 258.10 Mendelevium	102 No ☢ 259.10 Nobelium		

Solar system elemental abundances



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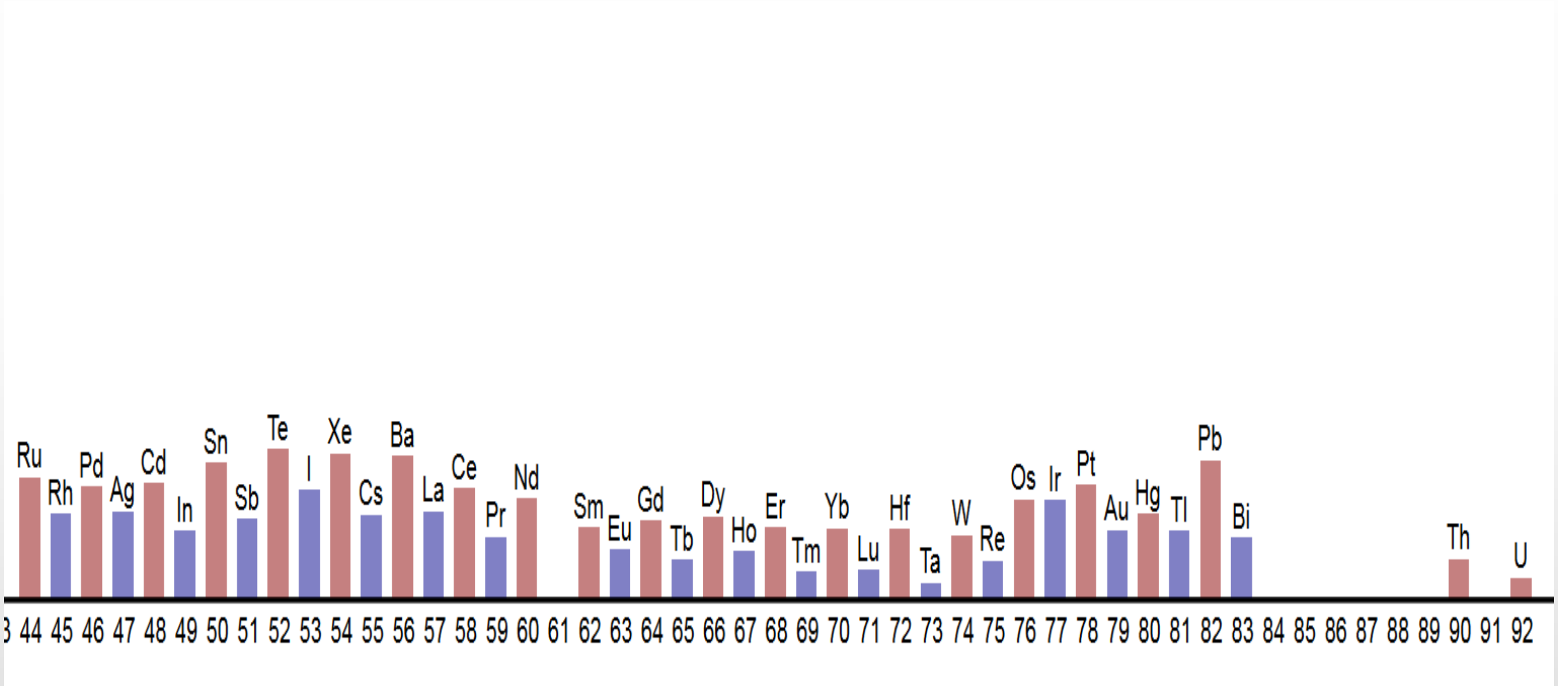
Solar system elemental abundances



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Elemental abundances in the Solar System

by atom-relative (to Si 10000)

Element	Atomic number	Atomic weight	Abundance (Urey 1950)
Hydrogen	1	1	400000000
Helium	2	4	31000000
Oxygen	8	16	215000
Neon	10	20	86000
Nitrogen	7	14	66000
Carbon	6	12	35000
Silicon	14	28	10000
Magnesium	12	24	9100
Iron	26	56	6000
Sulfur	16	32	3750
Argon	18	40	1500

Elemental abundances in the Solar System			
by atom-relative (to Si 10000)			
Element	Atomic number	Atomic weight	Abundance (Urey 1950)
Aluminum	13	27	950
Calcium	20	40	490
Sodium	11	23	440
Nickel	28	59	270
Phosphorus	15	31	100
Chlorine	17	35	90
Chromium	24	52	78
Manganese	25	55	69
Potassium	19	39	32
Titanium	22	48	24
Cobalt	27	59	18
Fluorine	9	19	16

Accretion – planets, asteroids

Gravity assembles bodies from the materials of the nebula.

In the inner region of the **Terrestrial Planets**, the materials of the nebula are largely the refractory minerals: silicates and metal oxides.

The volatiles such as **H**, **He**, **Ne**, **CH_4** and **H_20** are swept to greater distances in the solar system by the radiation pressure and winds issuing from the Sun. Beyond the "***ice line***" the **Gas Giants (Jupiter** and **Saturn)** and **Water Giants (Uranus** and **Neptune)** form.

What is Earth made of?

Our best model for Earth's bulk chemical composition is based on that of carbonaceous chondrites such as the Tagish Lake Meteorite.

Element	Composition by mass
Fe	32.0 %
O	29.7
Si	16.1
Mg	15.4
Ca, Al, Na, S	3.5
K	160 ppm (0.0187 ^{40}K)
Th	0.055
U	0.015

McDonough, 2003

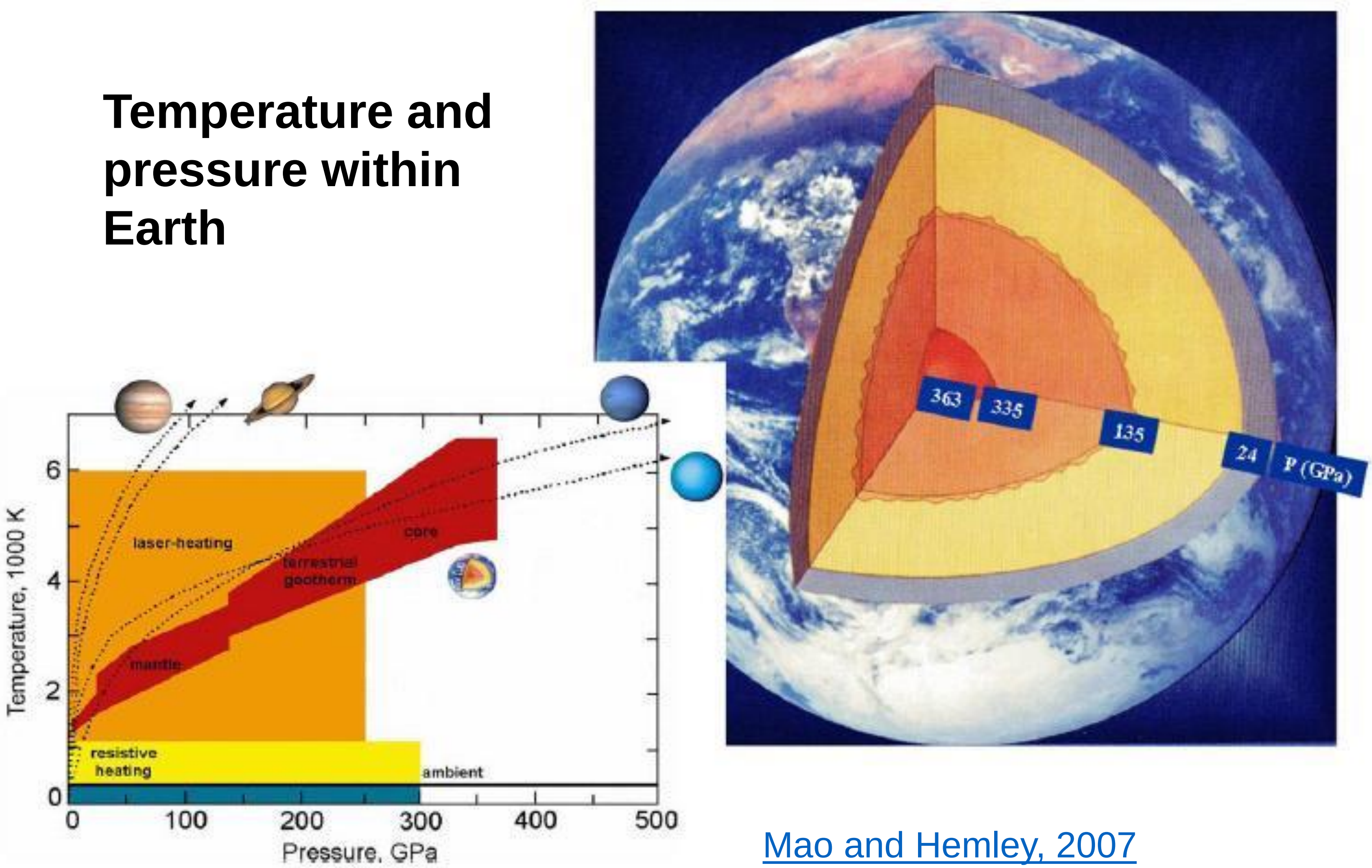
What is Earth made of?

Our best model for Earth's bulk chemical composition is based on that of carbonaceous chondrites such as the Tagish Lake Meteorite.

In bulk, by mass, it is thought to be composed of **Fe: 32%, O: 30%, Si: 16%, Mg: 15%, S: 2.9%, Ni: 1.8%, Ca: 1.5%,** and **Al: 1.4%**; with the remaining 1.2% consisting of trace amounts of other elements.*

The proportions of the major 4 elements that comprise **93%** of the total mass could be assembled into the mineral **Olivine** with chemical composition $\mathbf{FeMgSiO_4}$

Temperature and pressure within Earth



Mao and Hemley, 2007

The outer and inner core

The outer core is convecting vigourously; its temperature gradient must be very close to adiabatic. Still, we don't have good constraints on the thermal properties of the liquid outer core.

Temperature at the inner-core/outer-core boundary? Probably about *4500 K*.

Assuming an essentially iron-nickel inner core and adiabatic equilibrium, the inner core's central temperature is estimated to be about *5500 K*.

Mao and Hemley, 2007

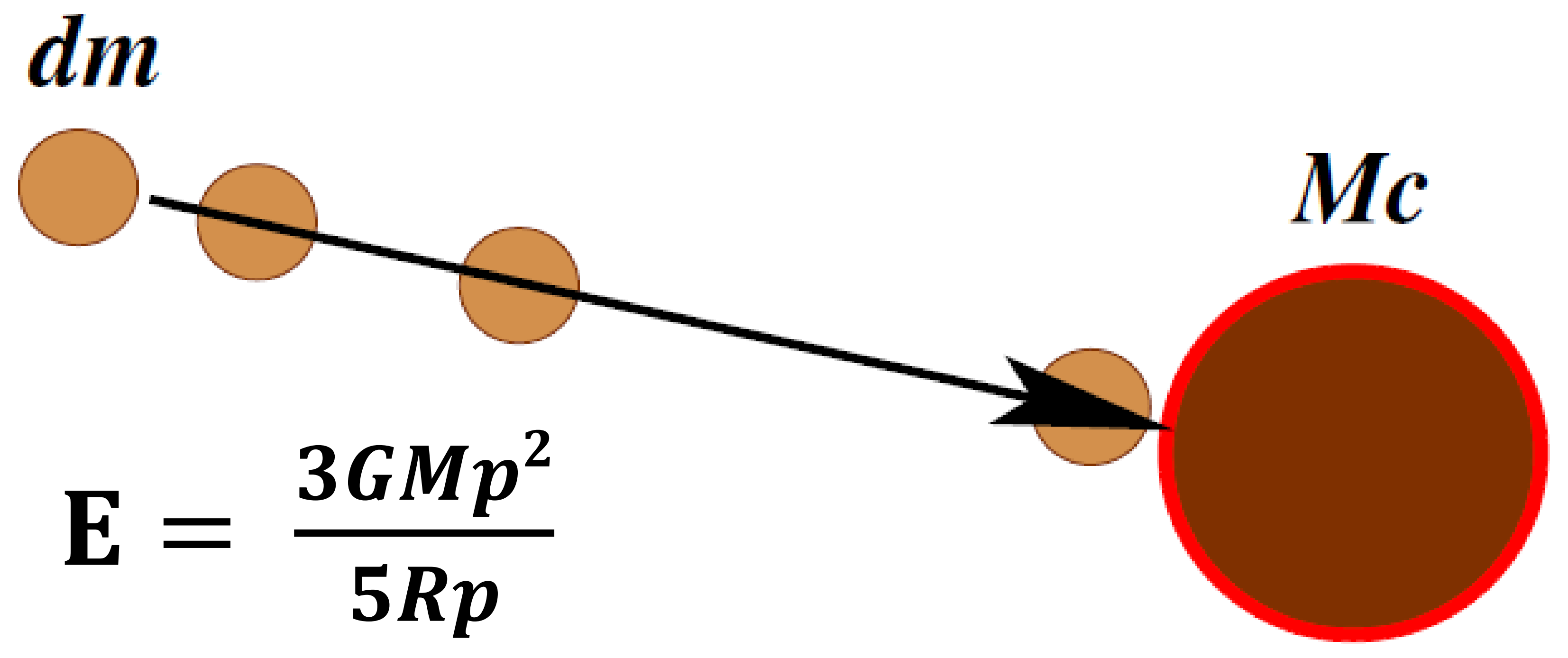
Heat from accretion

Mineral dusts and planetesmals are gravitationally attracted to some central mass concentration, $\boldsymbol{Mc}$. As these materials fall in, they gain kinetic energy which is deposited on the growing central mass. As the body, $\boldsymbol{Mc}$, grows to planet or stellar size, It accumulates **energy** from all of the in-falling mass. The energy heats the accreted mass and heats it to possibly very high temperature.

Differentiation

While most of the heat is re-radiated into space as the planet or body assembles, as temperature rises, the materials of the planet reassemble according to density. **Fe**, **Ni** and **siderophile** elements fall to the interior, forming the core and leaving a silicate mantle overlain by a crust of low density components.

Gravitational accretion



$$E = \frac{3GMp^2}{5Rp}$$

What **energy** of accretion is not re-radiated during the process is held as **heat** with a **temperature** that is determined by the **heat capacity** of the body's materials.

Heat capacity and T

Materials have very different capacities to hold heat. We call this physical ability **heat capacity, C_p**

A material with a high heat capacity holds heat with a low increase in temperature; one with a lower heat capacity requires a larger increase in temperature.

Heat capacity is usually measured according to the mass of a material with units: $\mathbf{J \cdot kg^{-1} \cdot K^{-1}}$ or $\mathbf{cal \cdot kg^{-1} \cdot K^{-1}}$. depending upon our units used for the heat energy, either **joules** or **calories***.

* The "diet" calorie is usually designated **Calorie** which is, in fact, 1 kilocalorie.

Heat capacities @ constant pressure C_p (25 C)

Material	Phase	J · K^{-1} · kg^{-1}	cal · K^{-1} · kg^{-1}
Water*	liquid	4181	1000
Wood	solid	1700-2900	407-694
Gypsum	solid	1090	261
Asphalt	solid	920	220
Concrete	solid	880	210
Marble, mica	solid	880	210
Brick	solid	840	201
Glass, silica	solid	840	201
Sand	solid	835	200
Soils	solid	800	191
Granite	solid	790	189
Hydrogen*	gas	14320	3421
Nitrogen	gas	1040	249
Air (STP)	gas	1012	242
Iron	solid	412	120
Gold	solid	125	30

* Note the relatively high heat capacity of water and gases

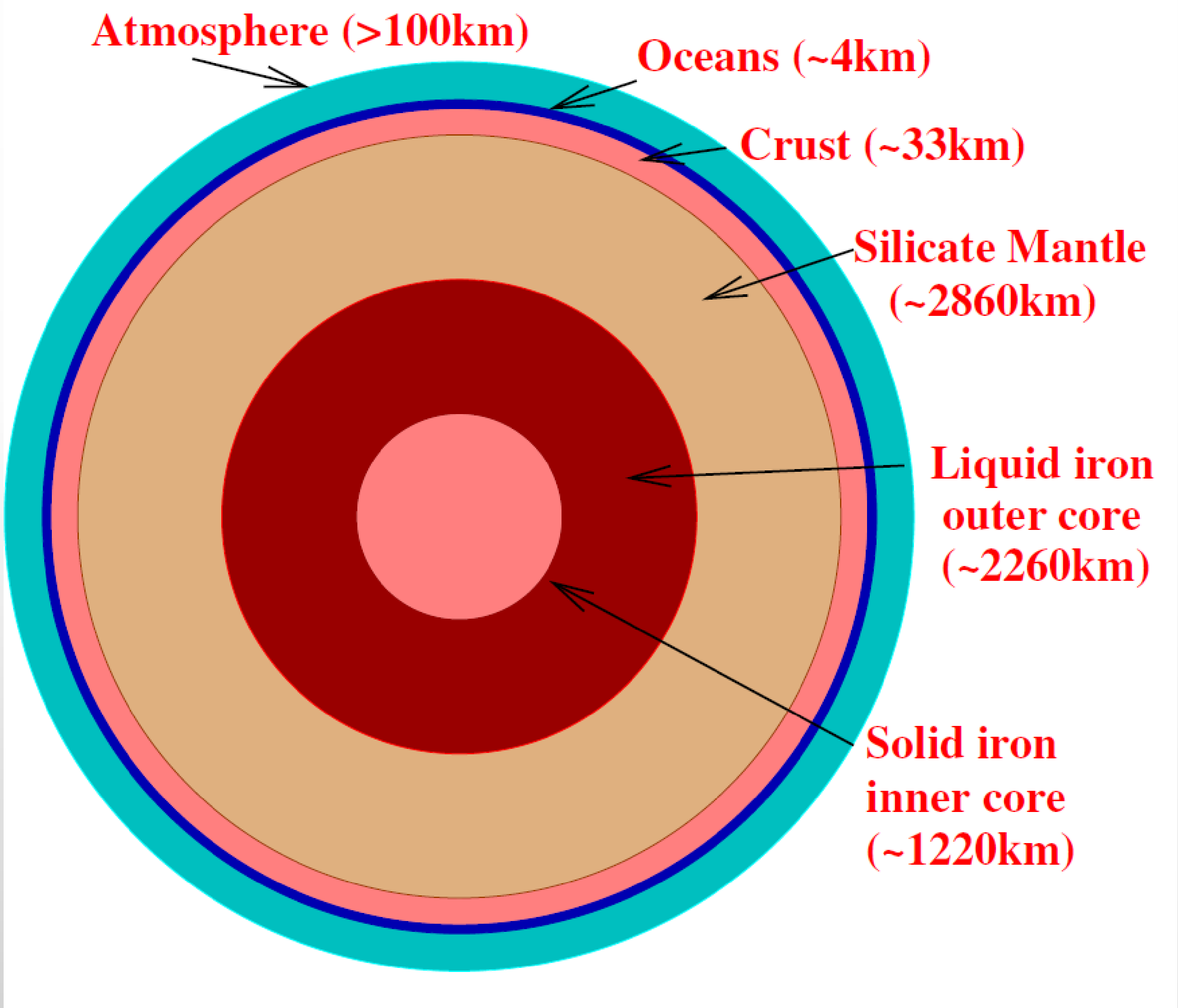
Temperature of accretion

Recall the total energy available from the accretion of a planet of mass $\boldsymbol{Mp}$ and radius $\boldsymbol{Rp}$. If one substitutes these measures for the Earth and consider its average $\boldsymbol{C_p}$ (approx. 1000 J · K^{-1} · kg^{-1}), we would find that the total heat assembled could easily vapourize the Earth:

$$\mathbf{E} = \frac{\boldsymbol{3GMp^2}}{\boldsymbol{5Rp}}$$

Most of the heat of accretion must have been re-radiated into space during the accretion process.

Structure of Earth



Composition of Earth’s mantle

Element	% by Mass	Compound	% by Mass
O	44.8		
Mg	22.8	SiO_2	46
Si	21.5	MgO	37.8
Fe	5.8	FeO	7.5
Ca	2.3	Al_2O_3	4.2
Al	2.2	CaO	3.2
Na	0.3	Na_2O	0.4
K	0.03	K_2O	0.04
Sum	99.7	Sum	99.1

https://en.wikipedia.org/wiki/Mantle_(geology)

Composition of Earth’s mantle

The proportions of the major 4 elements that comprise about 93% of the total mass of Earth could be assembled into the mineral **Olivine** with chemical composition **$FeMgSiO_4$**

Xenoliths from the mantle carried to the surface in volcanic eruptions often comprise olivine mineral but with a different composition: **$Fe_{0.2}Mg_{1.8}SiO_4$. Why?**

Most of the iron has been sequestered in Earth’s core.

The Moon-forming Event

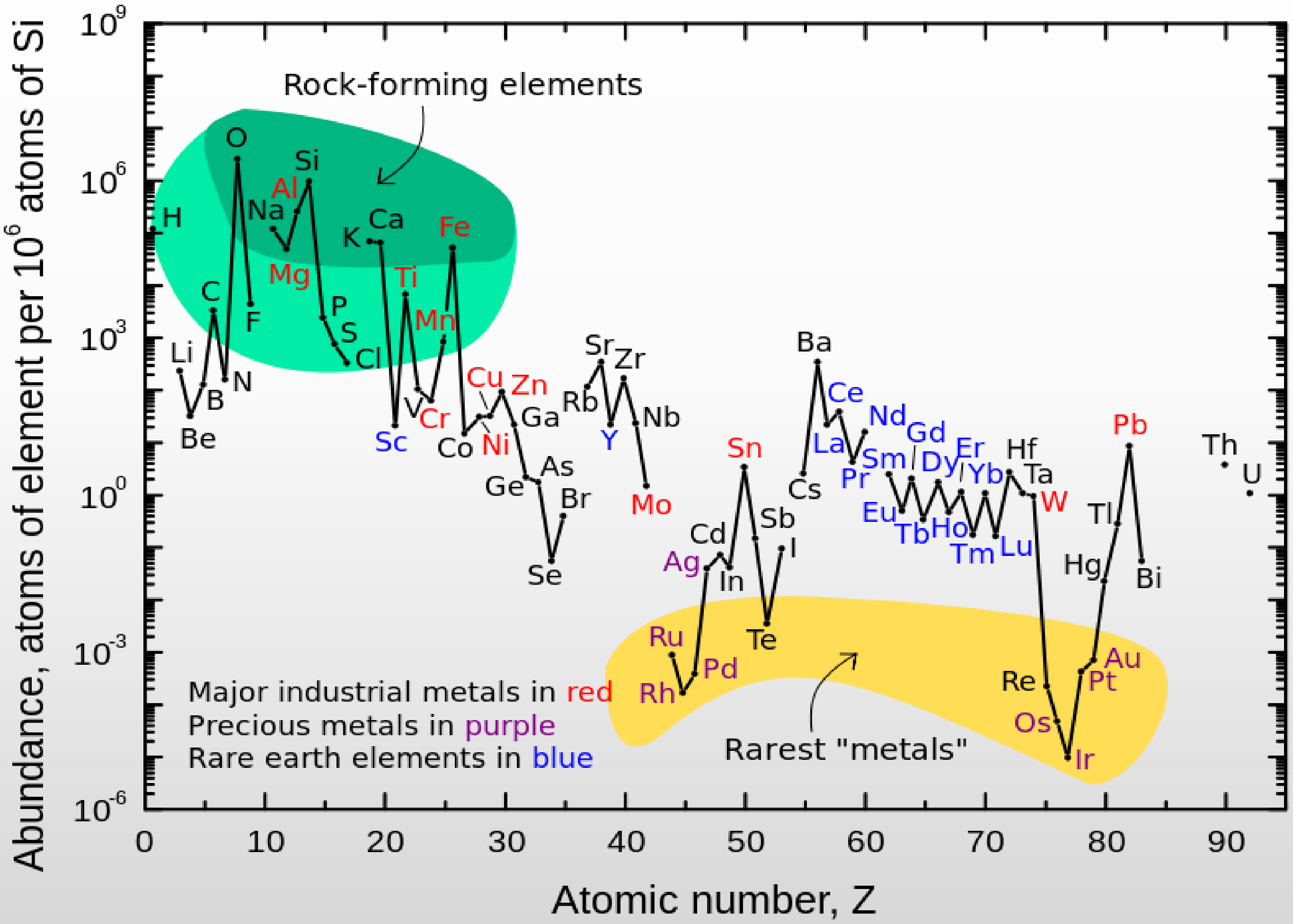
The preferred story: sometime following the original accretion of the Earth and preceding the crystallization of the oldest zircon (4.404 billion years ago), a collision with a "Mars-sized" body is thought to have splashed off our Moon.

The collision probably melted the outer shell of the Earth to a depth of 1000km. From this deep magma ocean, the original crust differentiated.

There are alternative theories including the fission and capture models.

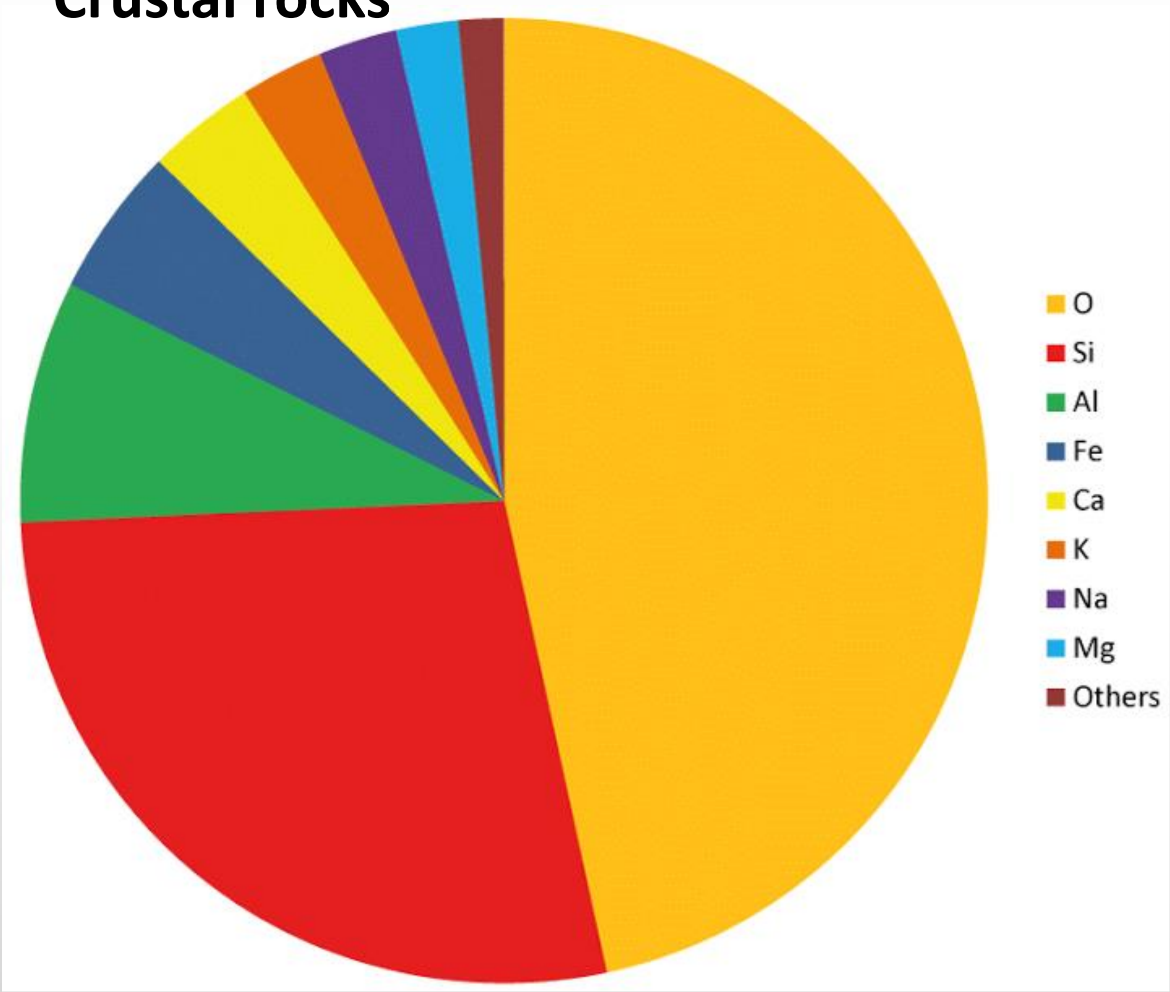
https://www.youtube.com/watch?v=vRf-hB8X7b0

Earth’s crustal elements



https://upload.wikimedia.org/wikipedia/commons/0/09/Elemental_abundances.svg

Earth’s crustal elements

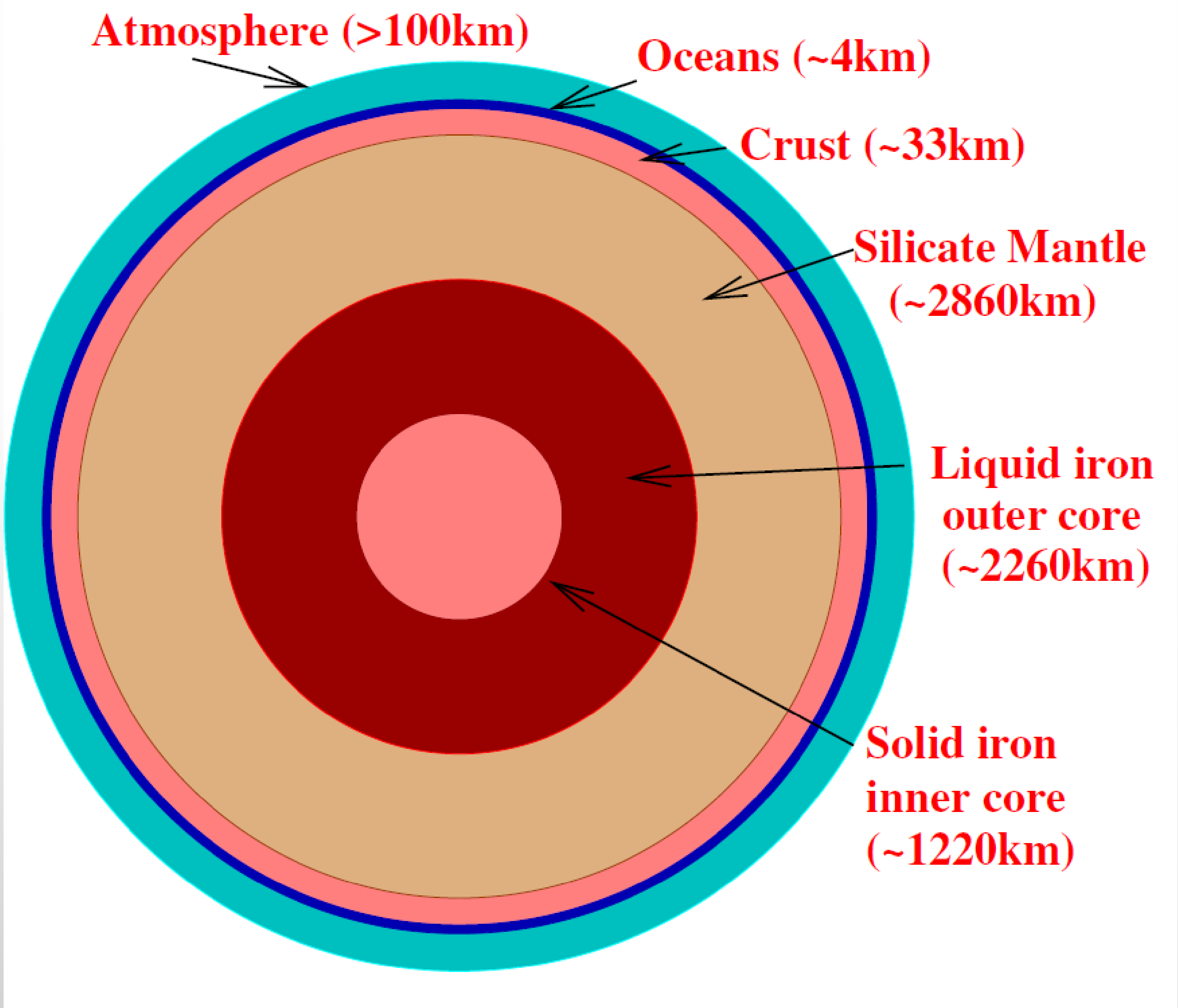

Crustal rocks

Oxygen	46.6%
Silicon	27.7
Aluminum	8.1
Iron	5.0
Calcium	3.6
Sodium	2.8
Potassium	2.6
Magnesium	2.1
Others	1.5

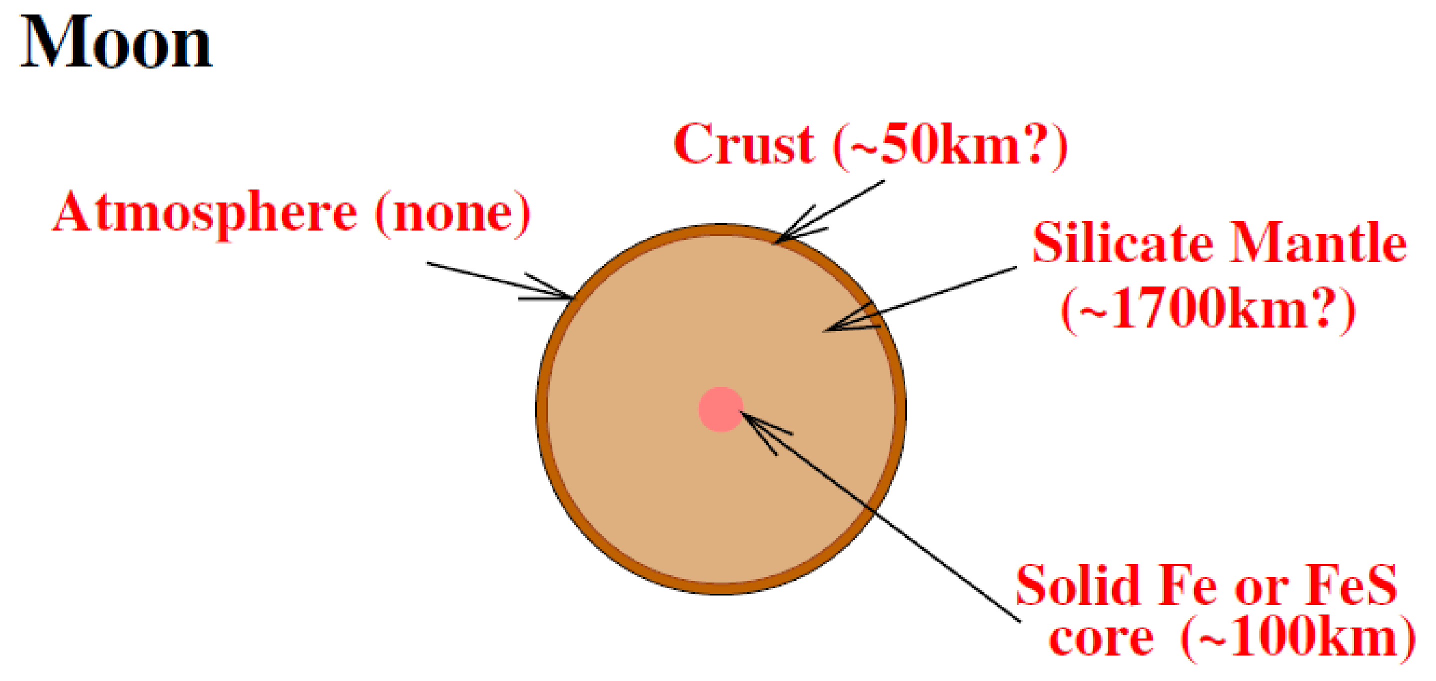
Hydrogen, included, as water is a major and important component in the near-surface crust and biosphere.

Crustal and biosphere elemental abundances

Structure of Planets -- Earth



Structure of Planets -- Moon

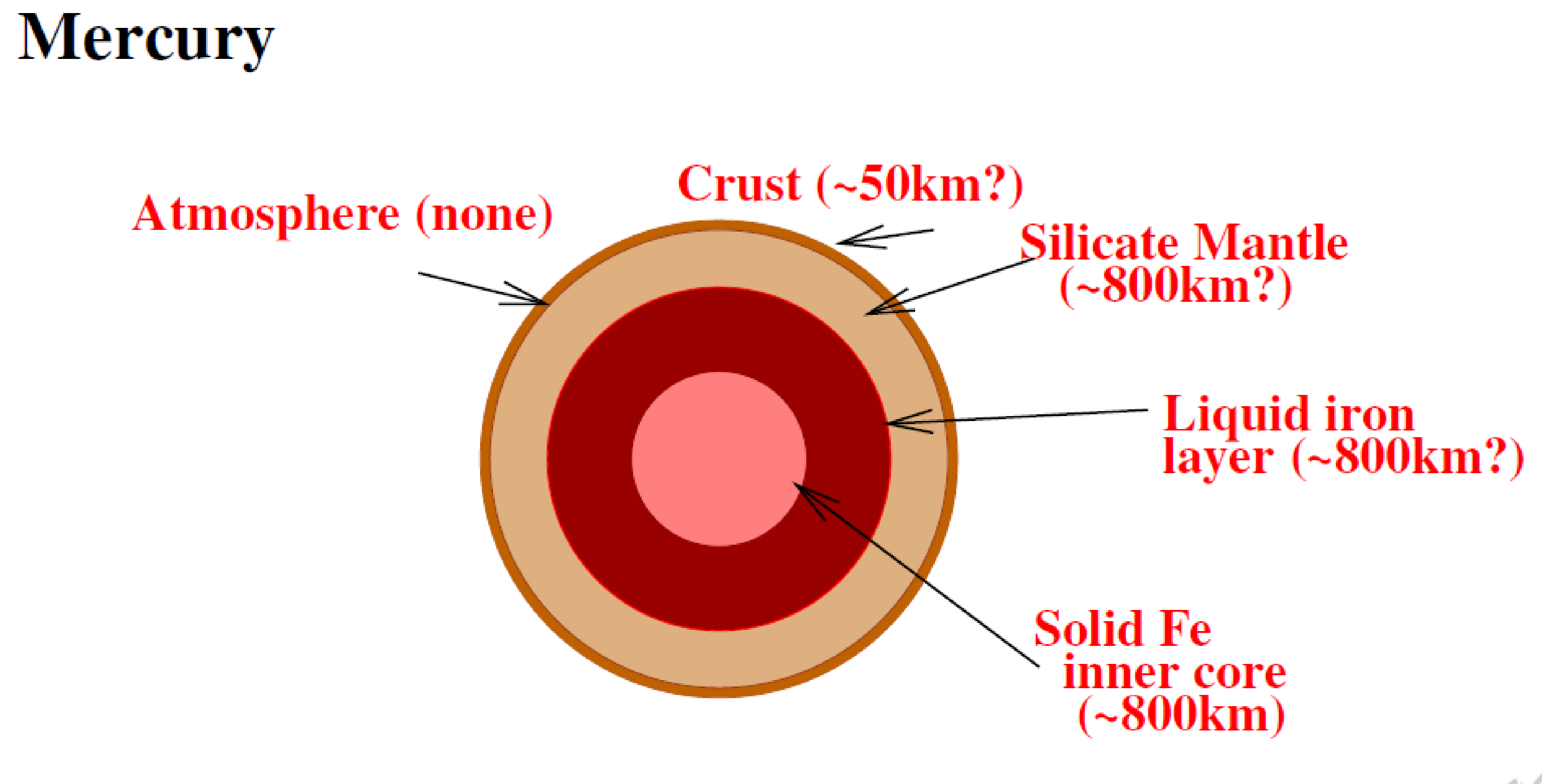


YouTube video of formation/evolution:
https://www.youtube.com/watch?v=WGTBJHFNywI

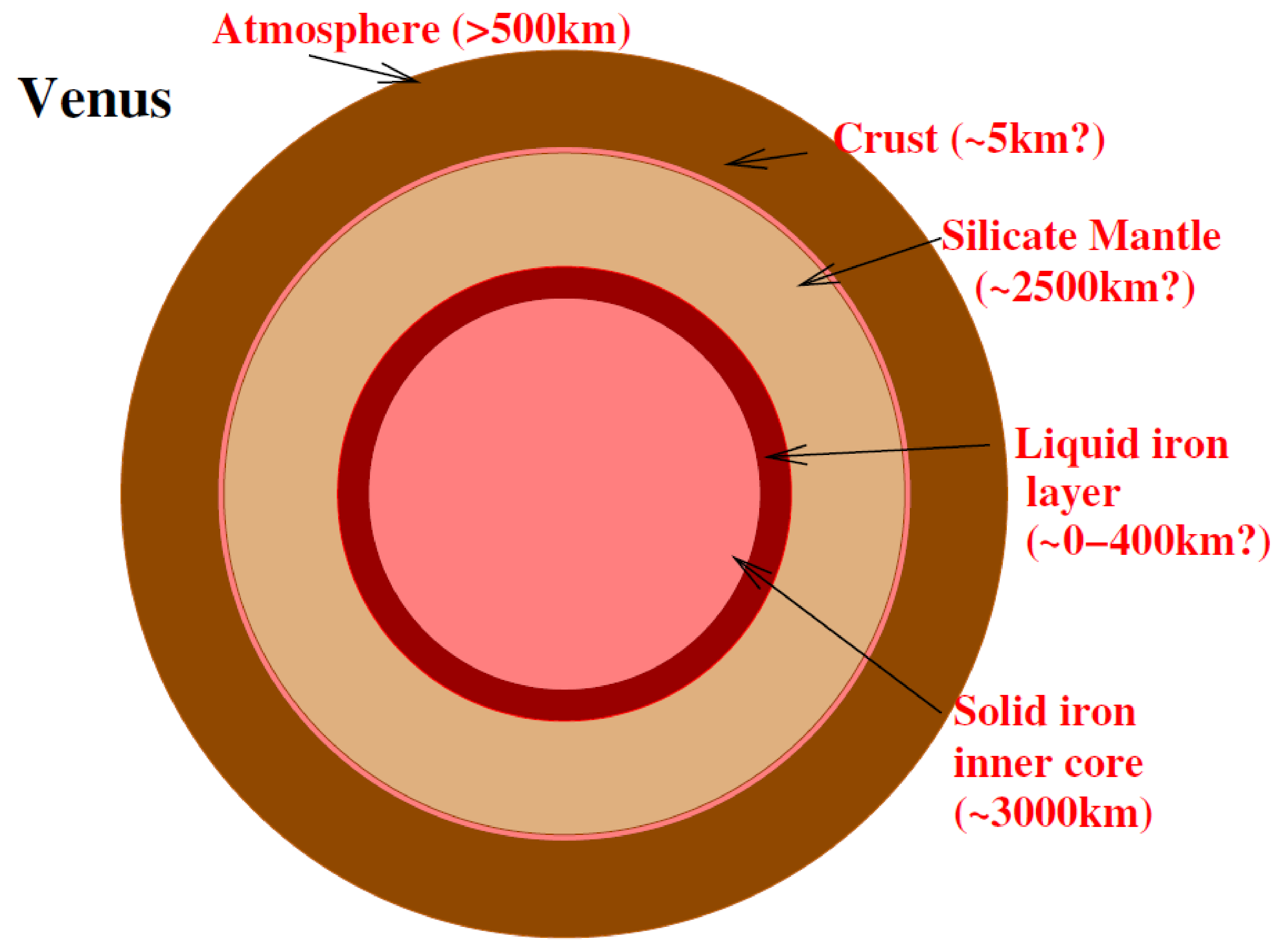
Apollo mission 1962-72

Apollo mission 1962-72: From ConceptualAcademy.com

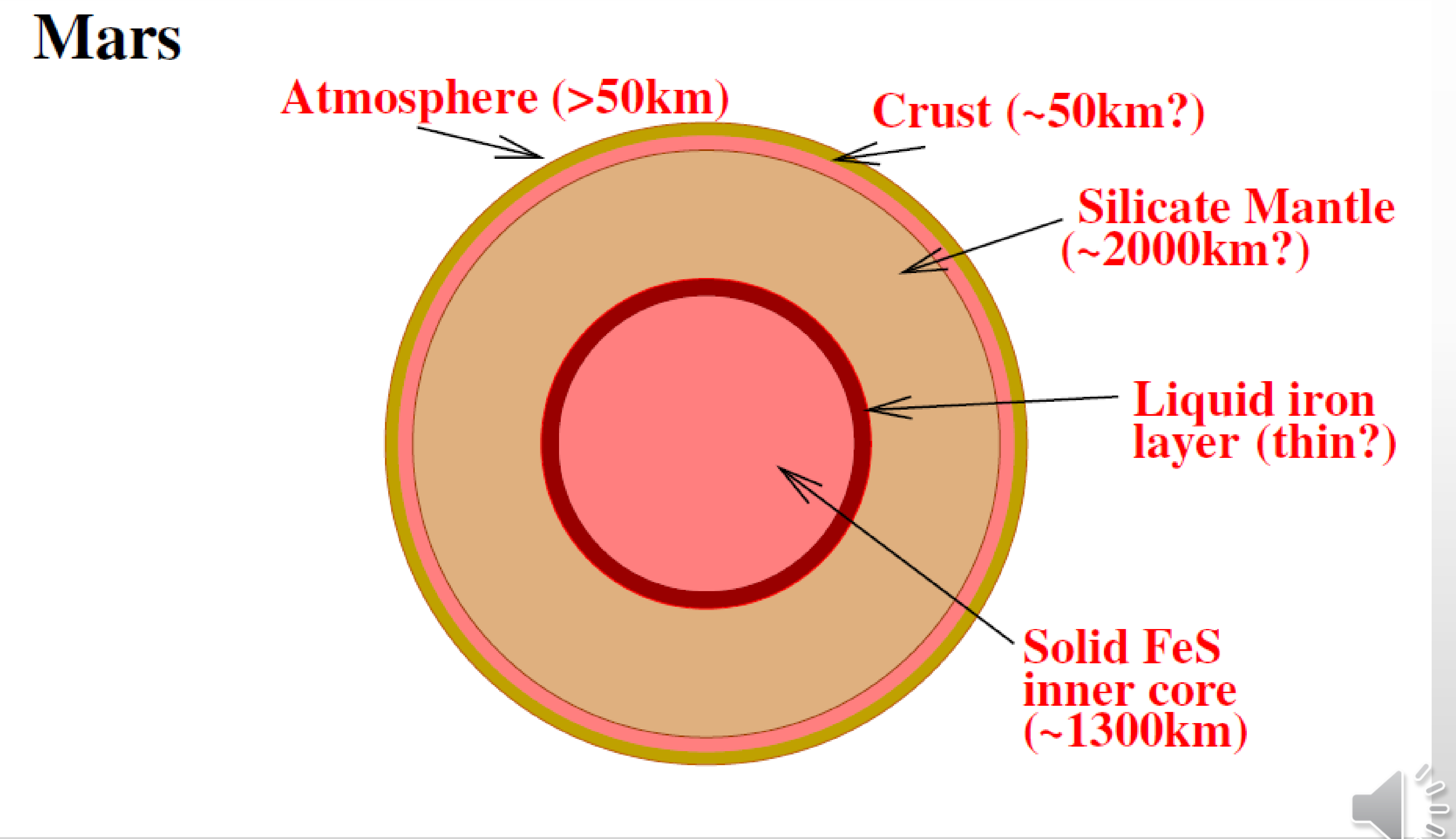
Structure of Planets -- Mercury



Structure of Planets -- Venus



Structure of Planets -- Mars

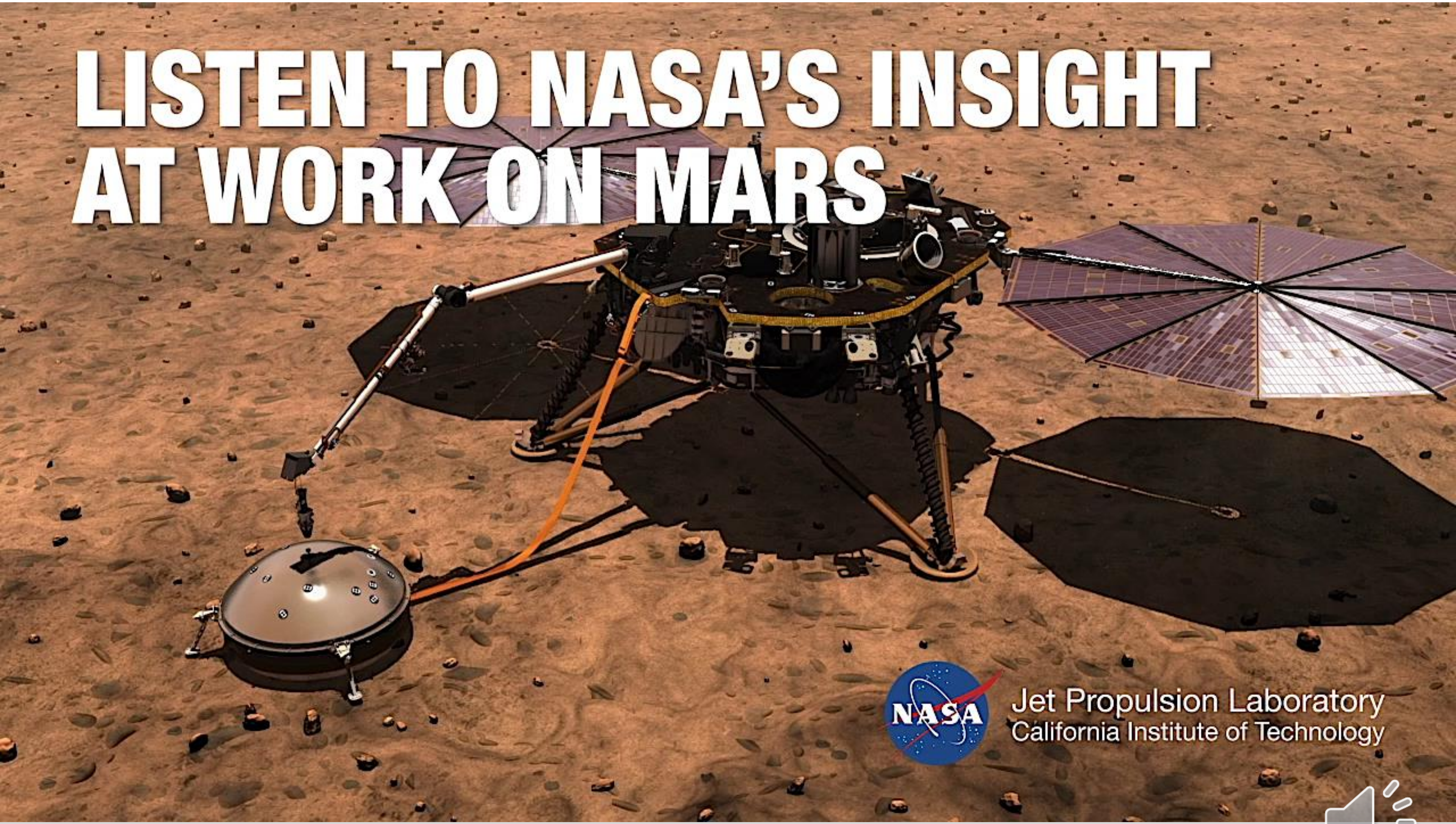


Structure of Planets -- Mars

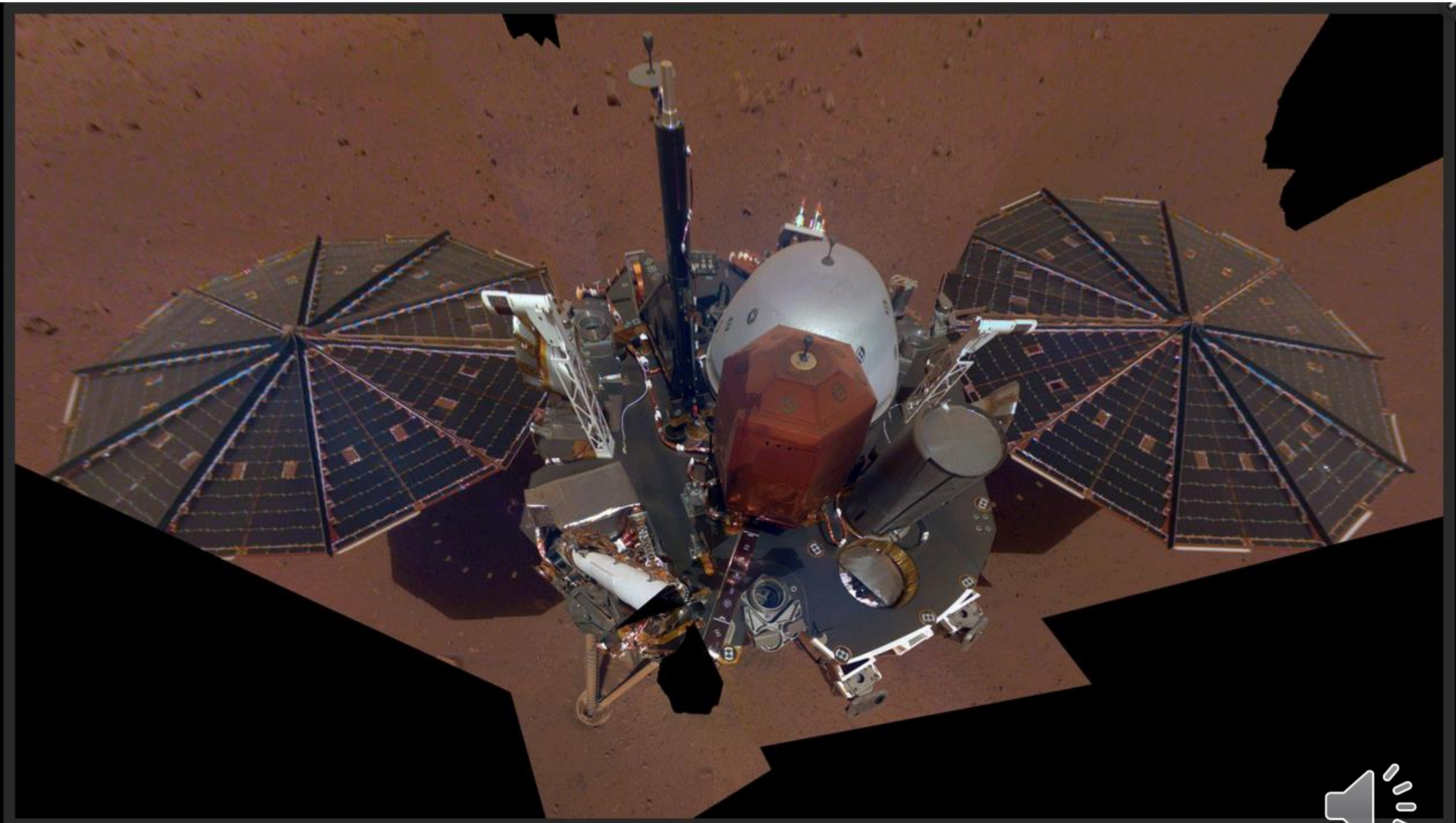
Instruments placed on the Moon by the Apollo astronauts have given us information about the Moon's internal structure. Seismic instruments recorded hundreds of "moonquakes" and the analysis of the seismic records brings us to the Moon model we have. In 1976, the Viking landers on Mars deployed seismic instruments but results of the seismic experiments were, at best, ambiguous.

Now, the ***InSight mission***'s landing on Mars with contemporary seismic and heat-flow instruments should help us to unravel the interior structure and condition of Mars.

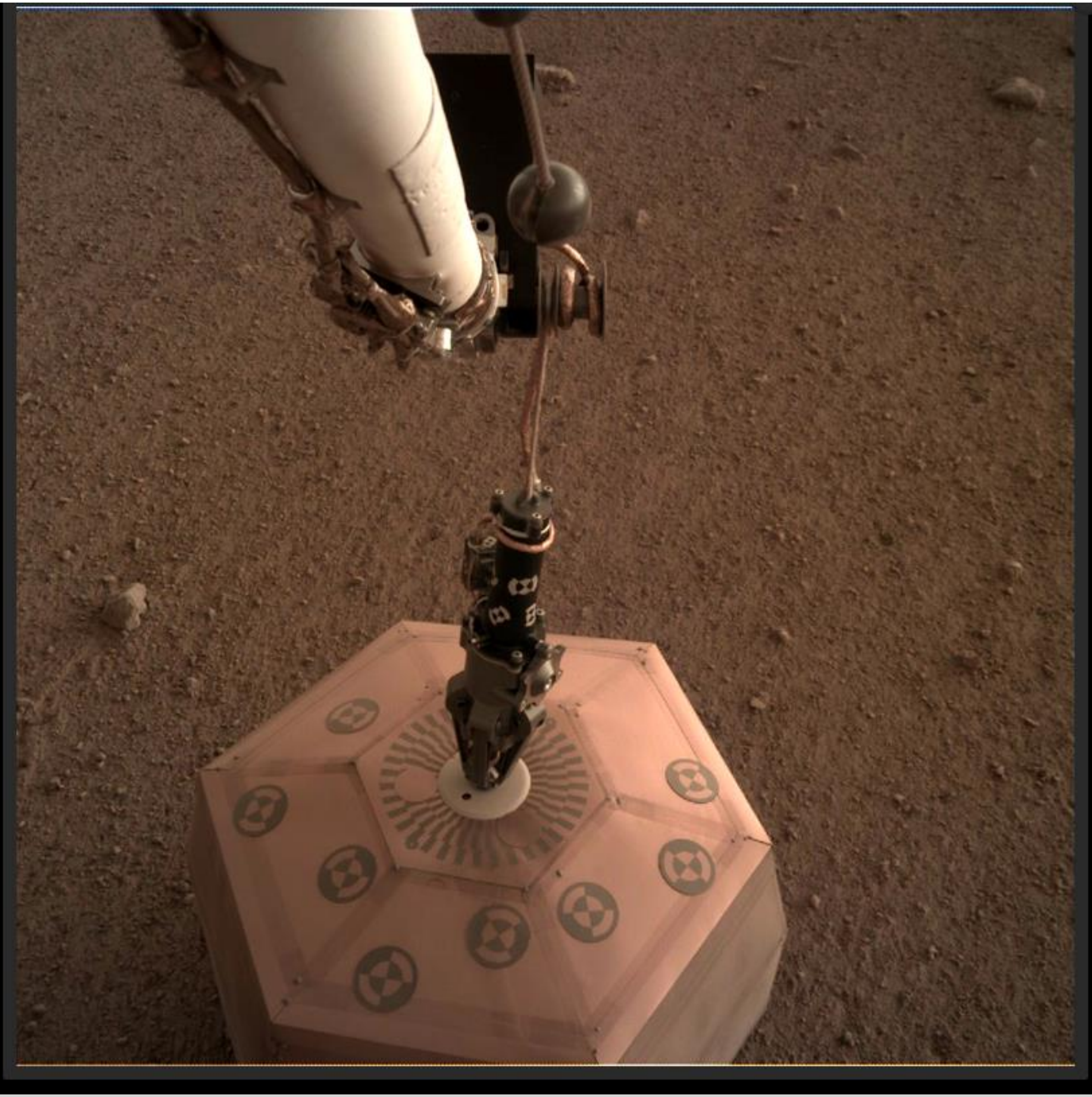
Structure of Planets -- Mars

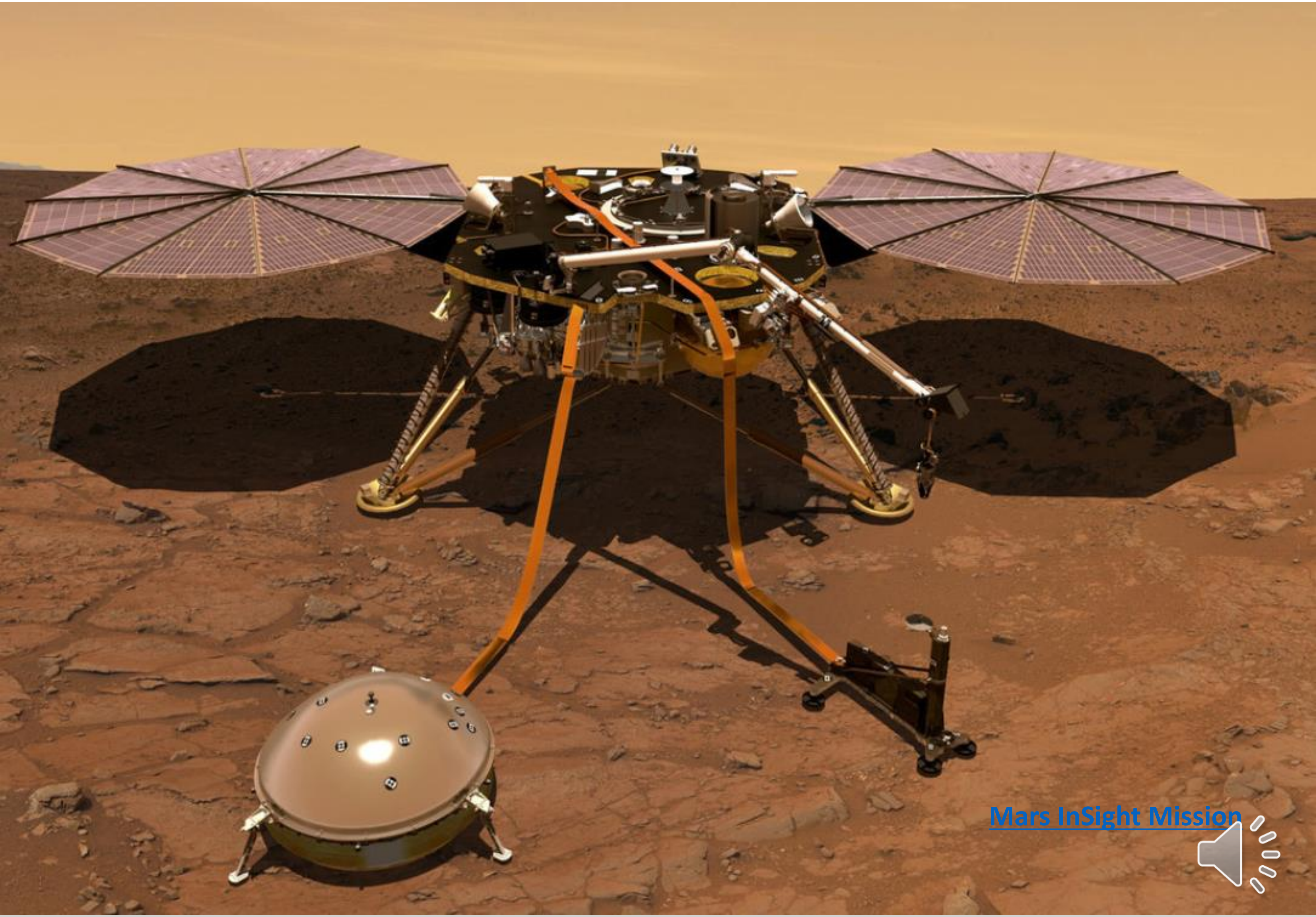


Structure of Planets -- Mars



InSight's First Selfie





Mars InSight Mission