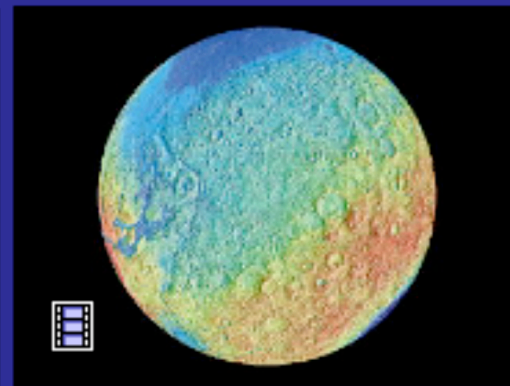
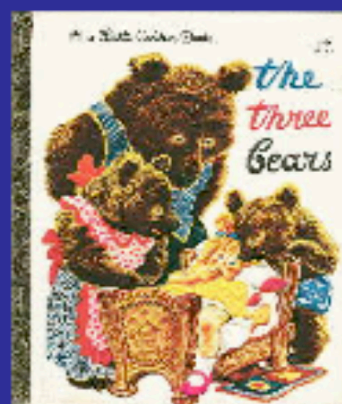
EARTH 351 FORMING A HABITABLE PLANET

Seth Stein & Donna Jurdy

Are
We
Alone?

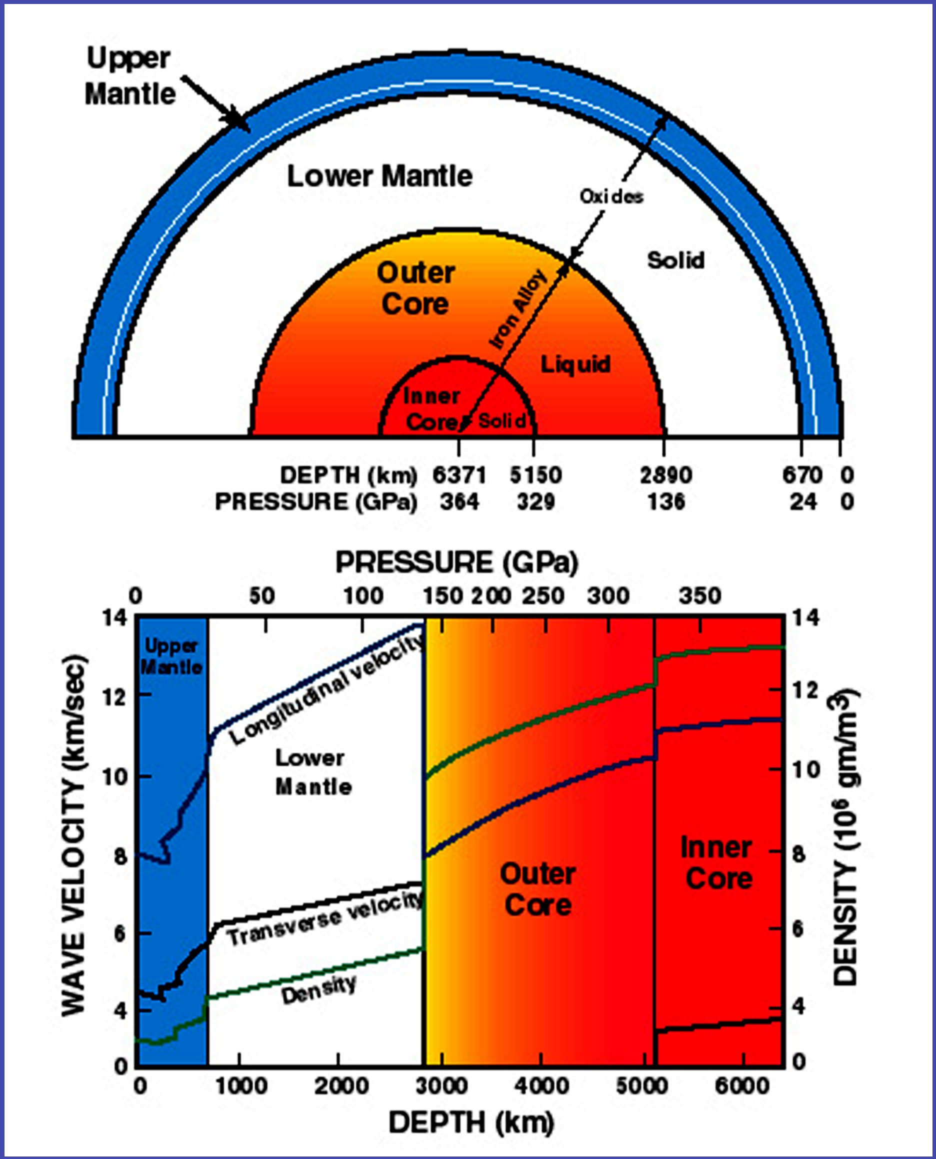
Why is Earth habitable, but not Venus and Mars?



To explore what conditions make planets habitable, start with with the most familiar case (which we don't fully understand)

EARTH' S COMPOSITION AND THERMAL STRUCTURE CONTROL ITS DYNAMICS & EVOLUTION



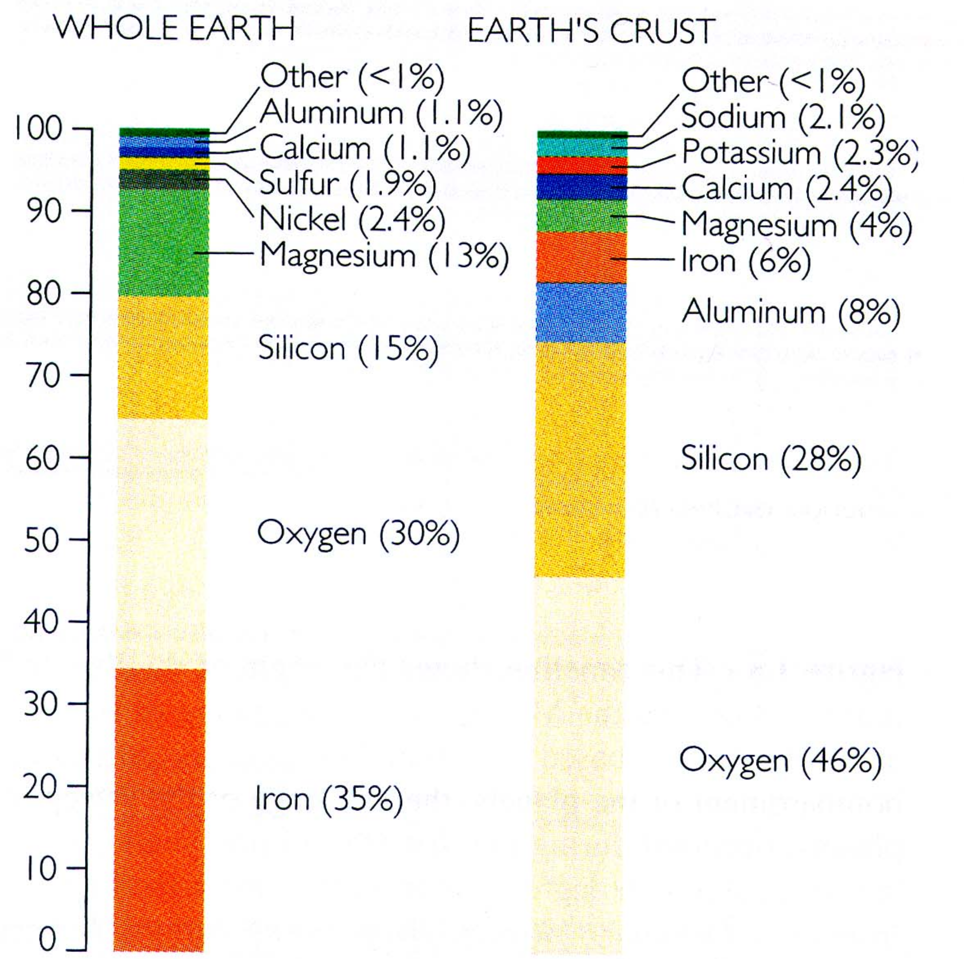
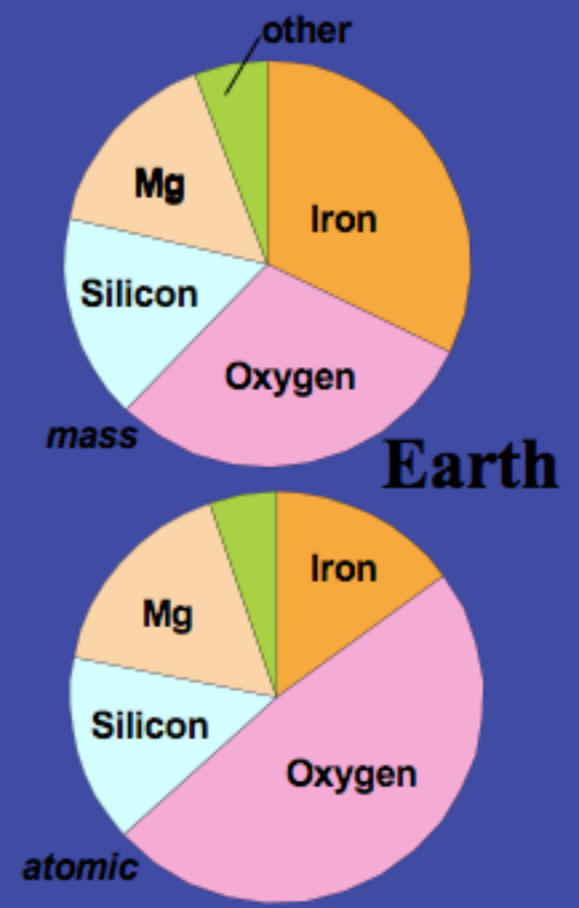
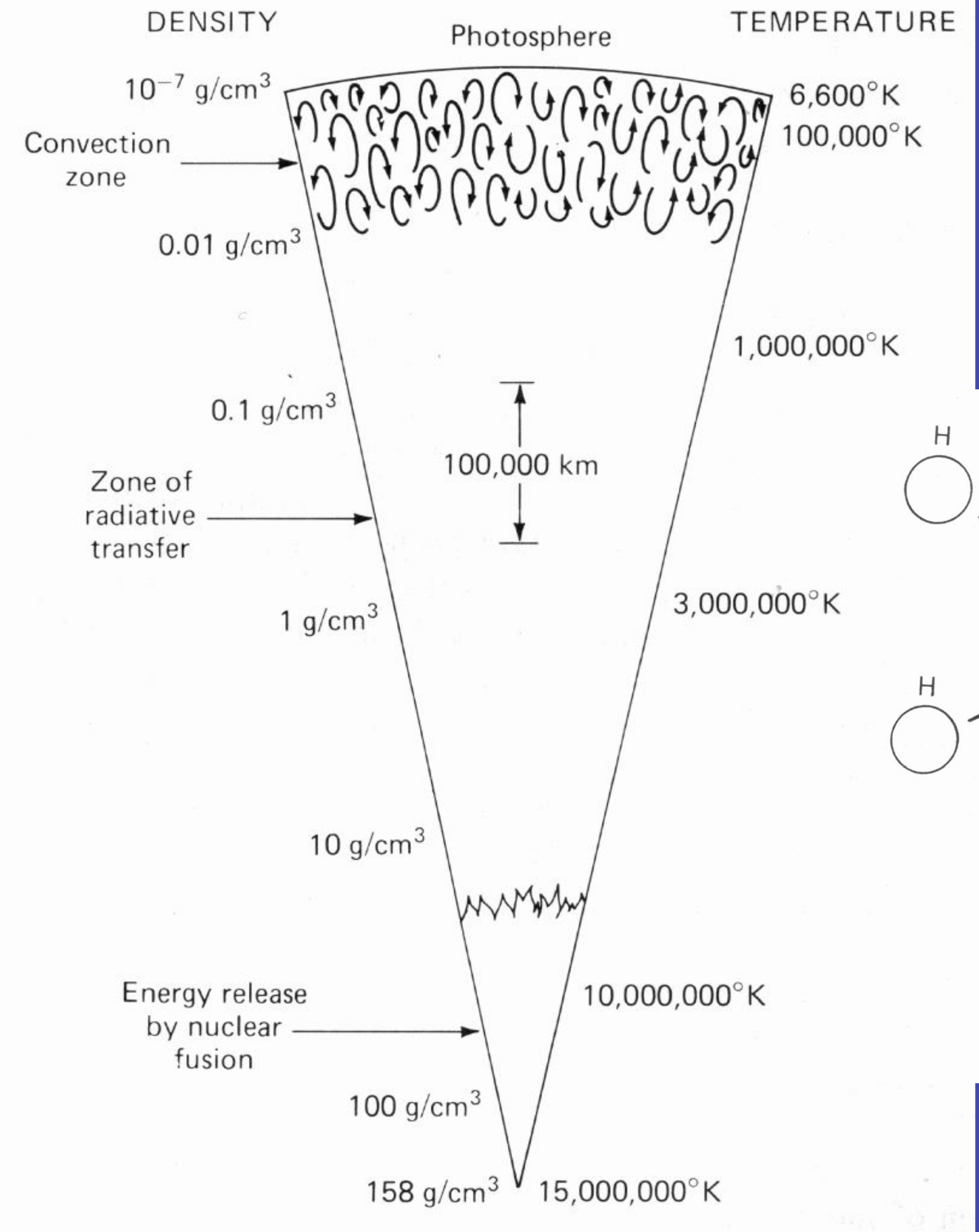
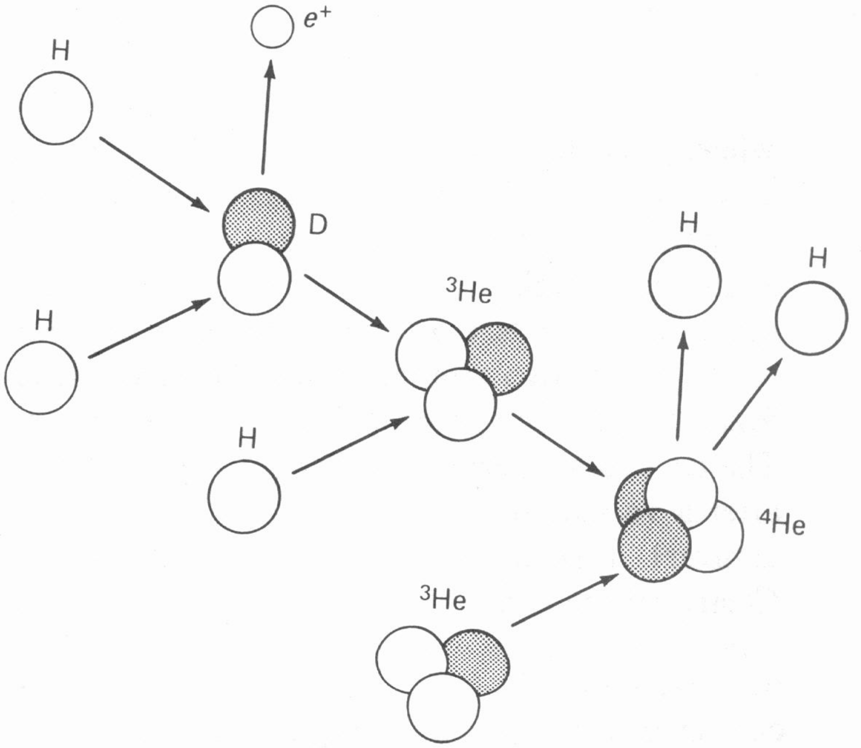


Figure 1.7 The relative abundance of elements in the whole Earth compared with that of elements in Earth's crust, given as percentages by weight. Differentiation has created a light crust, depleted of iron and rich in oxygen, silicon, aluminum, calcium, potassium, and sodium. About 90 percent of Earth consists of only four elements: iron, oxygen, silicon, and magnesium. Note also that oxygen, silicon, and aluminum alone account for more than 80 percent of the crust.

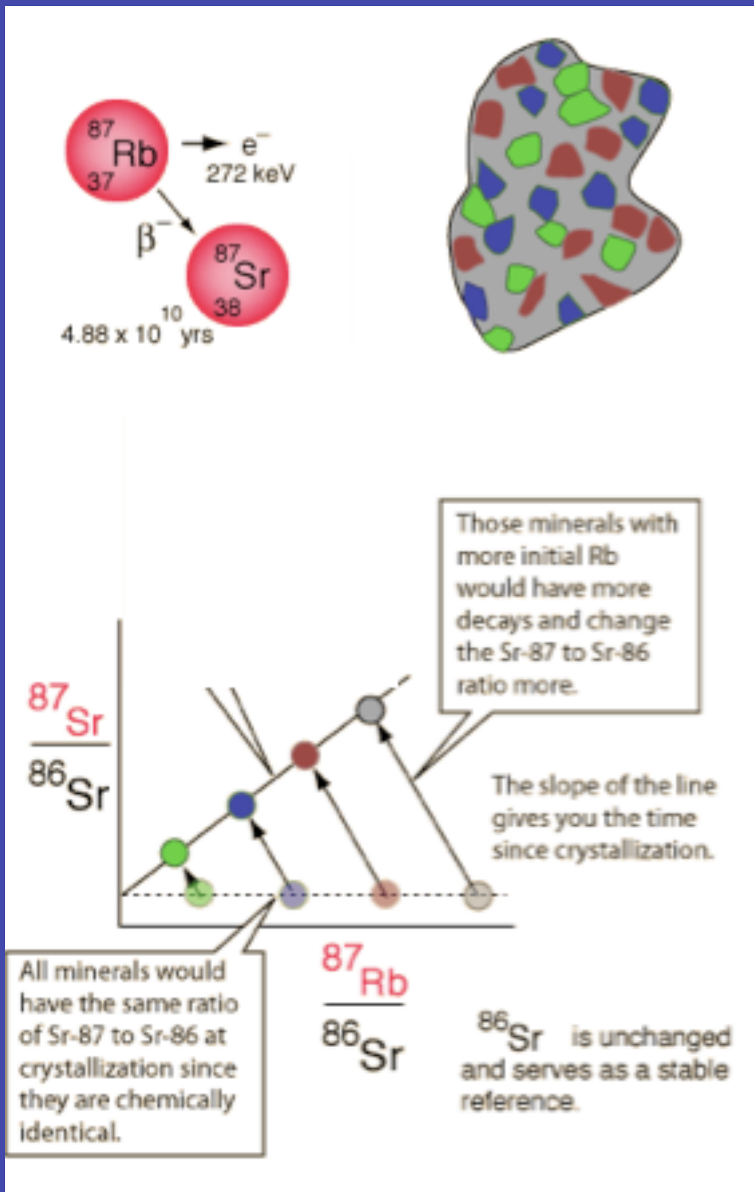


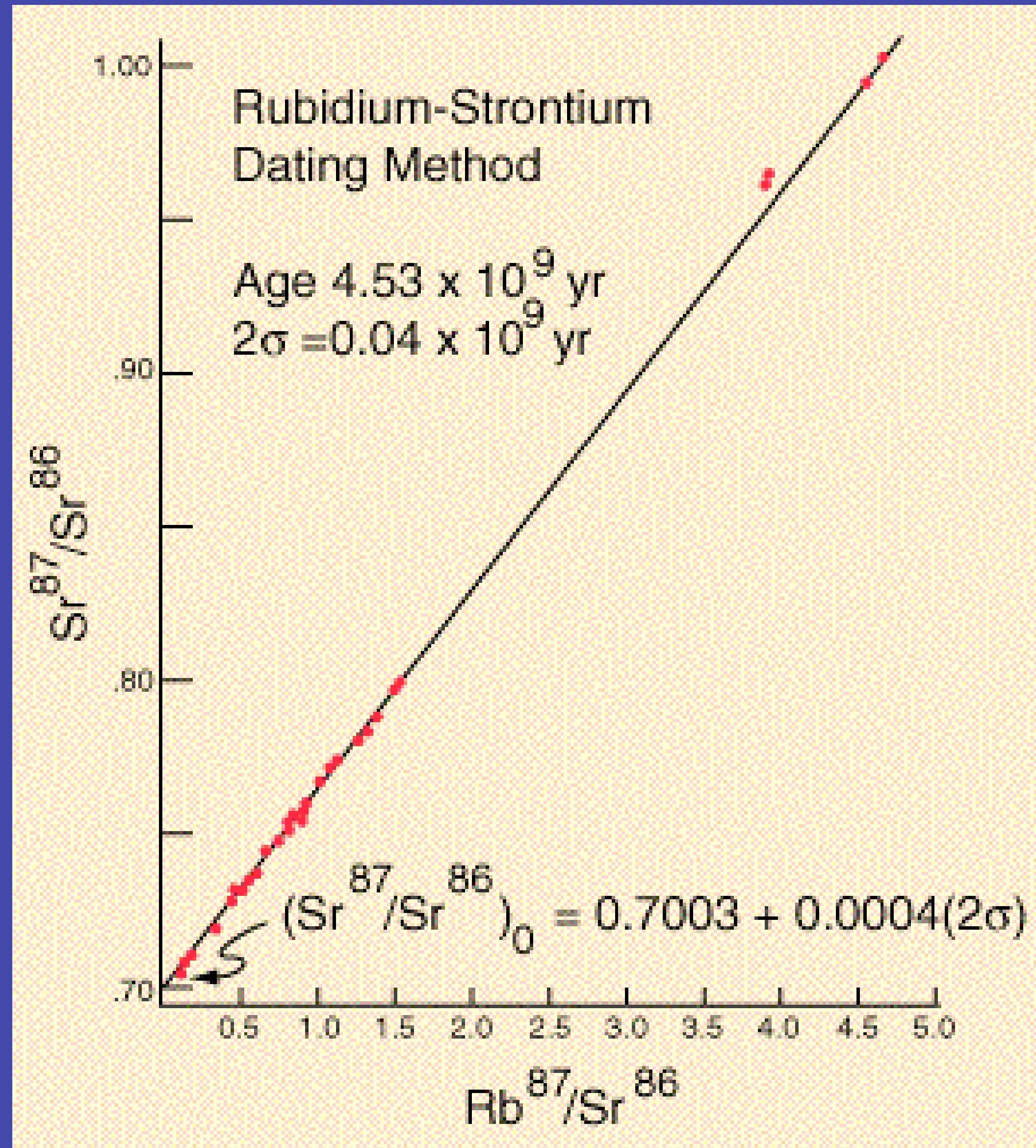
Press & Siever


DENSITY
Photosphere
TEMPERATURE
10^{-7} g/cm^3
6,600°K
100,000°K
Convection zone
0.01 g/cm^3
1,000,000°K
0.1 g/cm^3
100,000 km
Zone of radiative transfer
1 g/cm^3
3,000,000°K
10 g/cm^3
Energy release by nuclear fusion
10,000,000°K
100 g/cm^3
158 g/cm^3
15,000,000°K


H
e^+
D
H
^{3}He
H
H
H
^{4}He
^{3}He

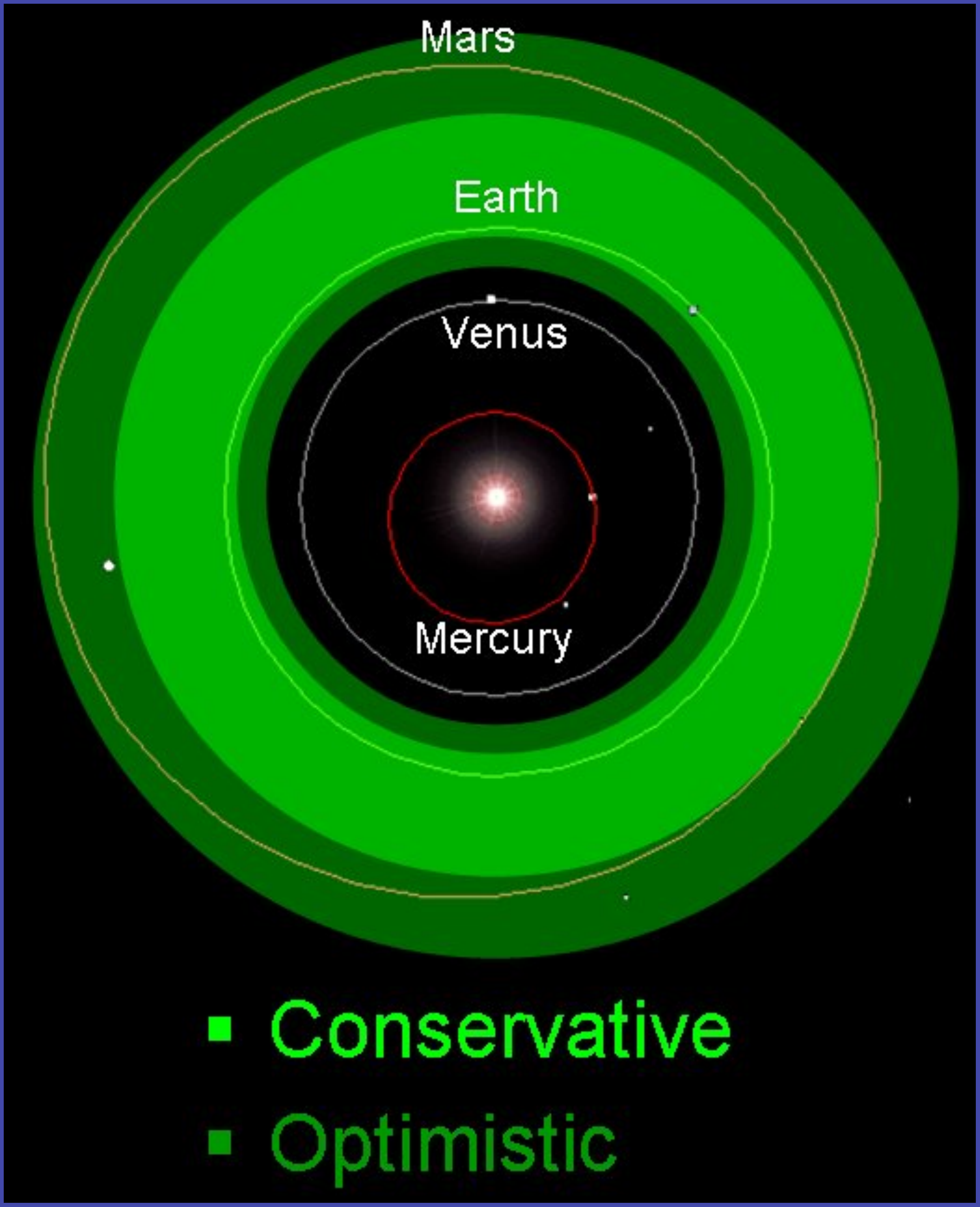
Wood





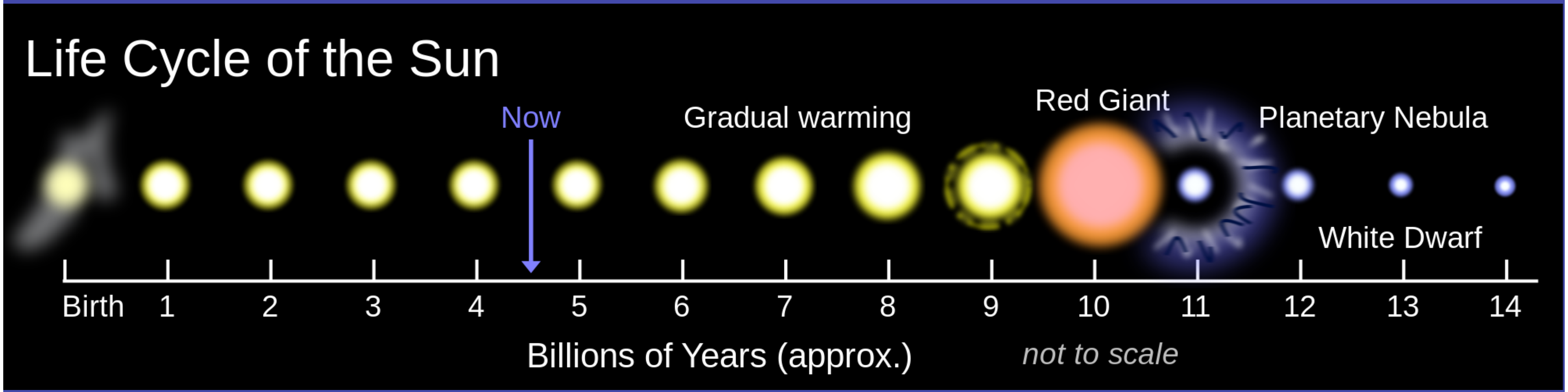
G. W. Wetherill, Ann. Rev. Nucl. Sci. 25, 283 (1975)

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/clkroc.html#c4



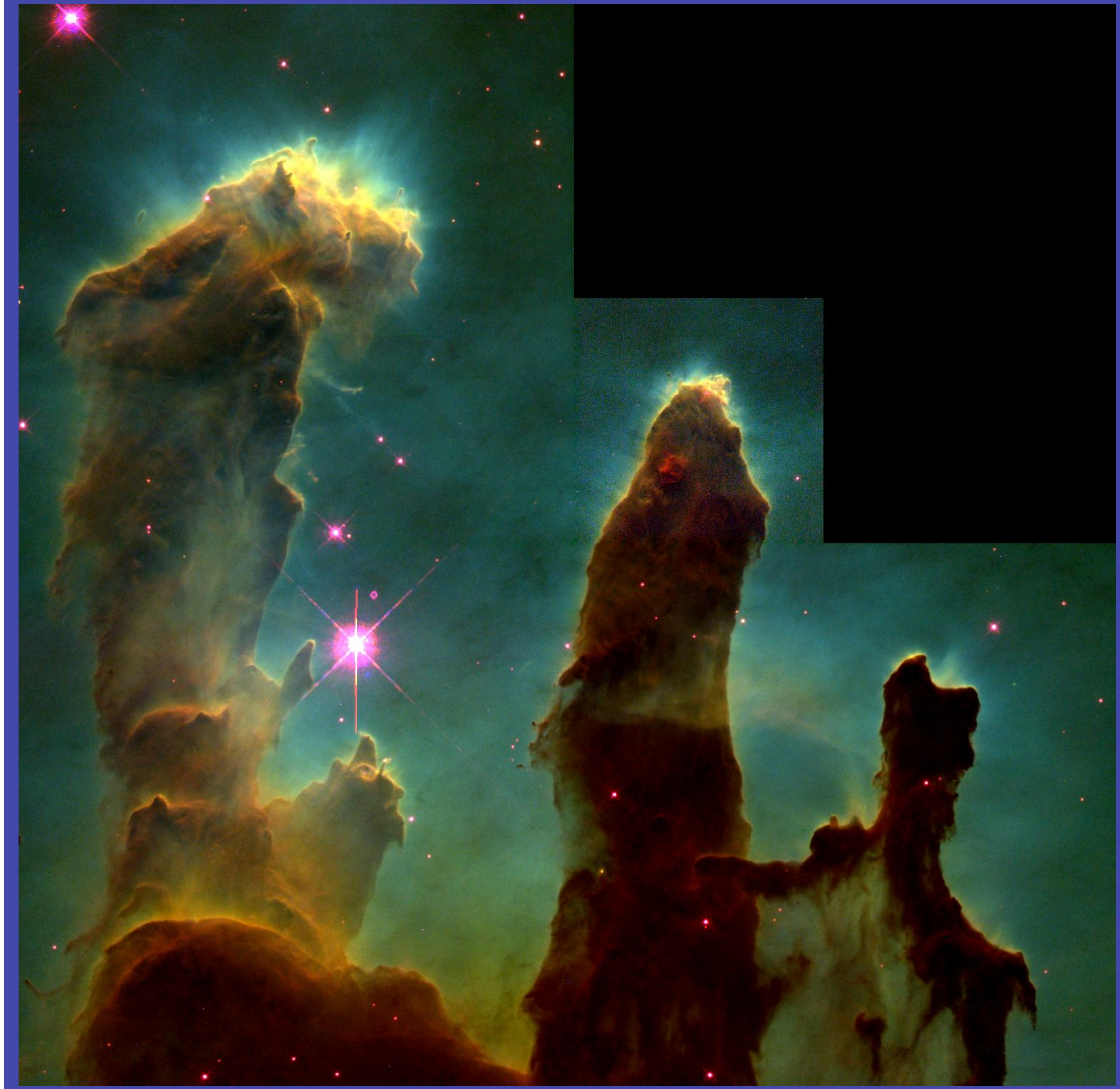
Habitable Zone Today

http://www.astronomy.ohio-state.edu/~thompson/161/HabitableZone.jpg

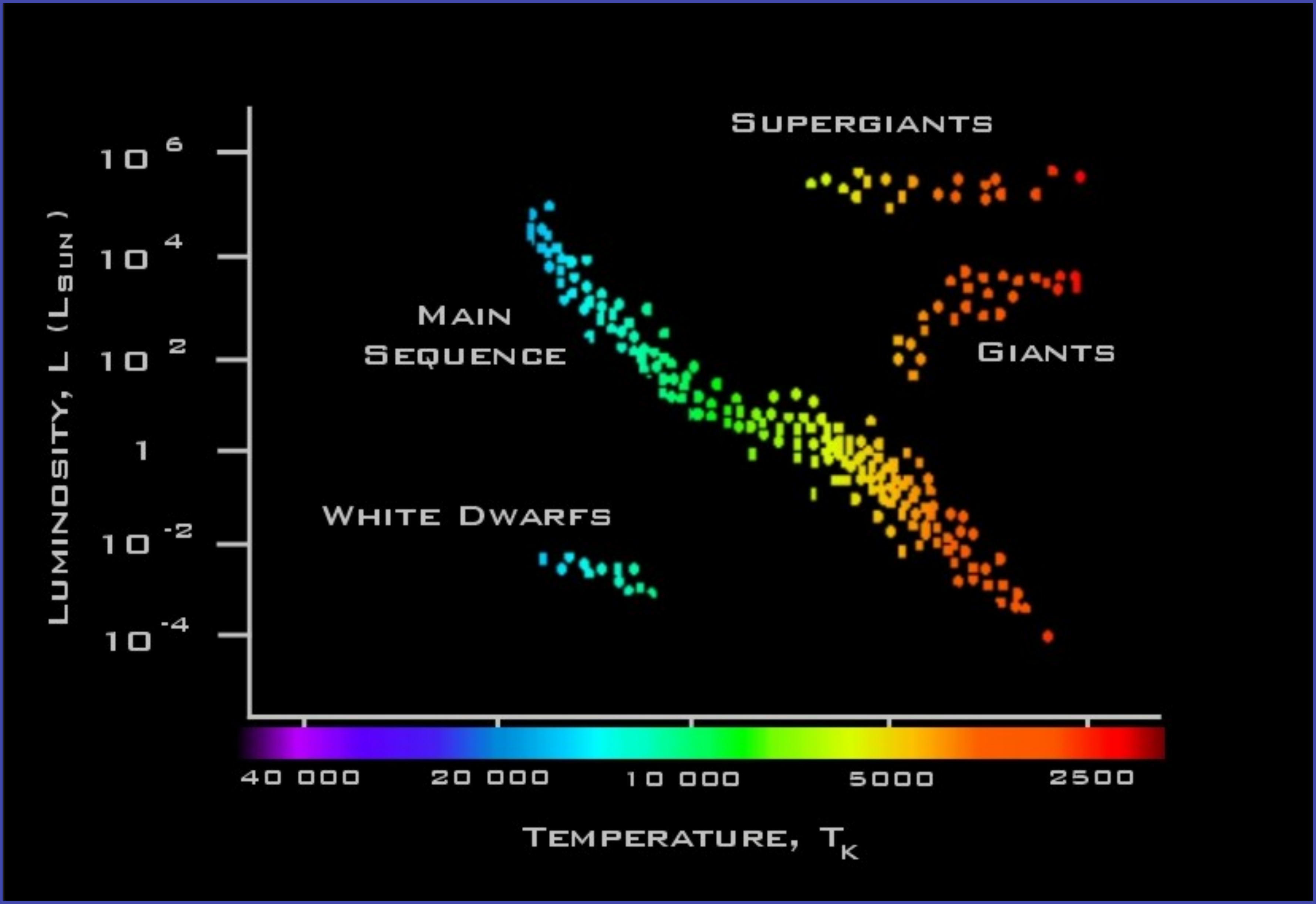


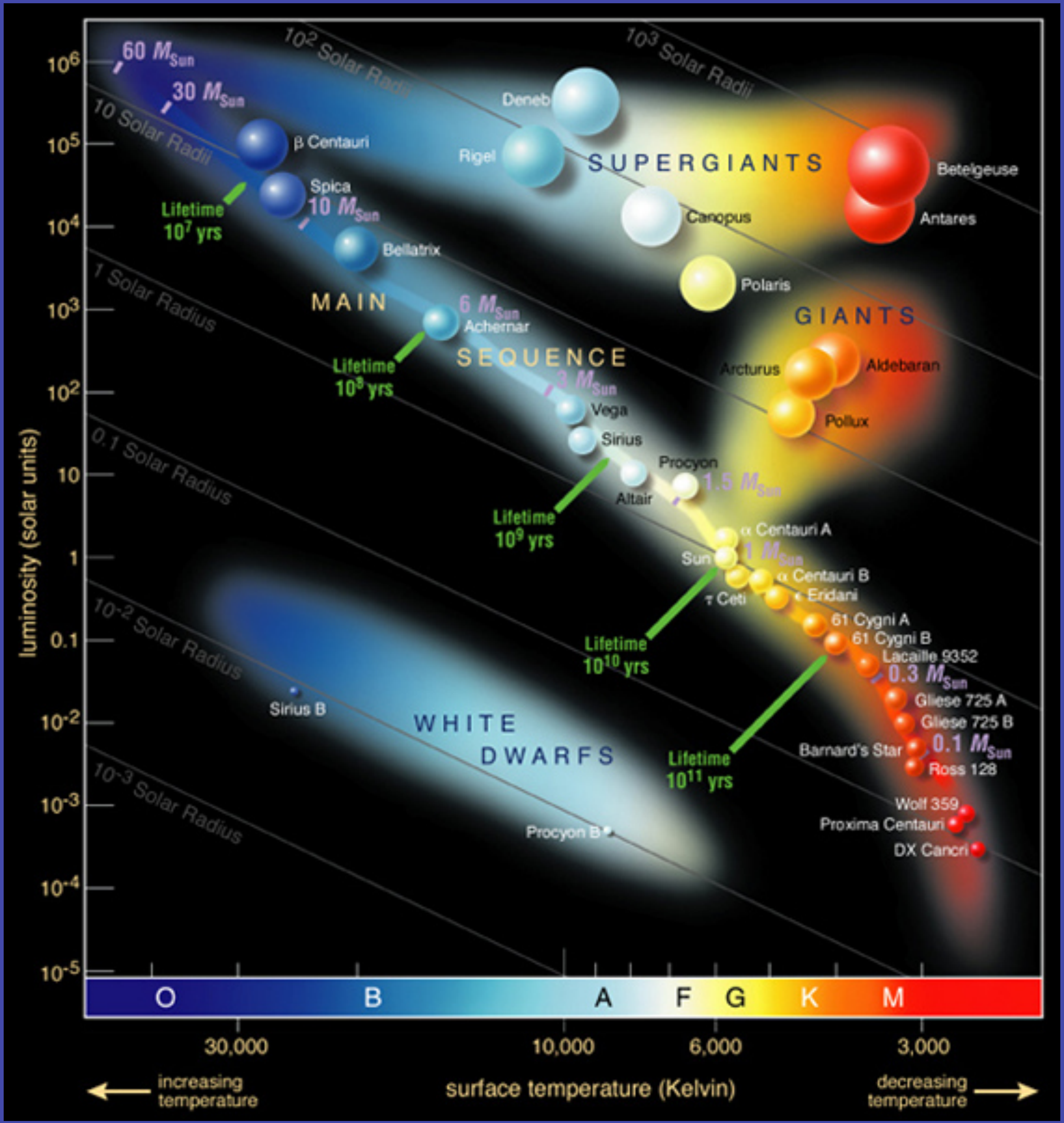
http://upload.wikimedia.org/wikipedia/commons/thumb/5/55/Solar_Life_Cycle.svg/2000px-Solar_Life_Cycle.svg.png

Star birth in Eagle Nebula

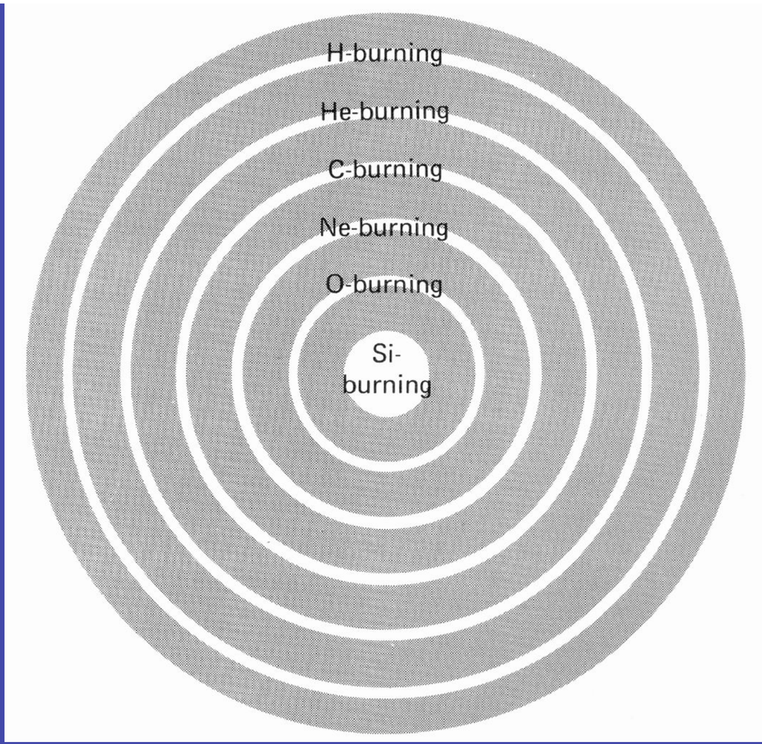


Hertzsprung-Russell diagram





60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
3 M_Sun
1.5 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature



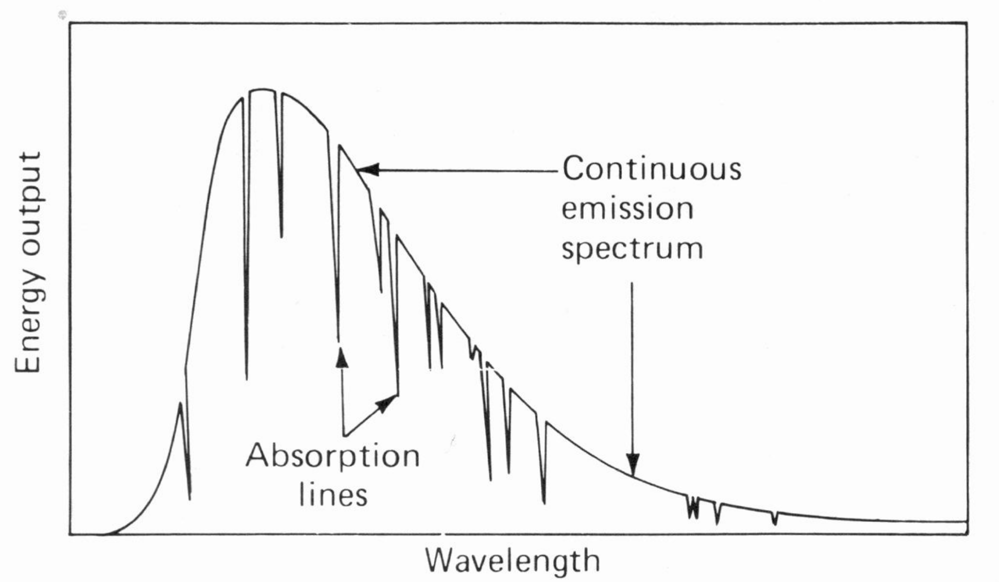


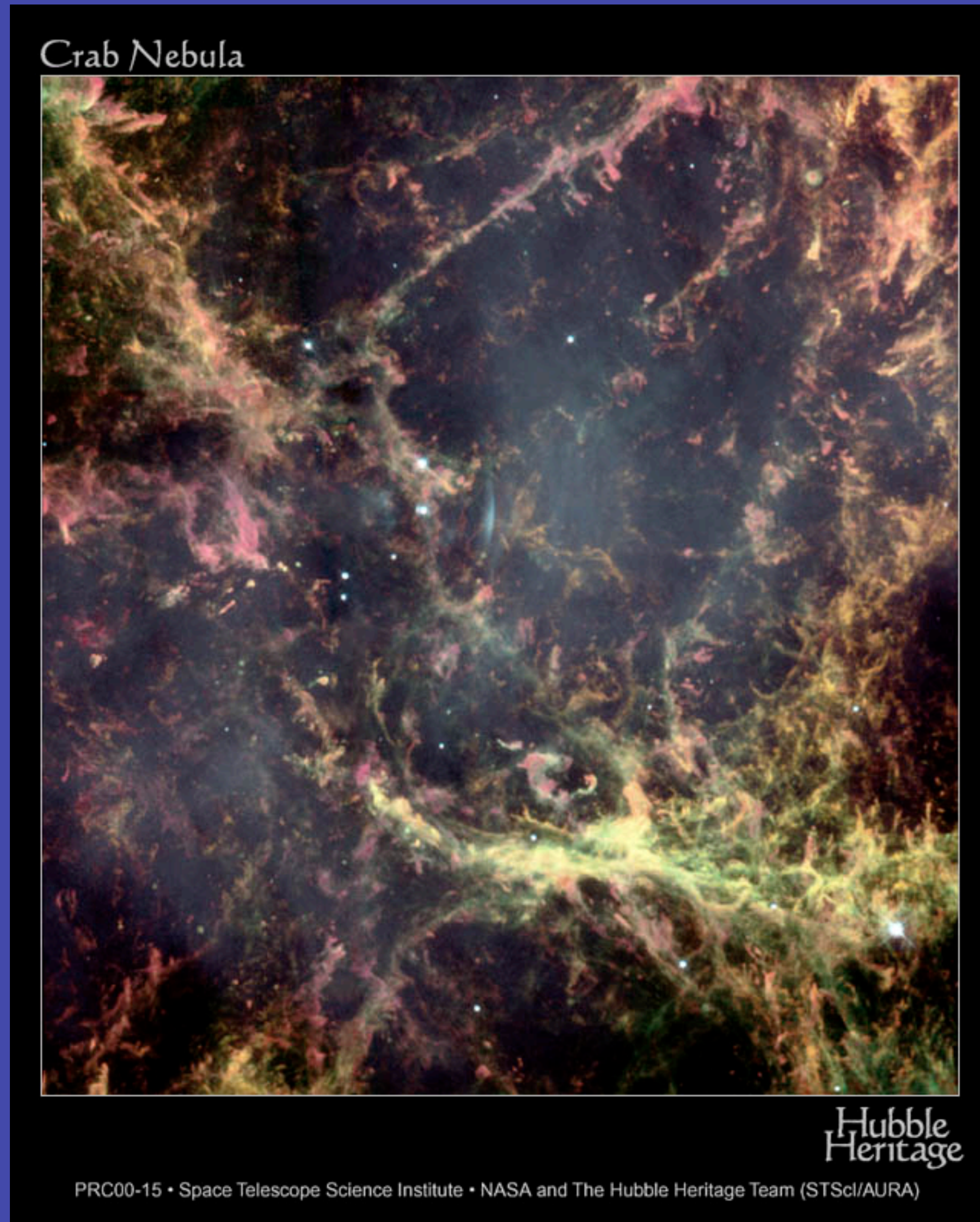
Table 6-1 Stages of Nuclear Energy Generation

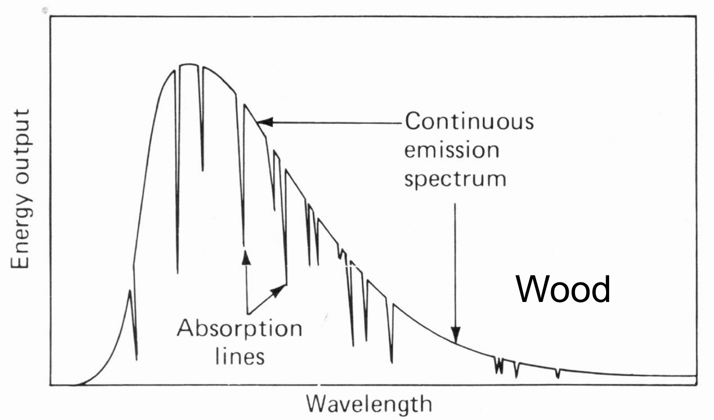
Name of Process	Fuel	Products	Approximate Temperature (°K)
HYDROGEN-BURNING	H	He	$1\text{–}3 \times 10^7$
HELIUM-BURNING	He	C, O	2×10^8
CARBON-BURNING	C	O, Ne, Na, Mg	8×10^8
NEON-BURNING	Ne	O, Mg	1.5×10^9
OXYGEN-BURNING	O	Mg to S	2×10^9
SILICON-BURNING	Mg to S	Elements near Fe	3×10^9

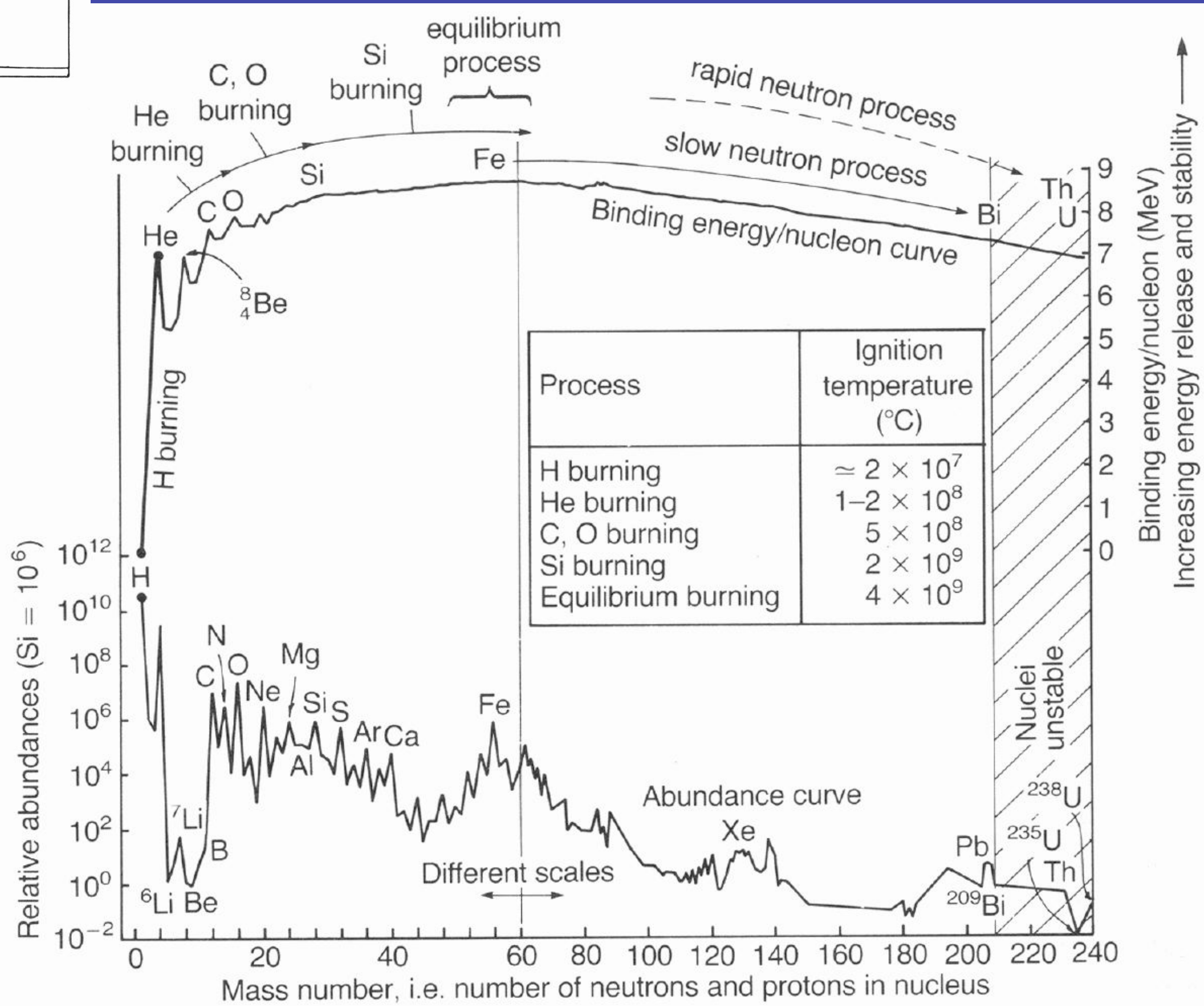
From A. G. W. Cameron, 1976, in Frontiers of Astrophysics, *E. H. Avrett ed. (Harvard University Press), 554 pp.*

Wood

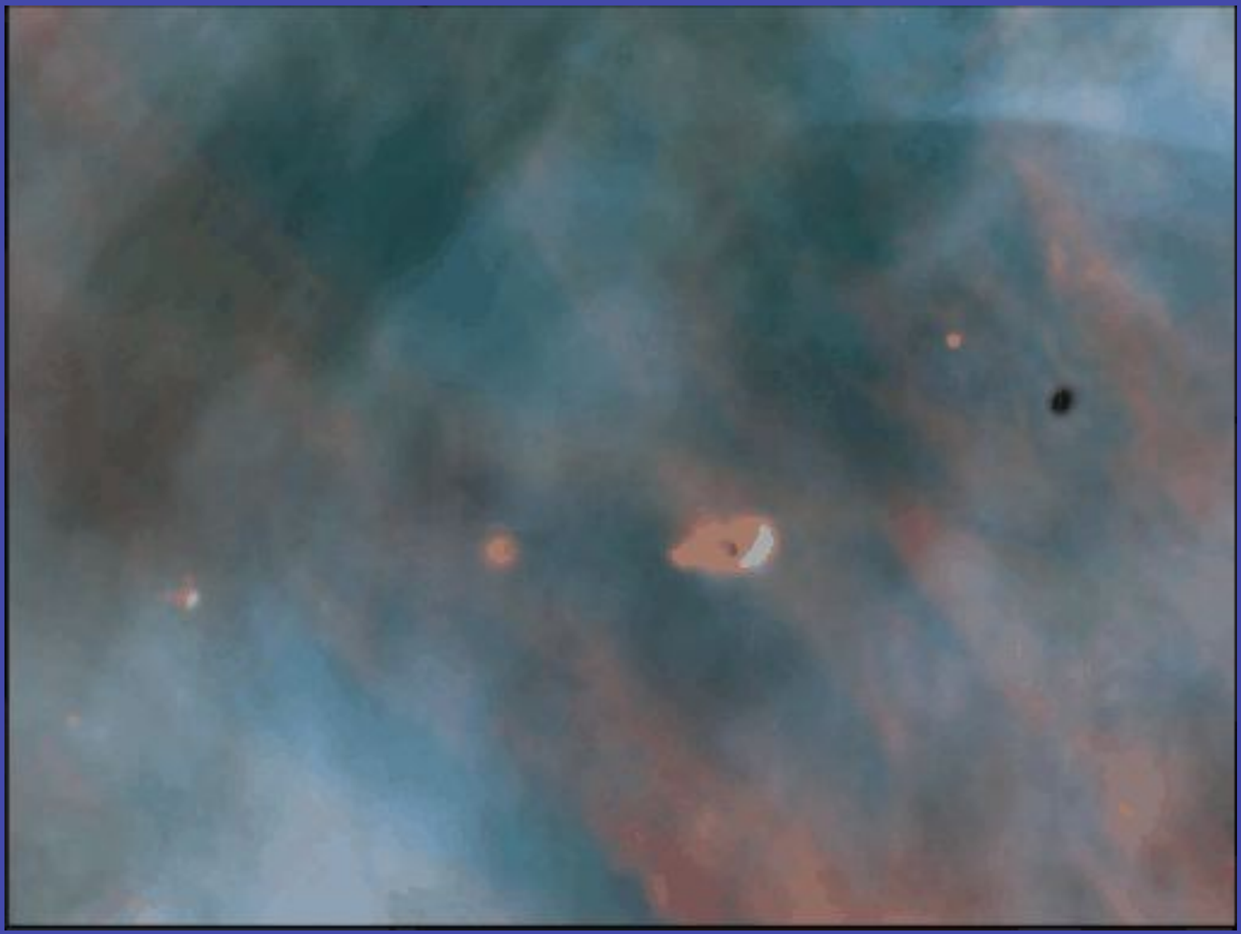
CRAB NEBULA - the remnant of a star about 10 times the mass of our sun that in 1054 exploded as a supernova





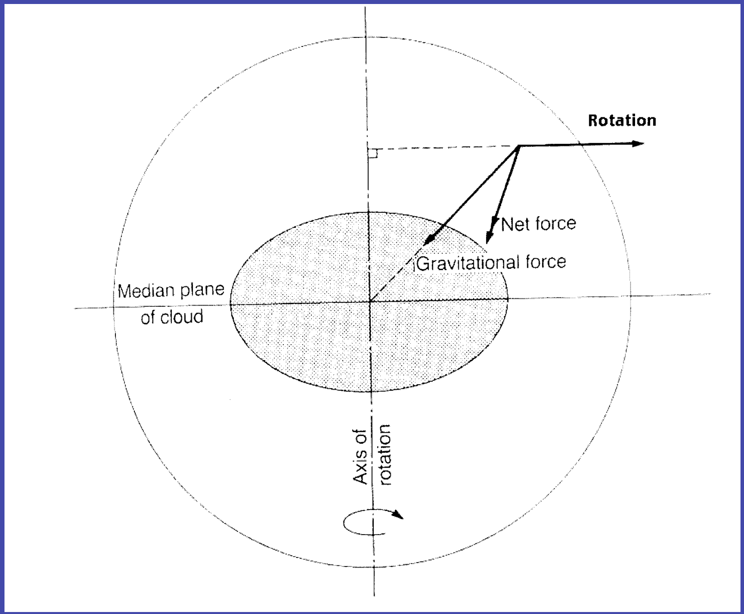


Brown & Mussett



HST image of the Orion Nebula, located in the same spiral arm of our Galaxy, showing five young stars surrounded by gas and dust trapped as the stars formed, that might evolve to planets.

The nebula flattens



Brown & Mussett

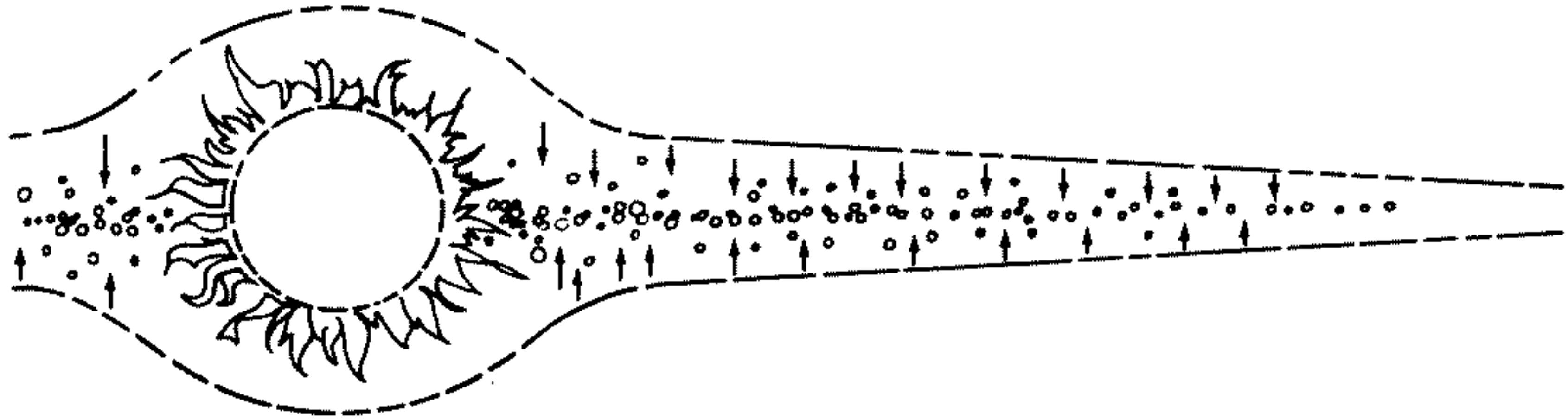
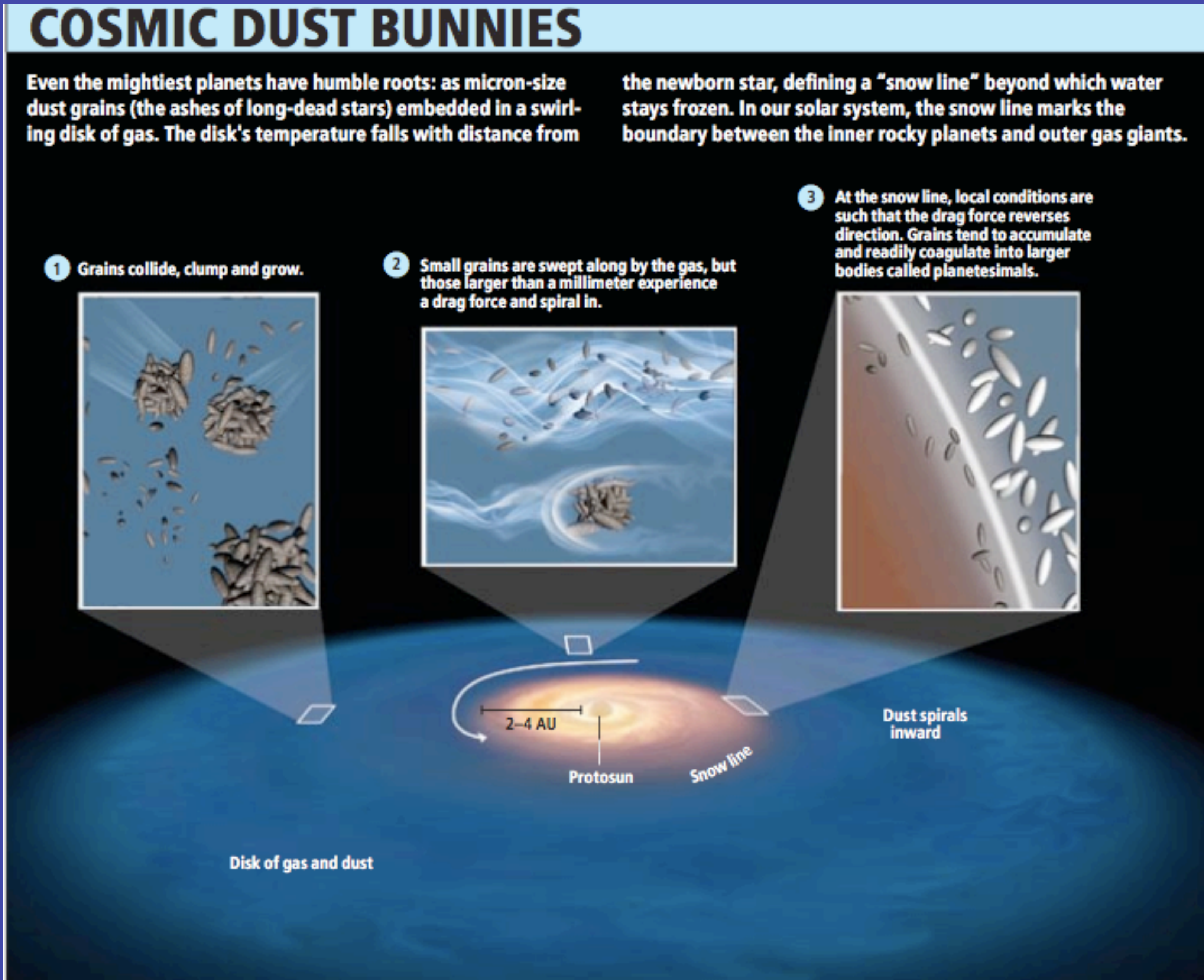


FIG. 7-8 Motion of solid particles, drawn by gravitational attraction of the nebula and protosun toward the midplane of the nebula (schematic).

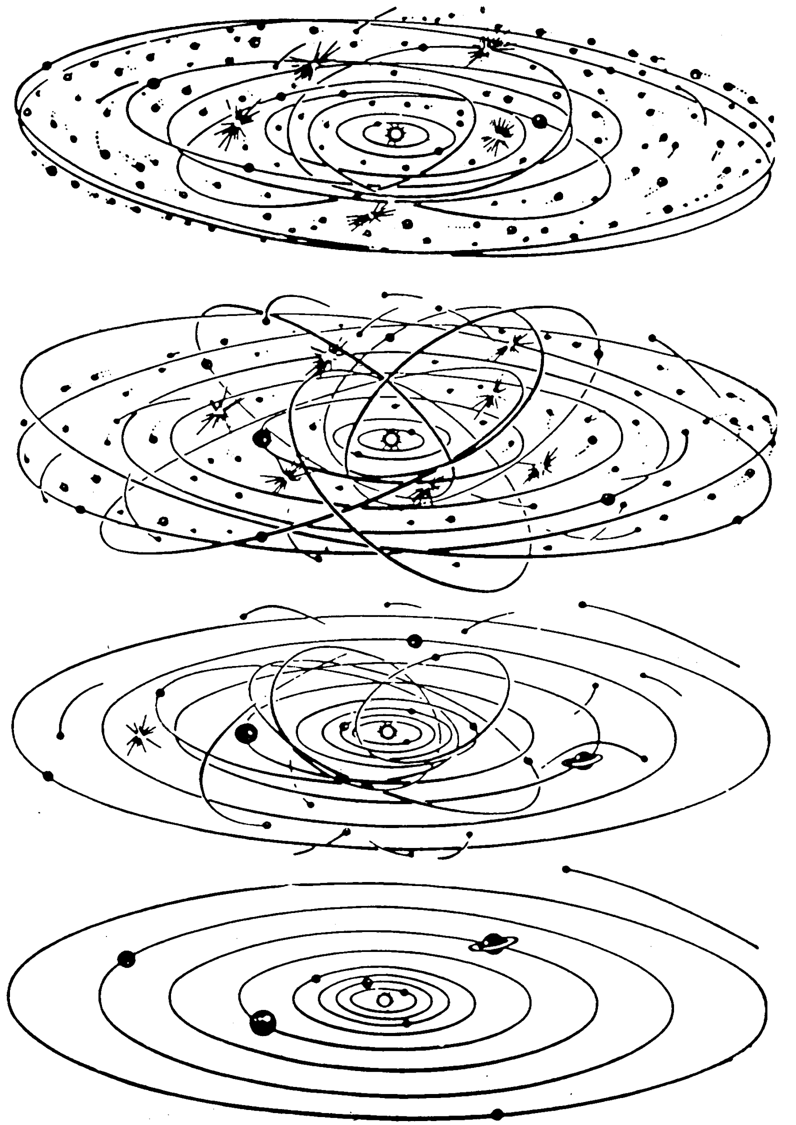


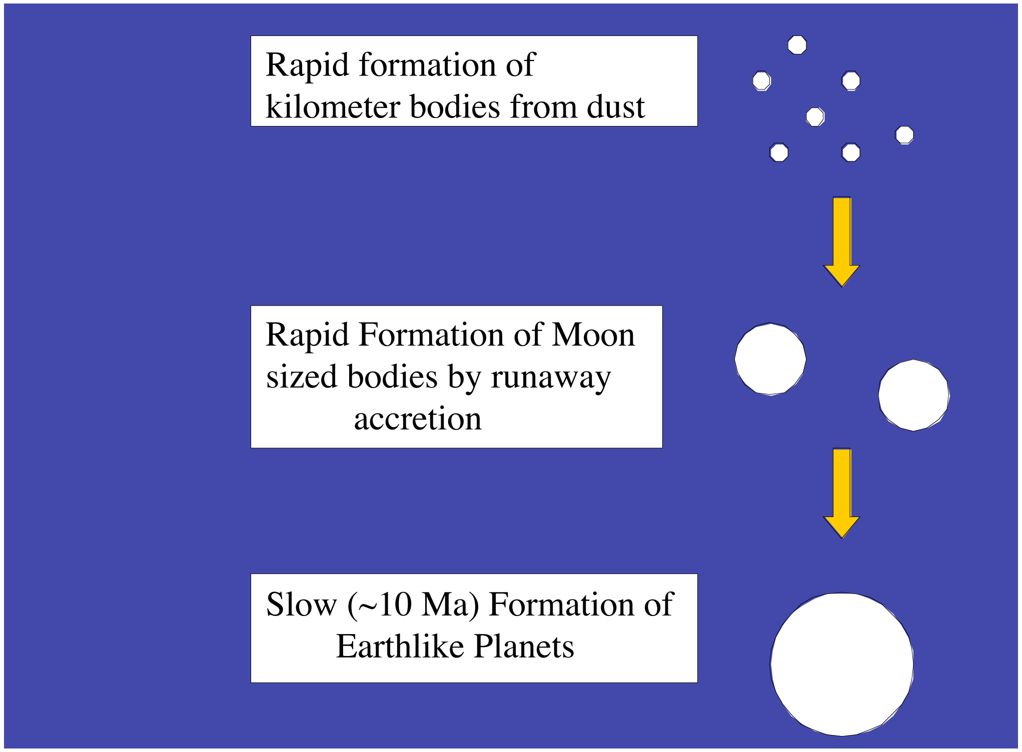
Lin, Sci. Am, May 2008

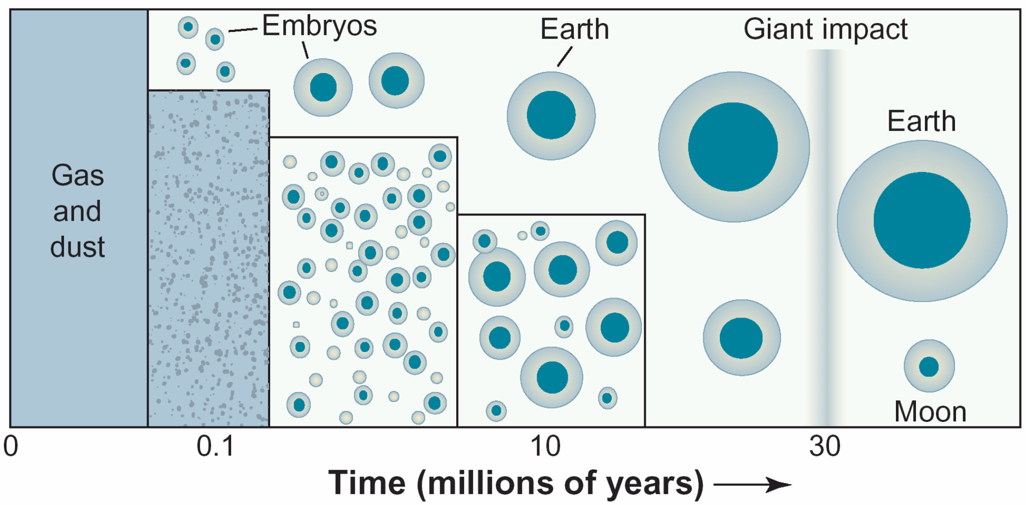
PLANETESIMAL ACCRETION


WALL STREET
IS
OUR STREET


DEAR 1%,
WE FELL ASLEEP
FOR A WHILE.
JUST WOKE UP.
SINCERELY, THE 99%
#OCCUPYWALLST
COURTESY LARRY BLUCHER/CNN IREPORT



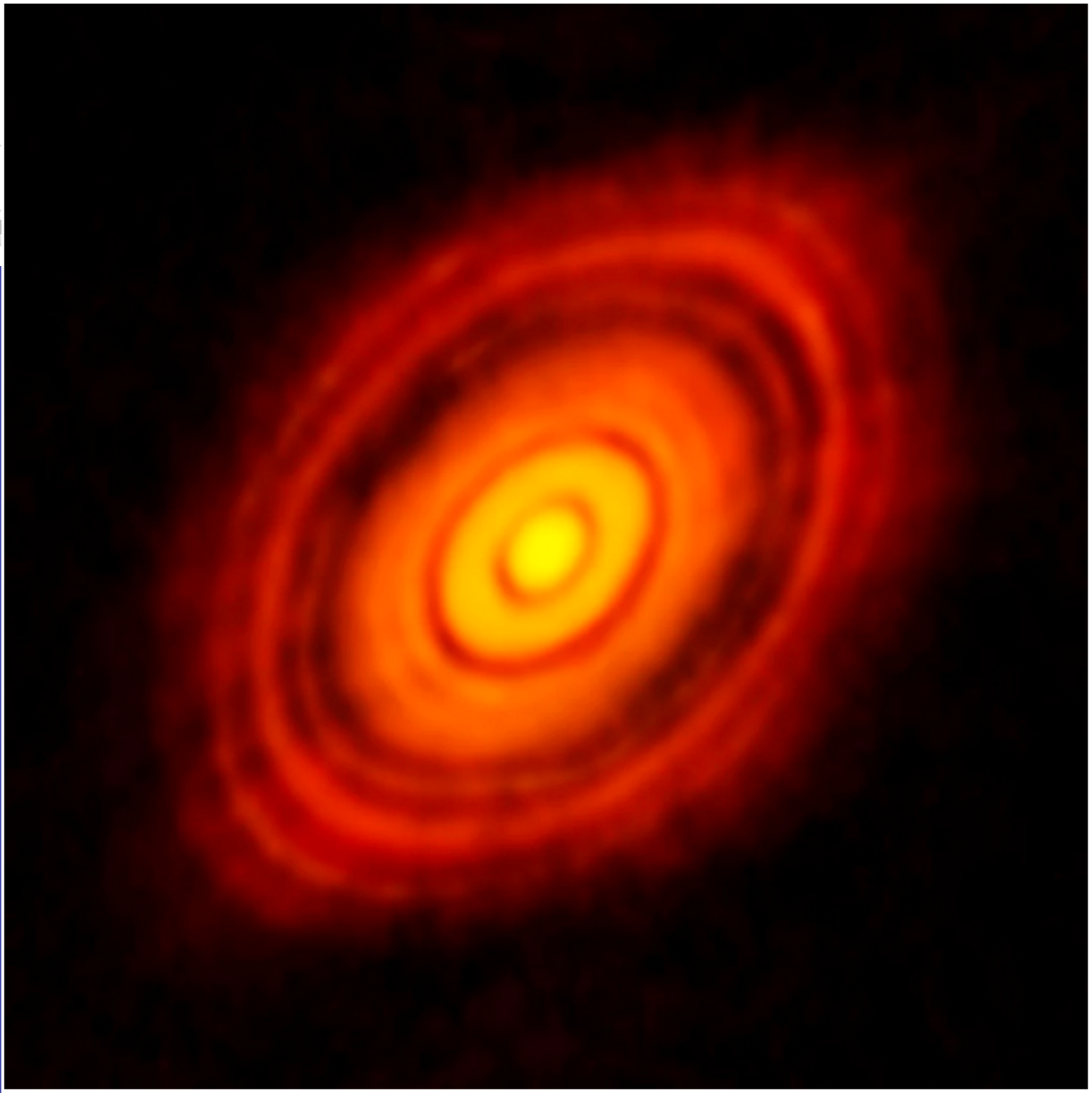




Planet formation

Planetary birth revealed in best image yet from world's most powerful telescope

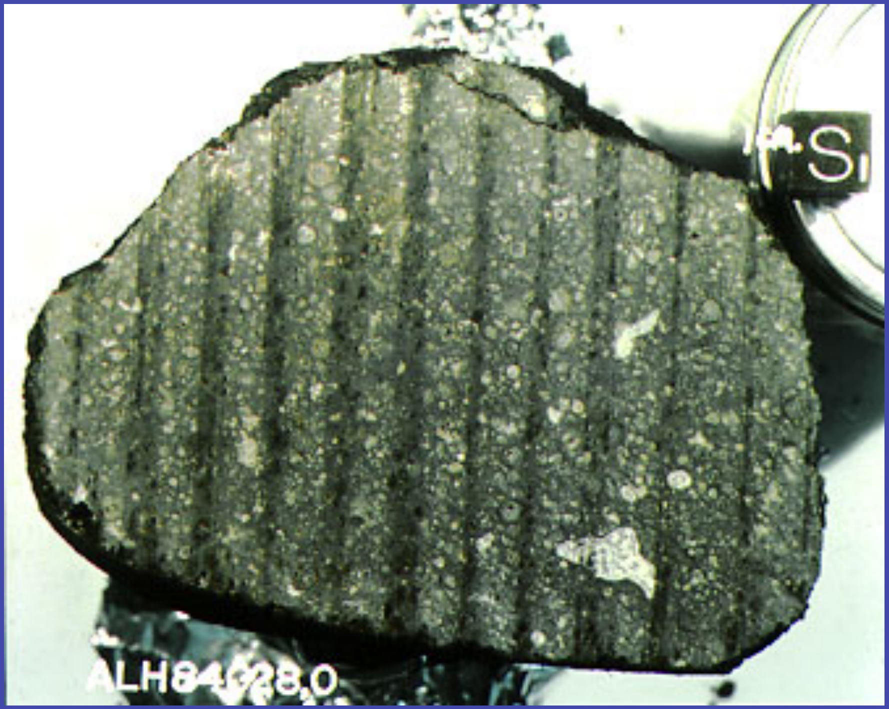
By **Rachel Feltman** November 6, 2014



WP

Meteorites

Iron



Carbonaceous chondrite

Black-Market Trinkets From Space

Mario Di Martino

LOOTED The Gebel Kamil crater in Egypt has been scoured for fragments prized by collectors and researchers.

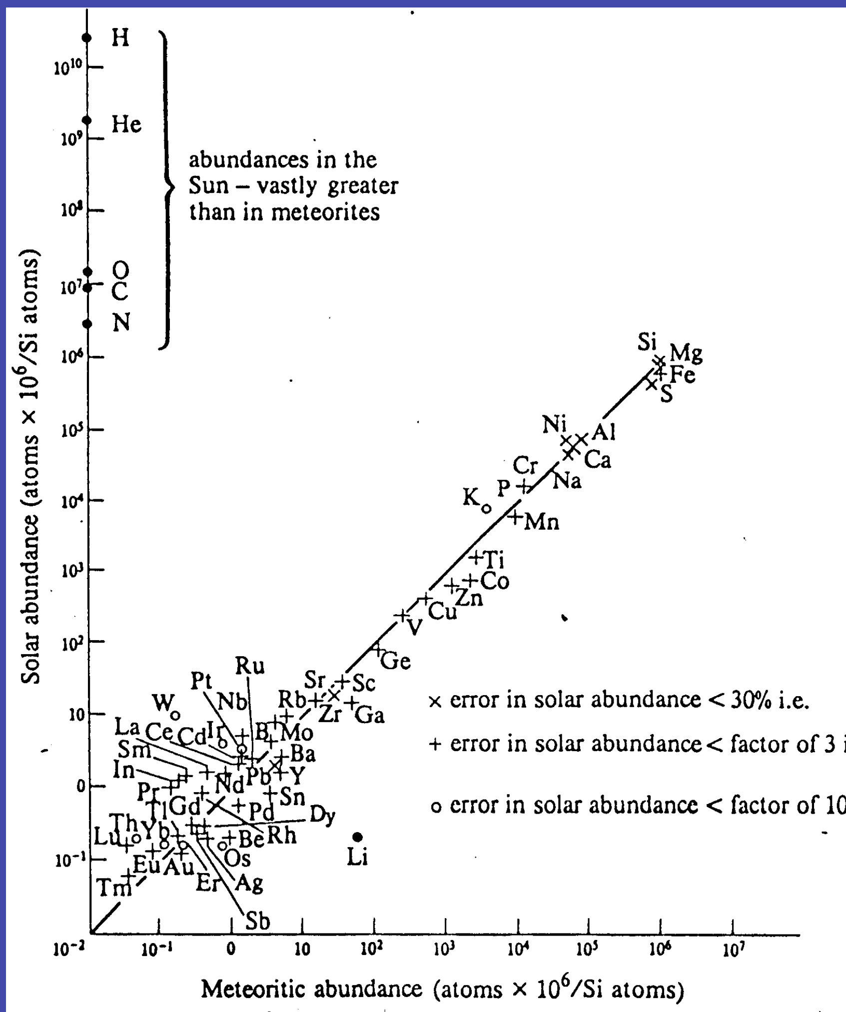
By WILLIAM J. BROAD
Published: April 4, 2011

NY Times

50,000 years ago

Iron meteorite 50 m diameter at ~12 km/s

Crater 1200 m diameter,160 m deep, 45 m rim



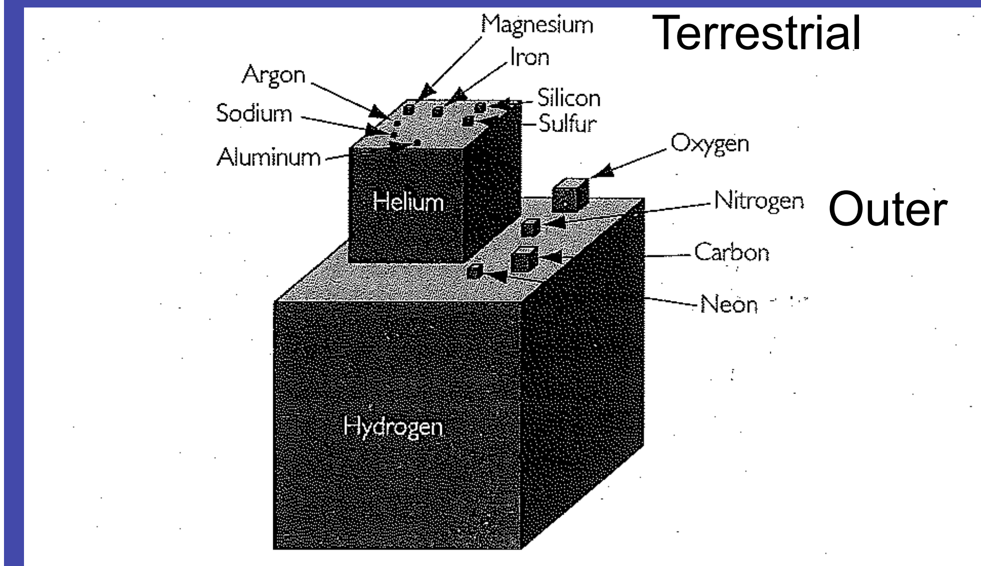
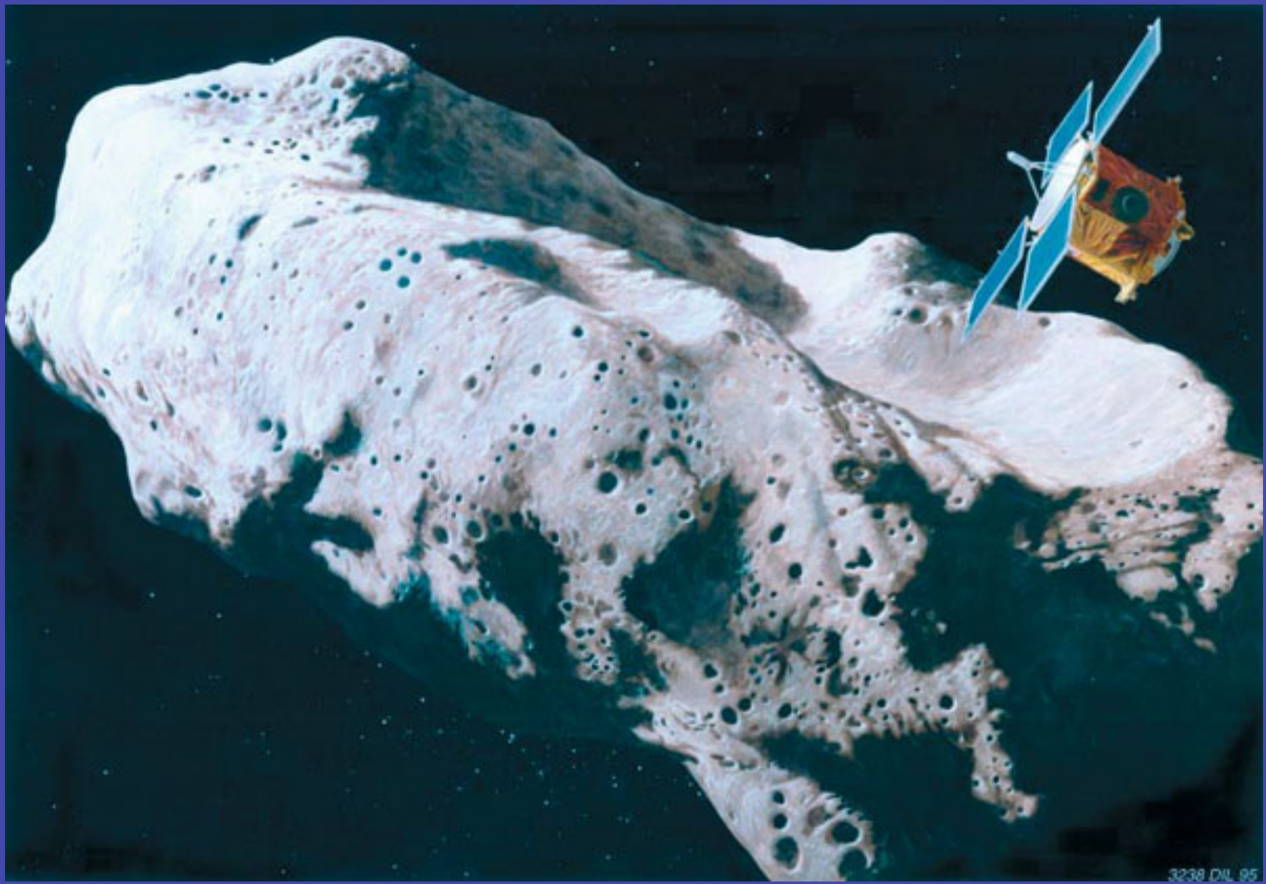


Figure 3.1 *The relative proportions (by number) of the most abundant elements in the Sun. Hydrogen and helium and the elements resting directly on top of the hydrogen cube dominate the composition of stars and Jovian planets. The terrestrial planets could not efficiently incorporate these elements and are composed largely of oxygen and the elements resting on the helium cube.*

Ward & Brownlee

Brown & Mussett

Near Earth Asteroid Rendezvous (NEAR) mission (2000)



Asteroid 433 Eros is a primitive sample from the solar system's beginnings. It has homogeneous structure, so never separated into a distinct crust, mantle and core. X-ray spectrometer has detected low levels of aluminum relative to magnesium and silicon, indicating an undifferentiated composition. Eros, or the parent body it could have broken from, has not experienced the extensive melting process that planets like Earth undergo in their development. Eros may be related to the primitive ordinary chondrites, the most common type of meteorite.

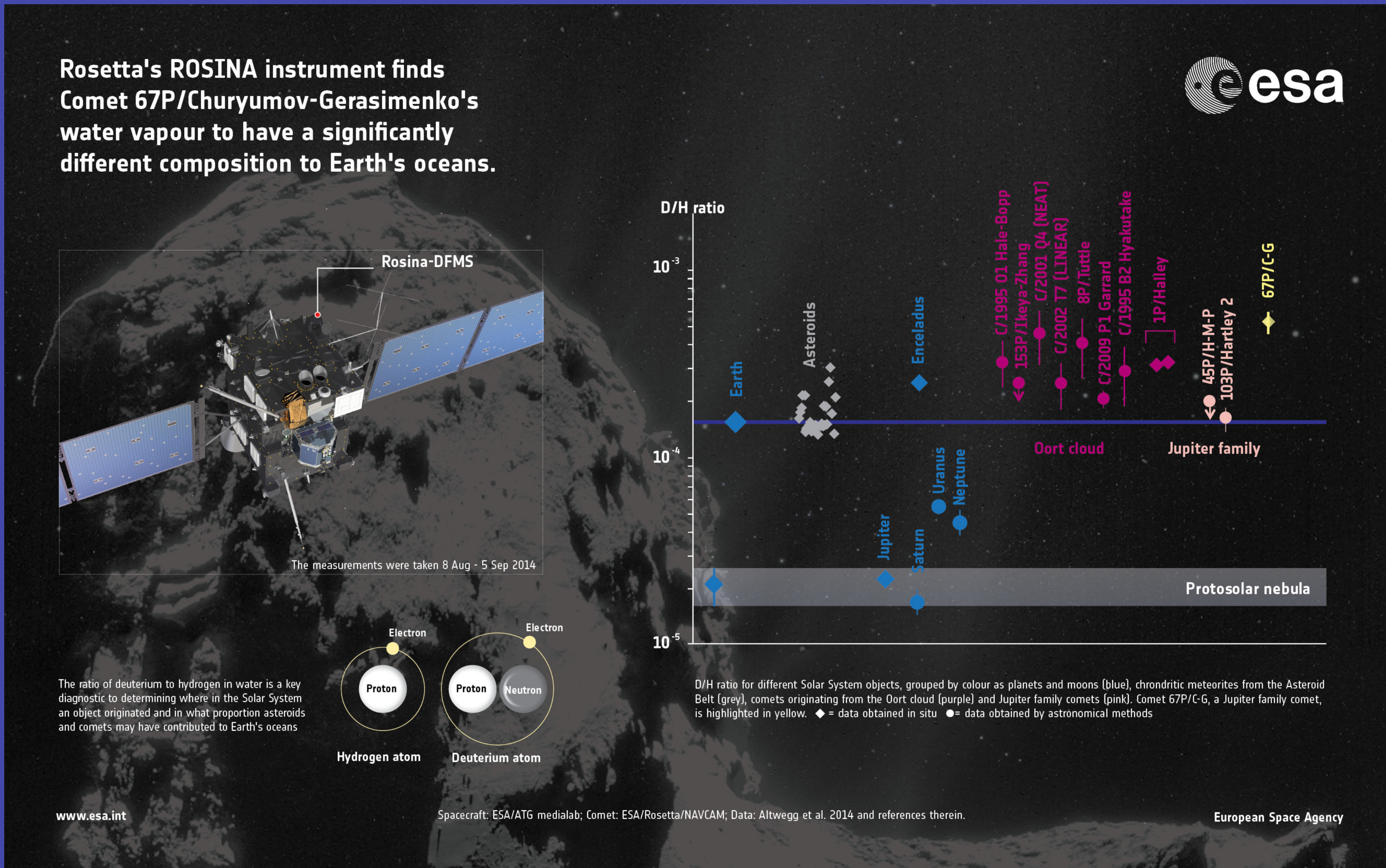
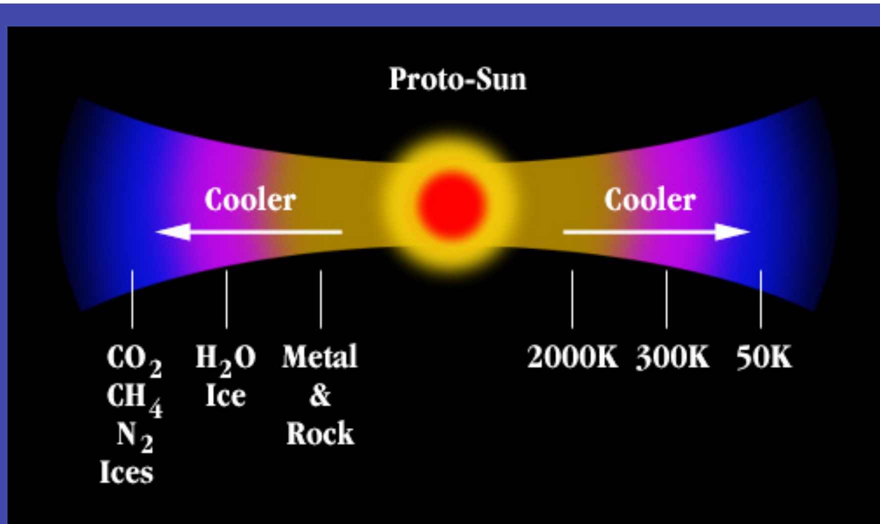

Rosetta's ROSINA instrument finds Comet 67P/Churyumov-Gerasimenko's water vapour to have a significantly different composition to Earth's oceans.
esa
Rosina-DFMS
The measurements were taken 8 Aug - 5 Sep 2014
D/H ratio
10-3
10-4
10-5
Earth
Asteroids
Enceladus
Jupiter
Saturn
Uranus
Neptune
C/1995 O1 Hale-Bopp
153P/Ikeya-Zhang
C/2001 Q4 (NEAT)
C/2002 T7 (LINEAR)
8P/Tuttle
C/2009 P1 Garrard
C/1995 B2 Hyakutake
1P/Halley
45P/H-M-P
103P/Hartley 2
67P/C-G
Oort cloud
Jupiter family
Protosolar nebula
Electron
Proton
Hydrogen atom
Electron
Proton
Neutron
Deuterium atom
The ratio of deuterium to hydrogen in water is a key diagnostic to determining where in the Solar System an object originated and in what proportion asteroids and comets may have contributed to Earth's oceans
D/H ratio for different Solar System objects, grouped by colour as planets and moons (blue), chrondritic meteorites from the Asteroid Belt (grey), comets originating from the Oort cloud (purple) and Jupiter family comets (pink). Comet 67P/C-G, a Jupiter family comet, is highlighted in yellow. ◆ = data obtained in situ ● = data obtained by astronomical methods
www.esa.int
Spacecraft: ESA/ATG medialab; Comet: ESA/Rosetta/NAVCAM; Data: Altwegg et al. 2014 and references therein.
European Space Agency

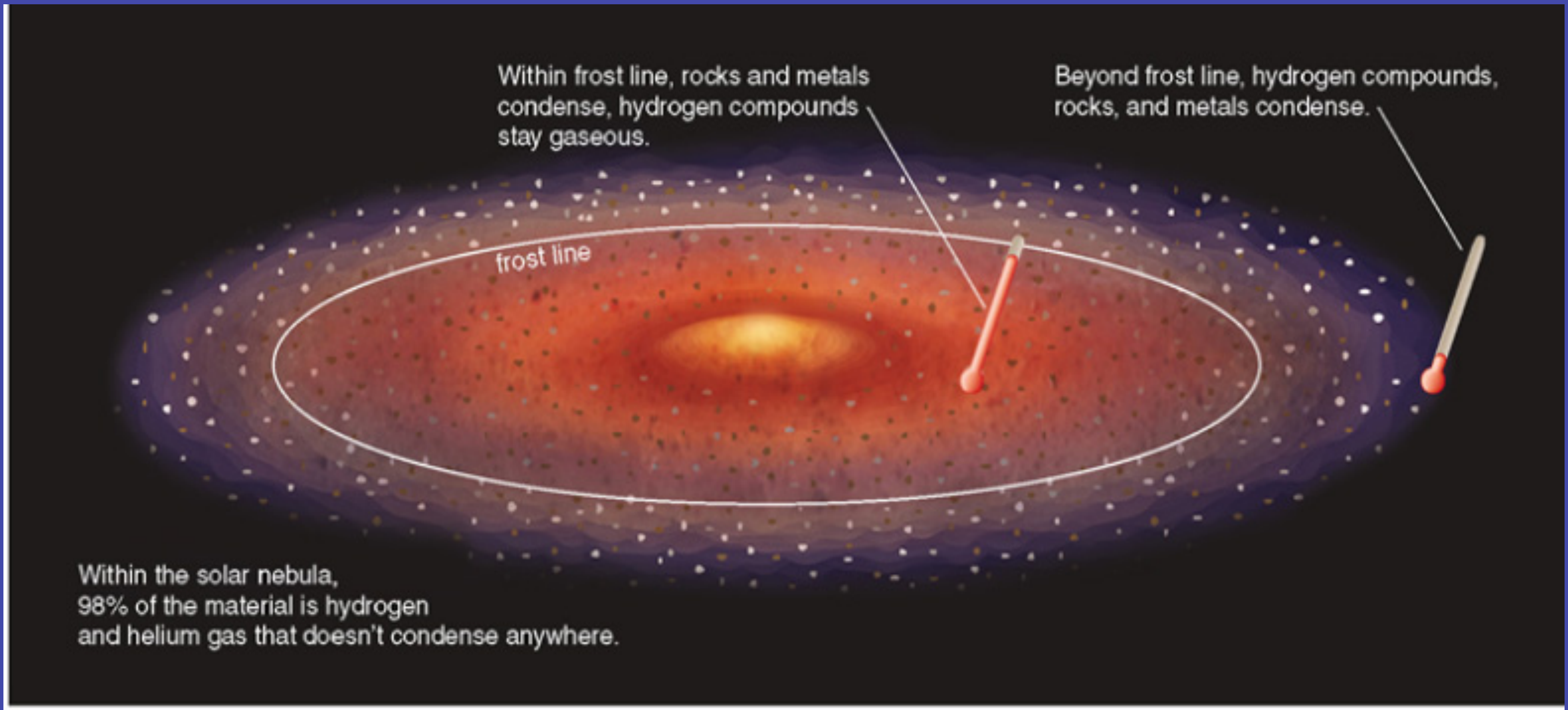
Table 5.1 Approximate condensation temperatures of Solar Nebula materials at 10^{-4}atm. (After Grossman & Larimer 1974.)

Mineral phase	*Composition*	*Condensation temperature (°C)*
corundum	Al_2O_3	1410 ↑
melilite	$Ca_2Al_2SiO_7$–$Ca_2MgSi_2O_7$	1205
perovskite	$CaTiO_3$	1200
spinel	$MgAl_2O_4$	1150
metallic iron	Fe (Ni)	1130
forsterite	Mg_2SiO_4 (–Fe_2SiO_4)	1120
diopside	$CaMgSi_2O_6$	1100
enstatite	$MgSiO_3$ (–$FeSiO_3$)	
anorthite	$CaAl_2Si_2O_8$	
		refractory
		volatile
alkali feldspar	$(Na,K)AlSi_3O_8$	980
troilite	FeS	430
magnetite	Fe_3O_4	135
ice, methane, etc.	H_2O, CH_4, CO_2, O_2, N_2, H_2, etc.	< 0 ↓



Brown & Mussett

Frost line ~ 3 AU



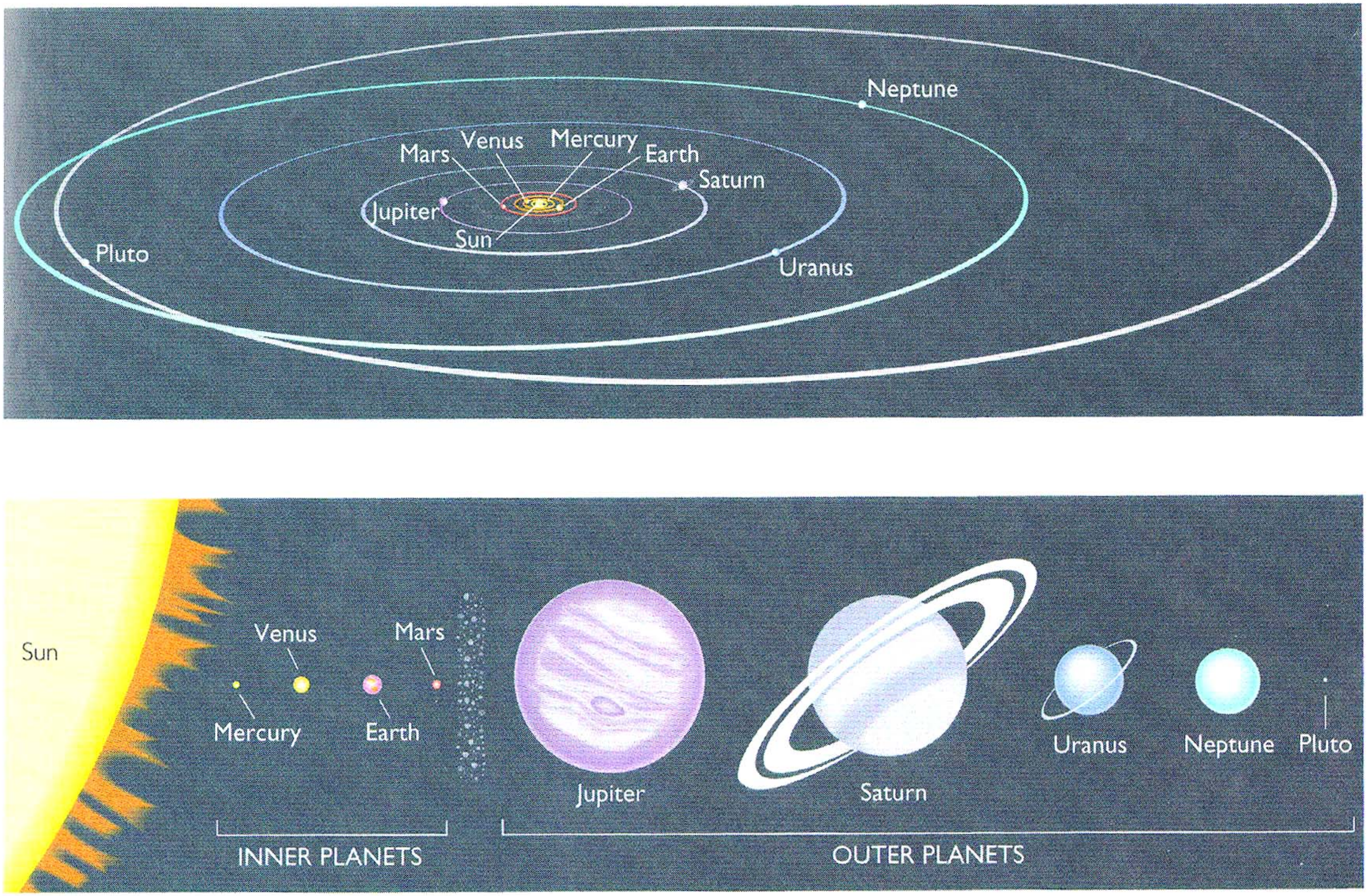


FIGURE 1.3 The solar system. The four inner planets—Mercury, Venus, Earth, and Mars—are closest to the Sun and are small and rocky. The four giant outer planets—Jupiter, Saturn, Uranus, and Neptune—and their satellites are mostly gaseous with rocky cores. The outermost planet, Pluto, is a snowball of methane, water, and rock. The upper panel shows the planetary orbits drawn roughly to scale; the distance from Pluto to the Sun averages about 5.9 billion km. The lower panel shows the relative sizes of the planets and the asteroid belt separating the inner and outer planets.

Press & Siever

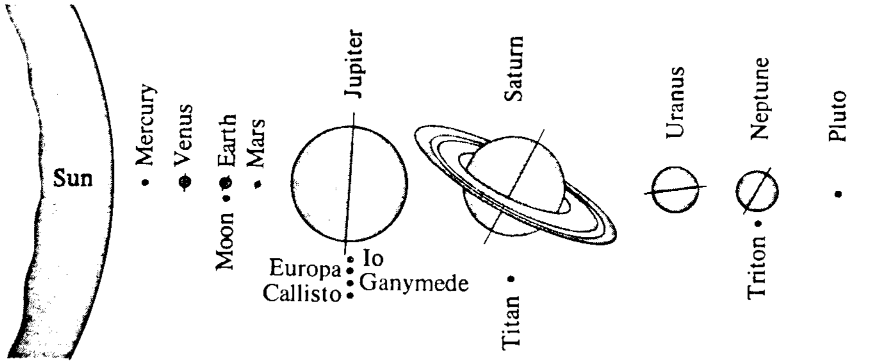


Figure 4.1 Relative sizes of the Sun, planets and moons. Only the seven largest moons are shown, as the others would be mere dots. The axes of rotation, where known, are shown. The separations of the bodies are *not* to scale.

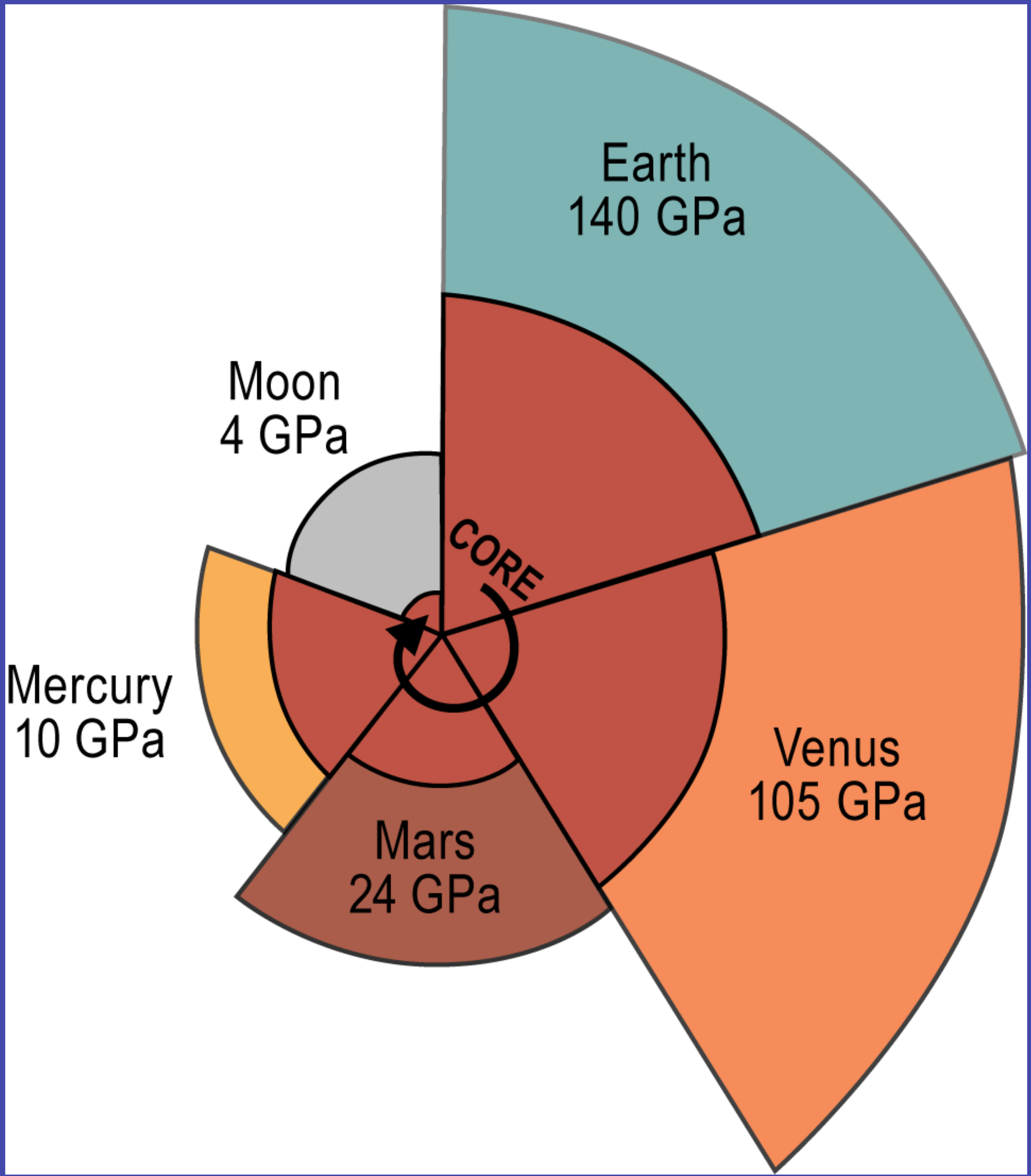
Table 4.1 Chief properties of the Sun, the planets and the Moon.

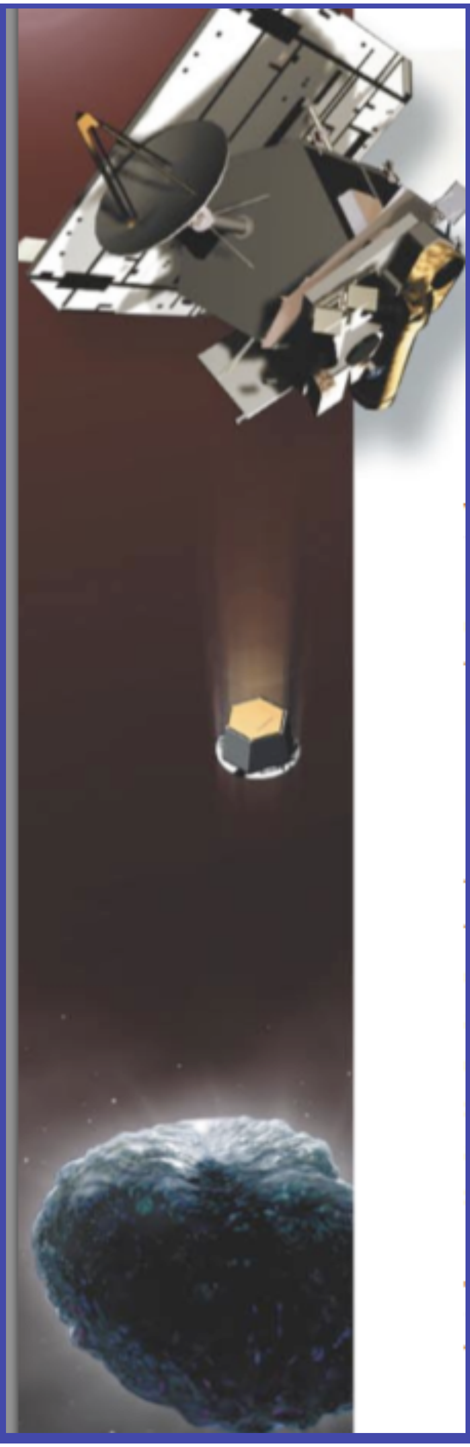
		Terrestrial planets					*Major planets*				
Property	*Sun*	*Mercury*	*Venus*	*Earth*	*(Moon)*	*Mars*	*Jupiter*	*Saturn*	*Uranus*	*Neptune*	*Pluto*
distance from Sun (mean value) (units of 10^6 km)	—	58	108	150	—	228	778	1427	2870	4497	5900
(Earth = 1)	—	0·39	0·72	1	—	1·52	5·20	9·54	19·2	30·1	39·4
mass (Earth = 1)	343 000	0·055	0·815	1	0·012	0·108	318	95	14·6	17·2	c.0·002
mean density (water = 1)	1·4	5·4	5·2	5·5	3·3	3·9	1·3	0·7	1·2	1·7	< 1·7
radius (km)	696 000	2440	6052	6378	1738	3394	71 400	60 000	25 900	24 750	1900
year, i.e. period of revolution about Sun (Earth years)	—	0·24	0·62	1	—	1·88	11·9	29·5	84·0	164	248
spin period, i.e. rotation about axis (days)	27	59	−243*	1	27·3	1·03	0·40	0·43	−0·89*	0·53	6·4
eccentricity of orbit	—	0·206	0·007	0·017	0·055	0·093	0·043	0·056	0·047	0·009	0·25
inclination of orbit, with respect to the Earth's (deg)	—	7	3·4	0	23 †	1·9	1·3	2·5	0·8	1·8	17·2
inclination of axis, with respect to axis of Earth's orbit (deg)	7	< 28	3	23	23 †	24	3	27	82	29	?
number of moons known	—	0	0	1	—	2	14	10	5	2	1?
atmosphere, chief constituents	—	none	CO_2	N_2, O_2	none	CO_2	H_2, He	H_2, He	H_2, He, CH_4	H_2, He, CH_4	none?
magnetic field, dipole moment‡ (Earth = 1)	3×10^6	$6{\cdot}6 \times 10^{-4}$	$< 10^{-4}$	1	$< 2 \times 10^{-6}$	3×10^{-4}	$1{\cdot}9 \times 10^4$	?	?	?	?

* Minus sign denotes rotation is retrograde, i.e. opposite to majority direction.
† That is, orbit is in plane of Earth's equator.
‡ That is, strength of equivalent bar magnet (but some planetary fields are poorly represented by a dipole).

Brown & Mussett

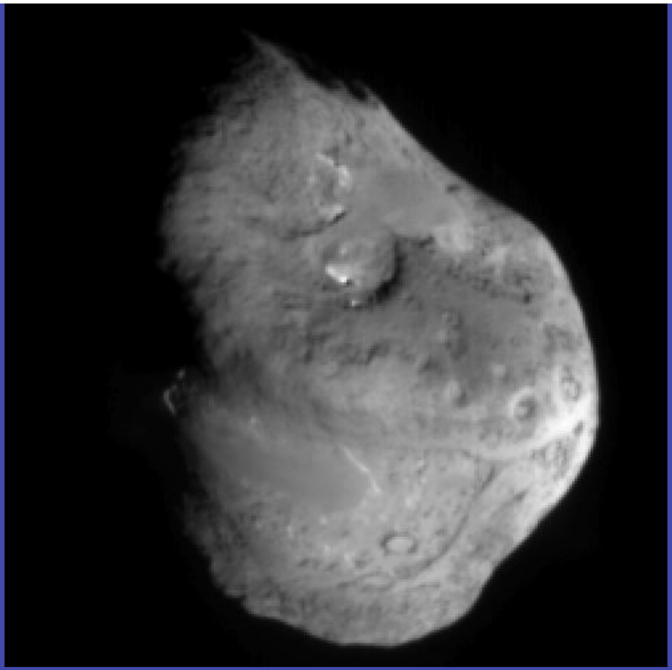
Mercury’ s core is too big

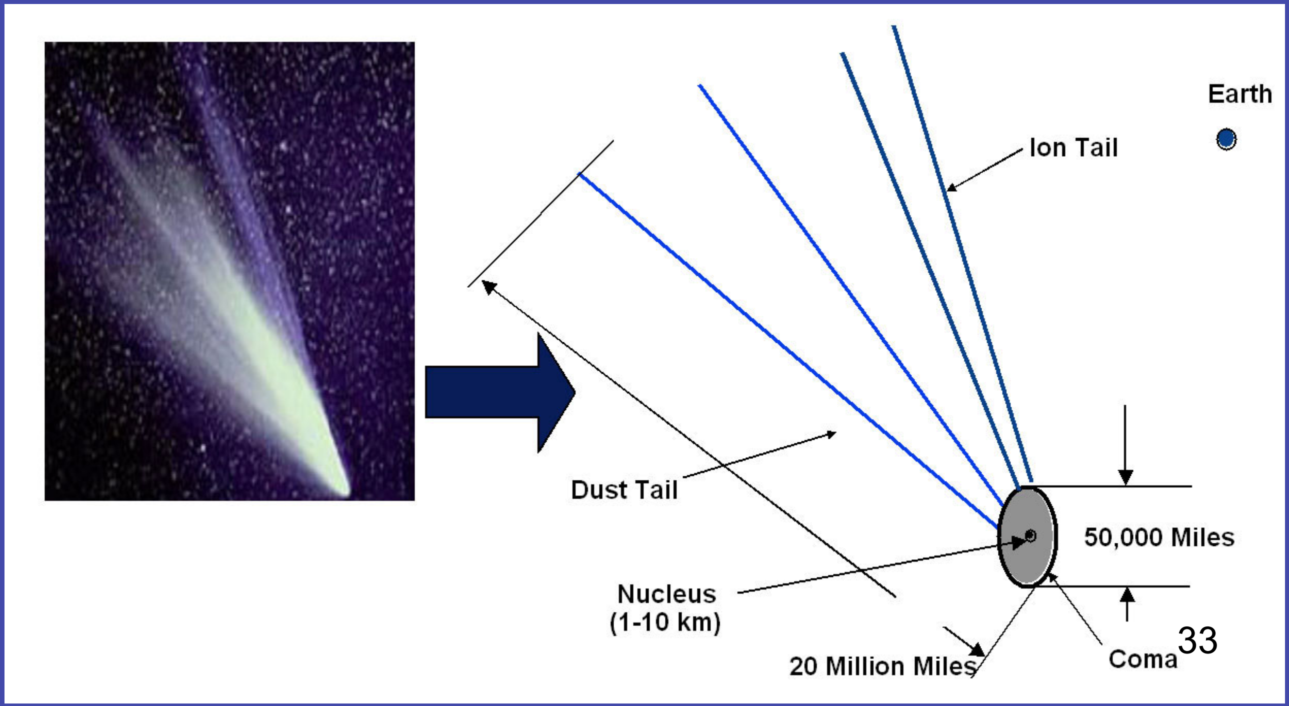




Comets

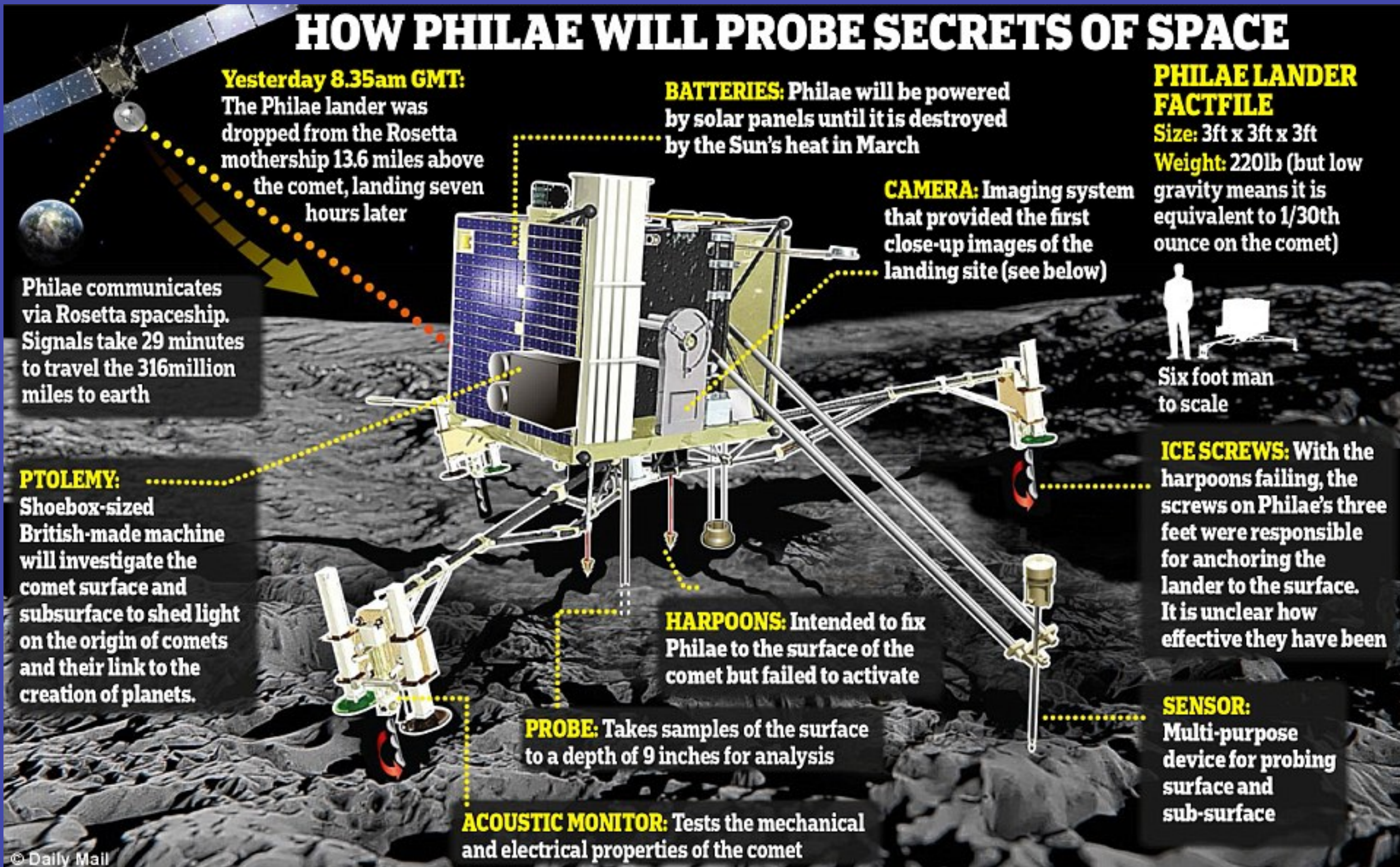
Nucleus of comet Tempel 1 imaged by the Deep Impact impactor. The nucleus measures about 6 kilometers across.





Scale of the comet (a side view)

Sources: The Washington Post, European Space Agency @ChiTribGraphics


HOW PHILAE WILL PROBE SECRETS OF SPACE
Yesterday 8.35am GMT: The Philae lander was dropped from the Rosetta mothership 13.6 miles above the comet, landing seven hours later
BATTERIES: Philae will be powered by solar panels until it is destroyed by the Sun's heat in March
PHILAE LANDER FACTFILE
Size: 3ft x 3ft x 3ft
Weight: 220lb (but low gravity means it is equivalent to 1/30th ounce on the comet)
CAMERA: Imaging system that provided the first close-up images of the landing site (see below)
Philae communicates via Rosetta spaceship. Signals take 29 minutes to travel the 316million miles to earth
Six foot man to scale
PTOLEMY: Shoebox-sized British-made machine will investigate the comet surface and subsurface to shed light on the origin of comets and their link to the creation of planets.
ICE SCREWS: With the harpoons failing, the screws on Philae's three feet were responsible for anchoring the lander to the surface. It is unclear how effective they have been
HARPOONS: Intended to fix Philae to the surface of the comet but failed to activate
SENSOR: Multi-purpose device for probing surface and sub-surface
PROBE: Takes samples of the surface to a depth of 9 inches for analysis
ACOUSTIC MONITOR: Tests the mechanical and electrical properties of the comet
© Daily Mail

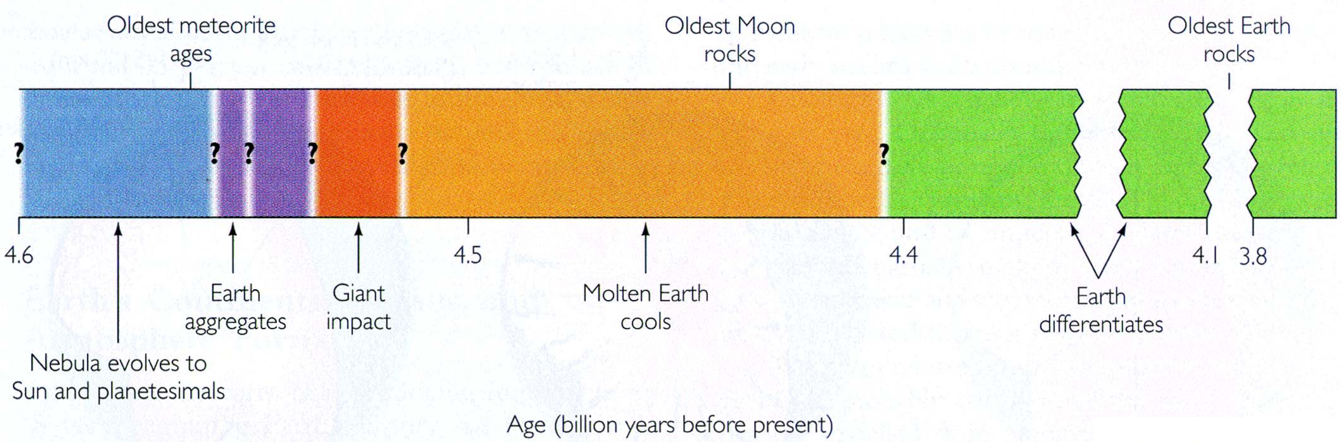


FIGURE 1.5 This timeline shows the origin of the Sun and Earth, the giant impact that melted much of the Earth and created the Moon, and the beginning of Earth's differentiation. The ages of the events listed above the bar are based on actual datings of meteorites and of lunar and Earth rocks. The question marks within the bar indicate a high degree of uncertainty about the timing of the events so marked. (Extensively modified from D. J. DePaolo, "Strange Bedfellows," *Nature,* Vol. 10, November 10, 1994, p. 131.)

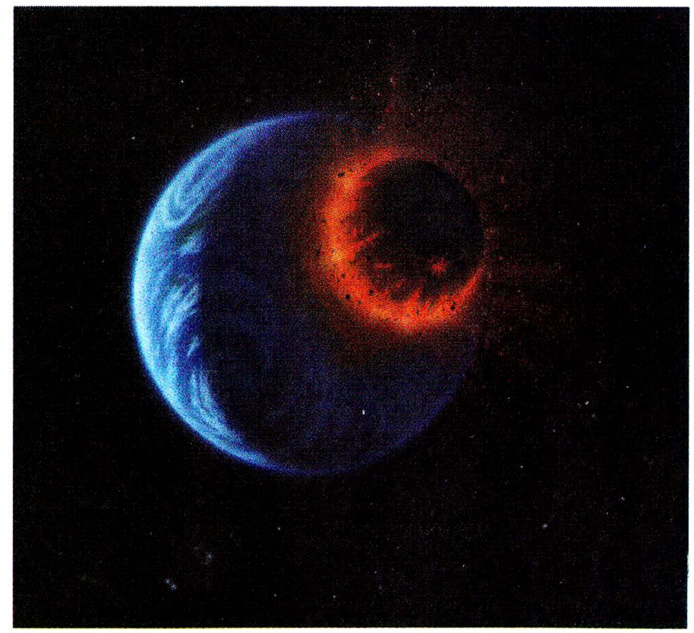
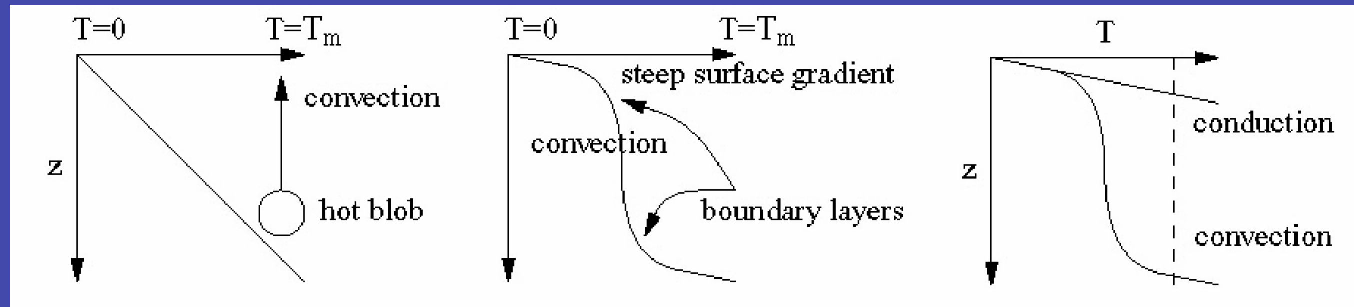


FIGURE 1.4 Artist's rendering of the collision of a Mars-size body with Earth about 4.5 billion years ago. The impact energy would have caused extensive melting of Earth and would have ejected debris that aggregated to form the Moon. (Painting by Alfred T. Kamajian, *Scientific American,* July 1994, cover.)

Press & Siever

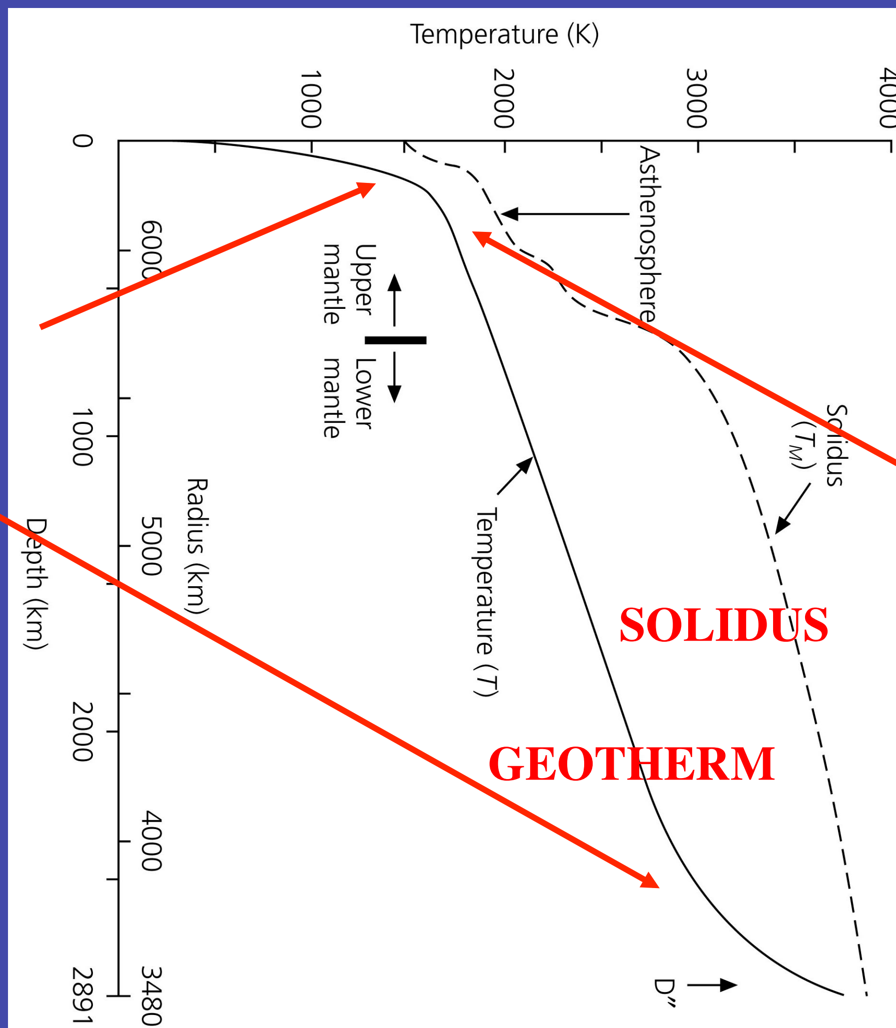
MANTLE CONVECTION GEOTHERM

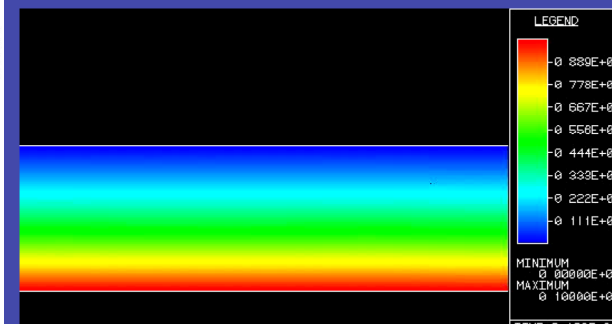


Thermal boundary layers

Lithosphere

Core/mantle boundary





Asthenosphere / LVZ

Geotherm close to solidus

Stein & Wysession

Earth's heat engine

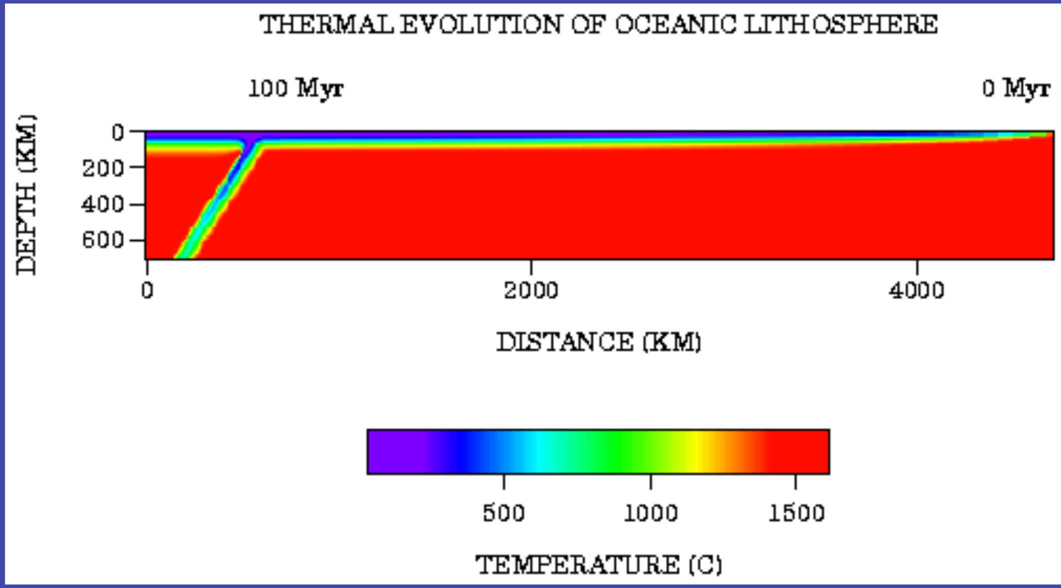
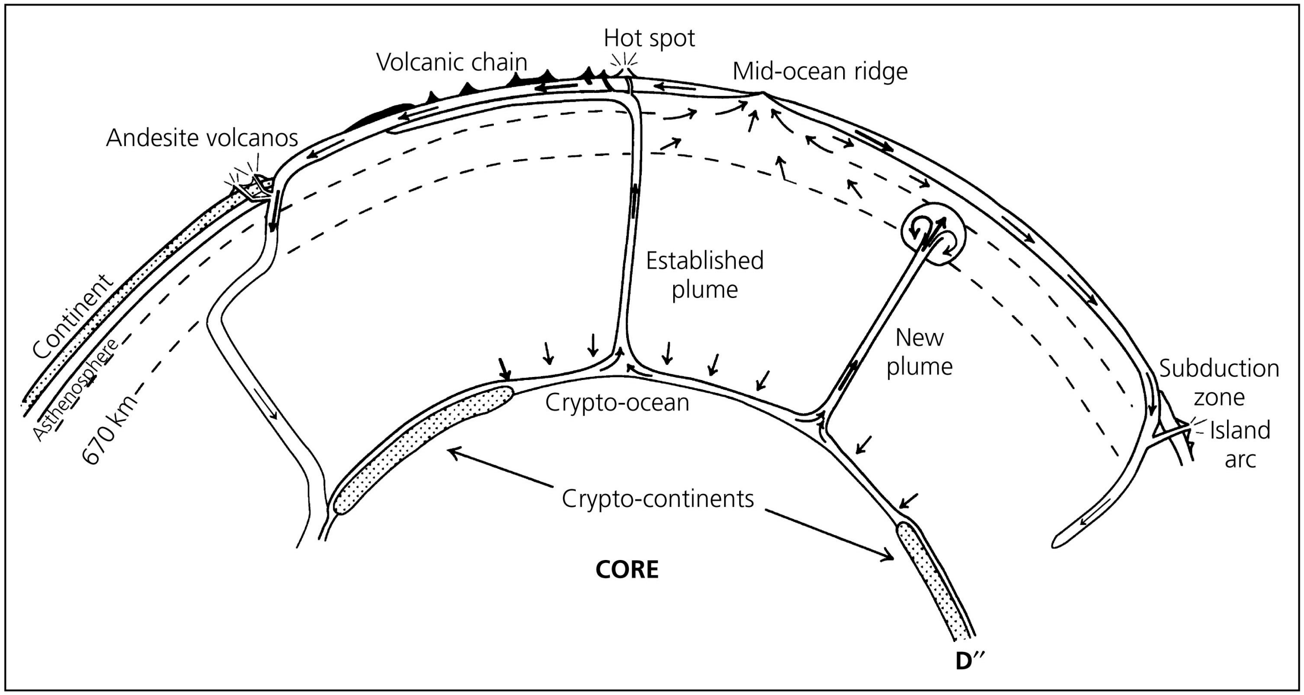
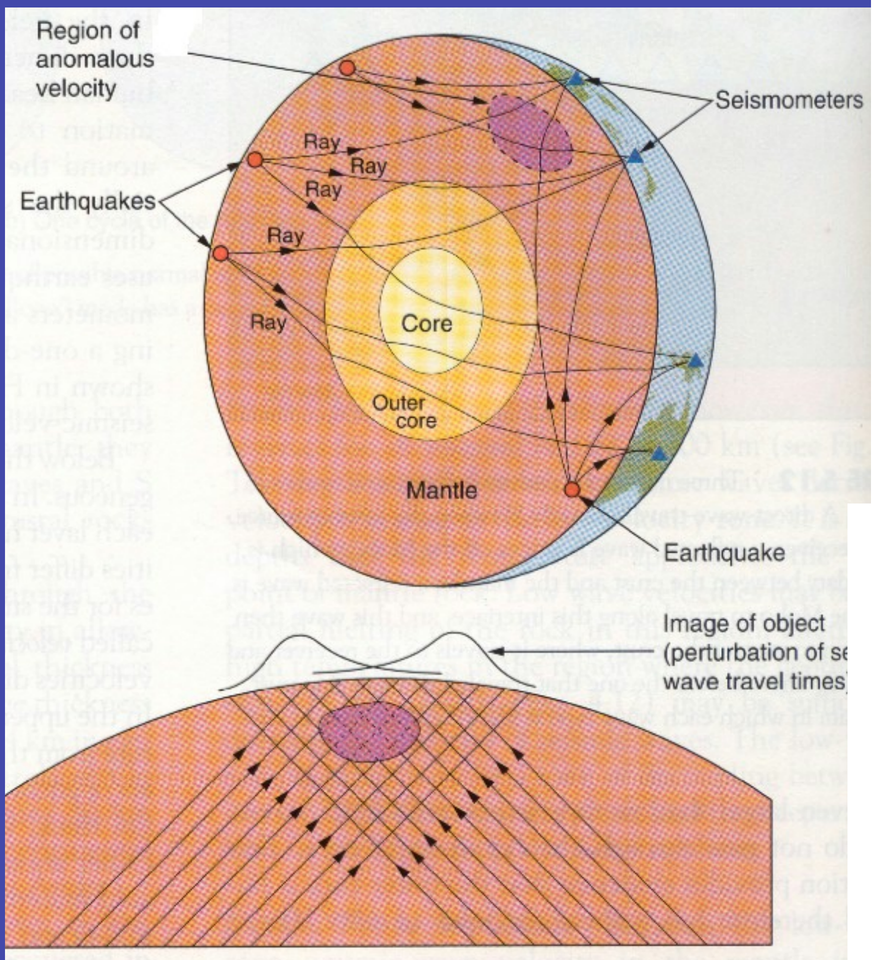
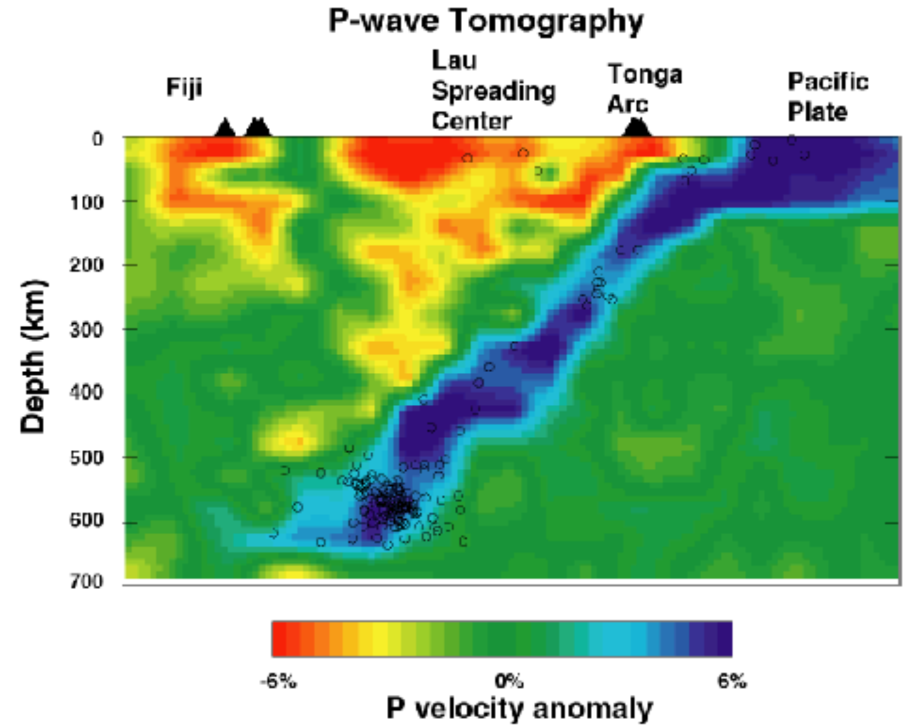


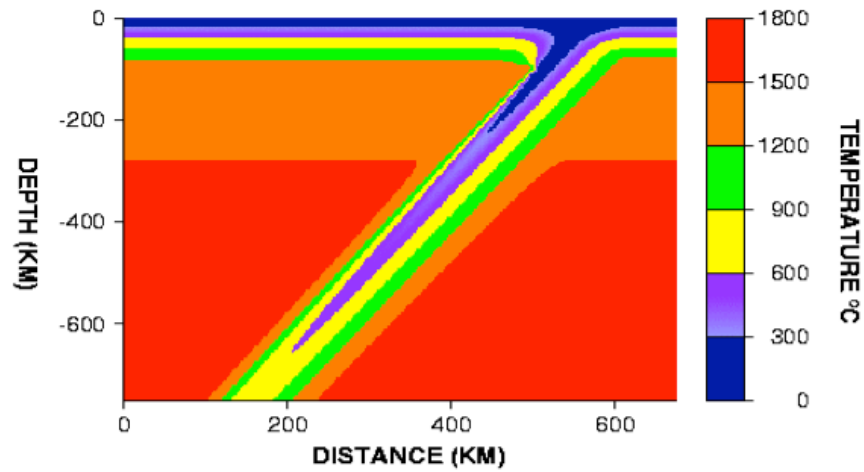
Figure 5.1-2: Diagram showing ideas about mantle convection.

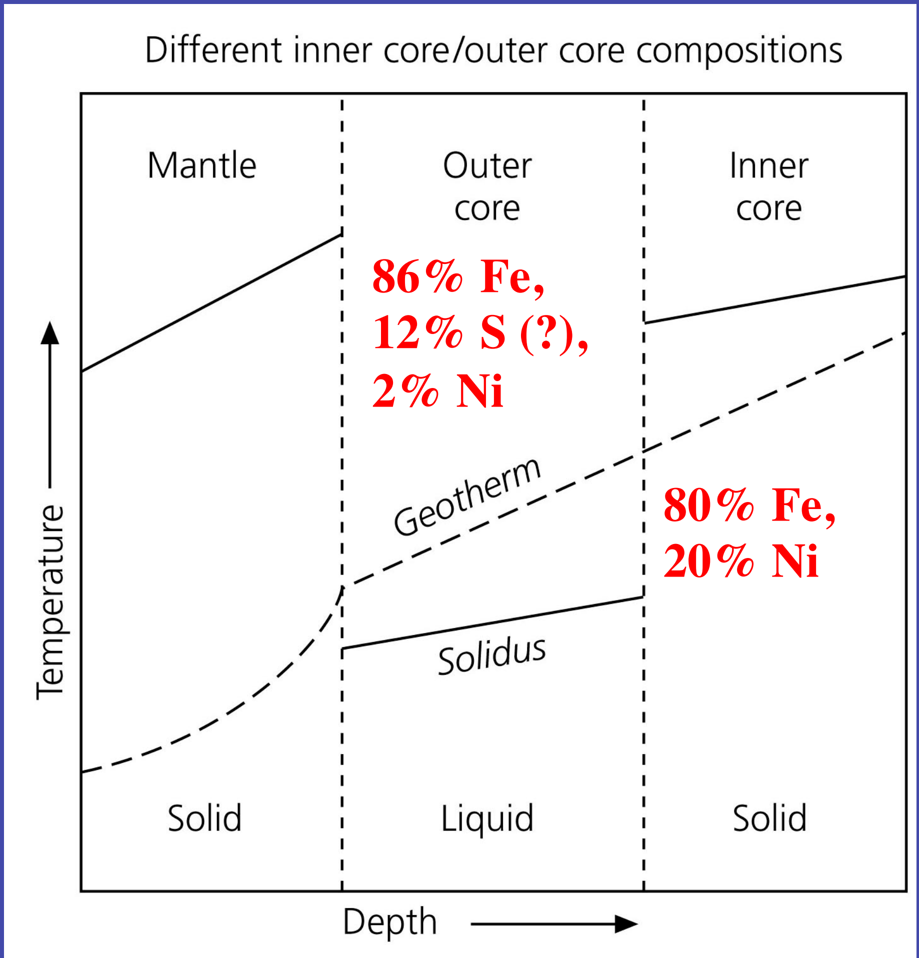


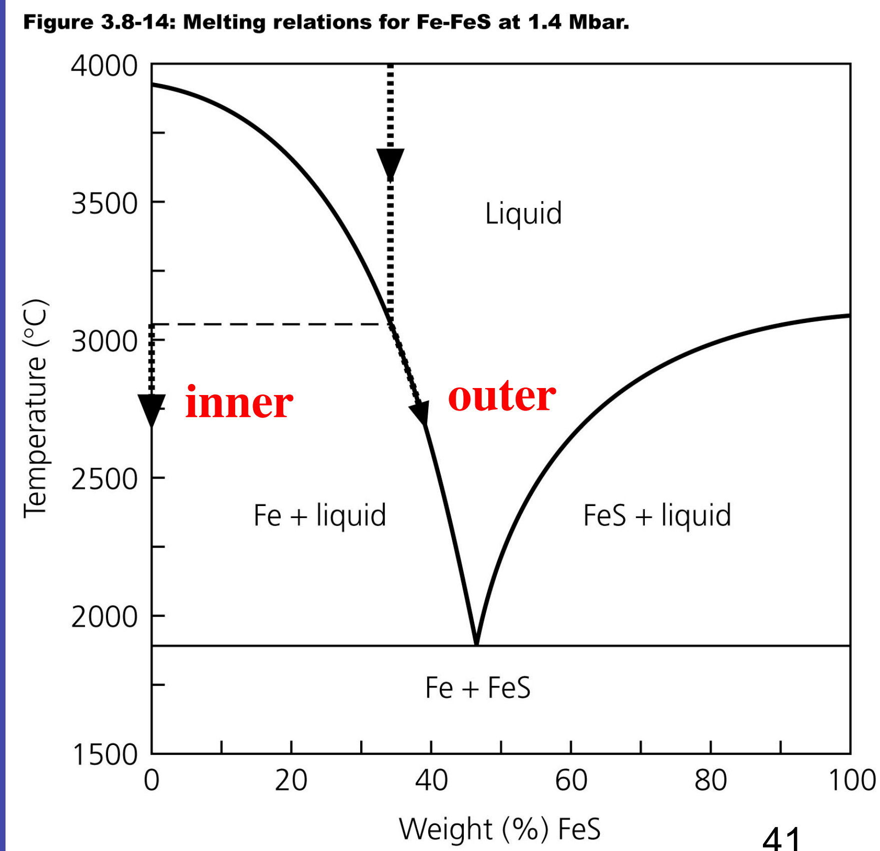
Stein & Wysession


Region of anomalous velocity
Seismometers
Earthquakes
Ray
Ray
Ray
Ray
Ray
Core
Outer core
Mantle
Earthquake
Image of object (perturbation of se
wave travel times)

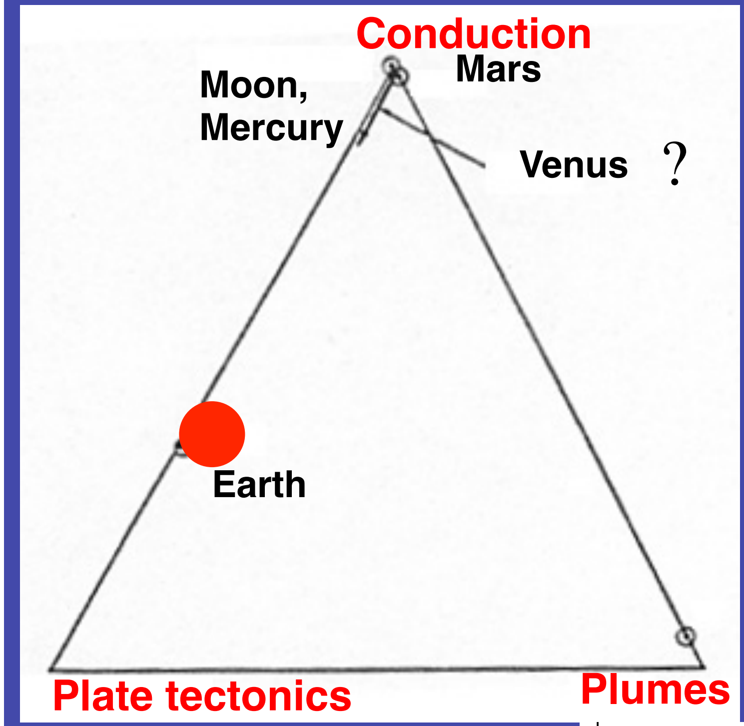

P-wave Tomography
Fiji
Lau Spreading Center
Tonga Arc
Pacific Plate
Depth (km)
0
100
200
300
400
500
600
700
-6%
0%
6%
P velocity anomaly


DEPTH (KM)
0
-200
-400
-600
0
200
400
600
DISTANCE (KM)
1800
1500
1200
900
600
300
0
TEMPERATURE °C

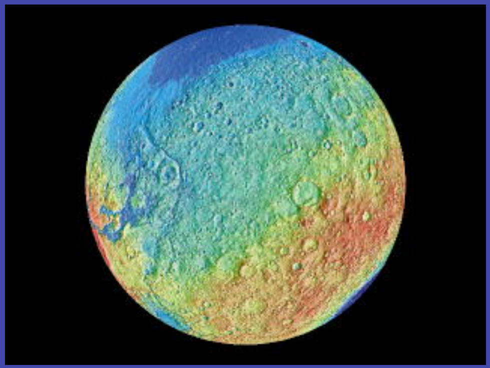


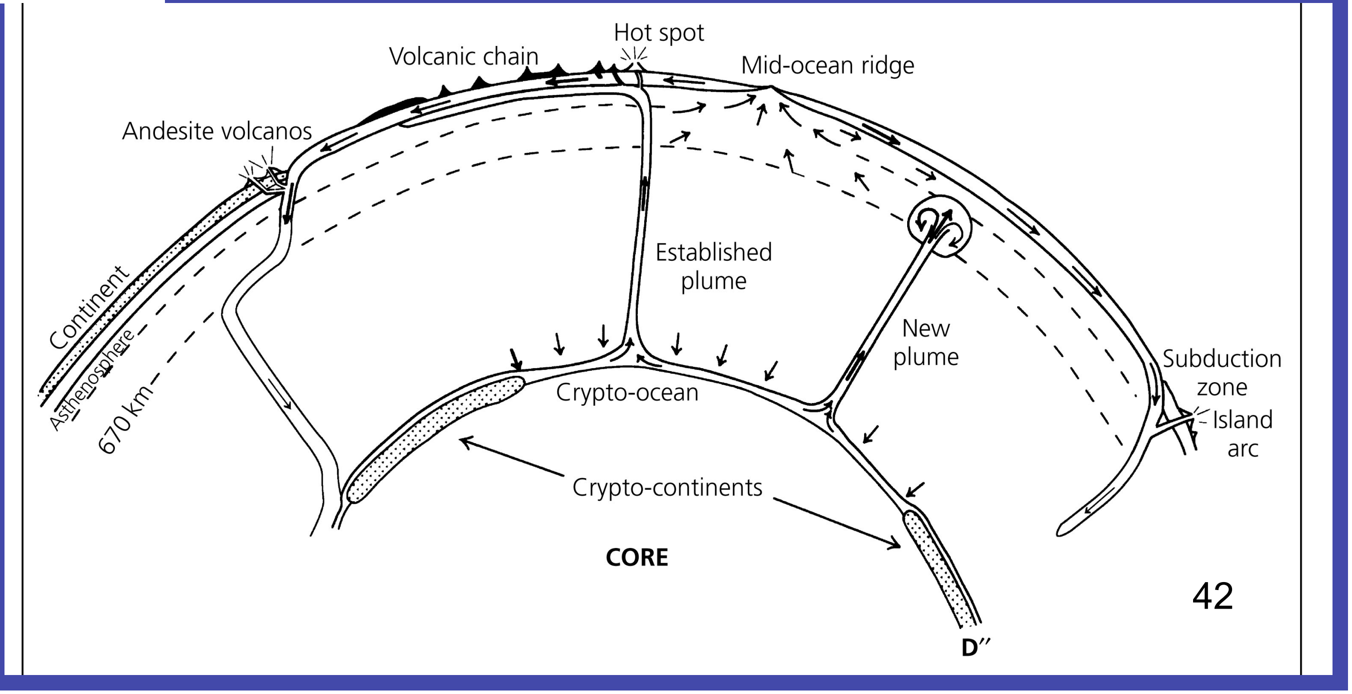


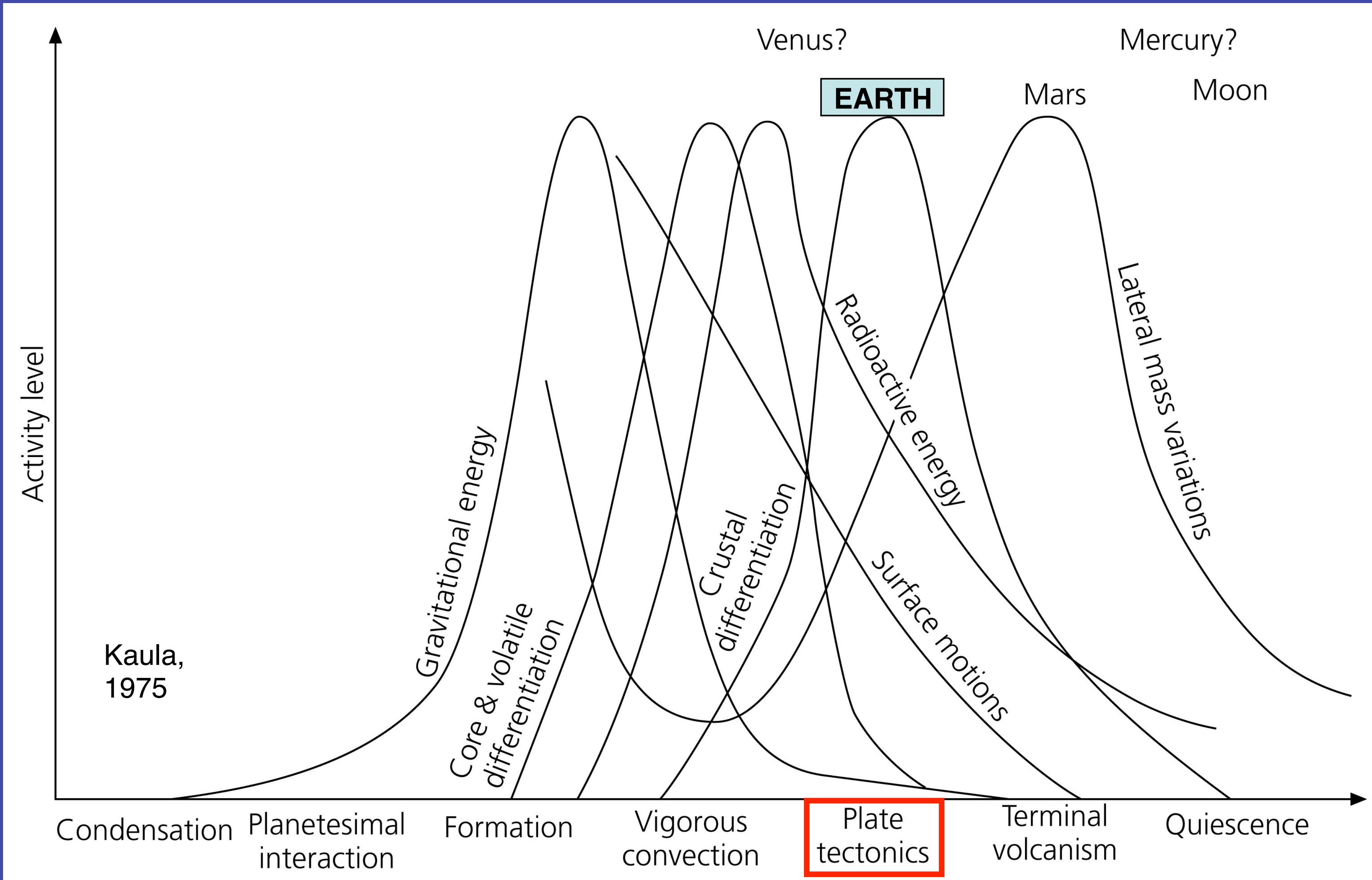
Stein & Wysession



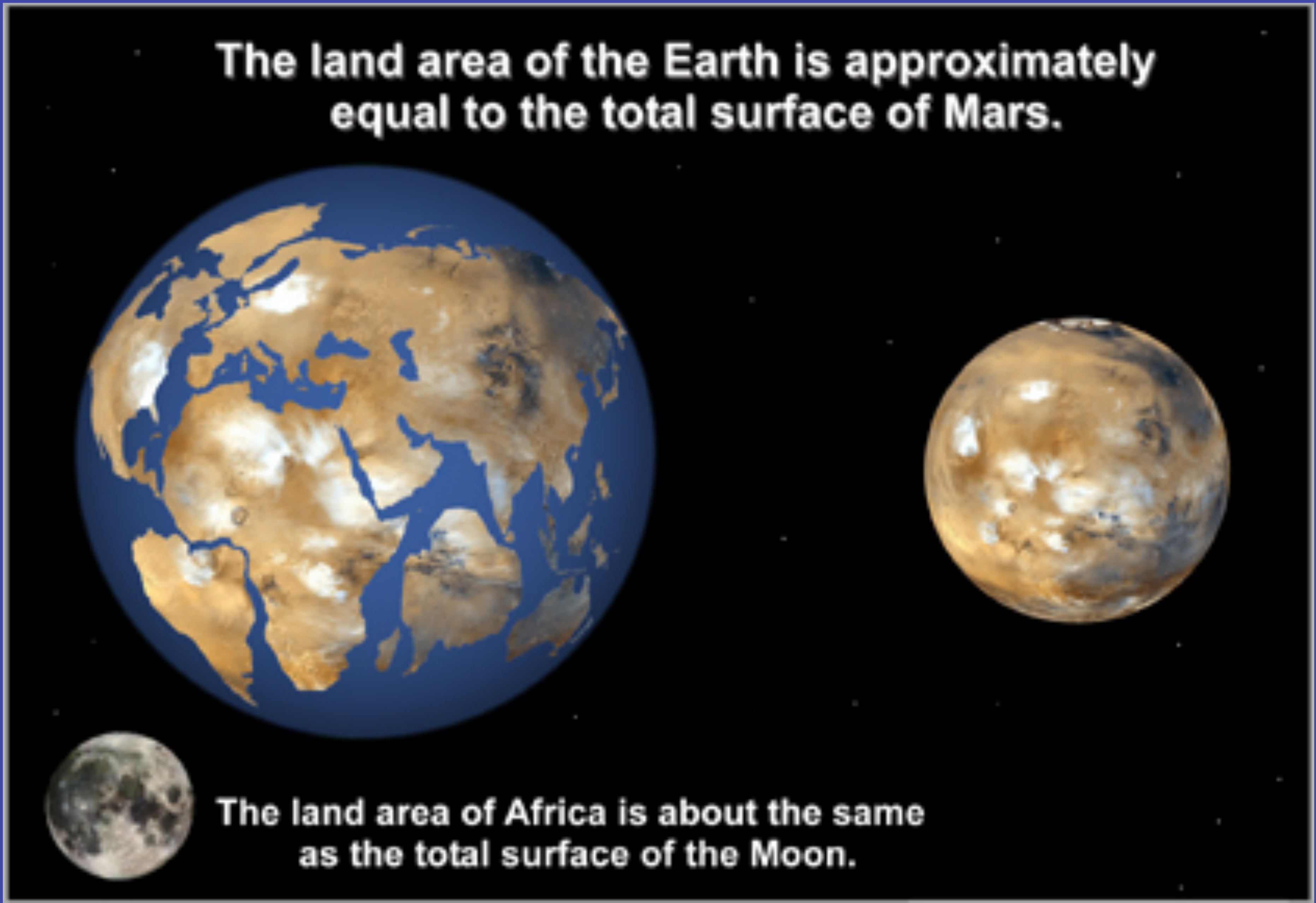
Solomon & Head, 1991

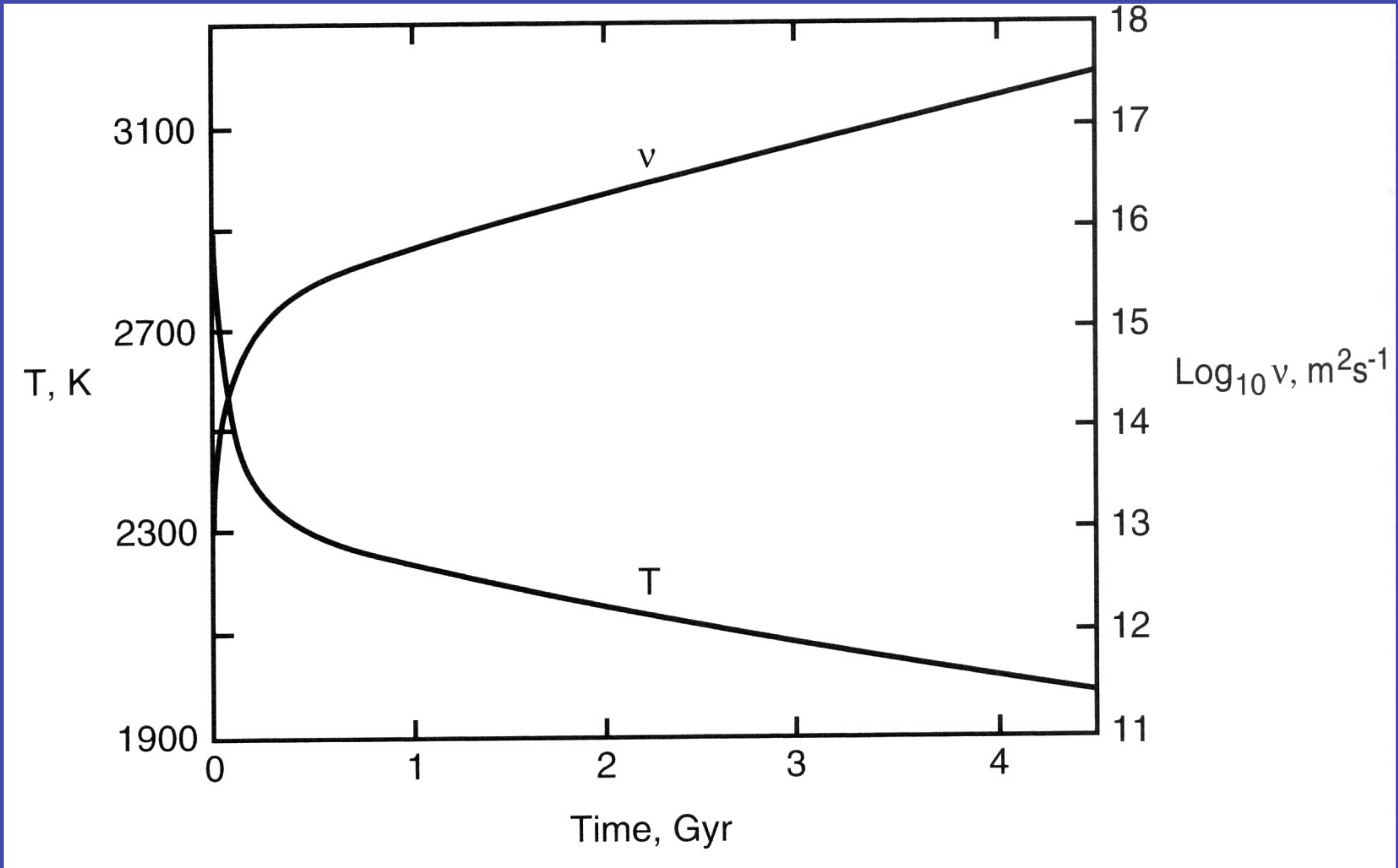






Stein & Wysession

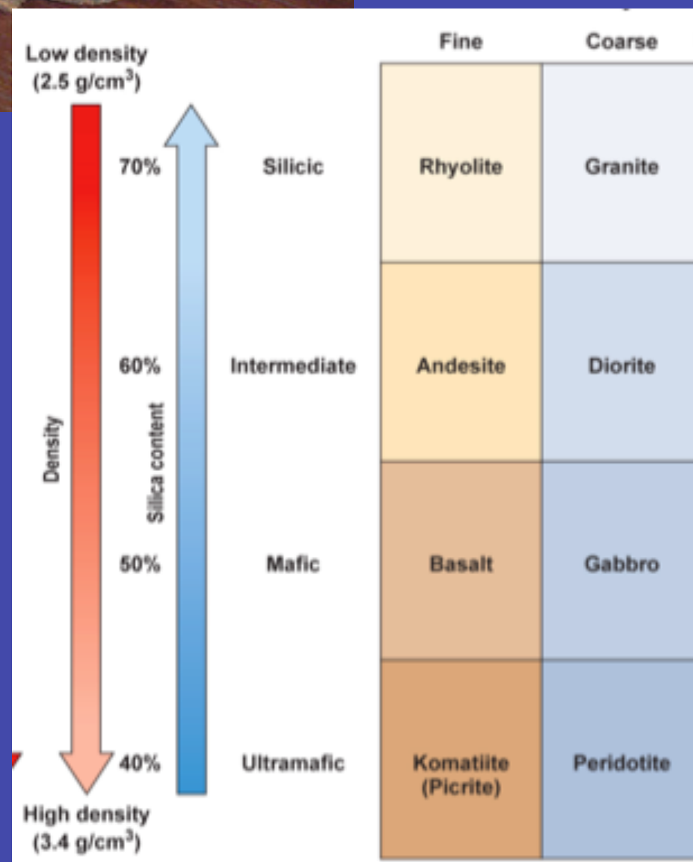

The land area of the Earth is approximately equal to the total surface of Mars.
The land area of Africa is about the same as the total surface of the Moon.

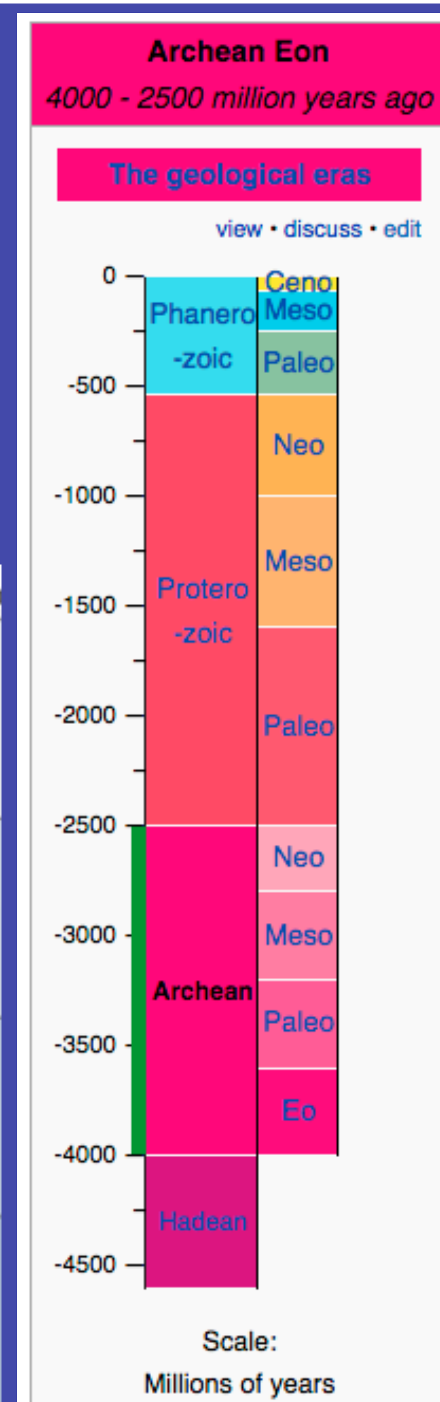


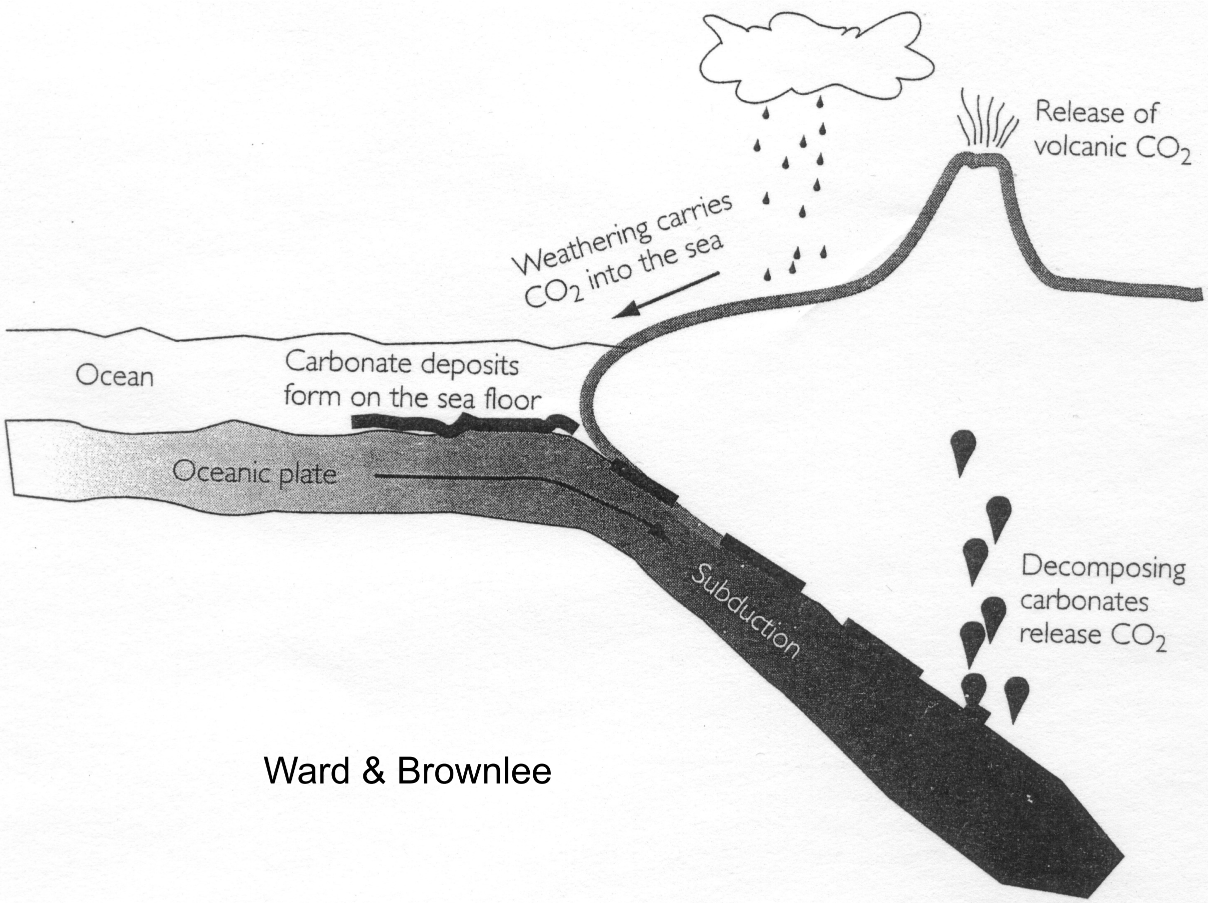
Schubert et al., 1980

http://all-geo.org/highlyallochthonous/2007/12/a-deskcrop-full-of-komatiite/

Komatiite







Ward & Brownlee

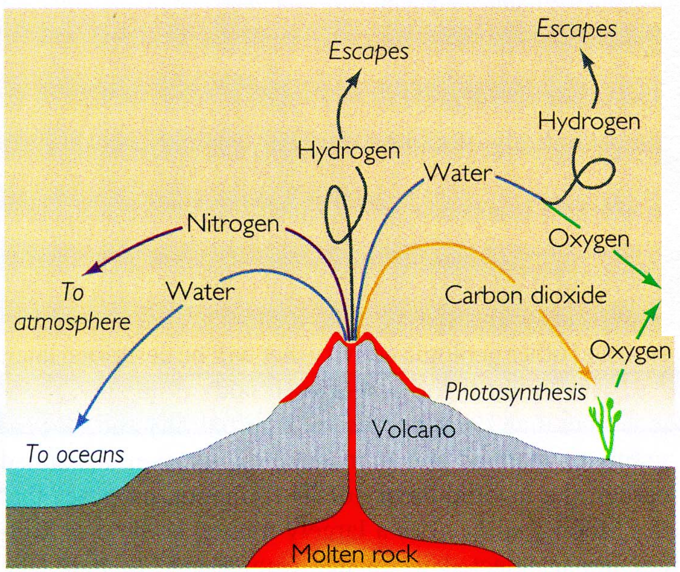
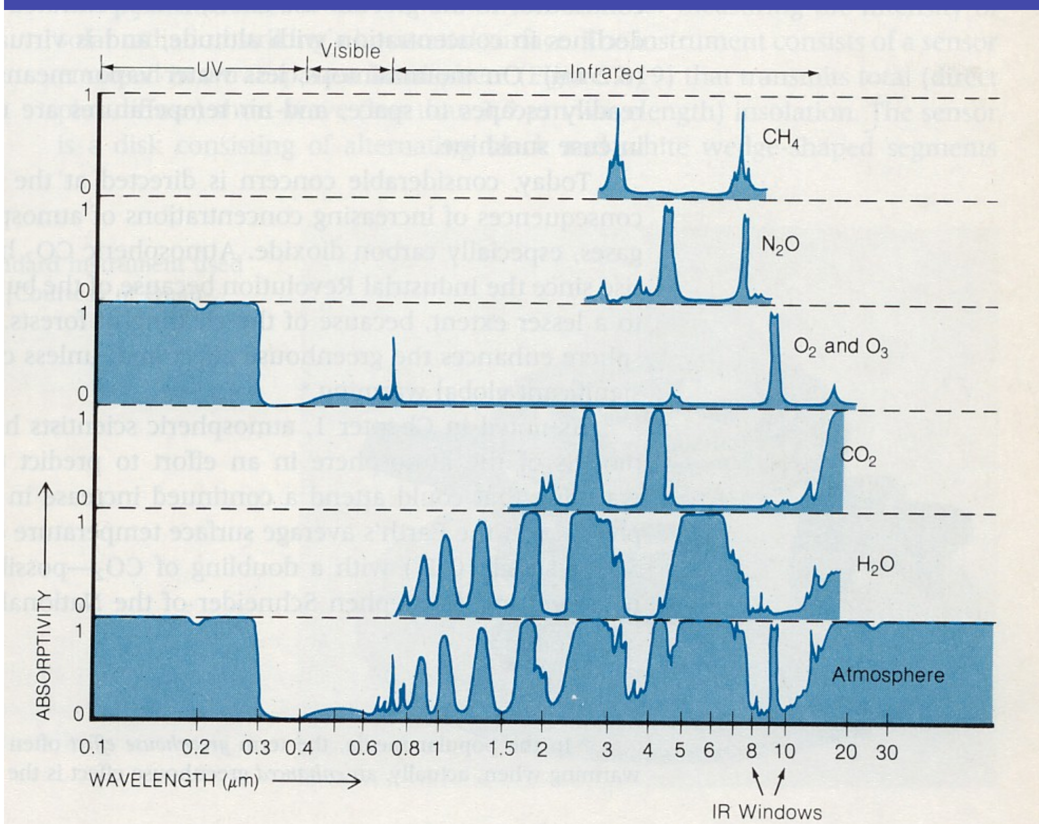
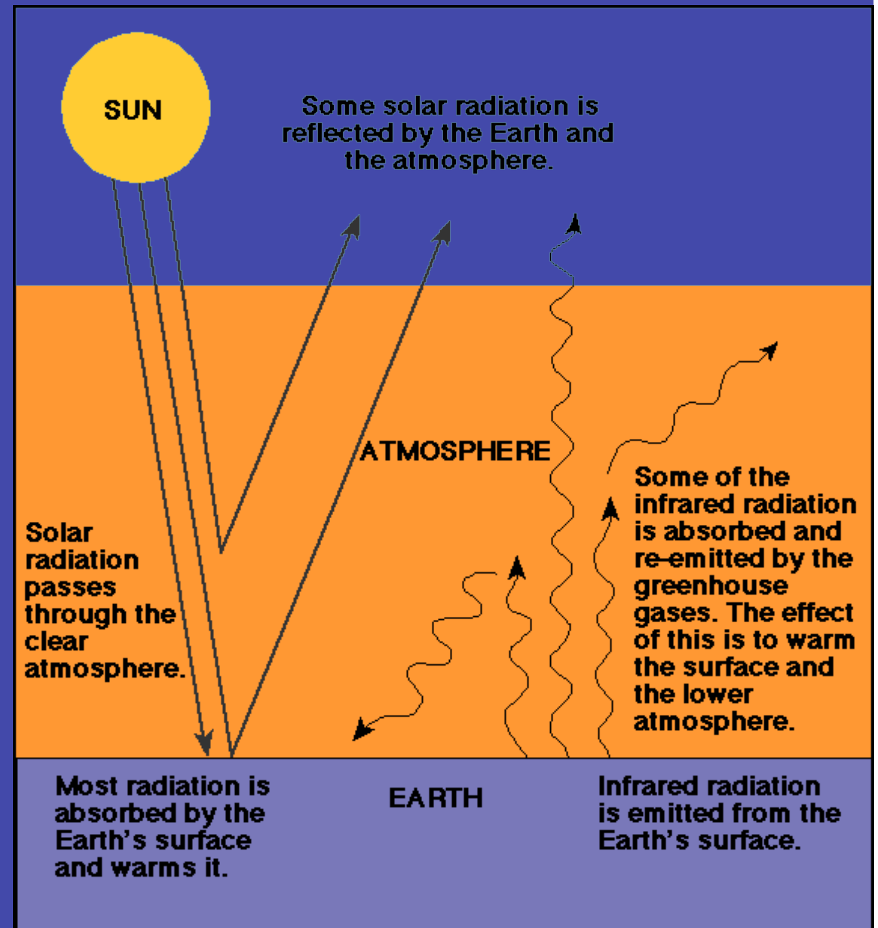


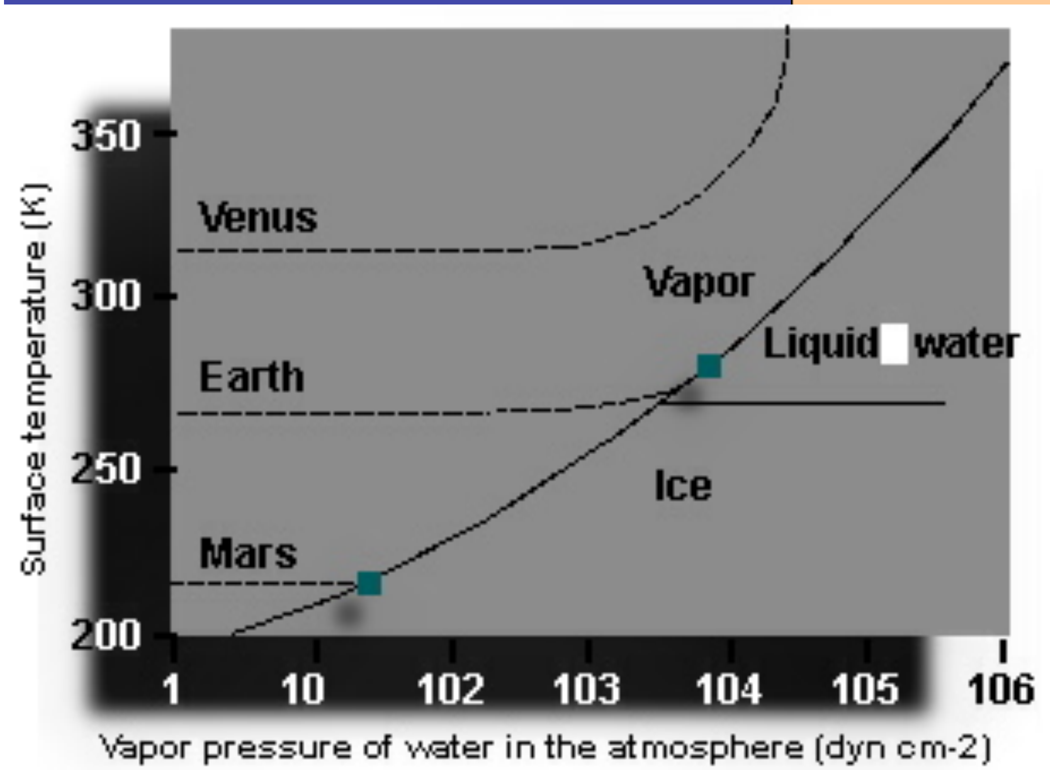
Figure 1.8 An example of interacting components of the Earth system. Volcanic activity has contributed enormous amounts of water, carbon dioxide, and other gases to the atmosphere and oceans and solid materials to the continents. Photosynthesis by plants removed carbon dioxide and added oxygen to the primitive atmosphere. Hydrogen, because it is light, easily escapes into space.

Press & Siever


UV
Visible
Infrared
CH4
N2O
O2 and O3
CO2
H2O
Atmosphere
ABSORPTIVITY
1
0
0.1 0.2 0.3 0.4 0.6 0.8 1.5 2 3 4 5 6 8 10 20 30
WAVELENGTH (μm)
IR Windows


SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
Solar radiation passes through the clear atmosphere.
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gases. The effect of this is to warm the surface and the lower atmosphere.
Most radiation is absorbed by the Earth's surface and warms it.
EARTH
Infrared radiation is emitted from the Earth's surface.

	VENUS	EARTH	MAPS
SURFACE PRESSURE	100,000 mb	1,000 mb	6 mb
		COMPOSITION	
CO2	>98%	0.03%	96%
N2	1%	78%	2.50%
A	1%	1%	1.50%
O2	0.00%	21%	2.50%
H20	0.00%	0.10%	0–0.1%
	12,140 km	12,753 km	6,785 km



VENUS - RUNAWAY GREENHOUSE

Dense atmosphere (90 times Earth's) composed mostly of CO_2 (carbon dioxide).

Thick clouds of sulfuric acid obscure the surface.

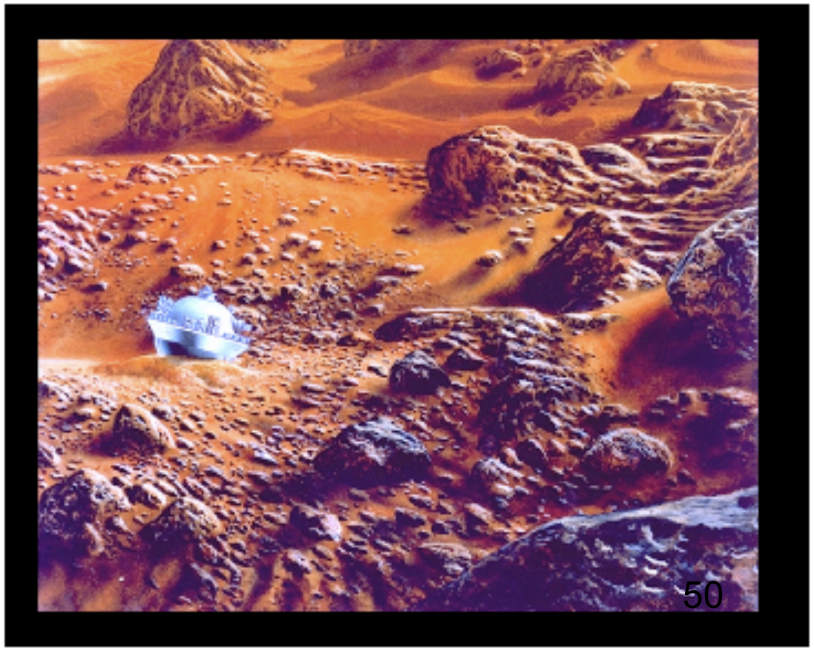
Atmosphere produces run-away greenhouse effect that raises Venus' surface temperature to over 450 deg C (hot enough to melt lead).

Venus' surface hotter than Mercury's despite being nearly twice as far from the Sun.

Venus probably once had lots of water like Earth that boiled away, leaving it quite dry.

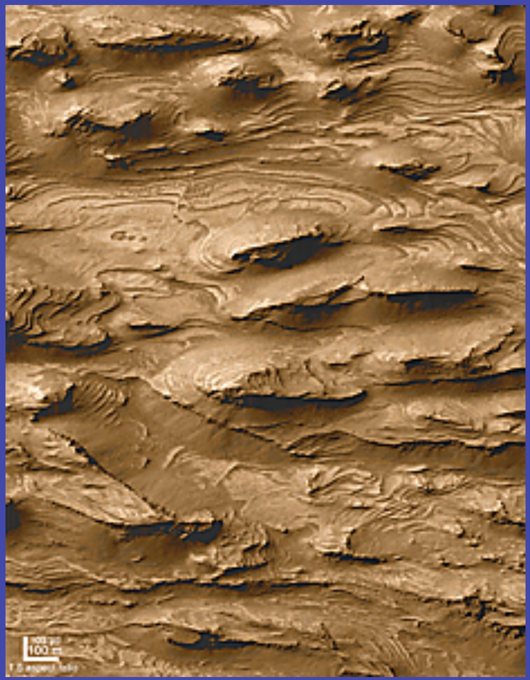
Earth might be like this if it were a little closer to the Sun.

Not yet clear why Venus turned out so differently from Earth



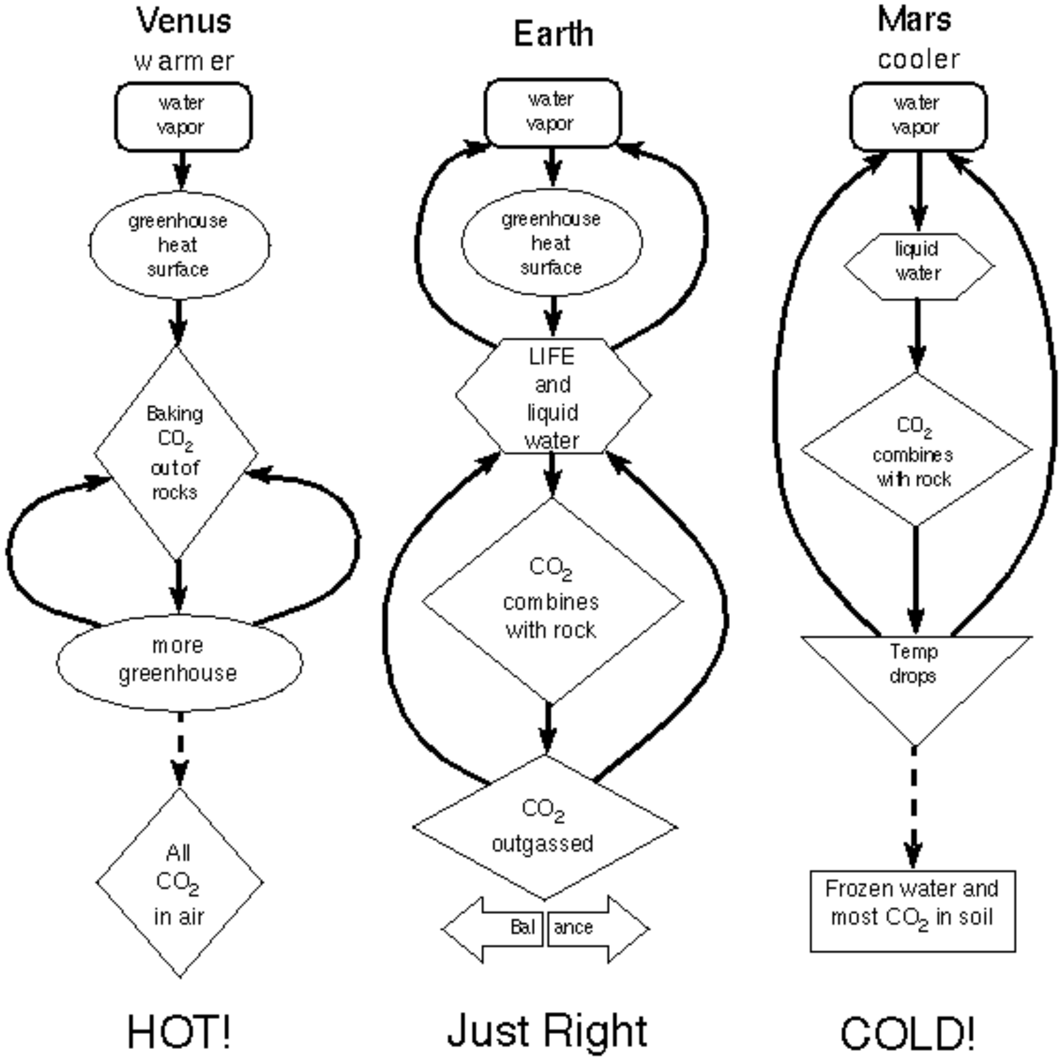
MARS - TOO COLD

In past Mars had liquid water, as shown by sediment deposits

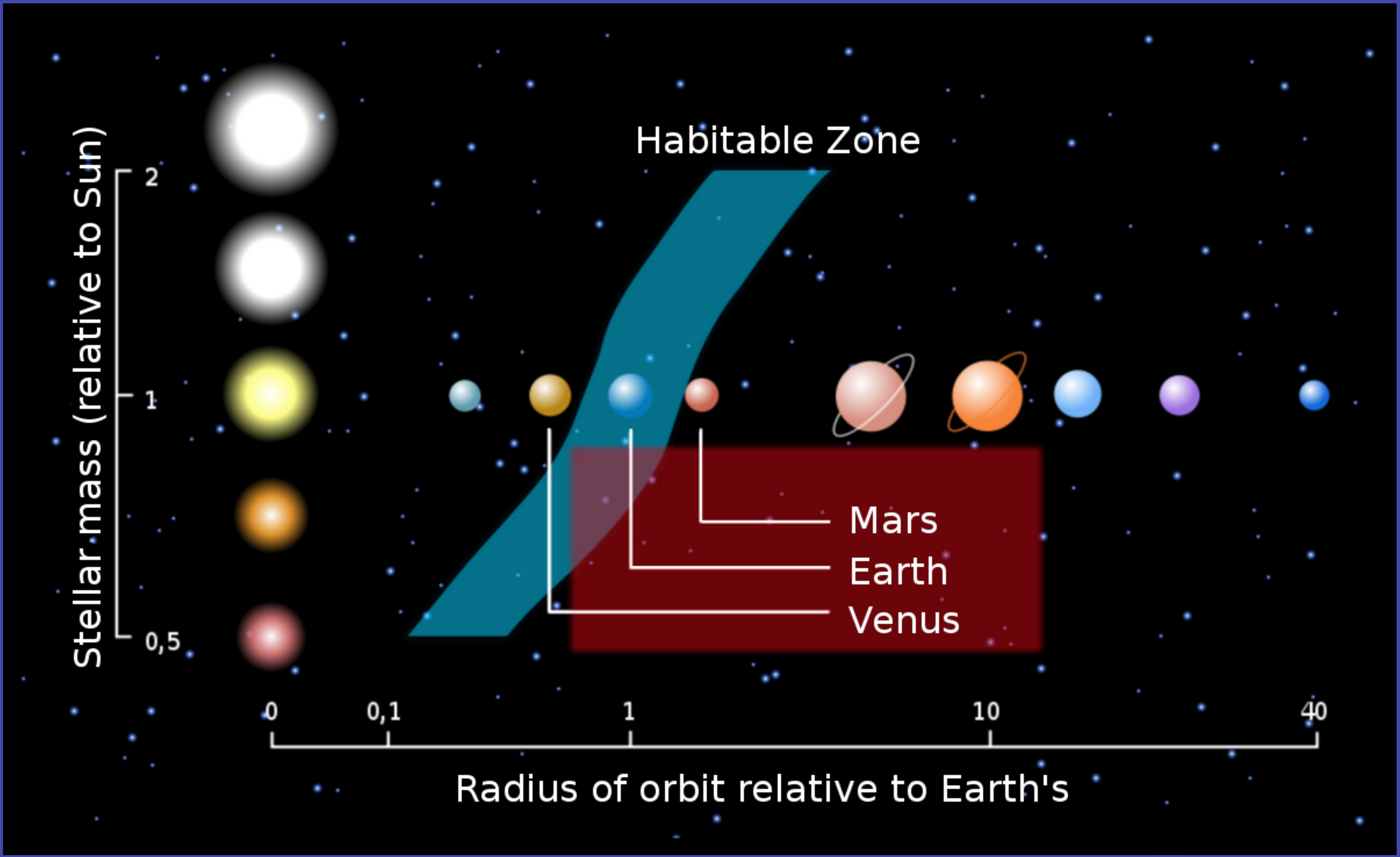


Now, however, it doesn't

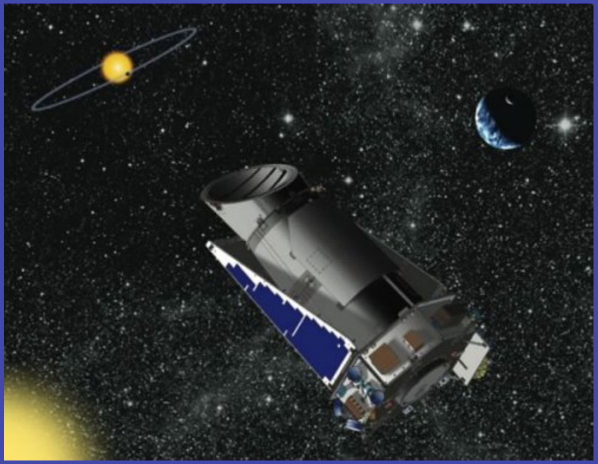
Somehow Mars climate changed, perhaps several times between hot/wet periods when "greenhouse" gases in atmosphere kept planet warm to cold/dry times without a greenhouse when the surface got too cold for liquid water and most life (if there ever was any)

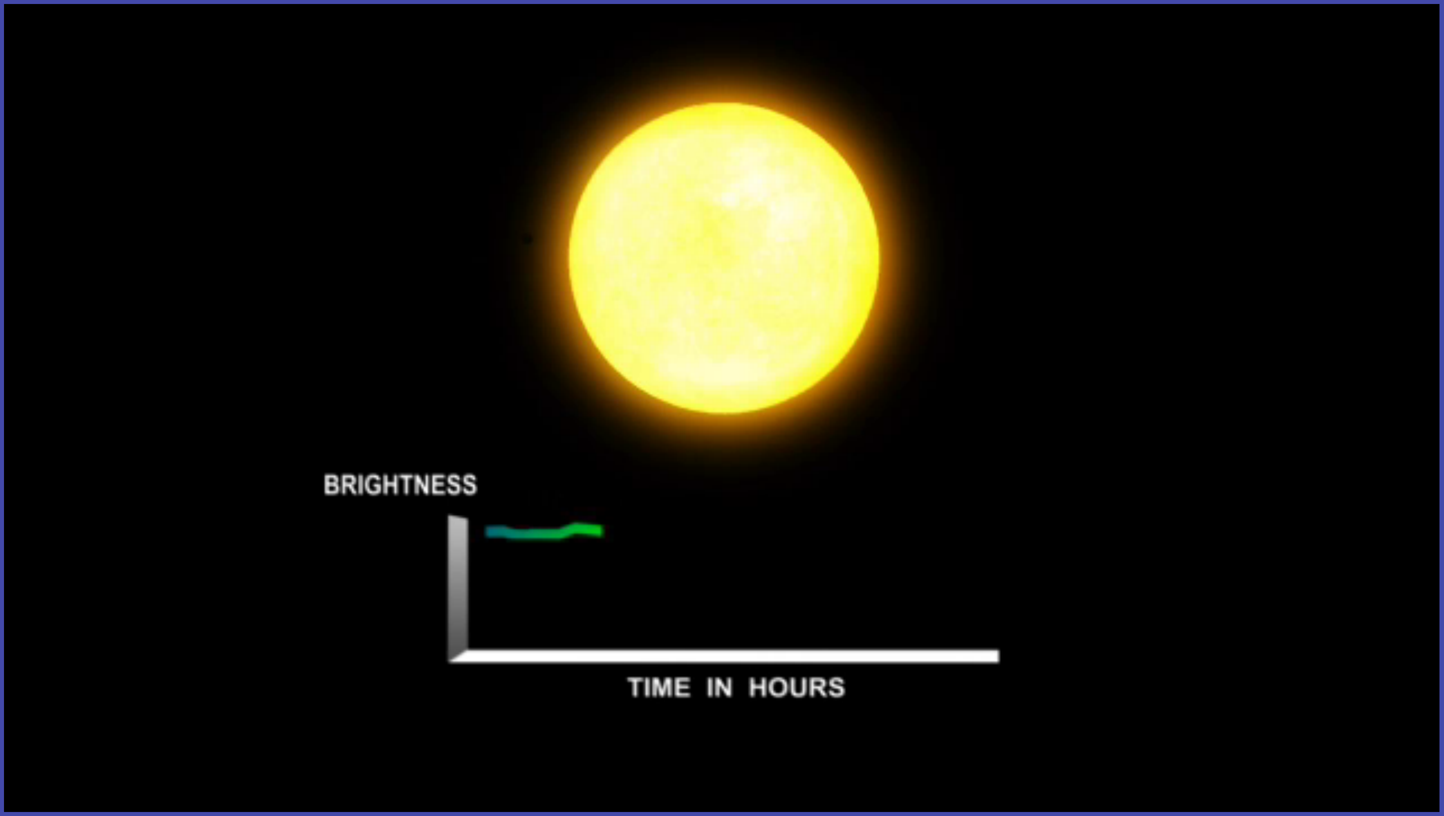


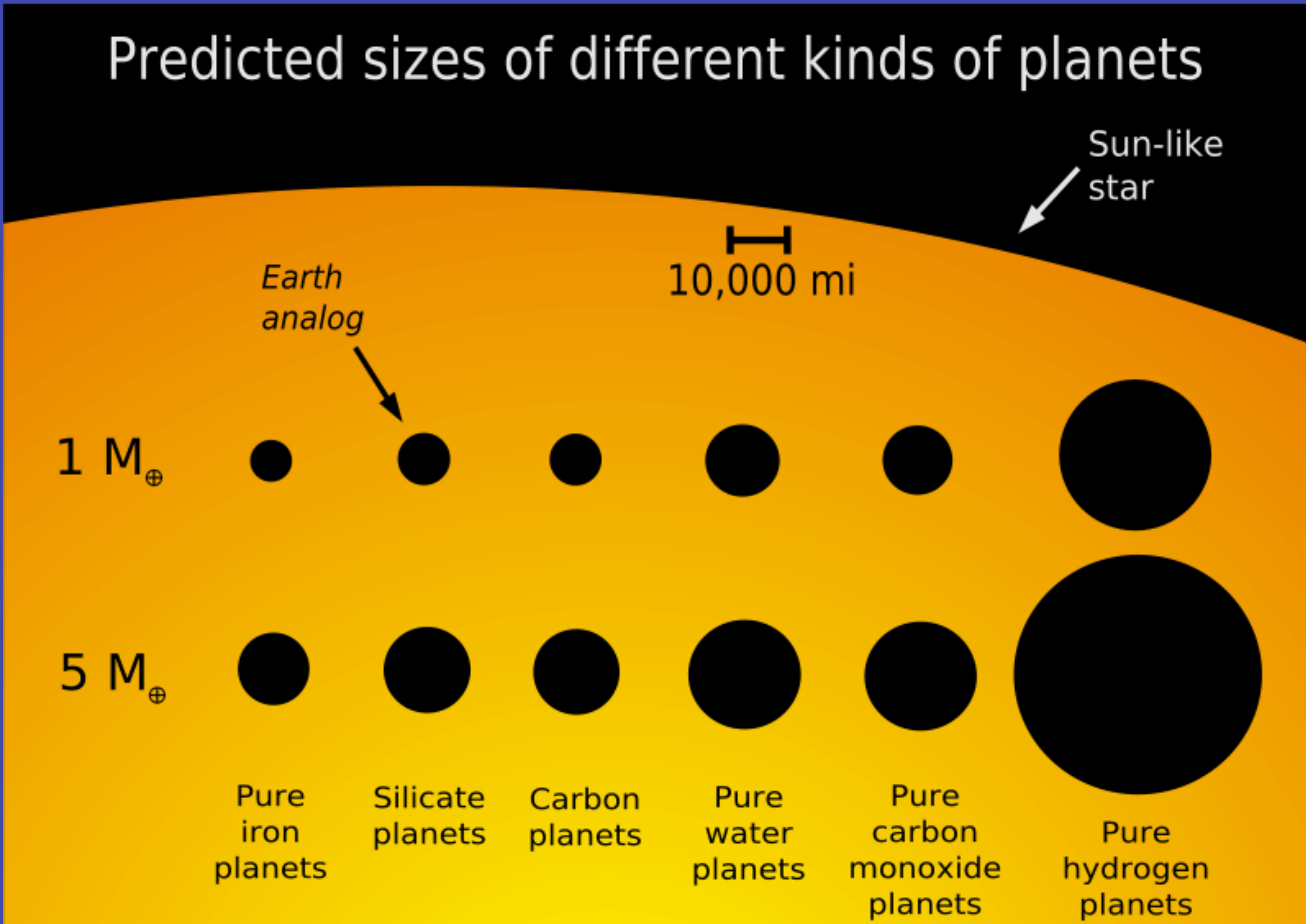
Venus has runaway greenhouse effect and no water left. Earth has life and liquid water keeping temperature balanced and most of its CO_2 in the rocks. Mars has runaway refrigerator with water frozen in permafrost layer and most of its CO_2 in the rocks or frozen on the surface.


Habitable Zone
Stellar mass (relative to Sun)
2
1
0,5
Mars
Earth
Venus
0
0,1
1
10
40
Radius of orbit relative to Earth's

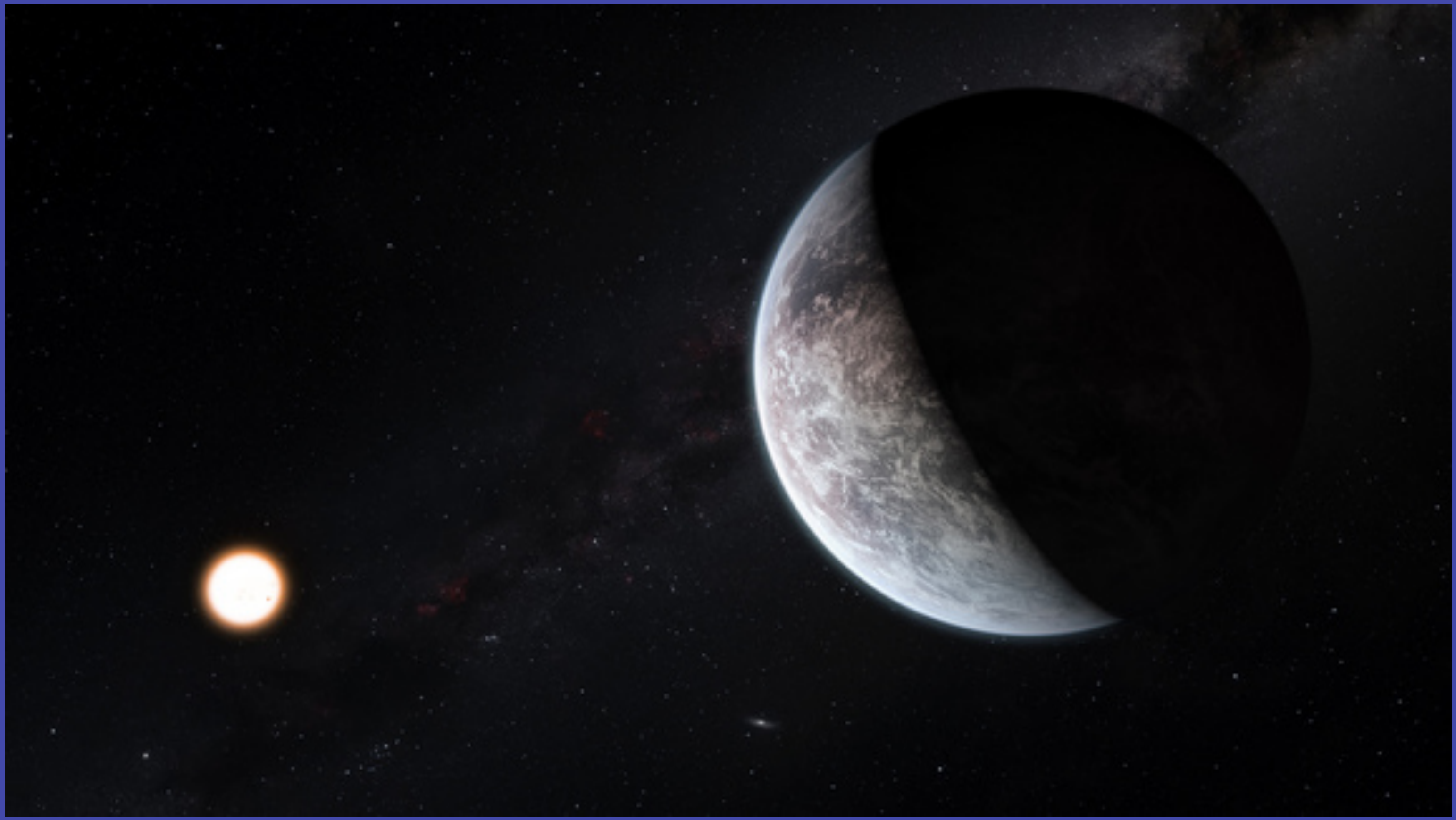
Kepler Mission







Predicted sizes of different kinds of planets
Sun-like star
10,000 mi
Earth analog
1 M⊕
5 M⊕
Pure iron planets
Silicate planets
Carbon planets
Pure water planets
Pure carbon monoxide planets
Pure hydrogen planets



This artist's impression shows the planet HD 85512b orbiting the Sun-like star HD 85512 about 35 light-years from Earth. This planet is about 3.6 times as massive as the Earth is at the edge of the habitable zone around the star, where liquid water, and perhaps even life, could potentially exist.