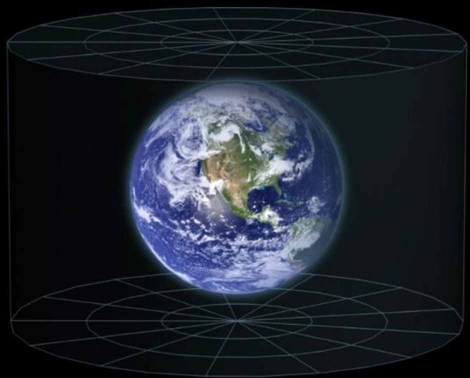
The Solar System
Origin and diversity of the planets

Our place in the Universe

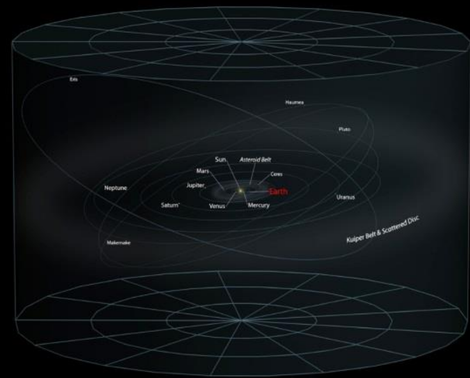
1 light-year = ~10 trillion km (10 10^{12} km)

EARTH



Earth diam.
13 10^3 km

OUR SOLAR SYSTEM

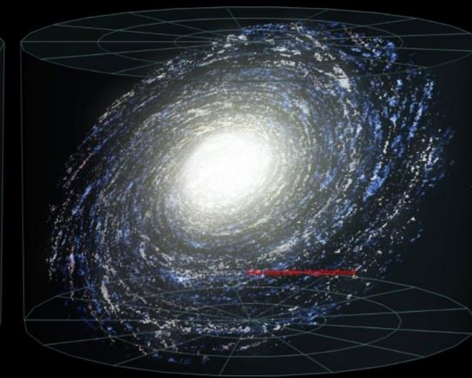


Dist. Earth-Sun
148 10^6 km
(17th century)

SOLAR INTERSTELLAR NEIGHBOURHOOD

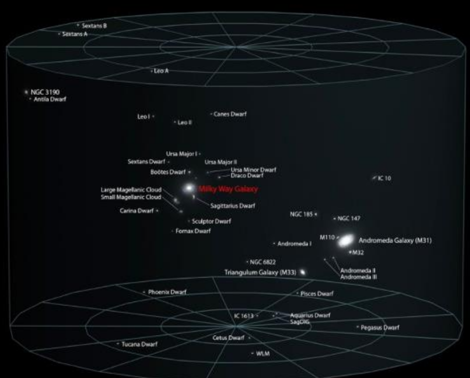
Dist. Earth-closest star
40 10^{12} km
(4 light-years) (19th century)

MILKY WAY GALAXY (~100 billion stars)



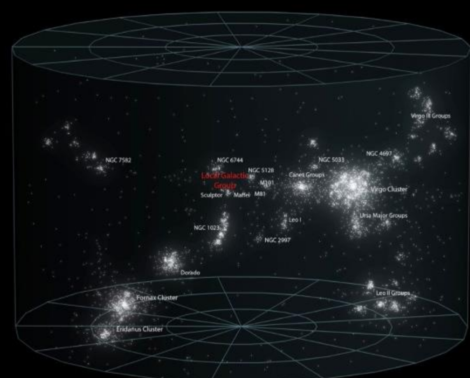
Milky Way diam.
10^{18} km
(10^5 light-years)

LOCAL GALACTIC GROUP

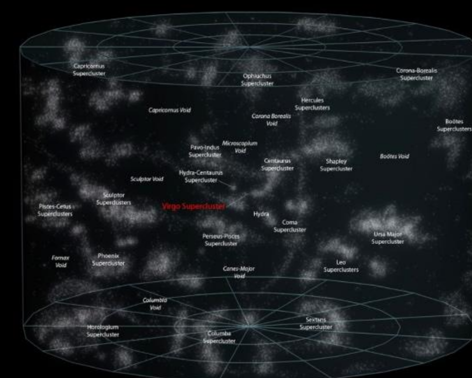


Dist. to nearest galaxy
2.5 10^6 l.-y.

VIRGO SUPERCLUSTER

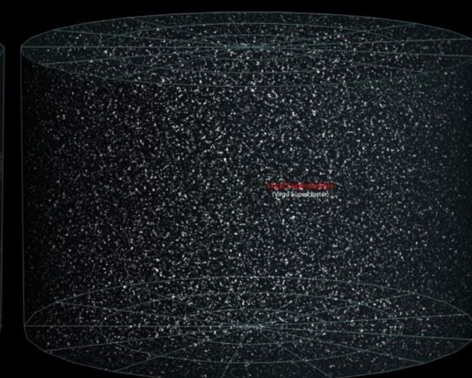


LOCAL SUPERCLUSTERS



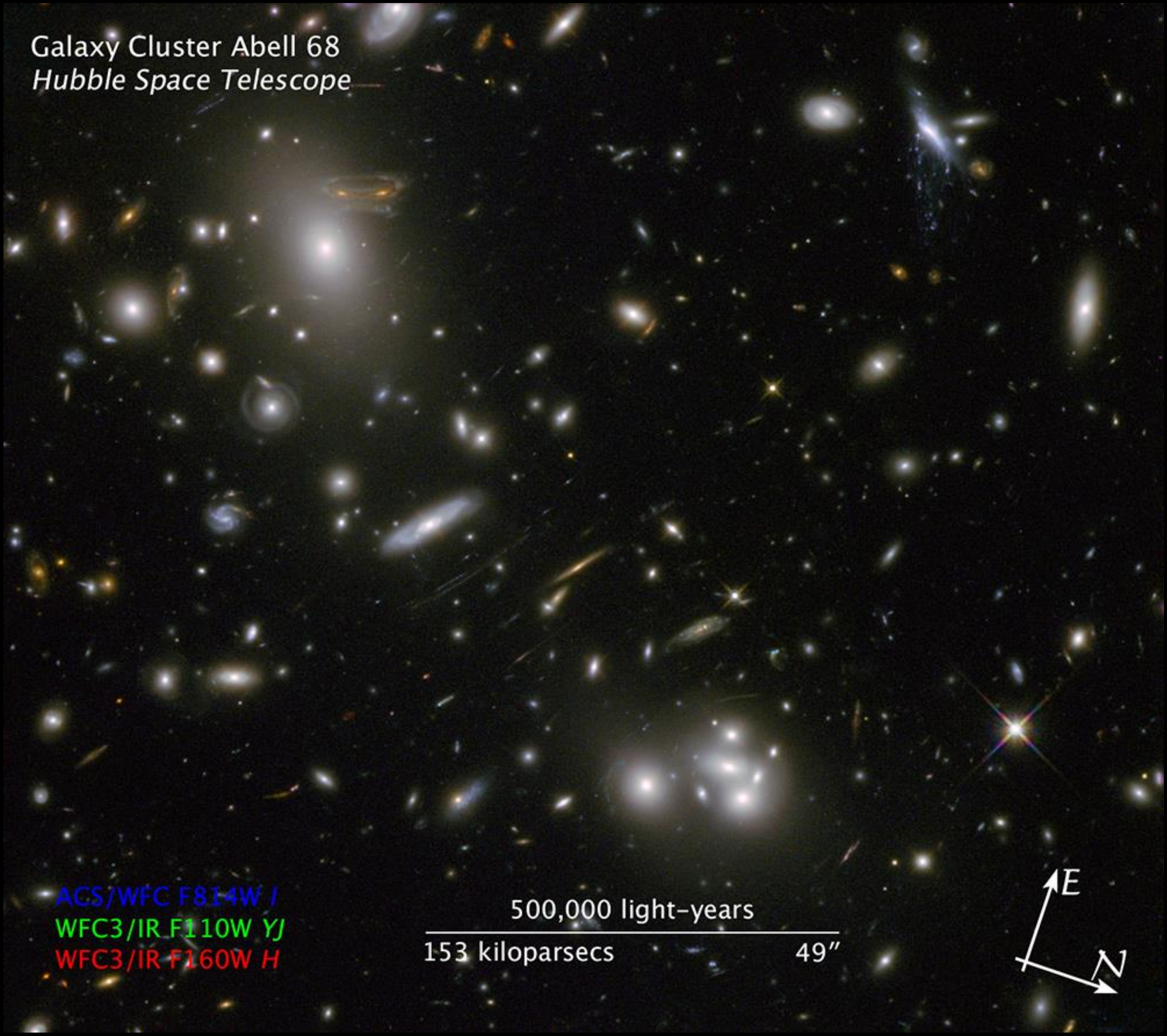
Dist. to nearest supercluster
300 10^6 l.-y.

OBSERVABLE UNIVERSE



Farthest galaxy observed
is 13.2 10^9 l.-y. away

wikipedia


Galaxy Cluster Abell 68
Hubble Space Telescope
ACS/WFC F814W I
WFC3/IR F110W YJ
WFC3/IR F160W H
500,000 light-years
153 kiloparsecs
49″
E
N

NASA

Our Solar System

INNER PLANETS
(TERRESTRIAL/ROCKY PLANETS)

OUTER PLANETS (GIANT PLANETS)

GAS GIANTS (mostly H, He)

"ICE*" GIANTS

* Made of elements heavier than H and He (e.g., O, C → H_2O, CH_4)

PLANETS

DWARF PLANETS

ASTEROID BELT

CERES: THE ONLY DWARF PLANET OF THE ASTEROID BELT

KUYPER BELT

* Kuyper Belt Objects (KBOs) or Trans-Neptunian Objects (TNOs)
KBOs are concentrated around 40 Au from the Sun

Age of the Universe:
13.7 billion years

Age of the Solar System
4.56 billion years

Objects of the Asteroid Belt are rich in silicate minerals and metals
Objects of the Kuyper Belt are rich in ices (source of comets)

Image by NASA

Planets and dwarf planets

MERCURY

2440 km
(radius)

VENUS

6052 km

EARTH *(Moon: 1737 km)*

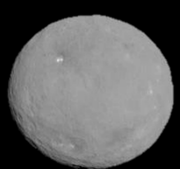
6378 km

MARS

3388 km

Images by NASA

Ceres



475 km

Pluto

1160 km

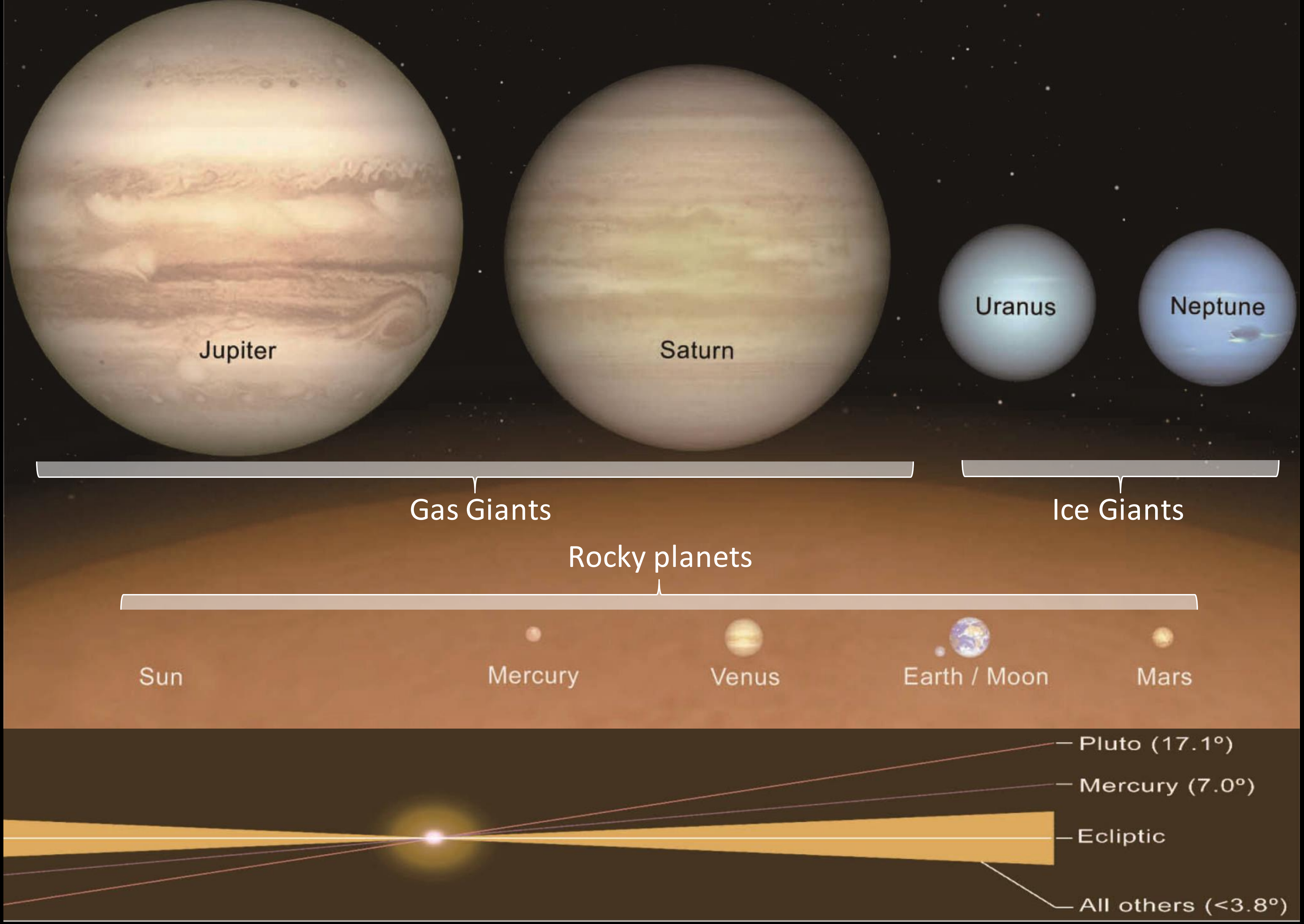
- A dwarf planet is an object:
  - in orbit around the Sun
  - with a rounded shape (gravity –mass– high enough to give it a rounded shape)
  - with a gravitational field too weak to have cleared its orbit; shares its orbit with objects of same size
  - that is not a satellite

Resolution B5 of the International Astronomical Union (2006)

NB: The dwarf planet Eris has a radius of 1163 km

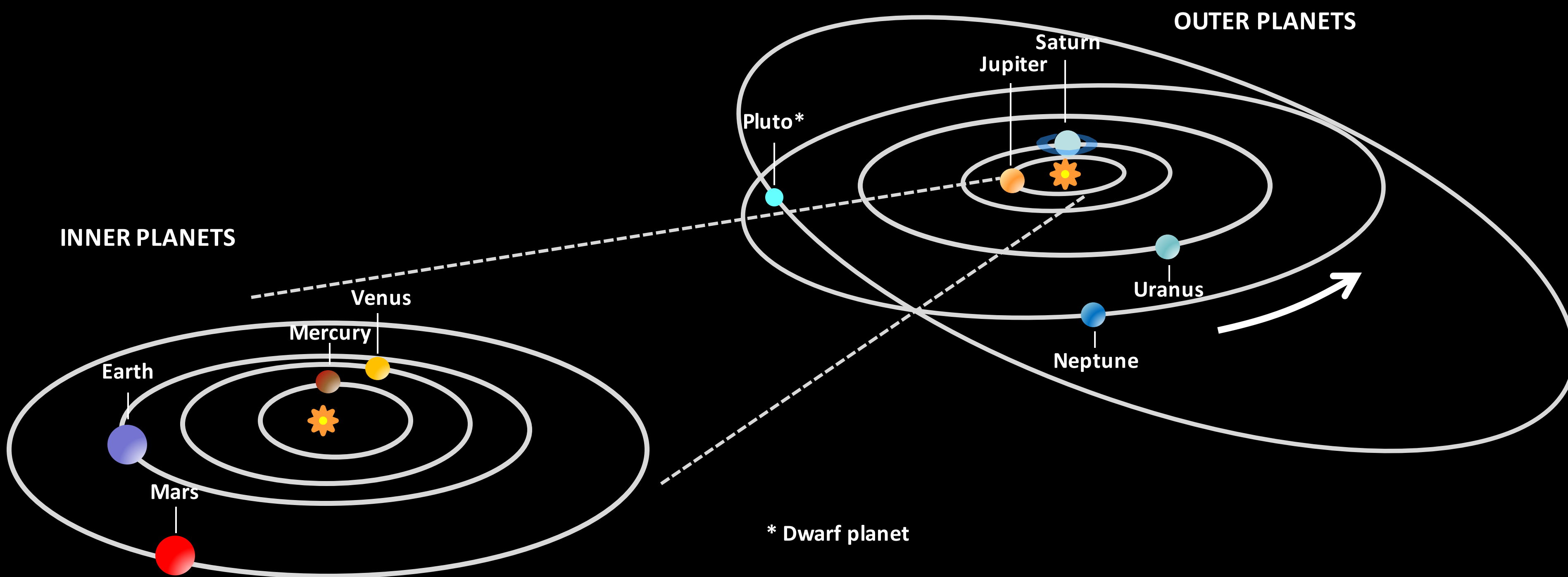
Asteroids are relatively small and have an irregular shape (radius < 200-300 km)

NASA



Mark A. Garlick 2002, The Story of the Solar System

What the model should explain



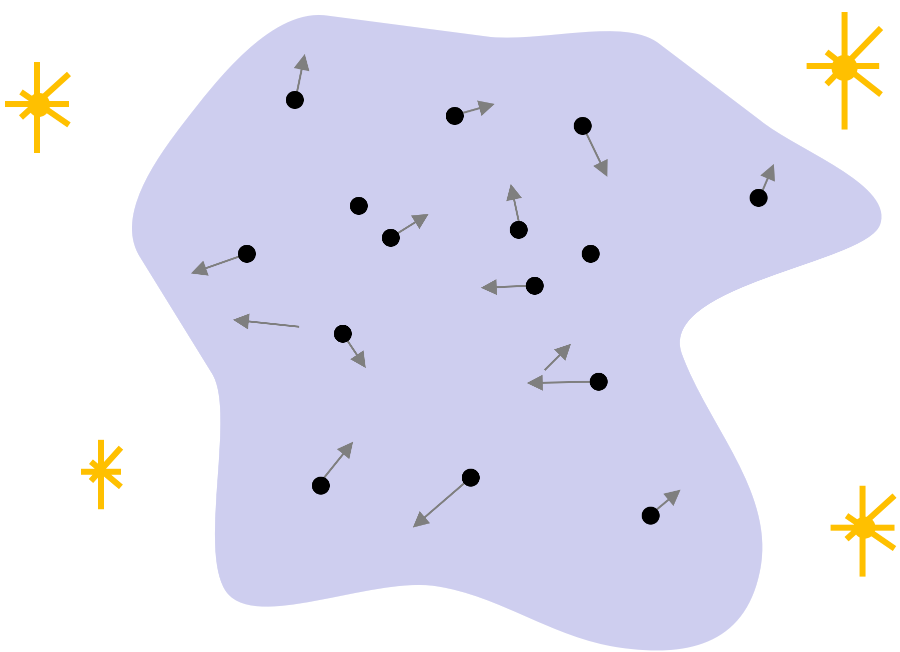
- Planets orbits the Sun in the same prograde direction (prograde = same direction as Sun's rotation)*
- Planetary orbits are nearly circular
- Planetary orbits lie in (or near) the equatorial plane of the Sun
- Inner planets (M, V, E, M) are small, dense, rocky (+ Fe)
- Outer planets (J, S, U, N) are large, made of gases (H, He) and ices
  J, S: mostly H, He   U,N: melted ices and rock

NB: prograde rotation except Venus (+ Uranus and Pluto with large tilts > 90 º)

* Counterclockwise (as seen from "above" ecliptic plane)

The nebular hypothesis Immanuel Kant (1724-1804) – Pierre Simon Laplace (1749-1827)

"The Sun and planets formed out of a single collapsing, rotating cloud of interstellar gas and dust, called a solar nebula." from Lang (2011), Cambridge Guide to the Solar System

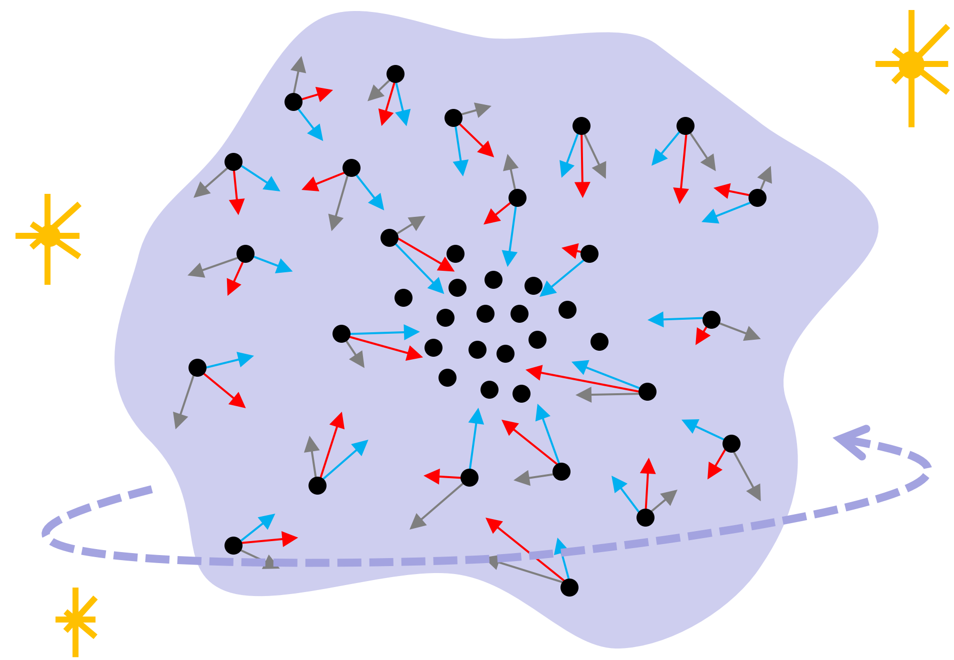


1. Could of gas (H_2, He) and dust (metal, rock, ice) = nebula

Initial velocity of particles

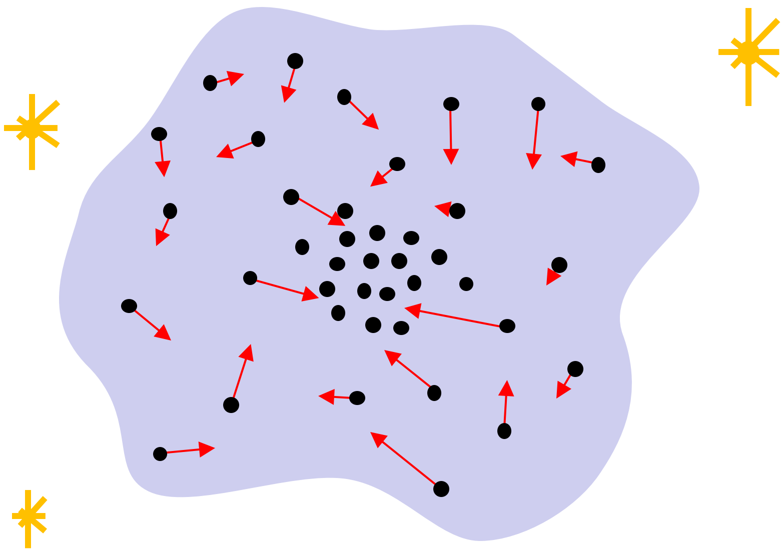
2. A denser region of the cloud attract surrounding matter

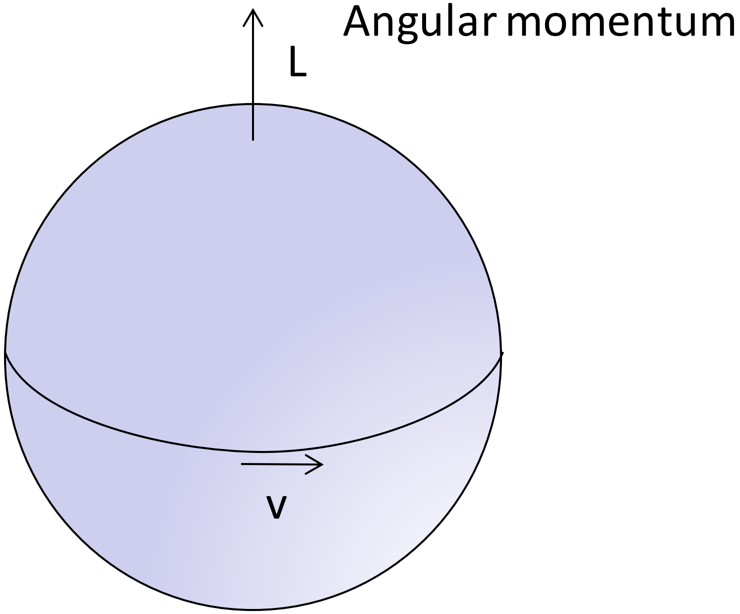
Gravitational pull



Matter is attracted toward the center and the average motion of all particles gives rise to a slow rotation of the cloud (with matter moving faster near the center)

Due to the gravitational attraction of the denser region of the nebula, particles are slowly deviated toward that region. They move along a curved path toward the dense region of the cloud (path determined by their initial speed and the force of gravity). There is always more particles spiraling in one direction than in the other (unlikely to have exactly 50-50!). Due to collisions and friction, most particles will tend to move in the same direction after some time (either clockwise or anticlockwise). The resulting motion is therefore a slow rotation of the cloud that accelerates as the cloud collapse on itself due to gravity.





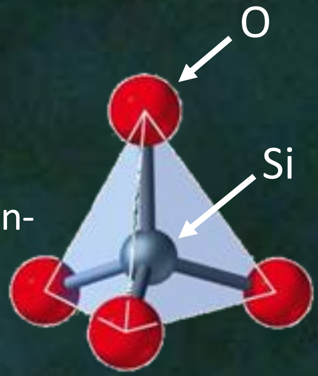
Eagle Nebula
(NASA, ESA, J. Hester, Hubble telescope)

Events can produce variations in density within interstellar clouds:

- Proximity of a massive star
- Shockwaves of a supernova explosion

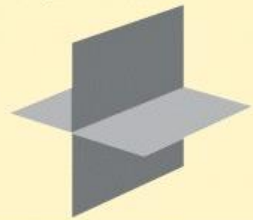
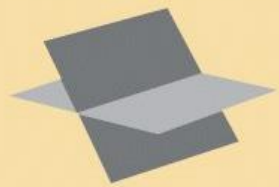
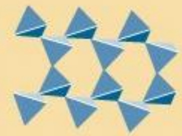
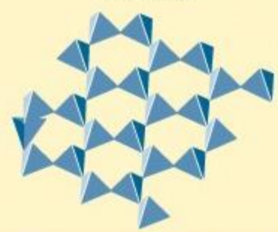
Dust particles rich in silicate minerals

Silicates are very common minerals on Earth. Their building blocks consist of silicon-oxygen tetrahedra



NB: One way to see dust clouds is to use telescopes which can detect the infrared radiation that dust particles emit.

Image by NASA

Mineral	Chemical formula	Cleavage planes and number of cleavage directions	Structure	Specimen
Olivine (a)	$(Mg,Fe)_2SiO_4$	1 plane 	Isolated tetrahedra 	
Pyroxene (b)	$(Mg,Fe)SiO_3$	2 planes at 90° 	Single chains 	
Amphibole (c)	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	2 planes at 60° and 120° 	Double chains 	
Mica (d)	Muscovite: $KAl_2(AlSi_3O_{10})(OH)_2$	1 plane 	Sheets 	
Feldspar (e)	Orthoclase feldspar: $KAlSi_3O_8$ Plagioclase feldspar: $(Ca,Na)\ AlSi_3O_8$	2 planes at 90° 	Three-dimensional frameworks 	

Understanding Earth

Image of the Eagle Nebula taken by Hubble ("pillars of creation")

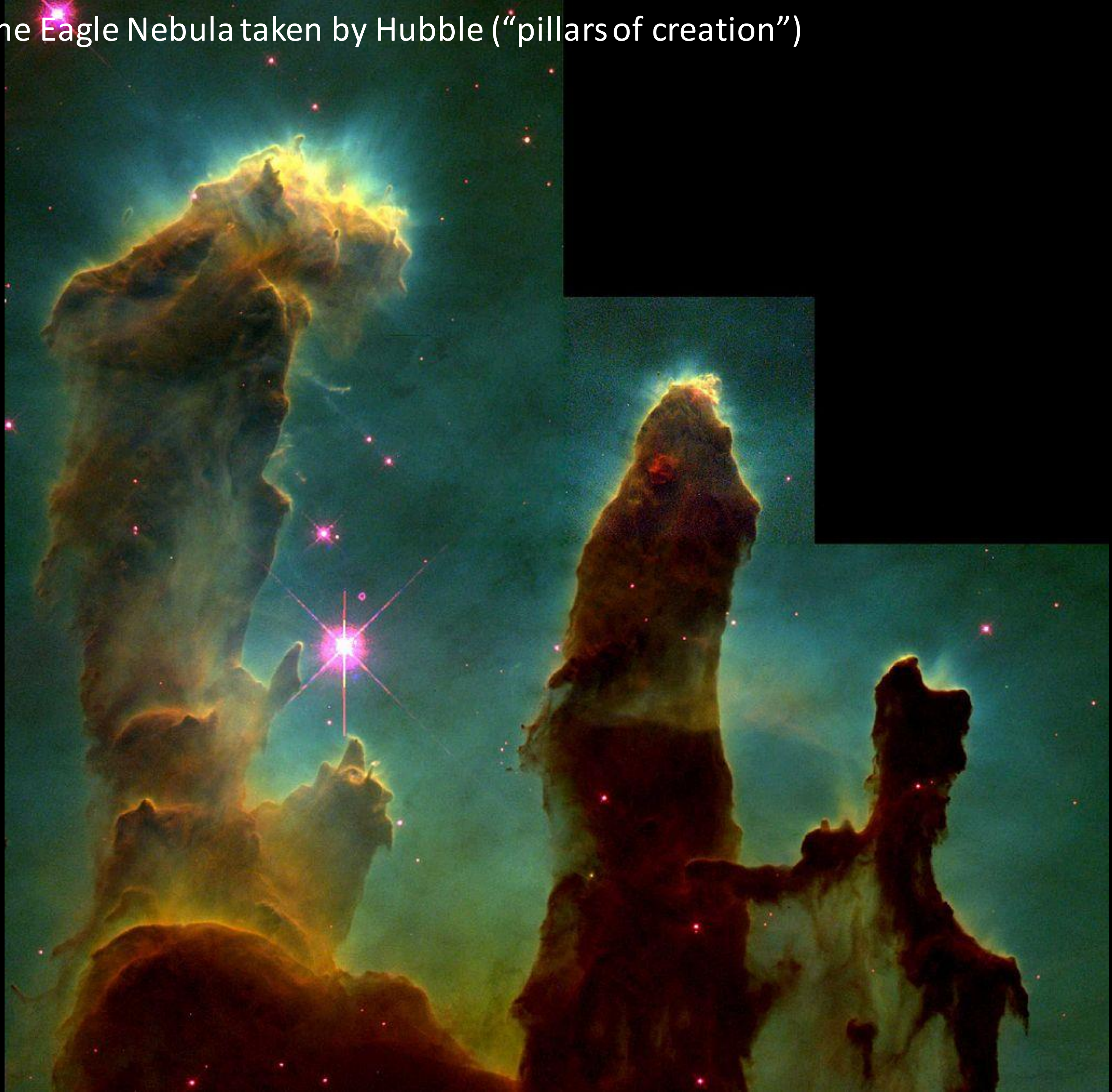
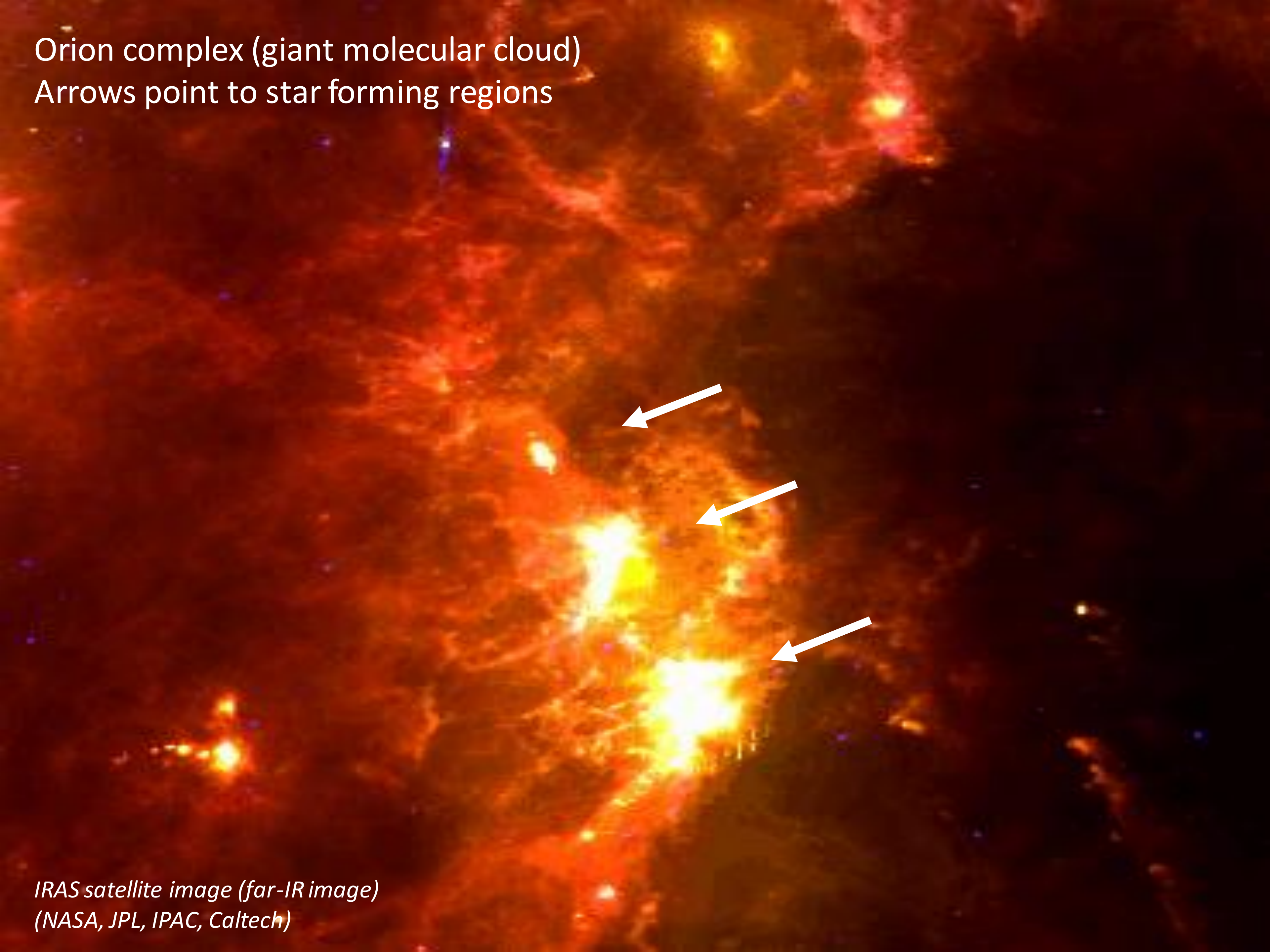


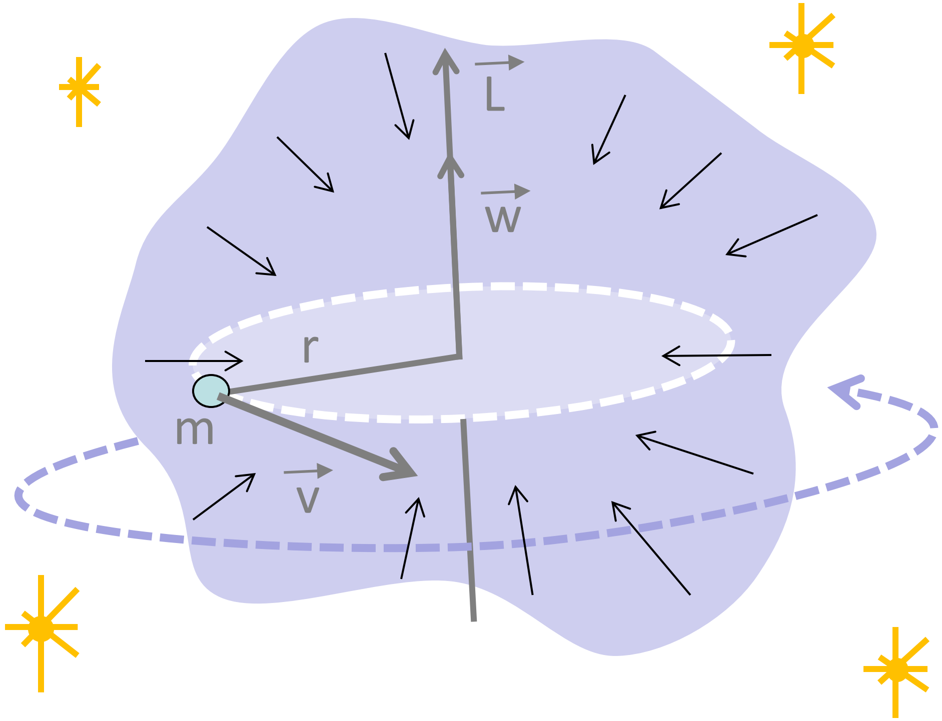
Image by NASA

Omega Nebula
(NASA, ESA, J. Hester, Hubble telescope)

Orion complex (giant molecular cloud)
Arrows point to star forming regions



IRAS satellite image (far-IR image)
(NASA, JPL, IPAC, Caltech)



3. Rotation velocity increases as the cloud contracts under the influence of gravity ("ice skater effect")

Conservation of angular momentum

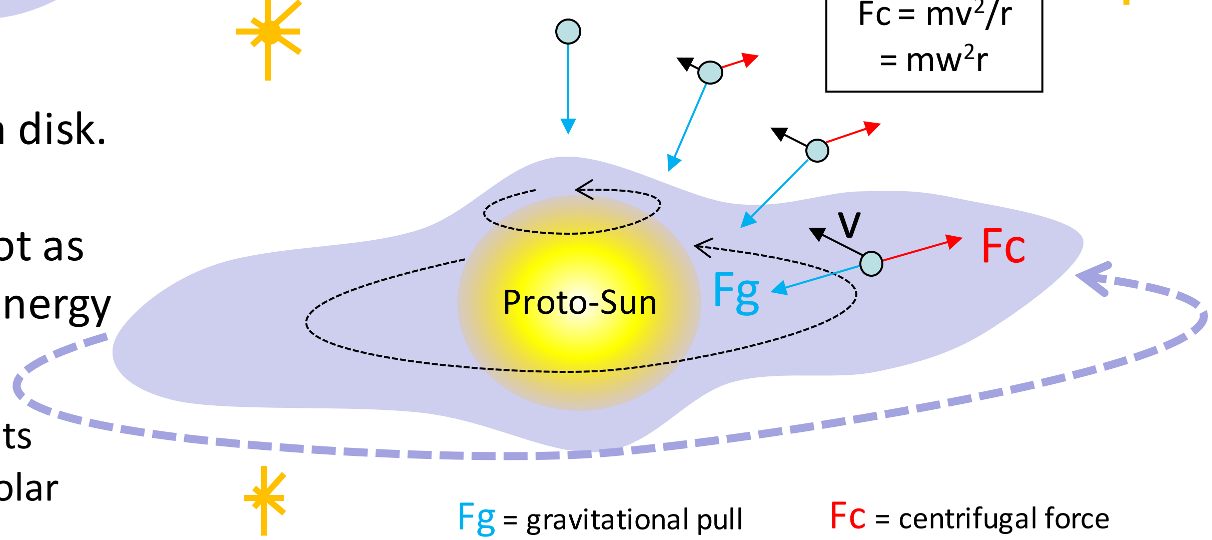
$$L = mvr = mwr^2$$

L = angular momentum
m = mass of the particle
r = distance from the center of rotation
v = linear velocity
w = angular velocity

$$Fc = mv^2/r = mw^2r$$

4. The cloud flattens into a disk. The center of the disk becomes increasingly hot as gravitational potential energy is converted into heat

Note that the Sun represents 99.9% of the mass of the solar system!

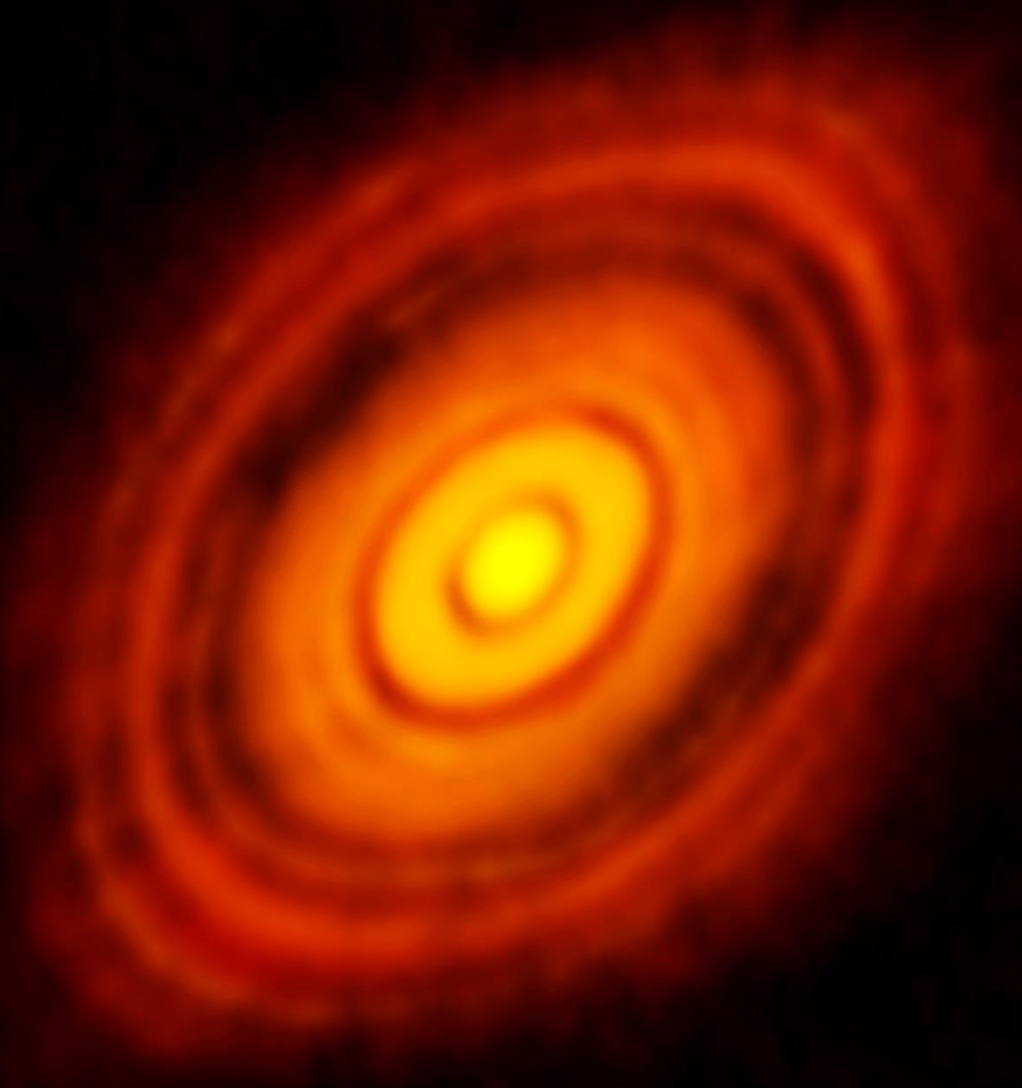


The centrifugal force (inertia) is max in the equatorial plane (linear velocity max.) and opposes the gravitational pull. There is no centrifugal force at the poles (linear velocity = 0), hence “no” force opposes gravity (except gas pressure) and matter falls toward the center of the cloud ("pizza effect").

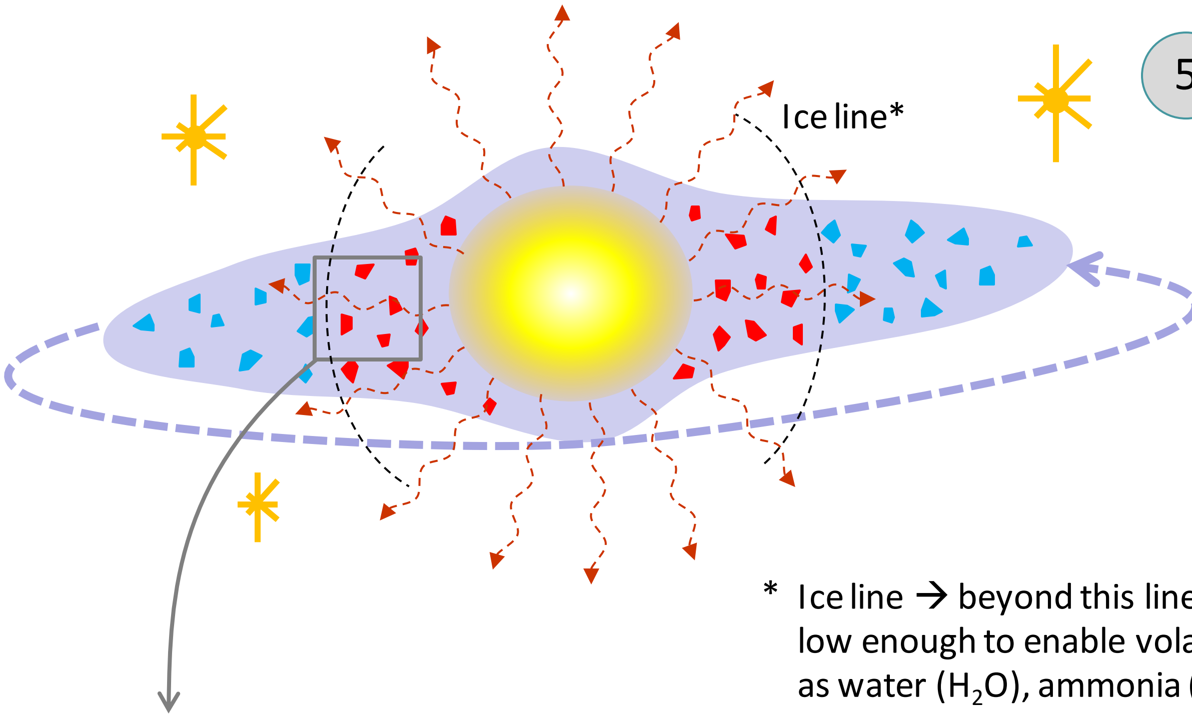

Young stars in the Orion nebula
Protostellar disk

“ALMA image of the protoplanetary disc around HL Tauri - This is the sharpest image ever taken by ALMA — sharper than is routinely achieved in visible light with the NASA/ESA Hubble Space Telescope. It shows the protoplanetary disc surrounding the young star HL Tauri. These new ALMA observations reveal substructures within the disc that have never been seen before and even show the possible positions of planets forming in the dark patches within the system.“

Credit: ALMA (ESO/NAOJ/NRAO)
www.eso.org



*Atacama Large Millimeter/Submillimeter Array

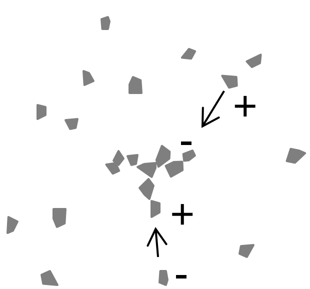


5. Volatile compounds (H_2, He, H_2O…) are blown away by the heat and solar wind (stream of particles, mainly protons and electrons). Compounds with a high melting point -refractory- (silicates, iron…) remains in the vicinity of the star.

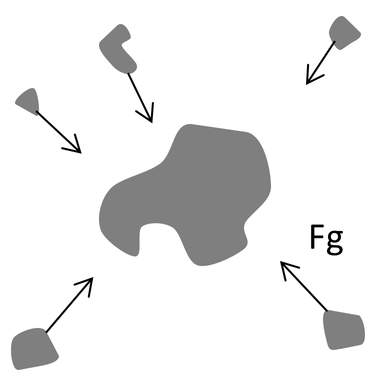
* Ice line → beyond this line, the temperature is low enough to enable volatile compounds, such as water (H_2O), ammonia (NH_3), methane (CH_4), to condense into ice. The giant planets formed beyond this line.

6. In the disk, matter coalesces into increasingly larger objects.

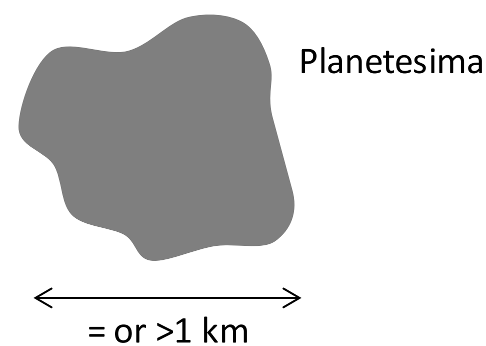
First, small grains are attracted by electrostatic force.



Then larger pieces begin to attract nearby objects by gravity



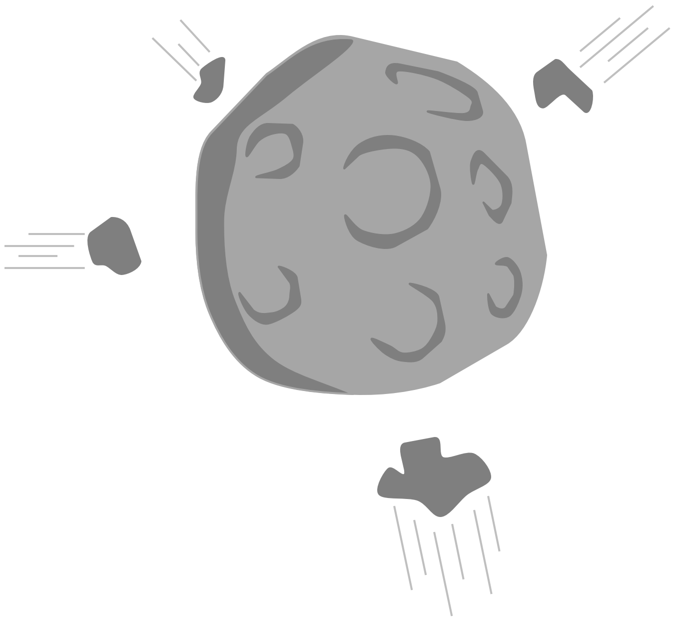
Gravity pulls together objects of increasing size.



https://www.youtube.com/watch?v=Q0kteyMDnwE

Closer to the proto-Sun:

Rocky material (e.g. silicates) and metals (e.g. Fe, Ni) coalesce to form the inner planets



Farther from the proto-Sun (beyond the ice line):

Gaseous (H_2, He) and icy compounds (H_2O, NH_3, CH_4)∗ coalesce to form the outer planets

∗ Together with some rocky material still present in the outer solar system

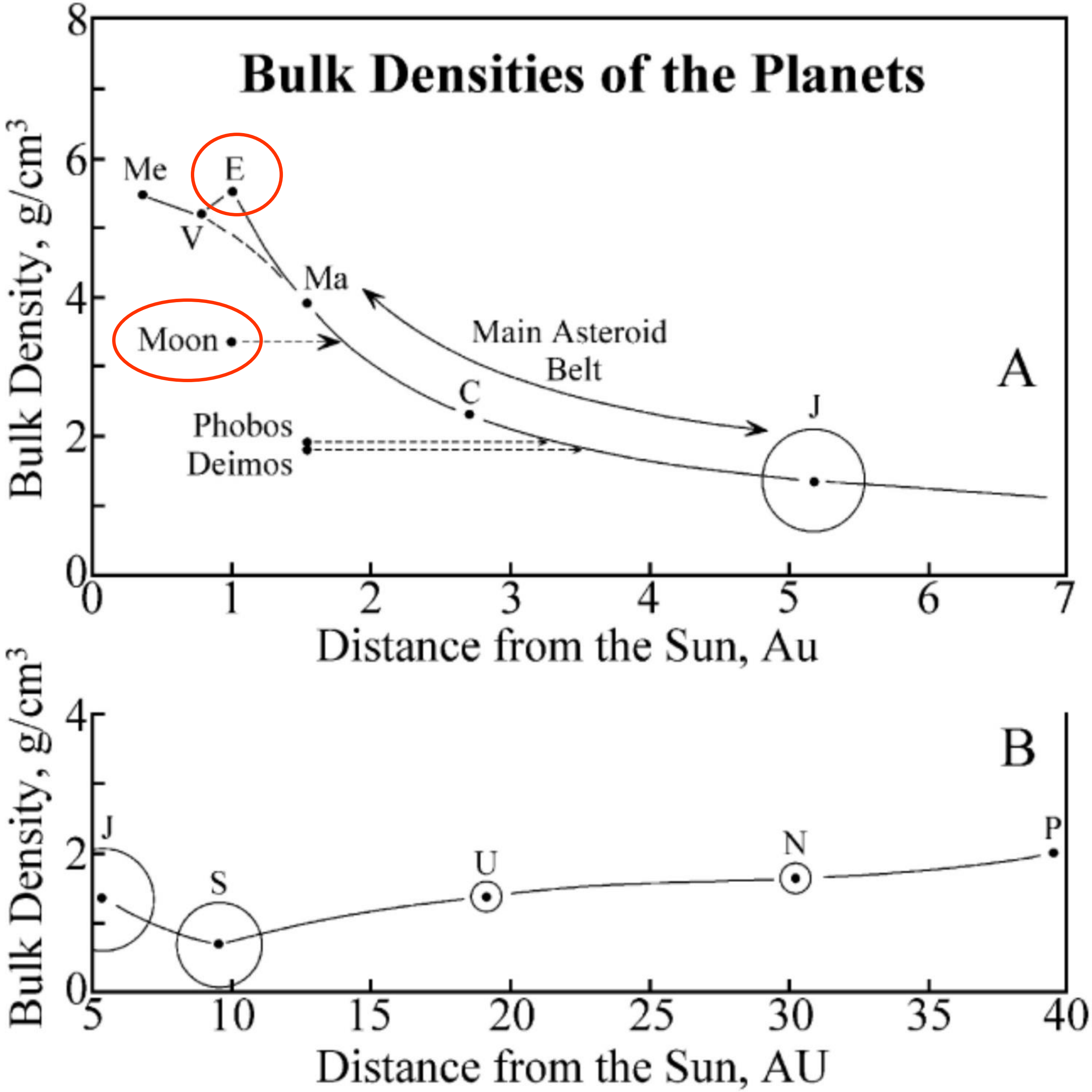
Ca-Al-rich inclusions found in some meteorites → Oldest age measured in the solar system! → 4.567 Ga

■ Table 29.2 Condensation Sequence in the Solar Nebula

Temperature (K)	Condensations and Reactions Occurring
1600	Condensation of refractory oxides such as CaO, Al_2O_3, TiO_2, and rare-earth oxides
1300	Condensation of metallic nickel–iron alloy
1200	Condensation of enstatite ($MgSiO_3$)
1200–490	Progressive oxidation of remaining metallic iron to FeO, which in turn reacts with enstatite to make olivine [$(Fe, Mg)_2SiO_4$]
1000	Reaction of sodium with Al_2O_3 and silicates to make feldspar and related minerals; condensation of potassium and other alkali metals
680	Reaction of H_2S with metallic iron to make troilite (FeS)
550	Combination of water vapor (H_2O) with calcium-bearing minerals to make tremolite
Ice line 425	Combination of water vapor with olivine to make serpentine
175	Condensation of water ice
150	Reaction of ammonia gas (NH_3) with water ice to make the solid hydrate $NH_3 \cdot H_2O$
120	Partial reaction of methane gas (CH_4) with water ice to make the solid hydrate $CH_4 \cdot 7H_2O$
65	Condensation of argon and leftover methane gas into solid argon and methane
<25	Condensation of neon, hydrogen, and helium (temperature probably never fell this low, so this step did not occur in solar nebula)

Modified from Lewis, John S. "The Chemistry of the Solar System." In *Scientific American*, vol. 230 (3), 1974.

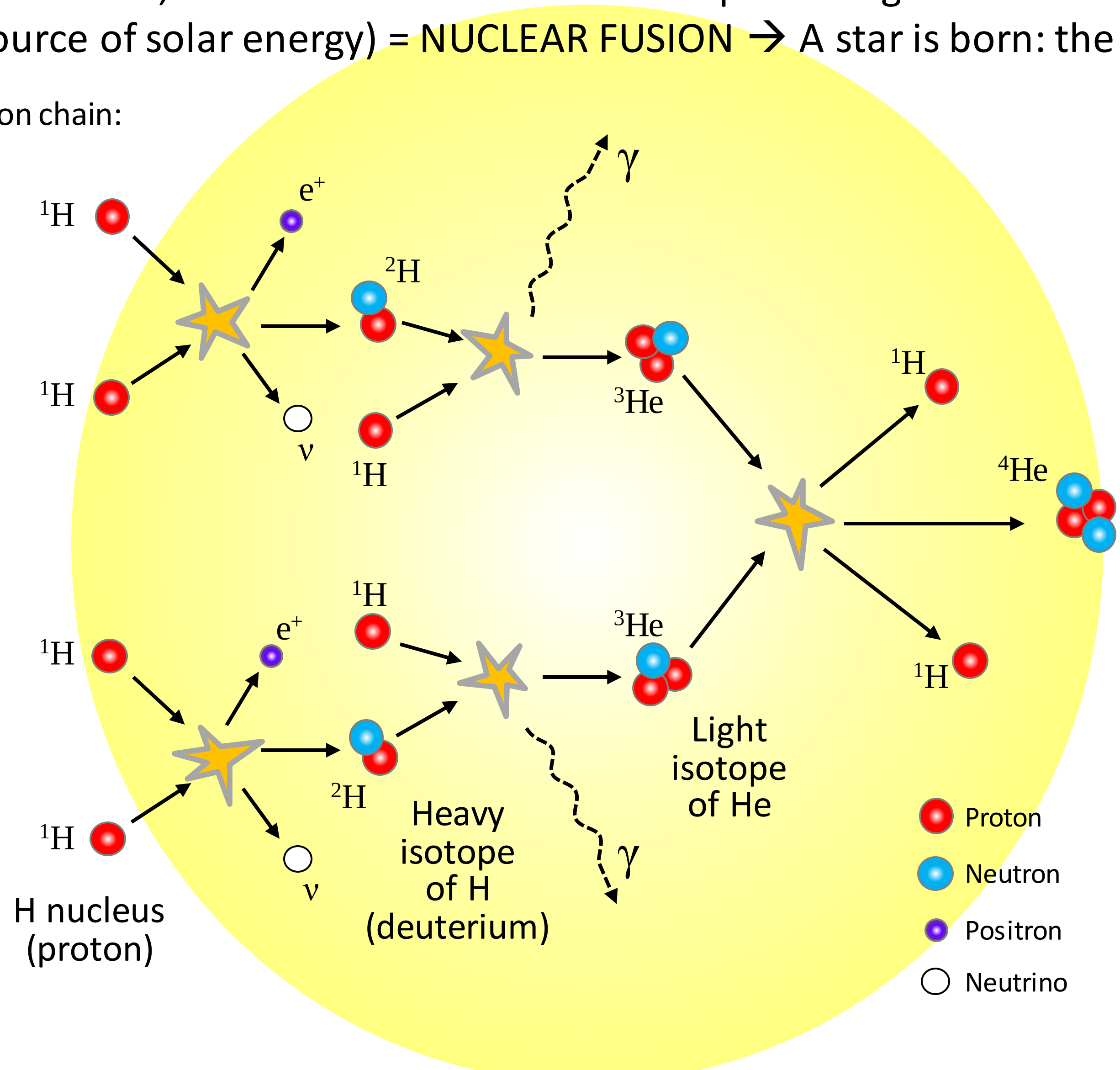
0ºK (kelvin) = -273ºC



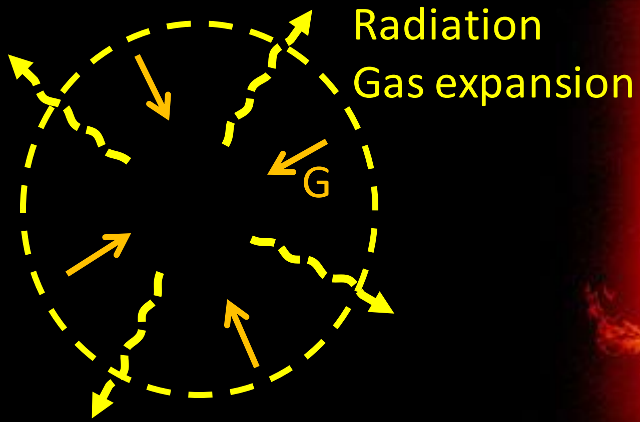
Faure and Mensing 2007, Introduction to Planetary Science

The center of the proto-Sun is so hot that hydrogen atoms are stripped of their electrons. The “soup” of electrons and protons is called a plasma. When temperature reaches 12x10^6 ºC, nuclei fuse in a chain reaction producing a tremendous amount of energy (source of solar energy) = NUCLEAR FUSION → A star is born: the Sun

Proton-proton chain:

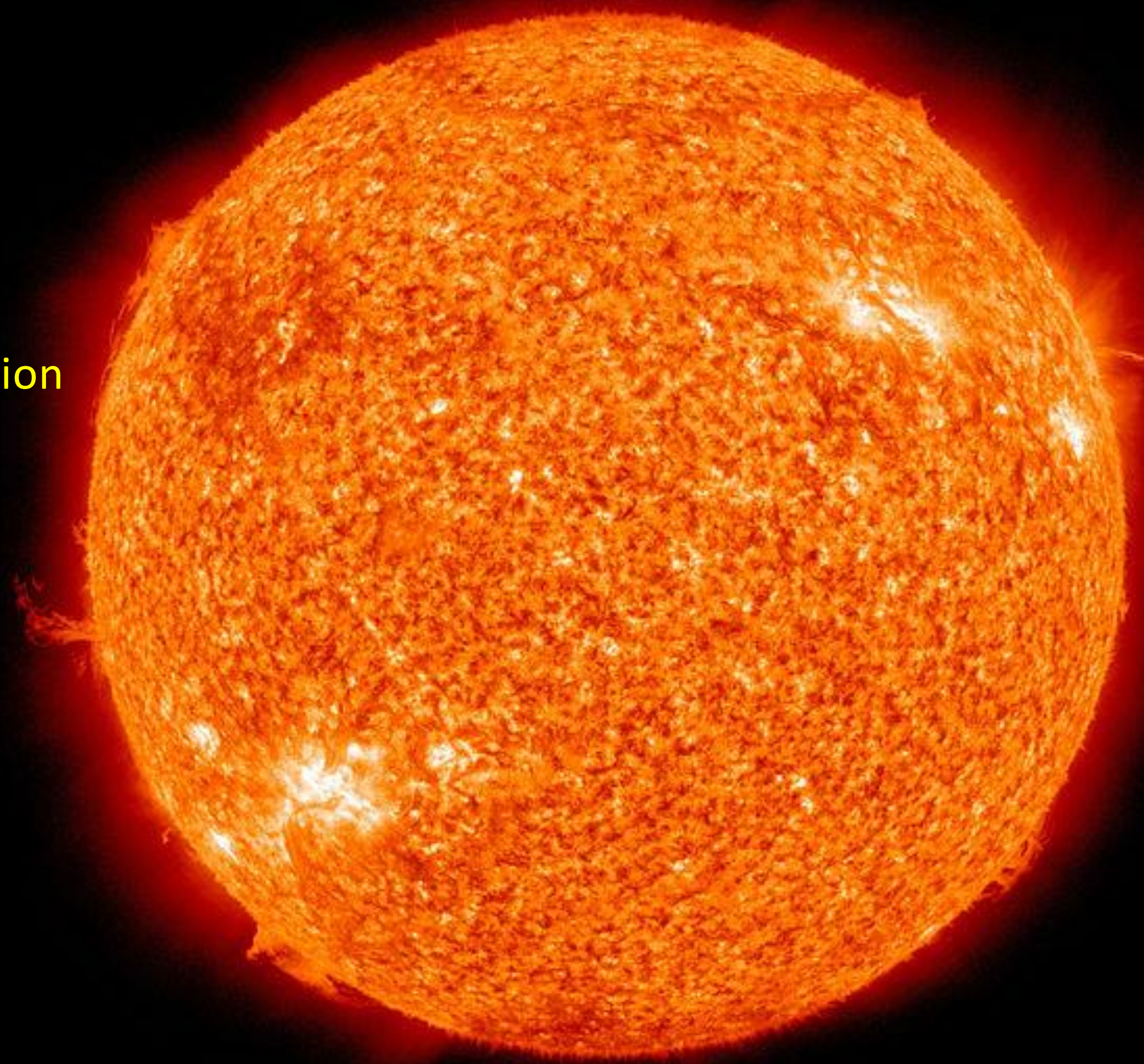


A star obtains the status of "main sequence star“ (like our Sun) once the outward forces (radiation + gas expansion) balance the inward gravitational pull.



After all the hydrogen inside the star is used up, the star collapses and the hydrogen present in the outer layer of the star starts to fuse and the outer layer expands. The star becomes a red giant (100x Sun’s current radius).

Our Sun has enough fuel for another 5 billion years.



NASA

The Story of the Solar System (Mark A. Garlick, 2002, Cambridge University Press)

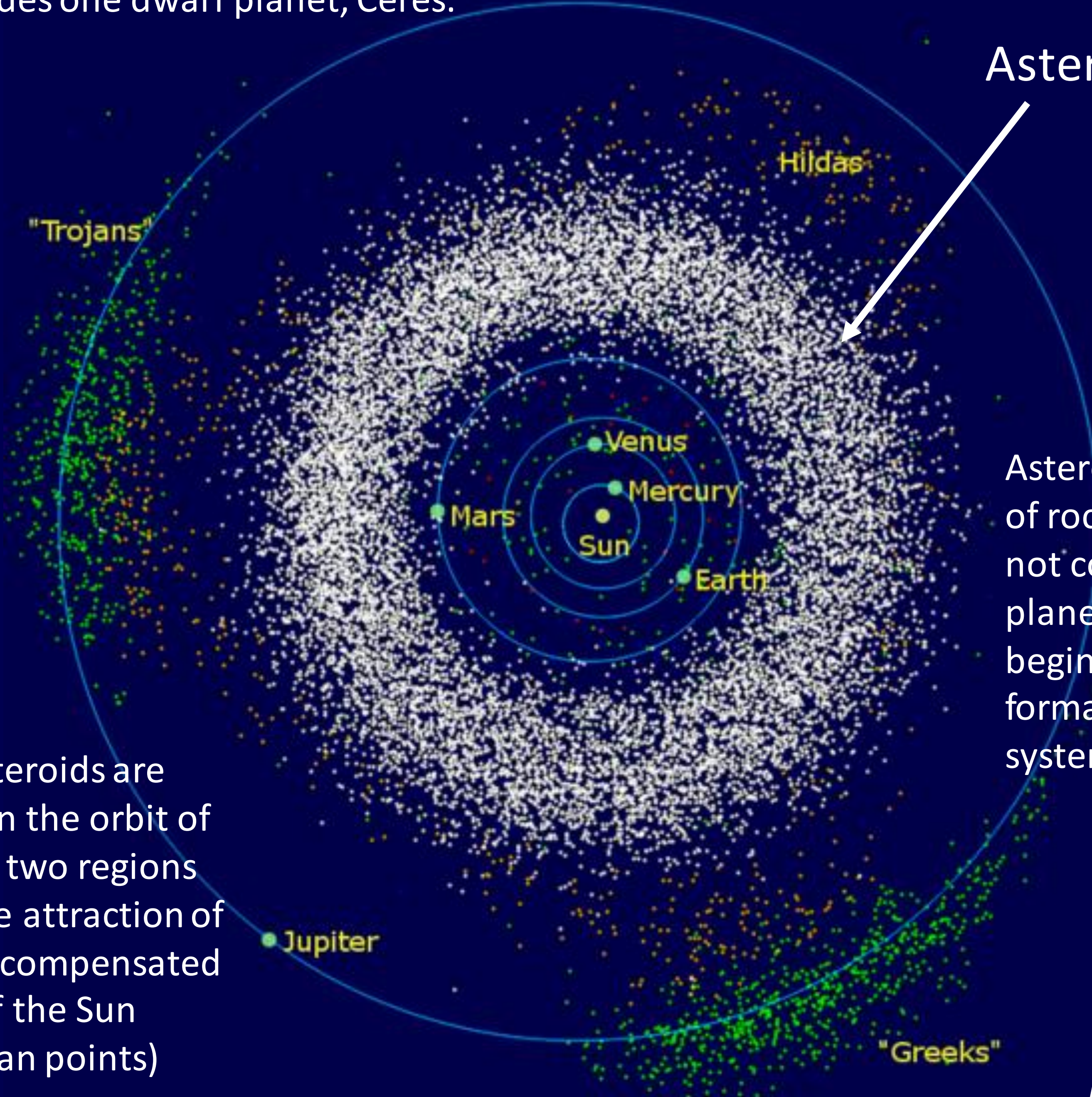
THE SUN

• Giant Molecular Cloud (nebula)	• 0
• Protosun (central region warming up to 10,000 ºC)	• 2.03×10^6 yrs
• Solar nebula flattened into a disk	• 2.13×10^6 yrs
• Main sequence star (Sun)	• $30\text{-}50 \times 10^6$ yrs

THE PLANETS

• Planetesimals/protoplanets	• 2.2×10^6 yrs
• Gas Giants, asteroids, comets	• $2\text{-}10 \times 10^6$ yrs
• Terrestrial planets	• $10\text{-}100 \times 10^6$ yrs
• Heavy Bombardment	• $100\text{-}1300 \times 10^6$ yrs

The Asteroid Belt, between the orbit of Mars and Jupiter, is composed of billions of asteroids and includes one dwarf planet, Ceres.



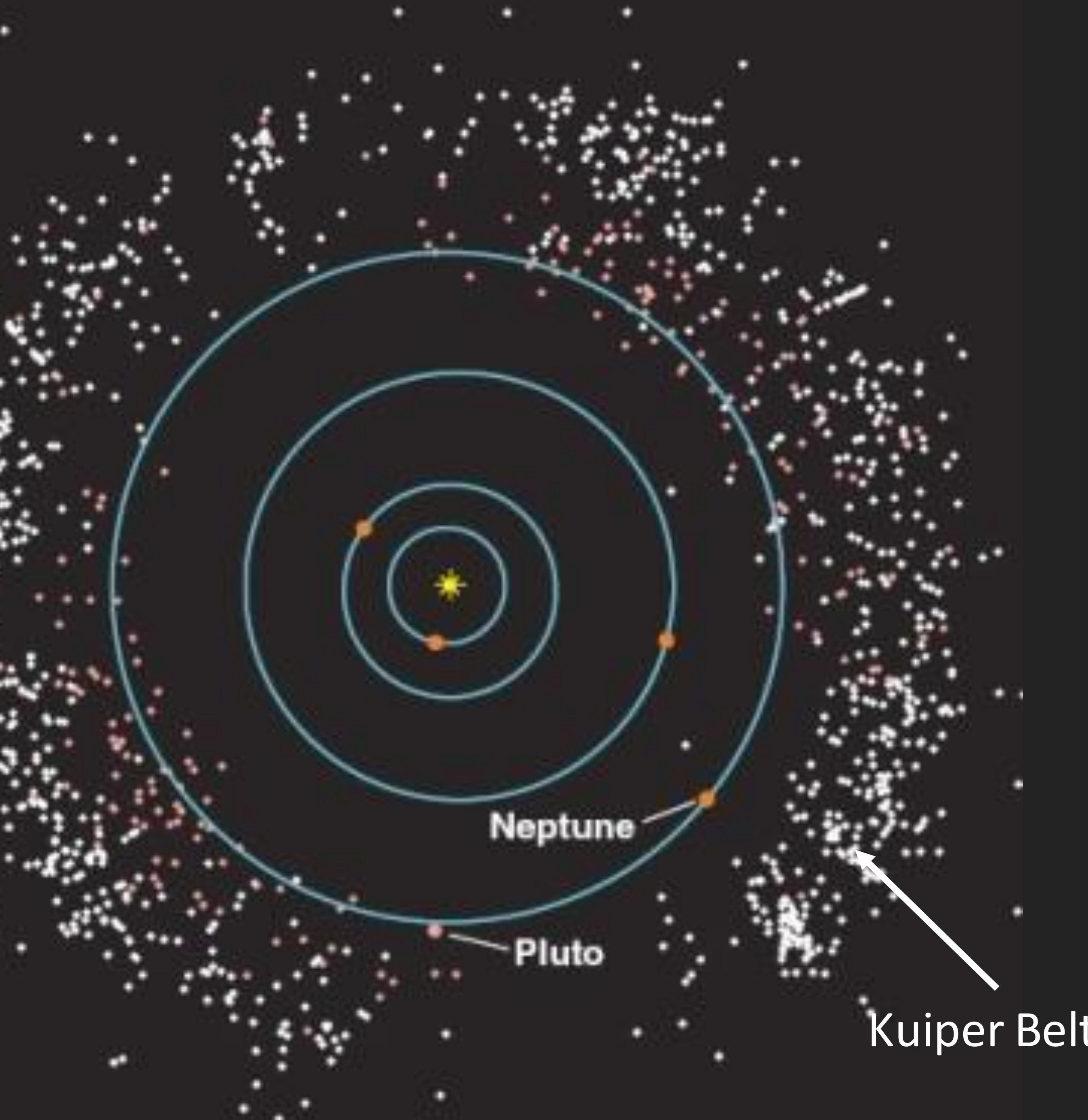
Asteroids are chunks of rocks which have not coalesced with planets at the beginning of the formation of the solar system.

Trojan asteroids are located on the orbit of Jupiter in two regions where the attraction of Jupiter is compensated by that of the Sun (Lagrangian points)

Image: Minor Planet Center

Comets are icy objects which have escaped planetary accretion (like asteroids).

The two reservoirs of comets are the Kuyper Belt and the Oort Cloud.

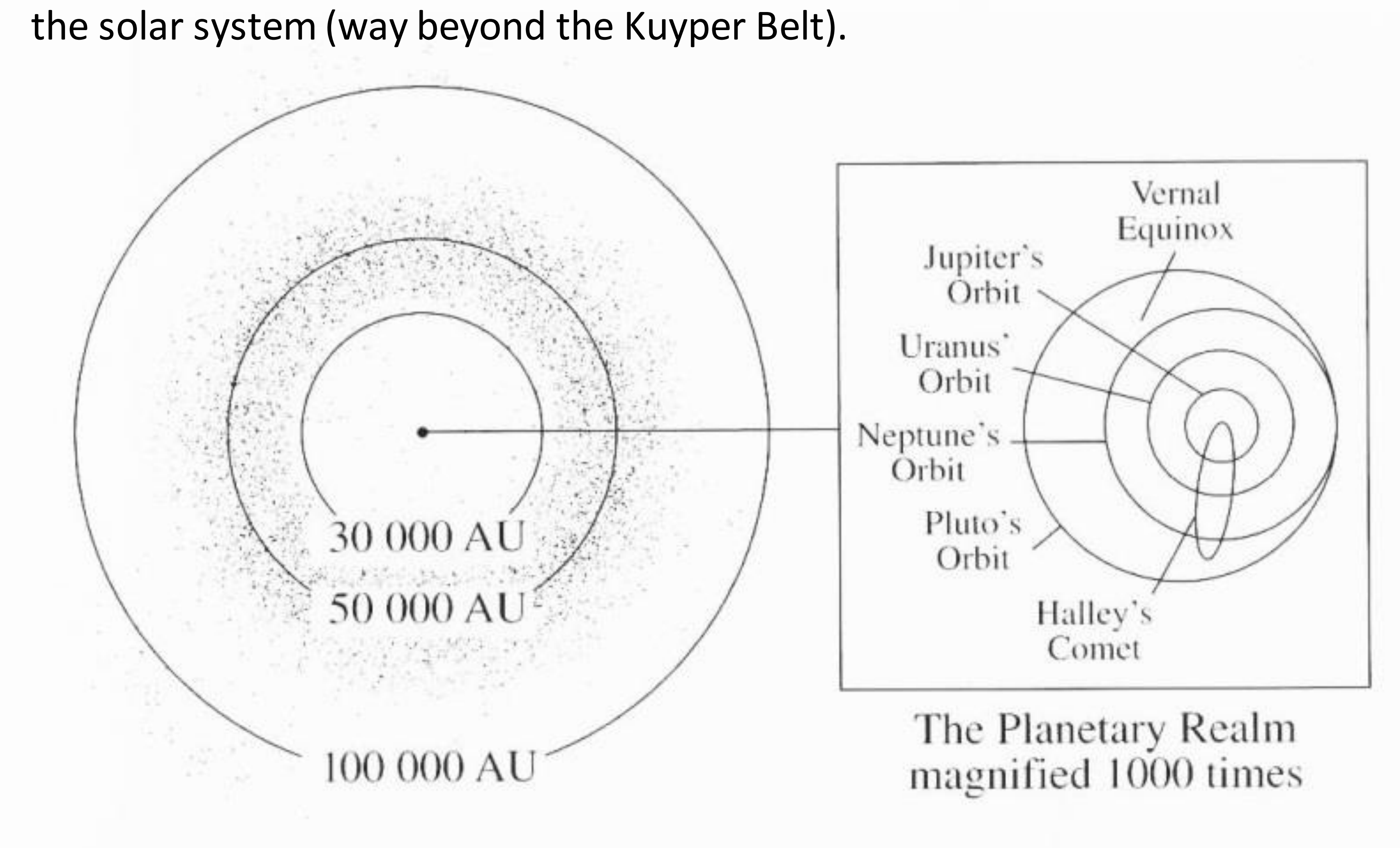


4 dwarf planets so far discovered in the Kuiper belt: Pluto, Haumea, Makemake, Eris

Image: Minor Planet Center

Oort Cloud

By studying the size and trajectory of comets, the Dutch astronomer Jan H. Oort (1900-1992) has postulated the existence of a "comet reservoir" surrounding the solar system (way beyond the Kuyper Belt).

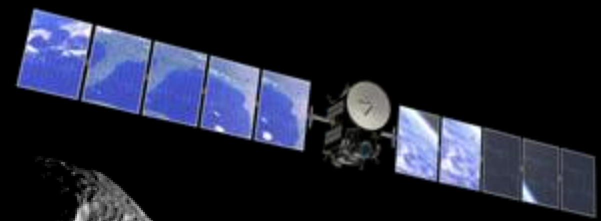


Lang 2011, the Cambridge Guide to the Solar System

Asteroids and comets give us information about the raw material that accreted to form the planets.

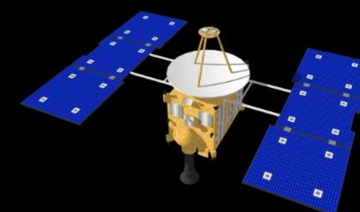
Most meteorites falling on Earth are pieces ejected during collisions between asteroids. Hence, their age can give us an idea of the age of the Solar System. The currently accepted age of the Earth is 4.56 Ga based on the age of meteorites.

Computer models suggest that it may have taken only 10 million years for the planets to form.



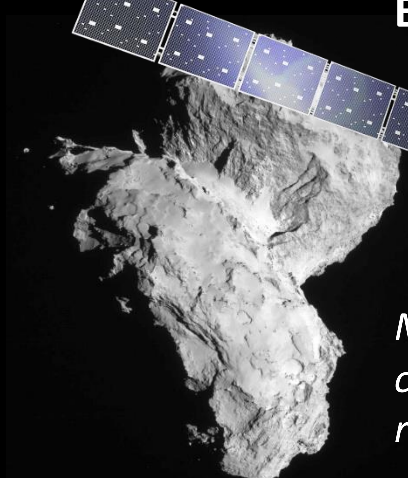
NASA DAWN MISSION

Exploration of Vesta and Ceres (Asteroid Belt, launched 2007, explored Vesta & Ceres)



JAXA HAYABUSA I* & II MISSION**

*Mapping and sampling of asteroid Itokawa & Ryugu (*launched 2003, returned 2010; **launched 2014, reached target 2018)*



ESA ROSETTA MISSION

Mapping and landing probe on comet Chury (launched 2004, reached target 2014)

NASA OSIRIS-Rex MISSION

Mapping and sampling of carbon-rich asteroid Bennu (launched in 2016, sampling-return 2020-2021)

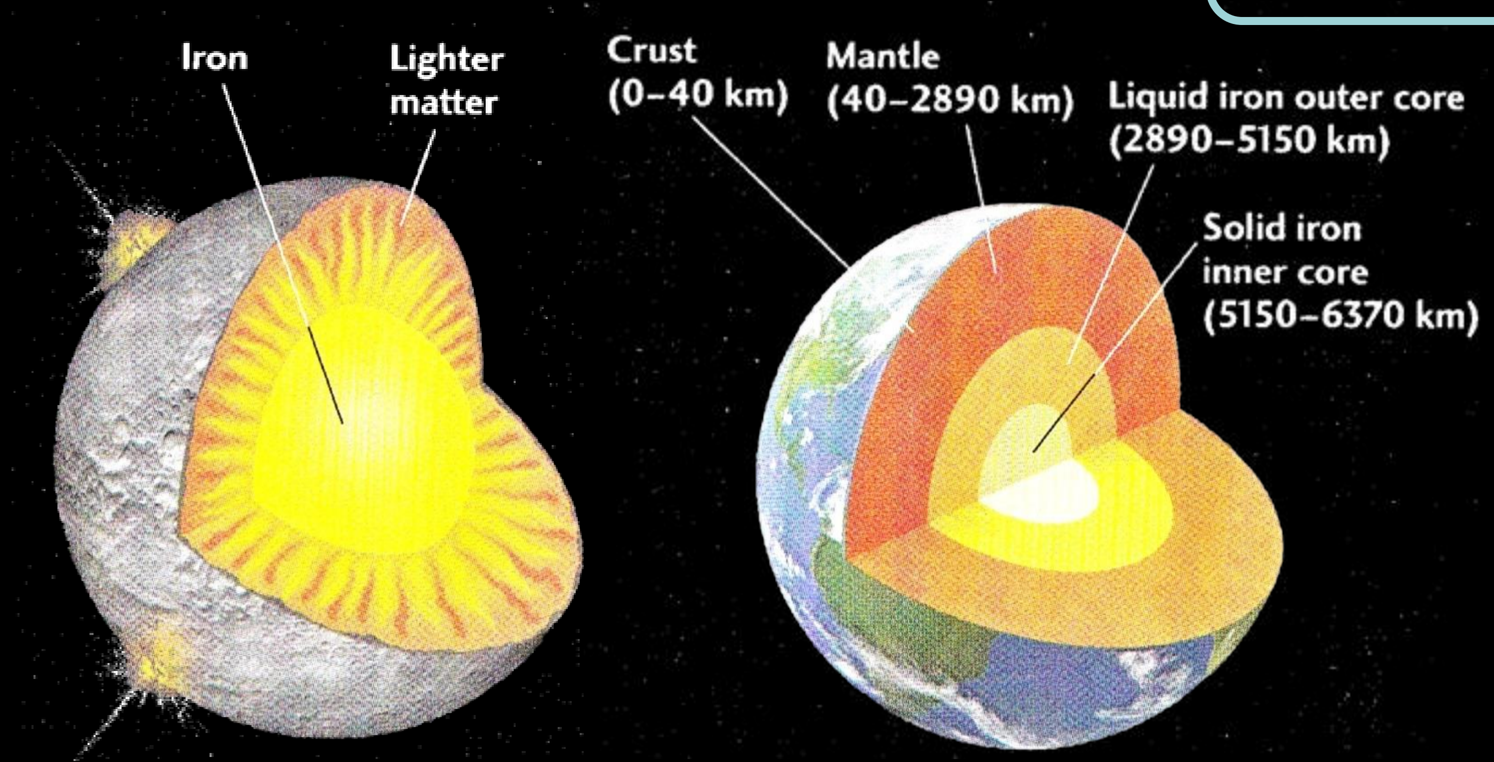
(NASA,ESA,JAXA)

Formation of Earth's layers

- Earth was in a molten state at the beginning of its history.
  - Impacts with meteorites and planetesimals (conversion of kinetic energy)
  - Radioactive decay
  - Gravitational contraction (conversion of gravitational potential energy)

- Matter redistributed according to differences in density:

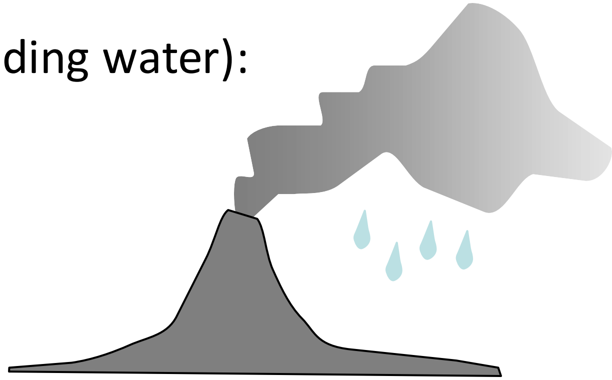
Gravitational differentiation



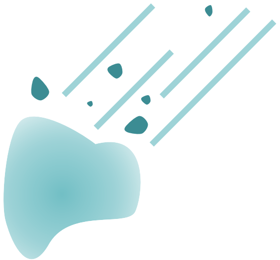
Understanding Earth 6th Ed.

Origin of Earth's atmosphere and water

- Two possible sources for volatile components (including water):
  - Volatiles trapped in the **Earth's interior** and released during volcanic activity



  - Volatiles from **meteorites** and (especially) **comets.**



- The composition of the primitive atmosphere was different from today:
  → H_2, N_2, CO_2, and H_2O. **NO OXYGEN!**
  - Oxygen was produced later by biological activity (**photosynthesis**)!
  - Once temperature began to fall, water vapor condensed in a liquid state and primitive oceans began to form (probably less than 200 Ma after the beginning of Earth's formation).

- The Moon

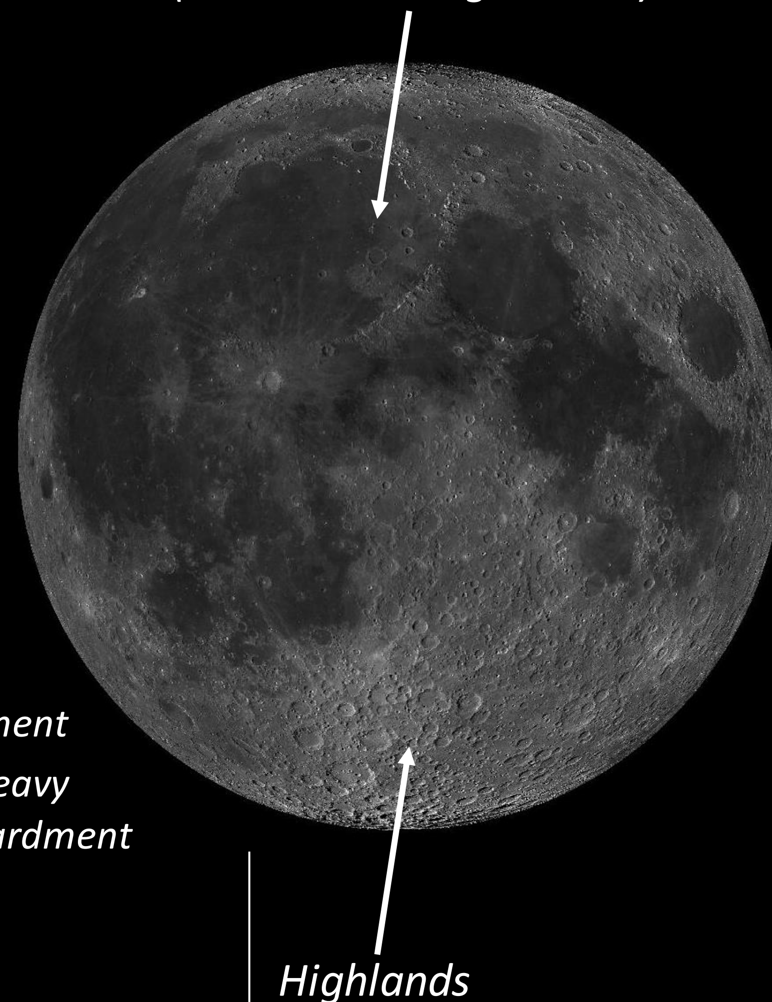
In the case of the Moon, we have access to the absolute age of surfaces with different crater densities (lunar rock samples brought back to Earth have been dated!).
Assuming craters form at a constant (known) rate, it is possible to calculate the absolute age of planetary surfaces.

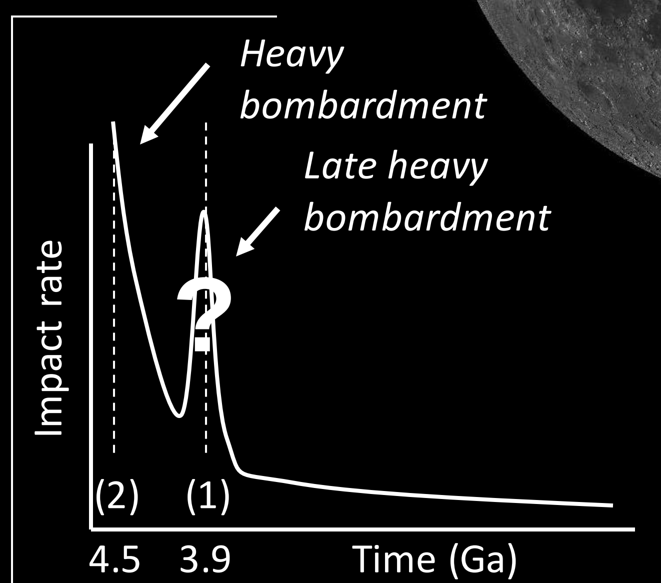
Lunar Reconnaissance Orbiter Camera

An old surface has more craters than a young surface.
It is possible to know the relative age of two surfaces by comparing their crater density.

- Main features of the Moon surface:
  - **Lowlands** (mare*, pl. maria)
    Surface with few craters (younger), consisting of basalt that has filled large craters
  - **Highands**
    Surface with many craters (older)

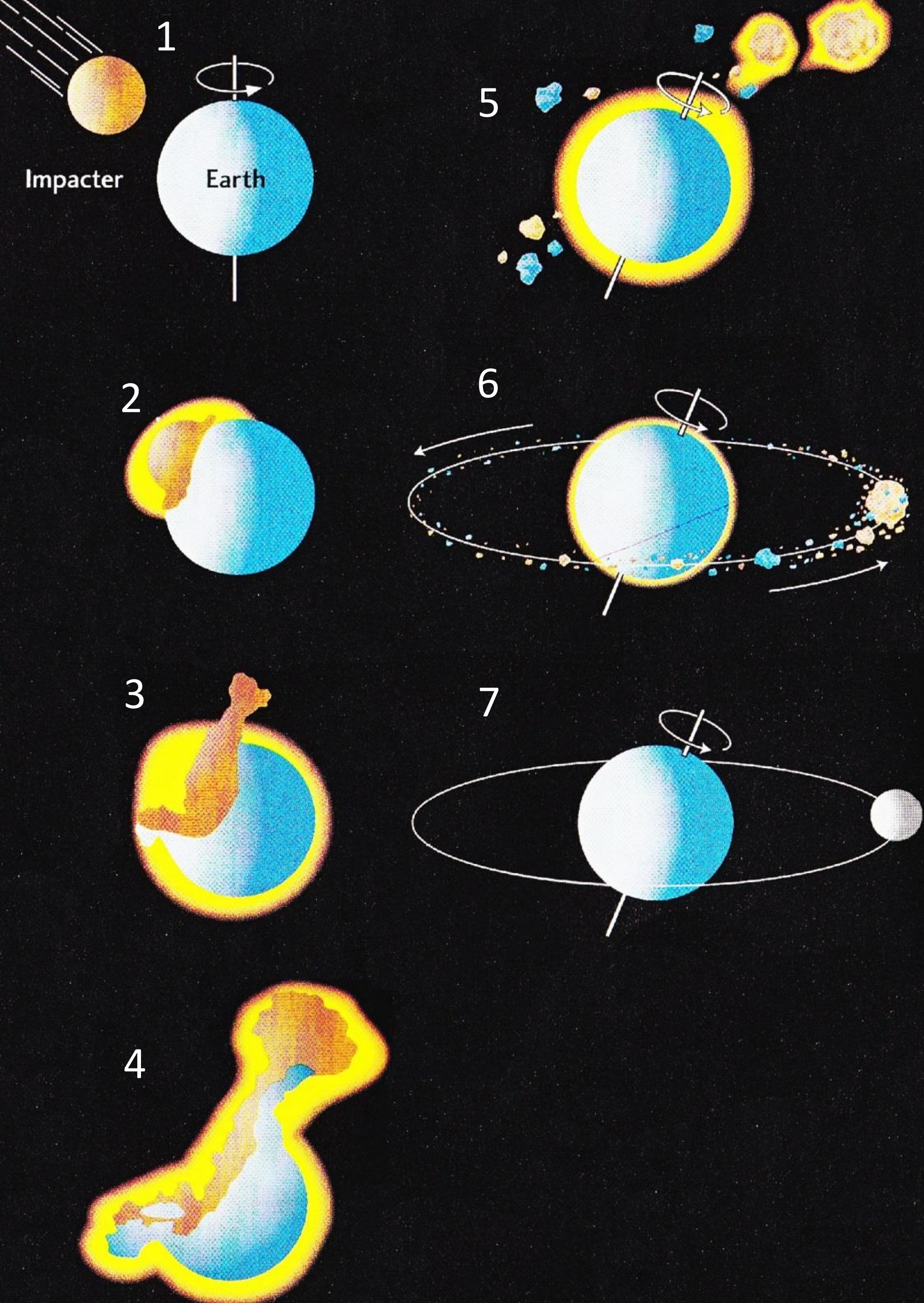
- Radiometric dating:
  - Lowlands (maria): 4 to 3.2 Ga **(1)**
  - Highlands: 4.5 to 4 Ga **(2)**





**Mare = latin word for "sea"*

NB: Hadean Eon: 4.6-4 billion years



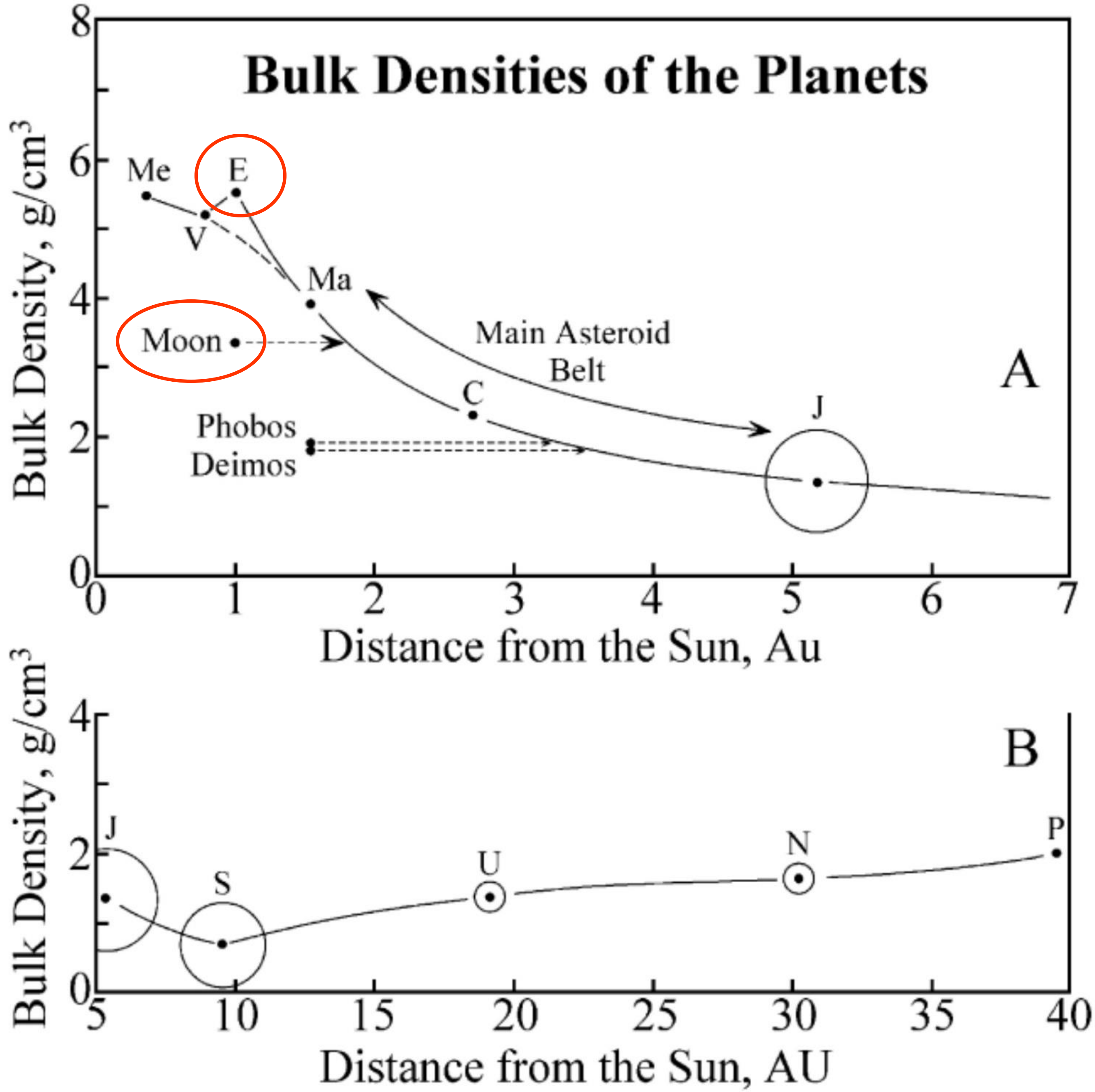
Understanding Earth 6th Ed.

The <u>Giant Impact Hypothesis</u> suggests a large planetesimal impacted the Earth 4.6 billion years ago and the Moon formed out of the ejected material.

Explains:

- Earth's tilt
- Lack of volatile material on the Moon (vaporized during its formation)
- Tiny iron-rich core of the Moon (source material: only crust and mantle)

The Moon may have derived primarily from the crust and mantle of the Earth and impactor, explaining the low density of the Moon.



Faure and Mensing 2007, Introduction to Planetary Science

The terrestrial planets and their characteristics

- Similarity
  - Layered structure (by gravitational differentiation)
    - A Fe-Ni core, a silicate mantle, and an outer crust

- Differences
  - Size
  - Mass
  - Dynamics (presence/absence of geological activity)
  - Atmospheric composition and pressure
  - Surface temperature
  - Density of craters (related to age of planetary surfaces)

- Basic characteristics of the terrestrial planets

	Mercury	Venus	Earth	Mars	Moon
Radius (km)	2440	6052	6378	3388	1737
Mass (Earth=1)	0.06 (large Fe-Ni core)	0.81	1 ($6x10^{24}$kg)	0.11	0.01
Mean density (g/cm^3)	5.43	5.24	5.52	3.94	3.34
Orbit period (Earth days)	88	224	365	687	27
Distance from the Sun (millions of km)	57	108	148	228	Control on T
Av. atmospheric pressure (bar)	10^{-12}	92	1	$7x10^{-3}$	
Composition of atmosphere	(H_2, He)	CO_2, H_2SO_4	N_2, O_2, CO_2	CO_2	
Temperature (°C)	-170 to 470	475	-60 to 50	-155 to 20	
DENSITY OF CRATERS	HIGH	LOW	LOW	HIGH	HIGH

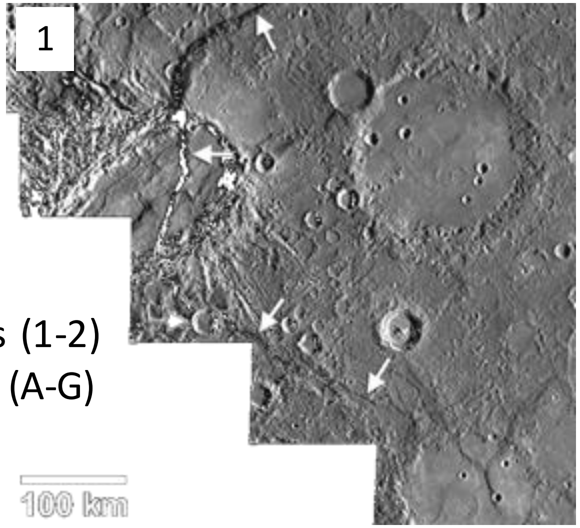
• Mercury

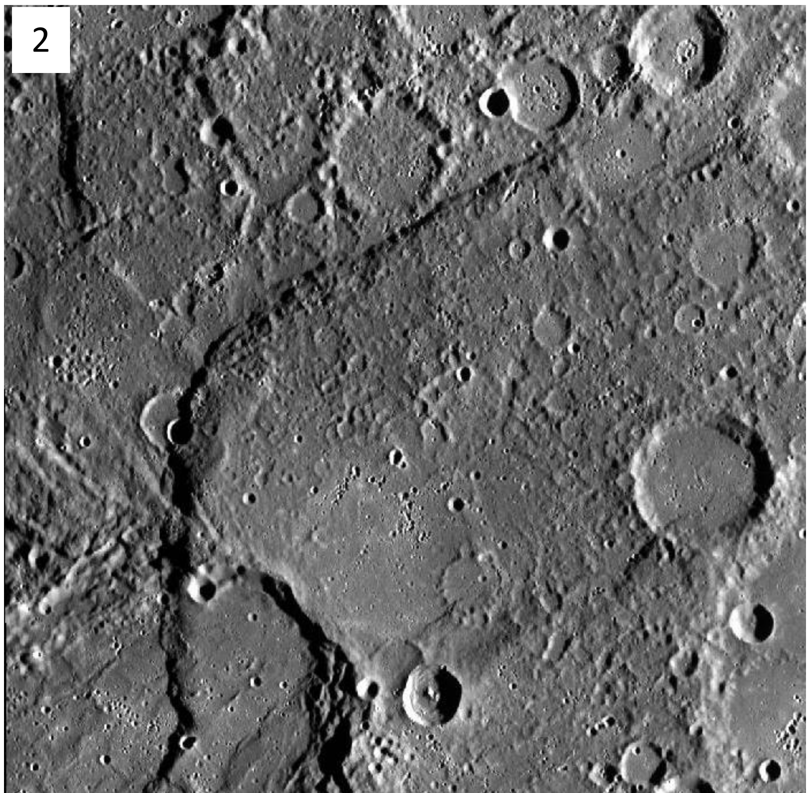
- Images of the surface of Mercury taken by Mariner 10 in 1974 and by Messenger (2004-2015).
- Very old surface: many craters
- Numerous escarpments (1-2 km high, 100s of km long), probably faults resulting from contraction during cooling of the crust.

Moon-like surface

NASA/JPL

Escarpments (1-2)
& lava flows (A-G)





Solomon et al. (2008)

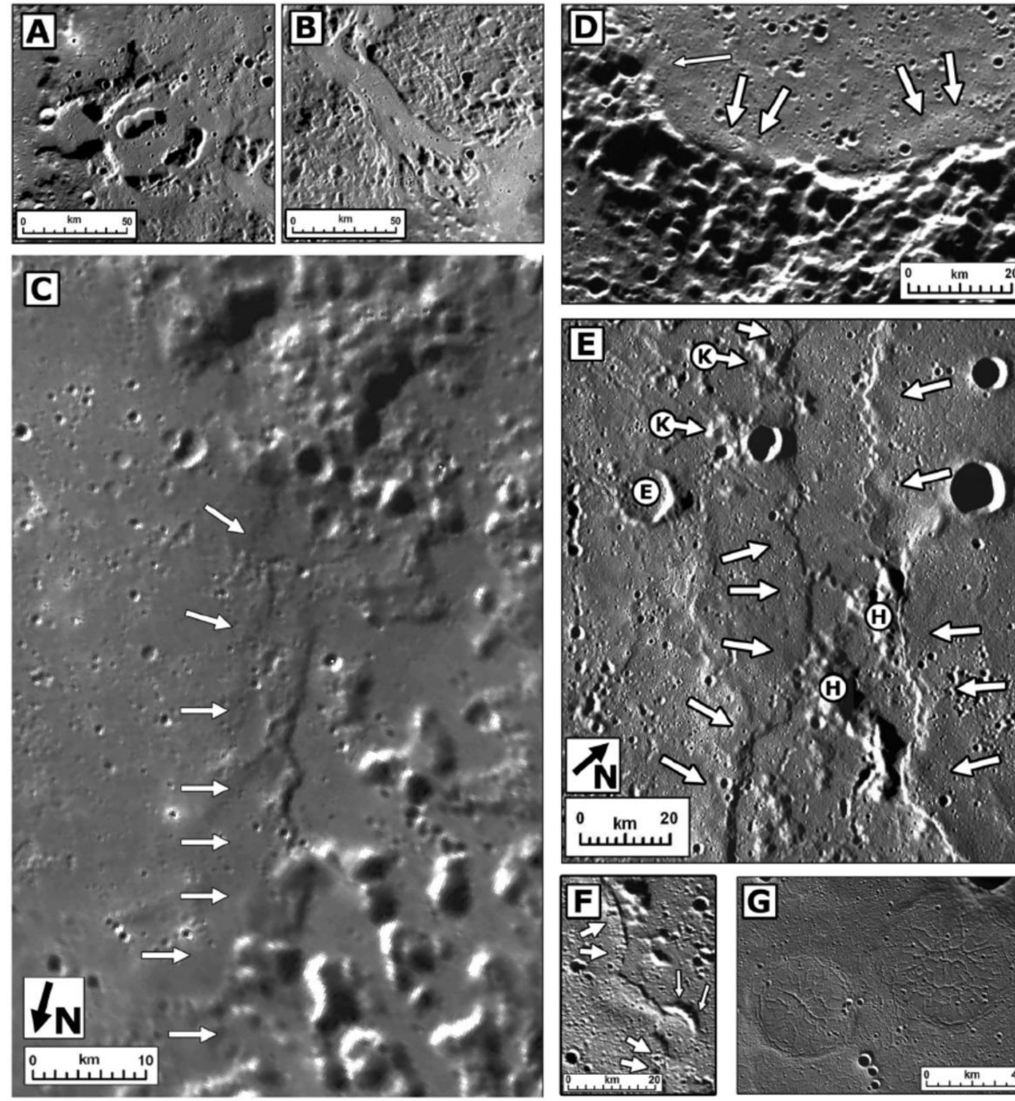


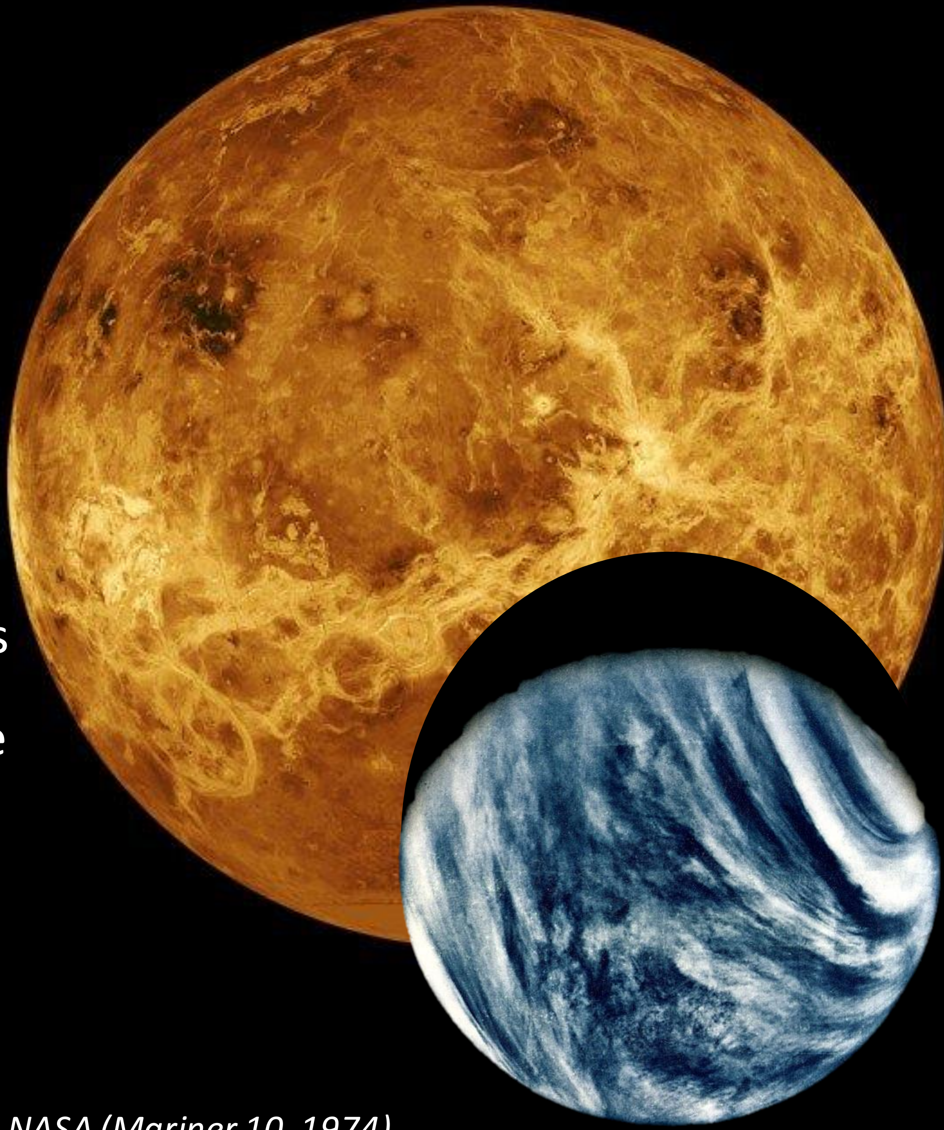
Fig. 3. Features interpreted to be related to lava flows in the northern smooth plains and vicinity. (**A**) Pits interpreted as source vents. (**B**) Teardrop-shaped hills and channel. (**C**) Distal smooth plains (left) embaying rough plains (right) (see Fig. 2) along a flow front–like contact (arrows). (**D**) Steep flow margin (broad arrows) within a flooded impact crater; narrow arrow points to possible flooding of a smaller crater. (**E**) Candidate lava flow fronts (arrows) embaying crater (E) and flooding the hills (H) between flow fronts to form kipukas (K). (**F**) Evidence for a flow front (broad arrows) descending into a preexisting crater (narrow arrows; note adjacent depressed part of flow). (**G**) Fissures inside flooded craters in the Goethe basin (G in Fig. 1). The location of these images and MESSENGER image numbers are given in the SOM.

Head et al. (2011)

• Venus

- First flyby by Mariner 2 in 1962
- First images of the surface by Russian Venera spacecrafts in 70s and 80s
- Very dense atmosphere of carbon dioxide, clouds of sulfuric acid and water vapor
- Very young surface with few craters because of intense tectonic activity ("flake tectonics"), and many active volcanoes.
- No rainfall on the surface (too hot): very little erosion

NASA (Magellan radar image)



NASA (Mariner 10, 1974)

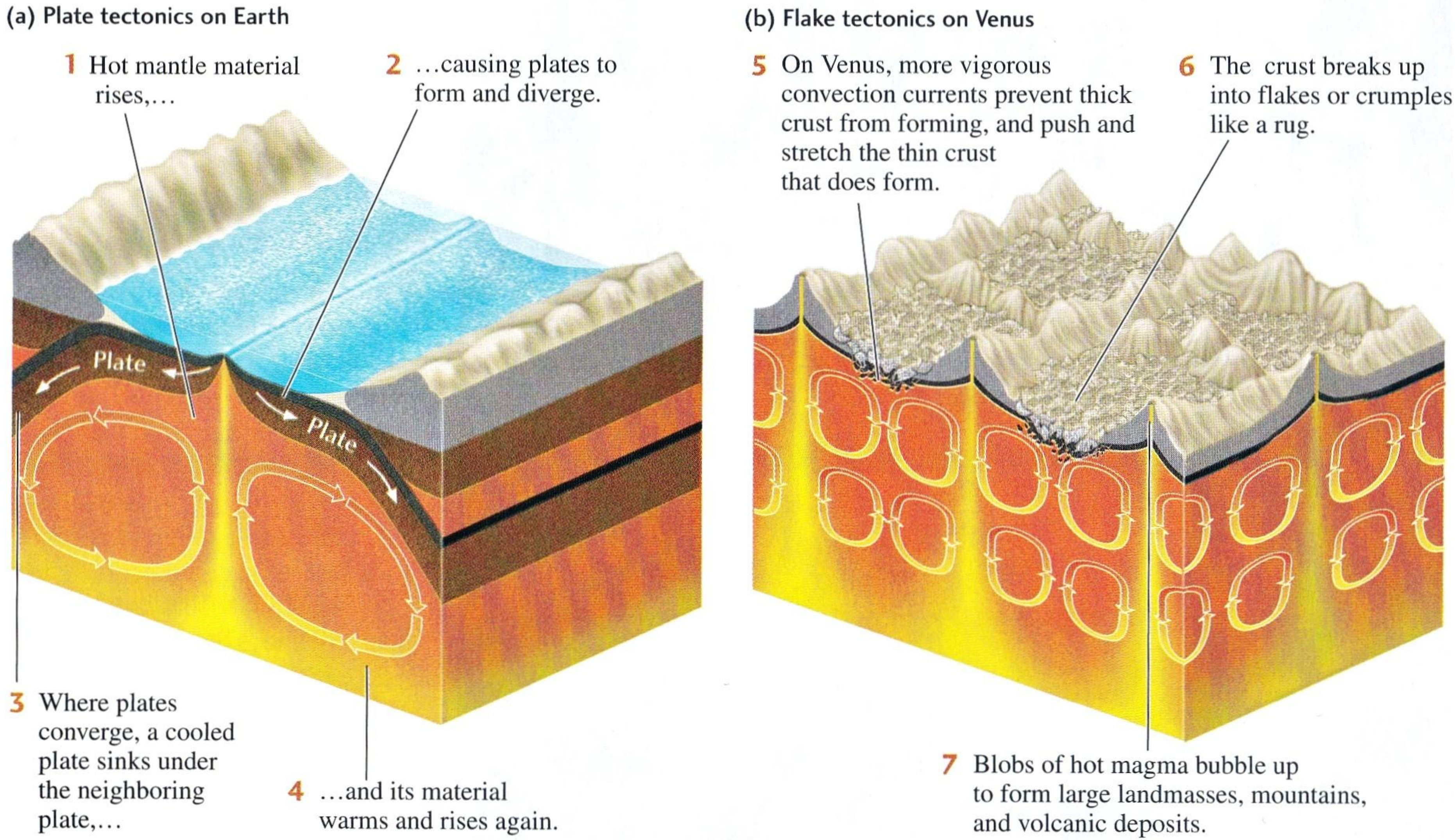
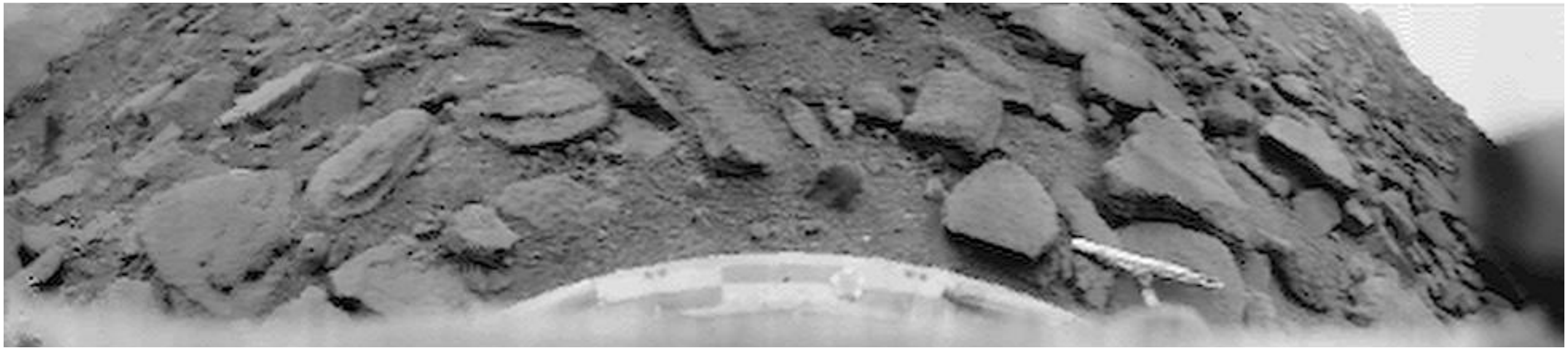


FIGURE 9.16 ■ Flake tectonics on Venus is very different from plate tectonics on Earth, but could be similar to tectonic processes on early Earth.

Understanding Earth

Venera missions to Venus launched by the Soviet Union (1961-1983)



Venera 9 Lander image taken in 1979
Venera 13 Lander image taken in 1981

Images processed by Don P. Mitchell

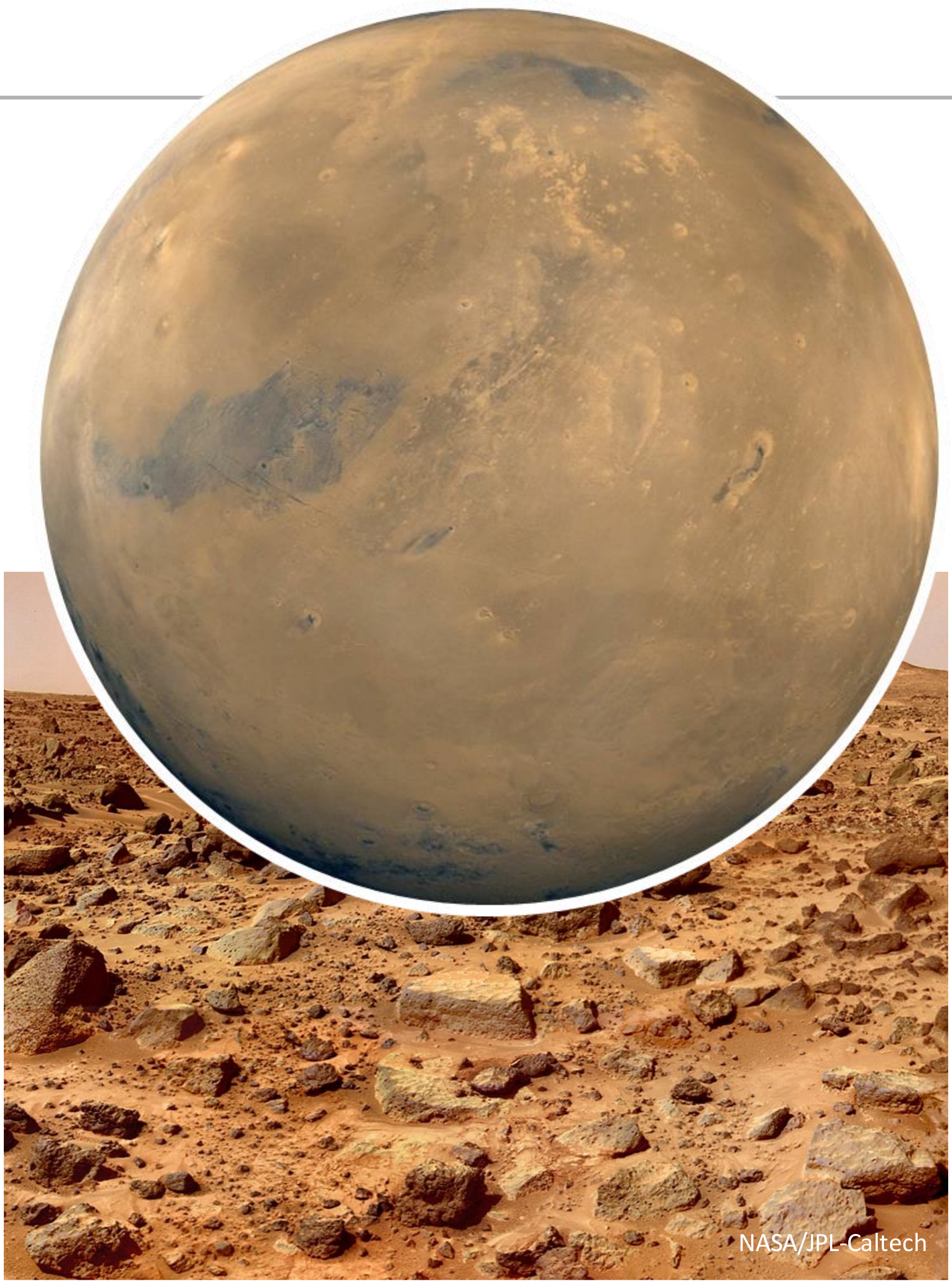
• Mars

- Mars is red because its surface is covered with iron oxide/hydroxide dust (rust).

- Water occurs on Mars as ice on and below the ground and as gas in the atmosphere.

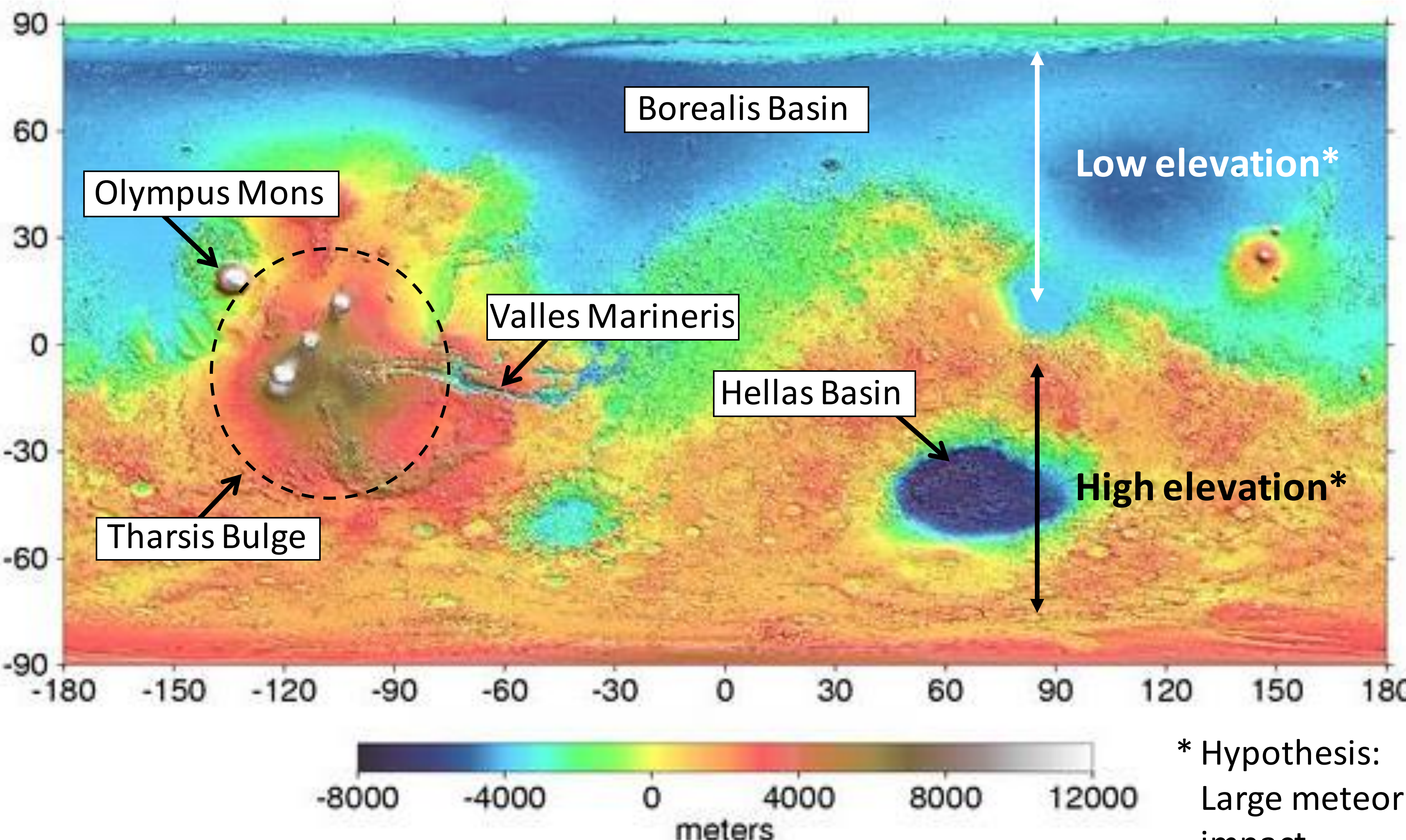
- The low temperature and low atmospheric pressure means that liquid water cannot occur today permanently at the surface of Mars.

- There is evidence of liquid water present on the surface of Mars in the distant past.


NASA/JPL-Caltech

Mars topography

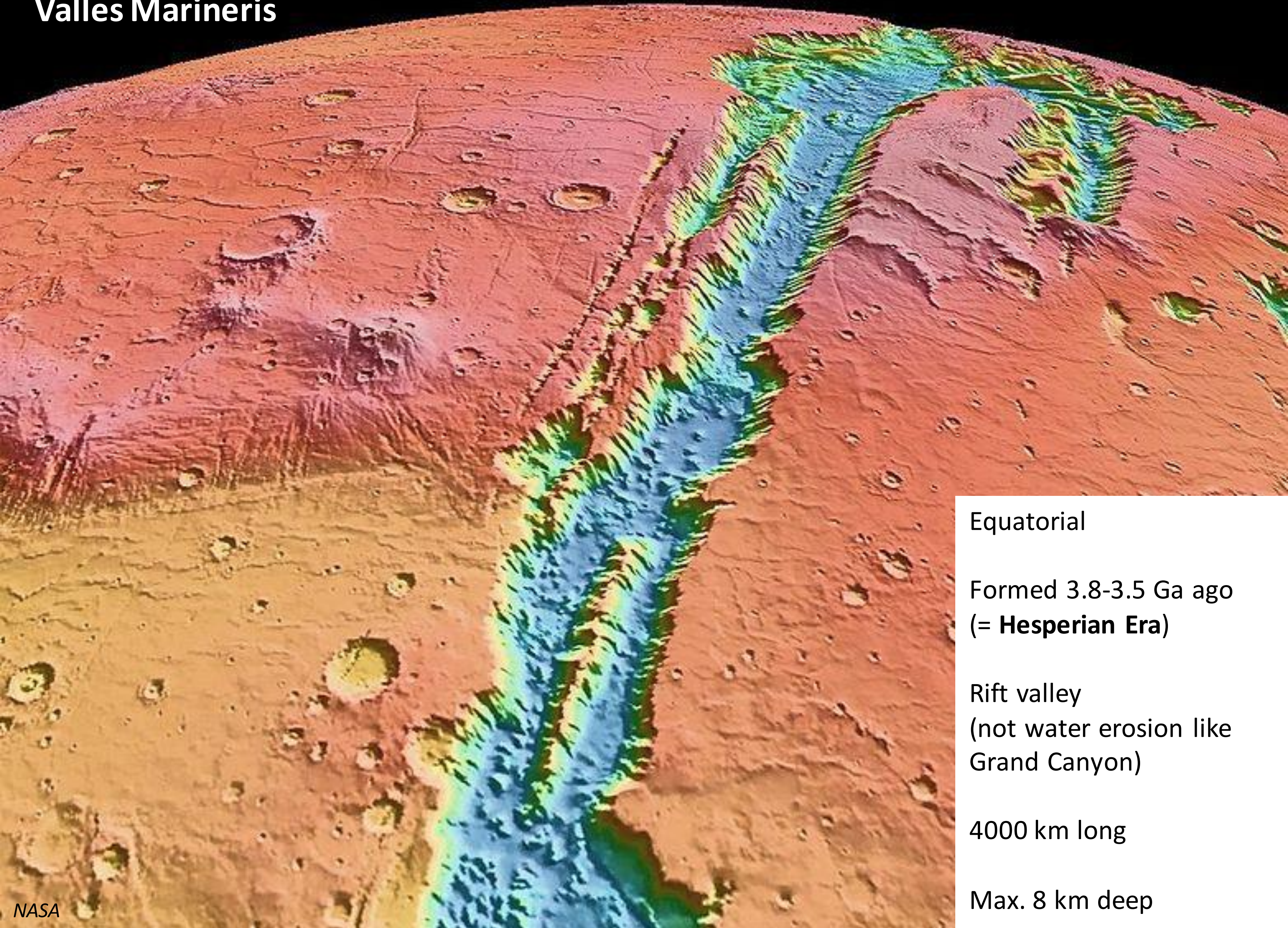
Olympus Mons height = 25 km   Valles Marineris depth = 8 km



* Hypothesis: Large meteorite impact

NASA

Valles Marineris



Equatorial

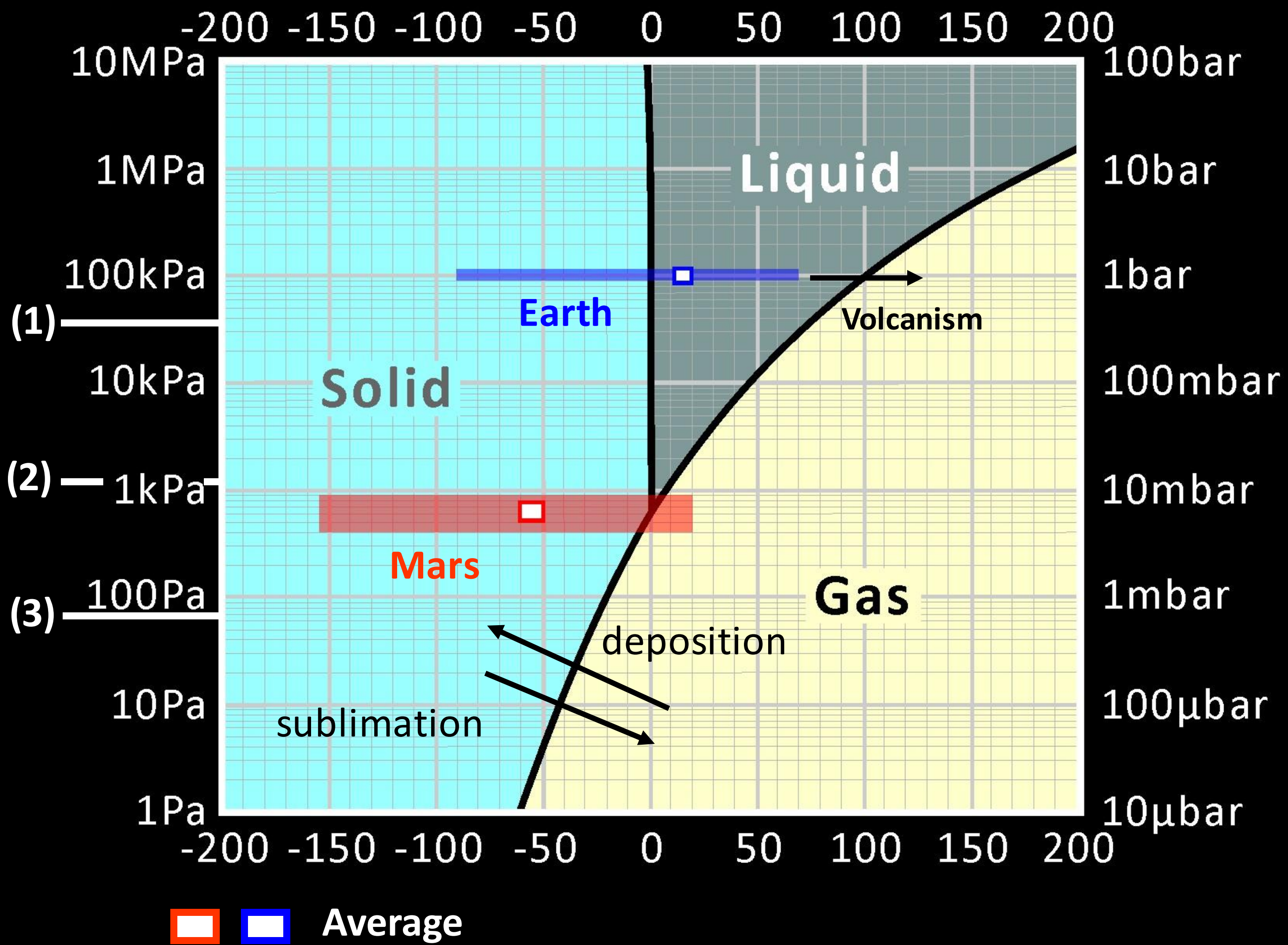
Formed 3.8-3.5 Ga ago
(= **Hesperian Era**)

Rift valley
(not water erosion like
Grand Canyon)

4000 km long

Max. 8 km deep

PHASE DIAGRAM OF WATER



(1) Atmospheric pressure at the top of Mount Everest, 8,850 m (0,3 bars)

(2) Atmospheric pressure at the bottom of Hellas Planitia, a 7-km deep depression on Mars (14 mbars)

(3) Atmospheric pressure at the top of Olympus Mons, highest elevation on Mars, 25 km (3 mbars)

Water on Mars

- Current conditions on Mars are not favorable for the formation of liquid water at or near the surface for an extensive period of time (very low temperatures and very low atmospheric pressures). There is however evidence for seasonal flows of liquid brines.

- Water is mainly present as **ICE**:

    POLAR ICE CAPS composed of water ice (H_2O) and dry ice (CO_2).

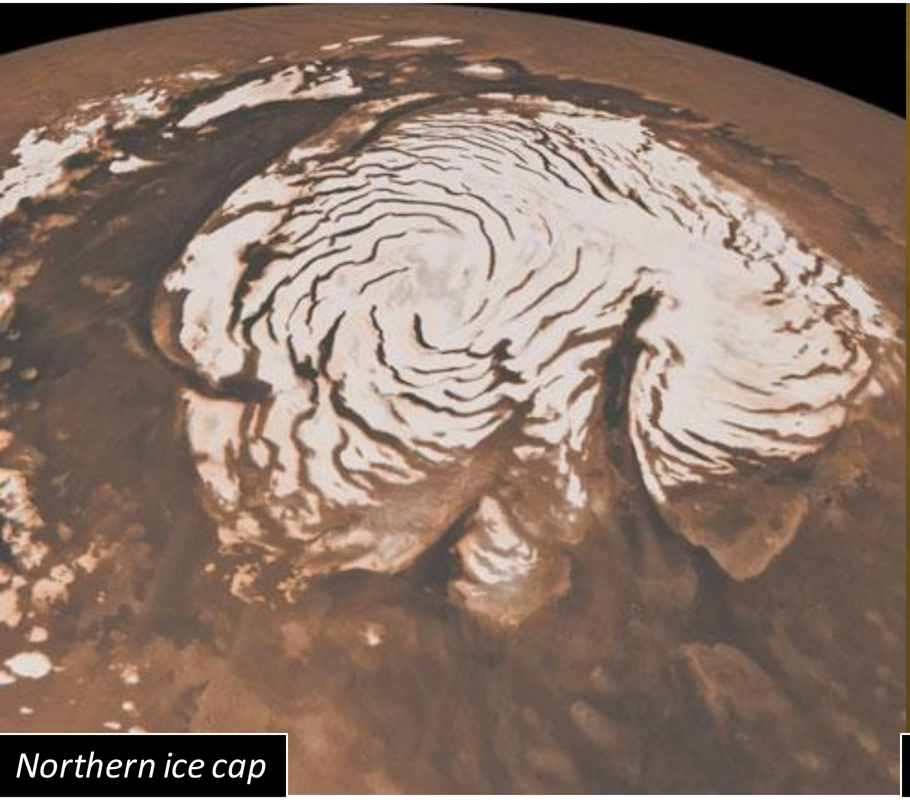
    SUBSURFACE ICE found from mid-latitudes to poles (soil prevents ice from sublimating).

    FROST at the surface of the ground (not permanent).

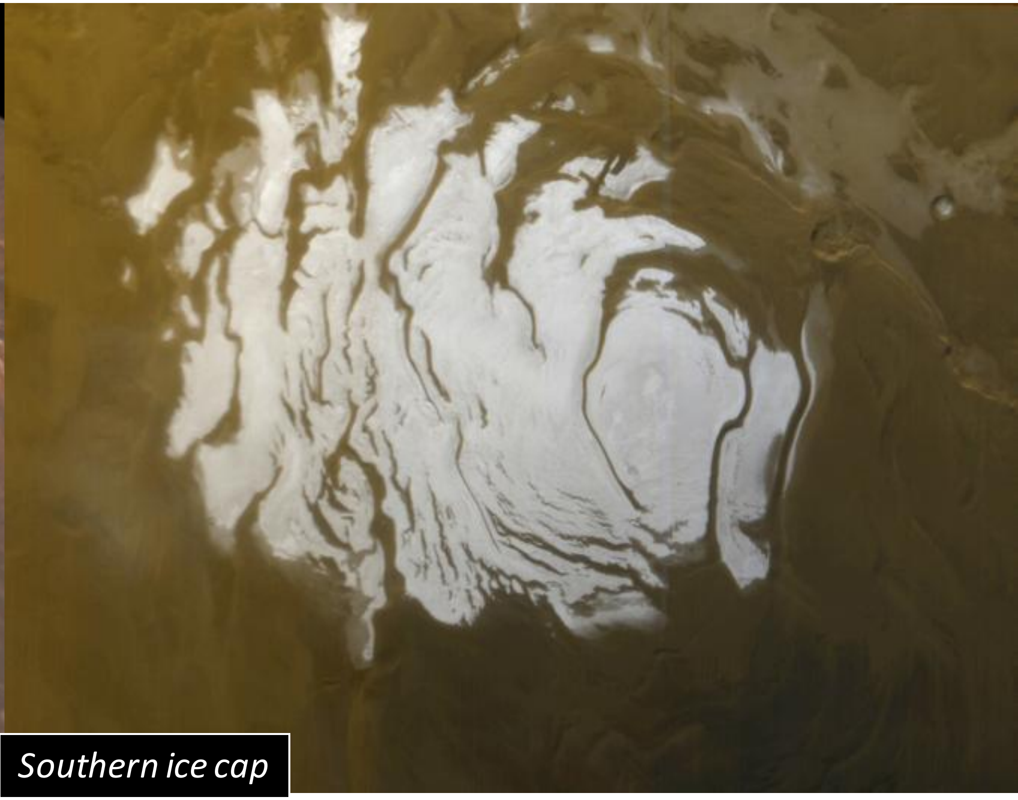
- Some water is also present as **GAS** in the atmosphere.

POLAR ICE CAPS are composed of an external layer of CO_2 ice (dry ice) underlain by water ice (in summer, water ice is exposed to the air in the NH but not in the SH)

Northern Ice Cap

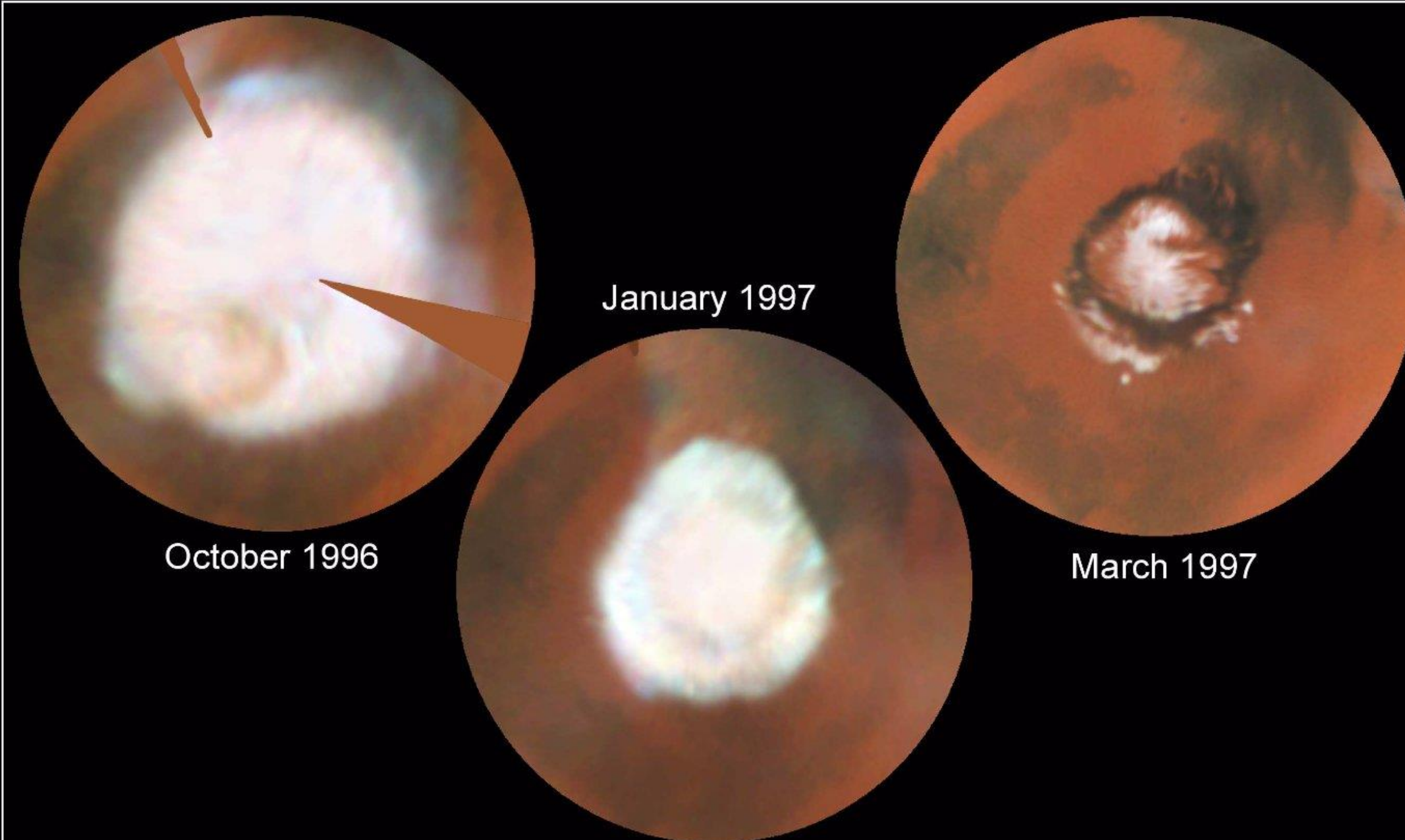


Southern Ice Cap



The dry ice sublimates in summer (seasonal ice). This results in large seasonal variations of CO_2 in the Martian atmosphere, which cause large variations of atmospheric pressure.

Mars Global Surveyor Mission NASA/JPL-Caltech/MSSS



Mars • North Polar Cap

Hubble Space Telescope • WFPC2

PRC97-15b • ST ScI OPO • May 20, 1997 • P. James (Univ. Toledo), T. Clancy (Space Science Institute), S. Lee (Univ. Colorado) and NASA

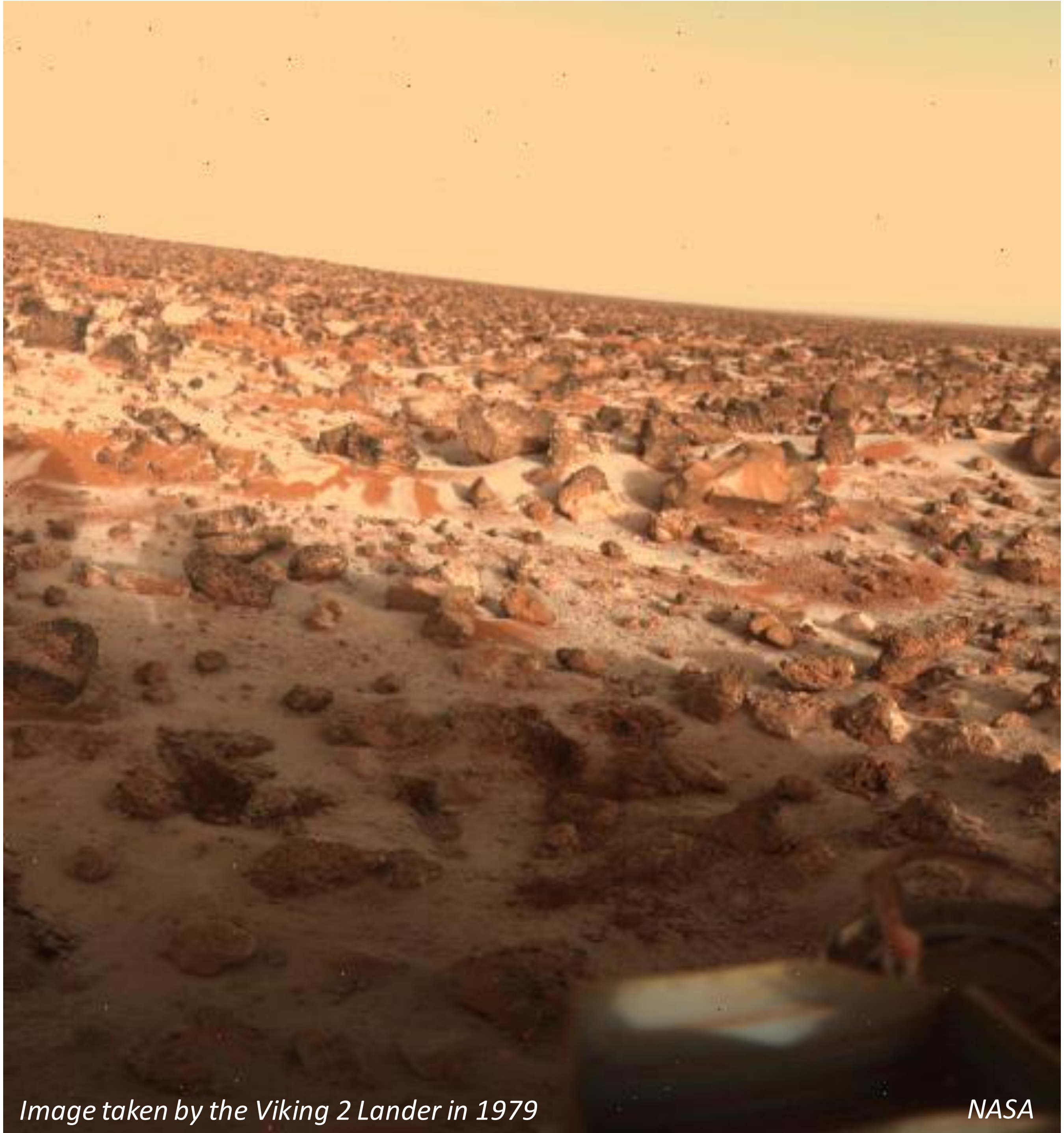
SUBSURFACE ICE

Images taken by Phoenix Mars Lander on June 15 and 19 2008

Ground ice sublimation

NASA/JPL-Caltech/University of Arizona/Texas A&M University

FROST



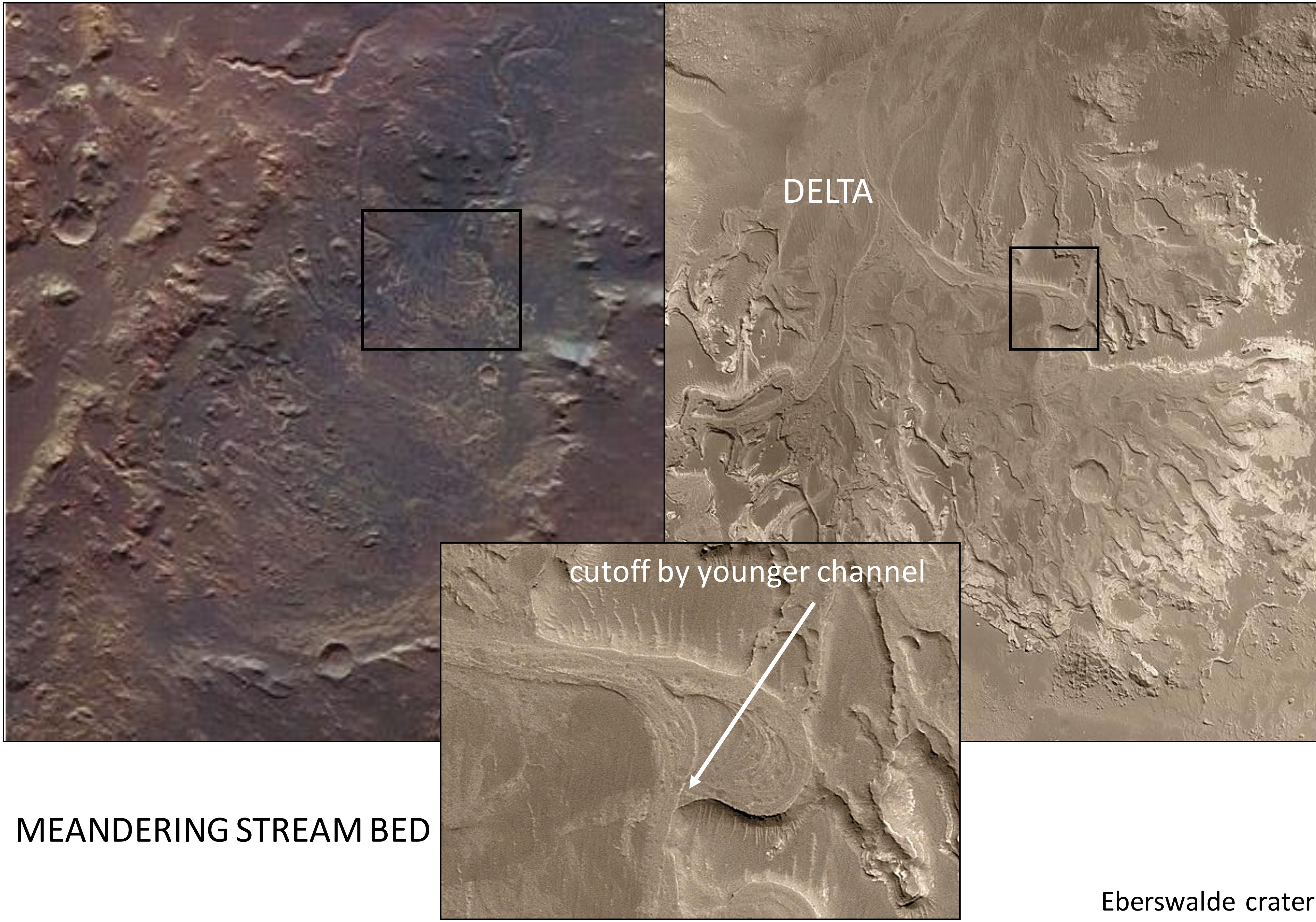
Evidence for the presence of liquid water in the past

Various lines of evidence (mostly 3-4 Ga ago)

1. Surface morphological features
   - **MEANDERING STREAM BEDS, DELTAS**
   - **OUTFLOW CHANNELS** (extremely large channels)
   - **Frozen sea?**

2. Lithology and sedimentology
   - **LAYERED SEDIMENTARY ROCKS**
   - **CROSS-STRATIFICATIONS**
   - **RIVER CONGLOMERATES**

3. Mineralogy
   - **MINERALS** that form in the presence of liquid water



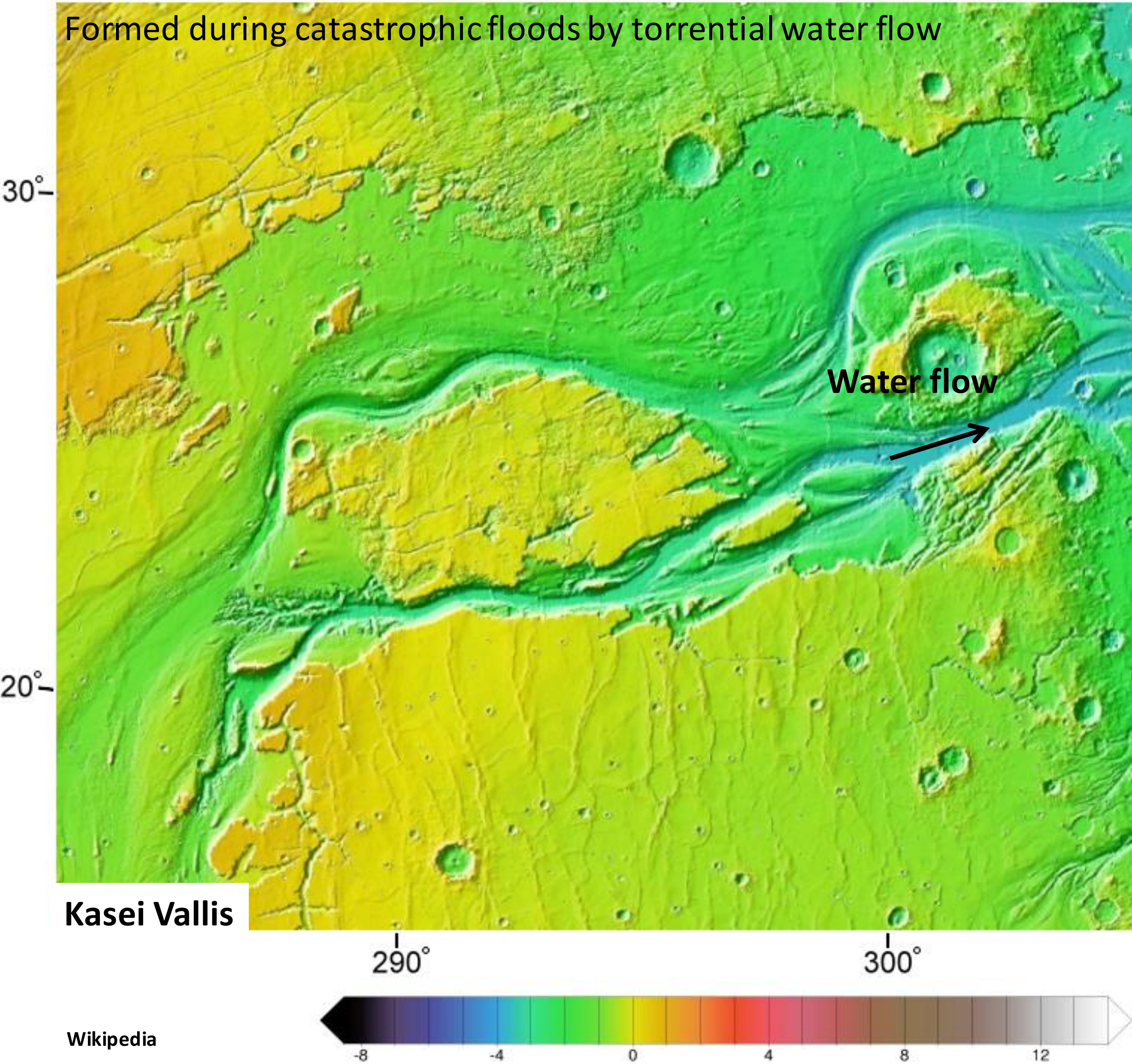
MEANDERING STREAM BED

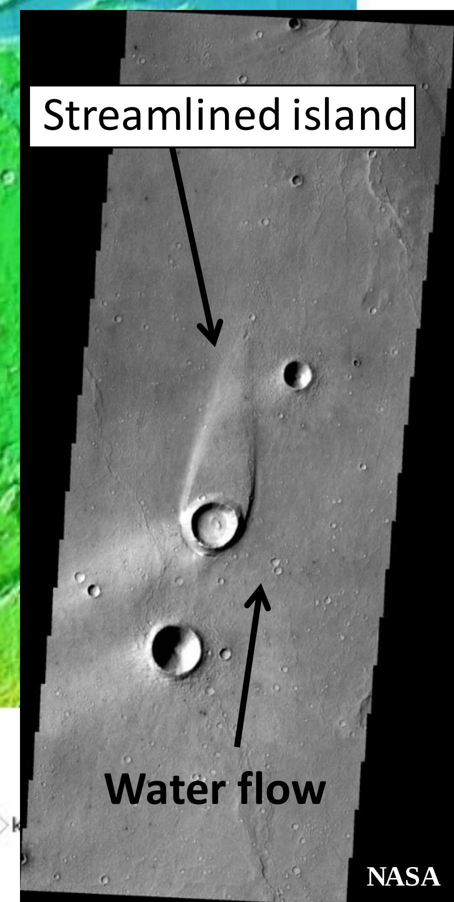
Eberswalde crater

NASA/JPL-Caltech/MSSS

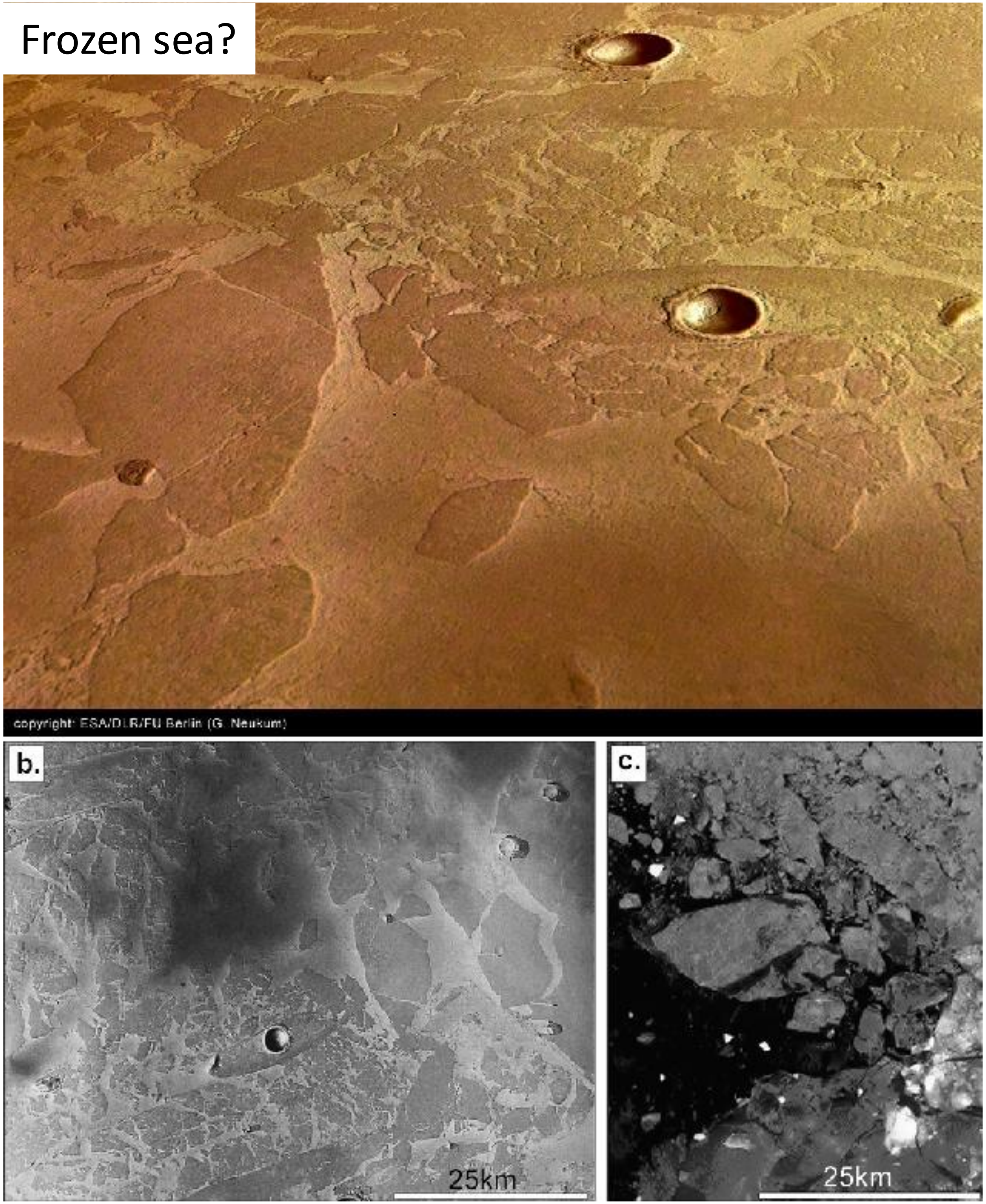
Large outflow channels (up to 100 km wide and 1000 km long)

Formed during catastrophic floods by torrential water flow





Frozen sea?



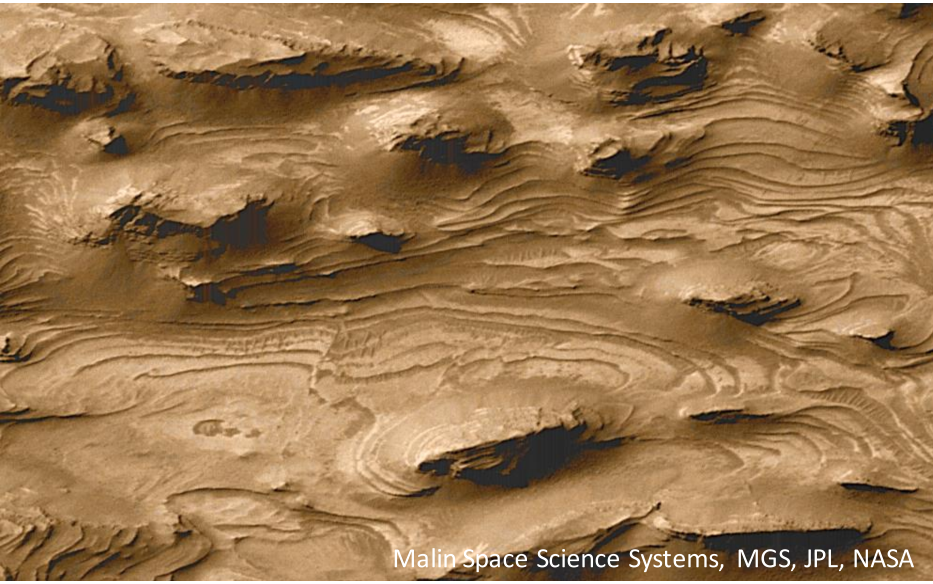
Images of the 'frozen sea' on Mars (a,b) from the High Resolution Stereo Camera of the ESA Mars Express mission, and pack-ice (c) in the terrestrial Antarctic.

Source: Matt Balme (the Open University)

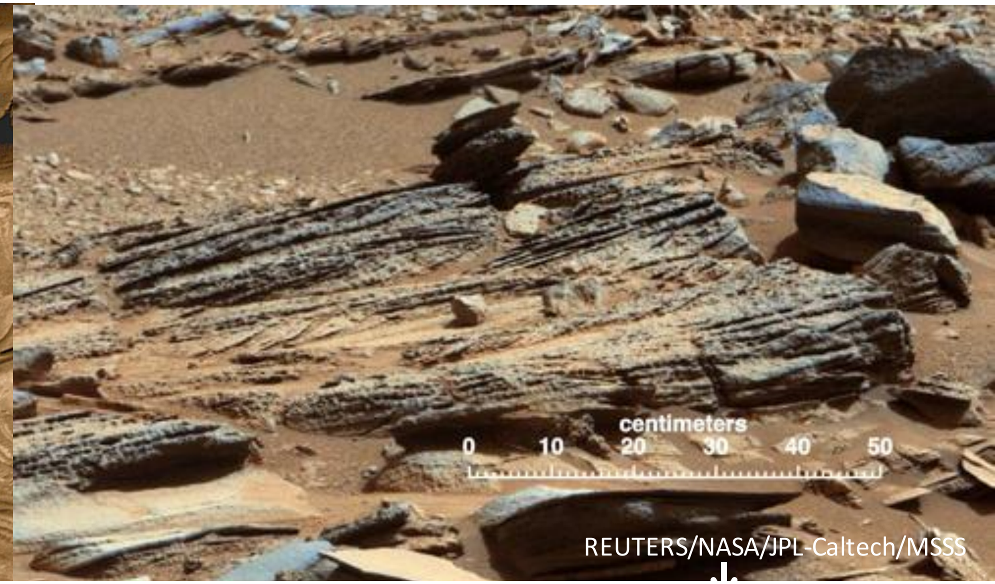
Water probably came from an underground source and came out through fractures. The water froze and formed pack ice before it became completely solid. The ice was covered by a layer of dust which prevented sublimation.

Lithology and sedimentology

Layered rocks in Candor Chasma



Cross-stratification (evidence of stream flow)

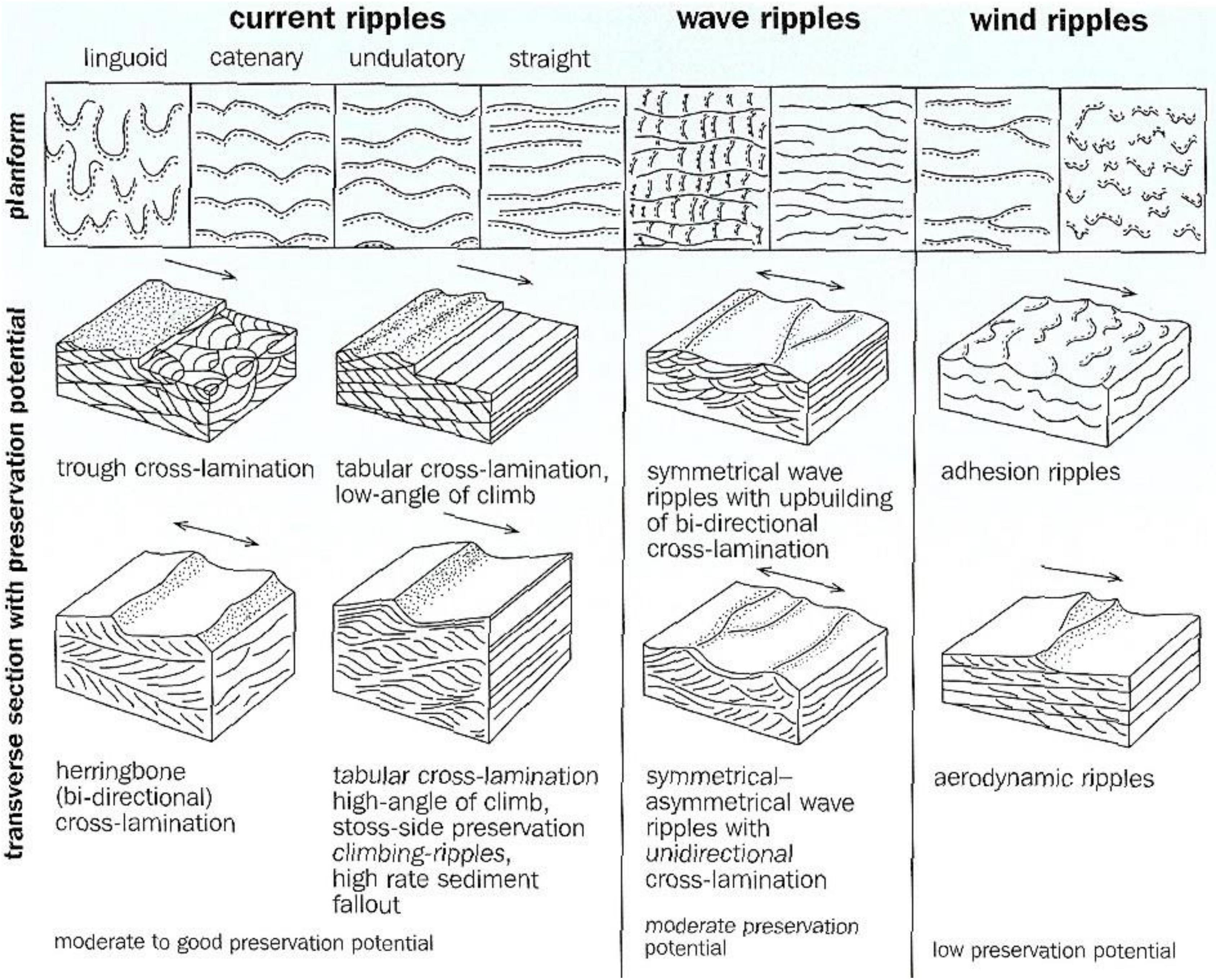


Ancient stream bed composed of sedimentary gravels and pebbles

Mars

3-cm large rounded gravel

Earth



From Stow (2005)

 SCIENCE • 9 OCTOBER 2015 • VOL 350 ISSUE 6257

Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars

J. P. Grotzinger,[1*] S. Gupta,[2] M. C. Malin,[3] D. M. Rubin,[4] J. Schieber,[5] K. Siebach,[1] D. Y. Sumner,[6] K. M. Stack,[7] A. R. Vasavada,[7] R. E. Arvidson,[8] F. Calef III,[7] L. Edgar,[9] W. F. Fischer,[1] J. A. Grant,[10] J. Griffes,[1] L. C. Kah,[11] M. P. Lamb,[1] K. W. Lewis,[12] N. Mangold,[13] M. E. Minitti,[14] M. Palucis,[1] M. Rice,[15] R. M. E. Williams,[14] R. A. Yingst,[14] D. Blake,[16] D. Blaney,[7] P. Conrad,[17] J. Crisp,[7] W. E. Dietrich,[18] G. Dromart,[19] K. S. Edgett,[3] R. C. Ewing,[20] R. Gellert,[21] J. A. Hurowitz,[22] G. Kocurek,[23] P. Mahaffy,[17] M. J. McBride,[3] S. M. McLennan,[22] M. Mischna,[7] D. Ming,[24] R. Milliken,[25] H. Newsom,[26] D. Oehler,[27] T. J. Parker,[7] D. Vaniman,[14] R. C. Wiens,[28] S. A. Wilson[10]

The landforms of northern Gale crater on Mars expose thick sequences of sedimentary rocks. Based on images obtained by the Curiosity rover, we interpret these outcrops as evidence for past fluvial, deltaic, and lacustrine environments. Degradation of the crater wall and rim probably supplied these sediments, which advanced inward from the wall, infilling both the crater and an internal lake basin to a thickness of at least 75 meters. This intracrater lake system probably existed intermittently for thousands to millions of years, implying a relatively wet climate that supplied moisture to the crater rim and transported sediment via streams into the lake basin. The deposits in Gale crater were then exhumed, probably by wind-driven erosion, creating Aeolis Mons (Mount Sharp).

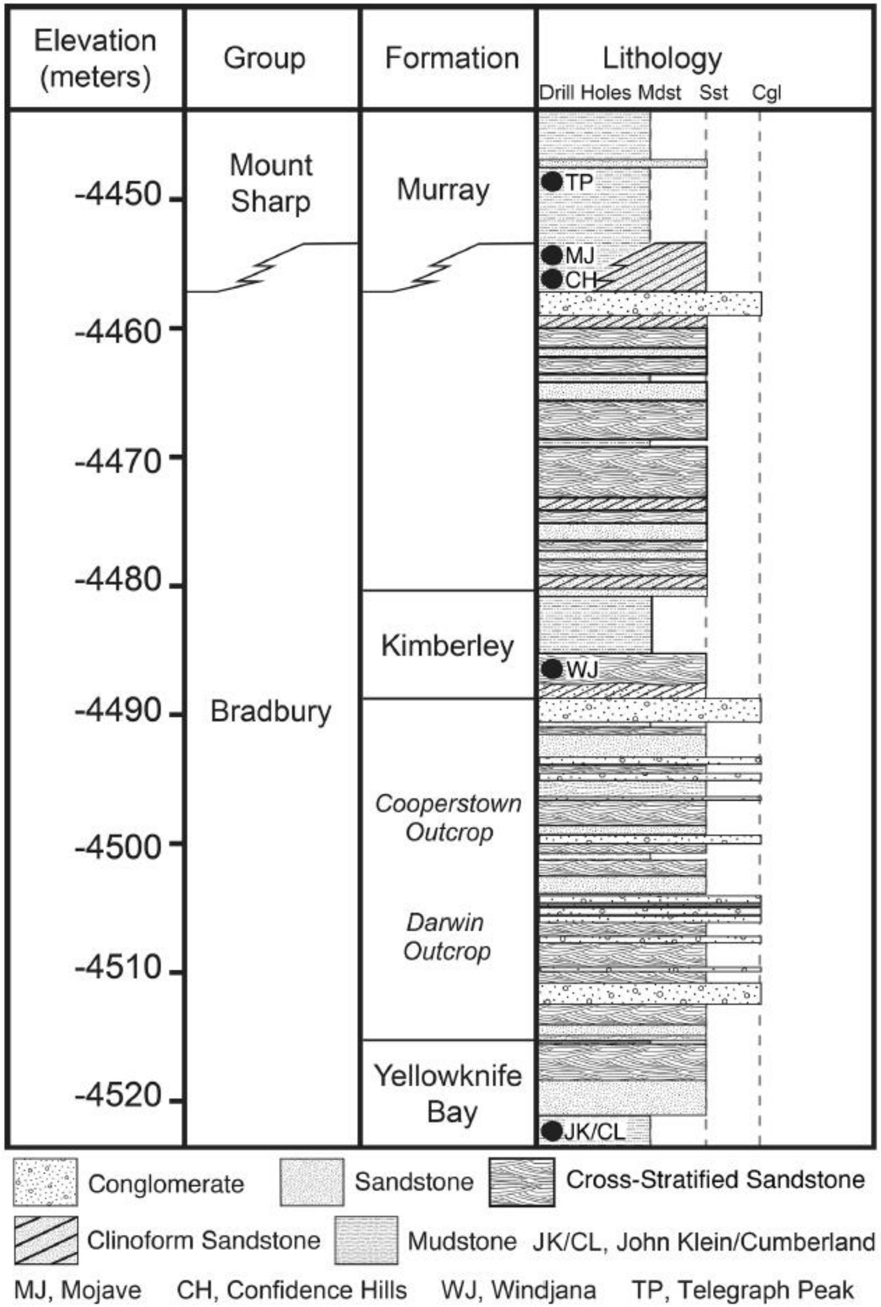
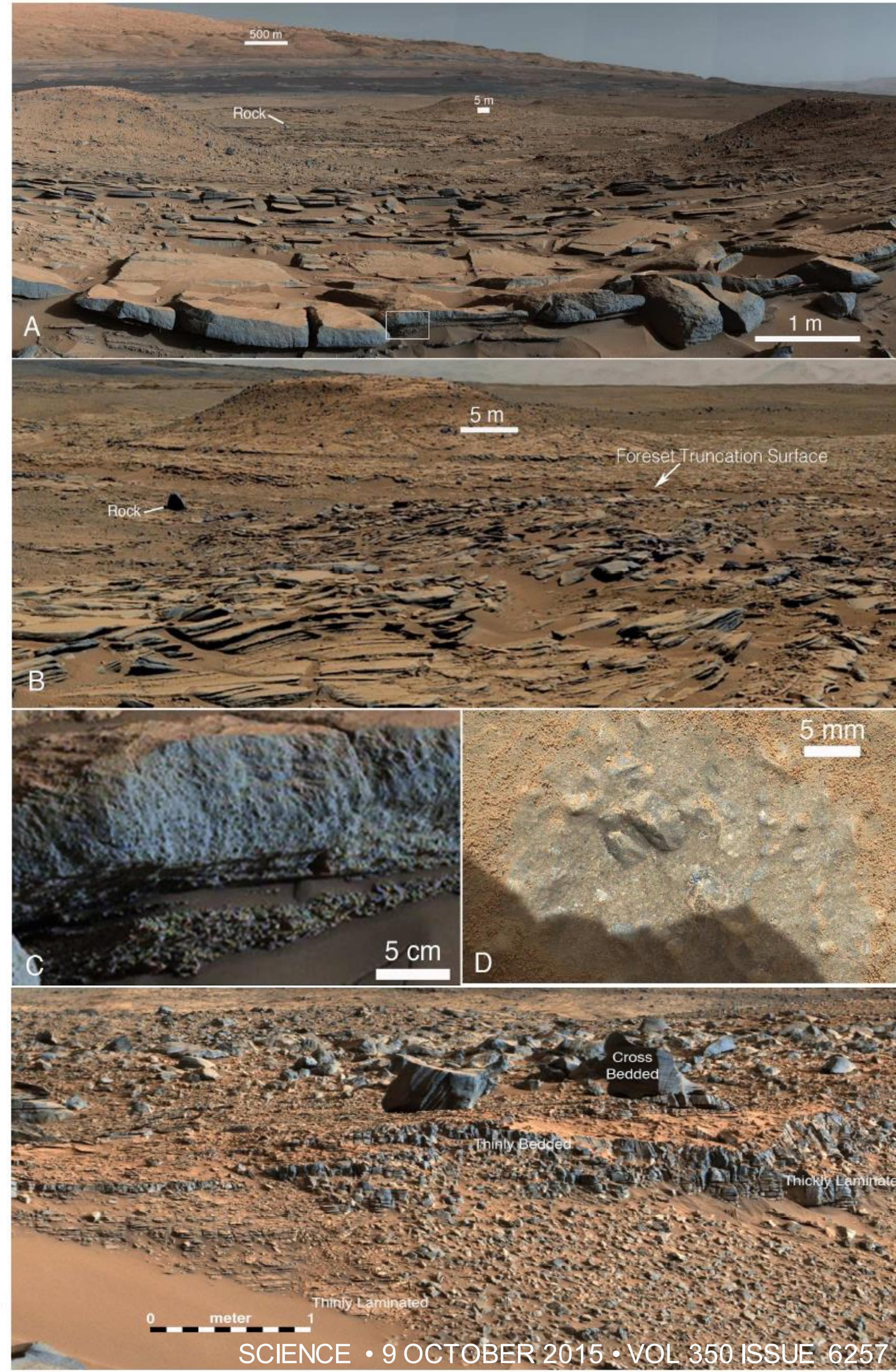


Fig. 2. Stratigraphic column for the sedimentary facies from Yellowknife Bay to Pahrump Hills. The contact between the Bradbury group (Aeolis Palus) and the Mount Sharp group (Aeolis Mons) is marked by interfingering of facies. Mdst, mudstone; Sst, sandstone; Cgl, conglomerate.



Minerals forming in the presence of liquid water and found on Mars:

1. Chloride salts (e.g. NaCl = halite)
2. Hydrated sulfates (e.g. $CaSO_4 \cdot 2H_2O$ = gypsum)
3. Hematite (Fe_2O_3, "blueberries")
4. Clay minerals
5. Hydrated silica ($SiO_2 \cdot nH_2O$ = opal)
6. Carbonates (e.g. $CaCO_3$ = calcite)

Note that the presence of these minerals does not necessarily imply the presence of surface water. These minerals could form underground in presence of groundwater.

"Blueberries": spherules of hematite (max 4 mm large) probably formed below ground surface when Fe^{2+}-rich fluids met with oxidizing groundwater

Credits: Mars Exploration Rover Mission, JPL, NASA (Image by Opportunity)

Image Credit: NASA/JPL - NASA/JPL/Cornell/USGS -

Equivalent on Earth:

Credit: Brenda Beitler, Univ. of Utah

Mars wet past: two competing hypotheses

4-3 billion years ago, Mars experienced…

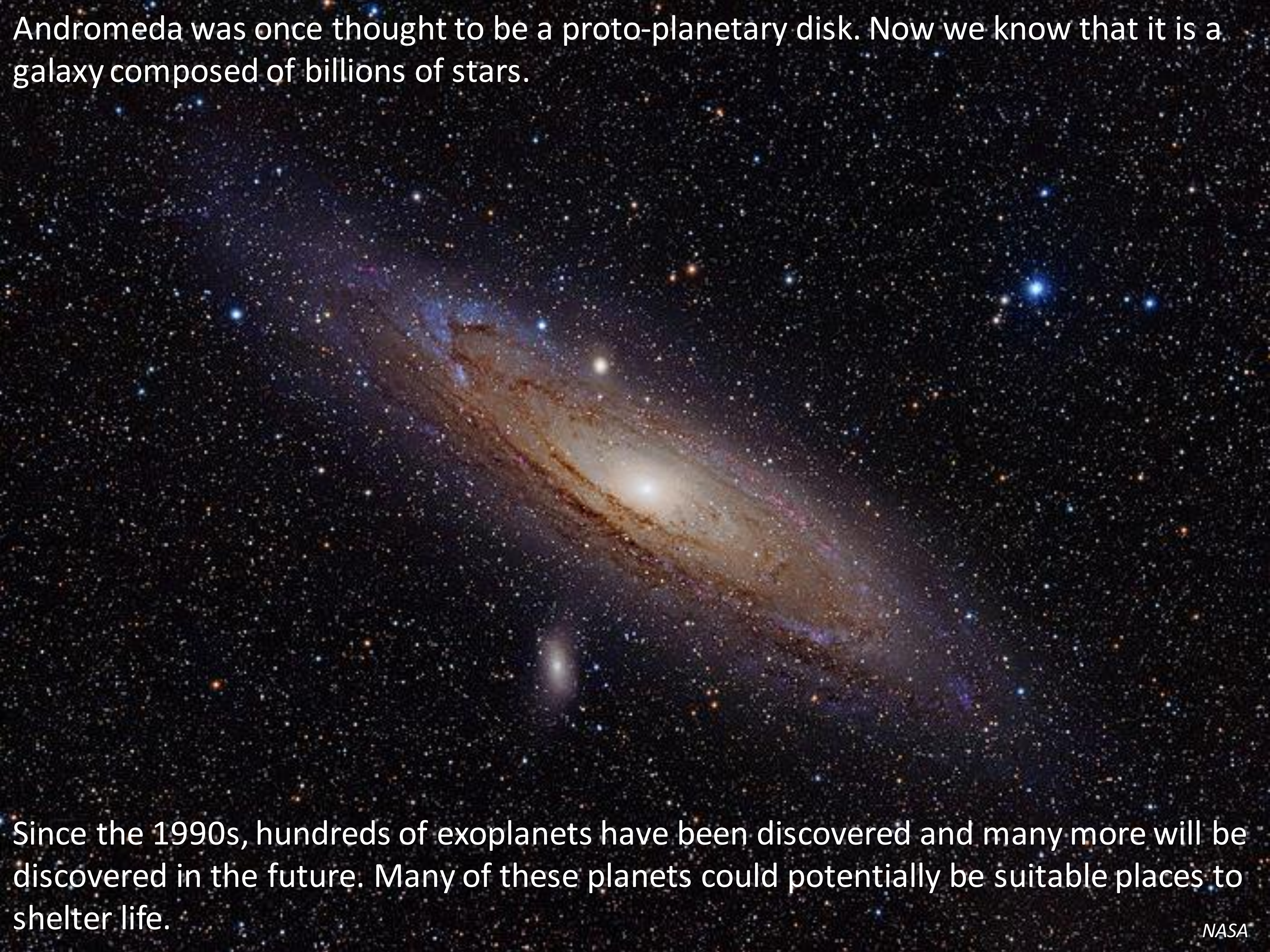
1. A sustained warm, wet period with frequent rain (this implies an atmosphere thicker than today)
= Life-friendly environment

2. An icy and dry period with short-lived catastrophic floods resulting from ice melting events after meteorite impacts or periods of enhanced volcanism
= Life-unfriendly environment

Consensus on the fact that Mars has been icy and (mostly) dry for the past 3 billion years.

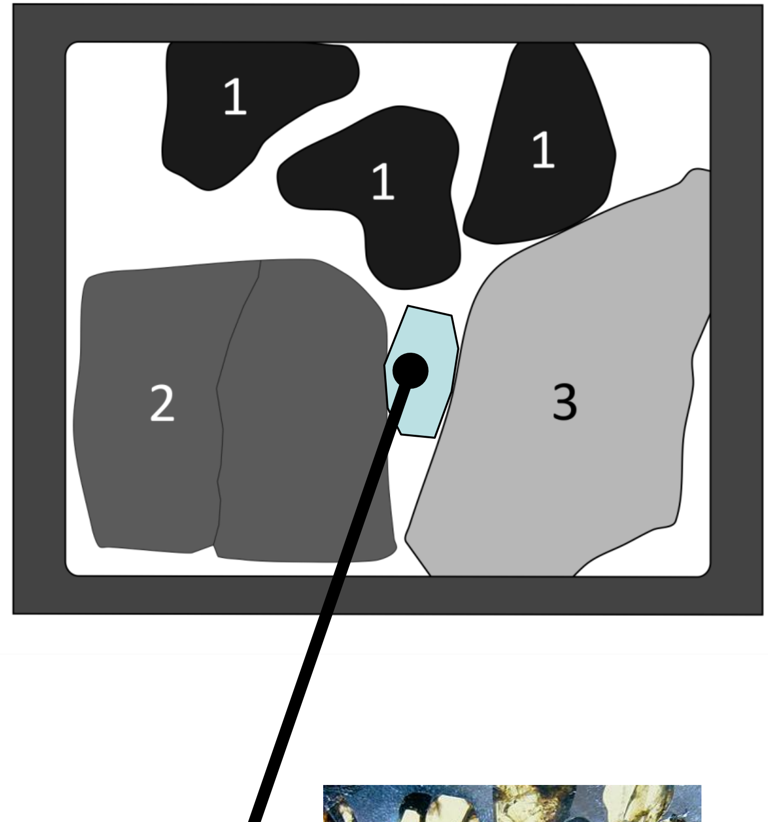
But the underground could be the next place to look for liquid water and perhaps forms of life…

Andromeda was once thought to be a proto-planetary disk. Now we know that it is a galaxy composed of billions of stars.



Since the 1990s, hundreds of exoplanets have been discovered and many more will be discovered in the future. Many of these planets could potentially be suitable places to shelter life.

NASA



1. Carbonaceous chondrite (Allende meteorite)

- Presence of Ca-Al-rich inclusions (white)

  Amongst first solids to have condensed in the protoplanetary disk (oldest age measured in the solar system! → 4.567 Ga)
- Chondrules (rich in olivine and pyroxene)
- Rich in carbon, organic compounds

Undifferentiated, composition of C-type asteroids

---

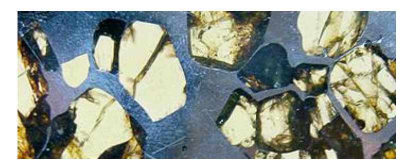
2. Ordinary chondrite

- Chondrules (rich in olivine and pyroxene)
- Rich in iron, nickel

Undifferentiated, composition of S-type asteroids

---

4. Pallasite



Wikipedia

- Rich in iron, nickel
- Rich in olivine inclusions

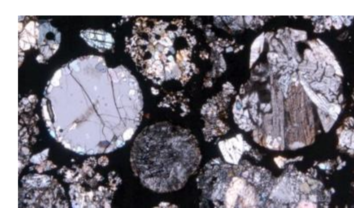
Fragment of the core-mantle boundary of a differentiated object

3. Iron meteorite (Gibeon meteorite)

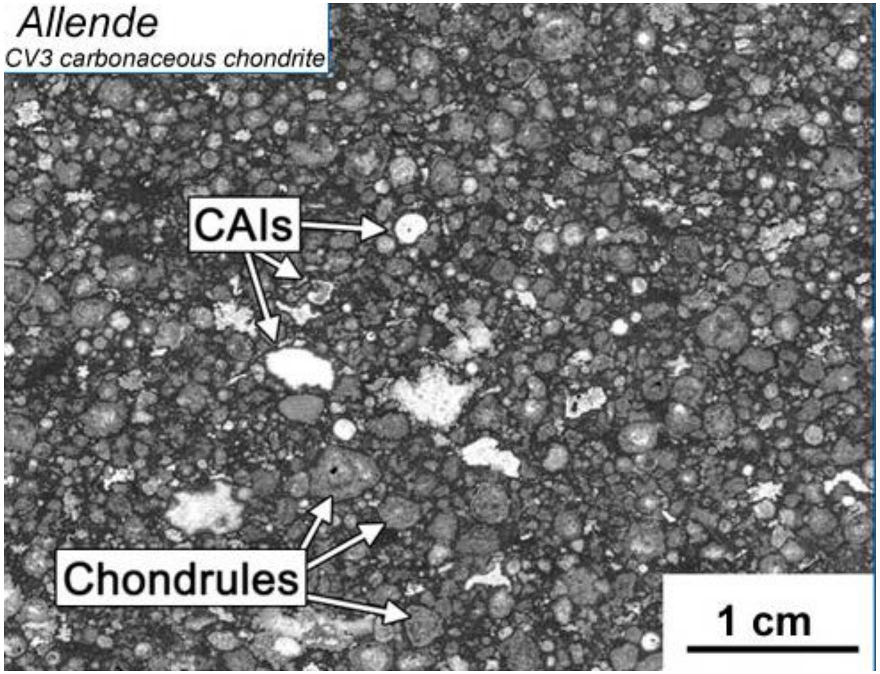
- Rich in iron, nickel

Fragment of the core of a differentiated object

CHONDRULES: few µm to 1 cm spheres made of silicate minerals formed when droplets of molten rock solidified in space → amongst oldest solids in the solar system. https://news.wisc.edu/comet-dust-reveals-unexpected-mixing-of-solar-system/**2019/11/14**

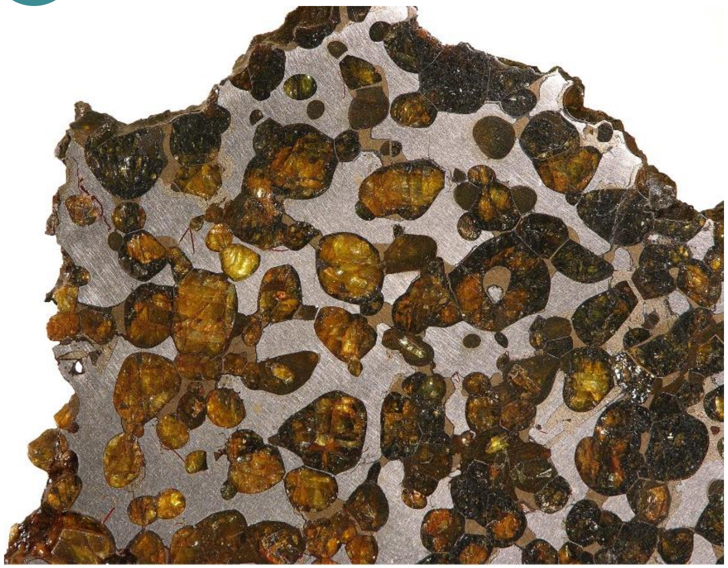


1. Carbonaceous chondrite (Allende meteorite)



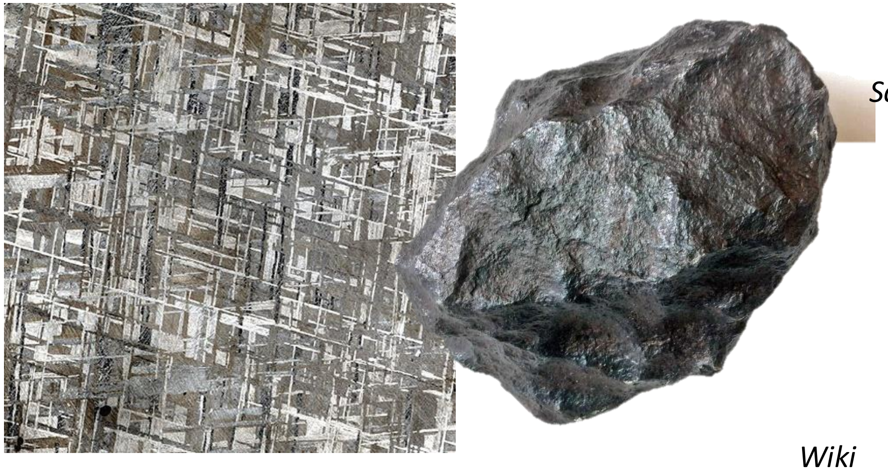
Taylor, G. J., 2012 (www.psrd.hawaii.edu)

4. Pallasite



Scott, E., Goldstein, J., and Yang, J., 2010 (www.psrd.hawaii.edu)

3. Iron meteorite (Gibeon meteorite)



Wiki