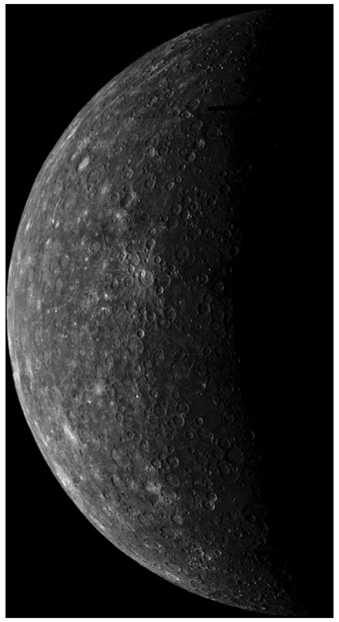
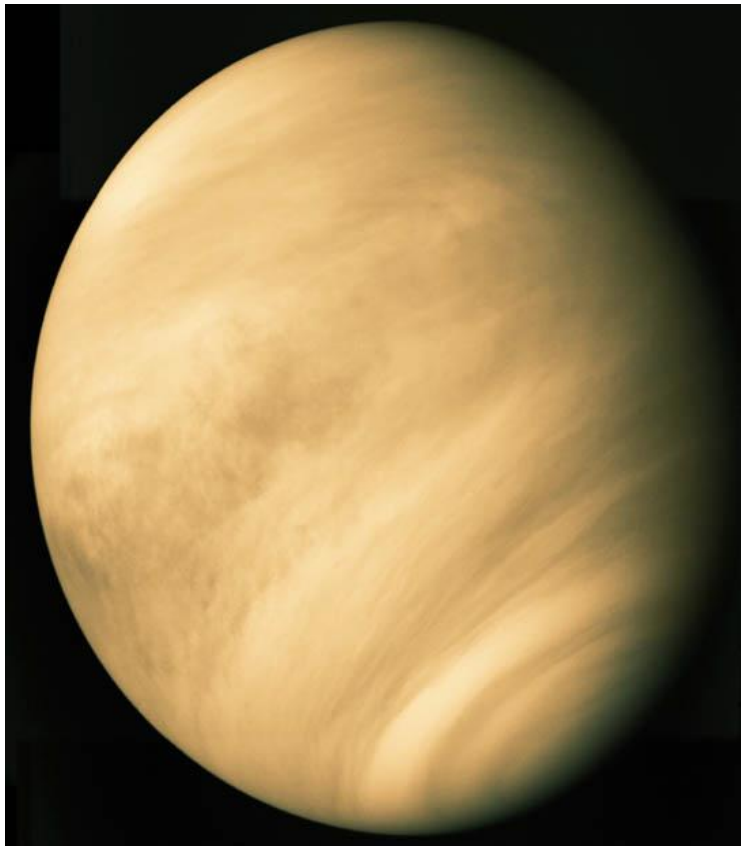
Exam 2 Review
Solar System Exploration through Jovian Planets

4 Terrestrial Planets

Mercury

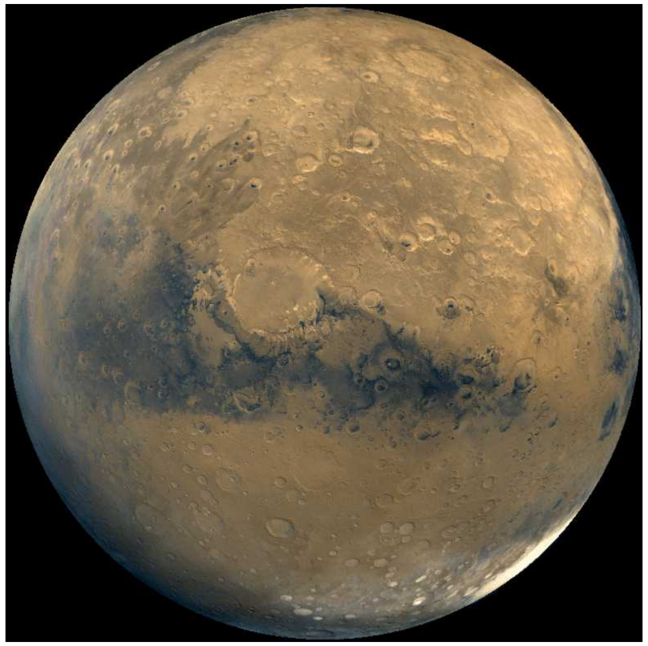


Venus



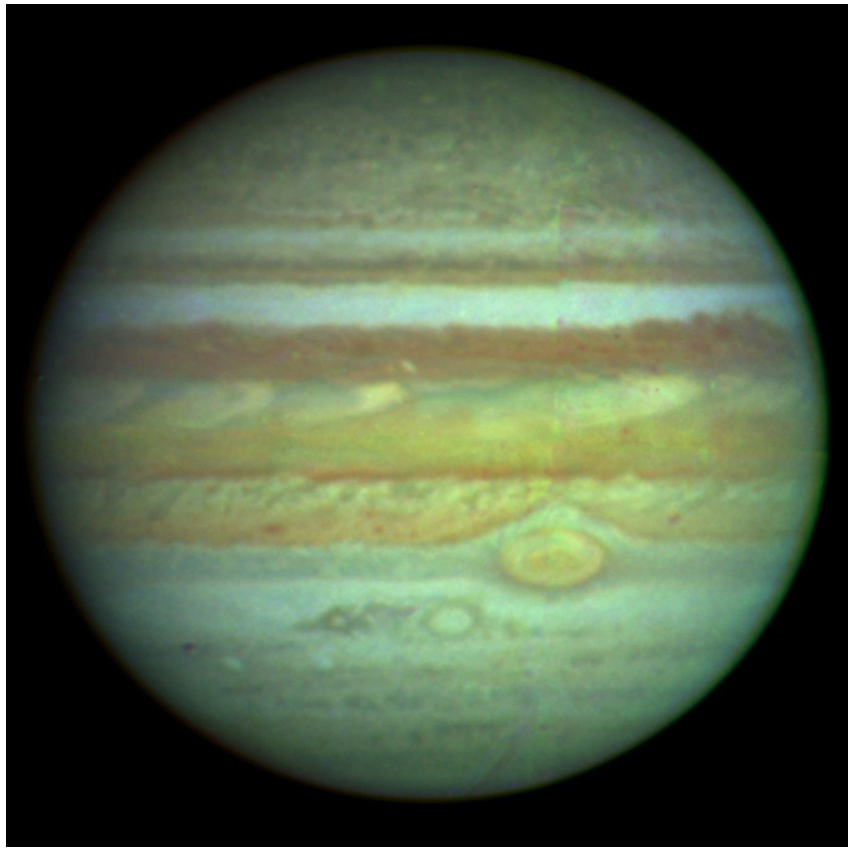
Earth

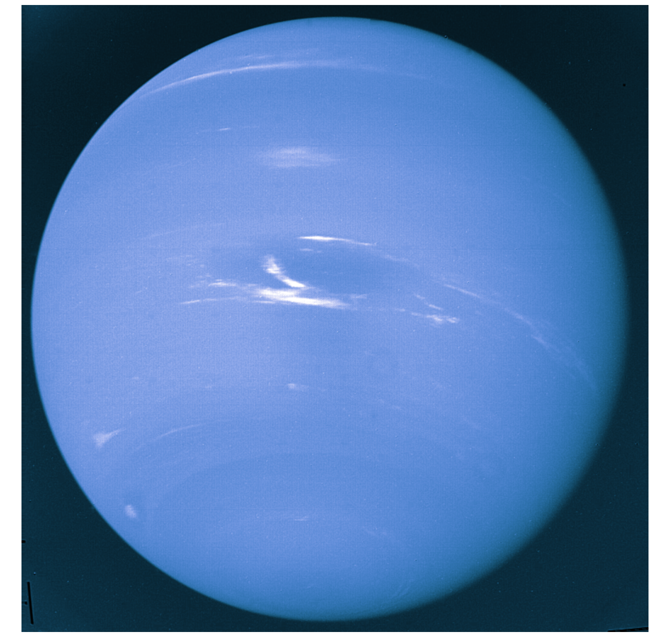
Mars



4 Jovian Planets

"Ice Giants"





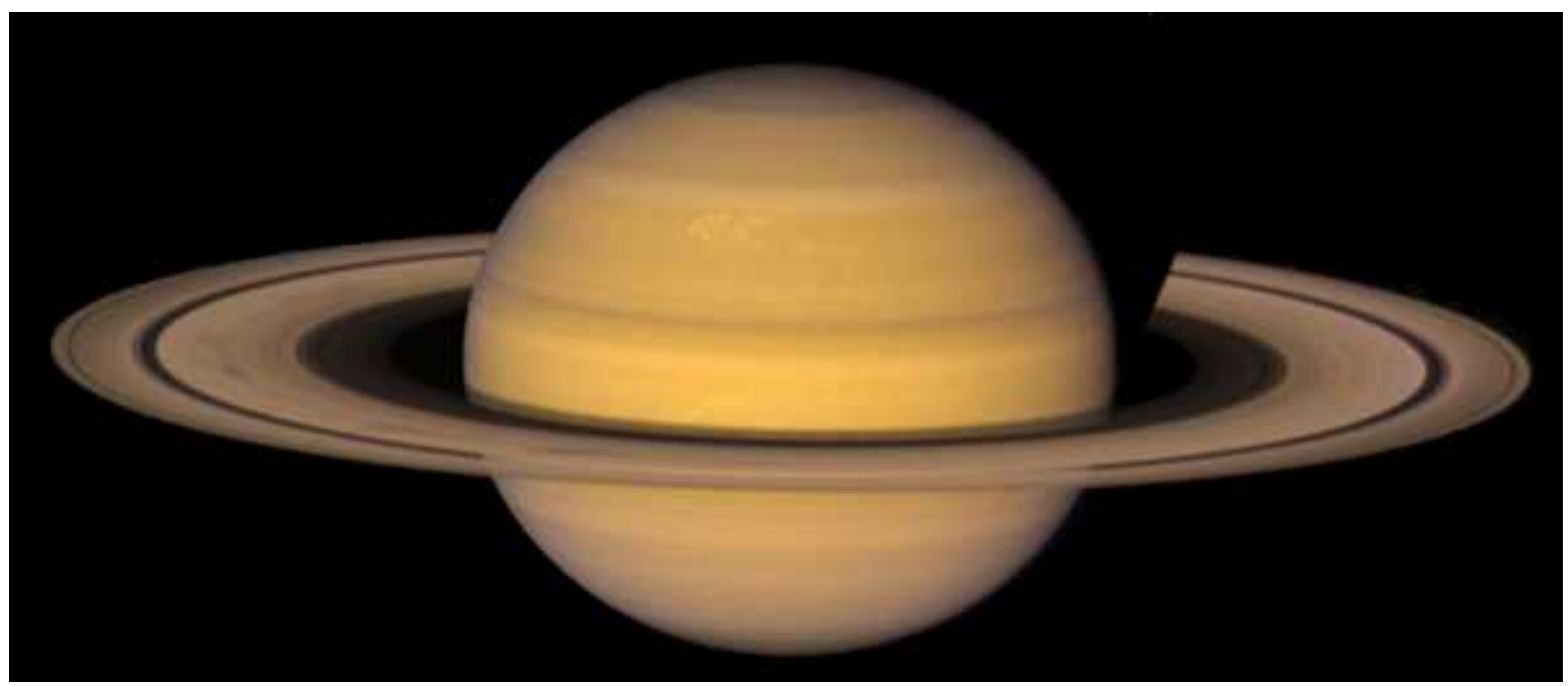
Uranus

Neptune

Jupiter

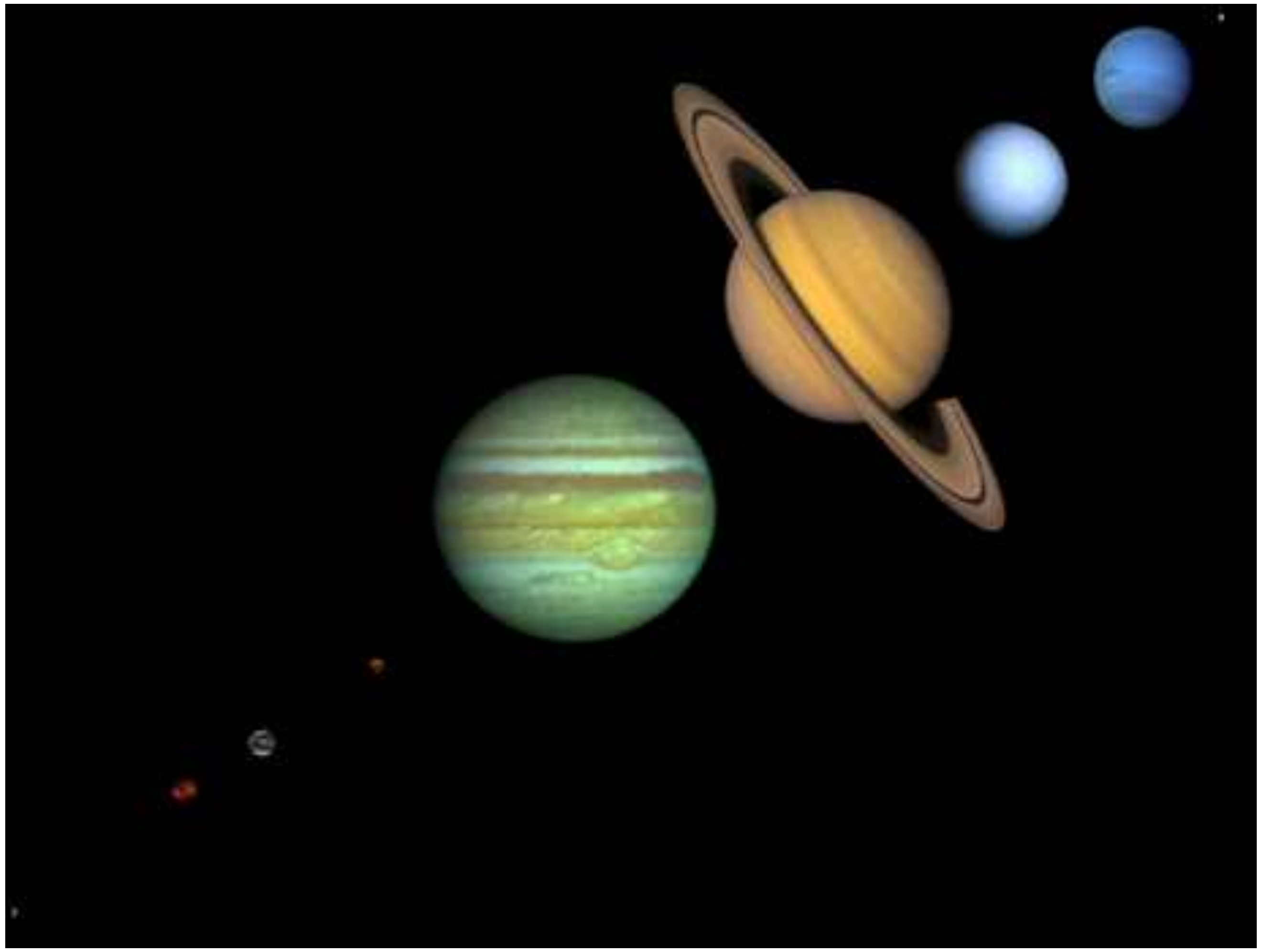
"Gas Giants"

Saturn



2 Main Classes of Planets

Terrestrial	**Jovian**
Mercury	Jupiter
Venus	Saturn
Earth	Uranus
Mars	Neptune
Small Diameters	Large Diameters
Small Masses	Large Masses
Large Densities	Small Densities
Few Moons	Many Moons
No Rings	Rings
Rock & Metals	H, He, (C, N. O)



Escape Speed & Planetary Atmospheres

Energy Needed to Escape to "Infinity"

$$\frac{GM_P m}{R_P}$$

Actual KE

$$\frac{mv^2}{2}$$

Escape Speed - The speed where KE = Energy Needed to Escape

$$\frac{GM_p m}{R_P} = \frac{mv_{esc}^2}{2}$$

$$or \quad v_{esc} = \sqrt{\frac{2GM_P}{R_P}}$$

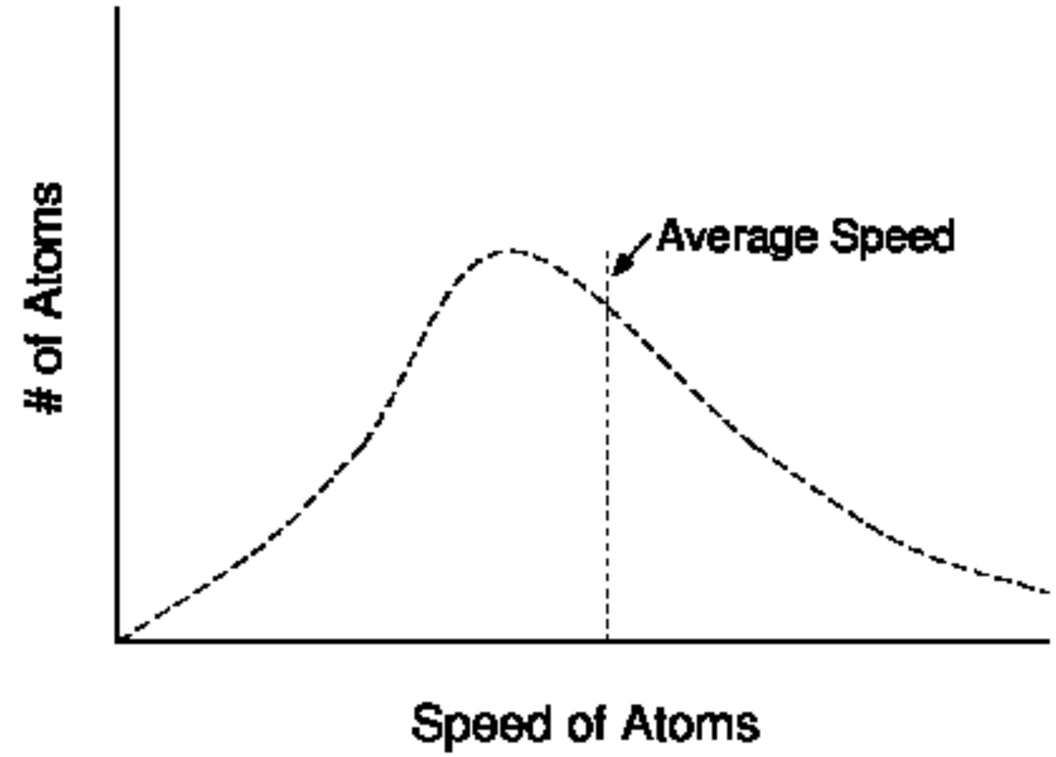
Actual Speeds of Atoms & Molecules

Equate the TE to the KE Needed for Escape

$$\frac{3kT}{2} = \frac{mv_{avg}^2}{2}$$

or

$$v_{avg} = \sqrt{\frac{3kT}{m}}$$



Rule of Thumb - A planet can retain a specific gas IF $v_{esc} \geq 6\ v_{avg.}$ For Earth, $v_{esc} = 11.2$ km/s

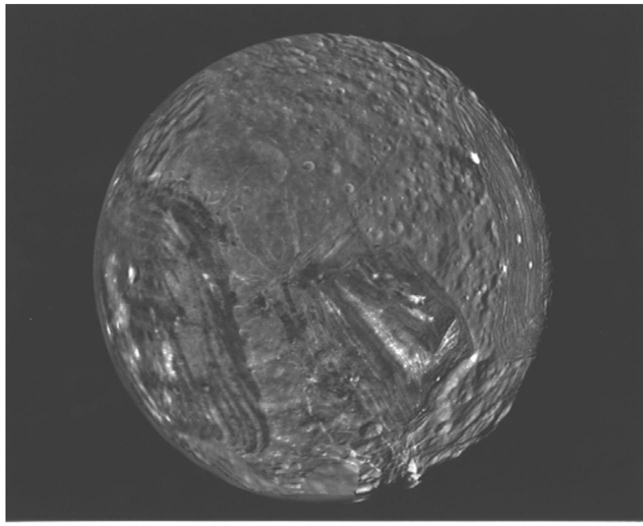
Oxygen (O_2) - $v_{avg} = 0.48$ km/s 6x0.48 km/s=3 km/s< 11.2 km/s

Hydrogen (H_2) - $v_{avg} = 1.9$ km/s 6x1.9 km/s=11.4 km/s ≈ 11.2 km/s

Earth retains oxygen but not hydrogen

Numerous moons, asteroids, comets, "Kuiper belt objects", "centaurs", and Pluto (actually a KBO)

Ganymede



Eros

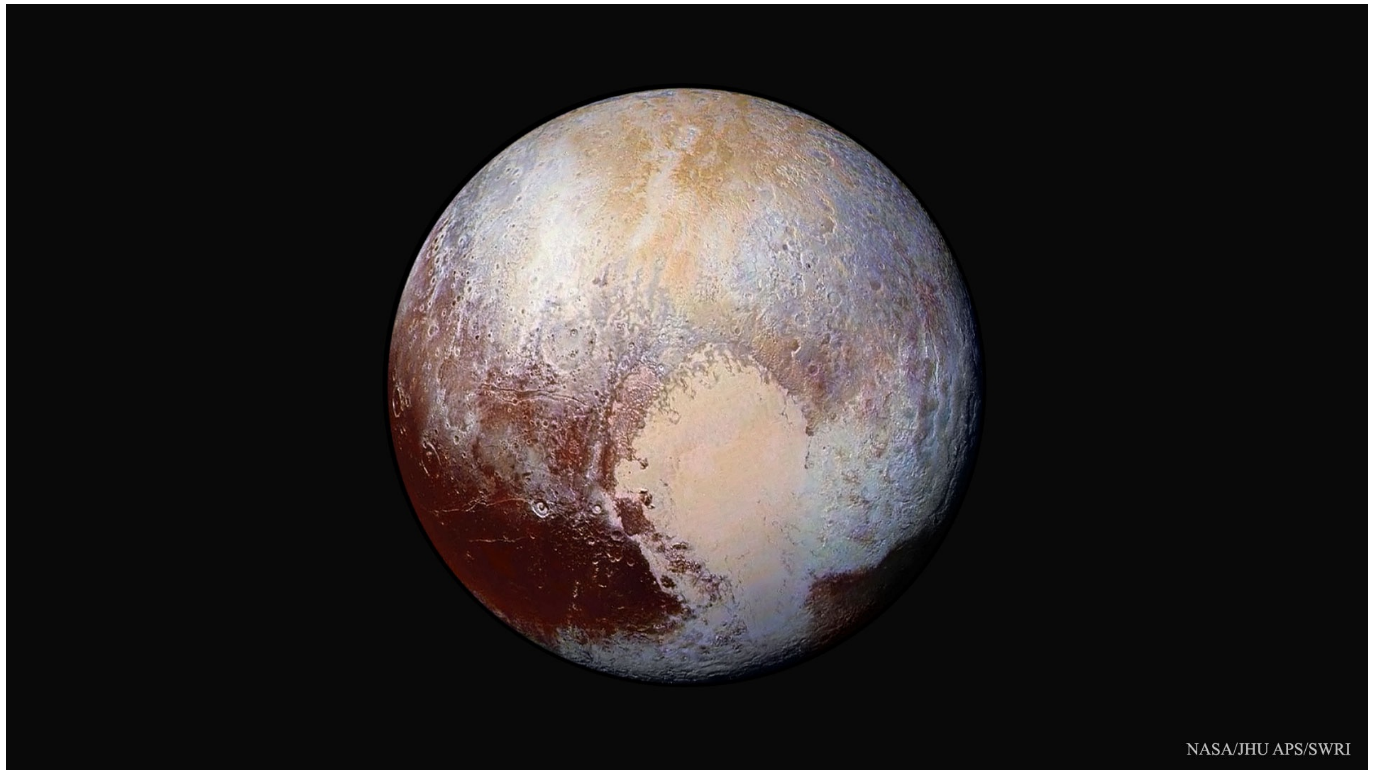
Titan

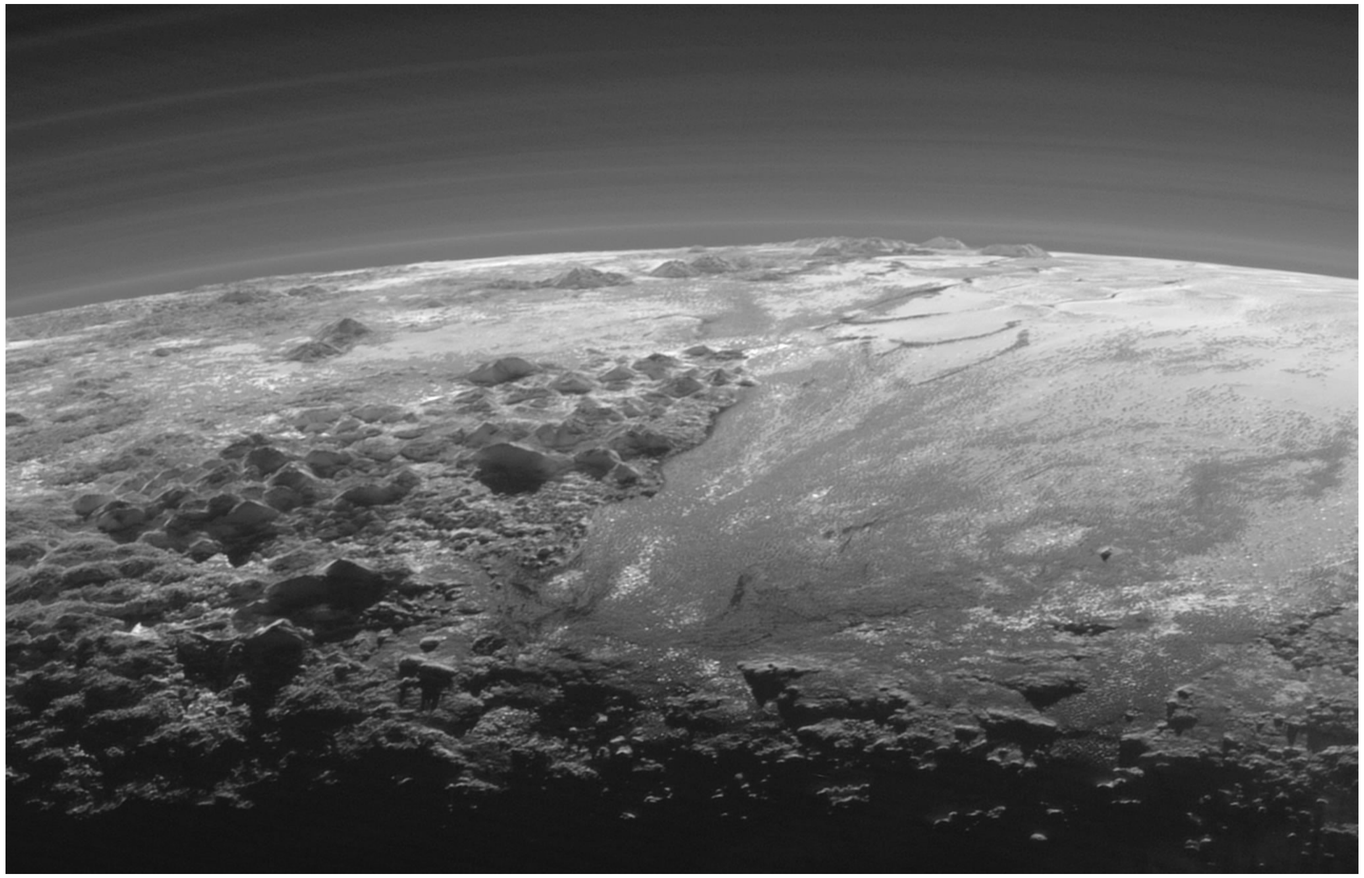
Miranda

Kuiper Belt

Hale-Bopp

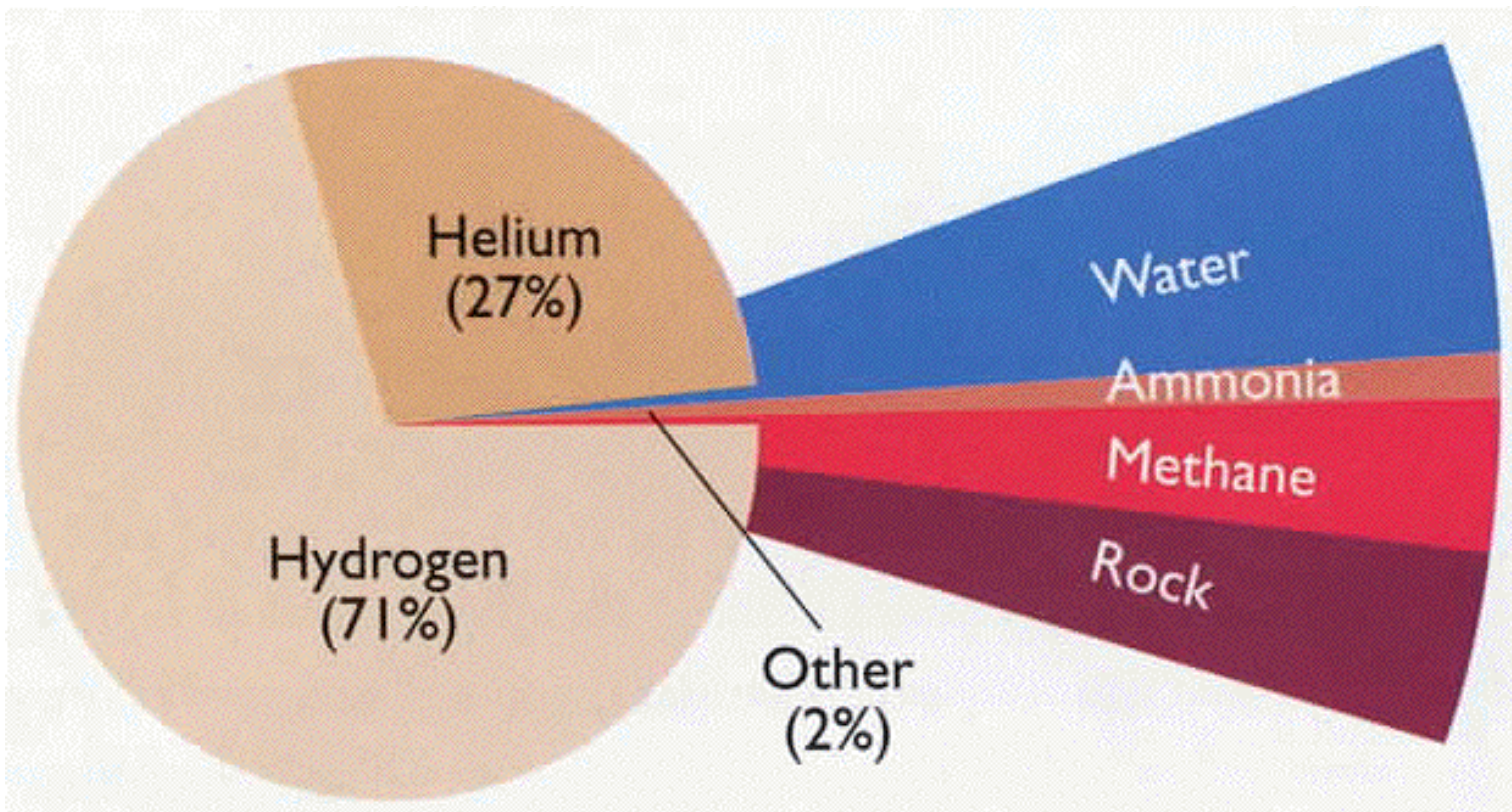
New Horizons at Pluto





Formation and Evolution of the Solar System

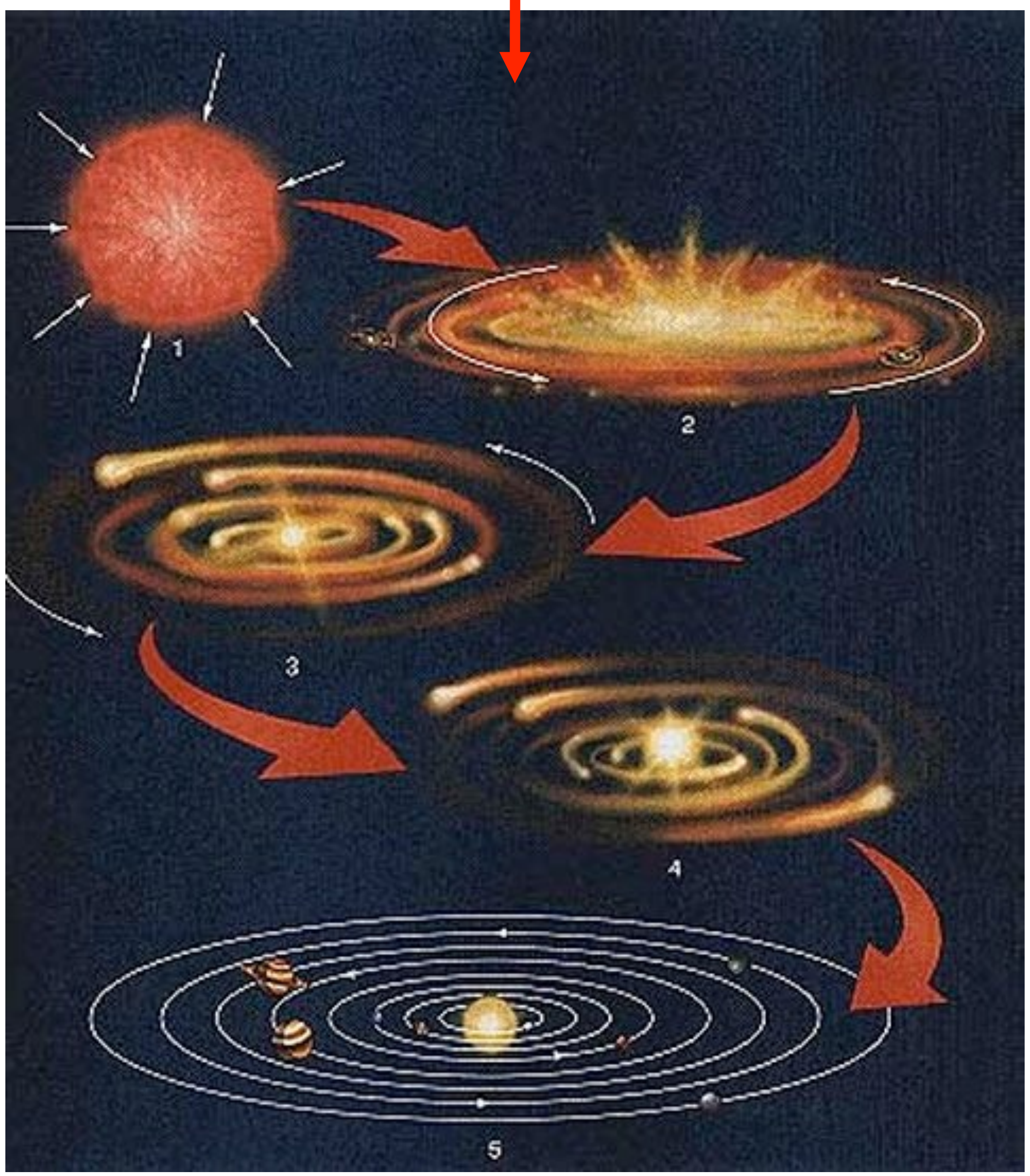
What's Initially Available:



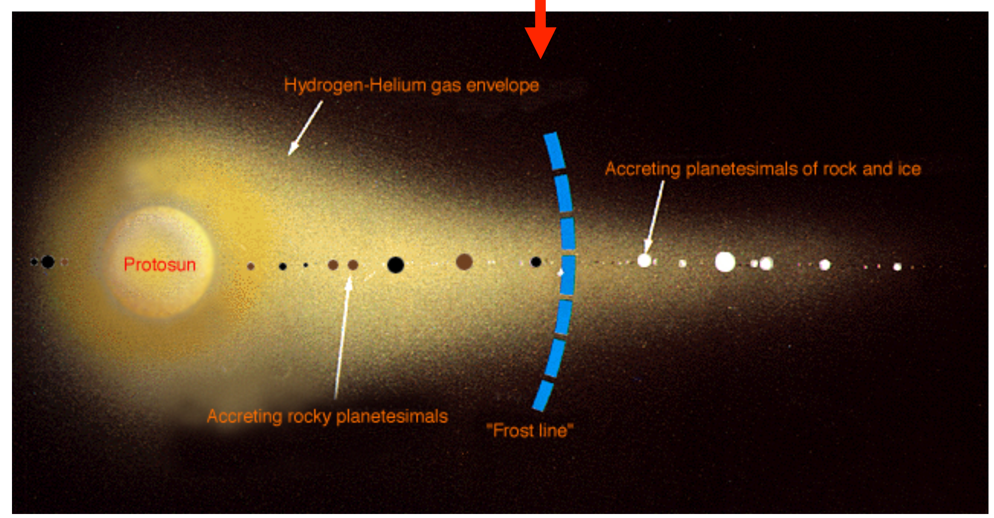
Solar Nebula - Composition

Nebular Model

Planets gradually form out of the rotating disk of gas & dust



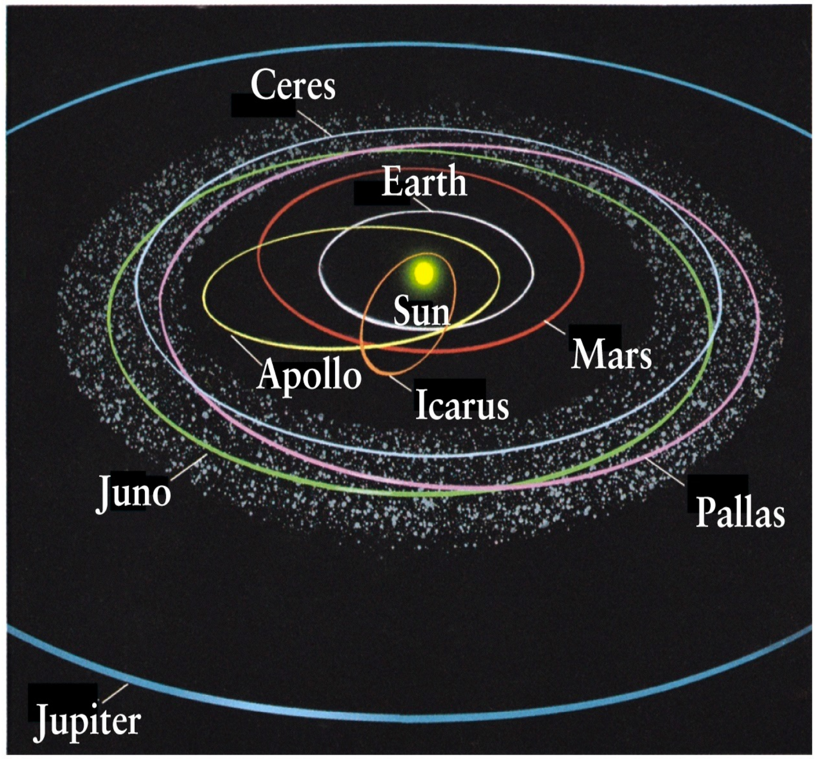
Beyond the “frost line”, ices can condense, allowing more massive planets to form

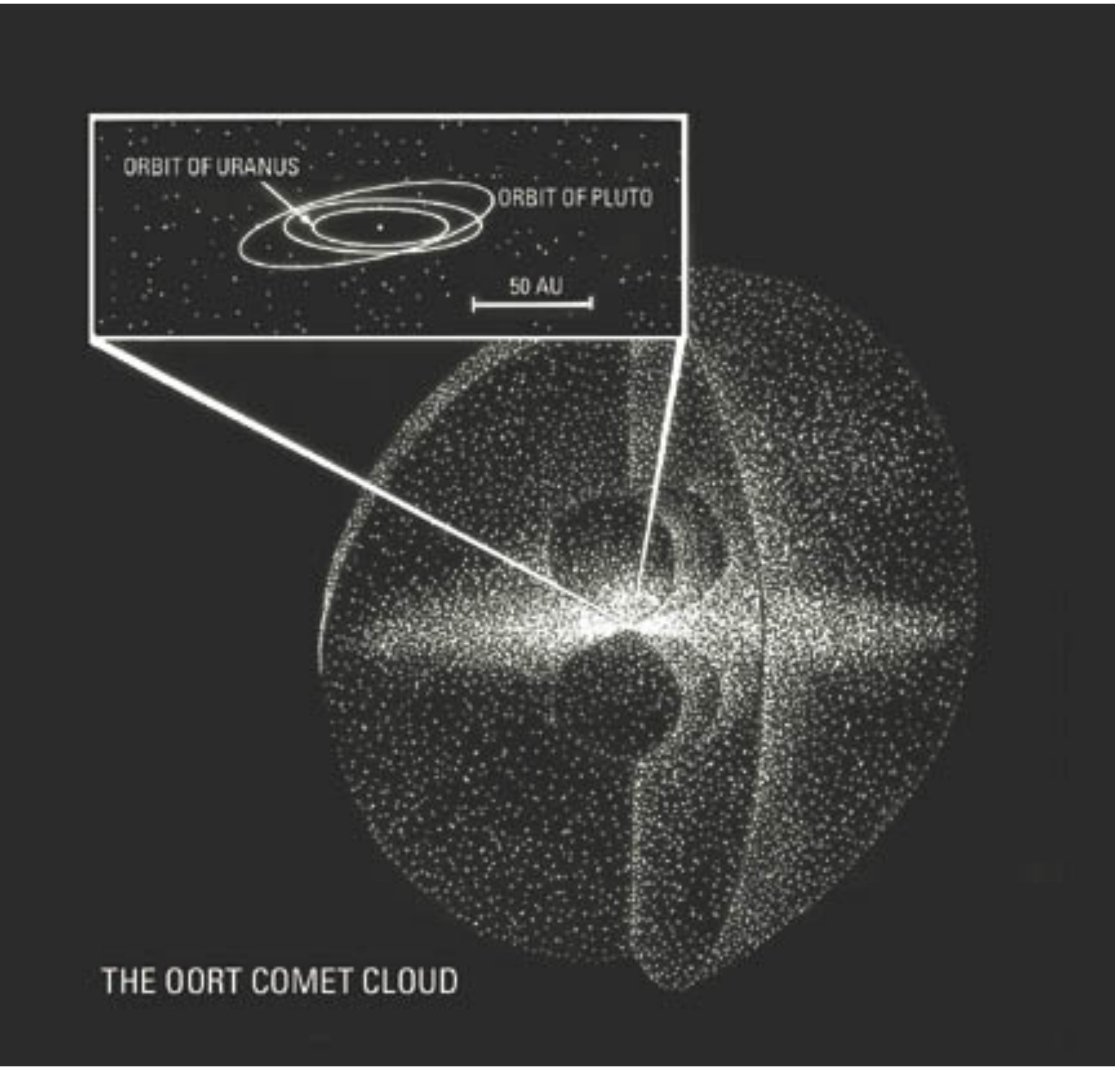


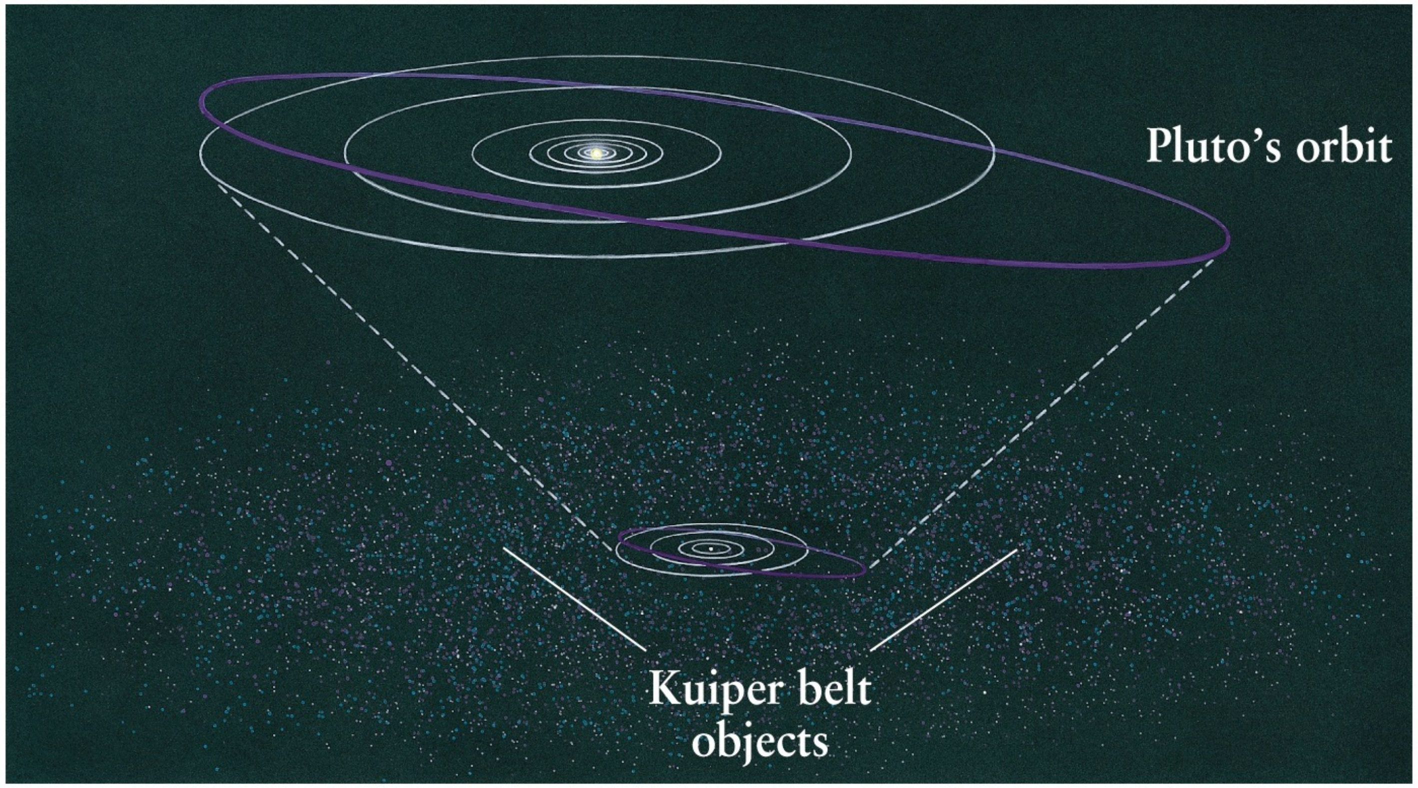
Refractories (rock, metal)

volatiles (ices & gas) and refractories

Planets, asteroids (minor planets), Kuiper Belt Objects (another form of minor planet)

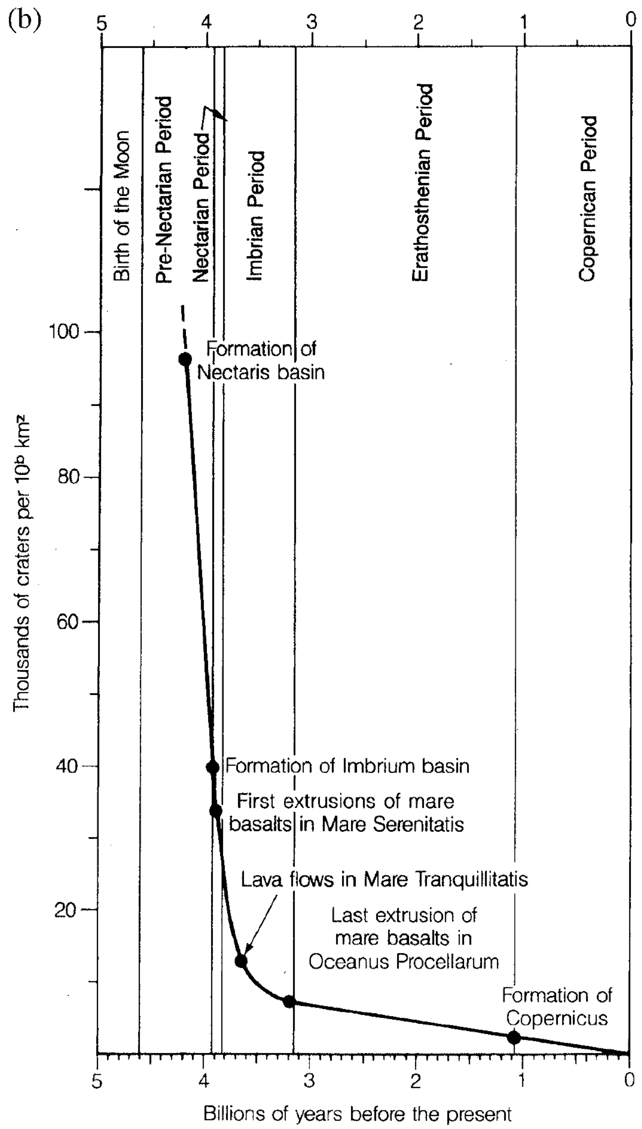


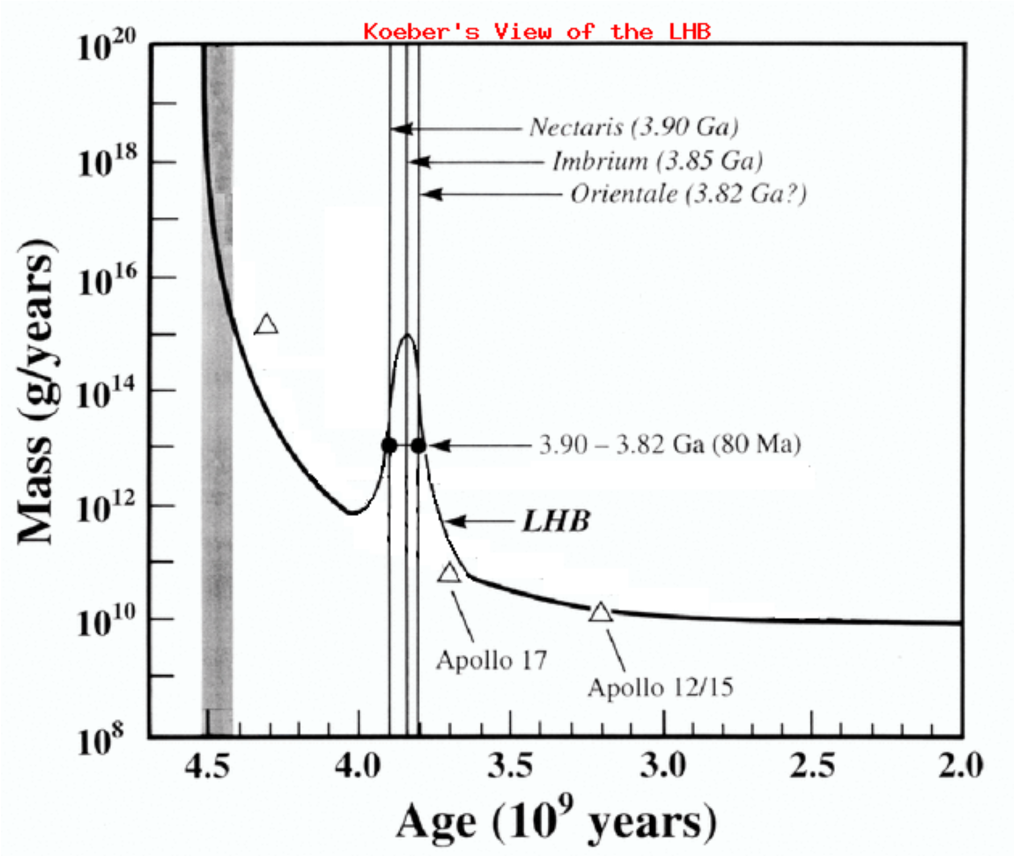




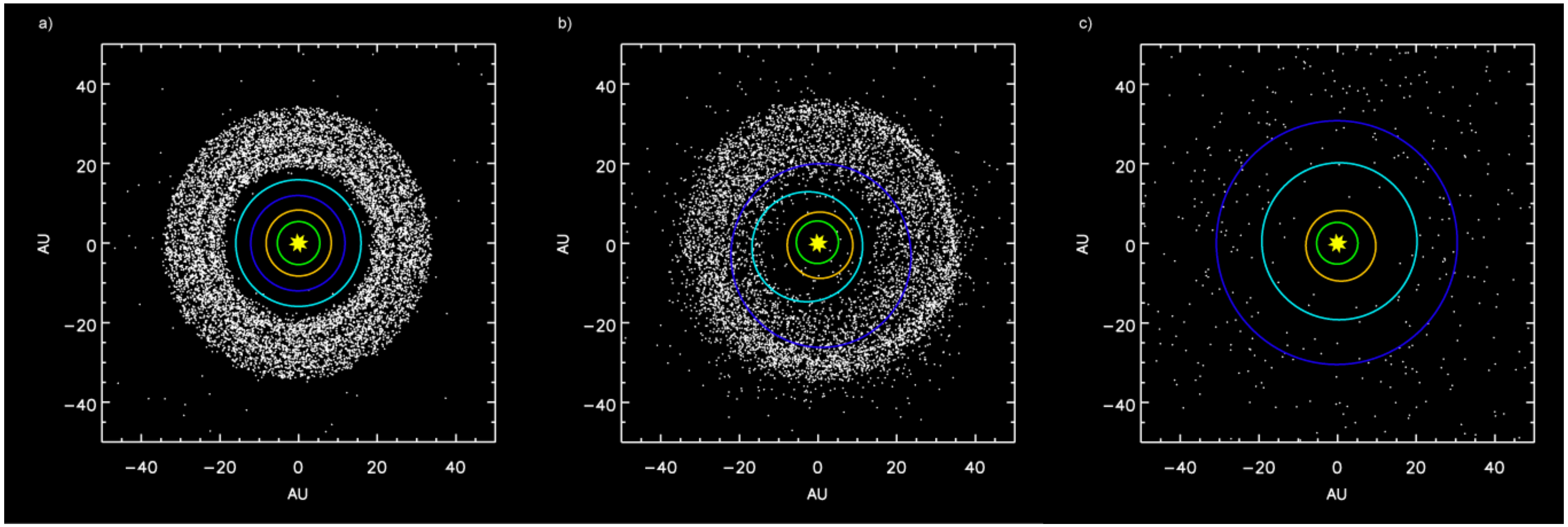
The History of the Solar System is Written on the Face of the Moon

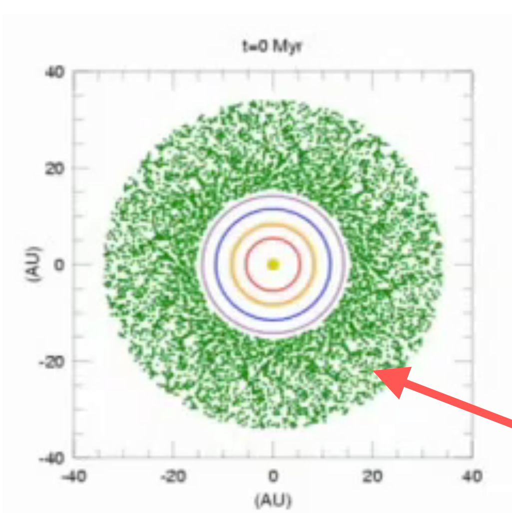
What Does the Moon Tell Us?
Two views





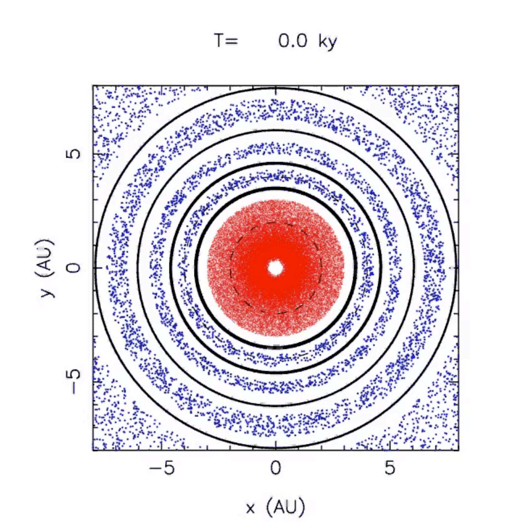
Mixing via Planetary Migration





← "Nice Model"

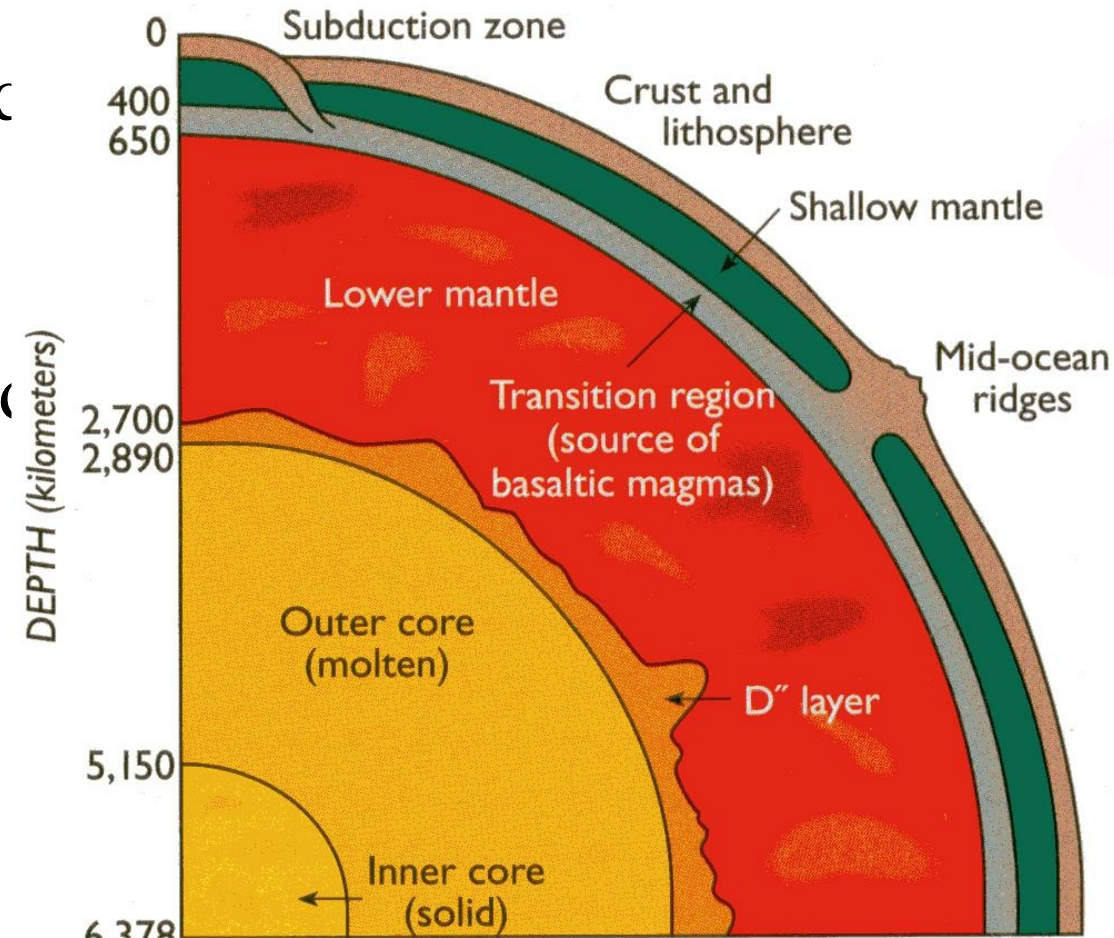
"Grand Tack" →

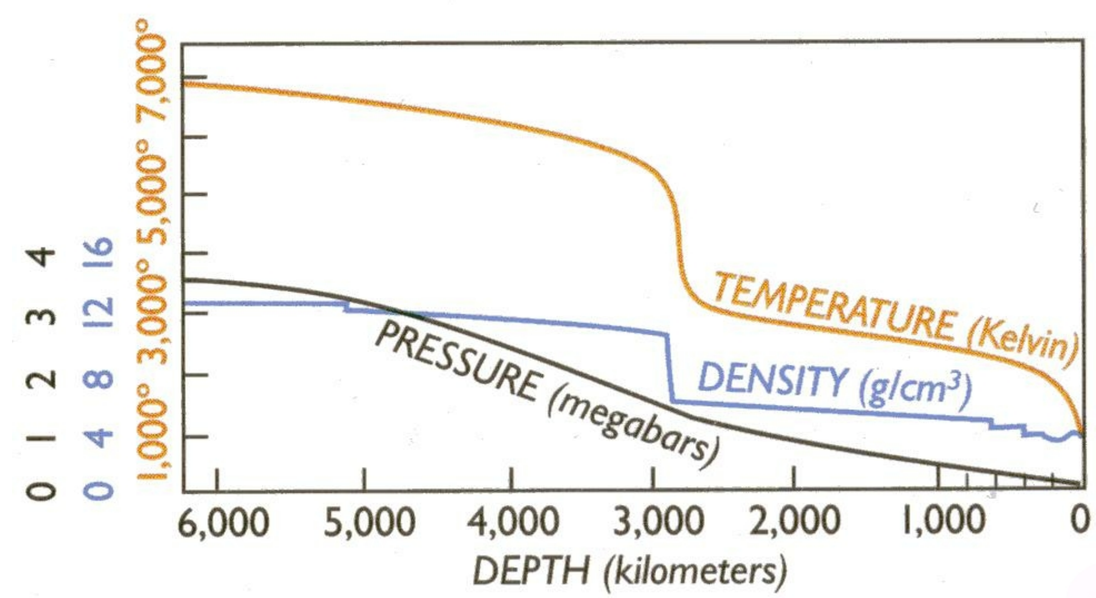


Kuiper Belt Objects
(Pluto, Eris, etc.)

Chemical Boundaries

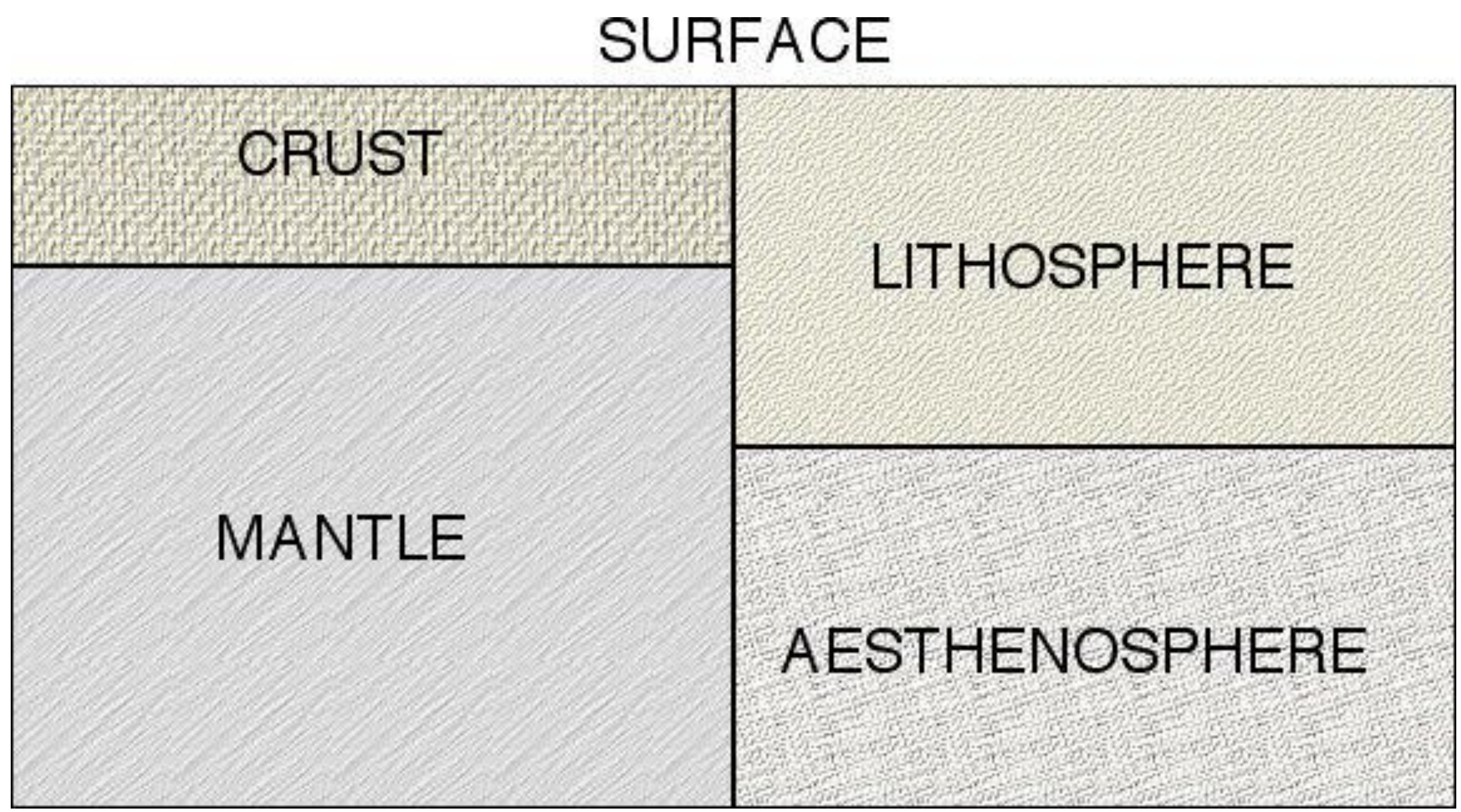
- **Core** - solid center & liquid envelope - mostly Fe with some Ni, S - motion in liquid core generates Earth's magnetic fielc
- **Mantle** - rock - mostly olivines & pyroxenes - location below the crust is detected by a change in seismic wave speec
- **Crust** -lighter rock - rich in feldspars
- Oceanic Crust - thinner crust under ocean floors
- Continental Crust - thicker - "floats" on mantle due to *isostatic equilibrium*



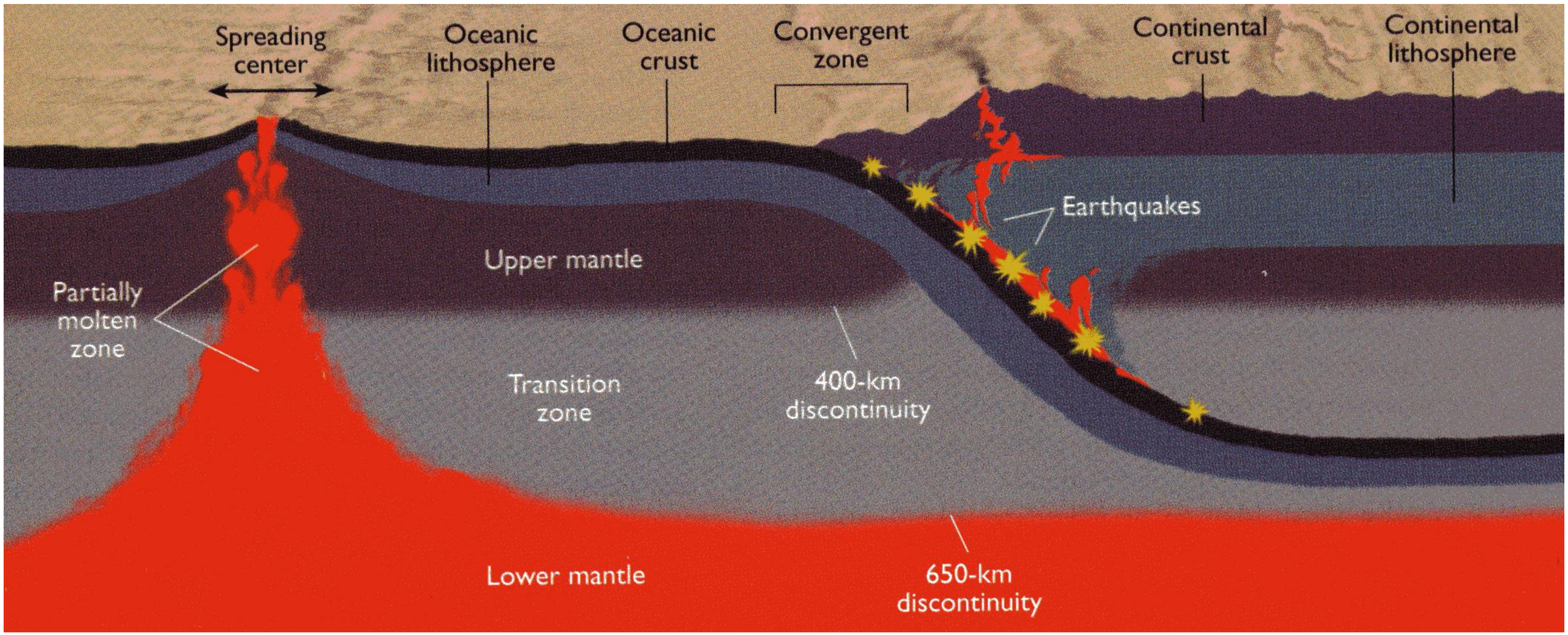


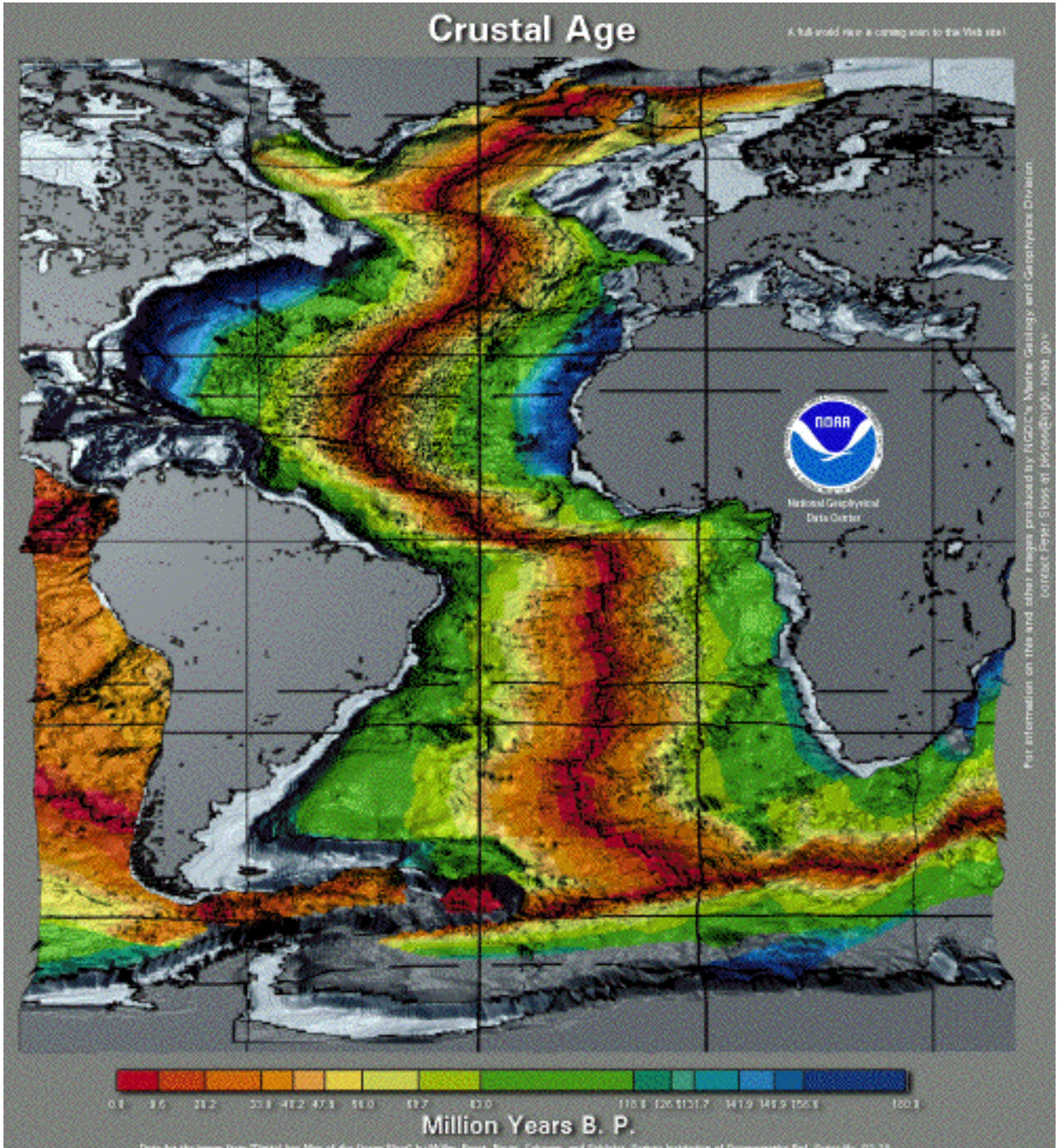
Physical Boundaries

- Crust & upper mantle - solid *lithosphere*
- Below is partly liquid *aesthenosphere*



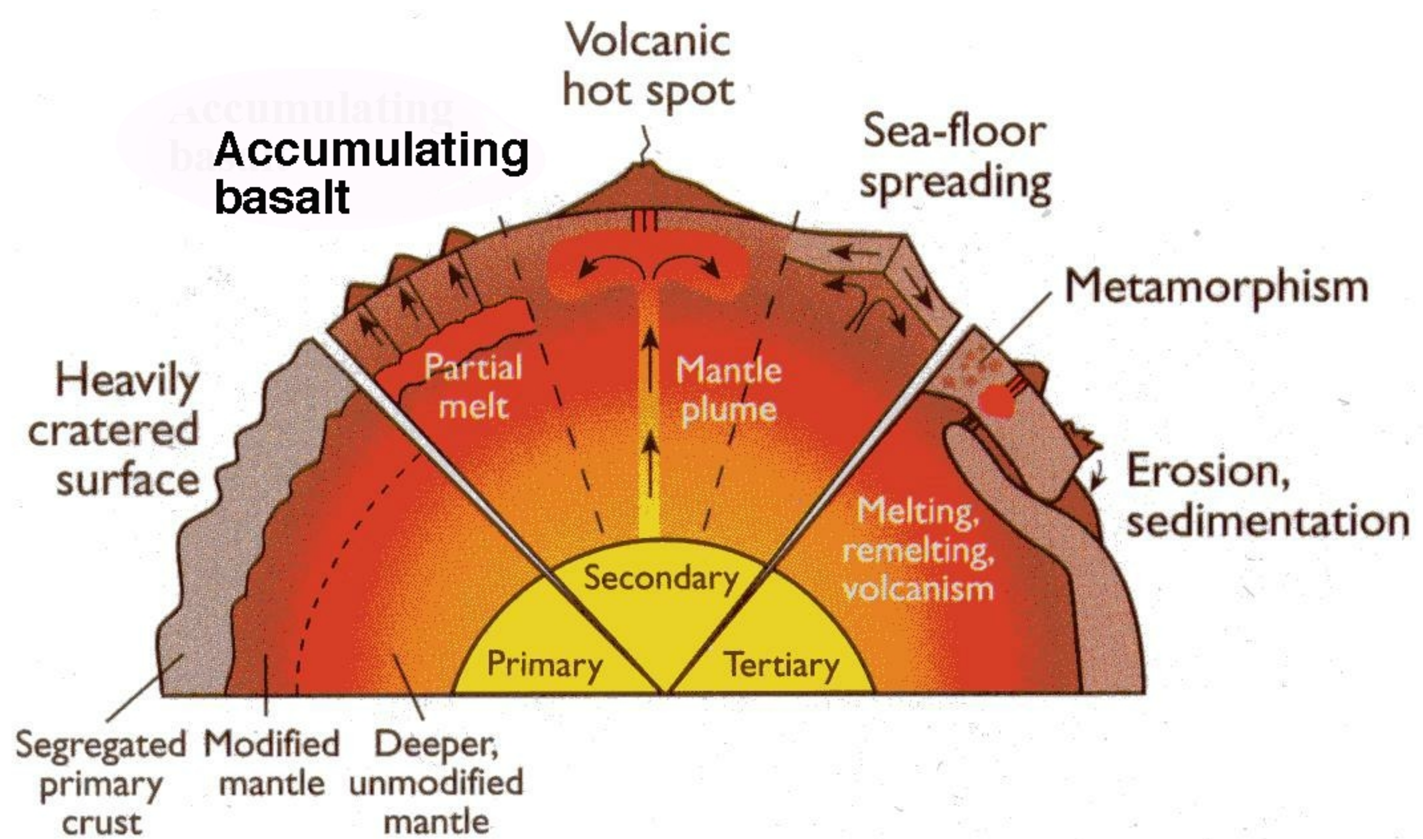
Chemical (crust/mantle) and physical (lithosphere/aesthenosphere) boundaries need not coincide!!


Spreading center
Oceanic lithosphere
Oceanic crust
Convergent zone
Continental crust
Continental lithosphere
Earthquakes
Upper mantle
Partially molten zone
Transition zone
400-km discontinuity
Lower mantle
650-km discontinuity


Crustal Age
NOAA
National Geophysical Data Center
Million Years B. P.
For information on this and other images produced by NGDC's Marine Geology and Geophysics Division

3 Stages of Crust Development

- ***Primary Crust*** **- original solidification, subject to heavy impact during early solar system ("*late heavy bombardment period*").**
- ***Secondary Crust*** **- hot mantle material reaches surface through volcanic action and new crust exposed in seafloor spreading.**
- ***Tertiary Crust*** **- further re-working of crust material by subduction, metamorphic processes, erosion, and sedimentation.**



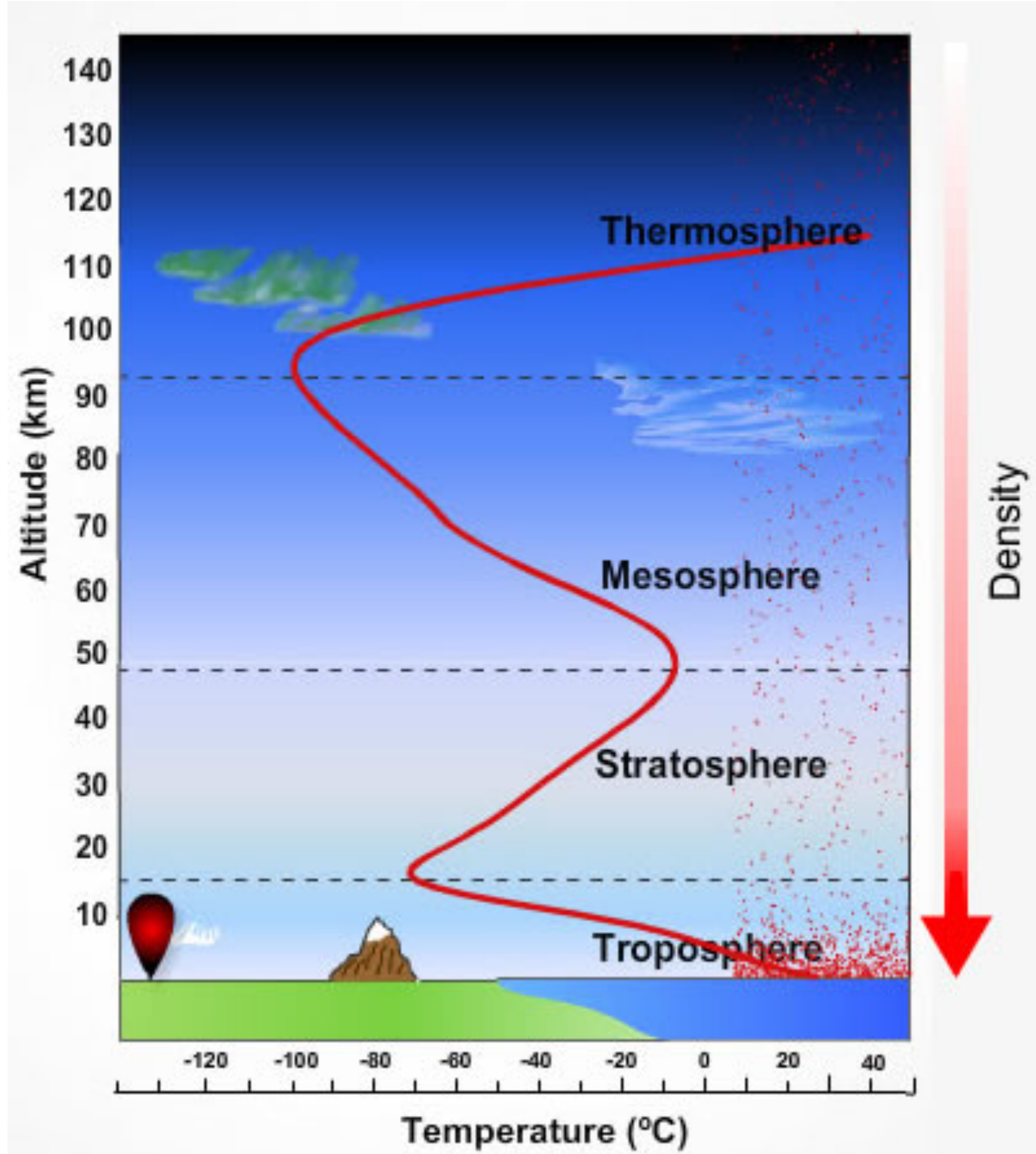
Today: no primary crust remaining (erosion, subduction, etc.)

Secondary crust: production still occurring at Mid-Atlantic Ridge, large shield volcanoes such as Hawaiian Islands

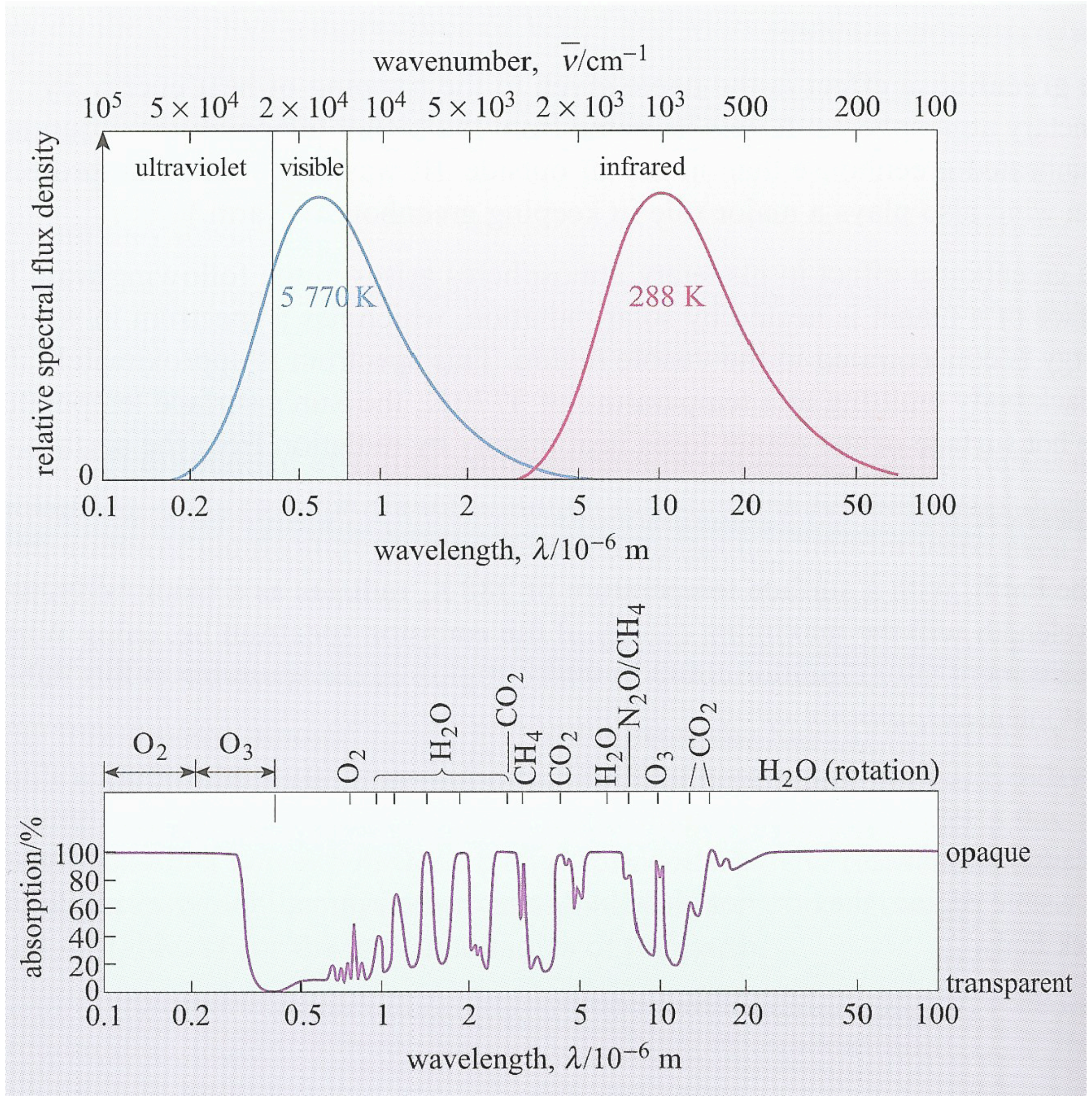
Tertiary crust: continents.

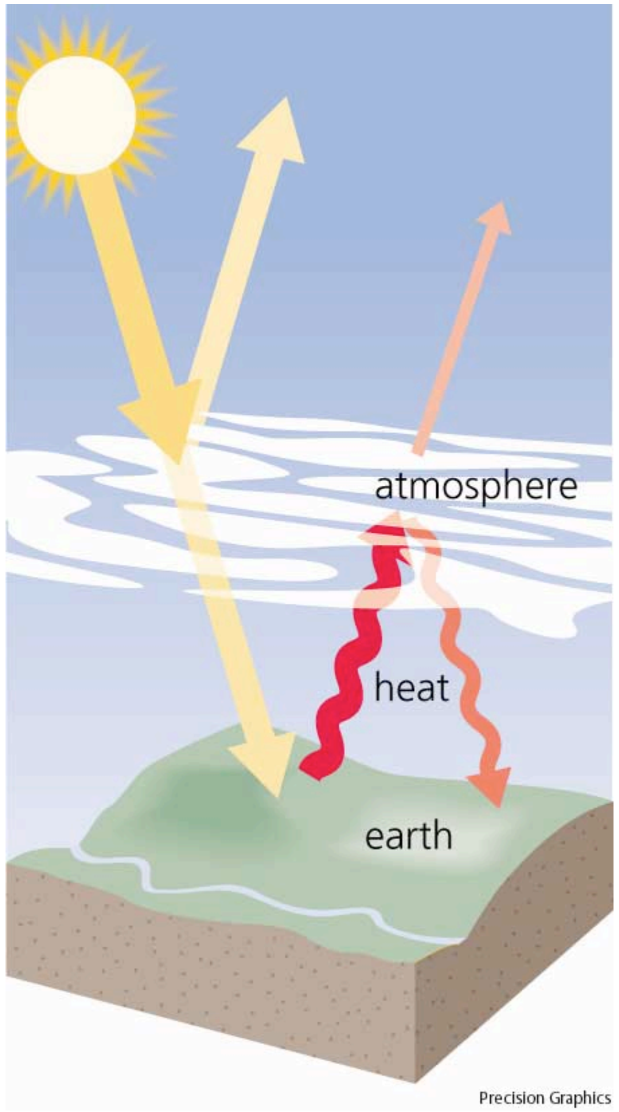
Earth's Atmosphere

- **Chemical Composition: 78% N_2, 21% O_2**
- ***Troposphere* heated by ground - weather**
- ***Stratosphere* heated by O_3 layer at 20-30 km**
- ***Mesosphere* - T drops**
- ***Thermosphere* - T rises due to UV and X-ray heating - ionizes the gas to produce ionosphere**



Greenhouse Effect





The greenhouse effect warms a planetary surface by warming the atmosphere above it. Due to the Sun's surface T, Light from the Sun peaks near wavelengths where the Earth's atmosphere is transparent, so little heating of it occurs. The light that is absorbed by the ground heats the ground, when then radiates at ***its*** characteristic T, which is a lot cooler, and peaks in the IR. Unlike visible wavelengths, the IR is filled with absorption bands due to various molecules. These molecules absorb the IR, effectively depositing that energy in the atmosphere, and warming it. The warm molecules radiate at those same wavelengths that they absorb at, and half of the radiation is back in the direction of the surface of the planet.

Climate Change Video

Urey Reaction

The removal of CO_2 from the atmosphere (and its return)

CO_2 + Silicate Rocks ---(liquid water) ---> SiO_2 + Carbonate Rocks

Earth's rocks and oceans contains enough CO_2 that, if released, would increase the mass of its atmosphere by 30x!!!

CO_2 is recycled into the atmosphere through volcanic action

The Moon

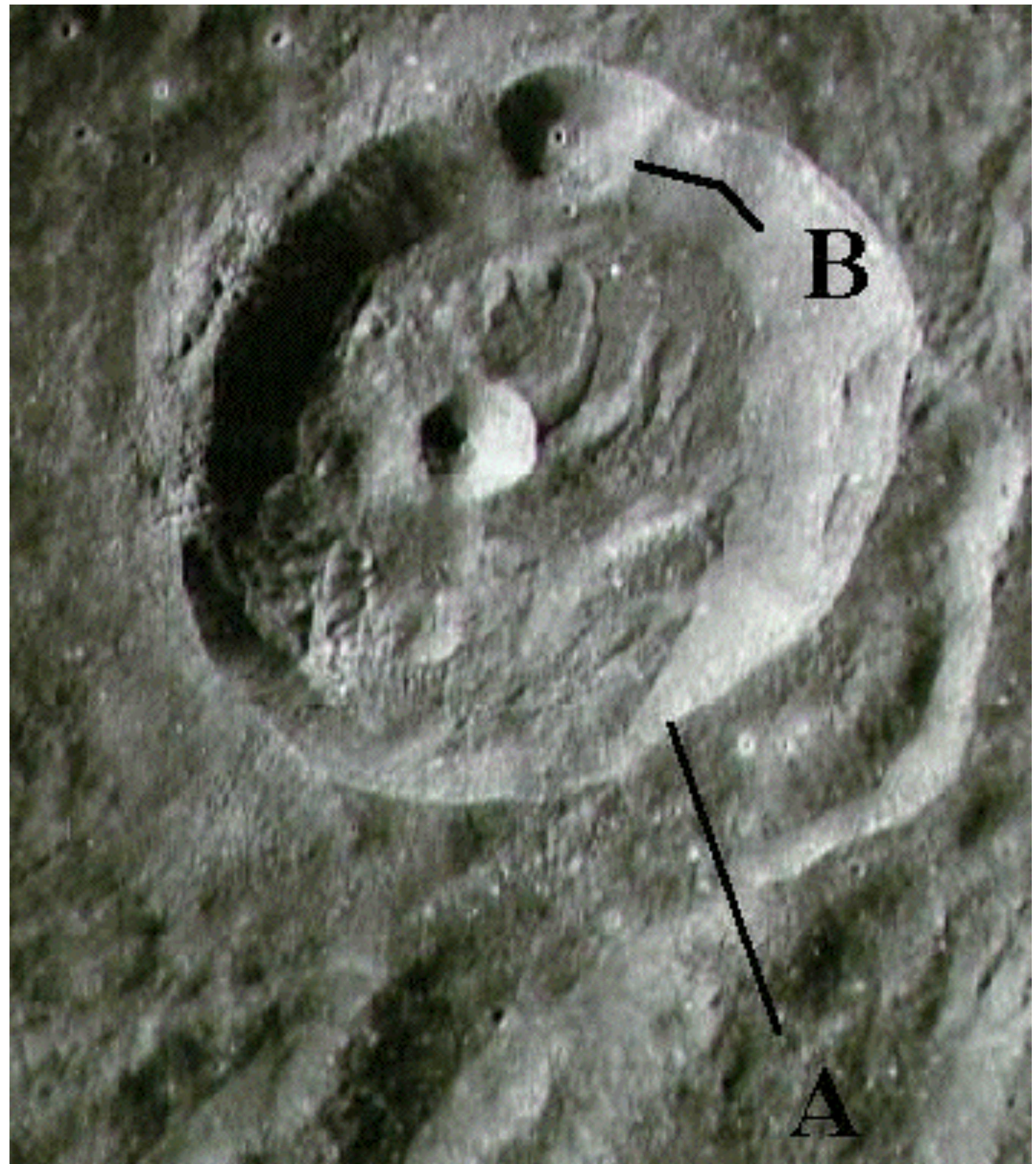
To help put Mercury in context

- $R_{Moon} \sim 1/4\ R_{Earth}$
- $M_{Moon} \sim 1/81\ M_{Earth}$
- $g_{Moon} \sim 1/6\ g_{Earth}$
- T=370K-120K
- Vesc = 2.4 km/s
- E-M distance increasing 4 cm/yr

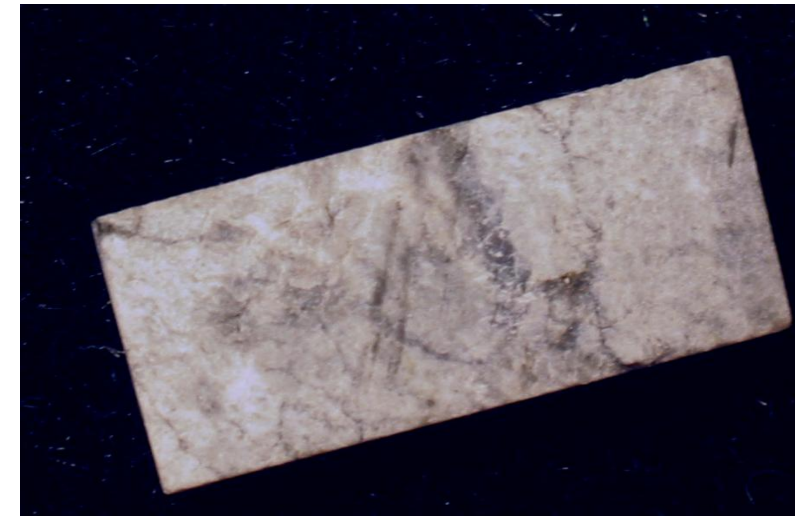
Age Dating on the Moon

Absolute - radioactive dating from 9 locations where we have samples

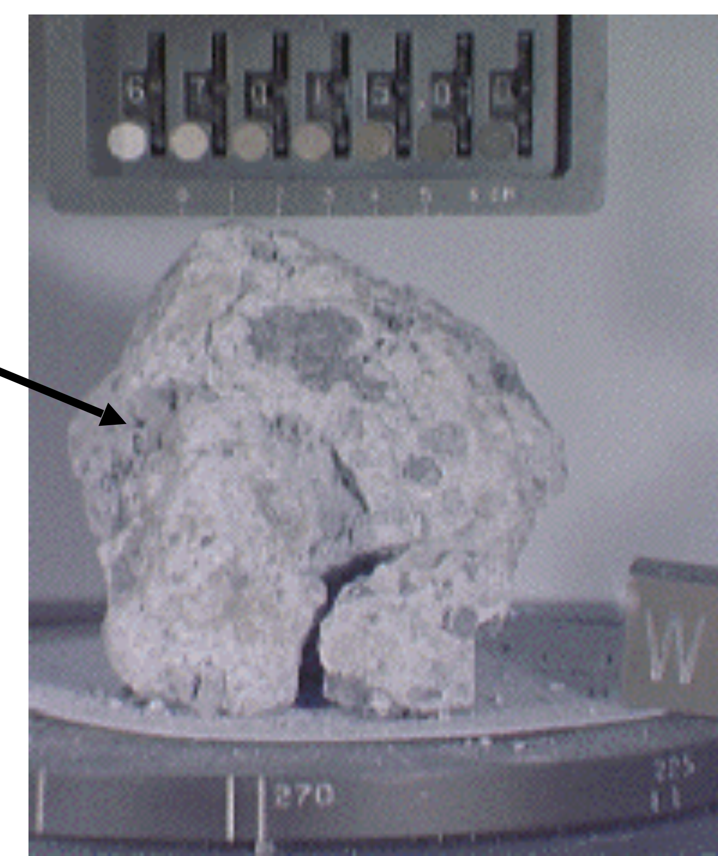
Relative - *superposition*



Terrae



- Essentially its *primary crust*
- Heavily impacted & "gardened" - *regolith*
- Mostly plagioclase feldspar (solidified first)
- Large mineral crystals - good *annealing* - perhaps a *magma ocean* originally?
- Next in solidification - *KREEP*
- Impact-processed *breccias*
- Ages typically 4.0-3.8 by
  (some 4.3 by!!)

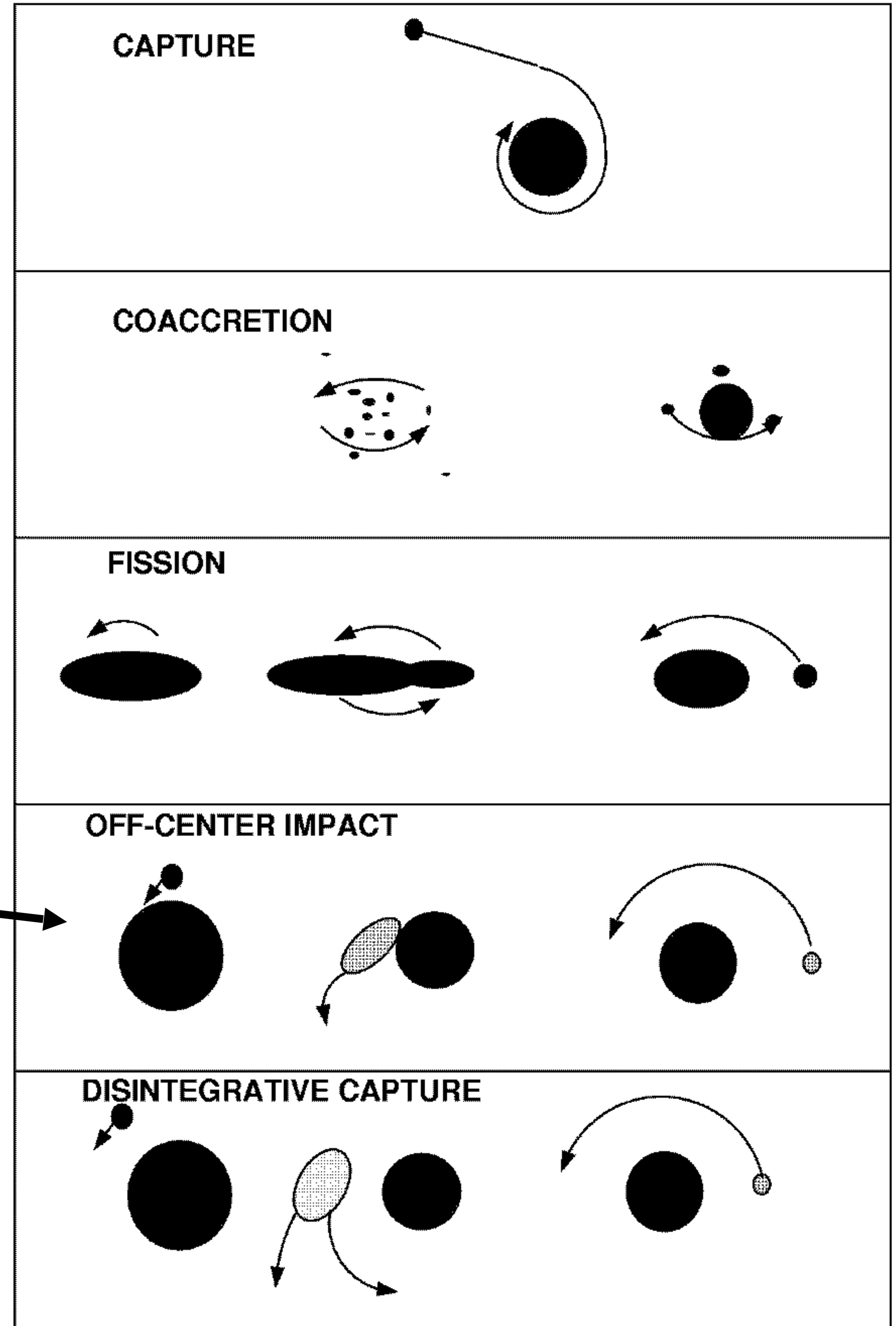


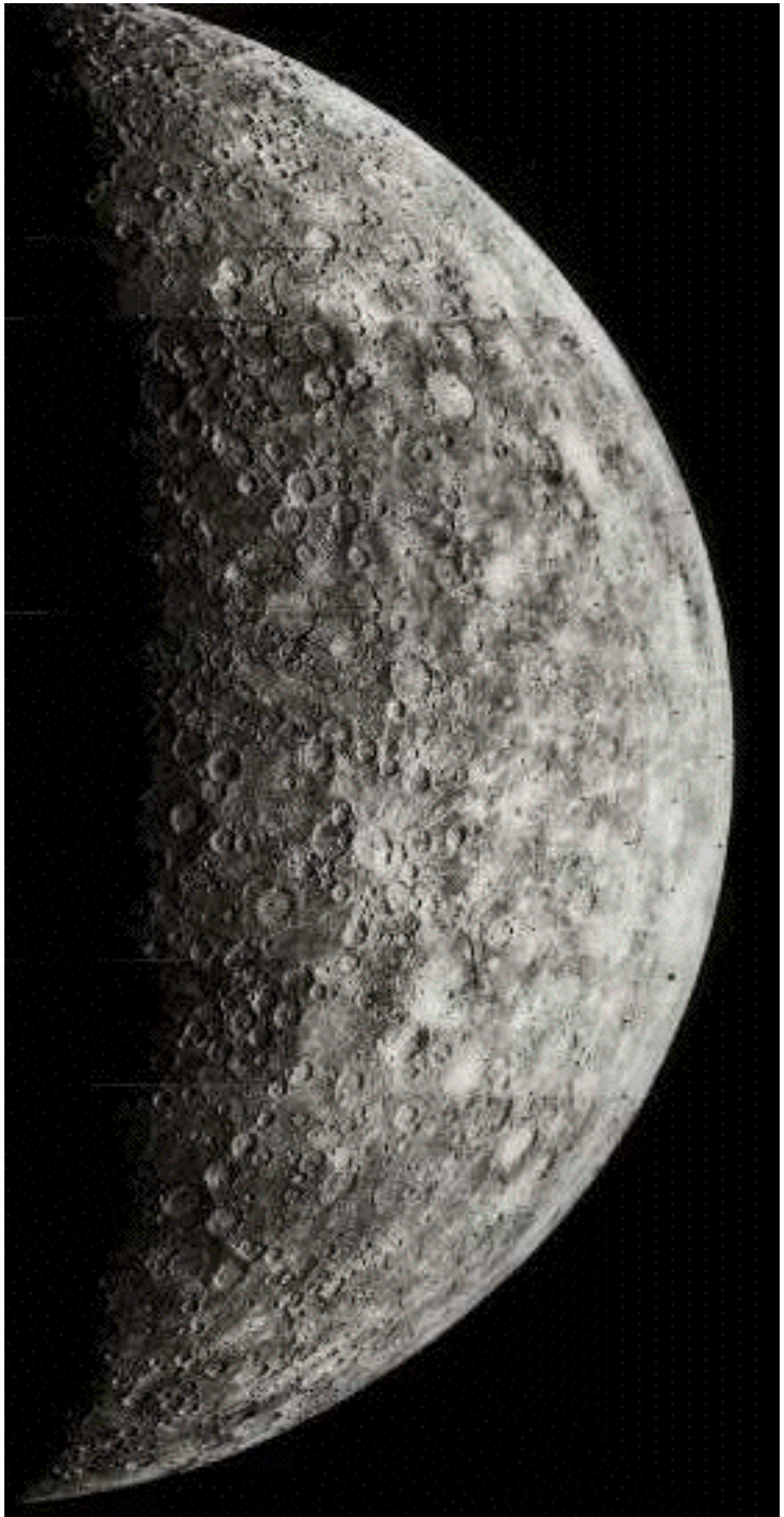
Maria

- Large filled impact basins - *secondary crust*
- Higher Fe content than terrae - looks darker
- Lower crater density - younger than terrae
- Small crystals - cooled quickly
- *Basalts* composed of pyroxenes, feldspars, metal oxides, olivines
- 3.8-3.1 by old

5 Models for the origin of the Moon - most now discounted

Currently the most popular model.



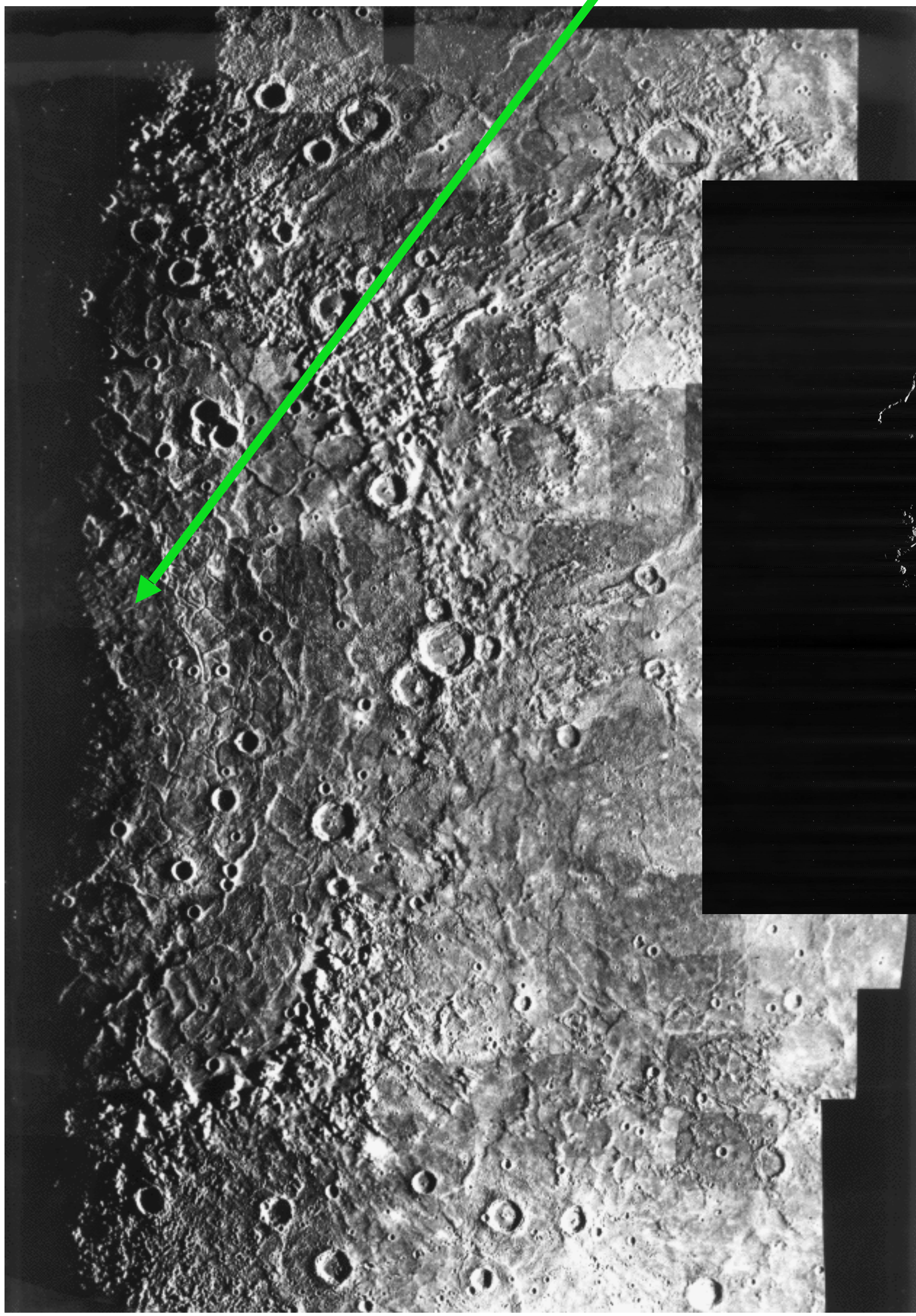


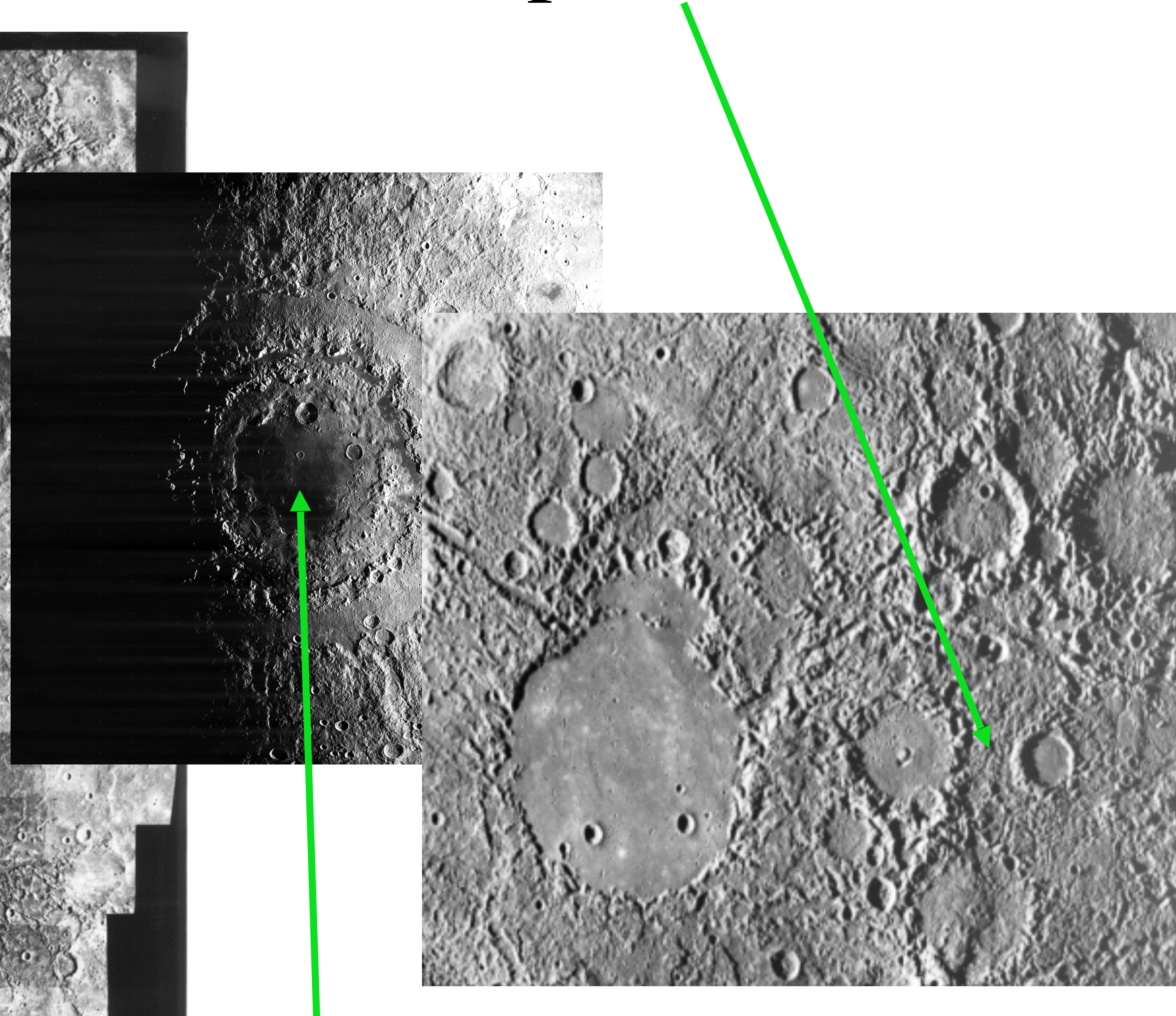
Mercury

Surface is Lunar-like, *but*:

- Essentially no mountains
- Has many scarps
- Fewer, smaller craters (not saturated)
- Only 1 known major mare/ basin feature - “Caloris”
- Has a region of hilly, jumbled terrain opposite Caloris Basin

Caloris & its antipodes

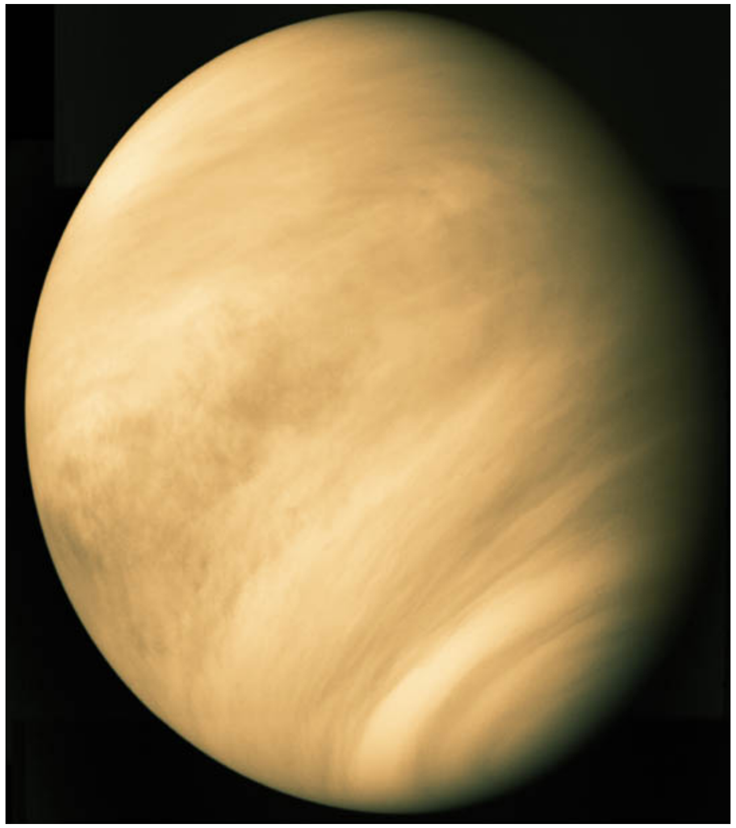


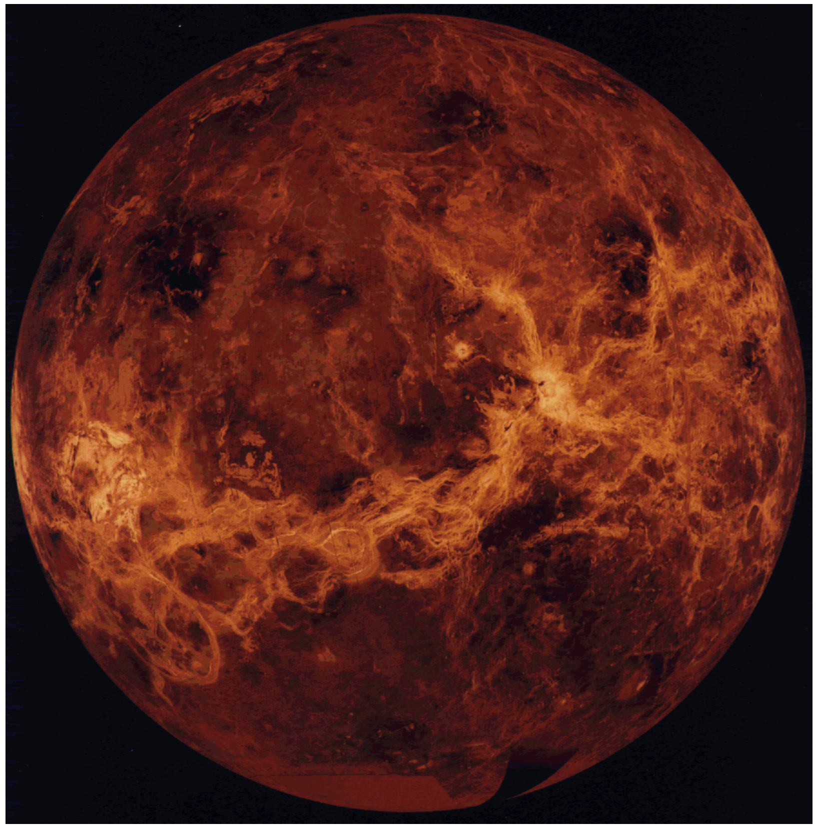


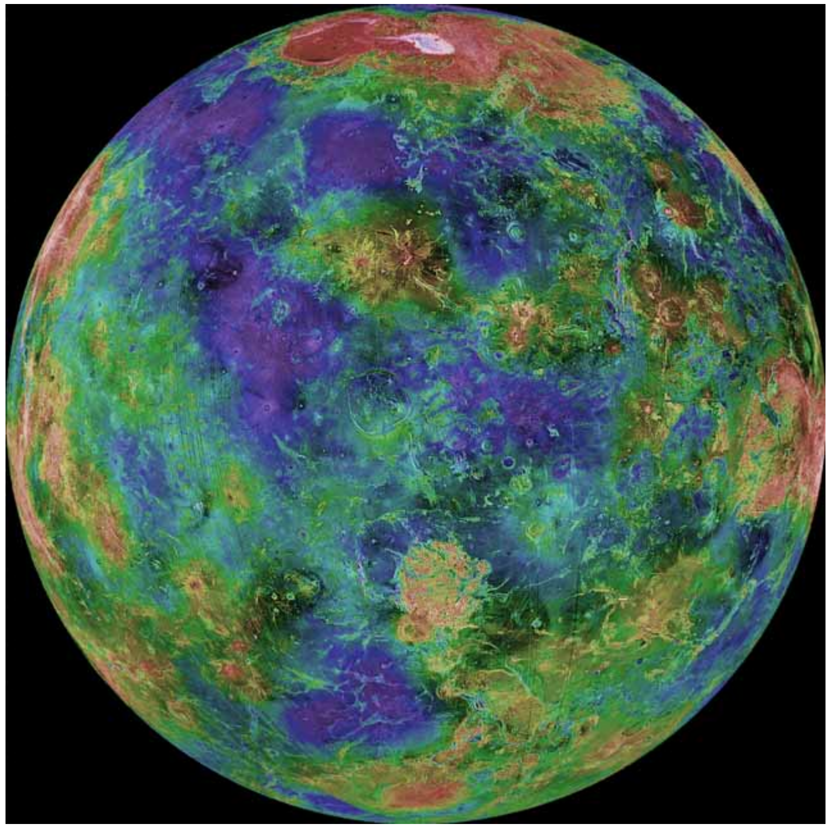
Moon’s Mare Orientale for comparison

Mariner 10 (1974-1975 flyby of Venus once and Mercury 3 times)
Magellan (1990-1994 orbiter)

3 faces of Venus







Visible Light (Mariner 10)

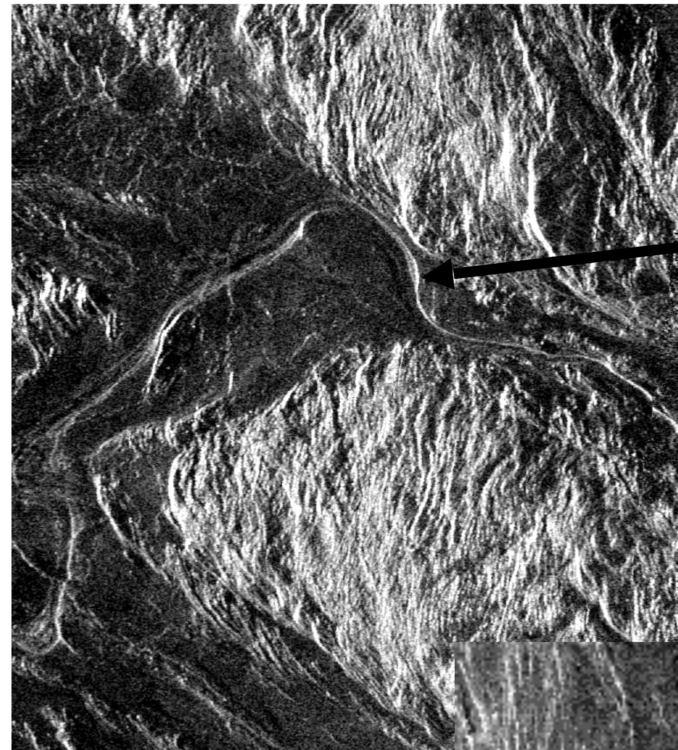
Radar map (Magellan) color as seen from surface

Radar map color-coded for elevation

Basaltic Surface

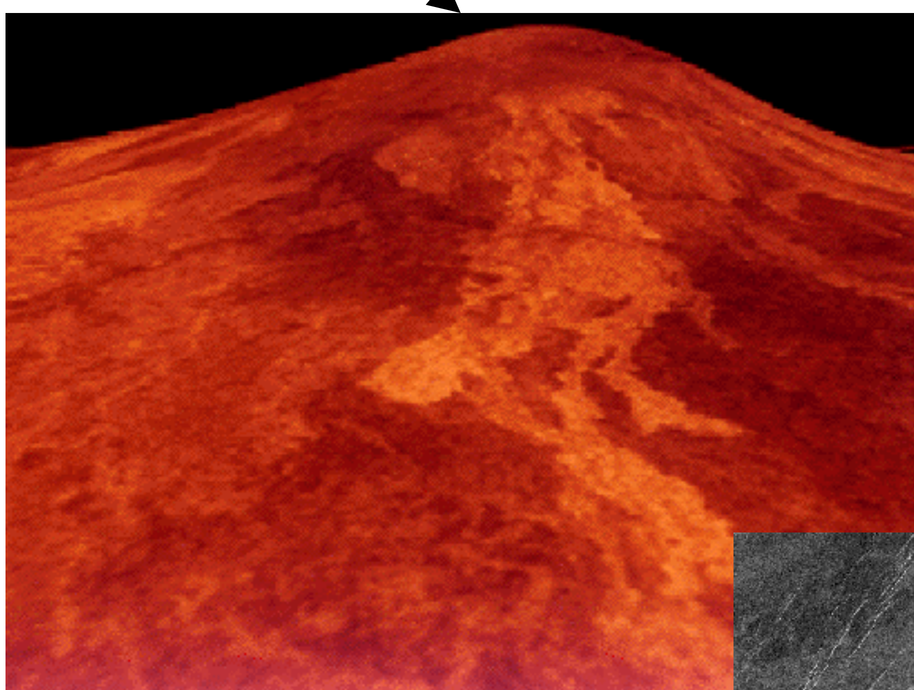
Venera-14 (1983)

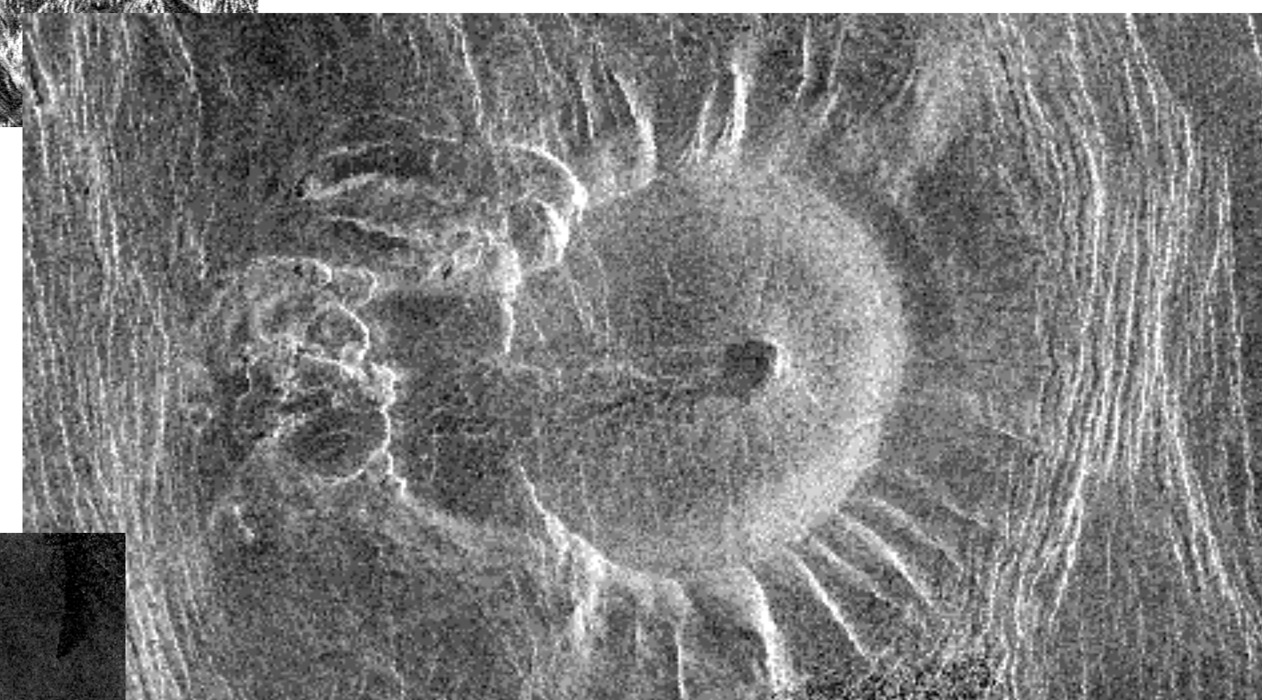
X-ray Fluorescence Spectrometer extended



Lava channel

Sif Mons

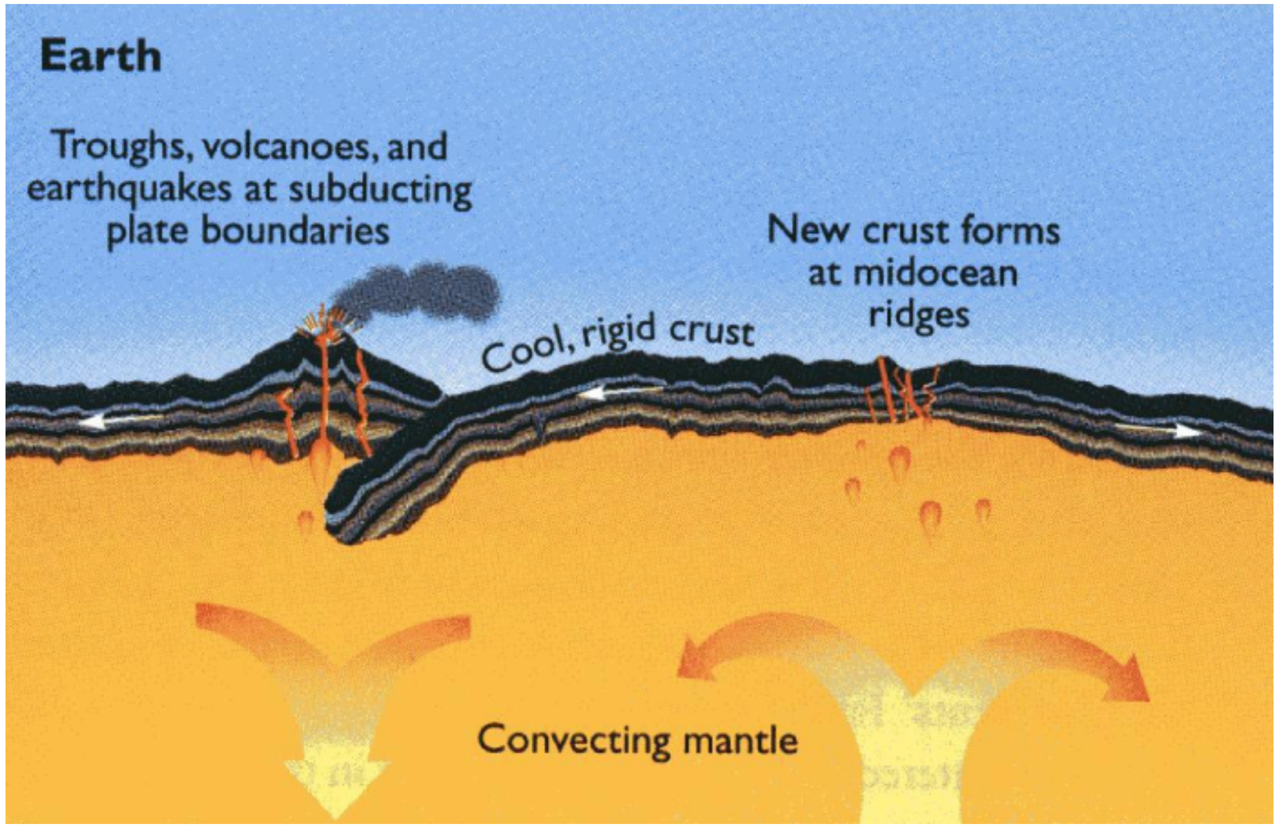


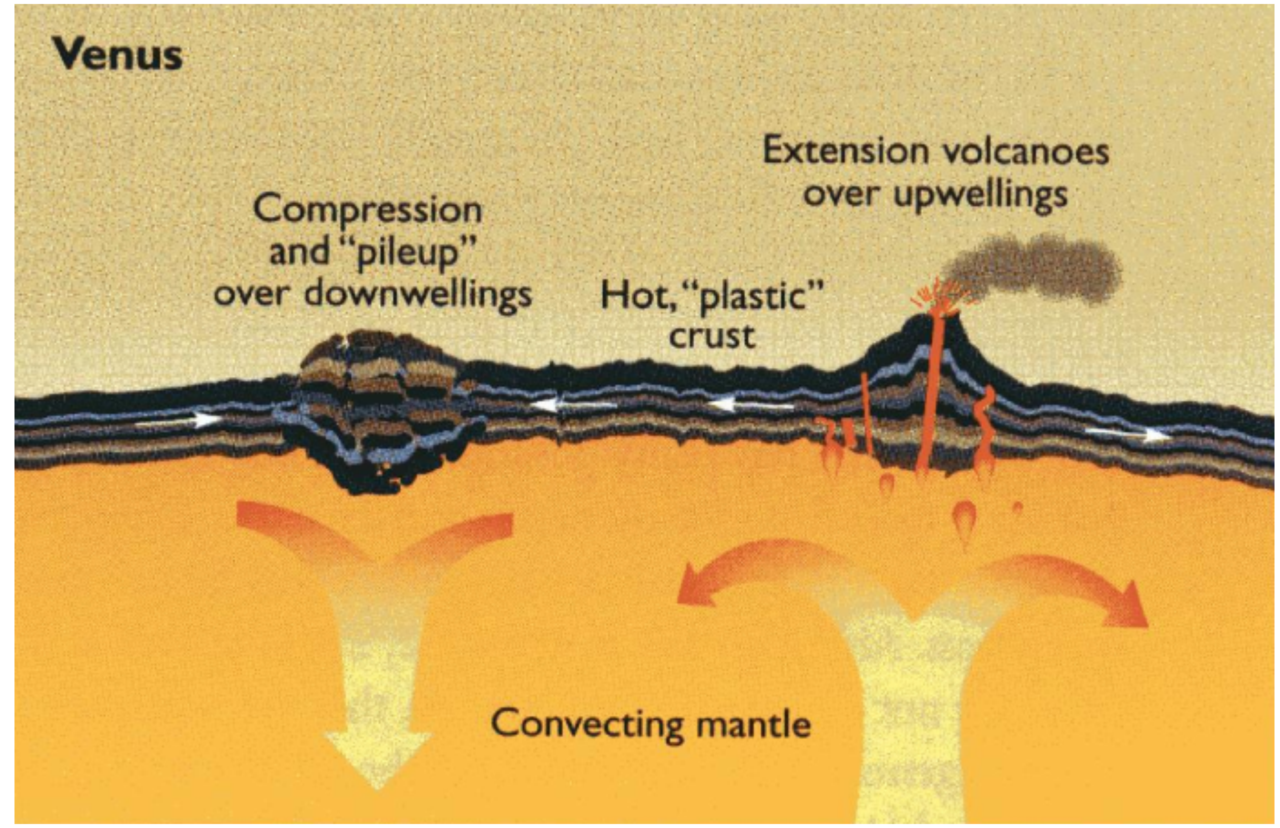


Lava domes

The “Tick”

Comparison of Plate Activity for Earth & Venus





Cool crust

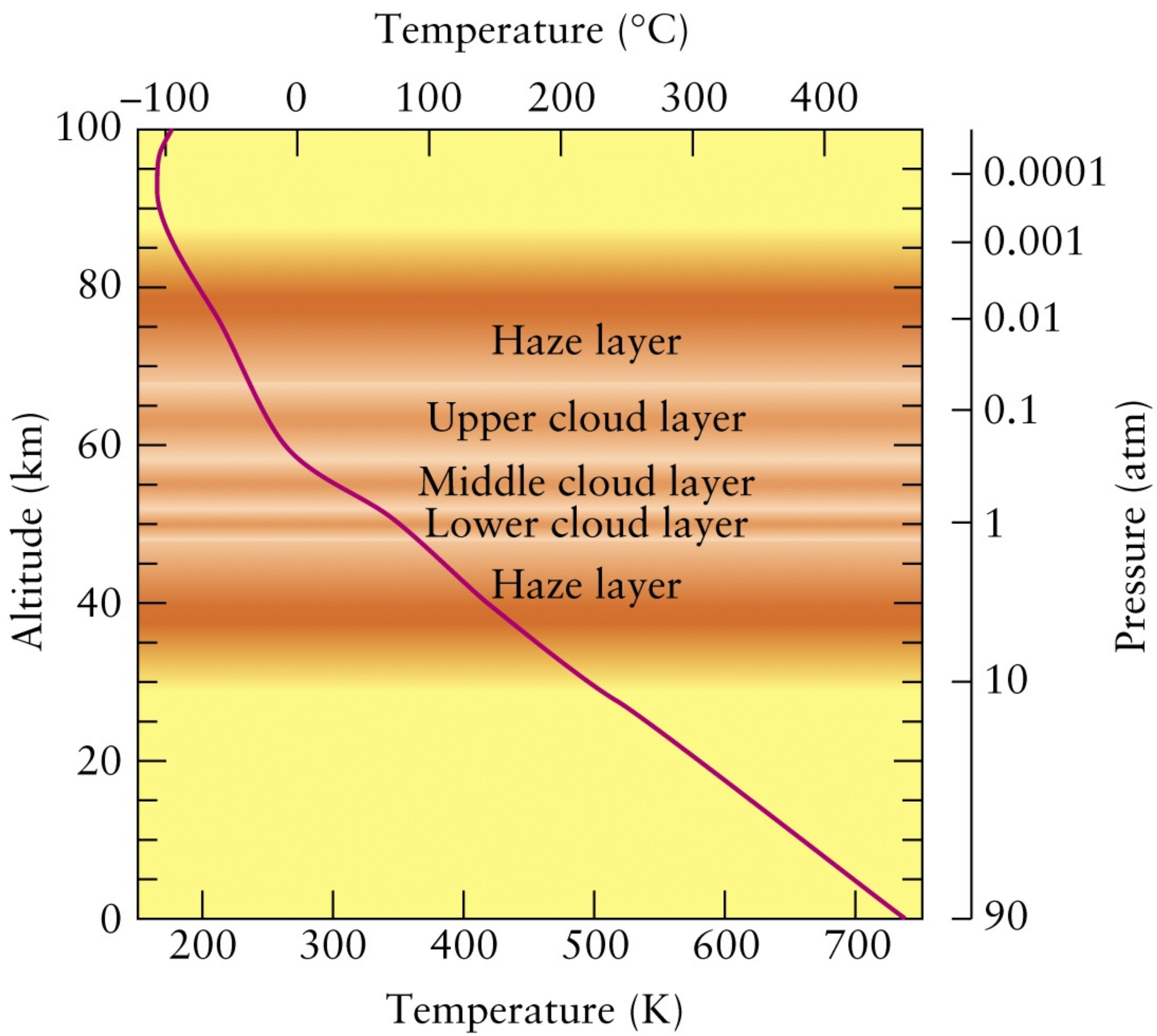
Water lubricates tectonic motion

Warm crust

No water

However, it appears that Venus underwent a *resurfacing* event about 500 million years ago, spurred on by widespread volcanism. Does it still have active volcanos??

- $96\%\ CO_2$, $3\%\ N_2$
- $P_{surface} = 90$ bars
- Clouds: Mostly Droplets of concentrated sulfuric acid (H_2SO_4)



For our own solar system:

Planet	$d_{(AU)}$	a	Predicted T	Observed T
Mercury	0.39	0.056	440	100-620
Venus	0.72	0.76	230	750 (and very uniform!)
Earth	1.00	0.39	250	180-330 (290 avg.)
Mars	1.52	0.16	220	130-290 (Sub-Solar Equatorial
Jupiter	5.2	0.51	104	160 (cloud tops)
Saturn	9.5	0.61	81	90 (cloud tops)

The freezing point of water is 273 K, and the boiling point is 373 K, under 1 Atm pressure. Venus is currently too hot for liquid water. Mars is too cold. The Earth is "just right".

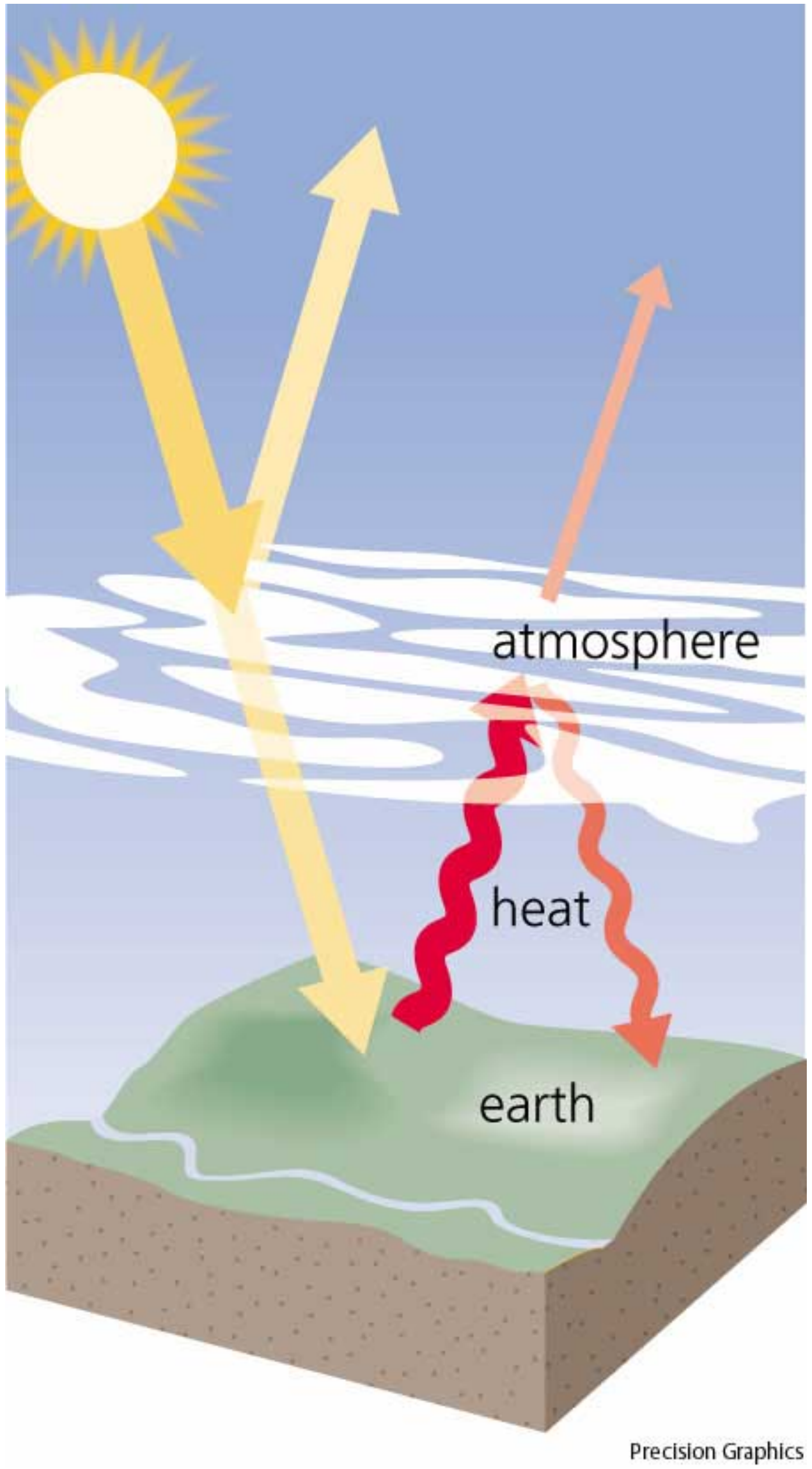
We can do the same calculation for other types of stars as well.

Question: Why are most of the planets hotter than this?

J & S - internal heat source - emit more than they absorb!

V & E - Greenhouse effect - we will need to add another term for this

Why is Venus so different? - Greenhouse Effect



1. Visible light, to which atmosphere is transparent, absorbed by ground - heats it
2. Ground re-radiates energy as infrared light, to which the atmosphere is opaque
3. Warmed atmosphere re-radiates some of the IR back to the ground, keeping everything warmer

Why Different Greenhouse Effects?

Earth's water removes CO_2 and sequesters it in rocks. The *Urey Reaction*, in its simplest form:

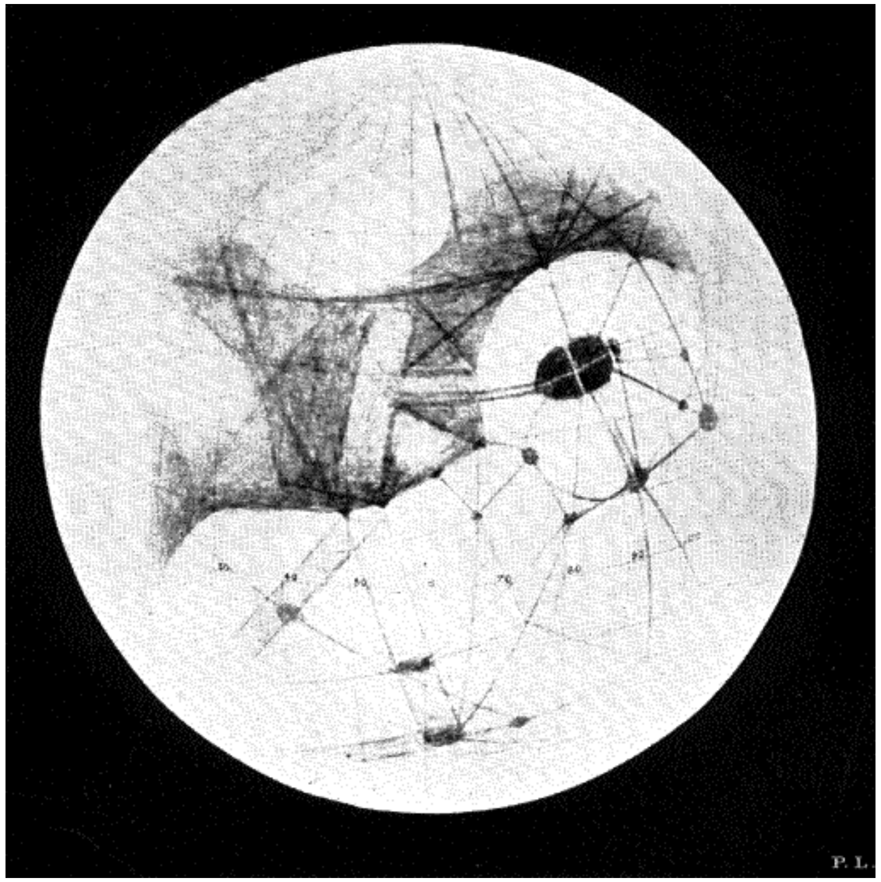
$$CO_2 + silicate\ rock \xrightarrow{liquid\ water} SiO_2 + carbonate\ rock$$

"Great Idea": *if all the CO_2 in rocks were released, we would have an atmosphere similar to that of Venus! (and we would all die…)*

1900 - Percival Lowell

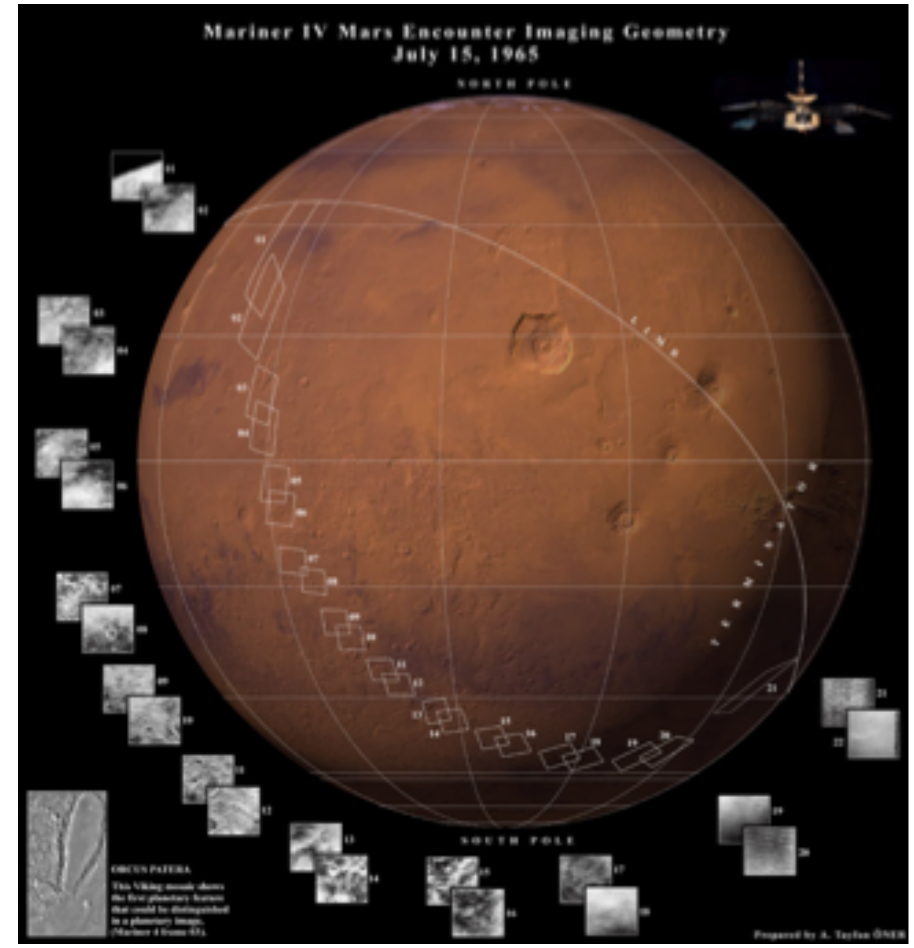
Claims to see canals on Mars

Describes physiological, social, and political traits of martians…..



Mariners to Mars

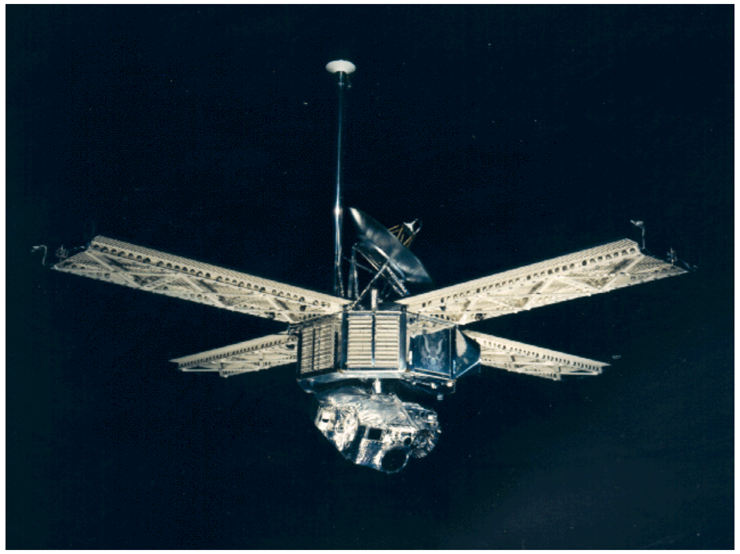
Mariner 4 - July 14, 1964. "Everything Changed" - Returning a whopping 22 (!!) pictures (many so poor as to be useless) during flyby, but it revolutionized our understanding of the planet.

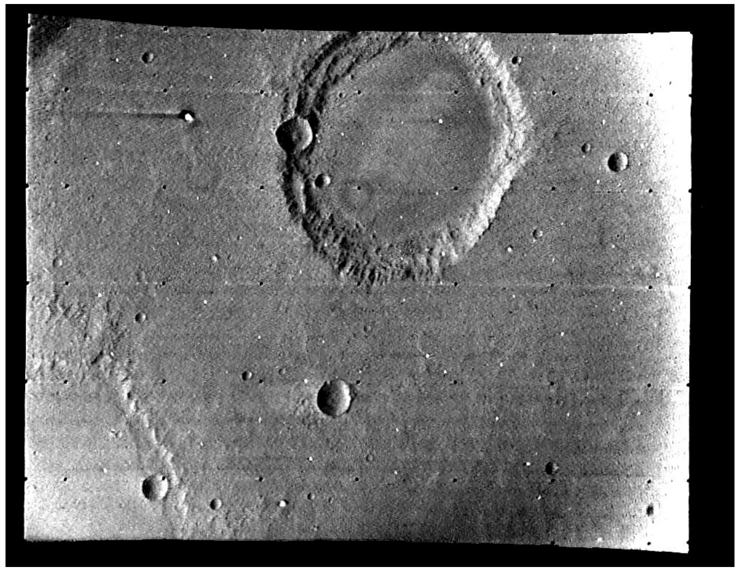


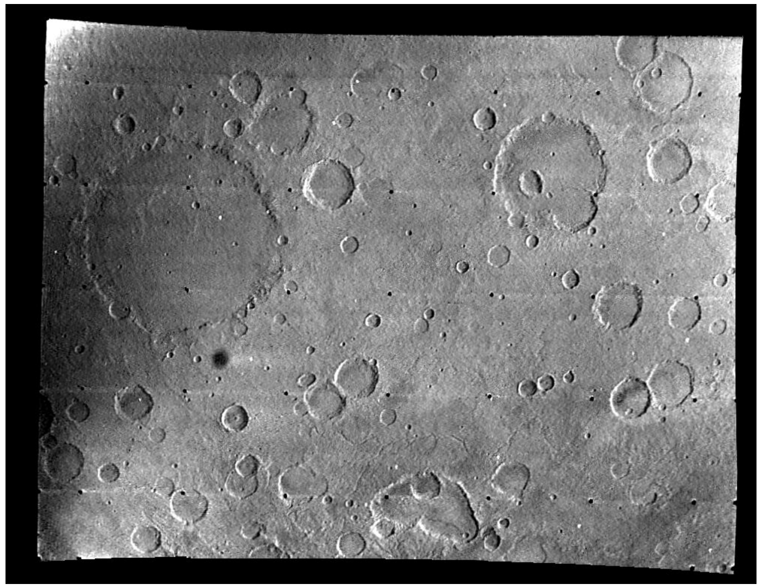
Lots of craters - looked much like our <u>lifeless</u> Moon. Elation & depression amongst planetary scientists

Mariners 6 & 7 - 1969

More of the same, but higher quality images



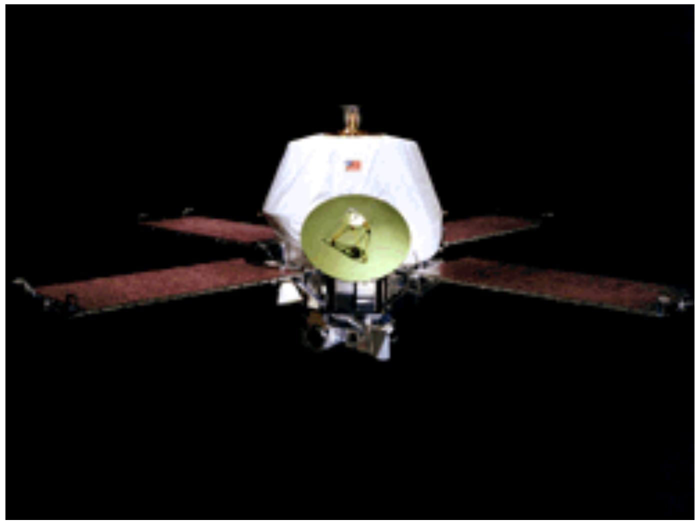


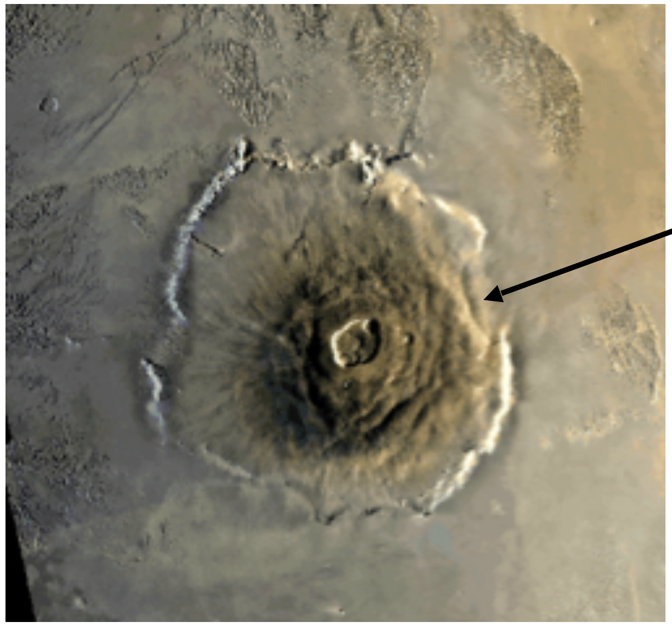


The impression created by Mariner 4 was not changed, only enforced. *Mars seemed as dead as the Moon*. There seemed little chance of finding anything resembling living organisms here, and even the hope of finding evidence for past life vanished.

But not so fast…..

Mariner 9 *Orbiter*



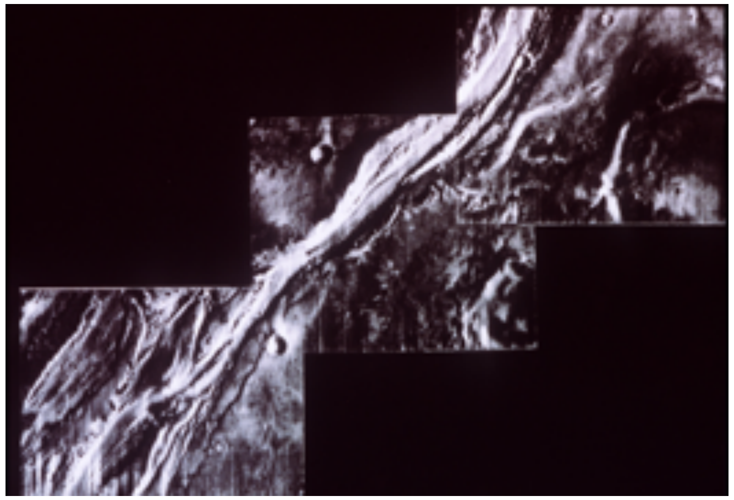


Volcanoes

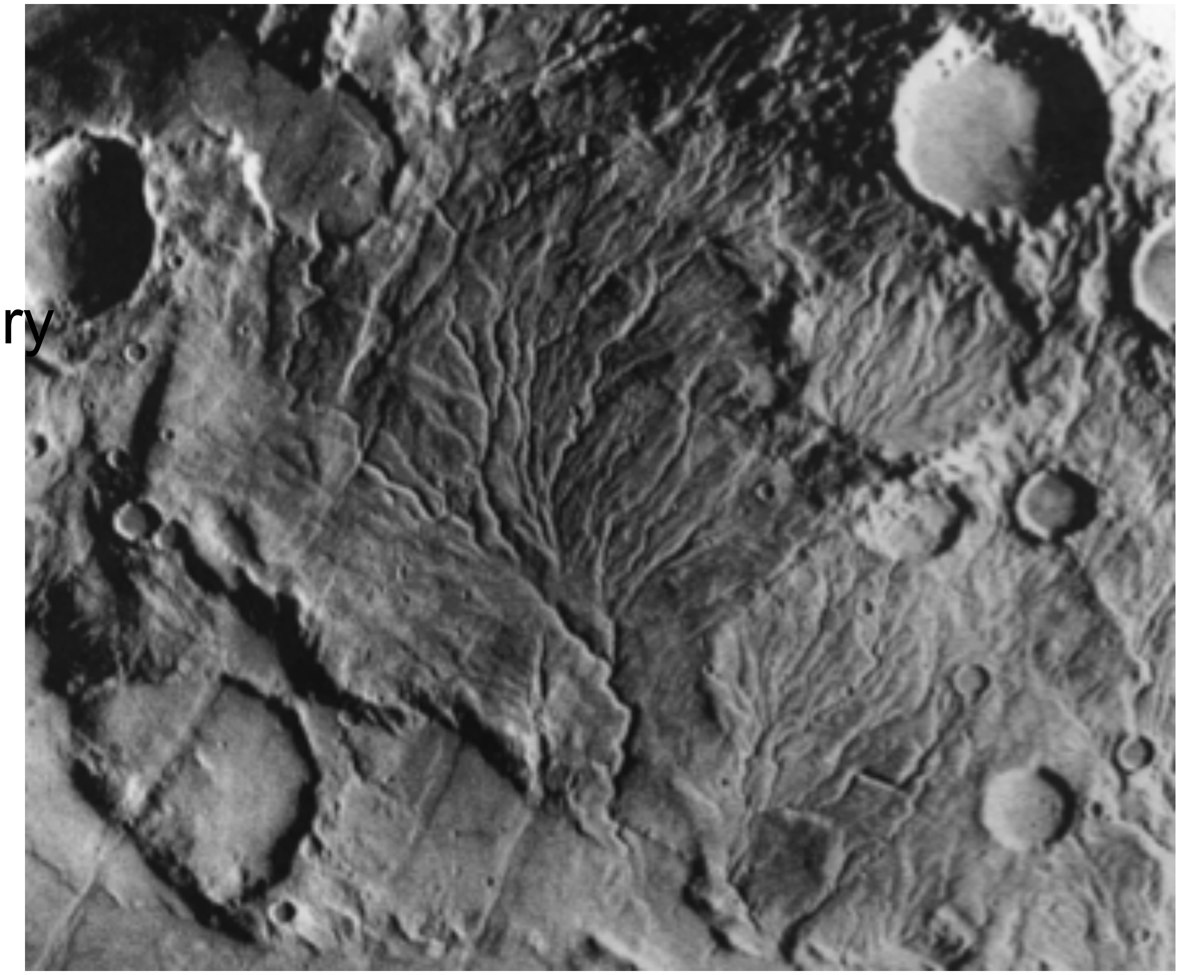
Gullies

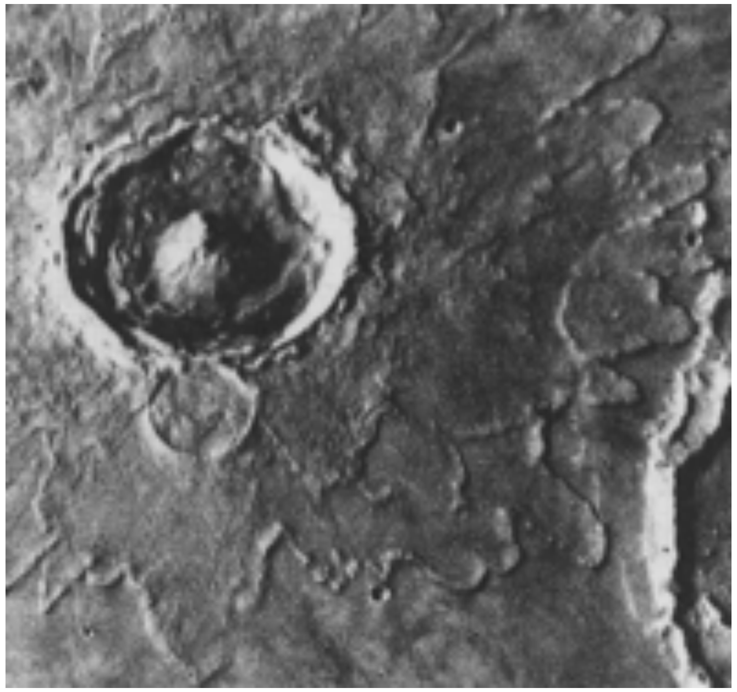
Collapsed Terrain (thaw in underground ice?)

Canyon walls with slumping and other erosional effects

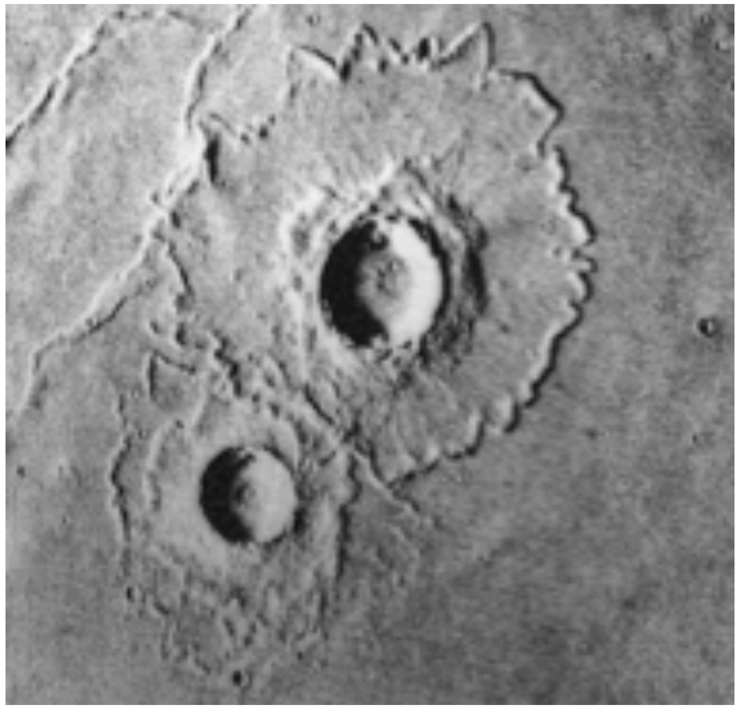


Sinuous “runoff channels” like dry riverbeds on Earth





“Lobate” craters - impacts in ground with ice? Only found far from equator



Viking 1 & 2 - 1976

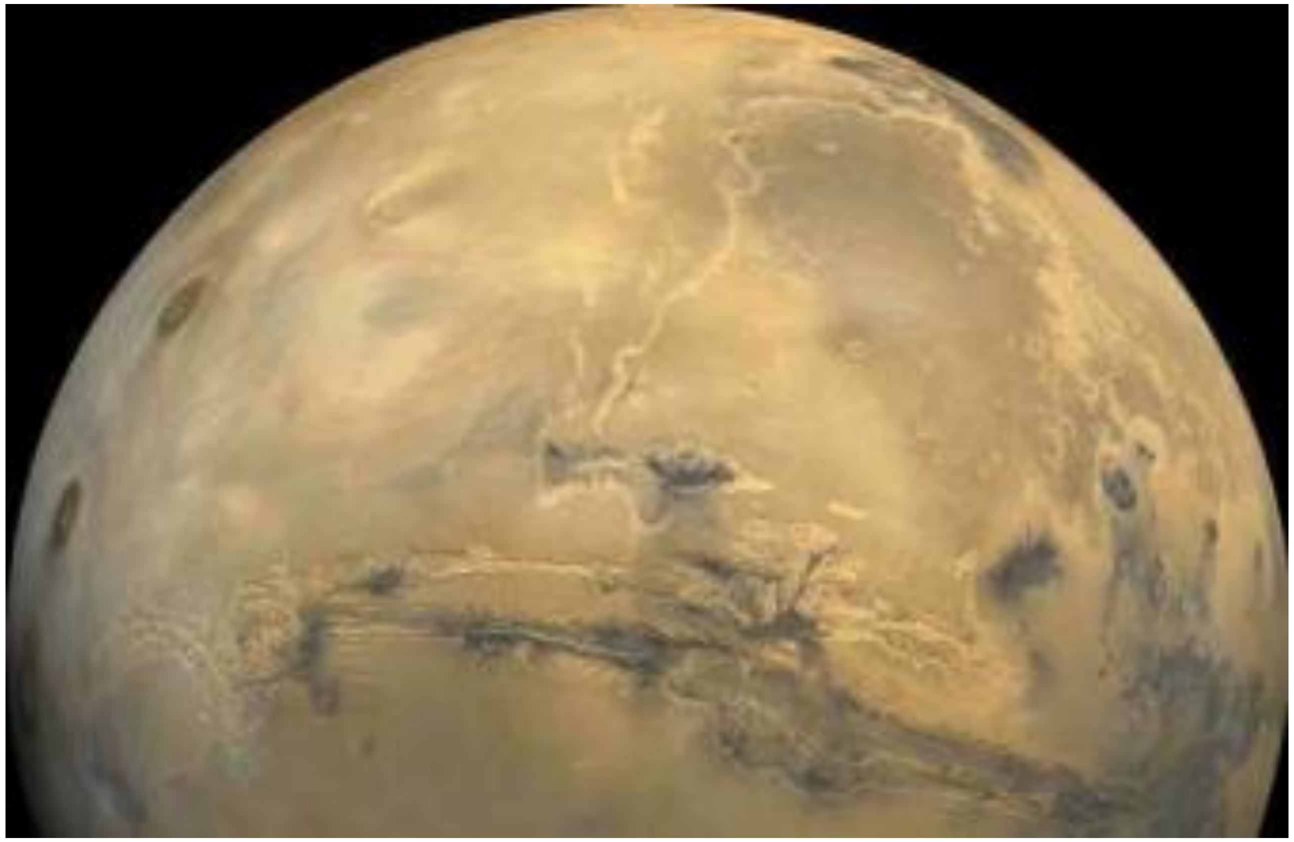
Each consisted of an Orbiter and a Lander

Viking 1

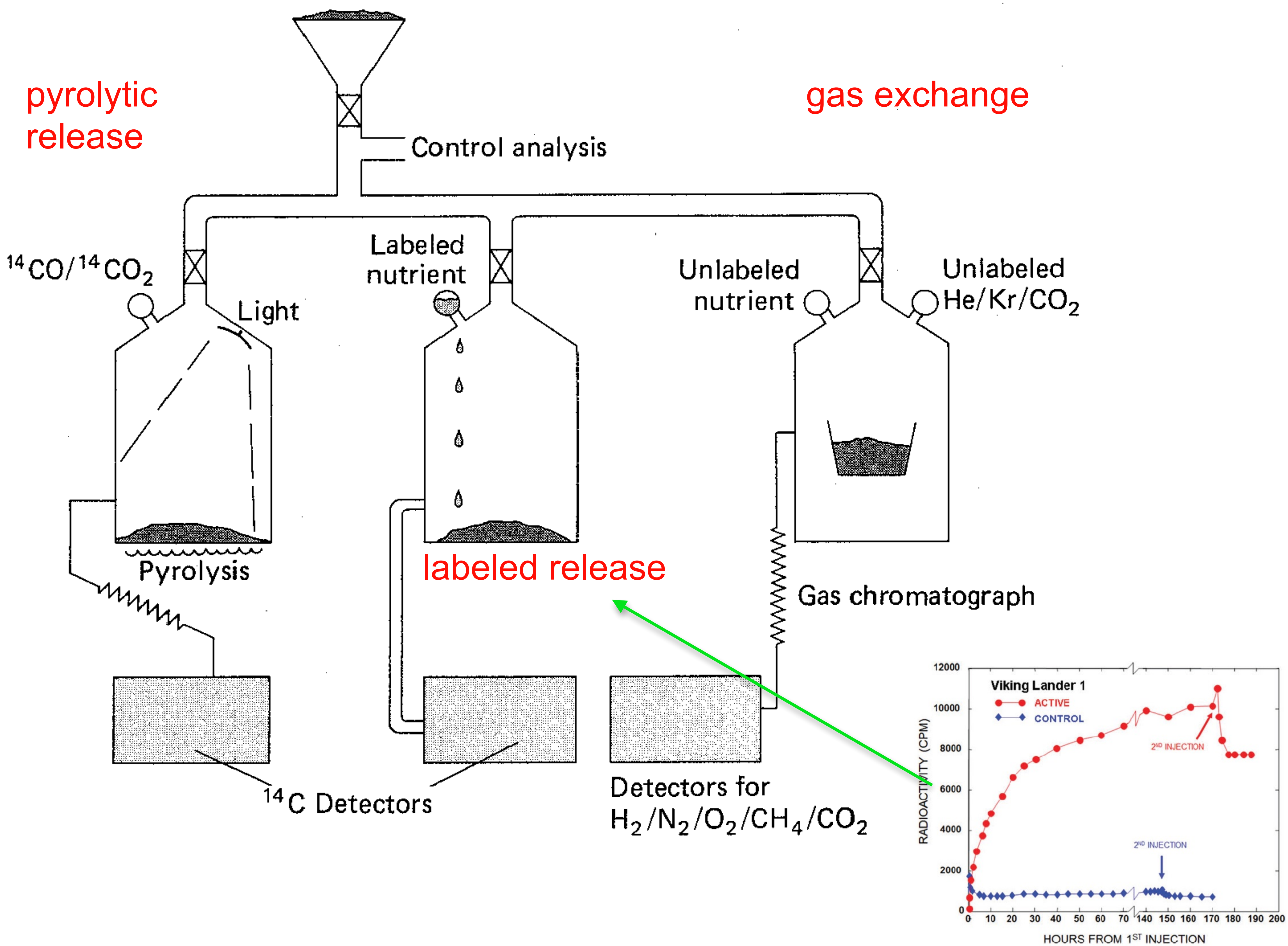
08.20.75: Launch
06.19.76: Arrival at Mars
07.20.76: Mars Landing
08.07.80: End of Mission (Orbiter)
02.01.83: End of Mission (Lander)

Viking 2

09.09.75: Launch
08.07.76: Arrival at Mars
09.03.76: Mars Landing
07.24.78: End of Mission (Orbiter)
04.12.80: End of Mission (Lander)

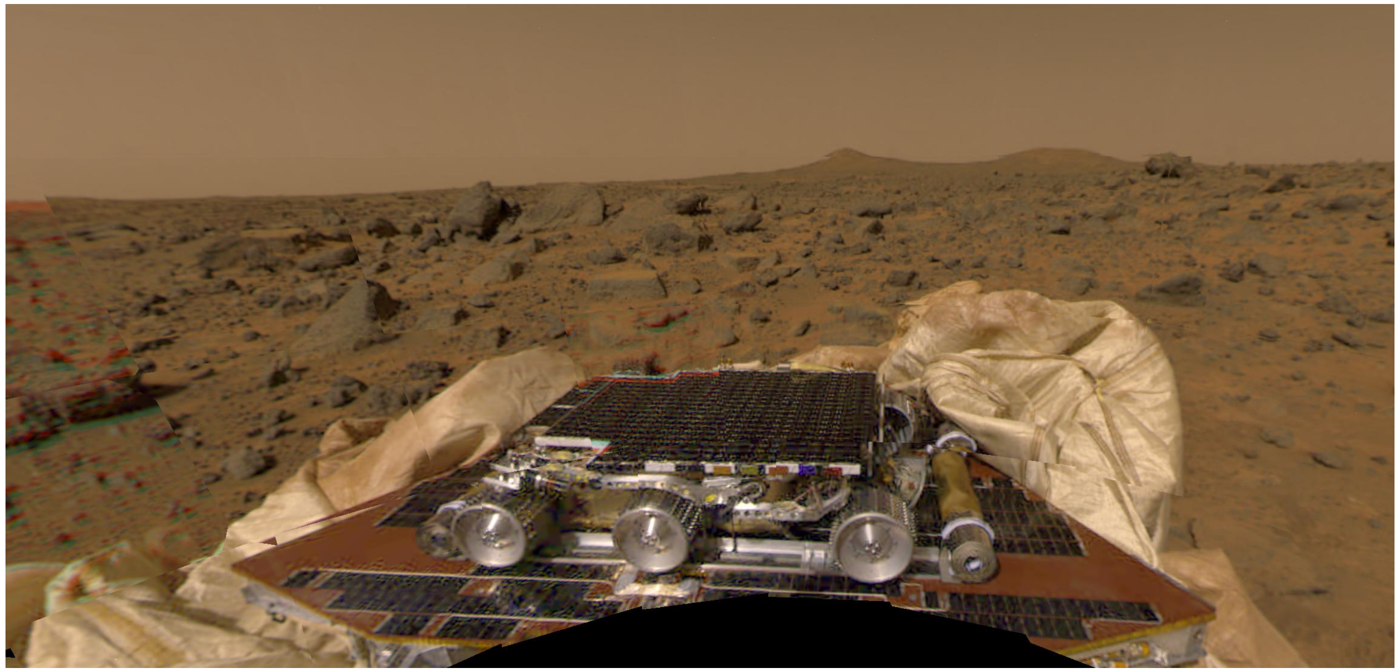


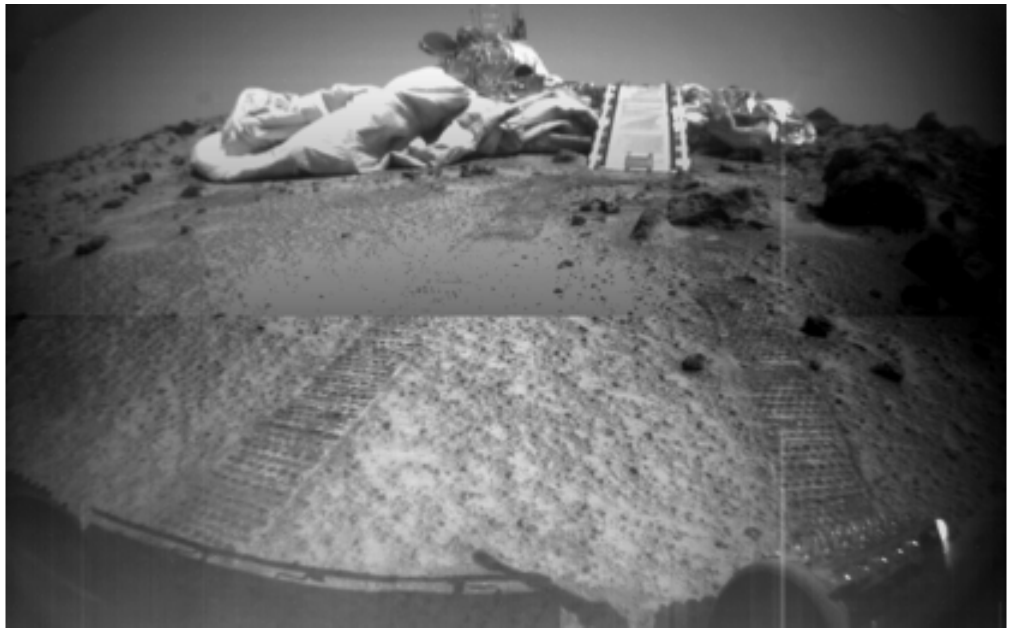
Biology Experiments - search for *biological activity*



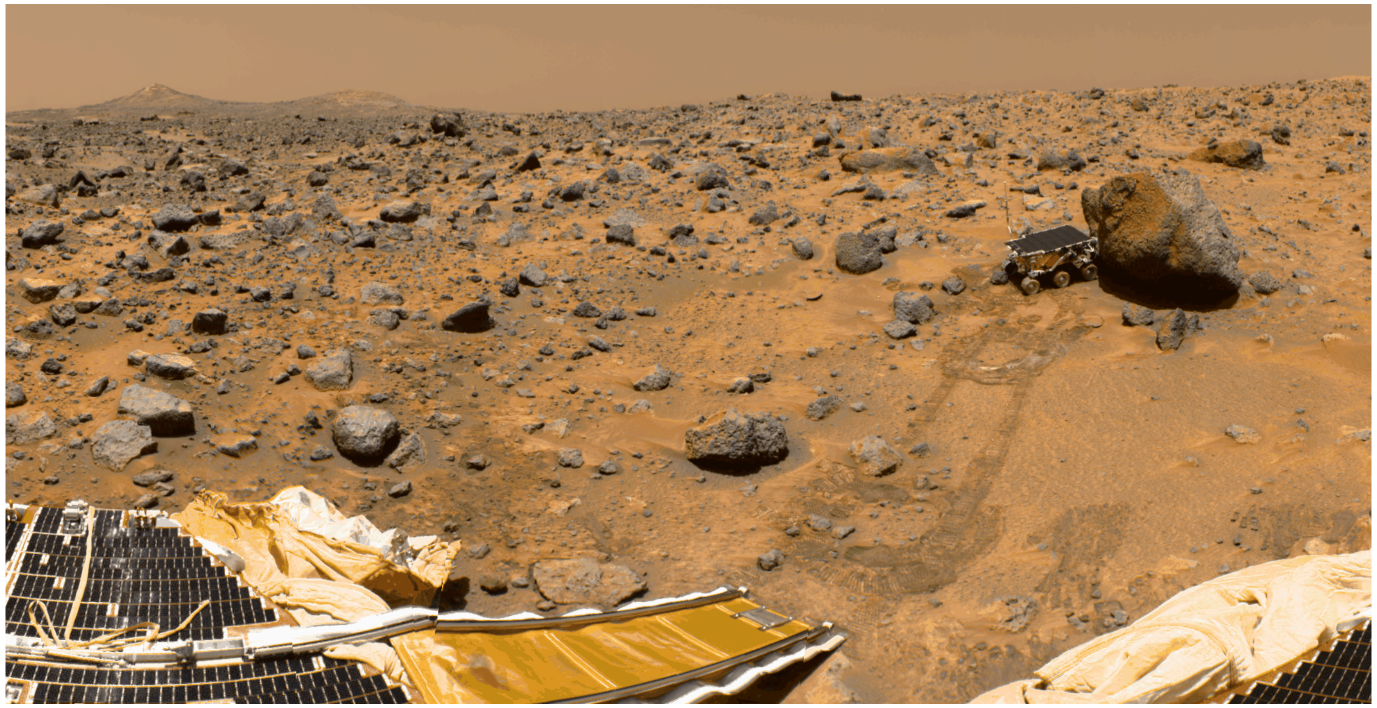
Mars Pathfinder - the first roving vehicle to visit Mars, but not the last!

Landed in Ares Vallis, where flowing water would deposit a variety of rock types

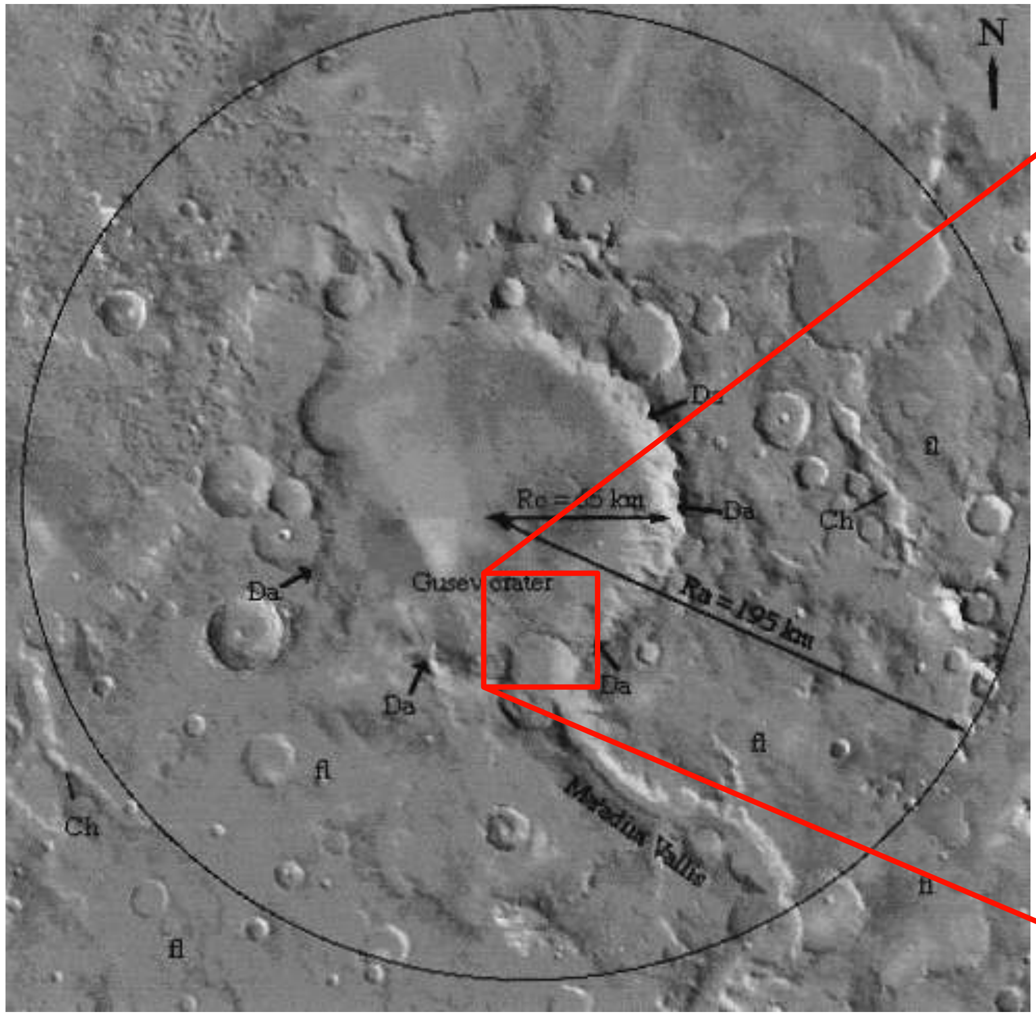


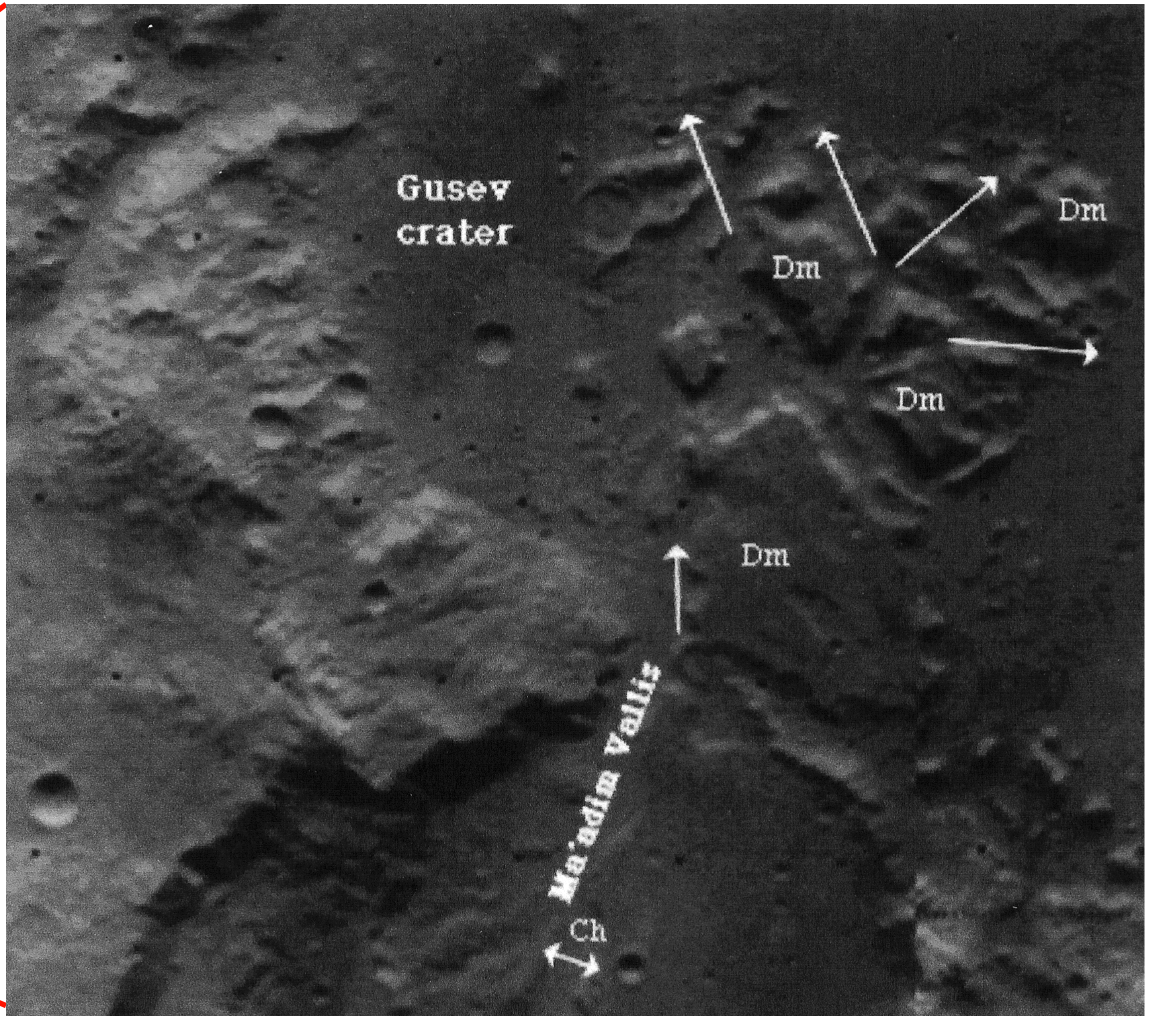


Carl Sagan Memorial Station, as seen by rover Sojourner



Site Selection

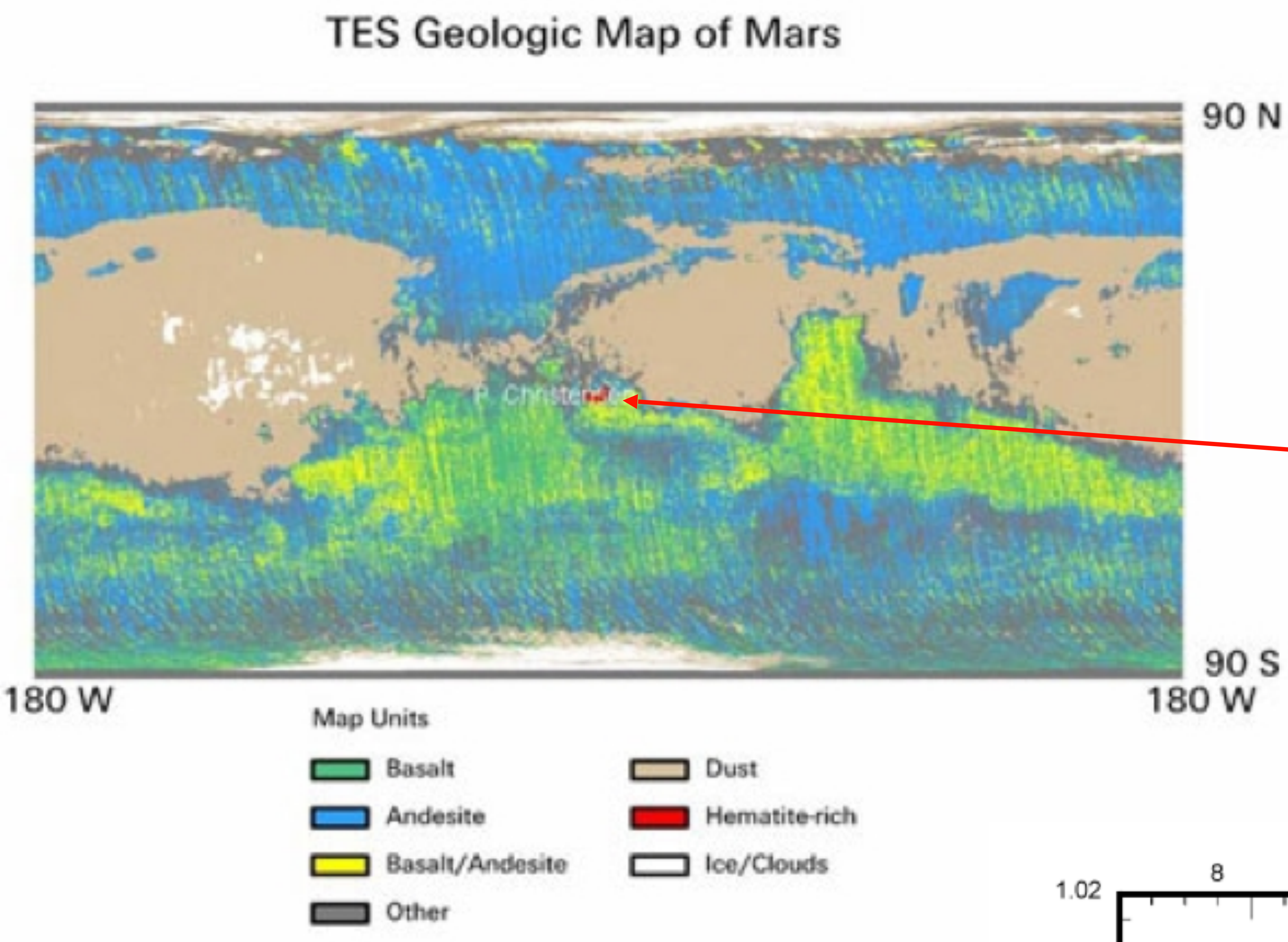


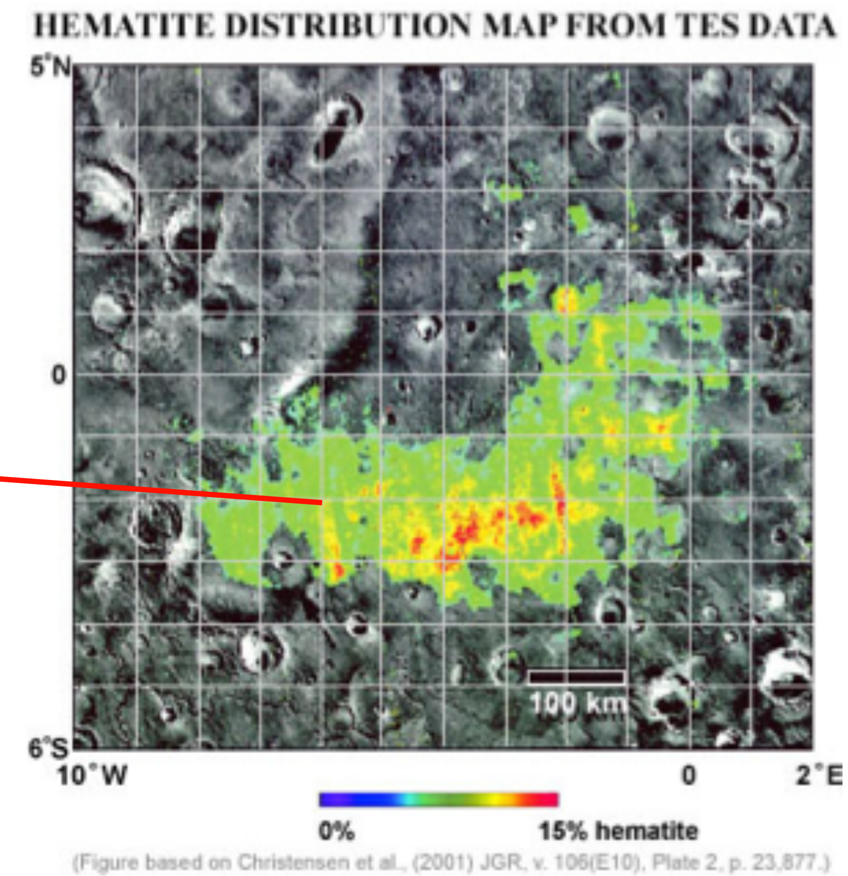


Gusev Crater - *physical* signs of water

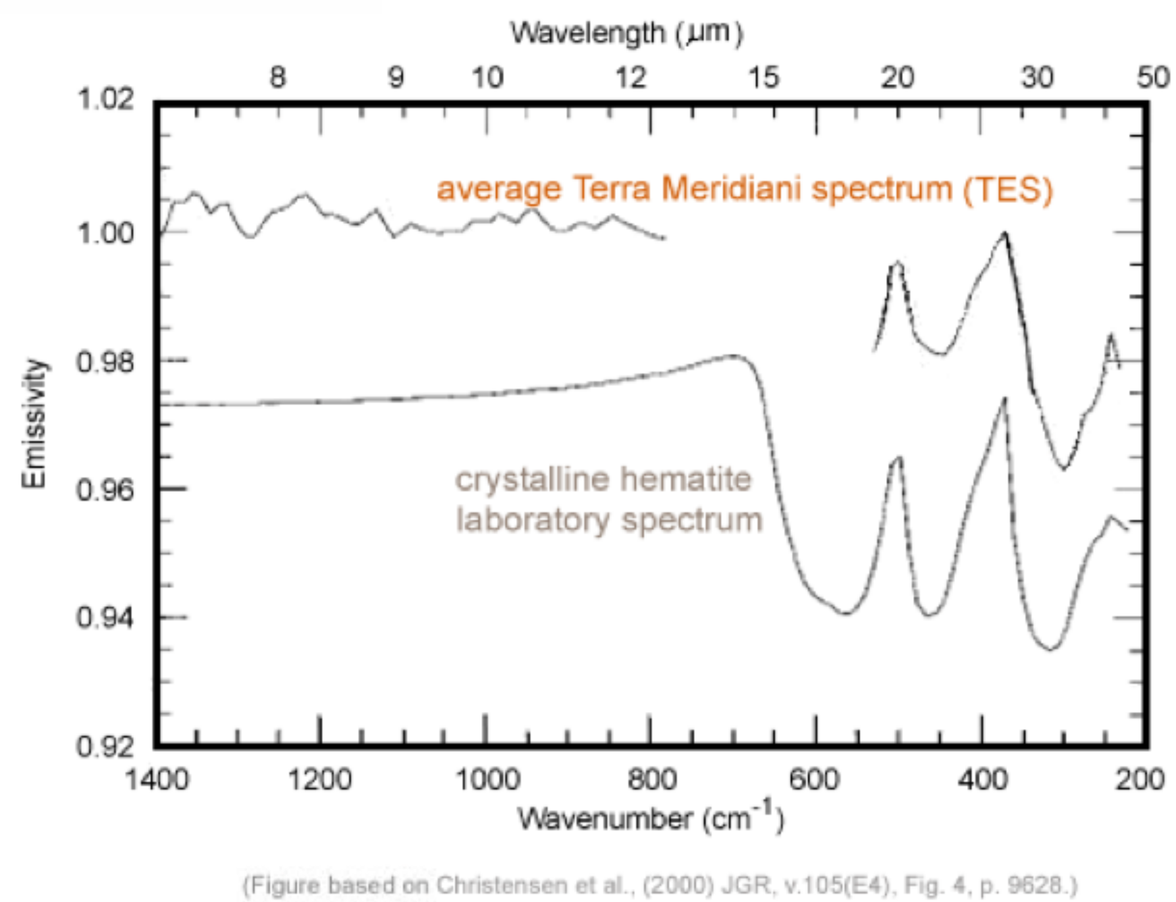
Target for “Spirit”

MER (and most other images) Courtesy NASA/JPL-Caltech

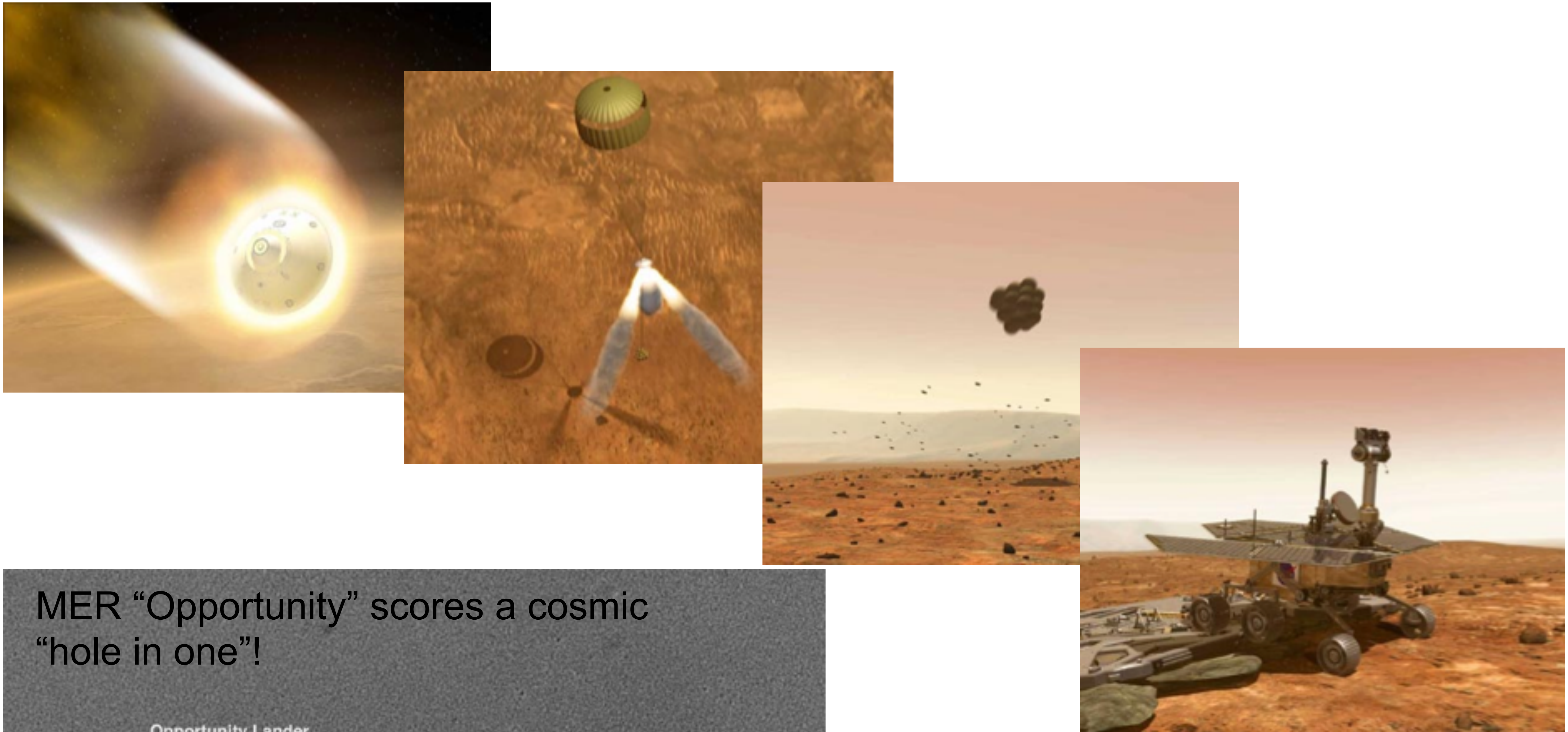




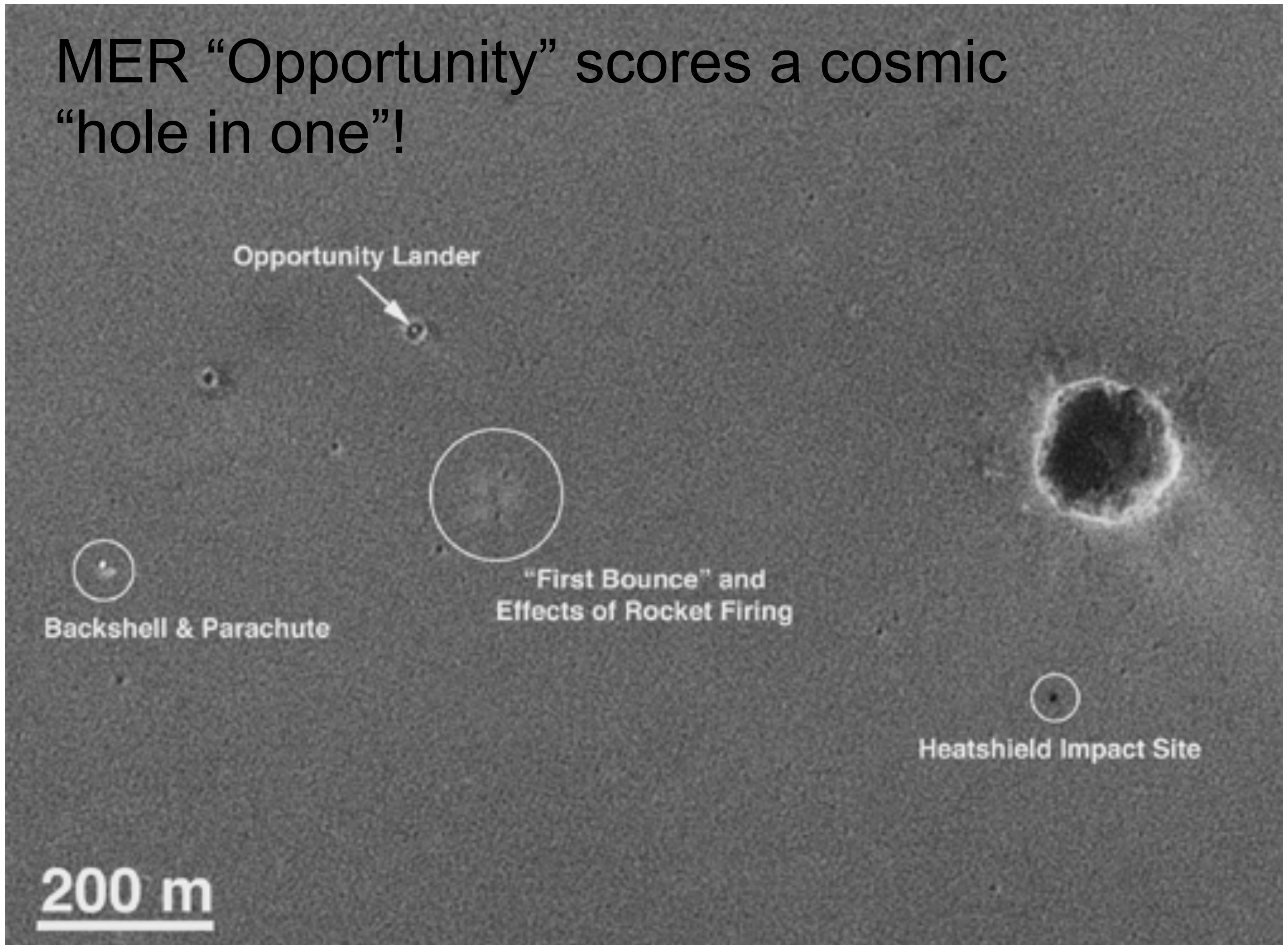
Meridiani Planum - *chemical* signs of water - **<u>hematite</u> *usually* forms in water**



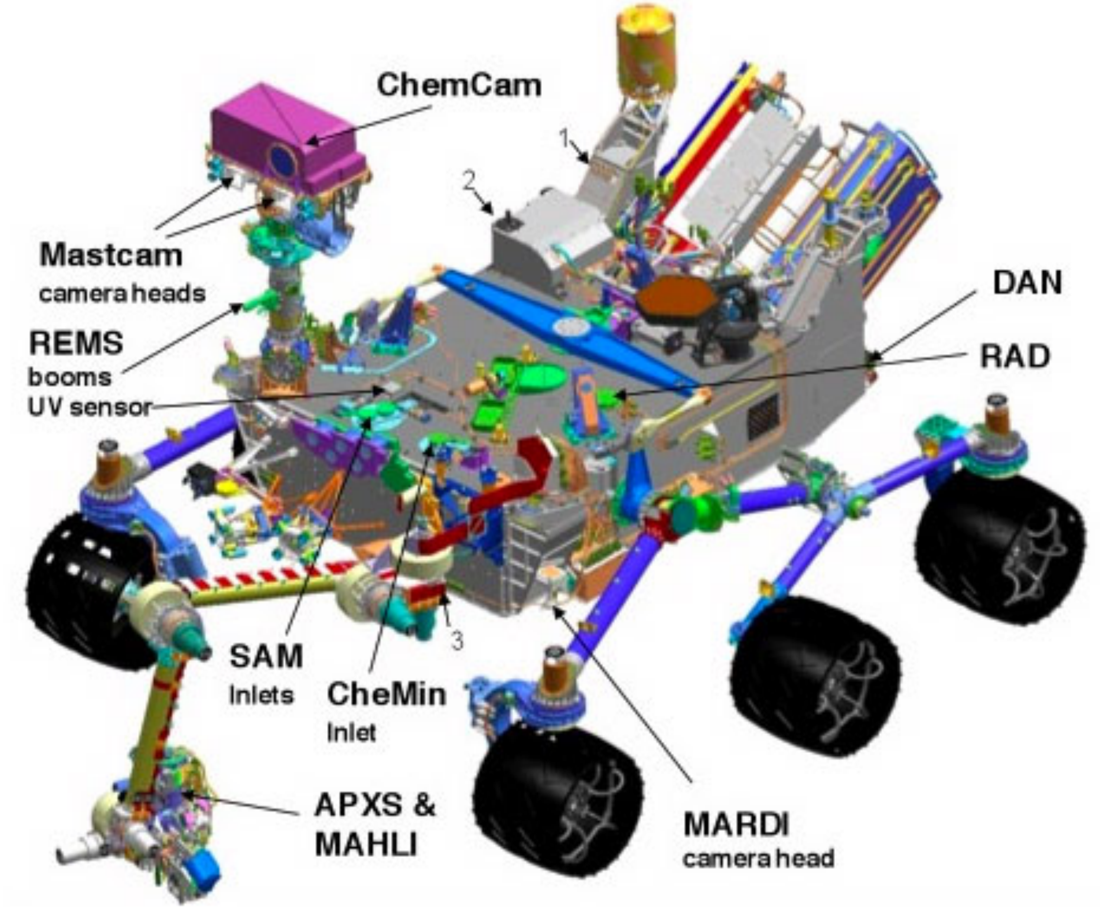
Target for "Opportunity"

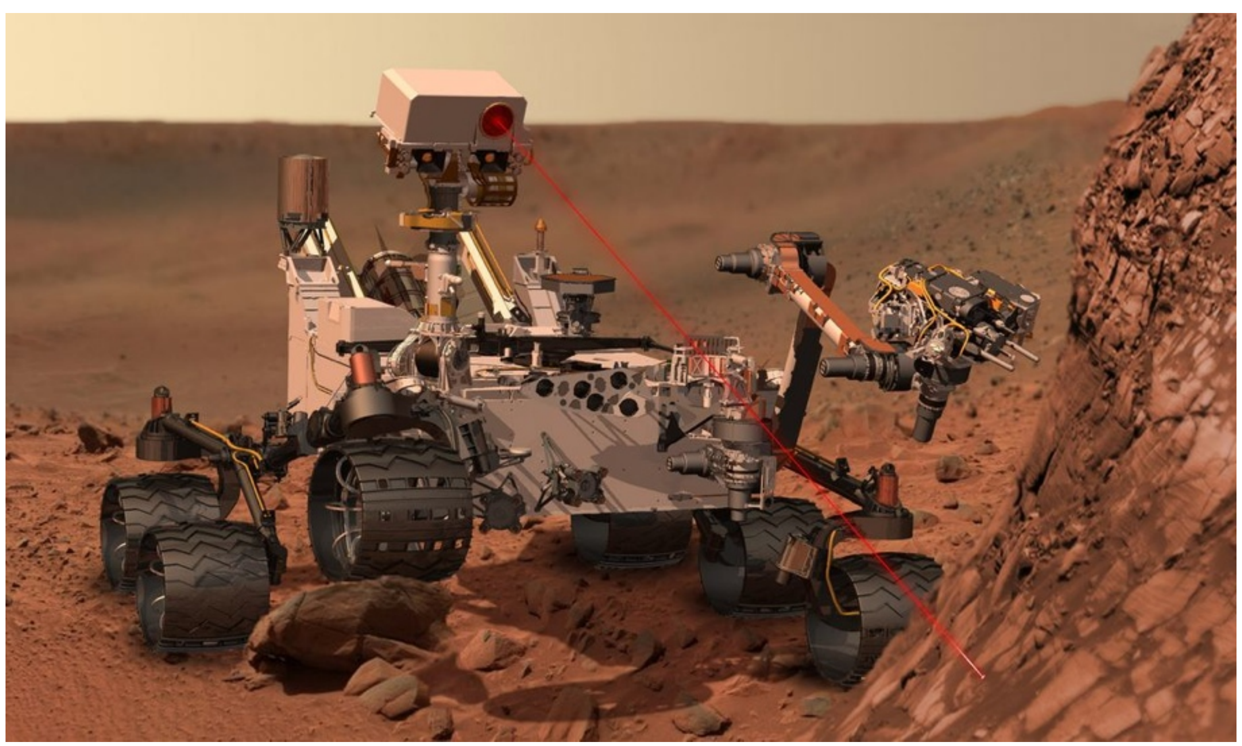


MER “Opportunity” scores a cosmic “hole in one”!



Mars Science Laboratory "Curiosity" lands on Mars August 2012





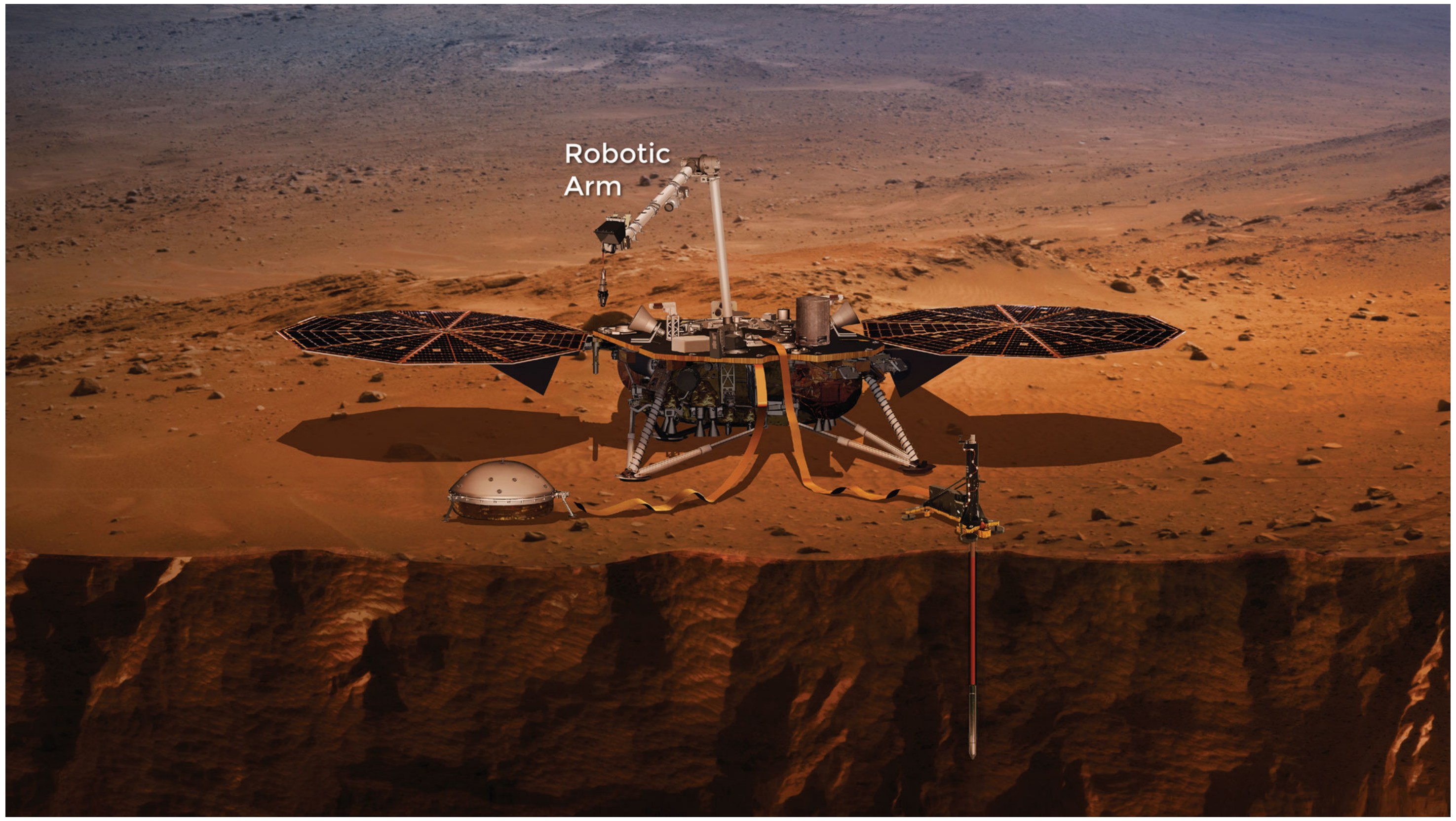
Landed using a "Sky Crane"!!

NASA's InSight
https://mars.nasa.gov/insight/

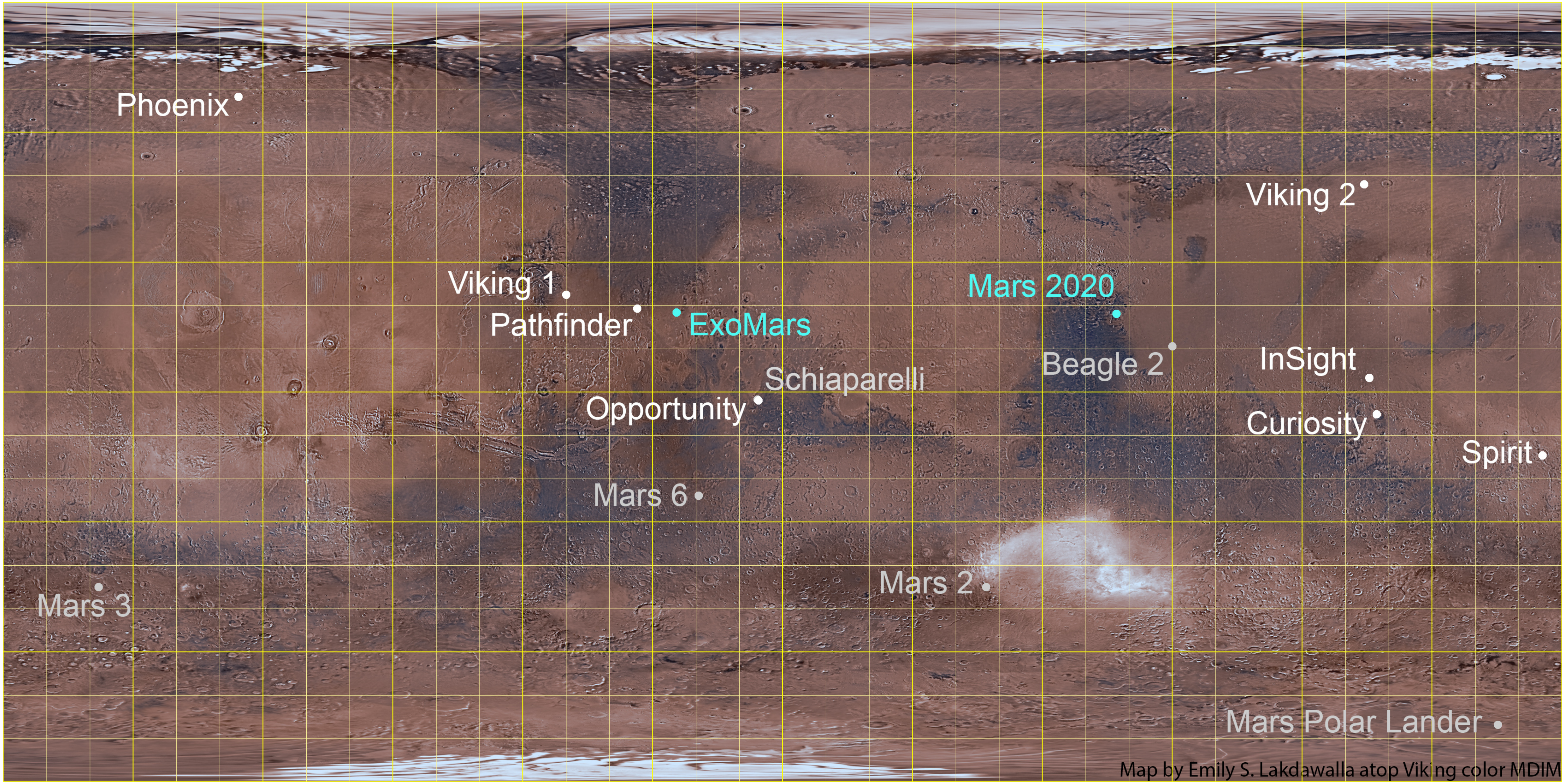
2 Main Goals:

Measure "Marsquakes"

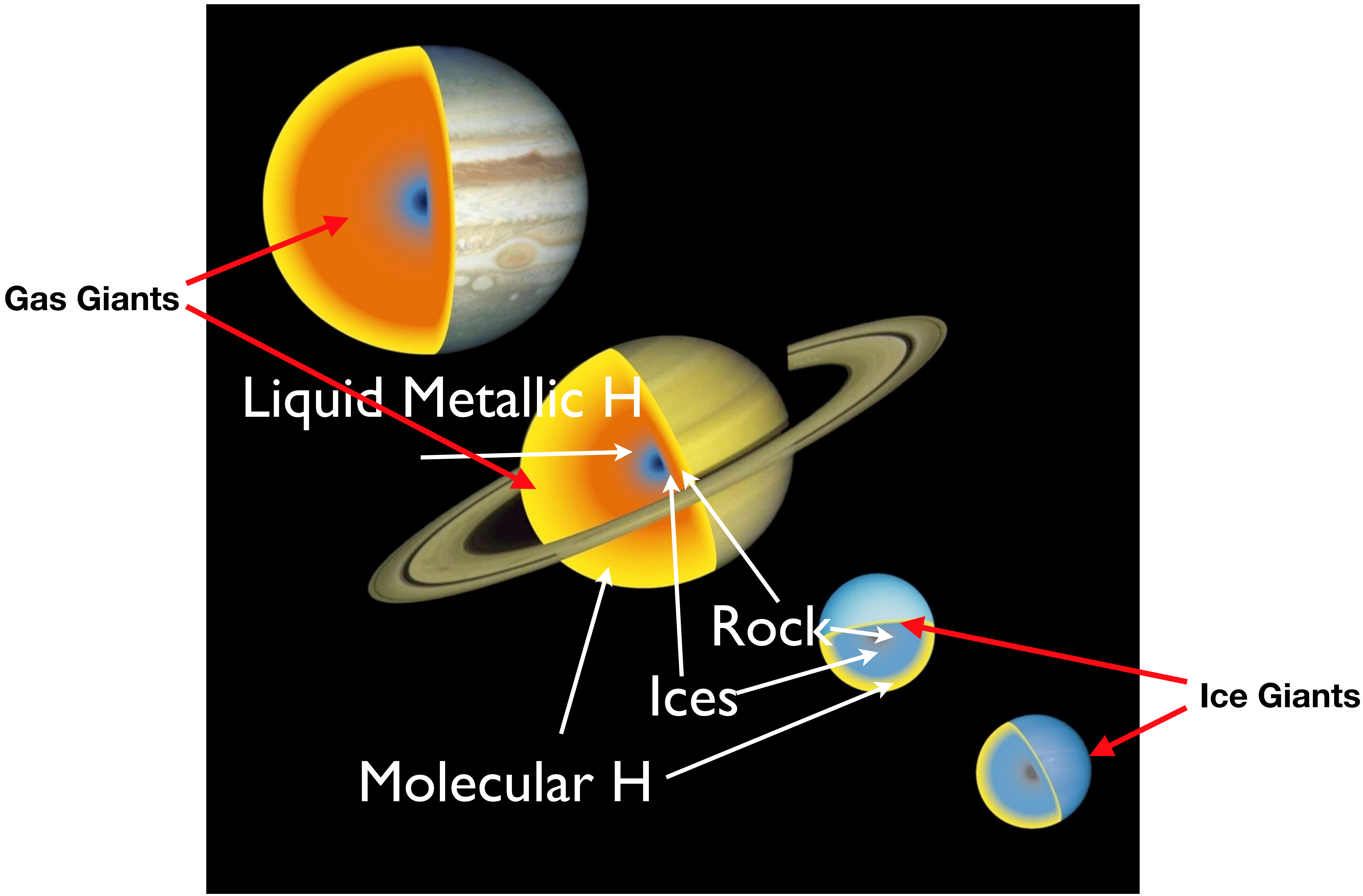
Measure heat flow



Past & Future Landing Sites

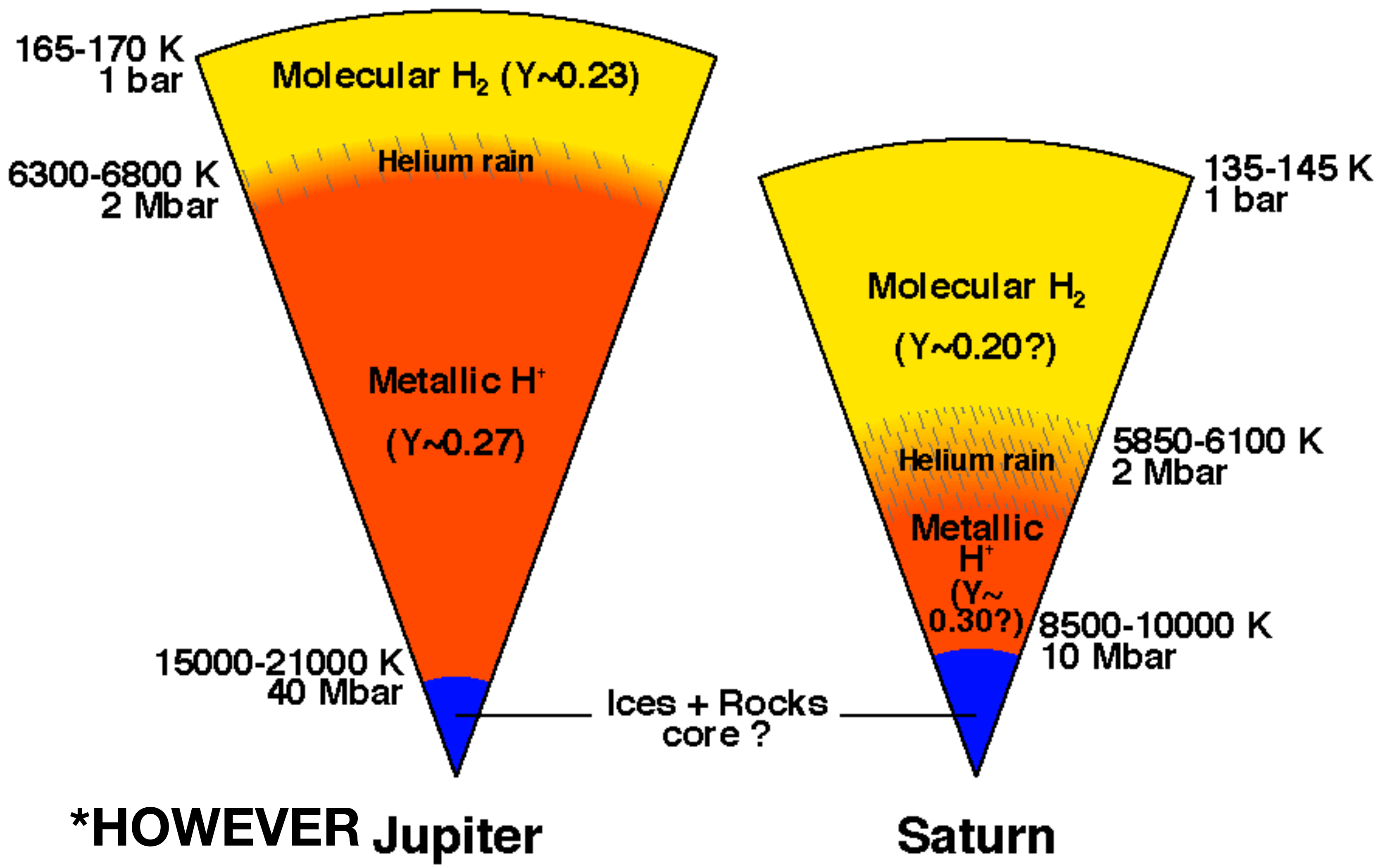


ExoMars (2020) will be a semi-autonomous rover
Mars 2020 is a rover with a helicopter



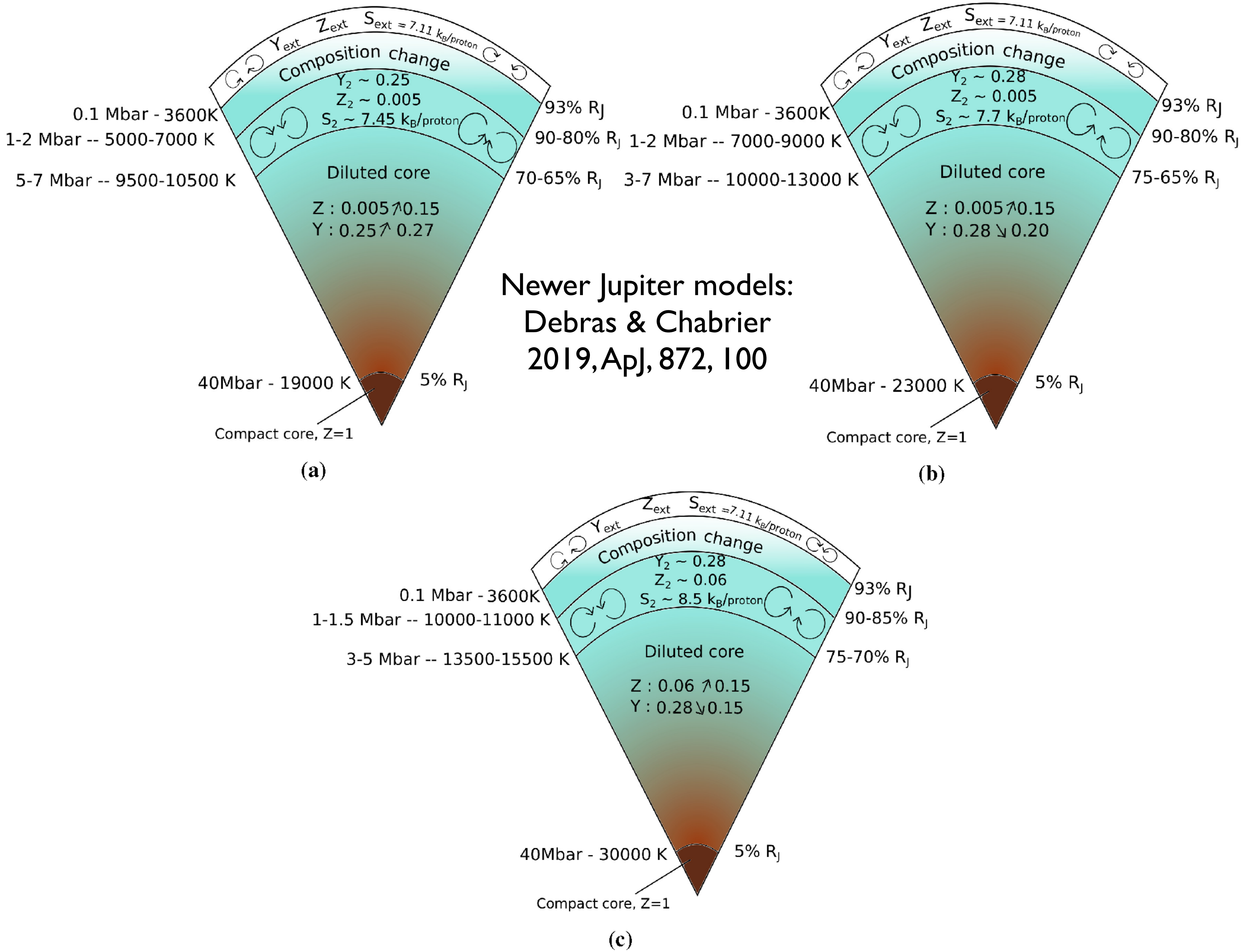
Interiors of Jovian Planets

Interior Conditions



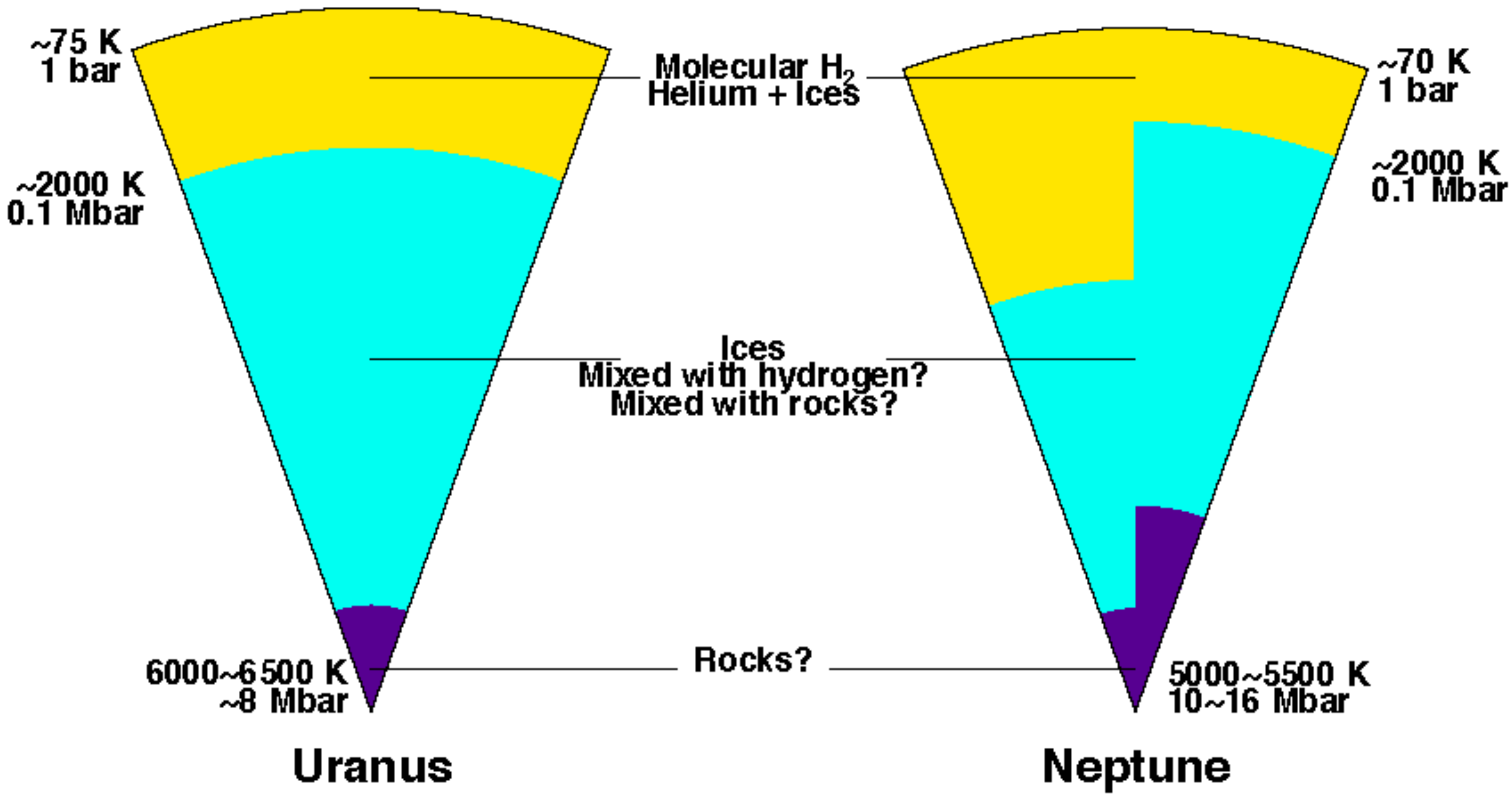
Schematic representation of the interiors of Jupiter and Saturn. The range of temperatures is estimated using homogeneous models and including a possible radiative zone indicated by the hashed regions. Helium mass mixing ratios Y are indicated. The size of the central rock and ice cores of Jupiter and Saturn is very uncertain (see text). In the case of Saturn, the inhomogeneous region may extend down all the way to the core which would imply the formation of a helium core.

from Guillot & Gautier 2015, Treatise on Geophysics, 2nd Ed.



Newer Jupiter models:
Debras & Chabrier
2019, ApJ, 872, 100
Yext Zext Sext = 7.11 kB/proton
Composition change
Y2 ~ 0.25
Z2 ~ 0.005
S2 ~ 7.45 kB/proton
Diluted core
Z : 0.005 ↗ 0.15
Y : 0.25 ↗ 0.27
0.1 Mbar - 3600K
1-2 Mbar -- 5000-7000 K
5-7 Mbar -- 9500-10500 K
40Mbar - 19000 K
93% RJ
90-80% RJ
70-65% RJ
5% RJ
Compact core, Z=1
(a)
Yext Zext Sext = 7.11 kB/proton
Composition change
Y2 ~ 0.28
Z2 ~ 0.005
S2 ~ 7.7 kB/proton
Diluted core
Z : 0.005 ↗ 0.15
Y : 0.28 ↘ 0.20
0.1 Mbar - 3600K
1-2 Mbar -- 7000-9000 K
3-7 Mbar -- 10000-13000 K
40Mbar - 23000 K
93% RJ
90-80% RJ
75-65% RJ
5% RJ
Compact core, Z=1
(b)
Yext Zext Sext = 7.11 kB/proton
Composition change
Y2 ~ 0.28
Z2 ~ 0.06
S2 ~ 8.5 kB/proton
Diluted core
Z : 0.06 ↗ 0.15
Y : 0.28 ↘ 0.15
0.1 Mbar - 3600K
1-1.5 Mbar -- 10000-11000 K
3-5 Mbar -- 13500-15500 K
40Mbar - 30000 K
93% RJ
90-85% RJ
75-70% RJ
5% RJ
Compact core, Z=1
(c)

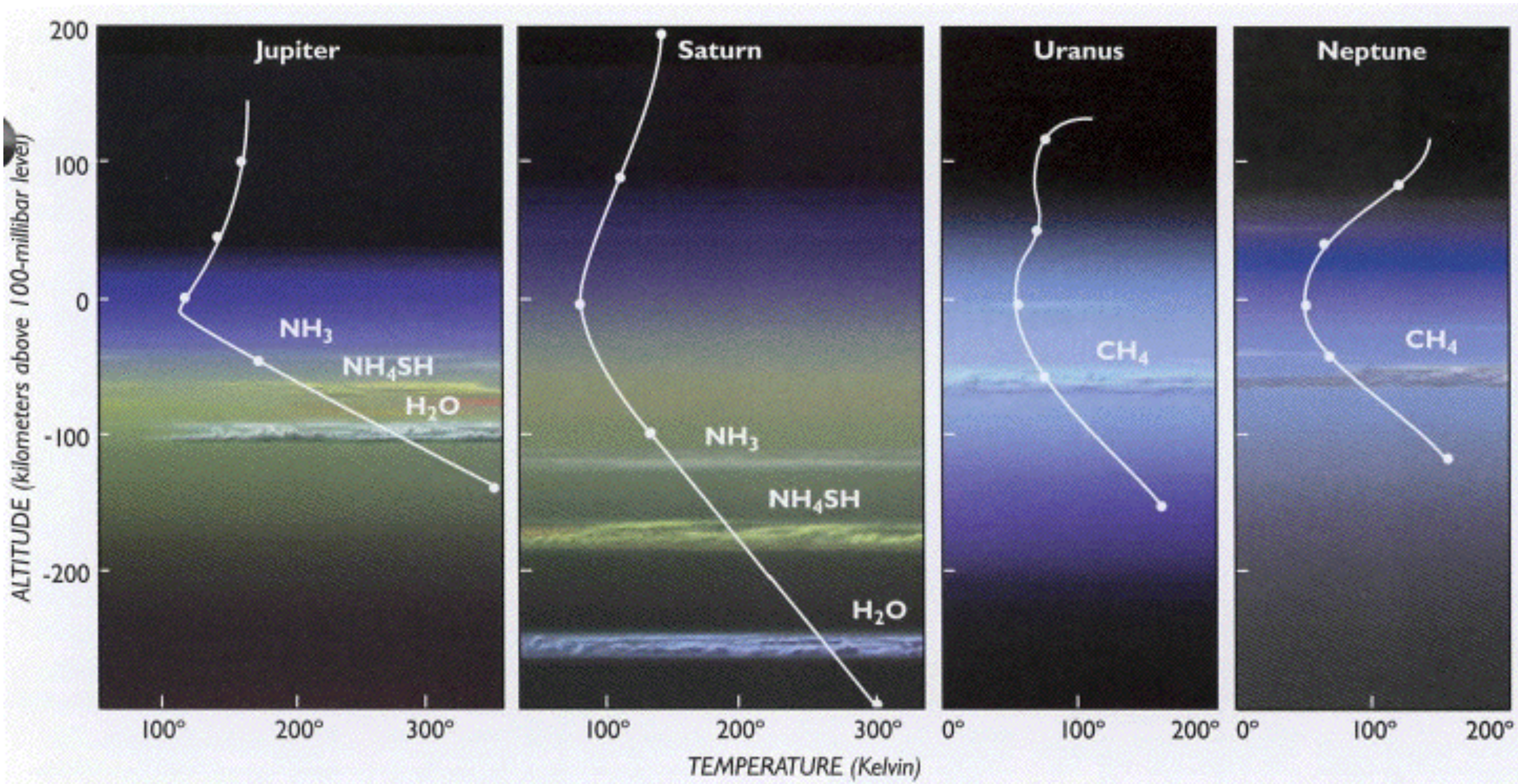
Yes, solutions are not unique for Uranus & Neptune, either.



Schematic representation of the interiors of Uranus and Neptune. The ensemble of possibilities for Neptune is larger. Two possible structures are shown.

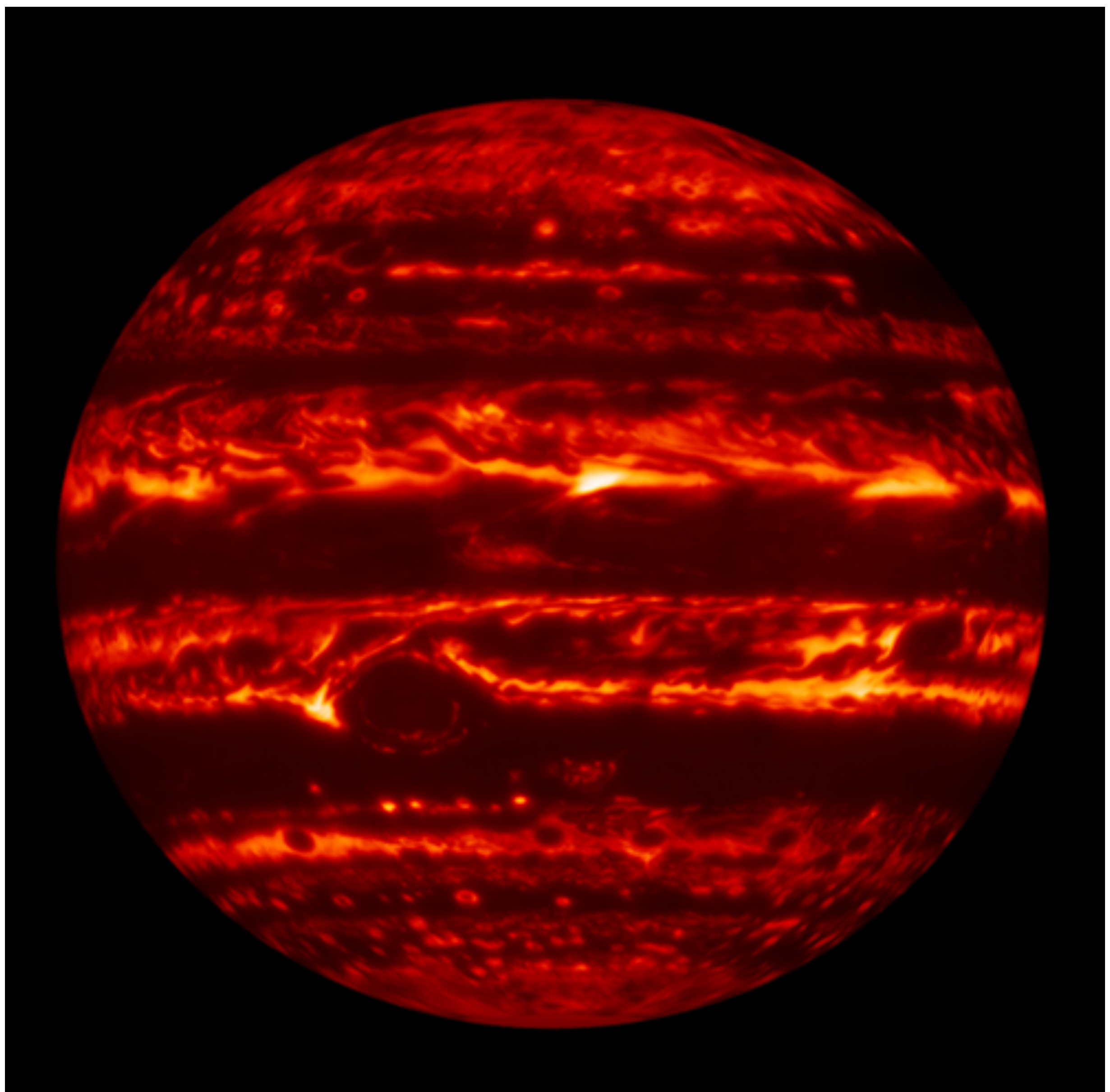
from Guillot & Gautier 2015, Treatise on Geophysics, 2nd Ed.

Outward appearances are determined by the run of temperature and pressure in their outer atmospheres



Predicted cloud compositions: H_2O deep, NH_4SH medium, and NH_3 high.

IR Emission Correlates with Depth



Cold

Warm

Cold

Warm

Cold

Infrared Excesses

- J, S, N emit significantly more energy that they receive from the Sun!
- Tail-end of formation/contraction process is still converting GPE into TE and leaking it into space.
- Saturn requires an additional source, probably He raining out of *LMH* layer.
- Uranus is a heat-wimp.

We will return to this later, when looking at their outer appearances - atmospheres.