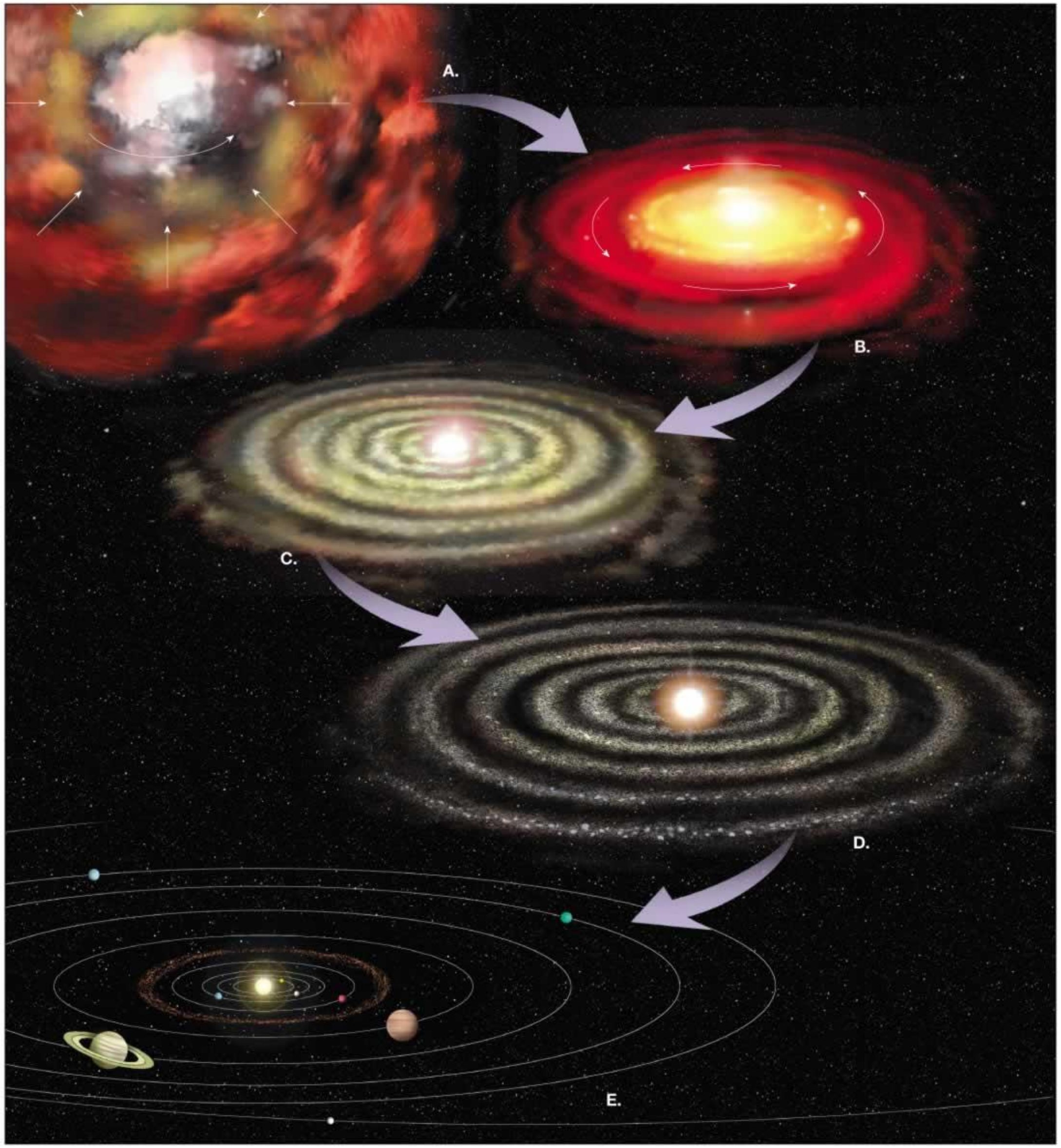
ASTRONOMY
STATE OF THE ART

2. Planets

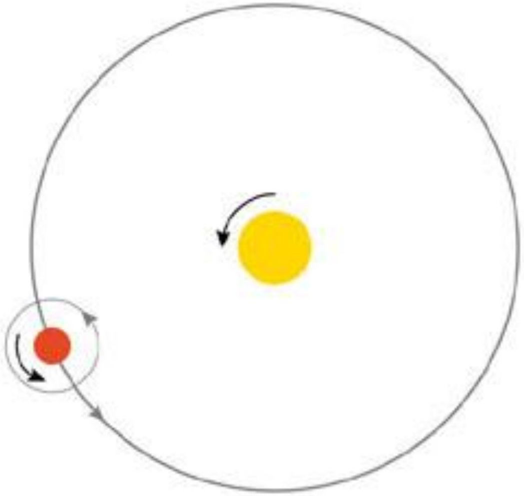
Chris Impey

Distinguished Professor
University of Arizona

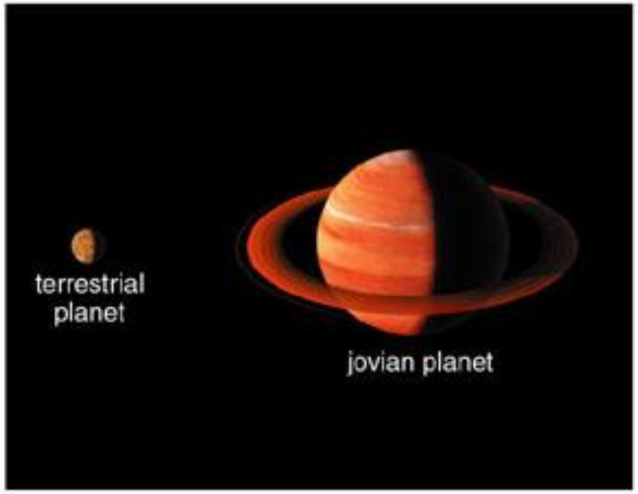
Formation



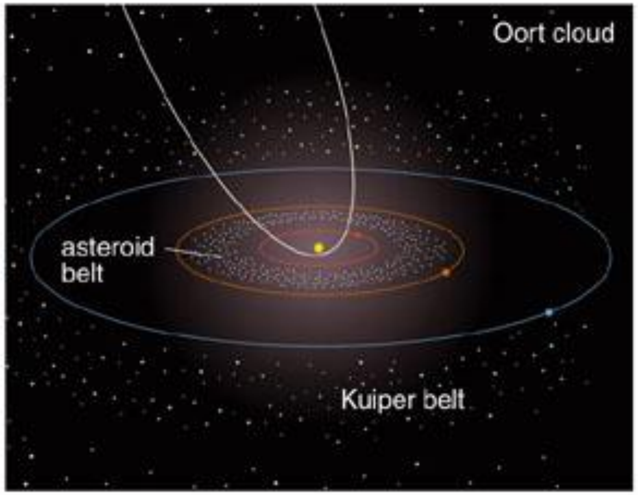
Summary: Four Major Features of our Solar System



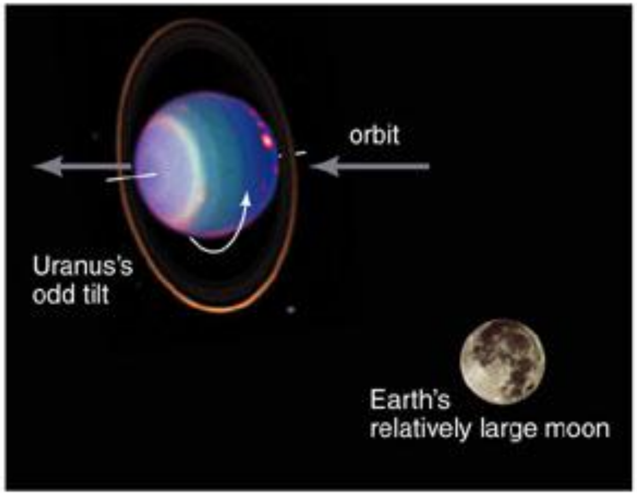
Large bodies in the solar system have orderly motions. All planets and most satellites have nearly circular orbits going in the same direction in nearly the same plane. The Sun and most of the planets rotate in this same direction as well.



Planets fall into two main categories: small, rocky terrestrial planets near the Sun and large, hydrogen-rich jovian planets farther out. The jovian planets have many moons and rings made of rock and ice. Pluto does not fit in either category.

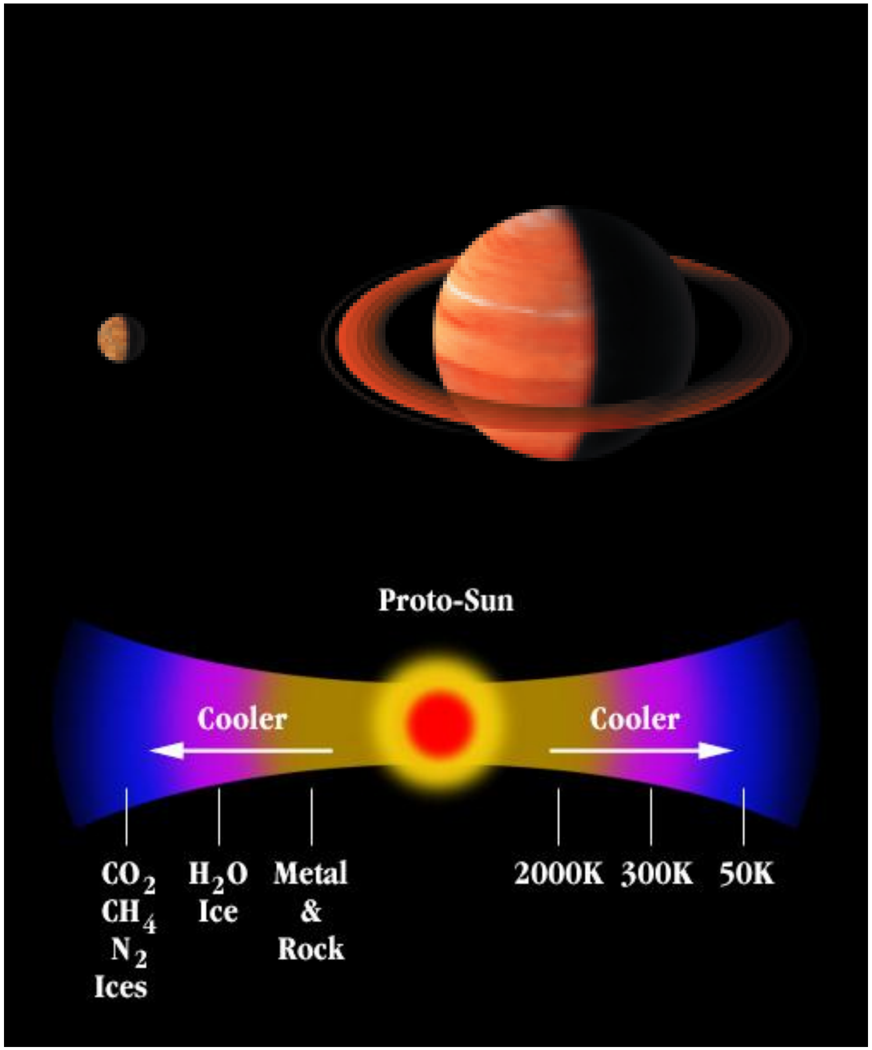


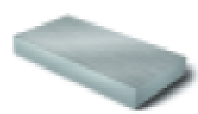
Swarms of asteroids and comets populate the solar system. Asteroids are concentrated in the asteroid belt, and comets populate the regions known as the Kuiper belt and the Oort cloud.

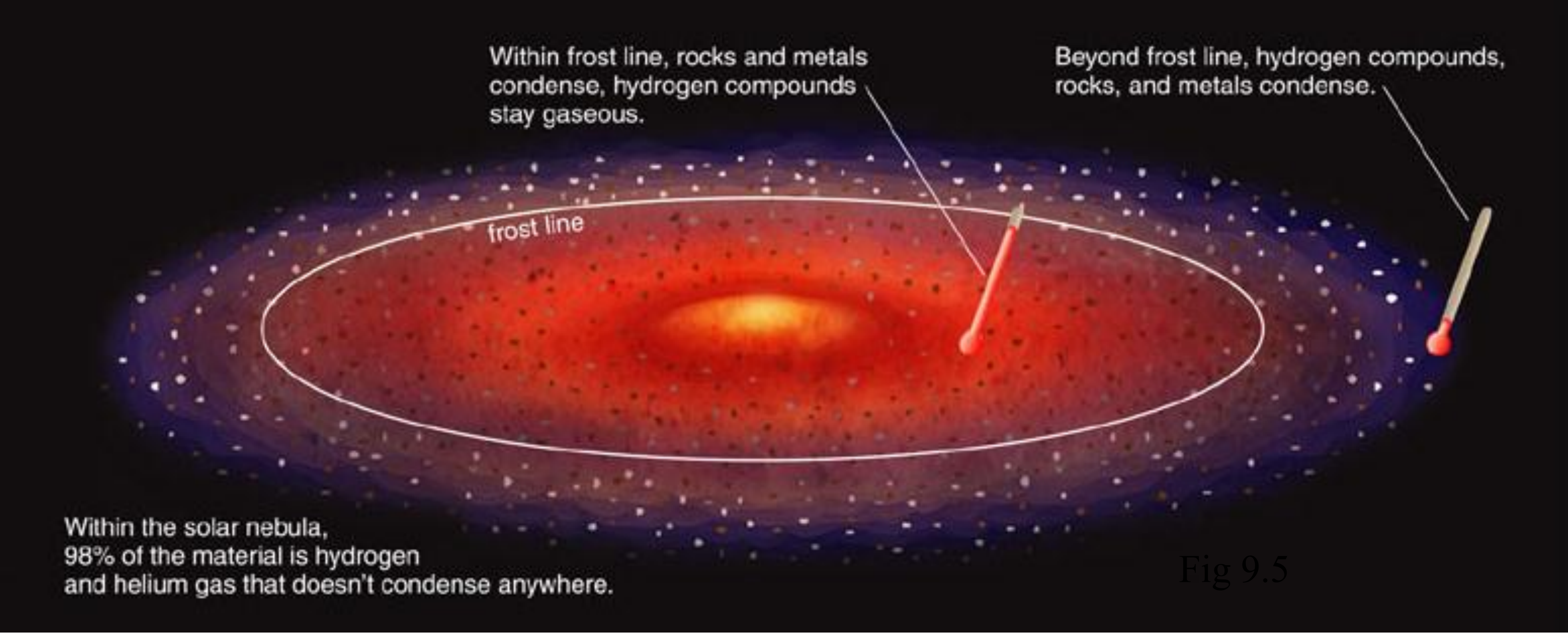


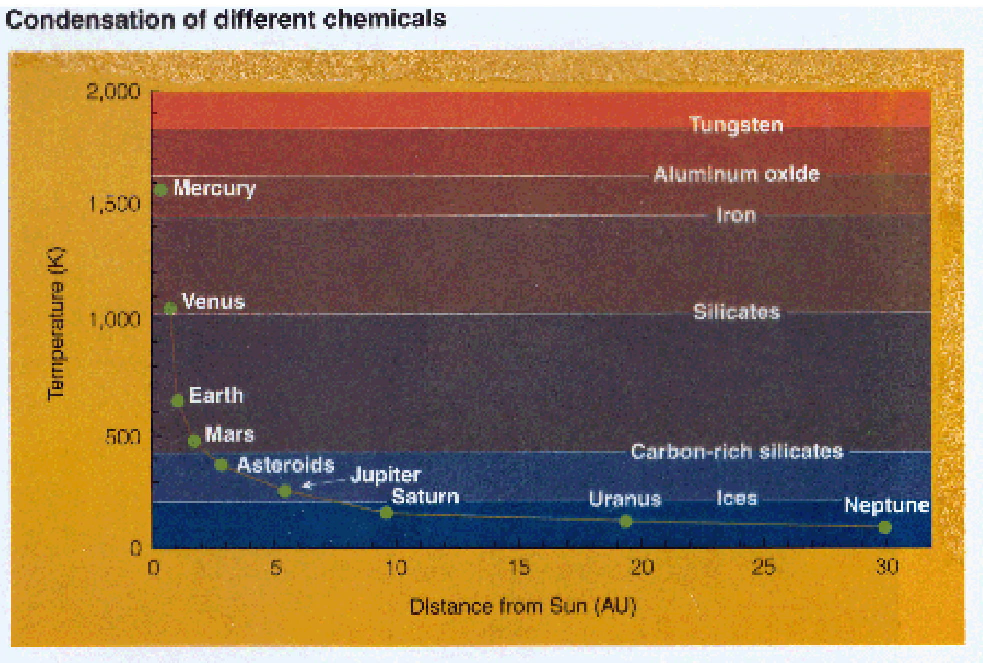
Several notable exceptions to these general trends stand out, such as planets with unusual axis tilts or surprisingly large moons, and moons with unusual orbits.

Why are there two types of planet, when all planets formed from the same nebula?



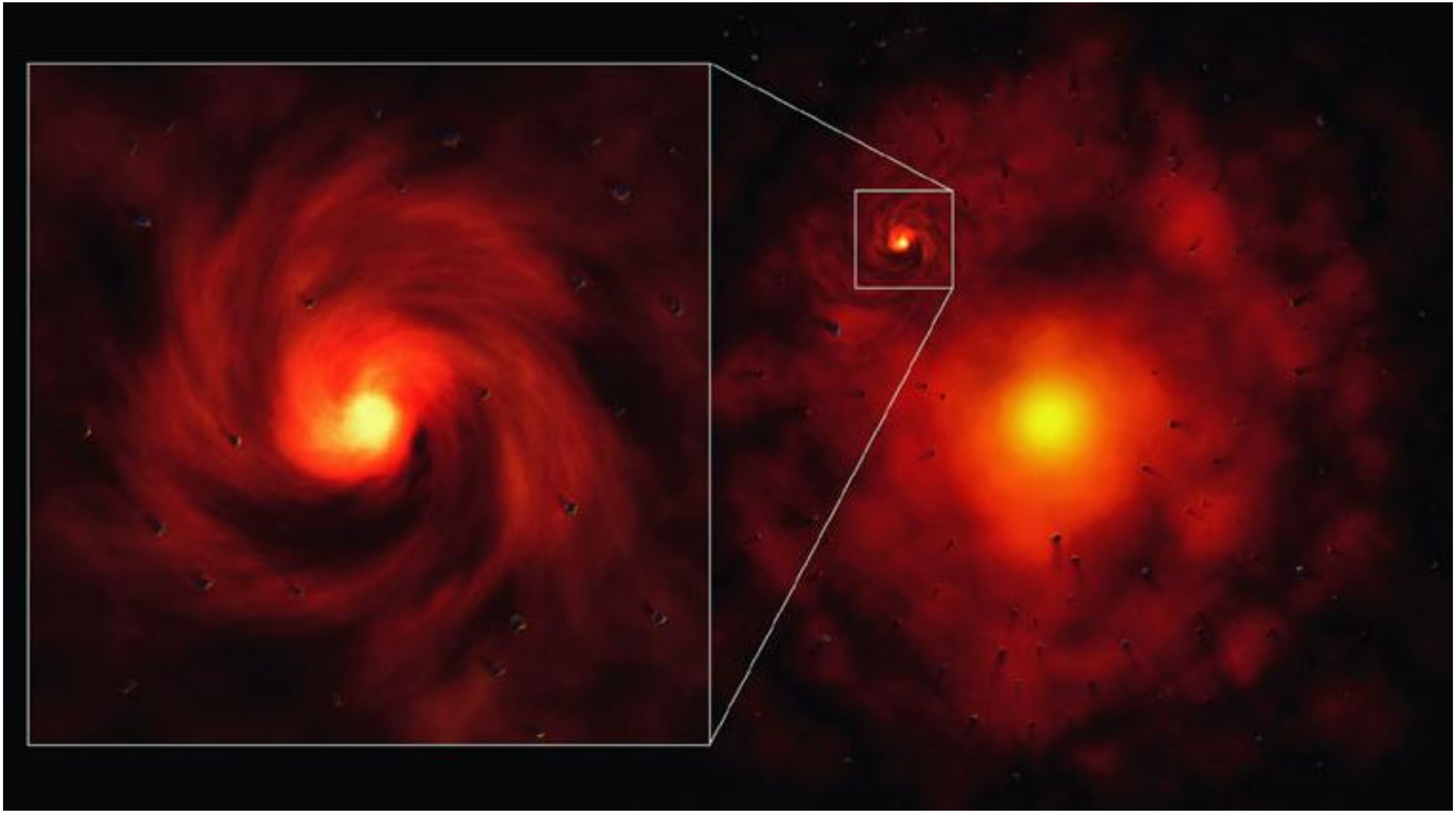
	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1,300 K	0.4%
Metals 	iron, nickel, aluminum	1,000–1,600 K	0.2%



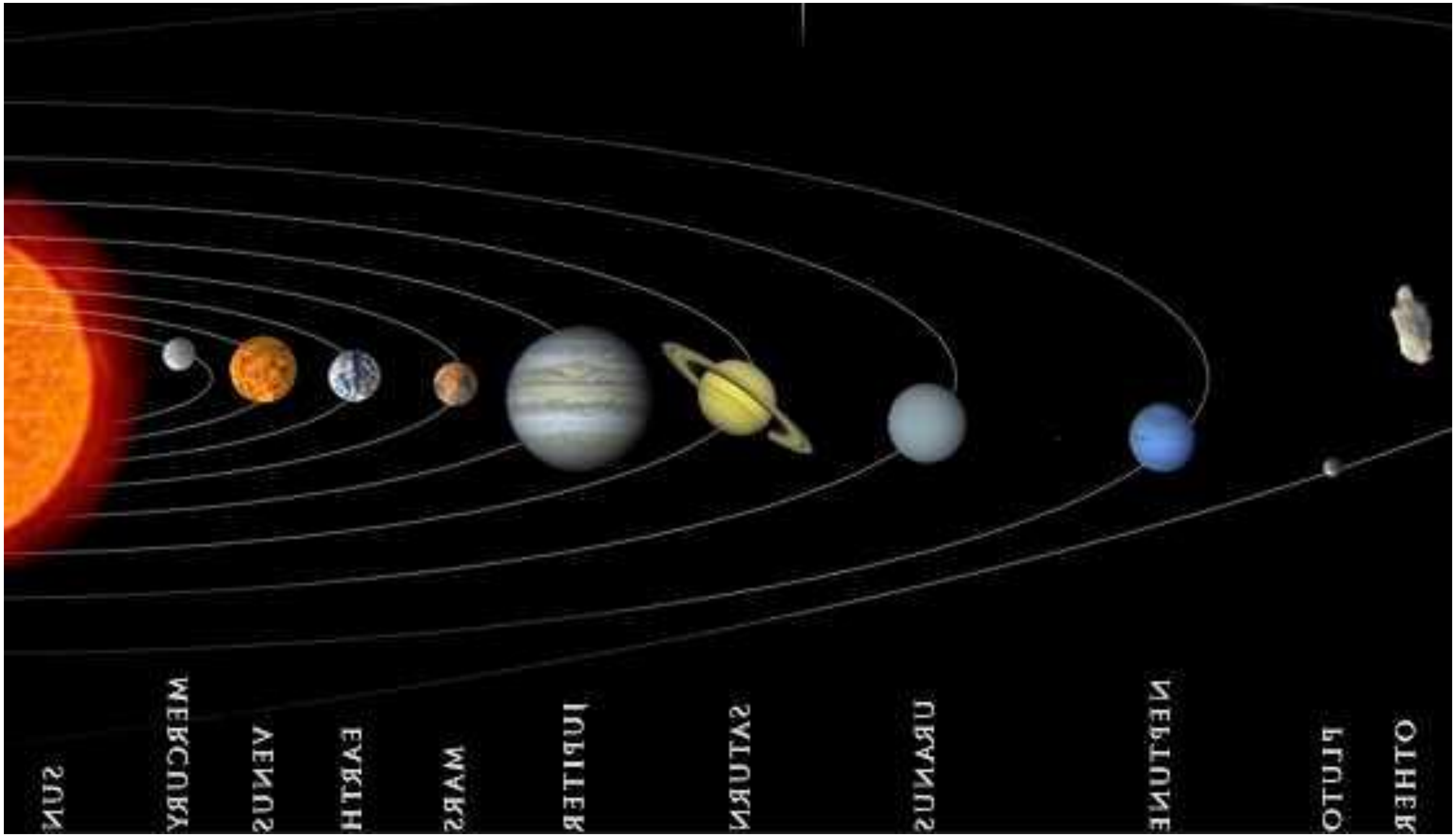


Inside the ***frost line***: it's too hot for hydrogen compounds to form ice.

Outside the ***frost line***: it's cold enough for ice to form.



Moons of the giant planets form in miniature disks

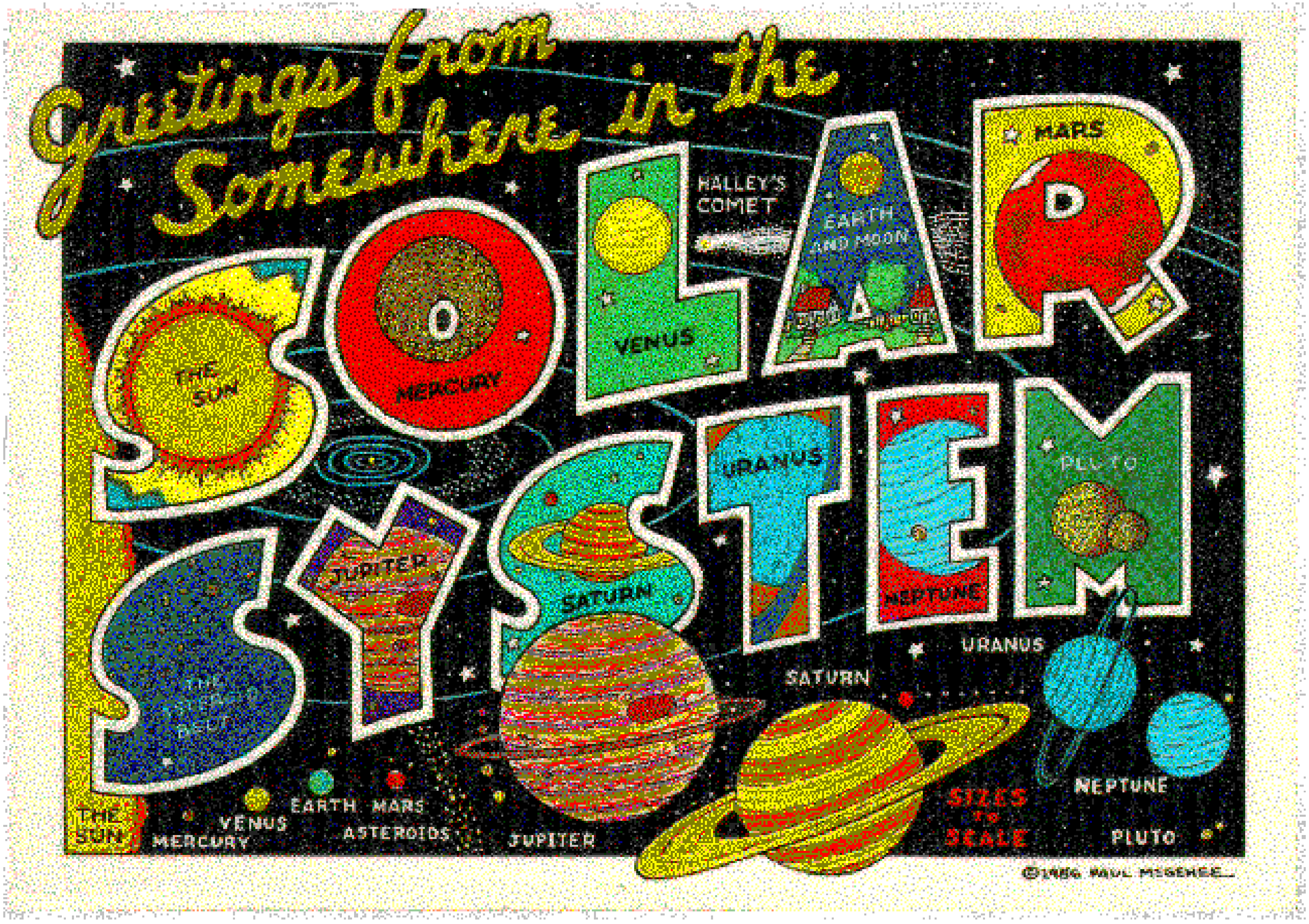


1. Outer planets get bigger because abundant hydrogen compounds condense to form ices over a rocky core.
2. Outer planets accrete and keep H & He gas because they're bigger, so gravity forms a big envelope of gas.

Earth’s moon was probably created when a very large planetessimal hit the newly formed Earth 4.5 by ago.

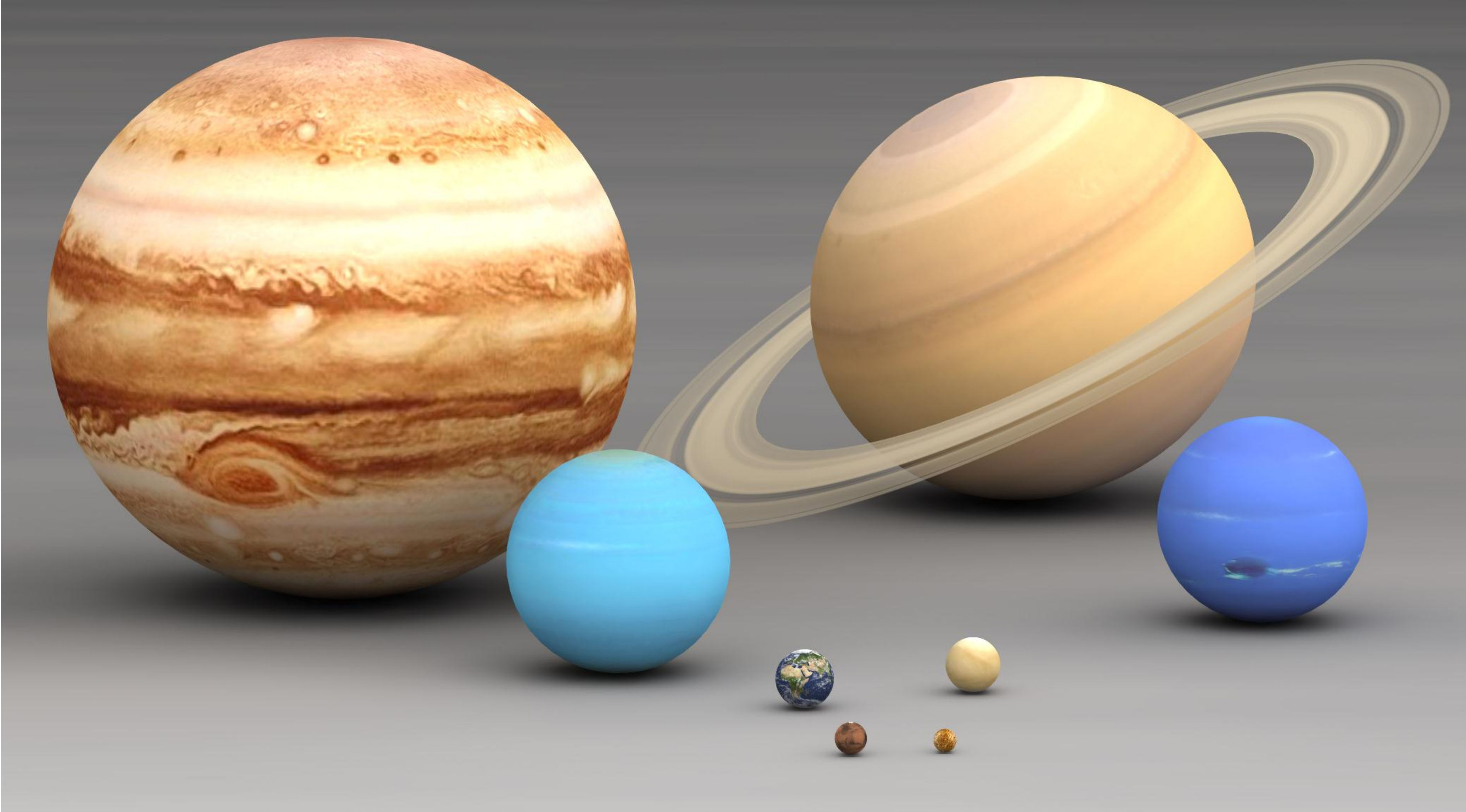
Also, other large impacts may be responsible for other exceptions like the rotation of Venus and Uranus.

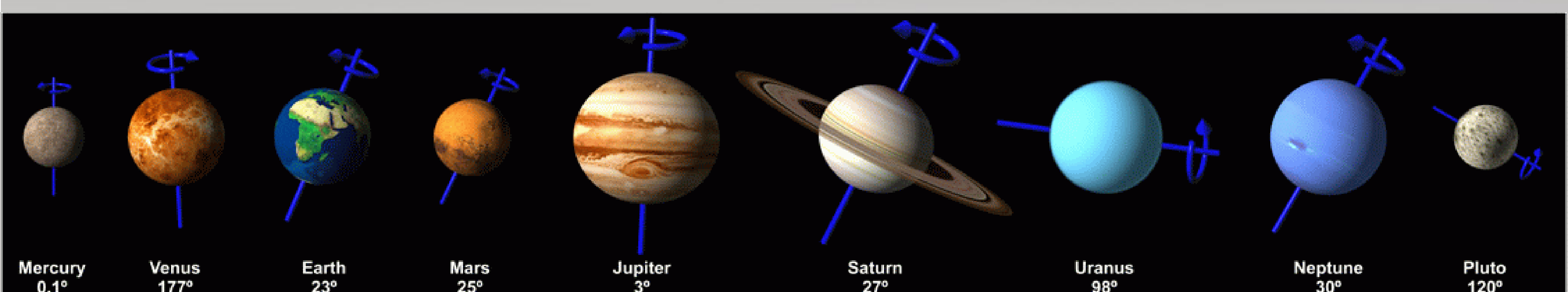
Comparisons



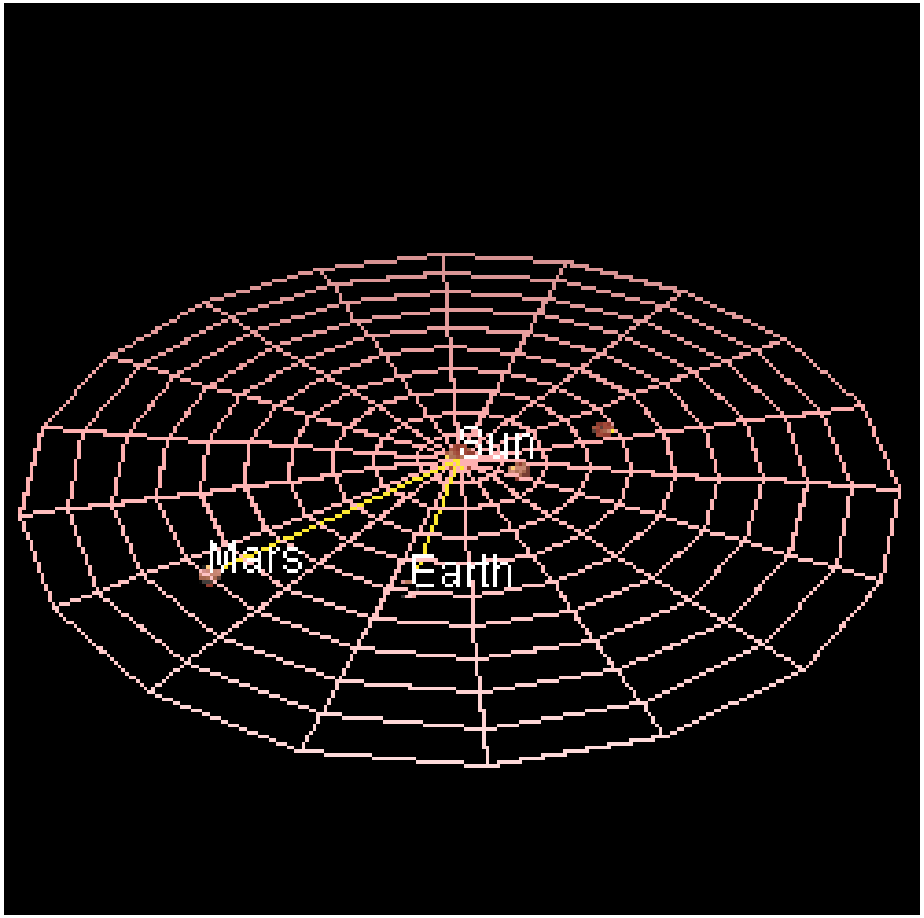
Comparison of Terrestrial and Jovian Planets

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density	Lower density
Made mostly of rock and metal	Made mostly of hydrogen, helium, and hydrogen compounds
Solid surface	No solid surface
Few (if any) moons and no rings	Rings and many moons
Closer to the Sun (and closer together), with warmer surfaces	Farther from the Sun (and farther apart), with cool temperatures at cloud tops

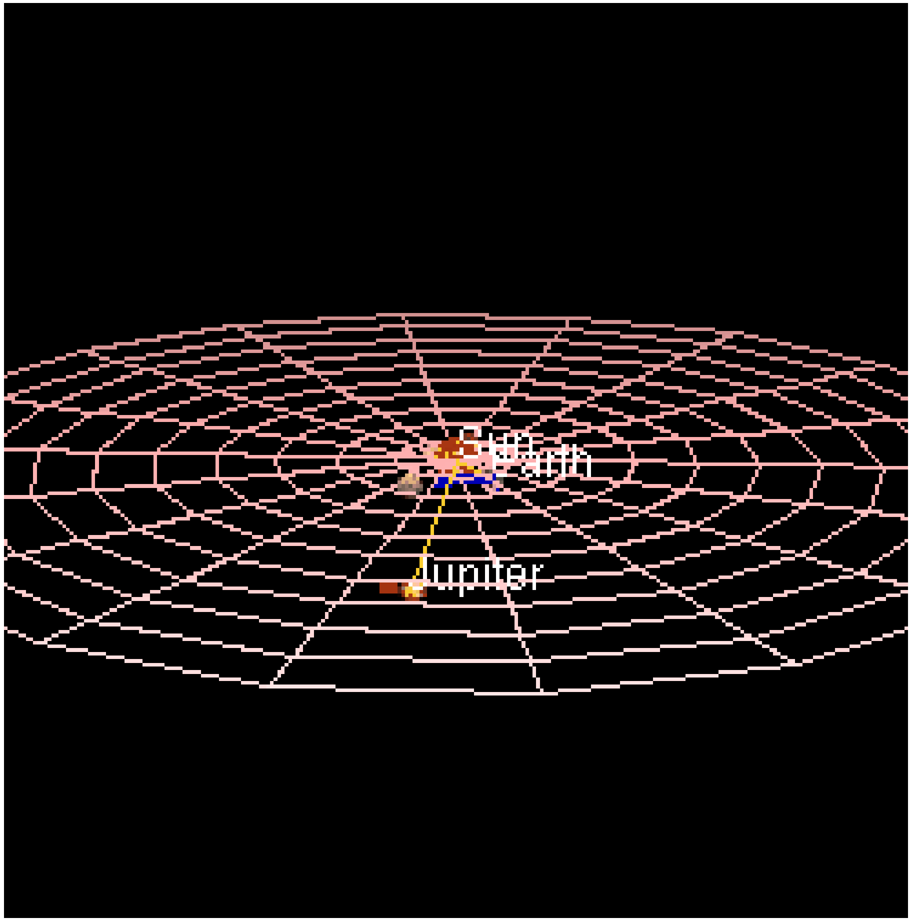



Mercury
0.1°
Venus
177°
Earth
23°
Mars
25°
Jupiter
3°
Saturn
27°
Uranus
98°
Neptune
30°
Pluto
120°

Orbits



Inner Solar System



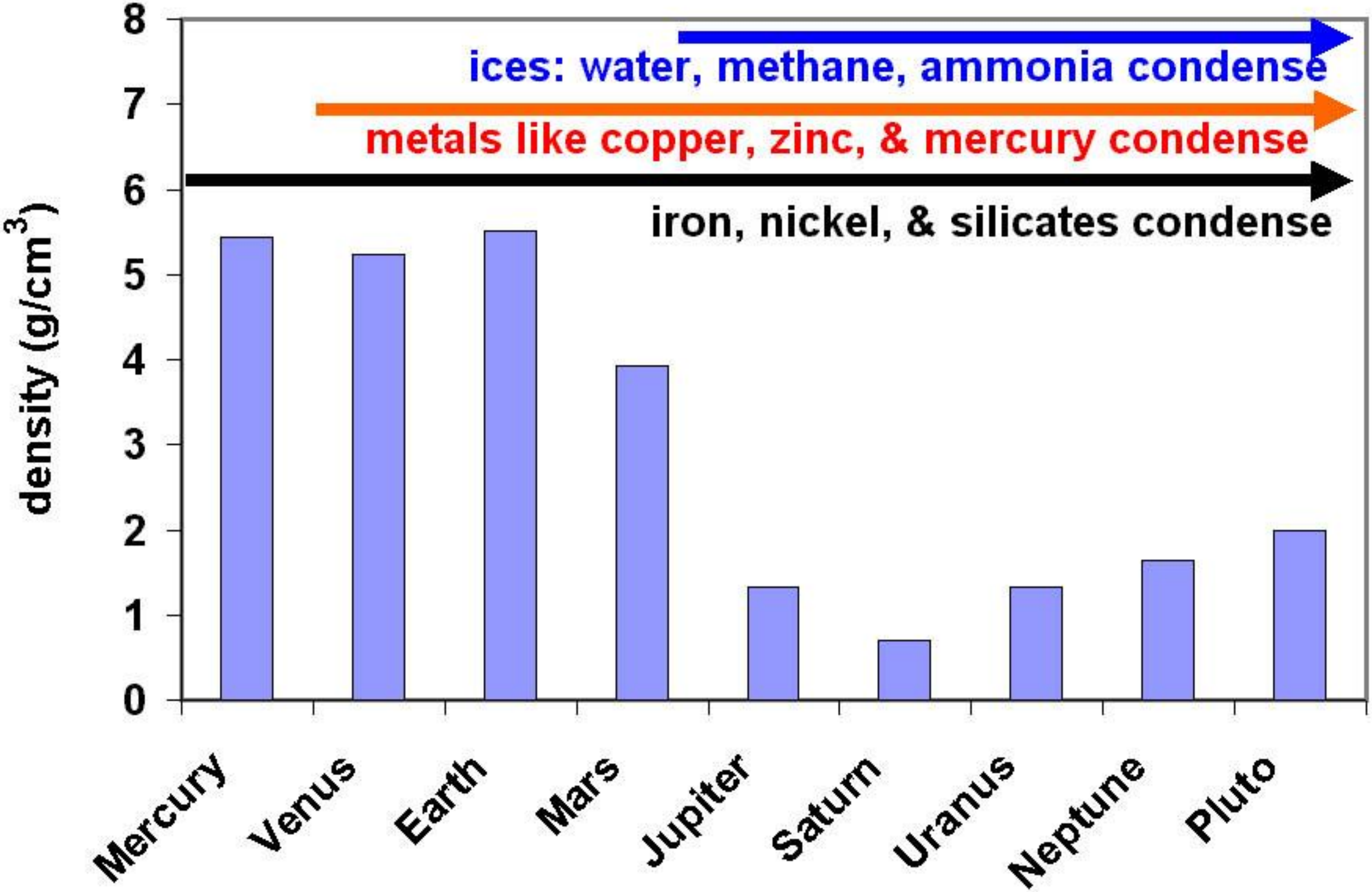
Outer Solar System

Comparative Planetology I

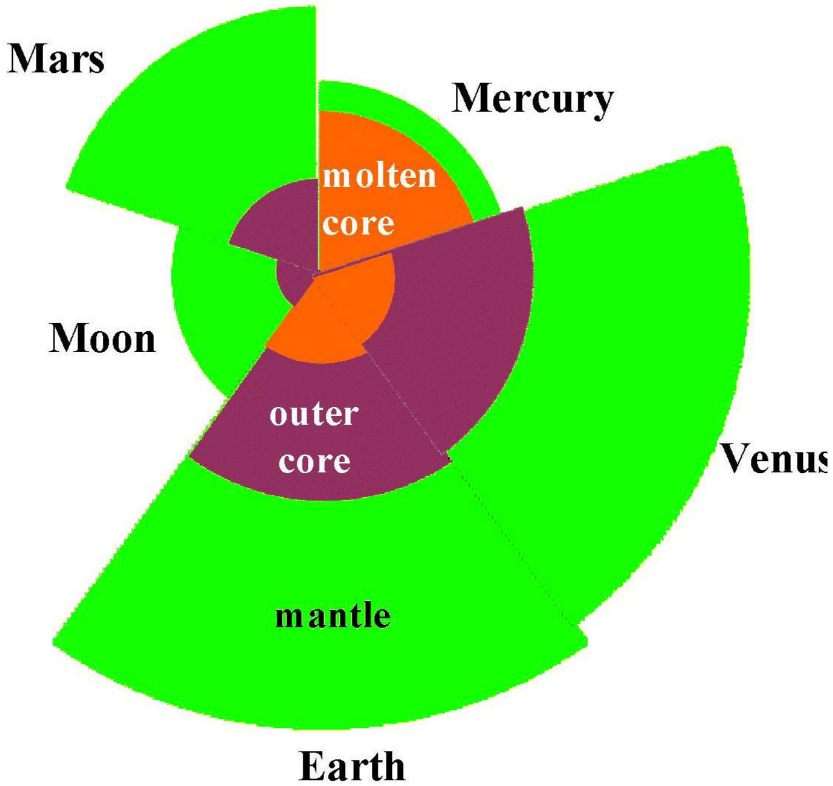
Object	Orbital Semimajor Axis (AU)	Orbital Period (Earth Years)	Mass (Earth Masses)	Radius (Earth Radii)	Number of Known Satellites	Rotation Period * (days)	Average Density (kg/m^3)	(g/cm^3)
Mercury	0.39	0.24	0.055	0.38	0	59	5400	5.4
Venus	0.72	0.62	0.82	0.95	0	–243	5200	5.2
Earth	1.0	1.0	1.0	1.0	1	1.0	5500	5.5
Moon	—	—	0.012	0.27	—	27.3	3300	3.3
Mars	1.52	1.9	0.11	0.53	2	1.0	3900	3.9
Ceres (asteroid)	2.8	4.7	0.00015	0.073	0	0.38	2700	2.7
Jupiter	5.2	11.9	318	11.2	63	0.41	1300	1.3
Saturn	9.5	29.4	95	9.5	56	0.44	700	0.7
Uranus	19.2	84	15	4.0	27	–0.72	1300	1.3
Neptune	30.1	164	17	3.9	13	0.67	1600	1.6
Pluto (Kuiper belt object)	39.5	248	0.002	0.2	3	–6.4	2100	2.1
Hale–Bopp (comet)	180	2400	1.0×10^{-9}	0.004	—	0.47	100	0.1
Sun	—	—	332,000	109	—	25.8	1400	1.4

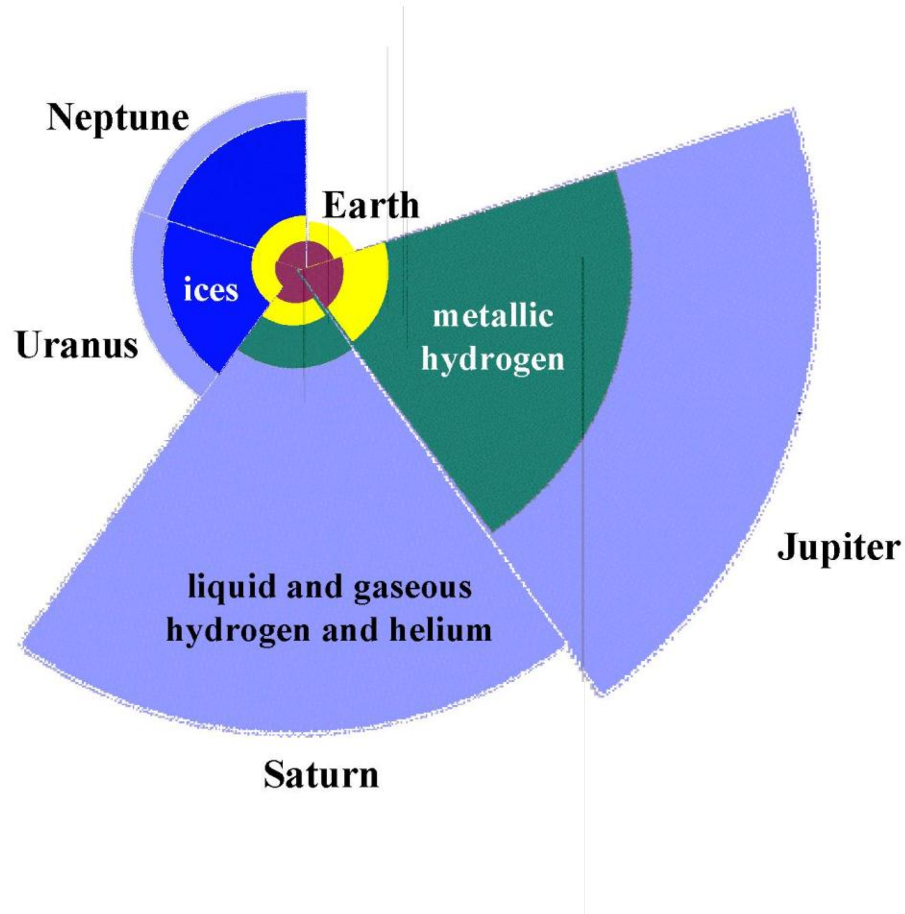
**A negative rotation period indicates retrograde (backward) rotation relative to the sense in which all planets orbit the Sun.*

Comparative Planetology II

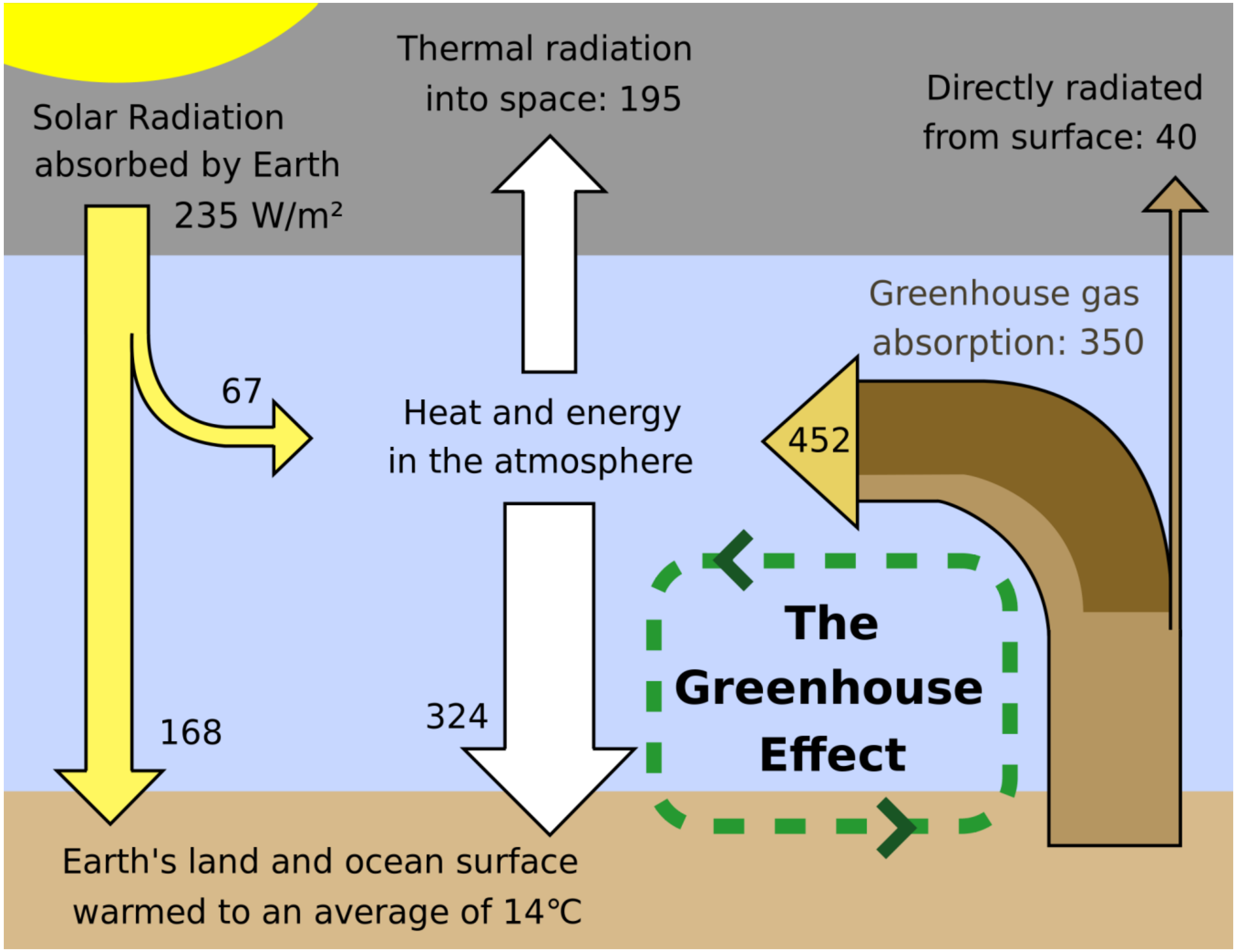


Comparative Planetology III



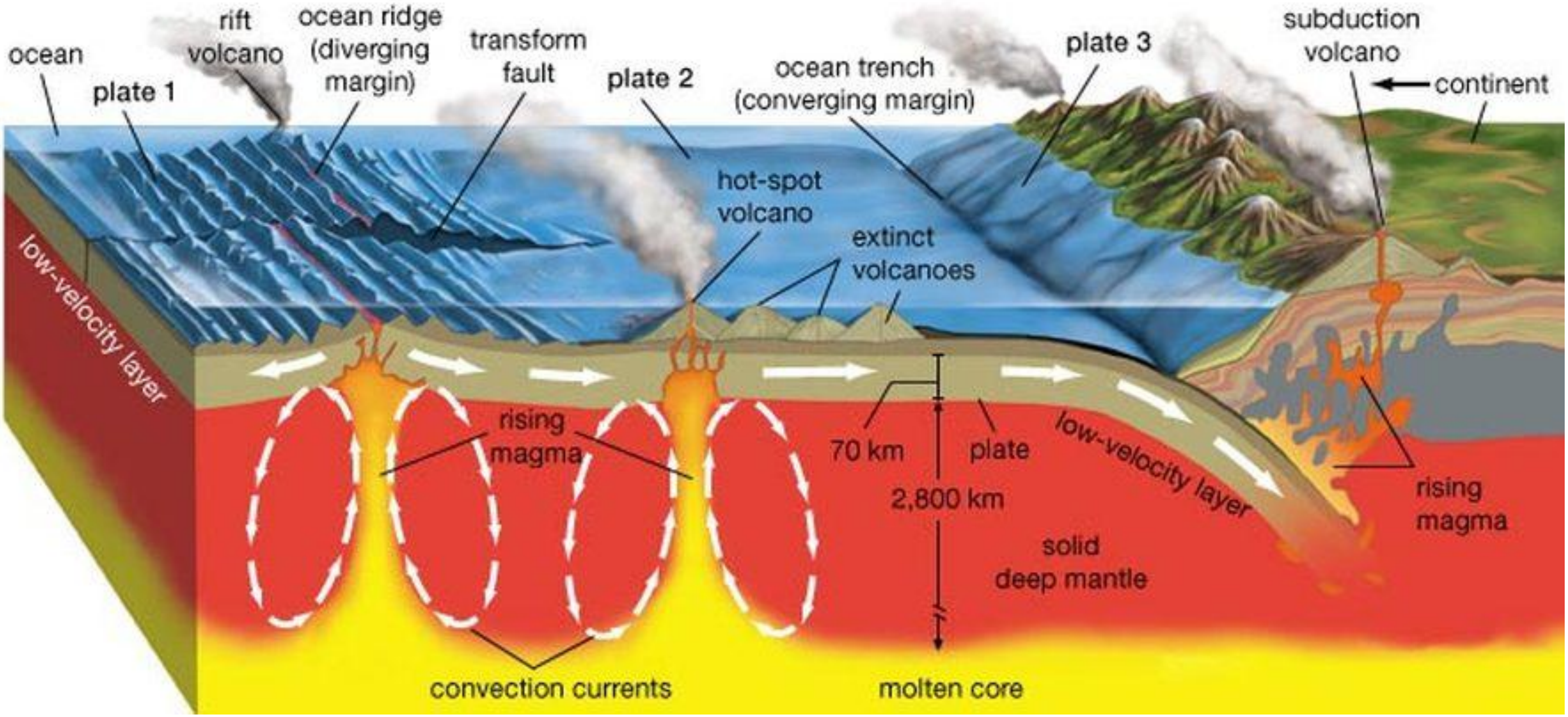


Atmospheric Heating



Larger mass planets can retain thicker (Greenhouse) atmospheres.
Extra 324 W/m^2 heats Earth from average temp of -18°C to +14°C.

Tectonic Activity

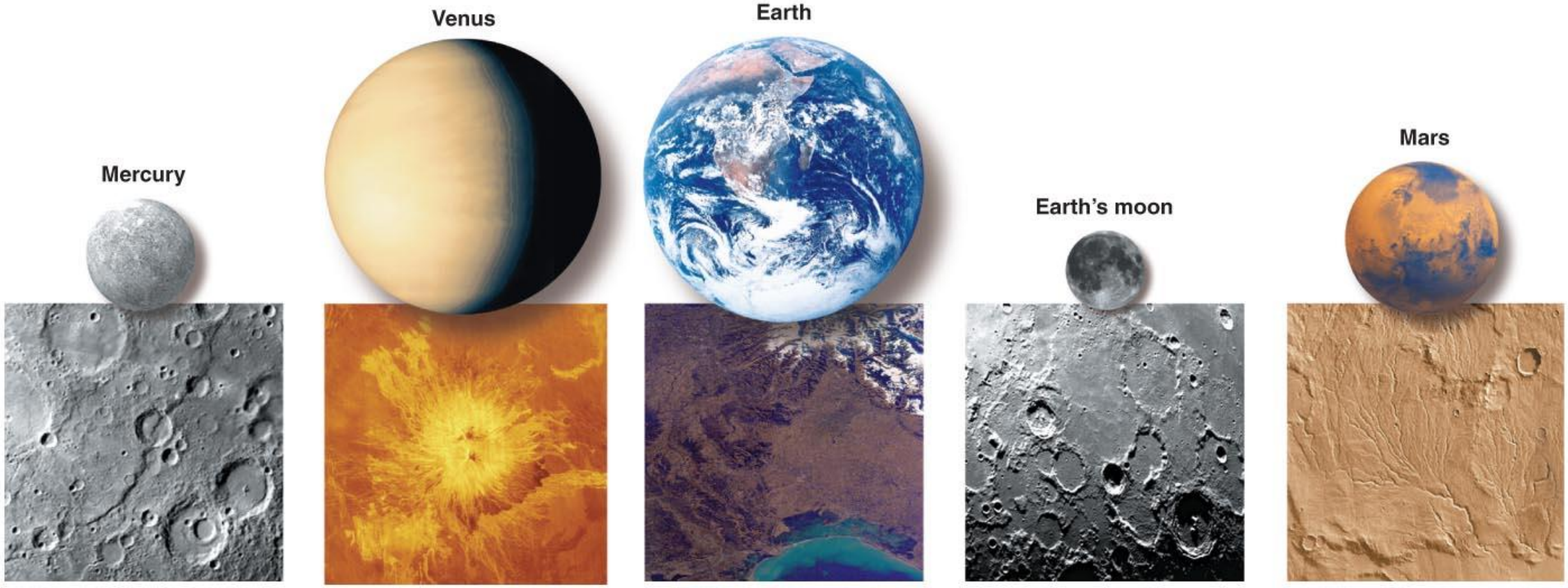


Larger mass planets create tectonic activity by radioactive heating. Magma flow drives crustal motion and releases $C0_2$ by volcanism.

Inner Planets

Small rocky bodies are unlikely to host life: they are too hot or too cold for water, no protective atmosphere, so too much UV radiation, and far too many cosmic rays.

a The Moon **b** Mercury



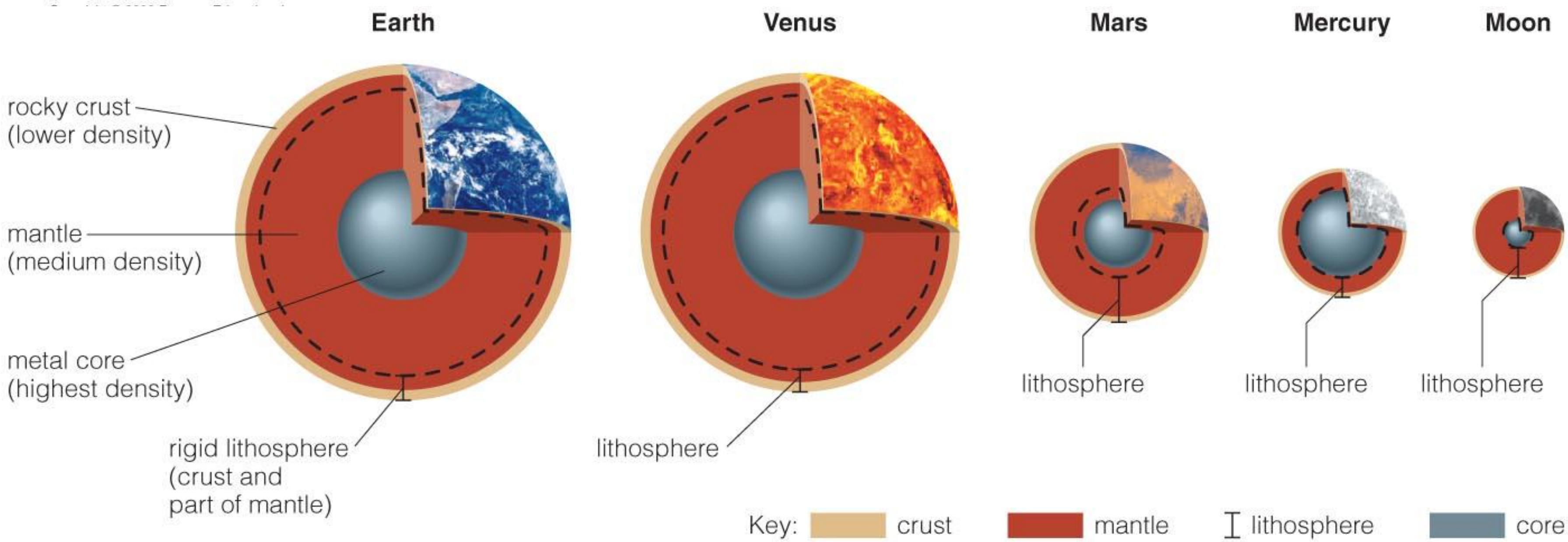
Heavily cratered Mercury has long, steep cliffs—one is the long curve going from upper right to lower left.

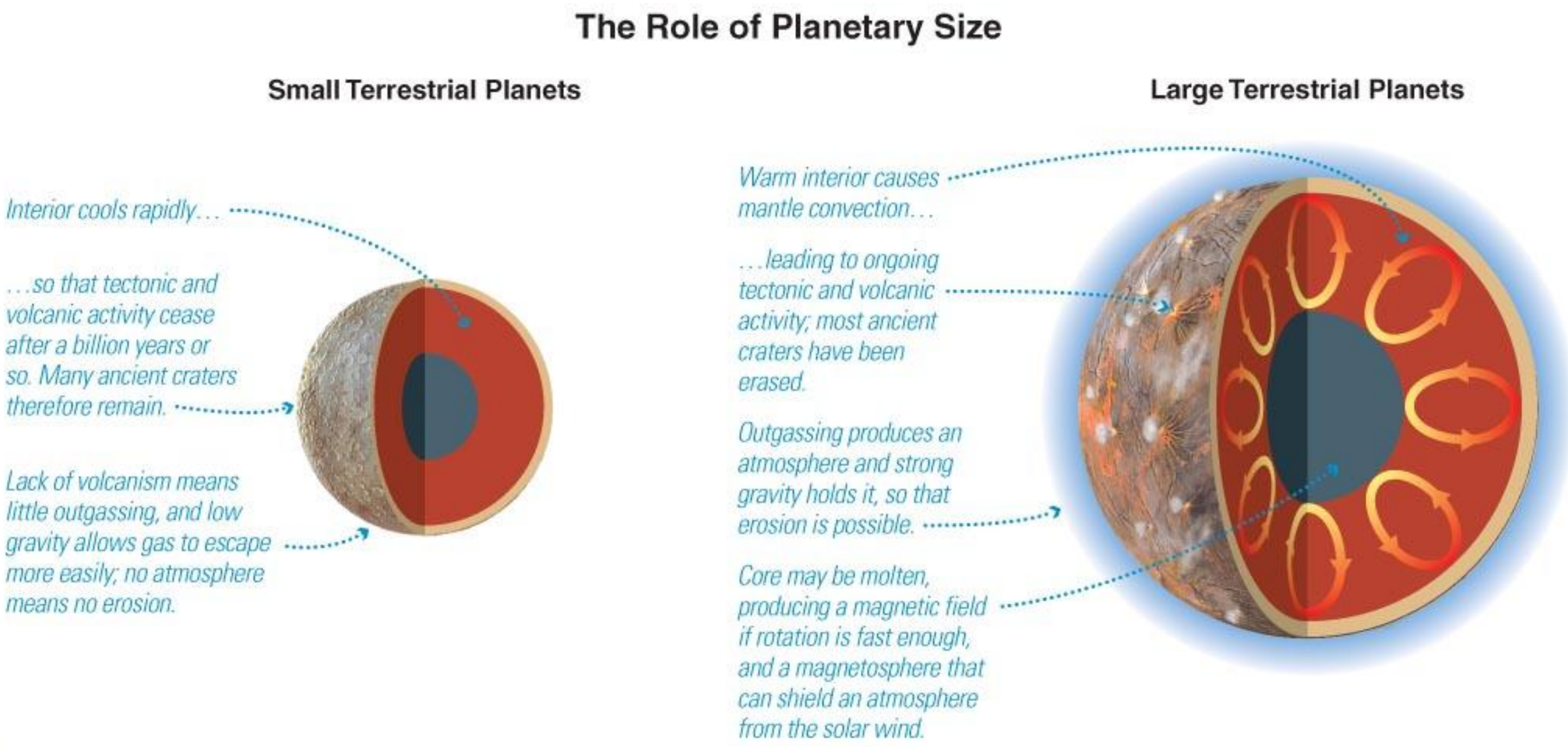
Cloud-penetrating radar obtained this view of a twin-peaked volcano on Venus. (The colors are not real.)

We see land, ocean, and snow-capped peaks in this view of Earth from orbit.

The Moon's surface is heavily cratered in most places.

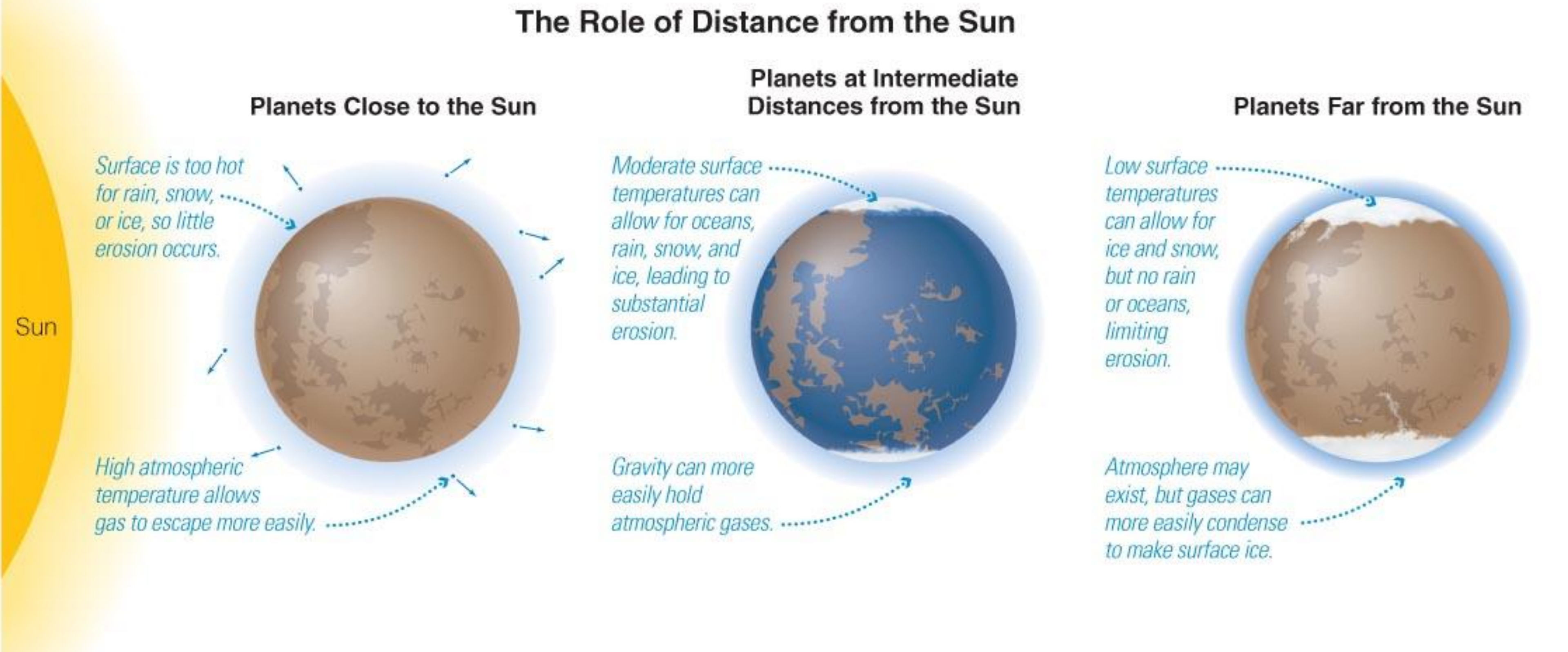
Mars has features that look like dry riverbeds, along with impact craters like those near the upper right.





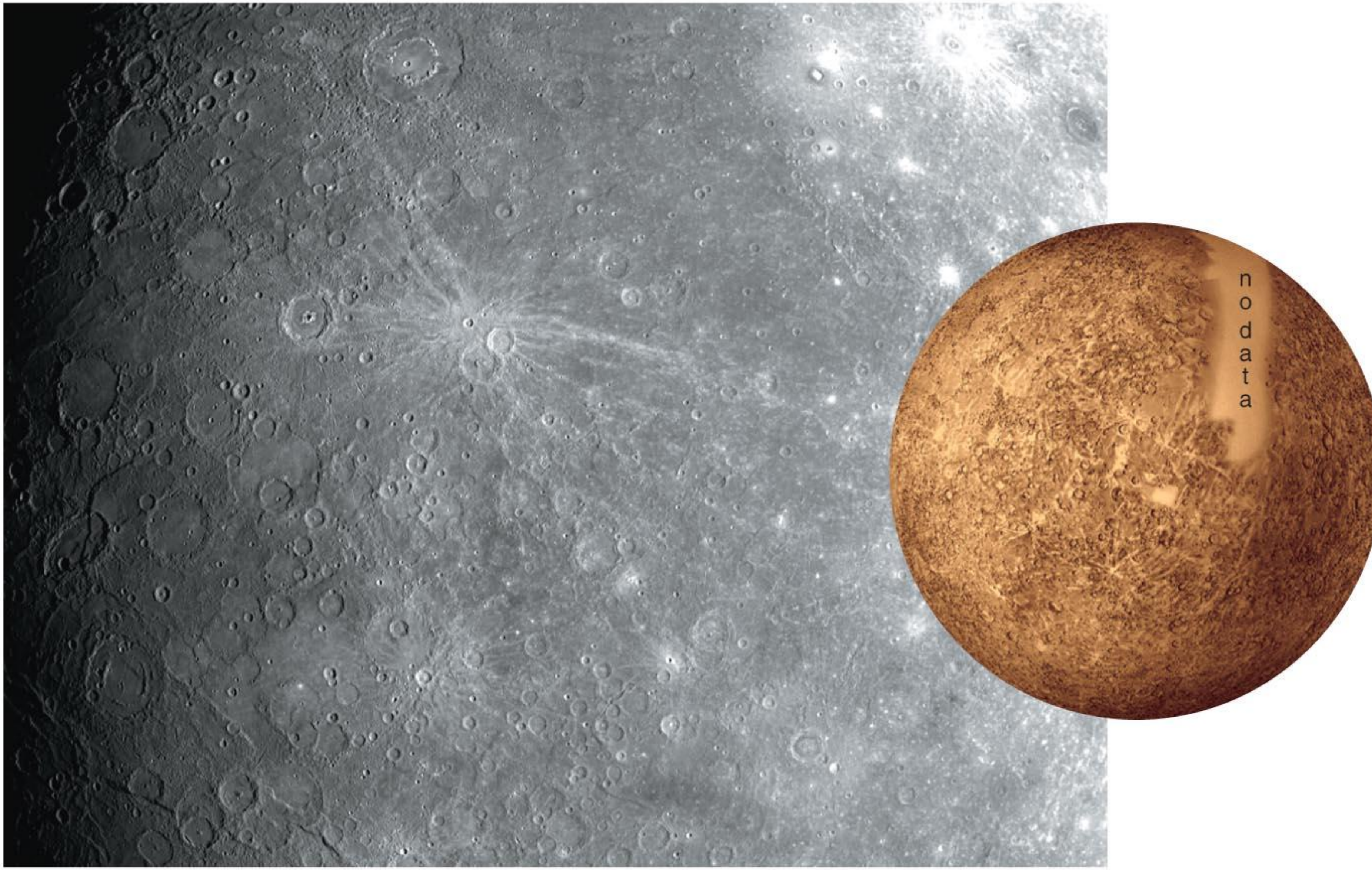
Small planets are geologically dead and cannot hold much or any atmosphere, so their surfaces are blasted by meteors and scorched by cosmic and UV rays.

Large planets have volcanism and plate tectonics, which renews the surface, emits carbon dioxide, and provides a chemical dynamism for possible biology.



Planets near their stars are hot and cannot keep light gases in their atmospheres. If they are very close, they tidally lock to the star, with one side always facing it.

Planets far from their stars are cool/cold and may not have liquids on the surface but they can hold on to a thick atmosphere and may have subterranean liquid.


no data

LCROSS bombed the Moon and showed there's ice in the permanently shadowed craters. Not much, but probably enough to support a future occupied lunar base.

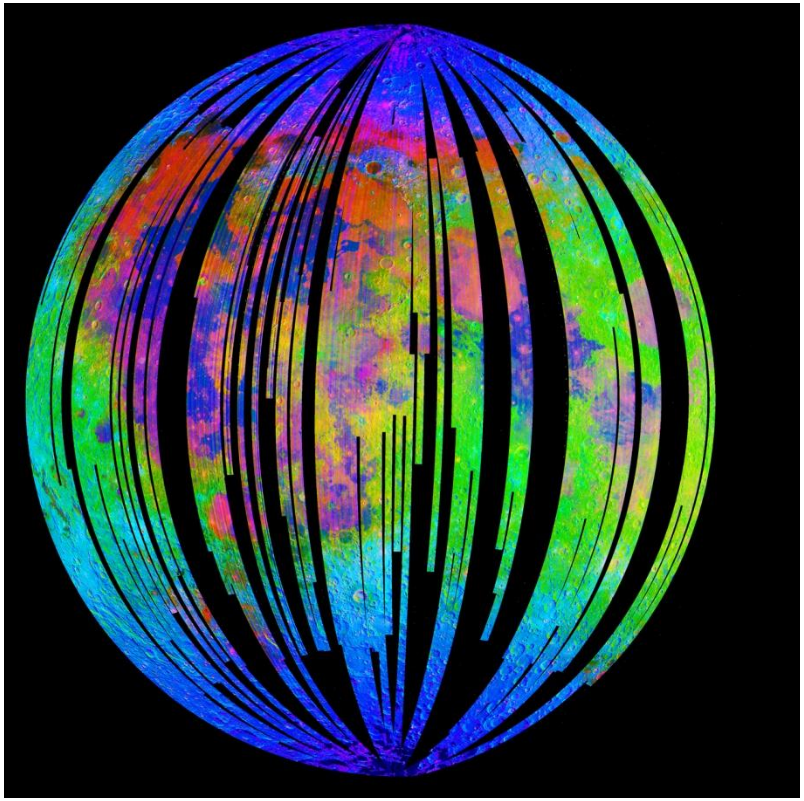
Water on the Moon

- Initial analysis of lunar rocks collected by Apollo astronauts did not reveal the presence of water on the Moon.

- Four spacecraft recently reported small amounts of H_2O and/or OH at the Moon:
  - India's Chandrayaan mission
  - NASA's Cassini mission
  - NASA's EPOXI mission
  - NASA's LCROSS mission

  The first three measured the top few mm of the lunar surface. LCROSS measured plumes of lunar gas and soil ejected when a part of the spacecraft was crashed into a crater.

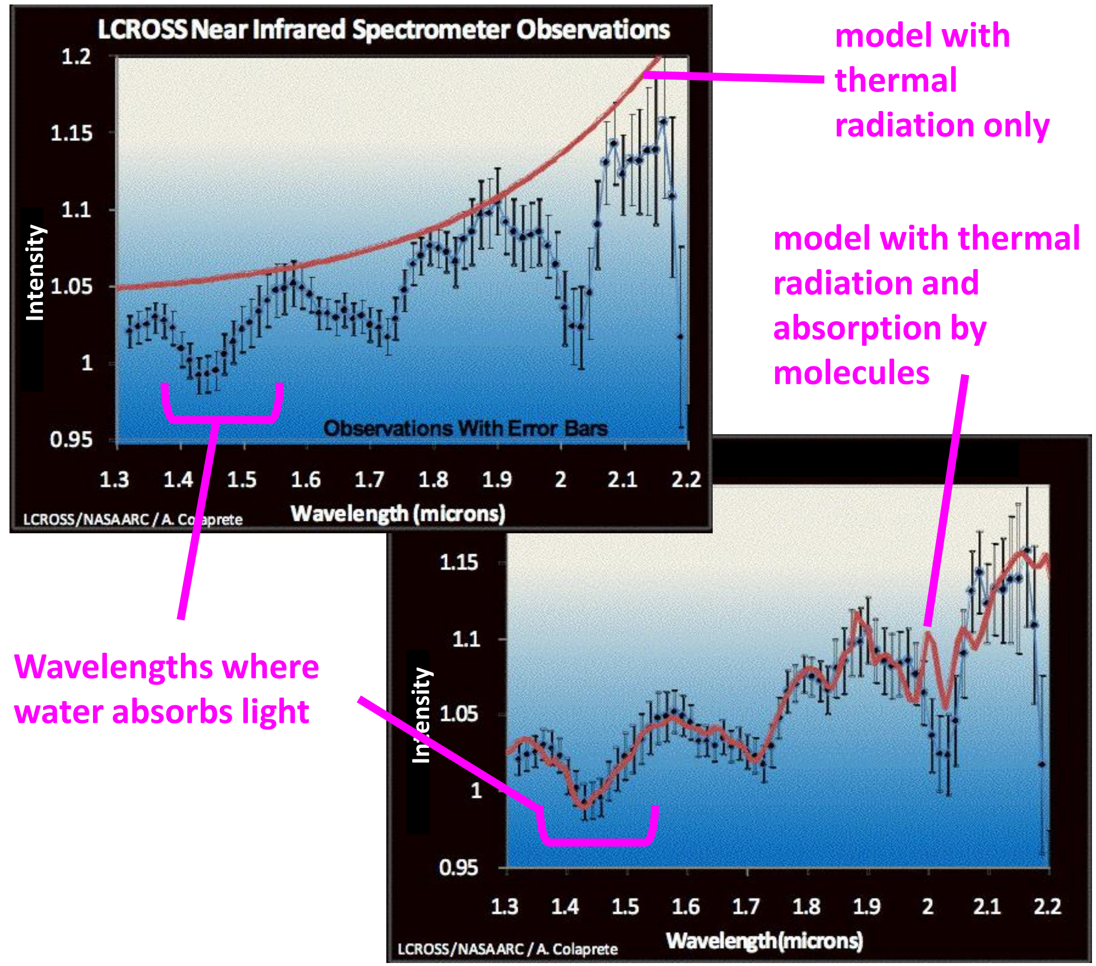
- *How much water?* Approximately **1 ton of lunar regolith will yield 1 liter of water.**



This false-color map created from data taken by NASA's Moon Mineralogy Mapper (M3) on Chandrayaan is shaded blue where trace amounts of water (H_2O) and hydroxyl (OH) lie in the top few mm of the surface.

Detecting Water

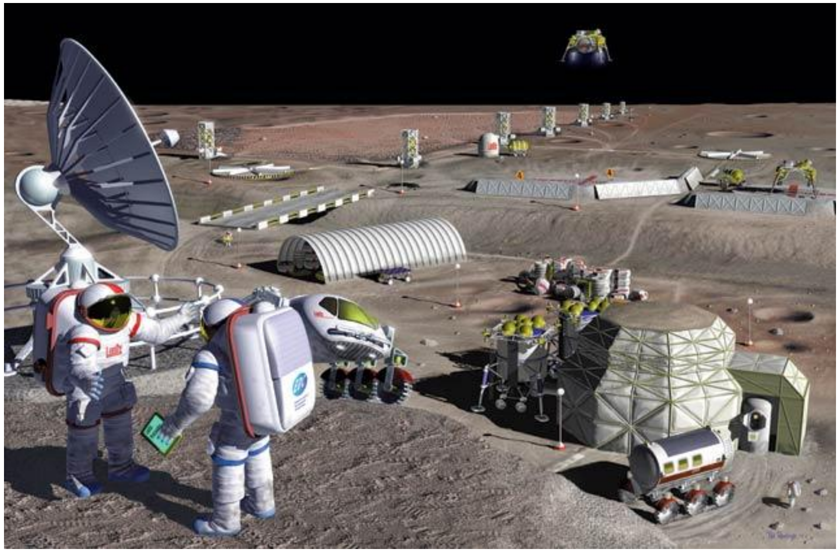
- Lunar soil emits infrared *thermal radiation*. The amount of emitted light at each wavelength varies smoothly according to the Moon's temperature.
- H_2O or OH molecules in the soil absorb some of infrared radiation, but only at specific wavelengths.
- All 4 infrared spectrographs measure a deficit of thermal radiation at the wavelengths, implying water is present.



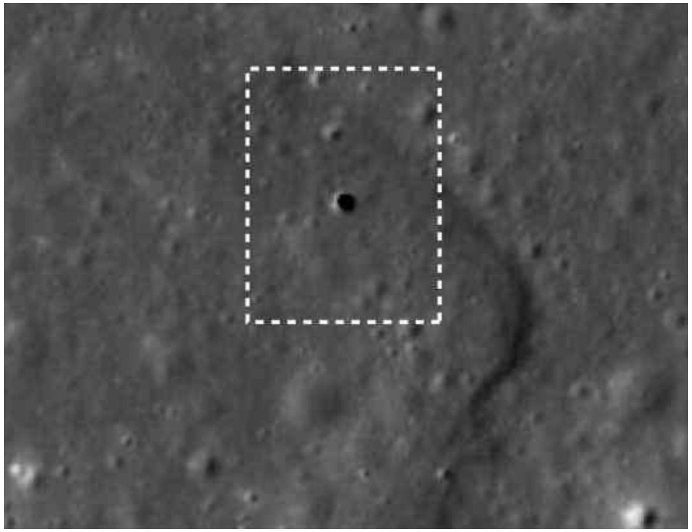
An infrared spectrum measured by LCROSS (black data points) compared to models (red line)

Follow the Water

- Lunar water may come from 'solar wind' hydrogen striking the surface, combining with oxygen in the soil. It may also arrive via meteorite and by comet impacts. Both processes are likely to operate.
- Lunar water may be 'bounced' by small impacts to the polar regions, forming ice in permanently shadowed craters.
- Similar processes may occur on other airless bodies (e.g., Mercury, comets, and asteroids).
- Water-laden lunar regolith may be a valuable resource, supporting future lunar exploration activities.

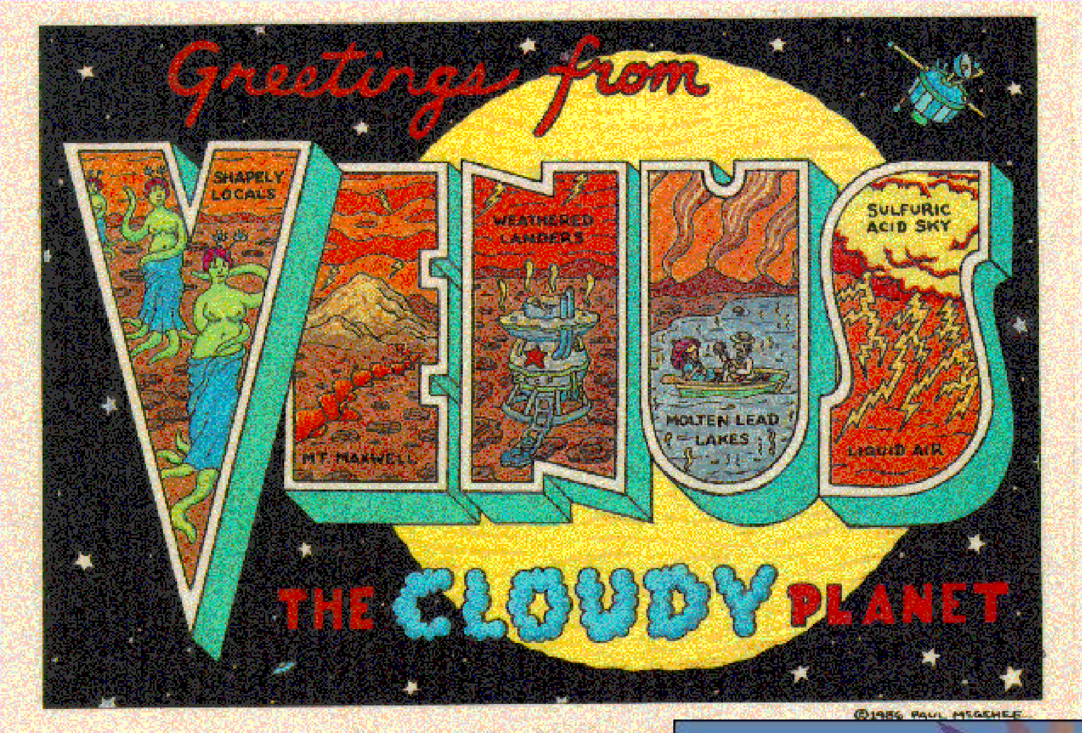


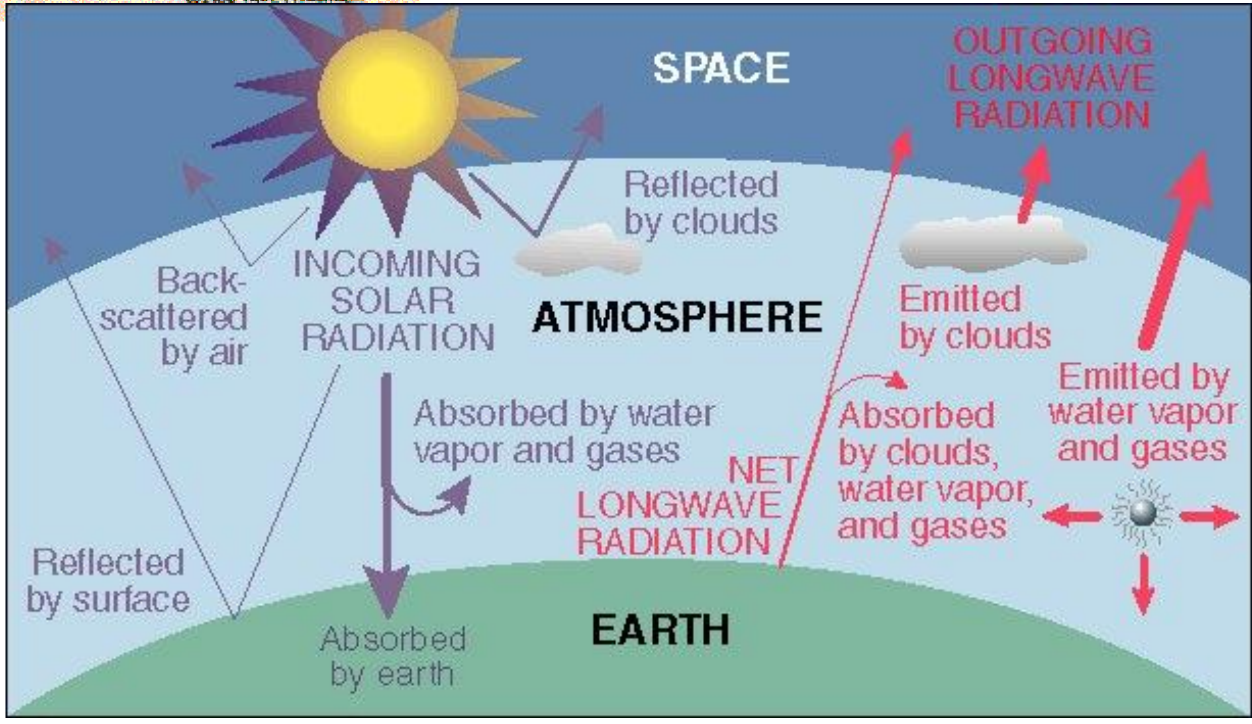
Discovery of water on the moon may support future activities on the Moon and beyond. Below: 100m lava tube as a possible habitat.



DID WE GO THERE, OR WAS IT A DREAM?

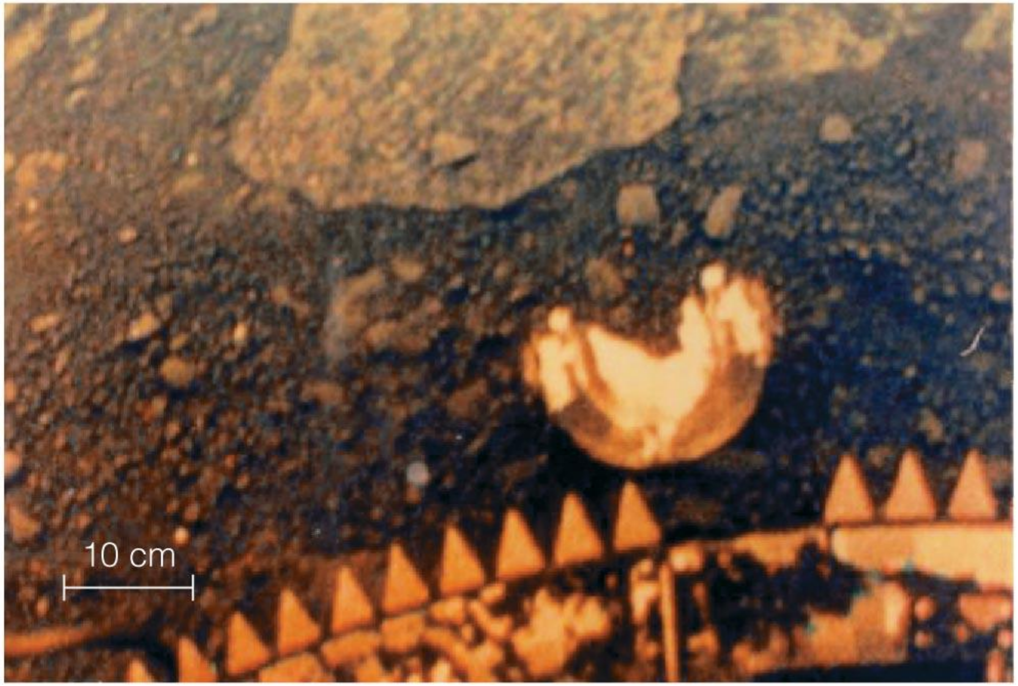

Flag
Apollo 17 Lunar Module
Challenger Descent Stage
LROC NAC 4x Enlargment
M109032389LE


Greetings from
VENUS
SHAPELY LOCALS
MT. MAXWELL
WEATHERED LANDERS
MOLTEN LEAD LAKES
SULFURIC ACID SKY
LIQUID AIR
THE CLOUDY PLANET


SPACE
OUTGOING LONGWAVE RADIATION
Reflected by clouds
Back-scattered by air
INCOMING SOLAR RADIATION
ATMOSPHERE
Emitted by clouds
Emitted by water vapor and gases
Absorbed by water vapor and gases
NET LONGWAVE RADIATION
Absorbed by clouds, water vapor, and gases
Reflected by surface
Absorbed by earth
EARTH

An Inferno

Venus is hot (900 degrees Fahrenheit), high pressure (100 atmospheres), toxic (sulfur dioxide, ammonia clouds), and baked dry. But before the runaway Greenhouse effect took hold, 2-3 billion years ago, it might have been temperate.



Mars

From Percival Lowell's "wishful thinking" of canals on Mars in the 19th century to Orson Wells radio broadcast in 1938, to lots of modern science fiction, Mars has been the subject of hopes, fears and fantasies.

The New York Times.

Copyright, 1938, by The New York Times Company.

NEW YORK, MONDAY, OCTOBER 31, 1938.

Radio Listeners in Panic, Taking War Drama as Fact

Many Flee Homes to Escape 'Gas Raid From Mars'—Phone Calls Swamp Police at Broadcast of Wells Fantasy

A wave of mass hysteria seized thousands of radio listeners throughout the nation between 8:15 and 9:30 o'clock last night when a broadcast of a dramatization of H. G. Wells's fantasy, "The War of the Worlds," led thousands to believe that an interplanetary conflict had started with invading Martians spreading wide death and destruction in New Jersey and New York.

The broadcast, which disrupted households, interrupted religious services, created traffic jams and clogged communications systems, was made by Orson Welles, who as the radio character, "The Shadow," used to give "the creeps" to countless child listeners. This time at least a score of adults required medical treatment for shock and hysteria.

and radio stations here and in other cities of the United States and Canada seeking advice on protective measures against the raids.

The program was produced by Mr. Welles and the Mercury Theatre on the Air over station WABC and the Columbia Broadcasting System's coast-to-coast network, from 8 to 9 o'clock.

The radio play, as presented, was to simulate a regular radio program with a "break-in" for the material of the play. The radio listeners, apparently, missed or did not listen to the introduction, which was: "The Columbia Broadcasting System and its affiliated stations present Orson Welles and the Mercury Theatre on the Air in 'The War of the Worlds' by H. G. Wells."

They also failed to associate the

TANDS PAT EW DEALER FOR SENATE

Candidate Opposes Minor Changes in Security Laws

THEORY OF TVA

Balanced, but Means 'Misery,' The Times

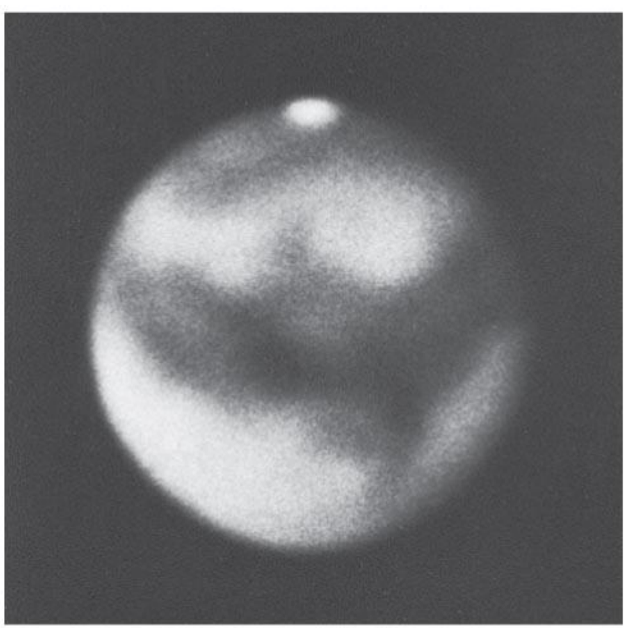
OUSTED JEW REFUGE IN AFTER BORD

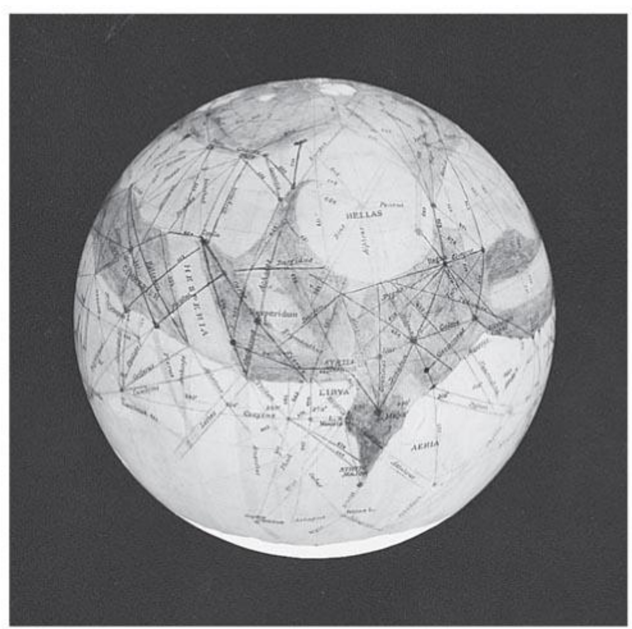
Exiles Go to Rela or to Camps Ma Distribution

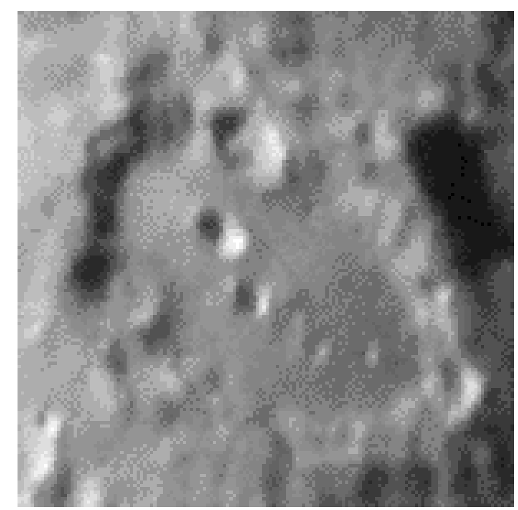
REVEAL CRUELT

Others Sent Back Pending Parleys the Two Gov

c., publishing as Pearson Addison-Wesley.





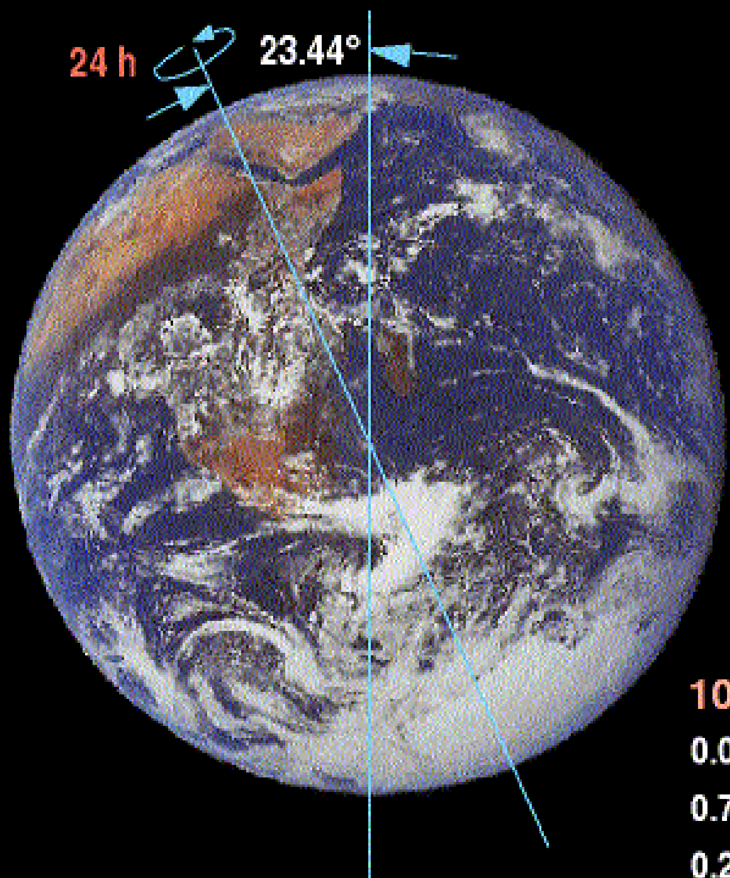


Moon – Variable Seeing

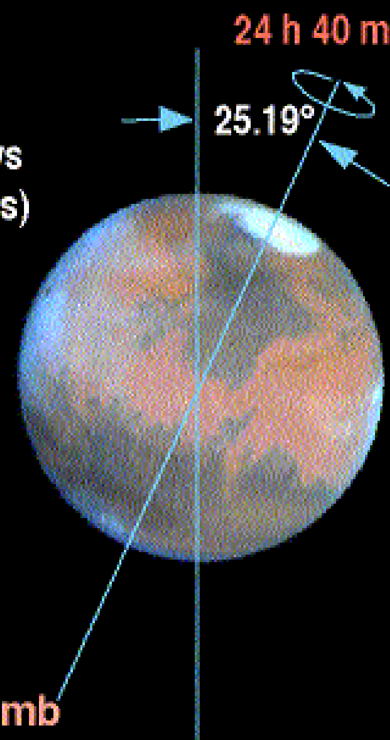
At the start of the broadcast.

Fifteen minutes later, with the switchboard lighting up and panic rising in New Jersey.

EARTH COMPARISON MARS

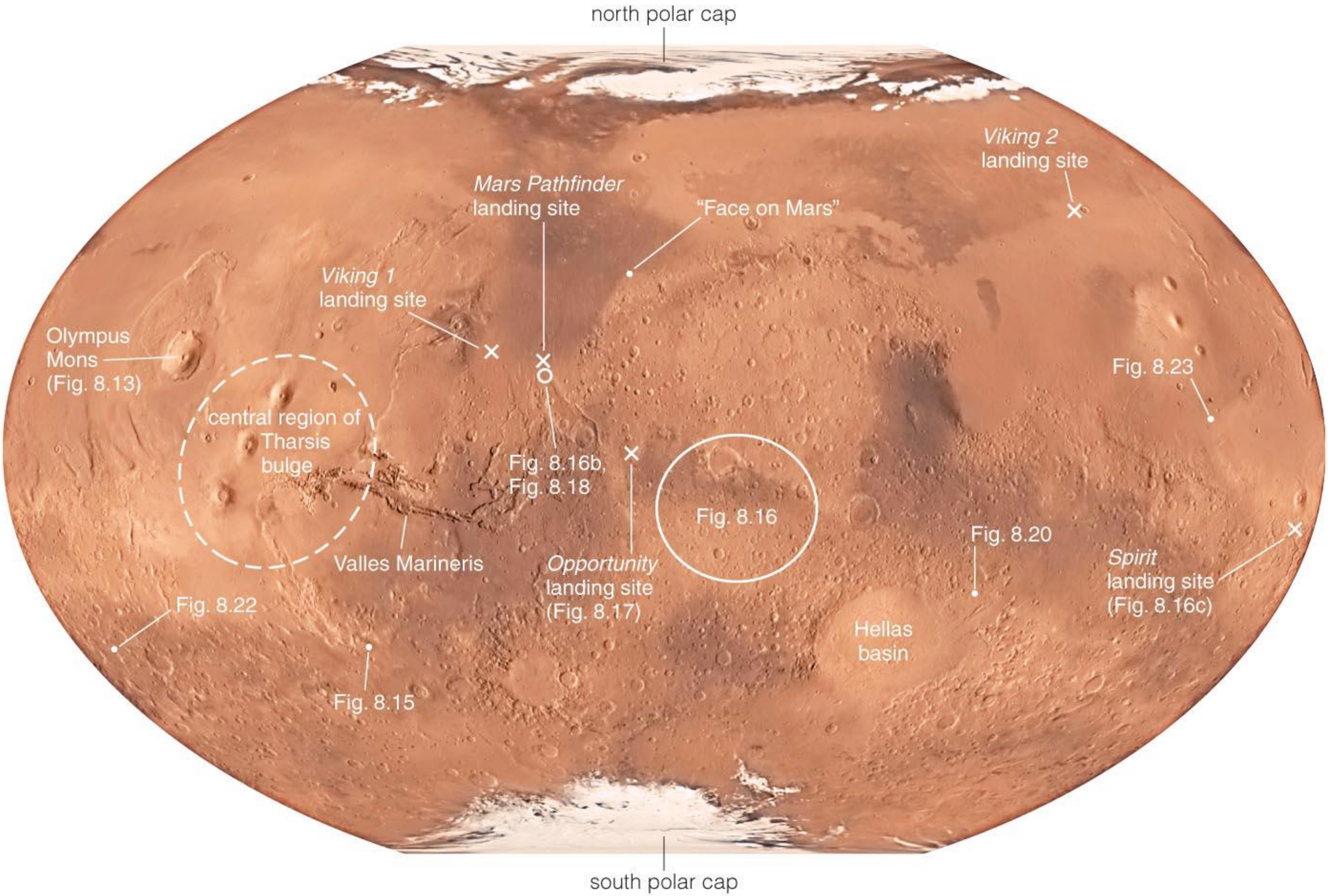


EARTH	COMPARISON	MARS
365 Days	YEAR	686 Days (667 Sols)
	GRAVITY	38% of earth
	SUNLIGHT	44% of earth
	ATMOSPHERE	
1013mb	Total	7.6 mb
0.00035	CO_2	0.95
0.781	N_2	0.027
0.210	O_2	0.0013
0 to 0.04	H_2O	0 to 0.00021
0.0093	Ar	0.016



Mars, courtesy
P. James and NASA

© U.Washington,Live from Earth and Mars (K.Dewar, J. Tillman)


north polar cap
Viking 2
landing site
Mars Pathfinder
landing site
"Face on Mars"
Viking 1
landing site
Olympus
Mons
(Fig. 8.13)
central region of
Tharsis
bulge
Fig. 8.23
Fig. 8.16b,
Fig. 8.18
Fig. 8.16
Valles Marineris
Opportunity
landing site
(Fig. 8.17)
Fig. 8.20
Spirit
landing site
(Fig. 8.16c)
Fig. 8.22
Hellas
basin
Fig. 8.15
south polar cap

Era	*Color Code in Figure 8.14*	*Time*
Early (Noachian)		4.6–3.8 billion years ago
Middle (Hesperian)		3.8–1.0 billion years ago
Recent (Amazonian)		1.0 billion years ago to the present

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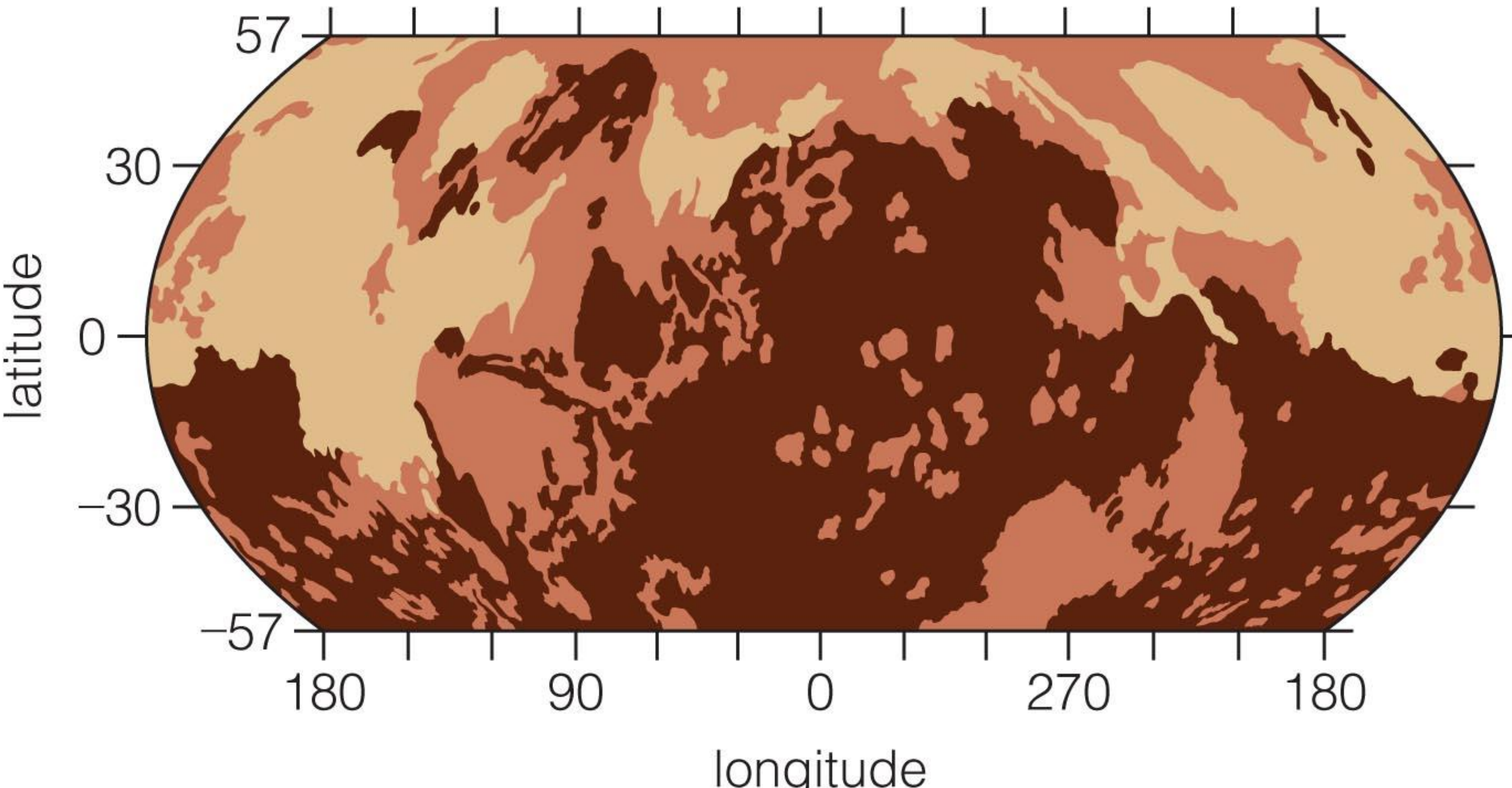
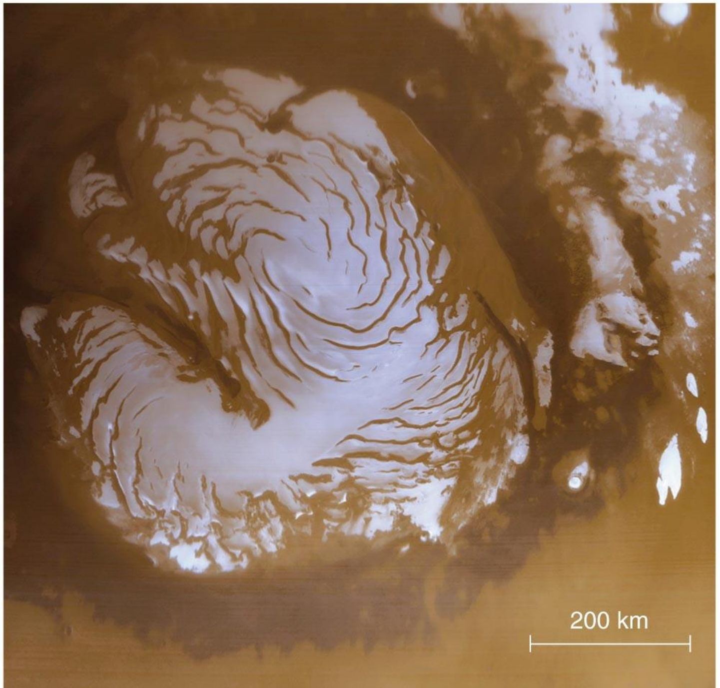
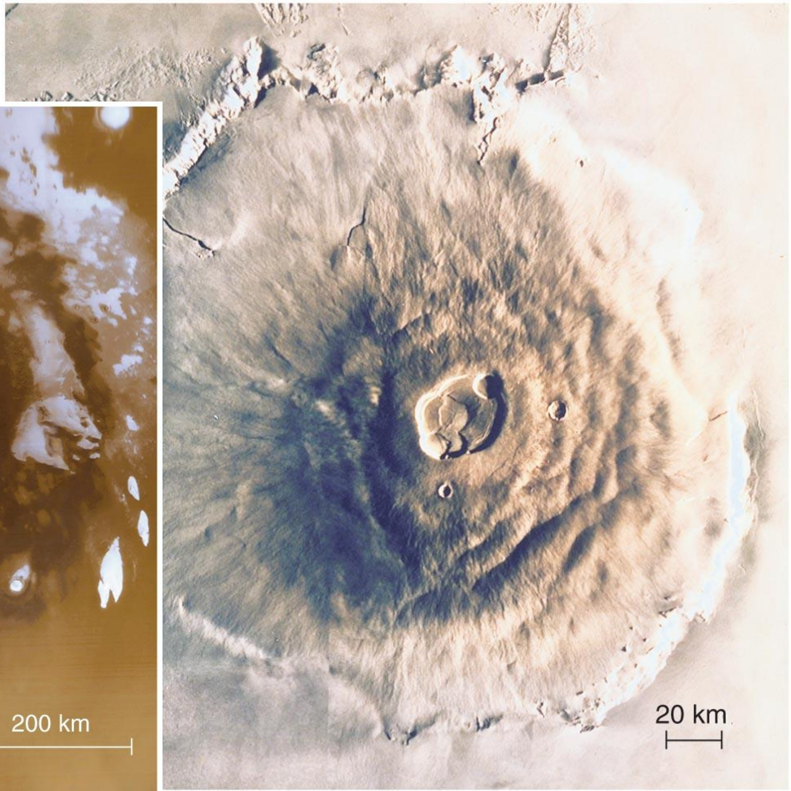
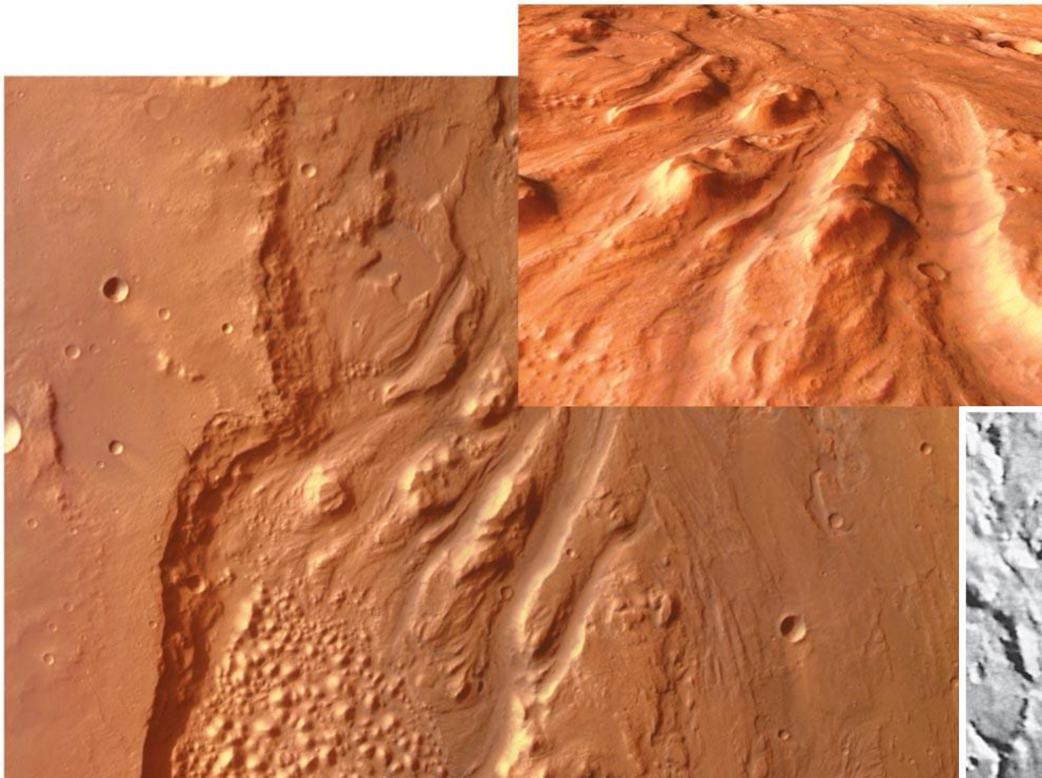


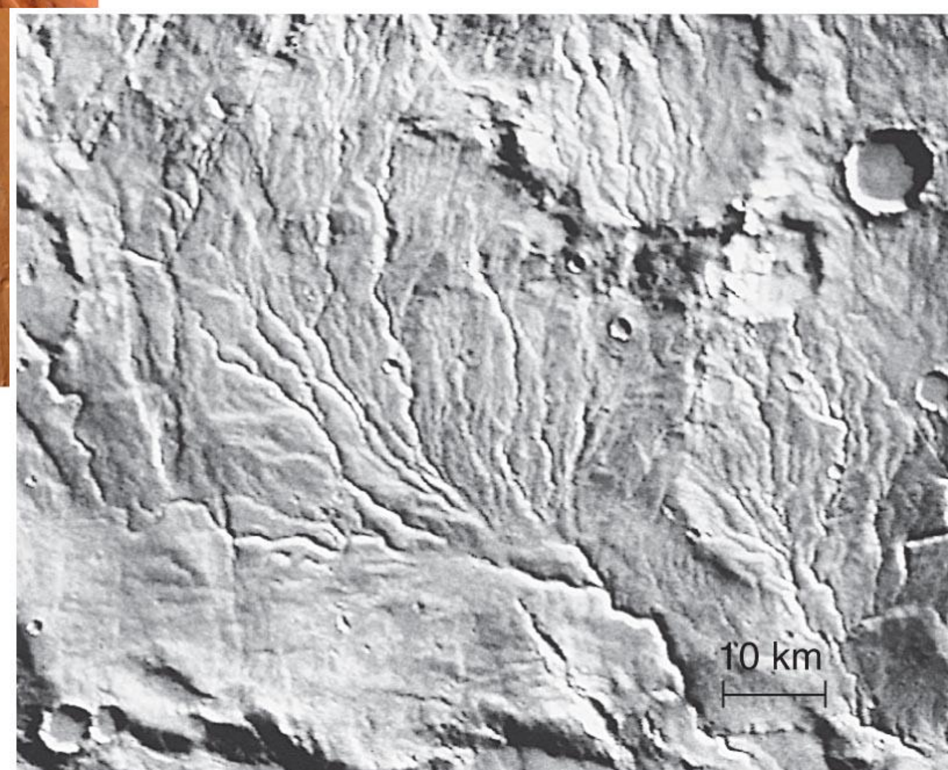
Mars has weather, a hydrological cycle, prior volcanism and tectonics



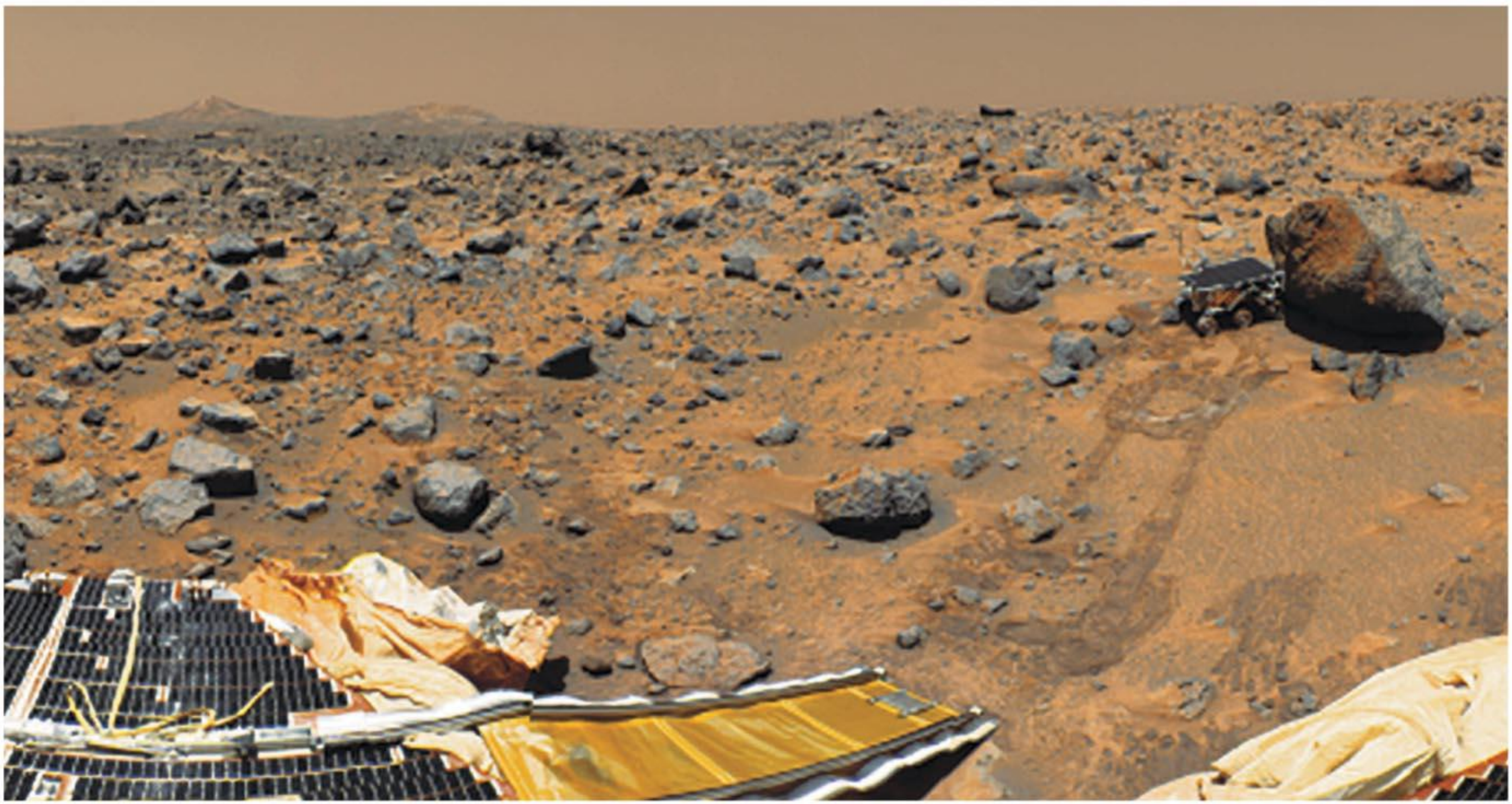


Mars and Water

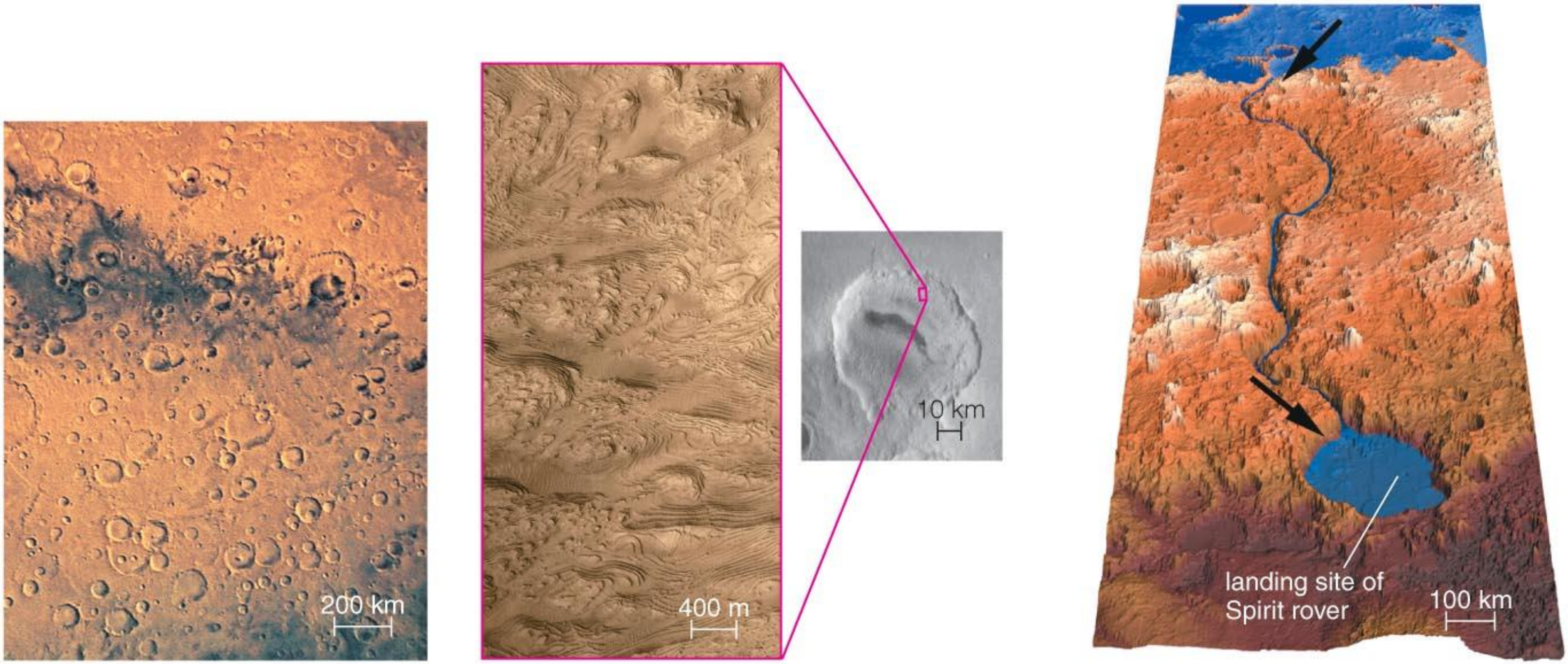




Mars is cold and arid now, but was almost certainly warmer in the past and probably has water kept liquid by pressure 50-100m below the surface. We've evidence of this.



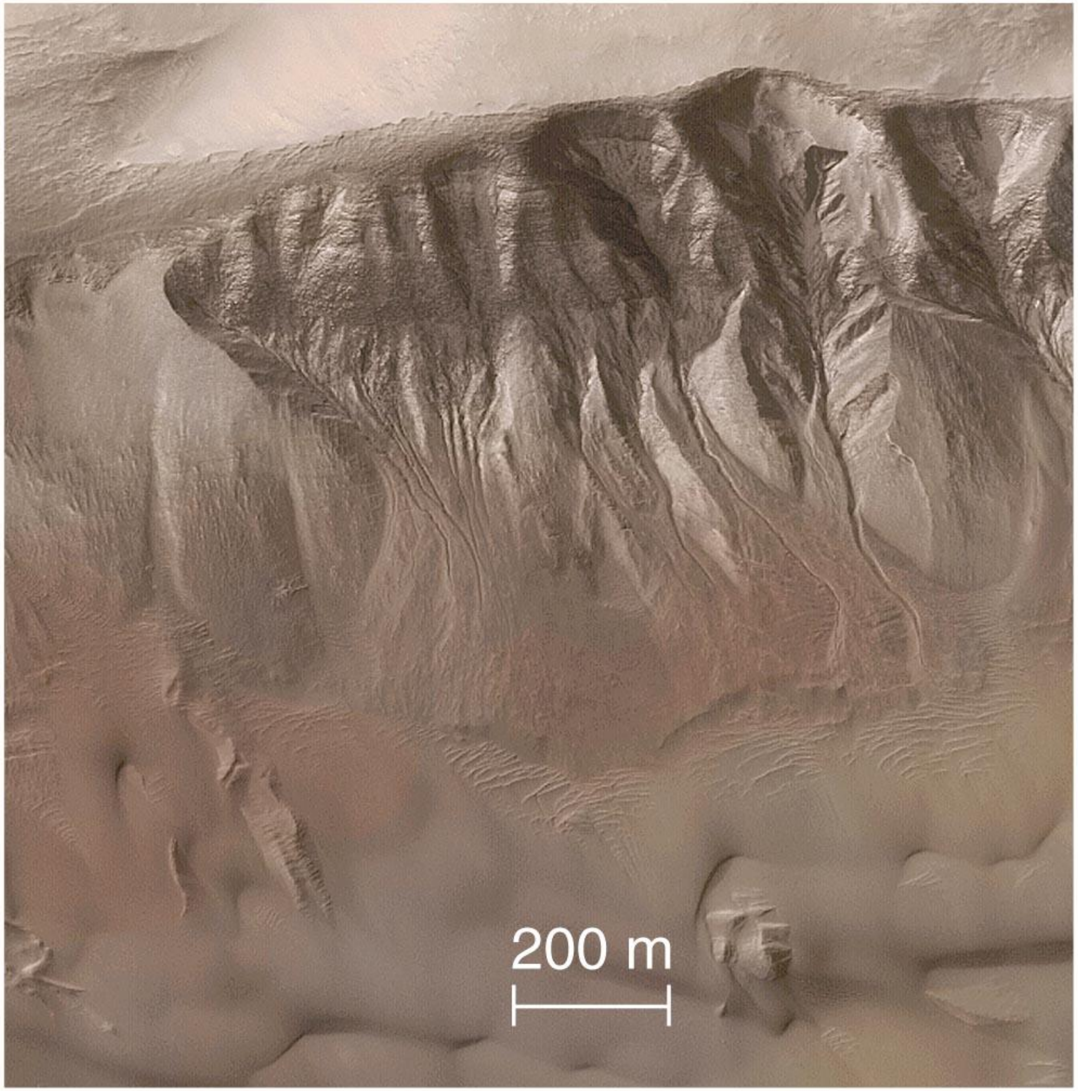
The evidence is strong, varied, but indirect. Some of the pieces of evidence have other explanations and no water is visible now. But all taken together, they are compelling.

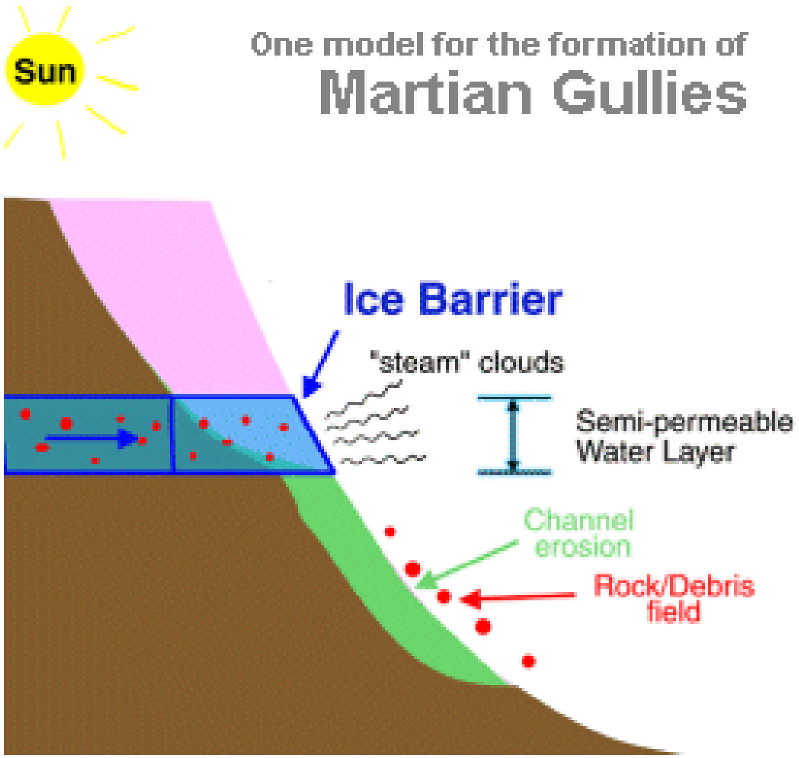


a This photo shows a broad region of the southern highlands. The eroded rims of large craters and the relative lack of small craters suggest erosion by rainfall.

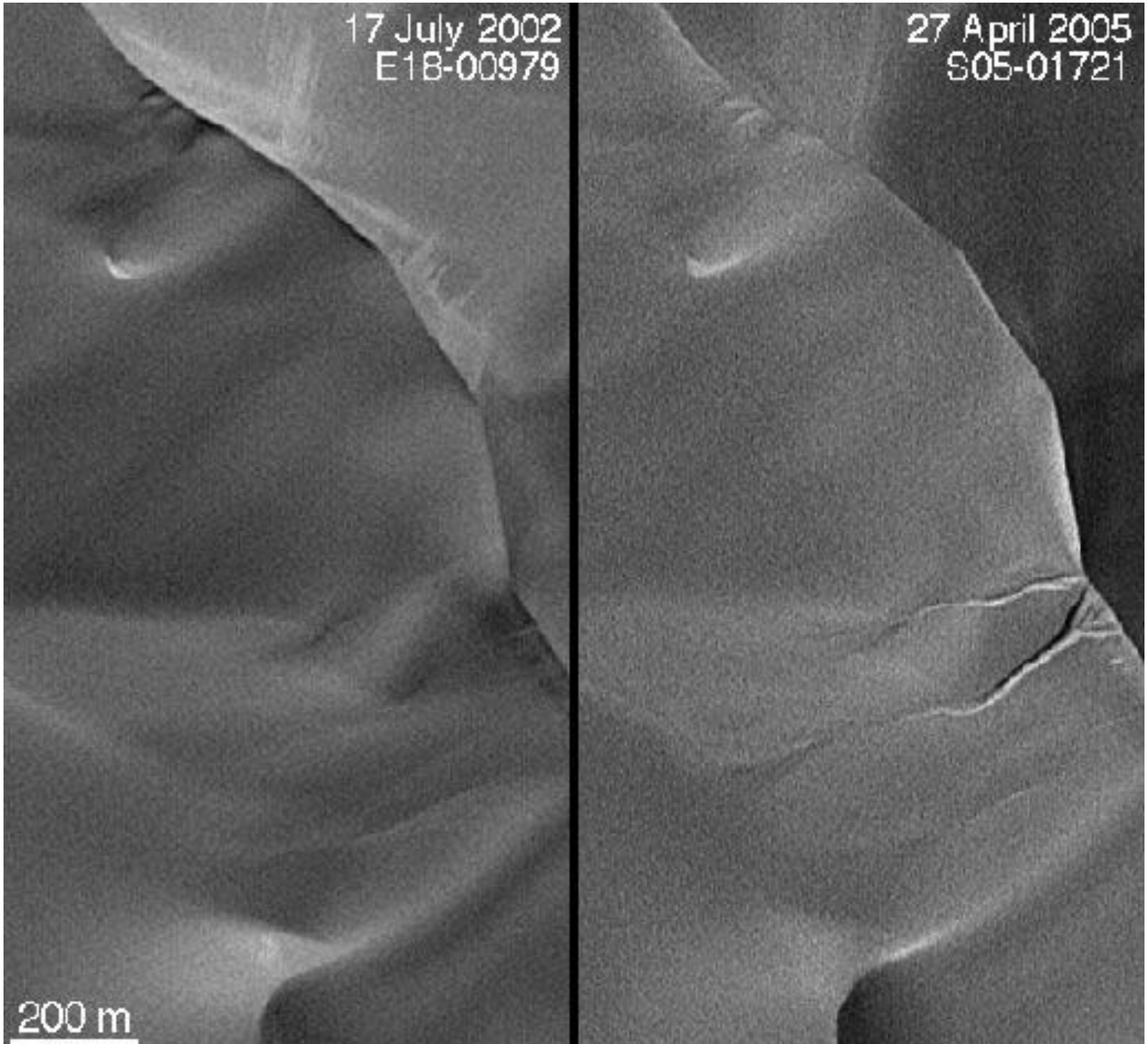
b The close-up view of this crater floor shows sculpted patterns that probably represent layers of sedimentary rock, presumably laid down at a time when water filled the crater.

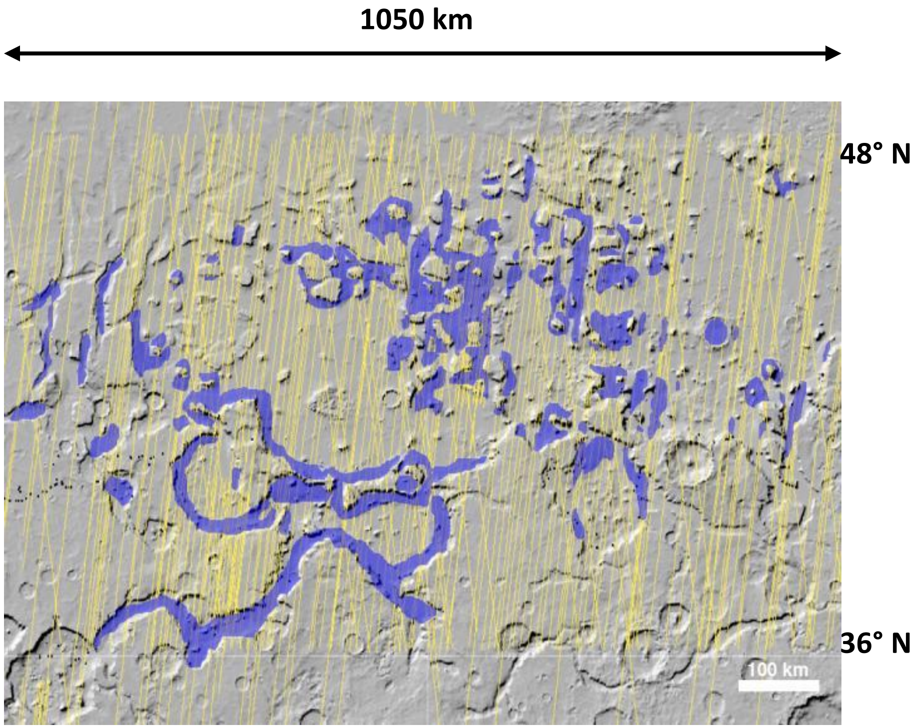
c This computer-generated perspective shows how a martian valley forms a natural passage between two possible ancient lakes (shaded blue); the lower crater is Gusev, where the *Spirit* rover landed. Vertical relief is exaggerated 14 times to reveal the topography.


200 m

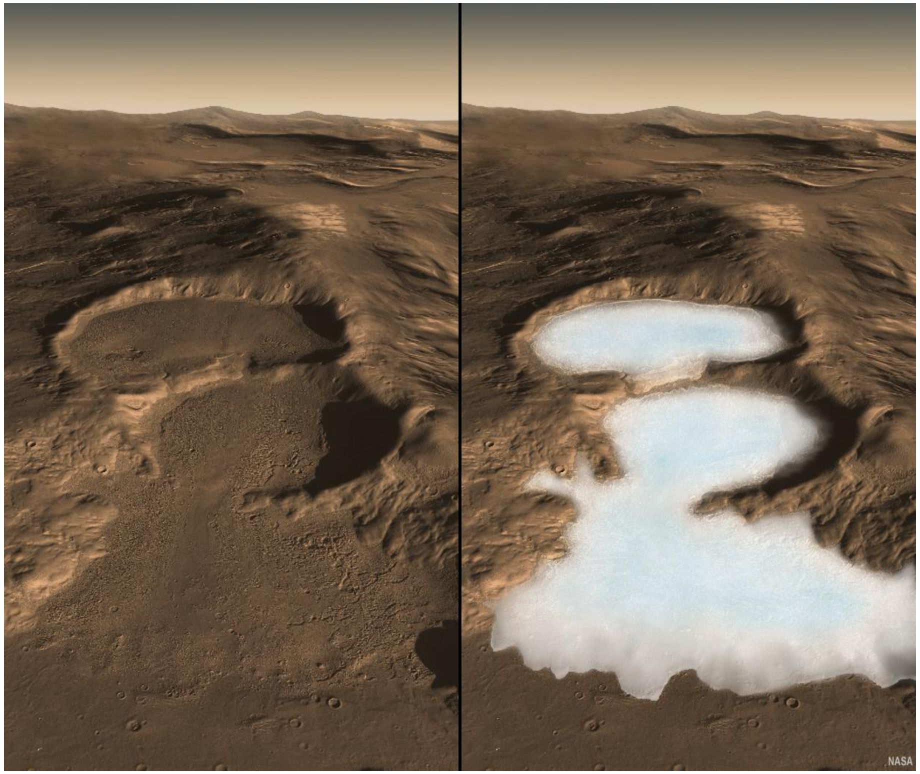

Sun
One model for the formation of
Martian Gullies
Ice Barrier
"steam" clouds
Semi-permeable
Water Layer
Channel
erosion
Rock/Debris
field

Provocative evidence – changes in the last few years!





Topography map from Mars Global Surveyor with the locations of buried glaciers (blue) in a northern hemisphere region of Mars, inferred from radar data. Buried glaciers are always found near steep slopes.

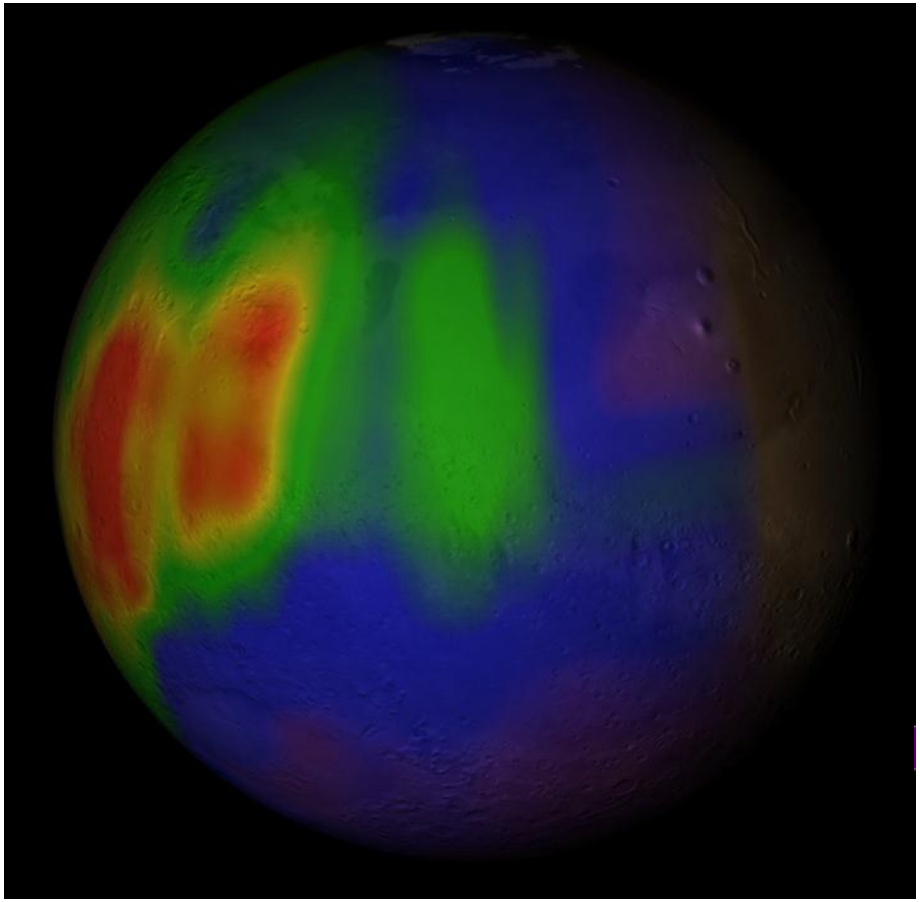


(Left) Perspective image of craters in southern hemisphere of Mars, created using NASA Mars Reconnaissance Orbiter images; (Right) Artist conception of ice underlying a surface layer, based on radar observations.

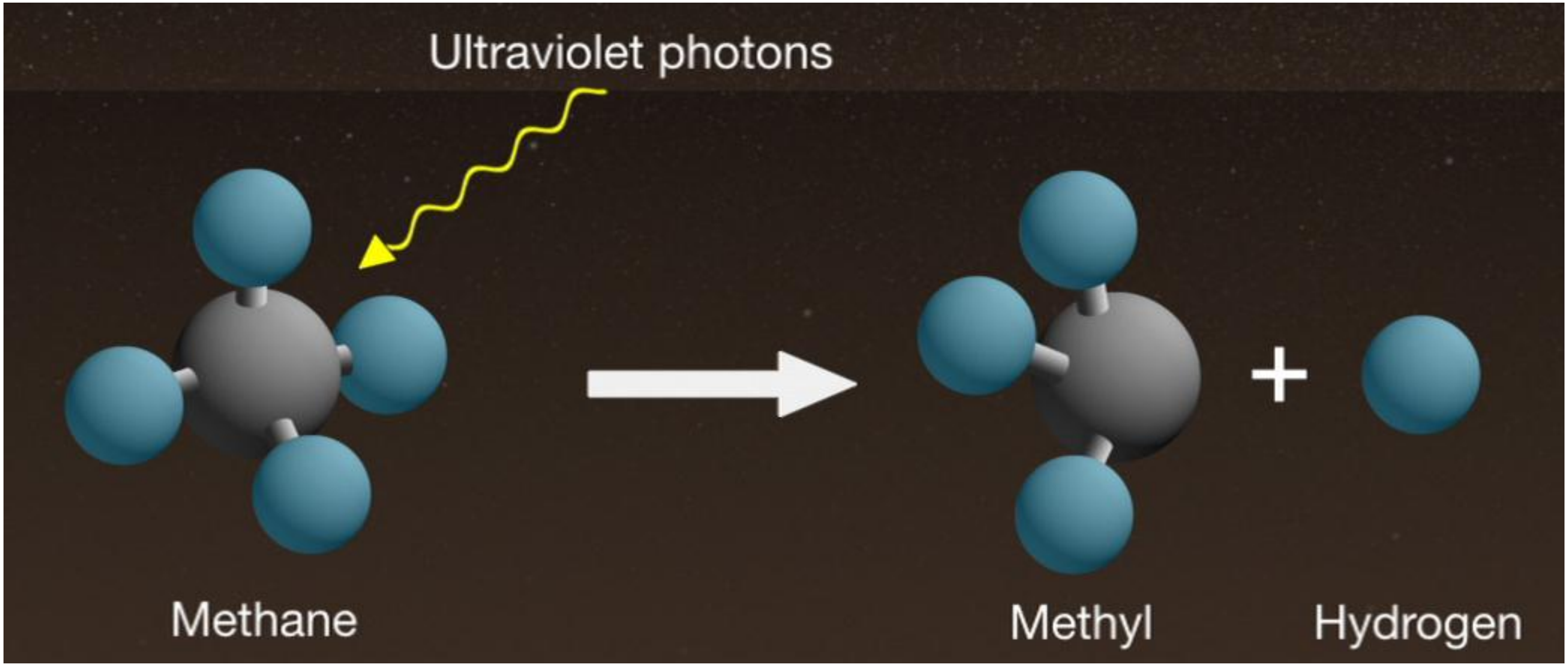
- Radar observations made from orbit reveal that nearly pure ice glaciers covered by a few meters of rock are common at mid-latitudes on Mars
- The layer of rock protects the ice from subliming in Mars' cold and dry climate
- Debris-covered glaciers at mid-latitudes on Mars are kilometers thick and may contain **enough ice to cover the entire planet in 20 cm of water**

Martian Methane

- Methane gas was recently detected in the Martian atmosphere using ground-based telescopes.
- The amount of methane is tiny and the distribution is patchy and it changes with time.
- Most methane in Earth's atmosphere is produced by life, raising questions about its origin on Mars.



View of Mars colored according to the methane concentration observed in the atmosphere. Warm colors depict high concentrations.



UV photons have enough energy to break molecules apart

- Methane in the atmosphere should be destroyed by UV light within a few hundred years.
- Methane seen now must therefore have been produced recently.
- Variations in space and time suggest that it was recently released from the subsurface in localized areas.

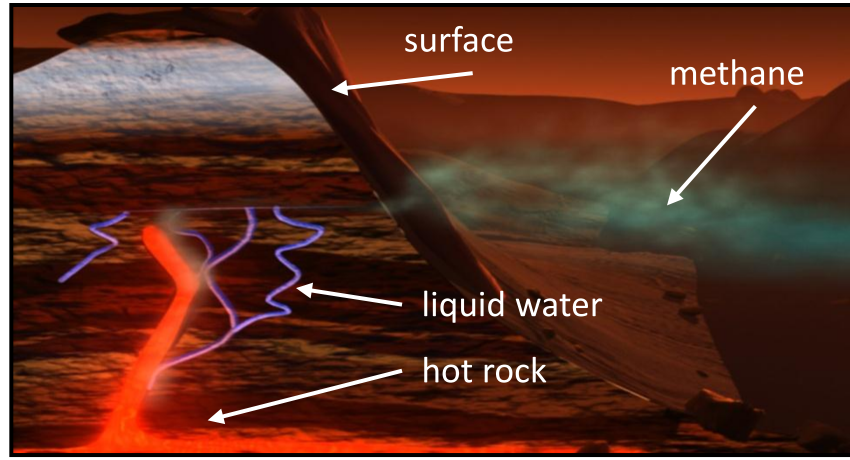
Dynamic Mars

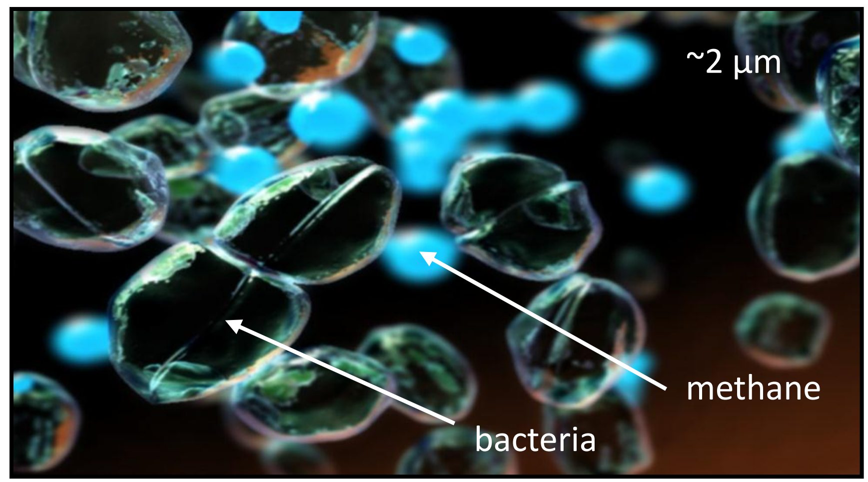
- Where can the methane come from? From analogy with Earth, there are two leading theories for <u>the origin of recent subsurface methane at Mars</u>:

  1. Methane is produced by water-rock interactions.
  2. Methane is produced by bacteria, in regions where liquid water is found.

  Either theory implies that the Martian subsurface is dynamic.

- Future observations can test for trace chemicals associated with each process.

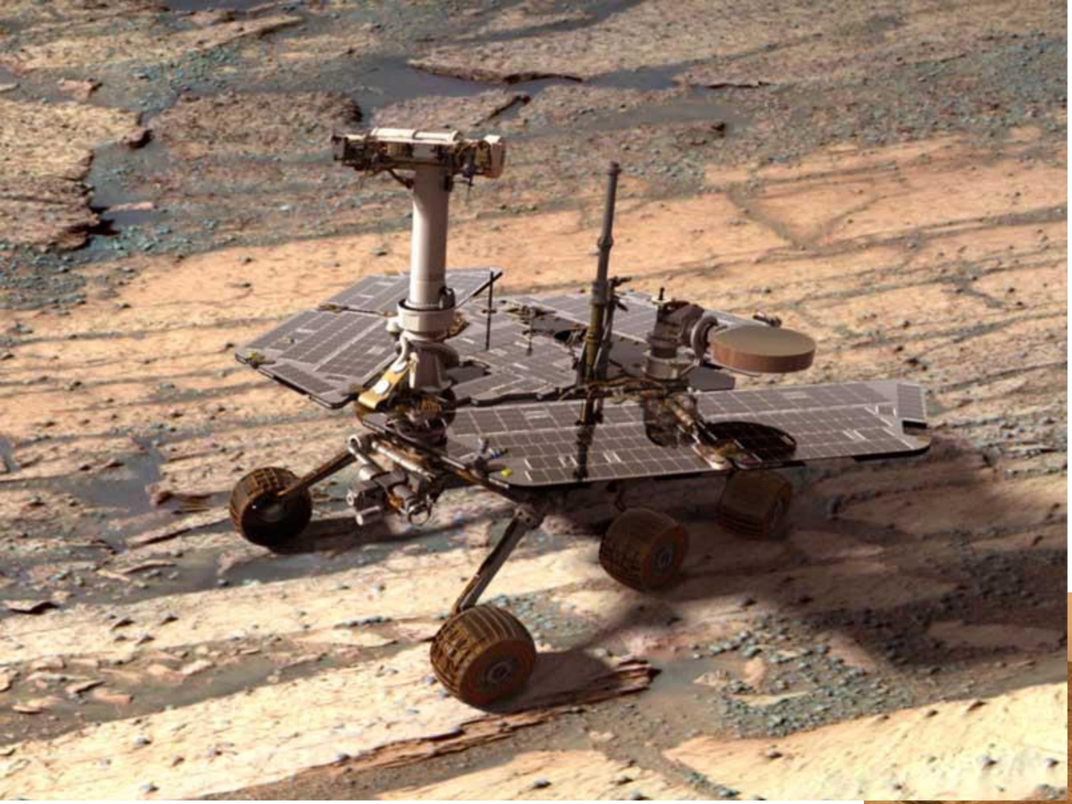




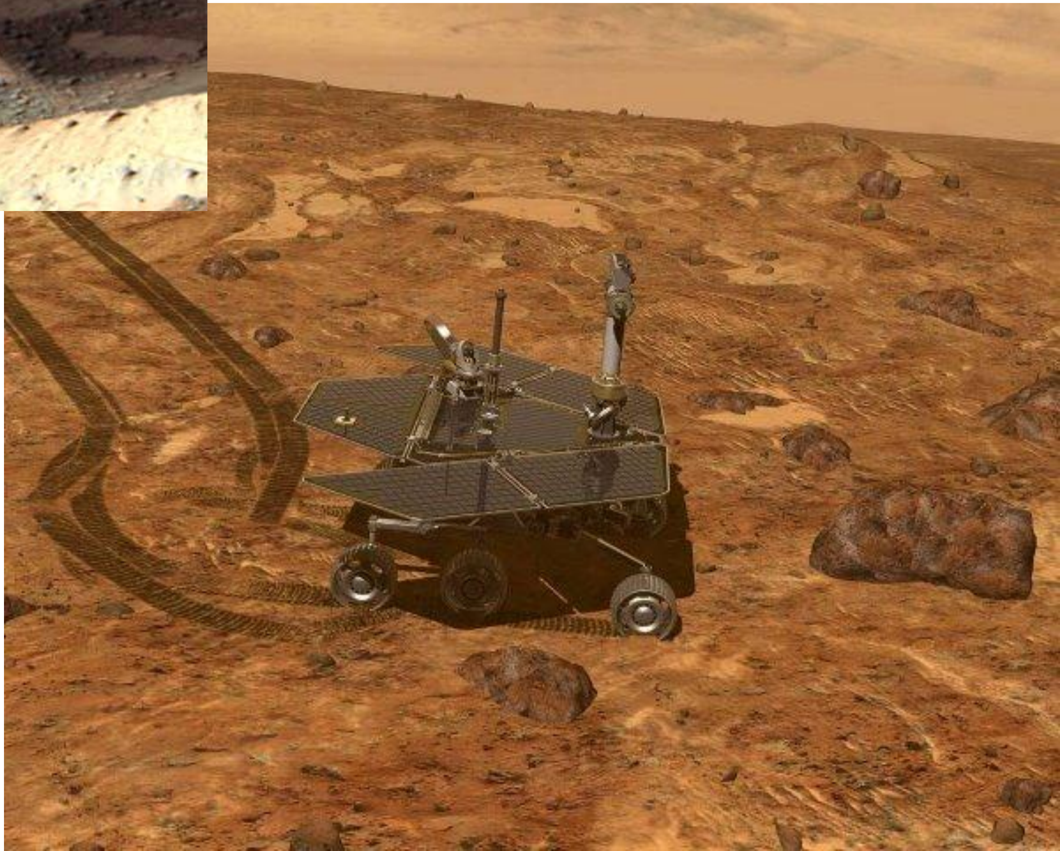
Methane on Mars could be produced chemically through liquid/rock interactions (top) or biologically (bottom)

Mars up Close

Mars In Detail

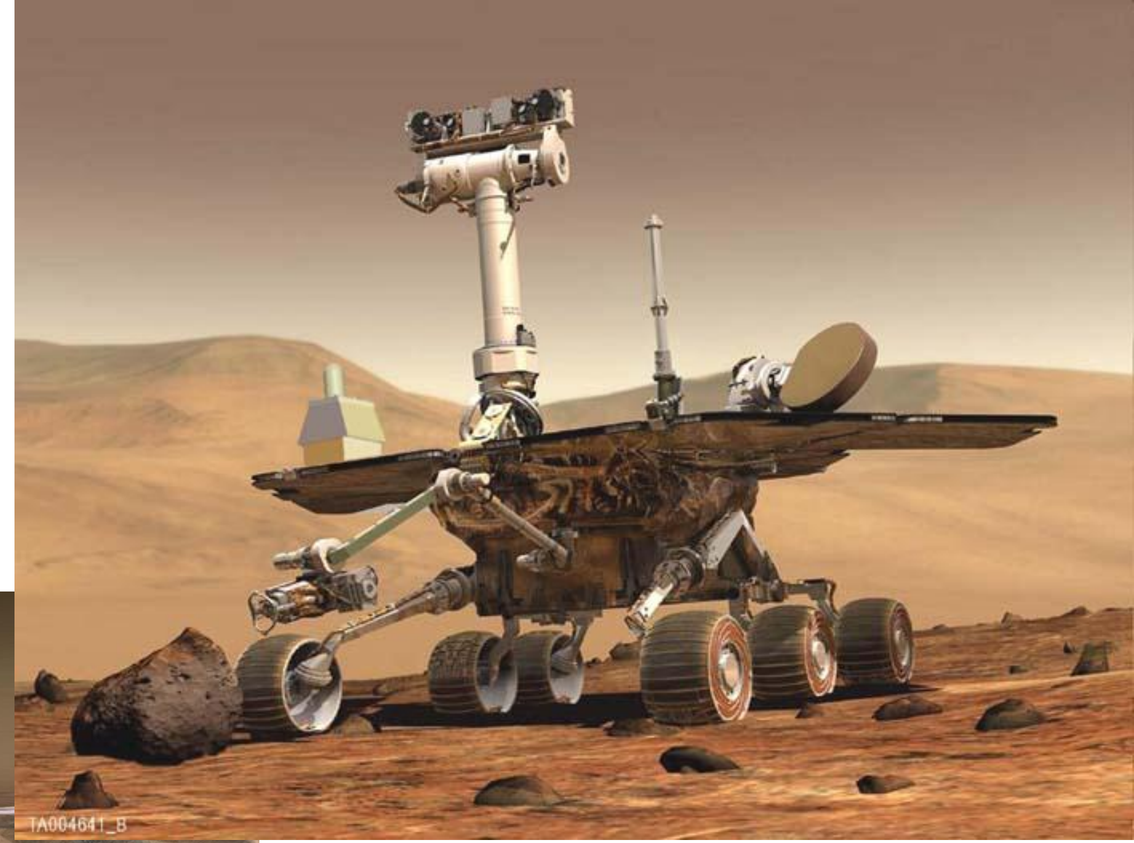


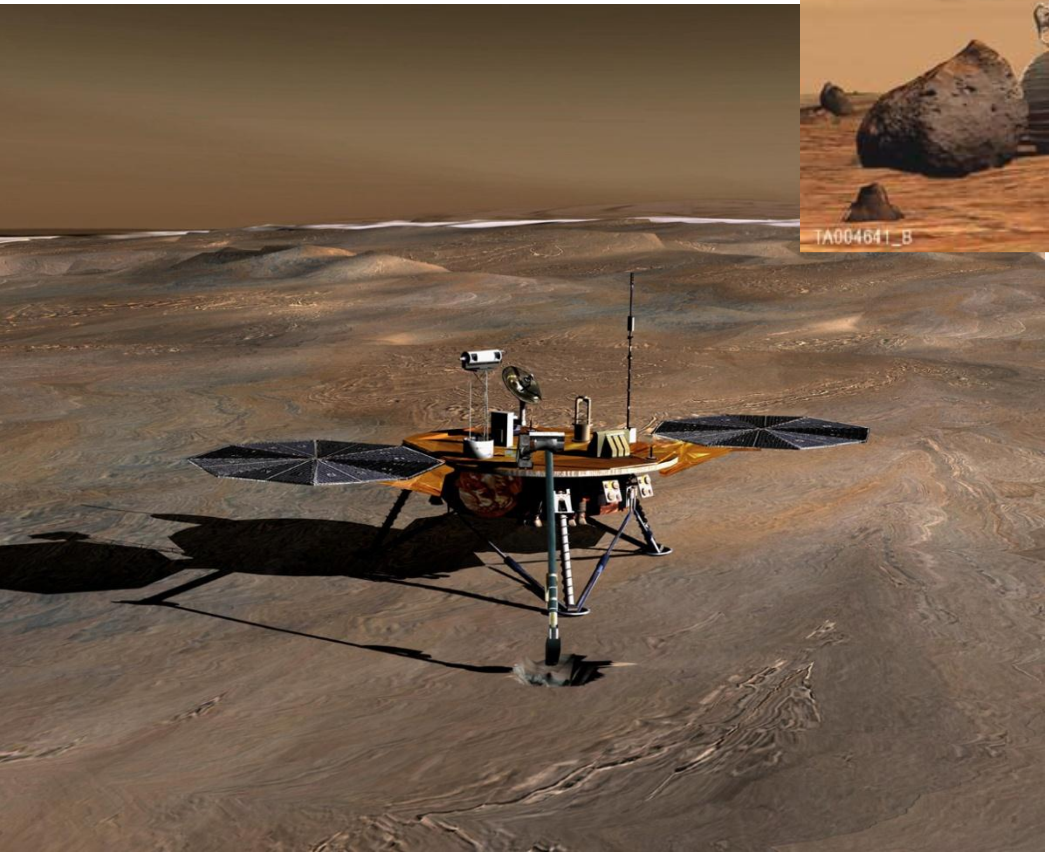
Spirit and Opportunity defied expectations by lasting for many years (RIP Spirit), rather than the nominal 3 months.



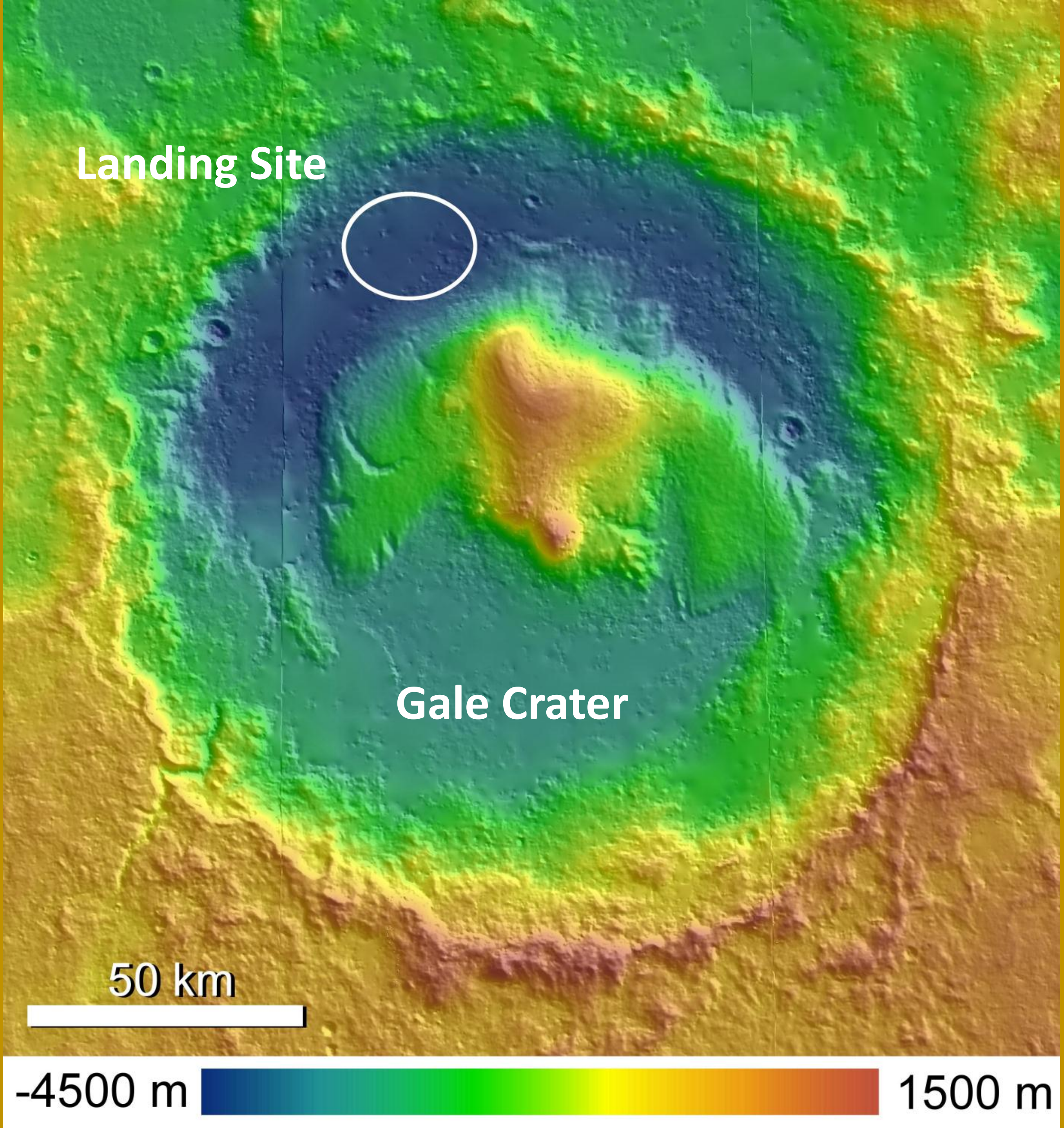
Exceptionally durable robots, they’ve found an abundance of firm evidence for standing bodies of water in the distant past on Mars.

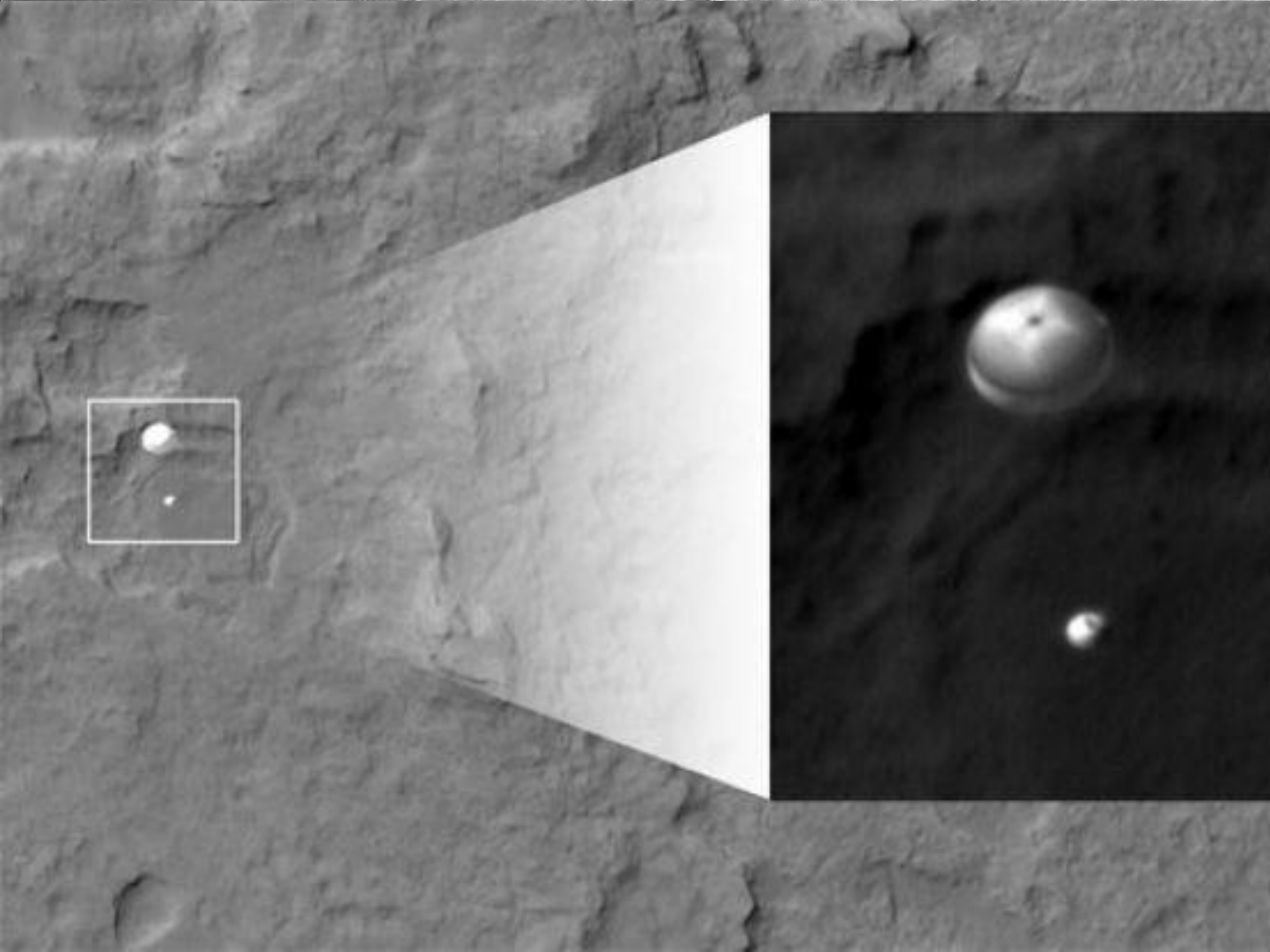
Phoenix, at the polar region for 6 months in 2008, saw perchlorate, brine and evidence for a hydrological cycle.



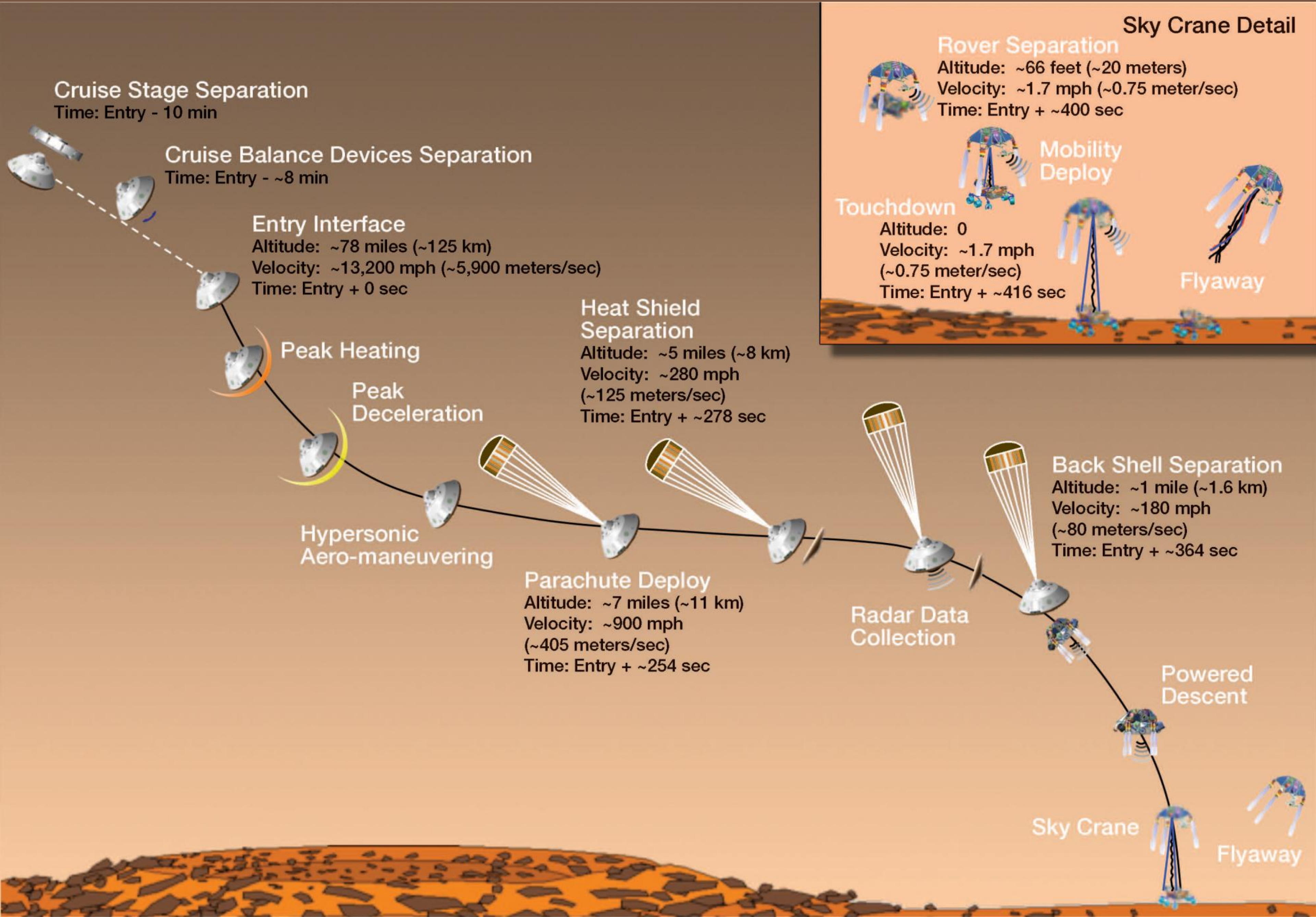


Curiosity (MSL) is a next generation rover, safely landed in August 2012, with sophisticated set of 12 instruments on board.


Landing Site
Gale Crater
50 km
-4500 m
1500 m



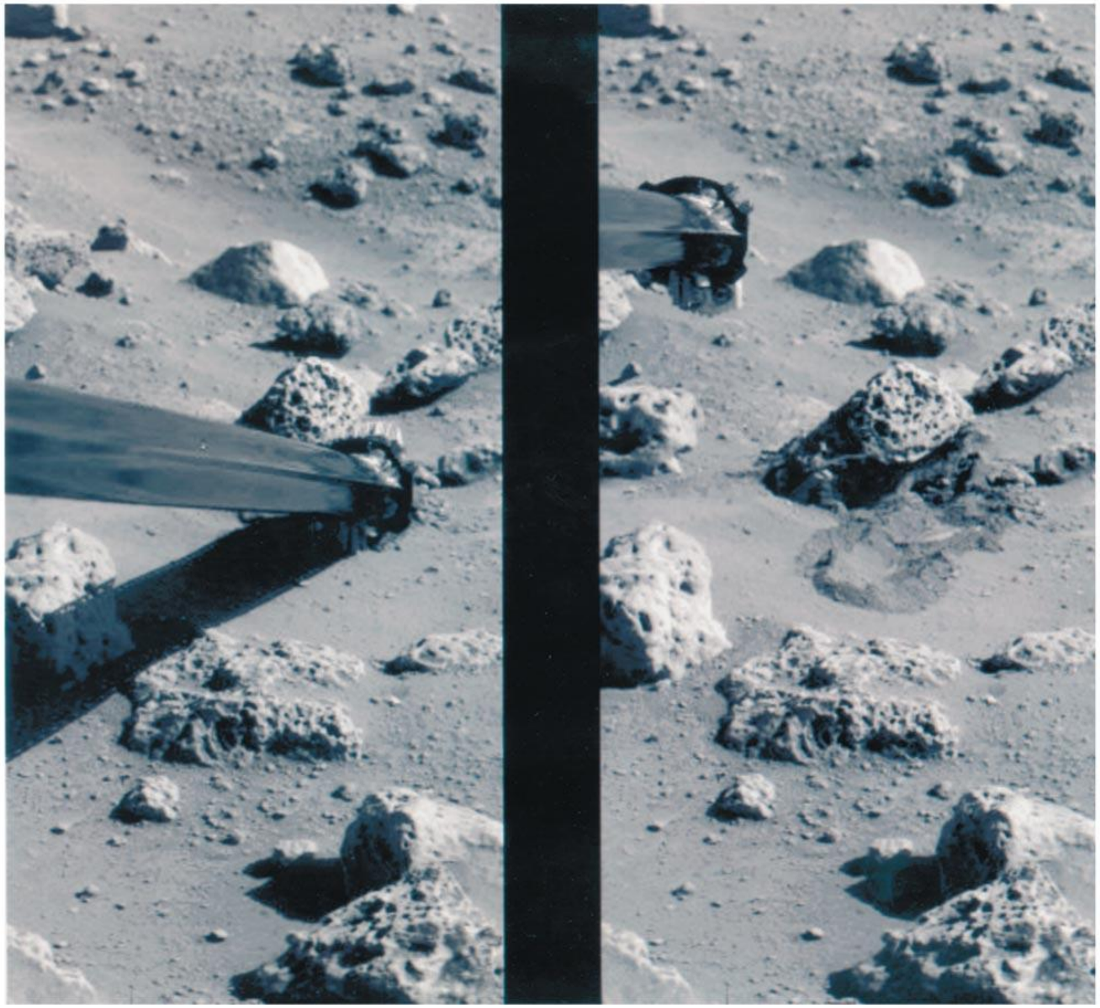
CURIOSITY DESCENT SEQUENCE



Curiosity - the View from Gale Crater

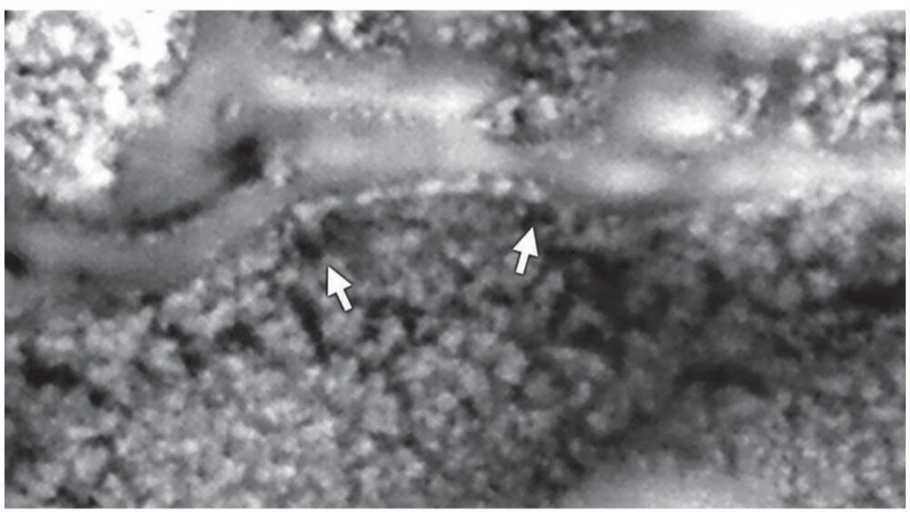
Future Mars

Evidence for Life



Results from the Viking landers in 1976 were ambiguous – no clear signs of metabolisms at work, but unexplained levels of reaction and chemical activity in one of the experiments (the PI is convinced it might have been biological).

Evidence from the Allen Hills meteorite was tantalizing but in the end not convincing. We need better experiments on Mars landers or, better, the return of samples to the Earth.

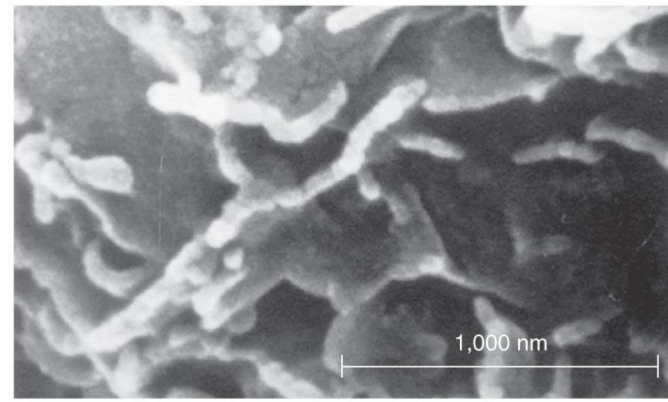


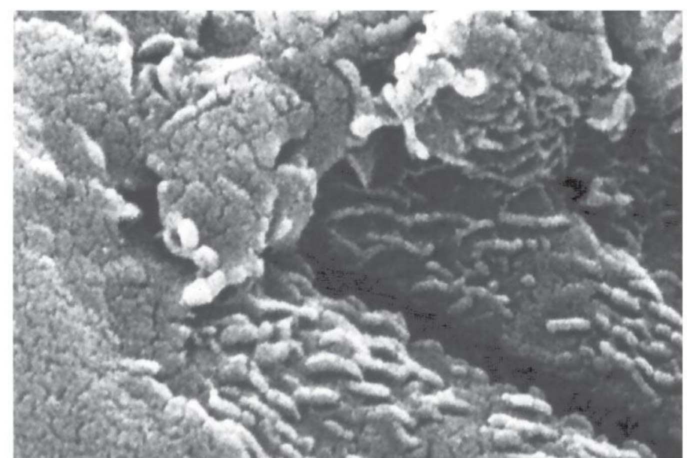
Top:

Earth

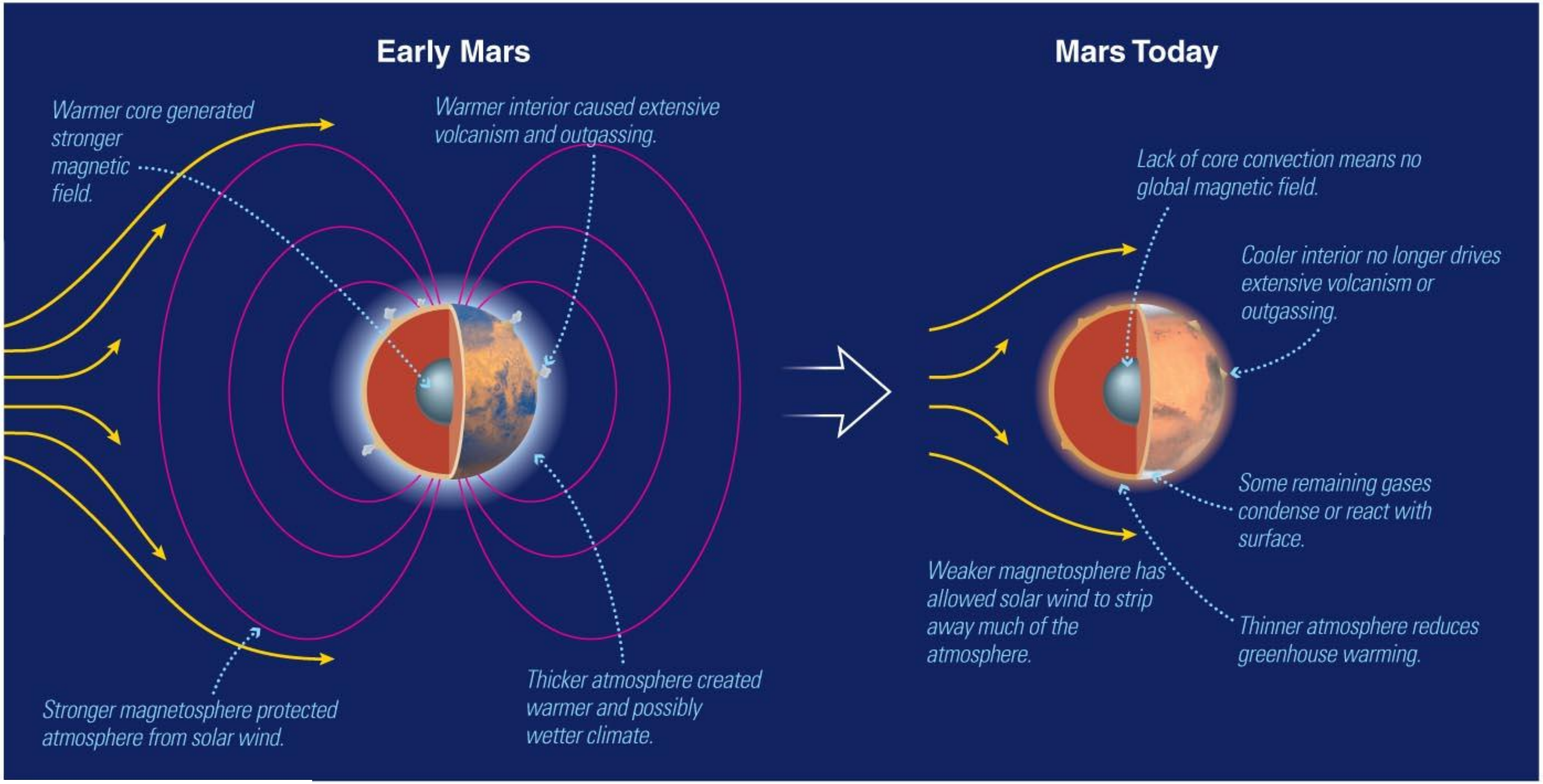
Bottom:

Mars

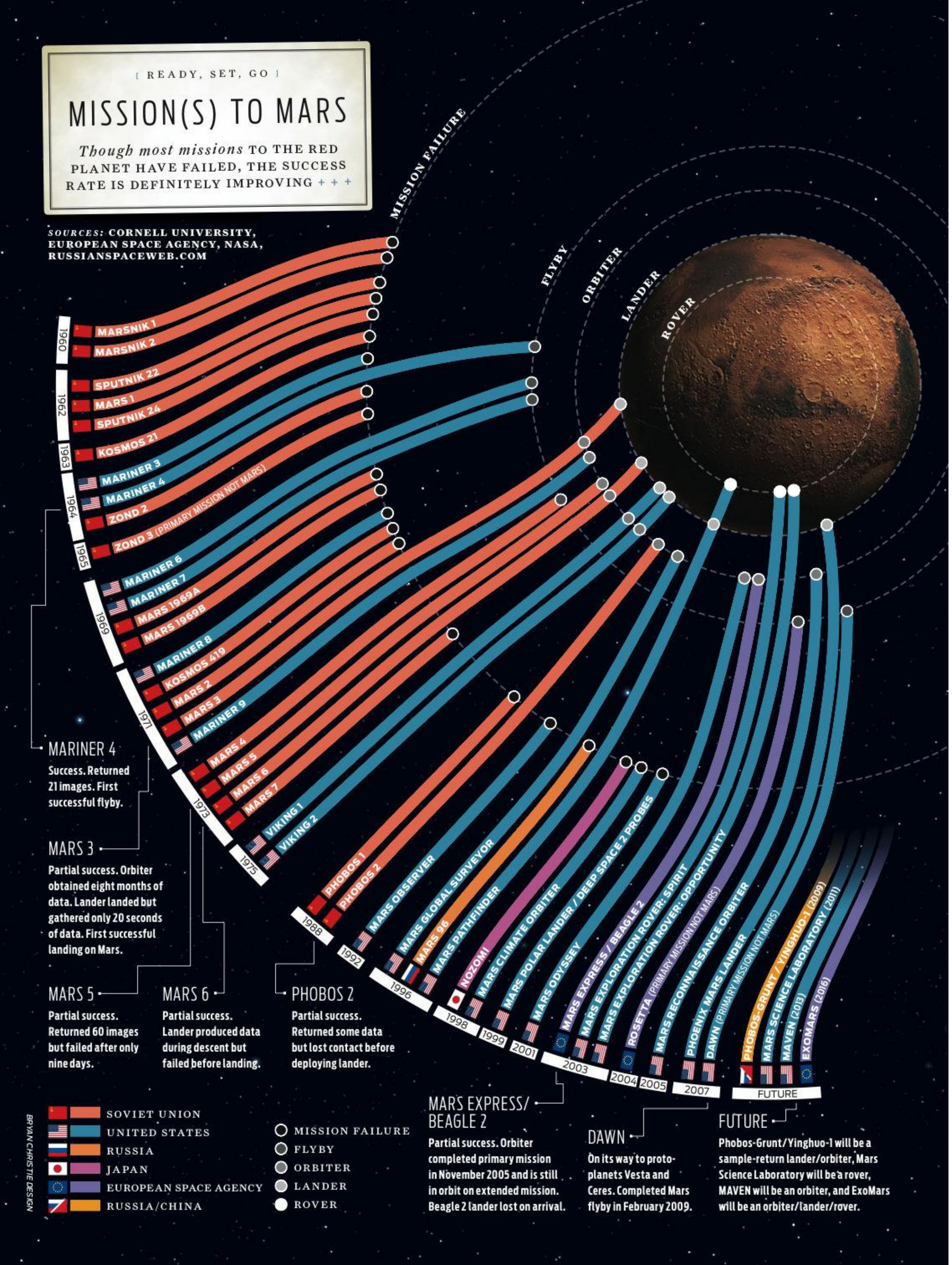




Climate Change on Mars



But the Sun was 25% dimmer 3 billion years ago; it's not clear if Mars actually had long-lived, stable surface water.

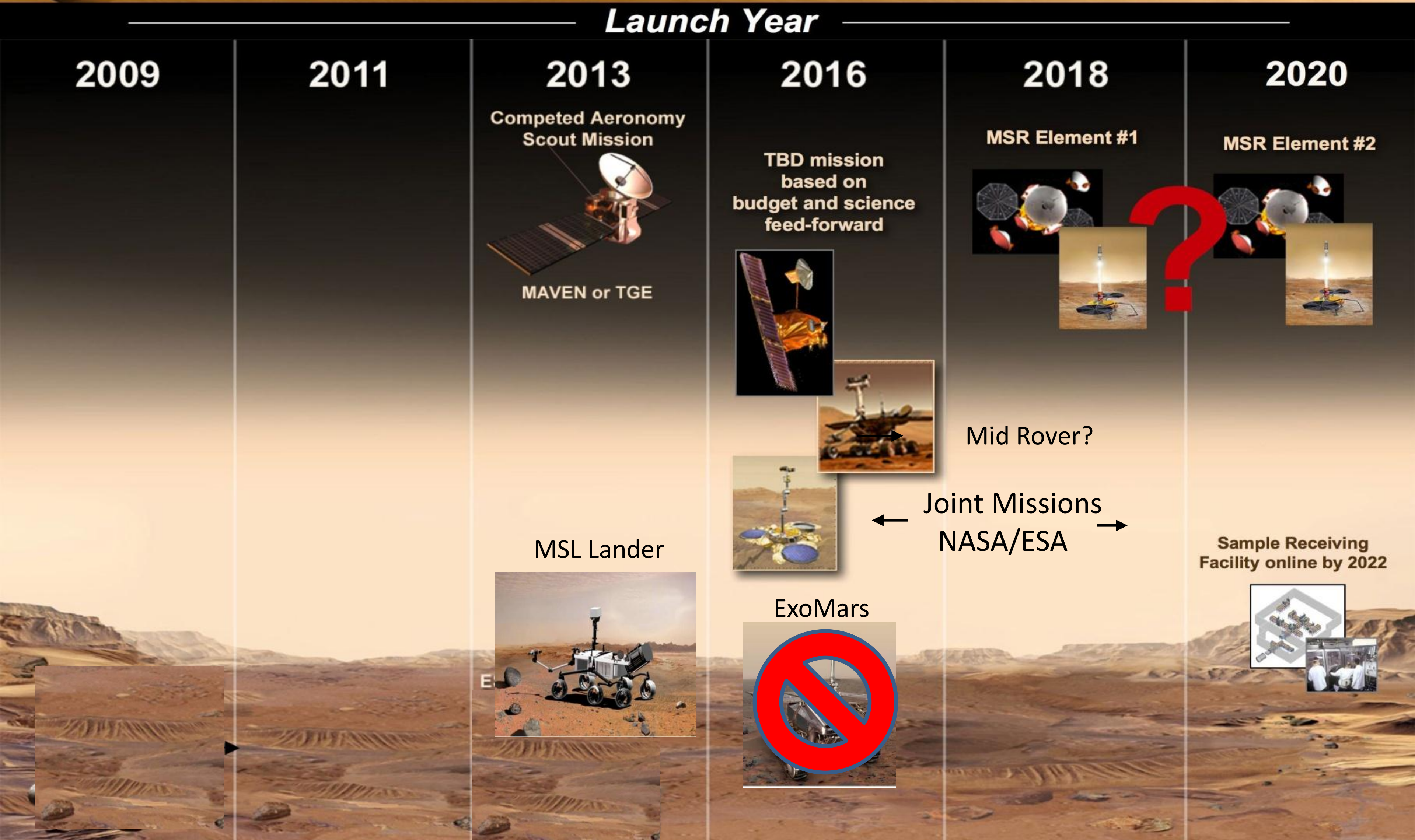


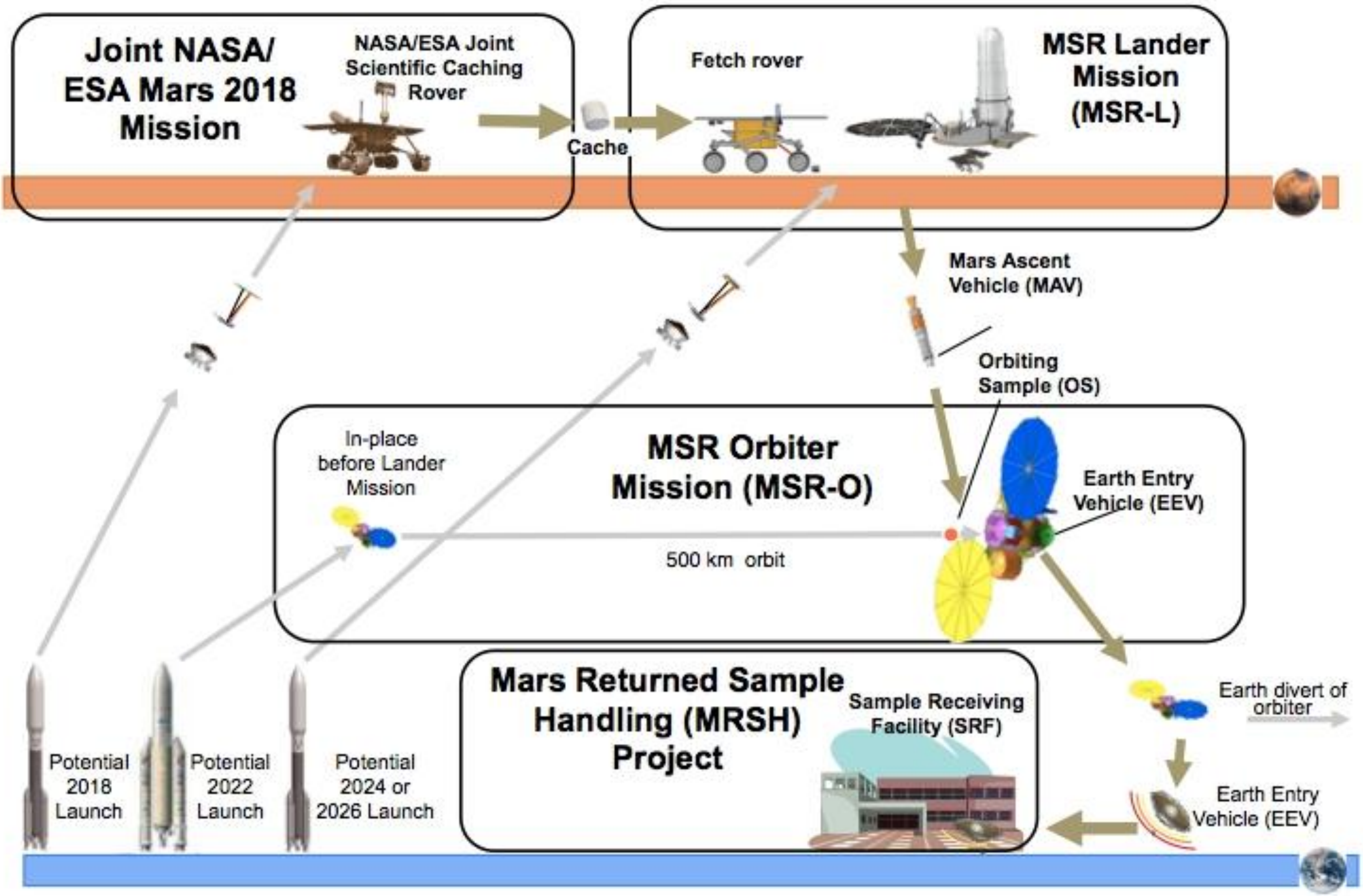
Despite conventional wisdom that Mars is a "death planet," the success rate there is steadily improving!

Overall success rates Venus/Moon/Mars:

60s	**38/109**	**35%**
70s	**40/55**	**73%**
80s	**13/15**	**87%**
90s	**13/18**	**72%**
00s	**20/22**	**91%**

Looking Ahead to Next Decade

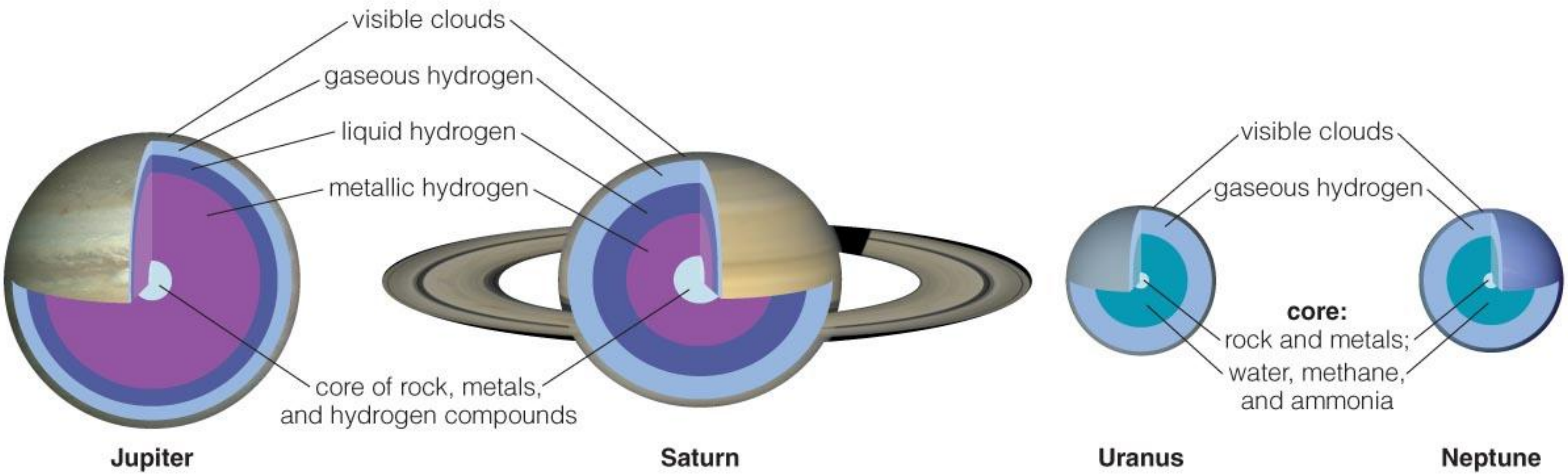




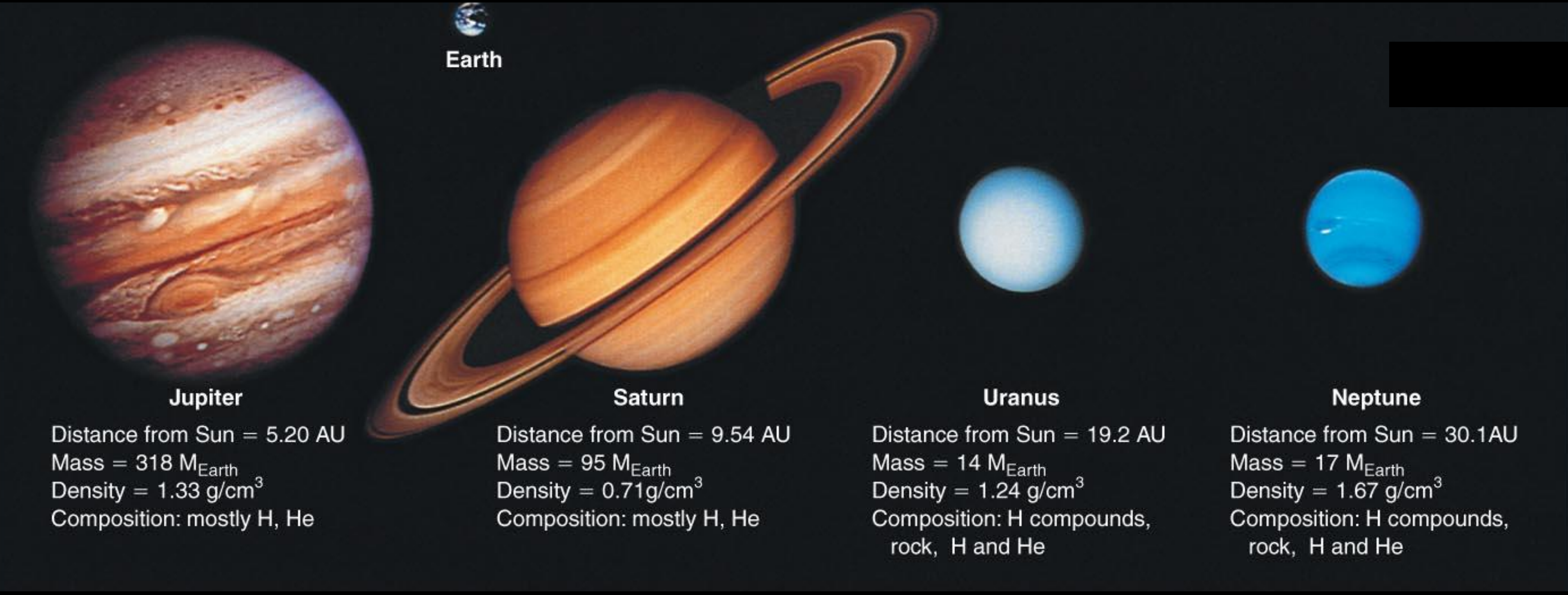
Joint NASA/ ESA Mars 2018 Mission
NASA/ESA Joint Scientific Caching Rover
Cache
Fetch rover
MSR Lander Mission (MSR-L)
Mars Ascent Vehicle (MAV)
Orbiting Sample (OS)
In-place before Lander Mission
MSR Orbiter Mission (MSR-O)
Earth Entry Vehicle (EEV)
500 km orbit
Mars Returned Sample Handling (MRSH) Project
Sample Receiving Facility (SRF)
Earth divert of orbiter
Earth Entry Vehicle (EEV)
Potential 2018 Launch
Potential 2022 Launch
Potential 2024 or 2026 Launch

Jovian Planets

Jovian planets are far from the Sun and cold, but the lower regions of their hydrogen-helium atmospheres are warmer. They each have rocky cores 3-5 times the mass of Earth but conditions are very extreme there – very high pressure, no sunlight, high temperature. All four possess magnetic fields, large and diffuse ring systems, & extensive sets of satellites.

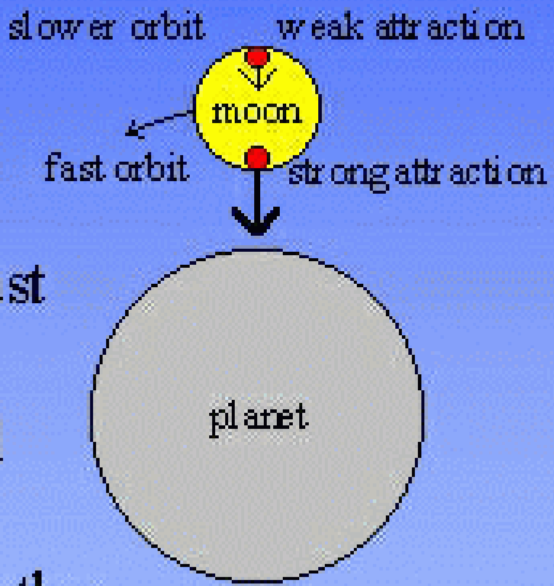


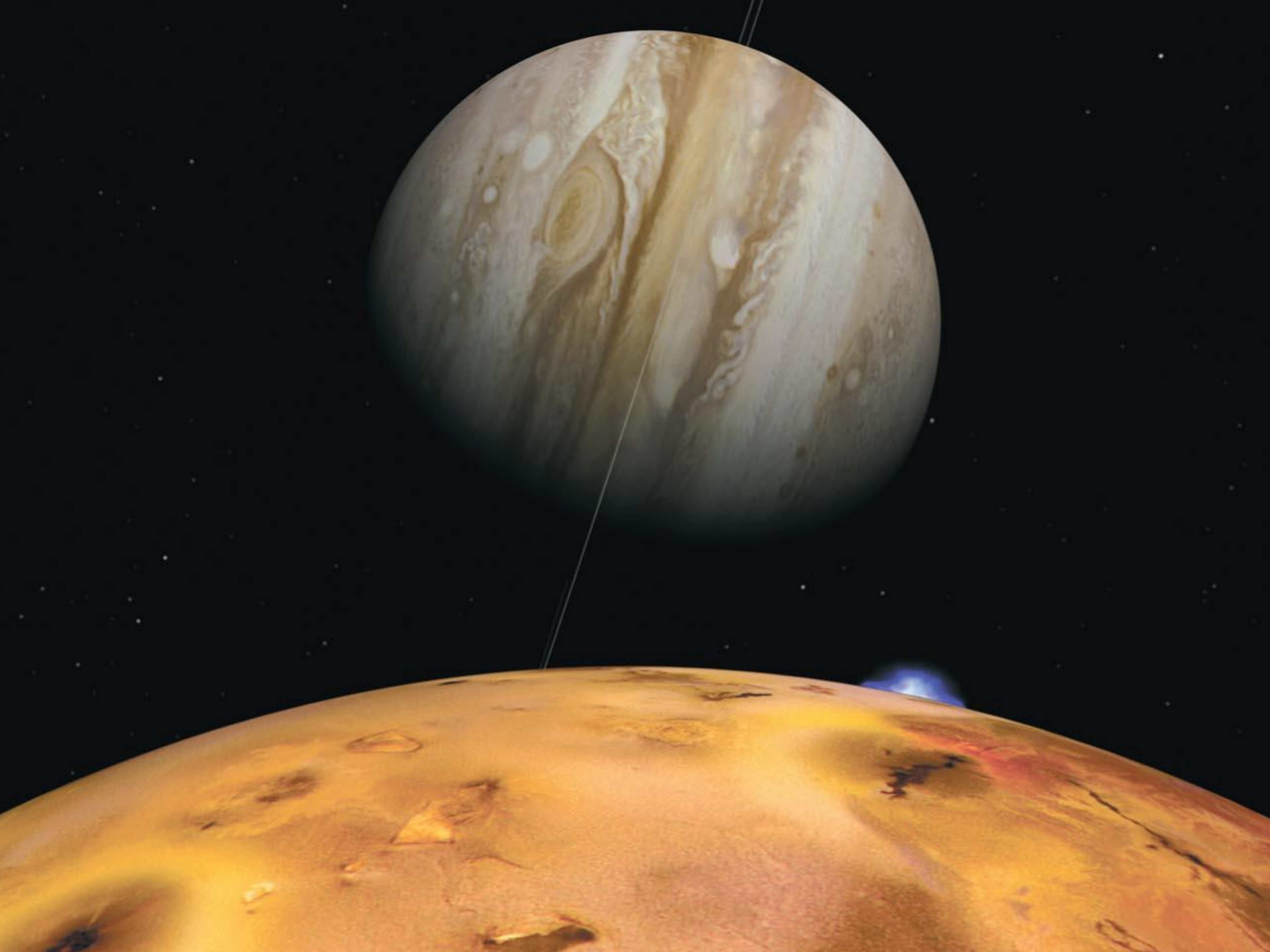
Giant Planets to Scale



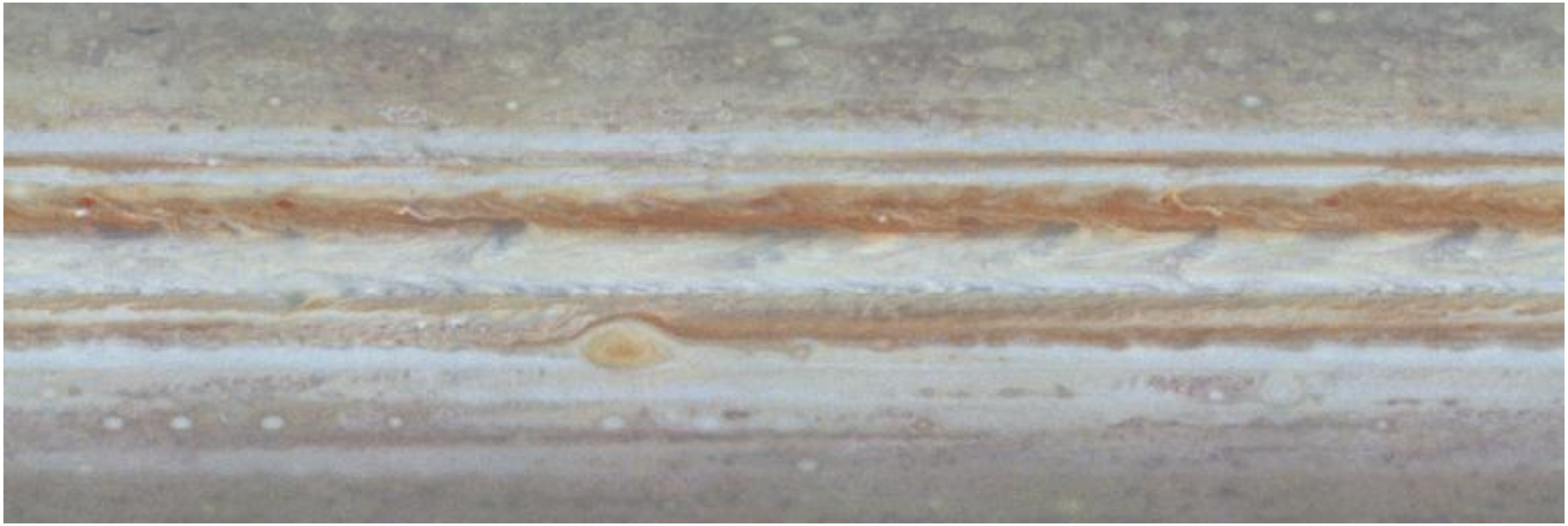
Roche Limit

- Why hasn't Saturn's ring material coalesced into a moon?
- Rings are within the *Roche limit*
- A moon held together by its own gravity must be able to move as one body. This means it must withstand the difference in gravitational force between its nearest and furthest points from the planet. This difference gets greater the nearer the moon is to the planet. The *Roche limit* is the closest the moon can get to the planet before it breaks up

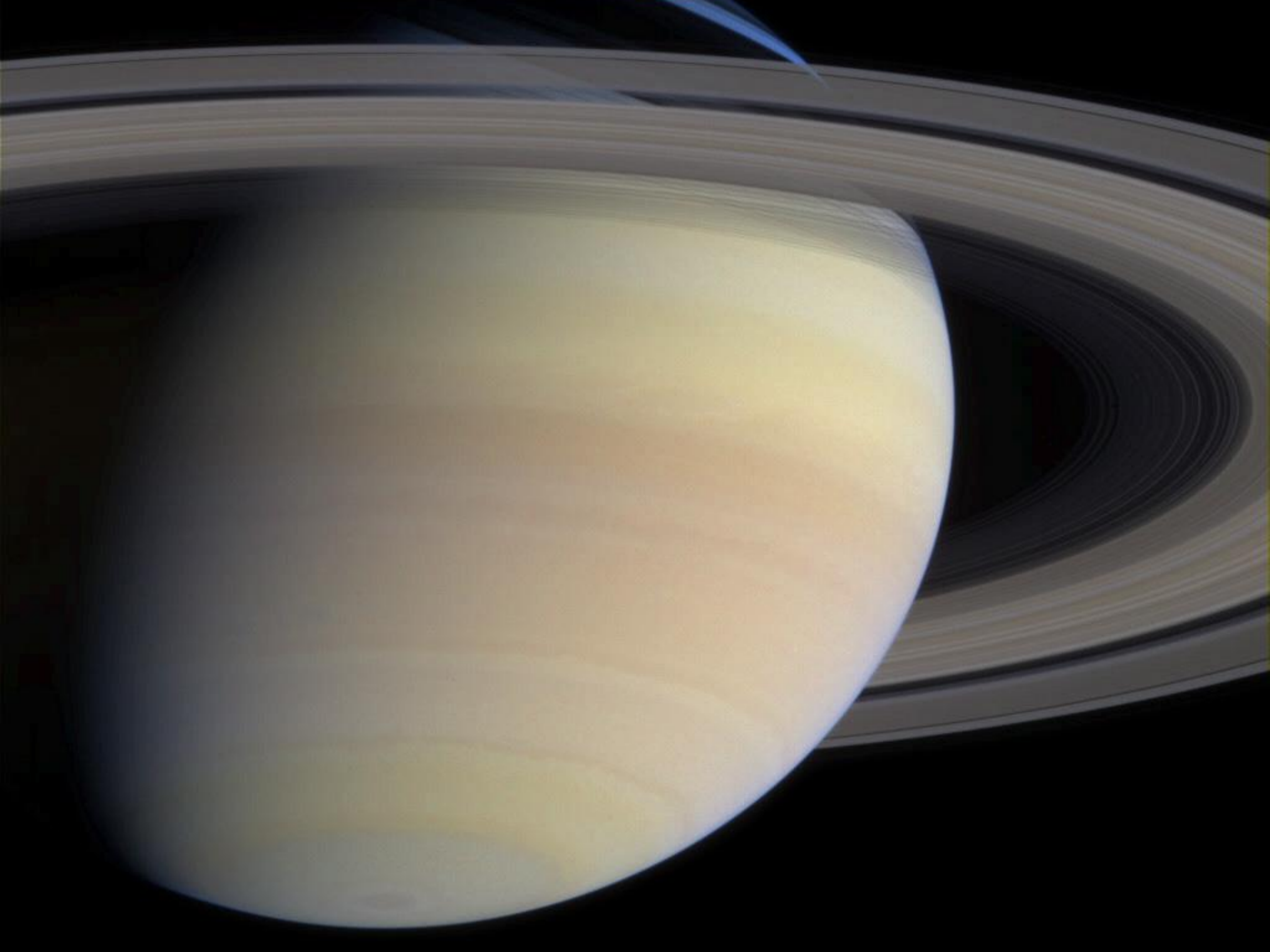




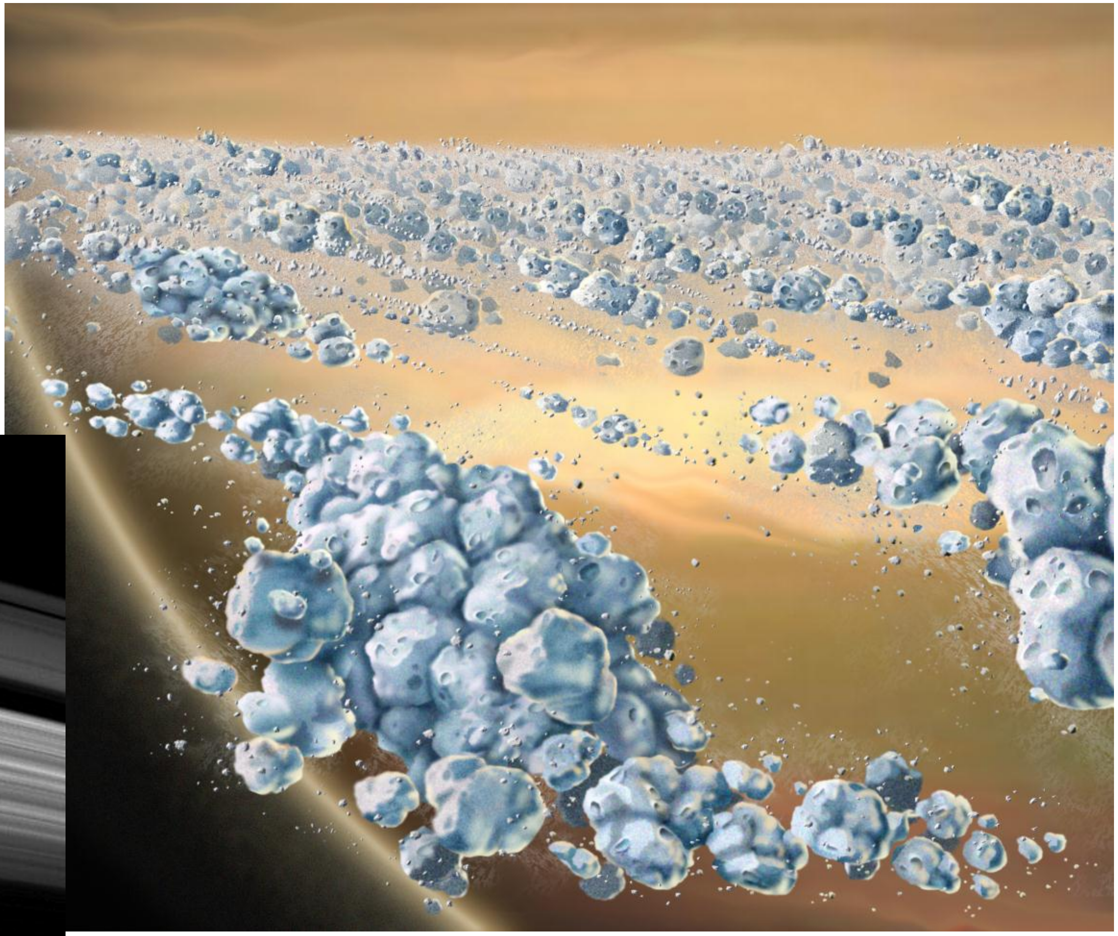
Weather on Jupiter

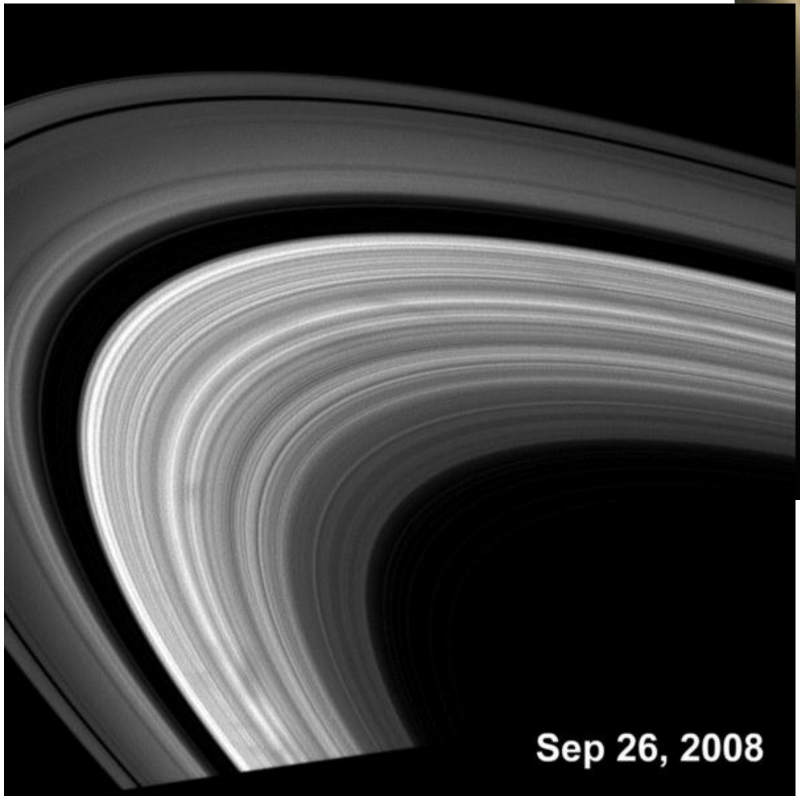


Jupiter's cloud belts all whip along at 300-400 mph. The Great Red Spot has been observed since the telescope was invented so it is at least 400 years old.



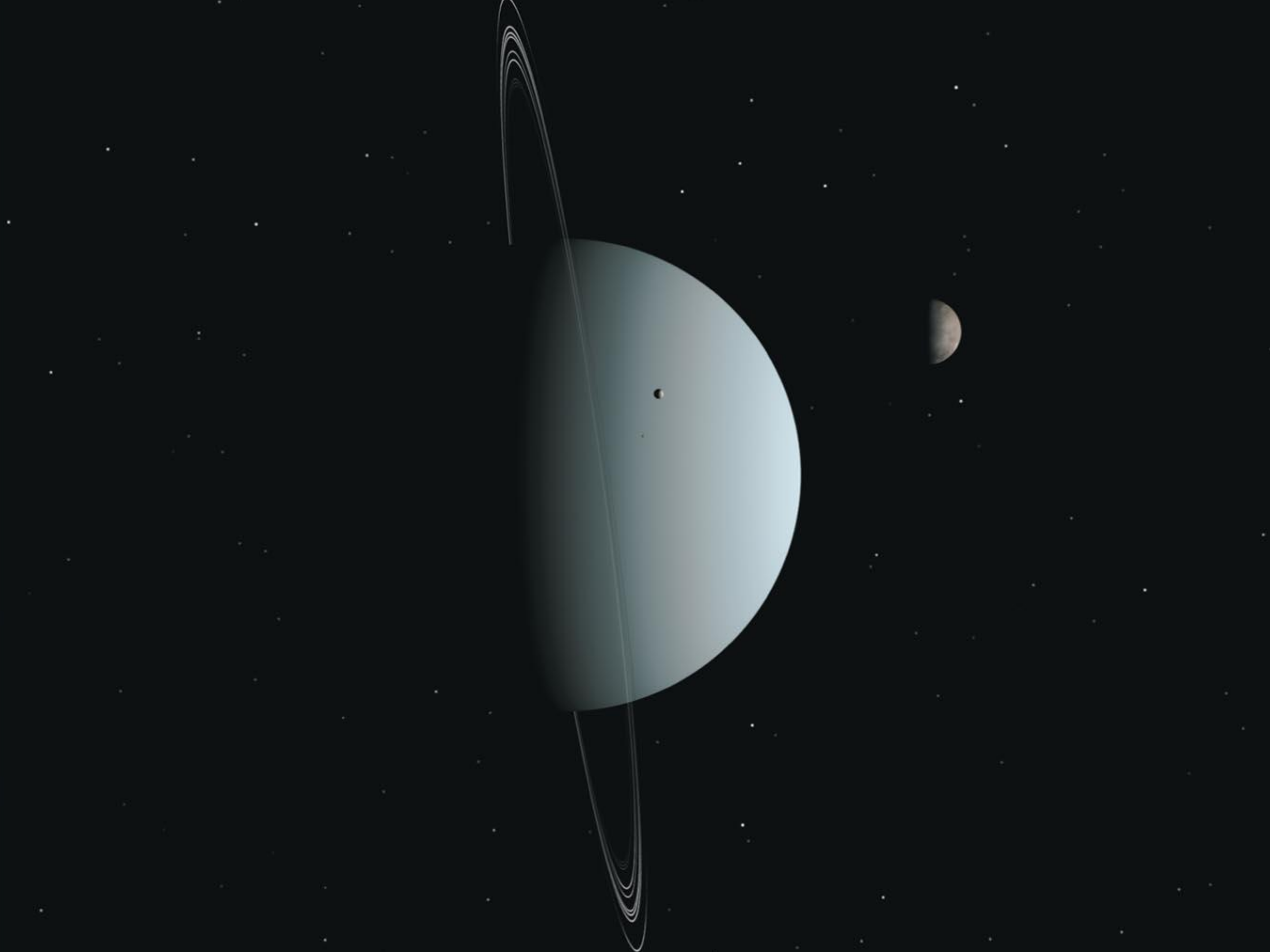
Rings around Saturn

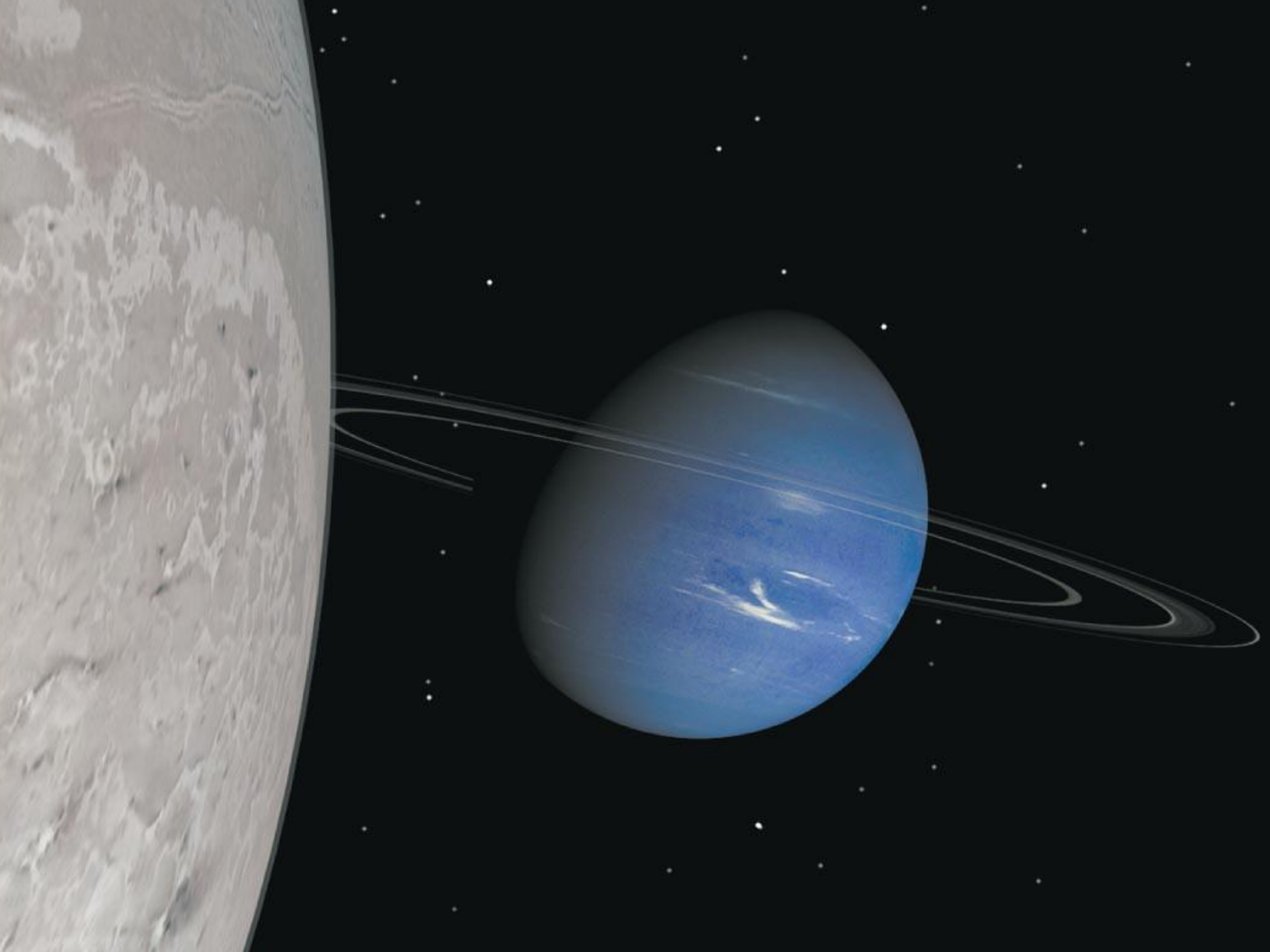




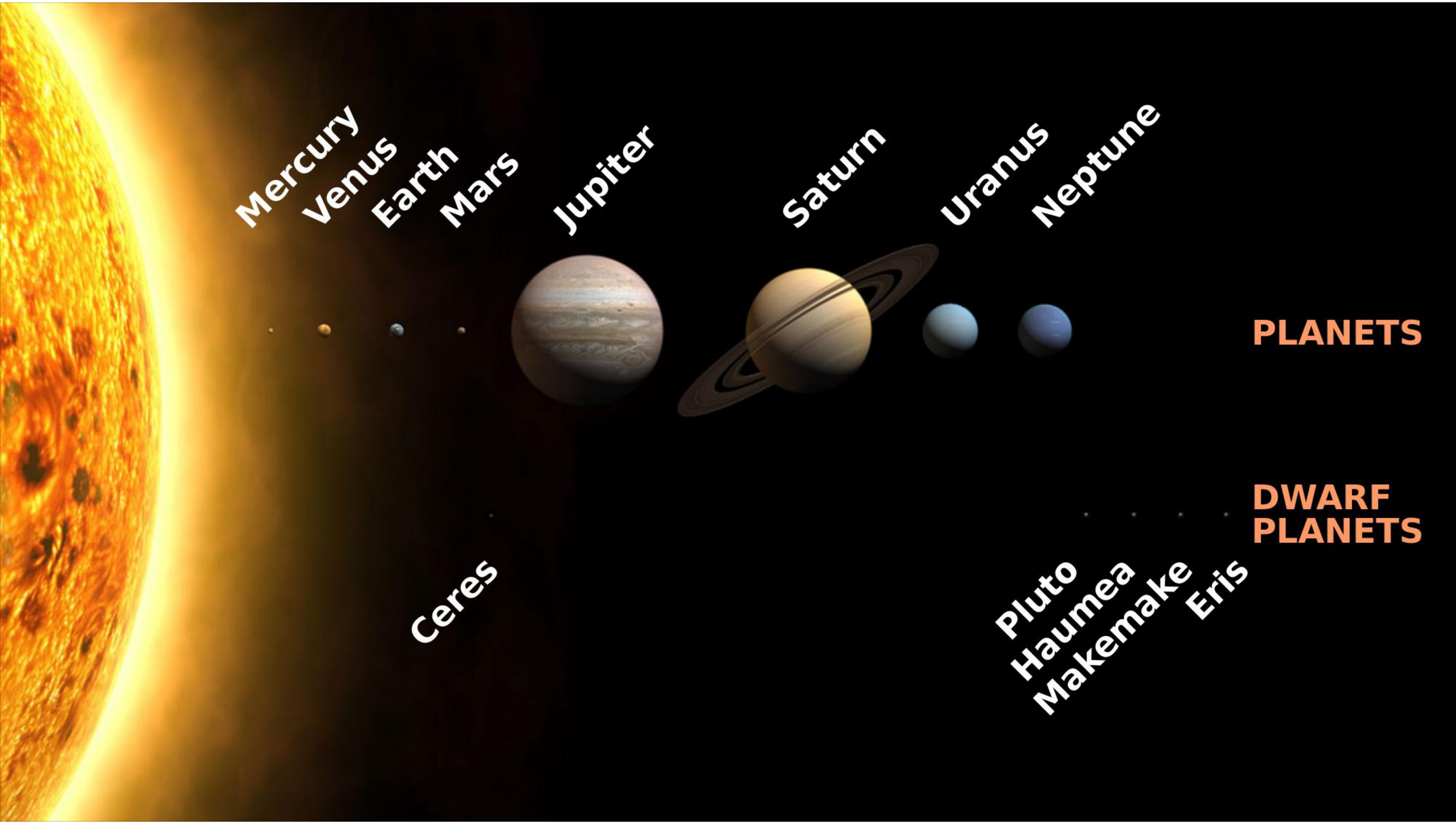
Cassini Mission Overview

Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), July 2004 - July 2017



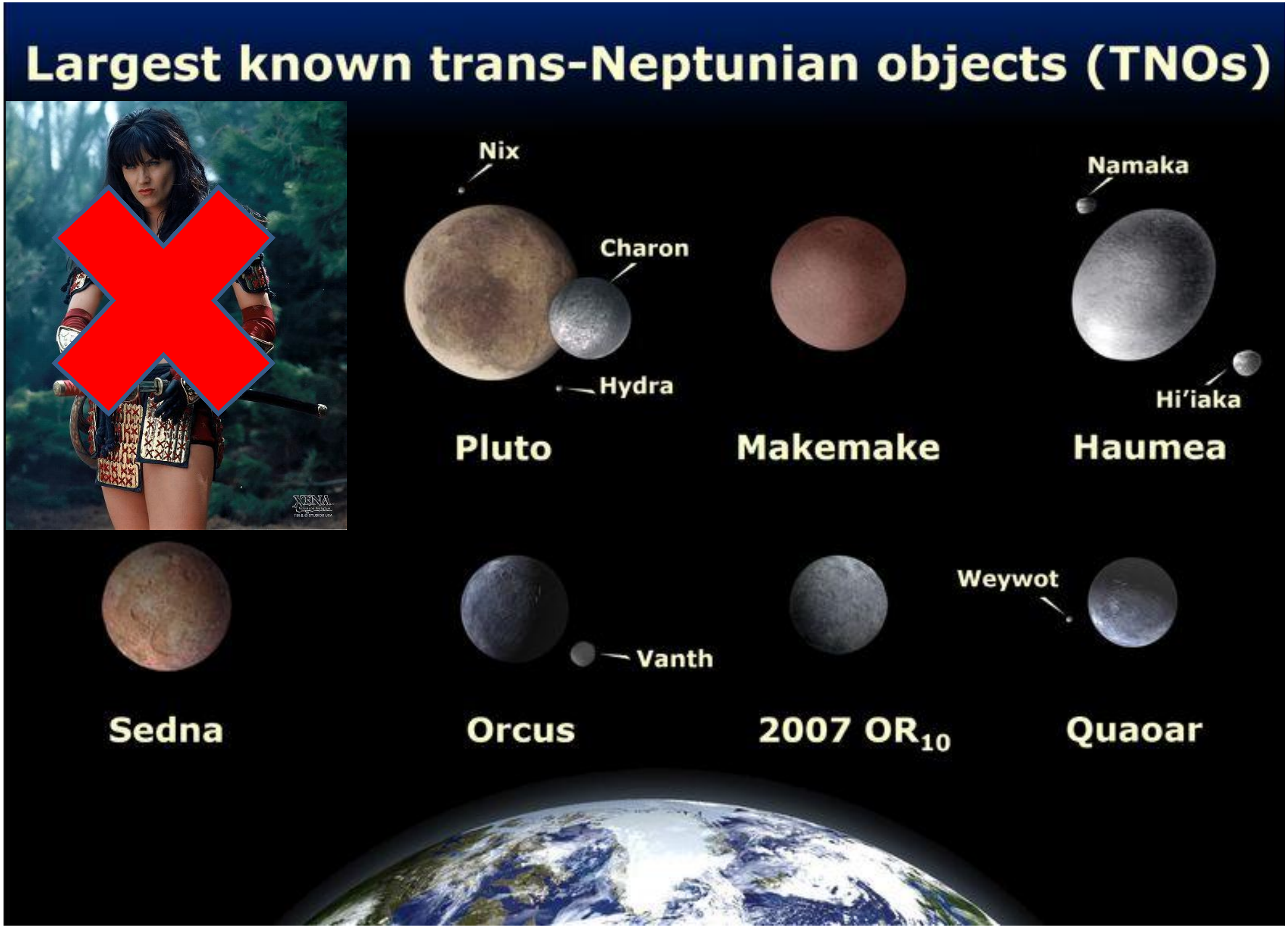


Outer Regions

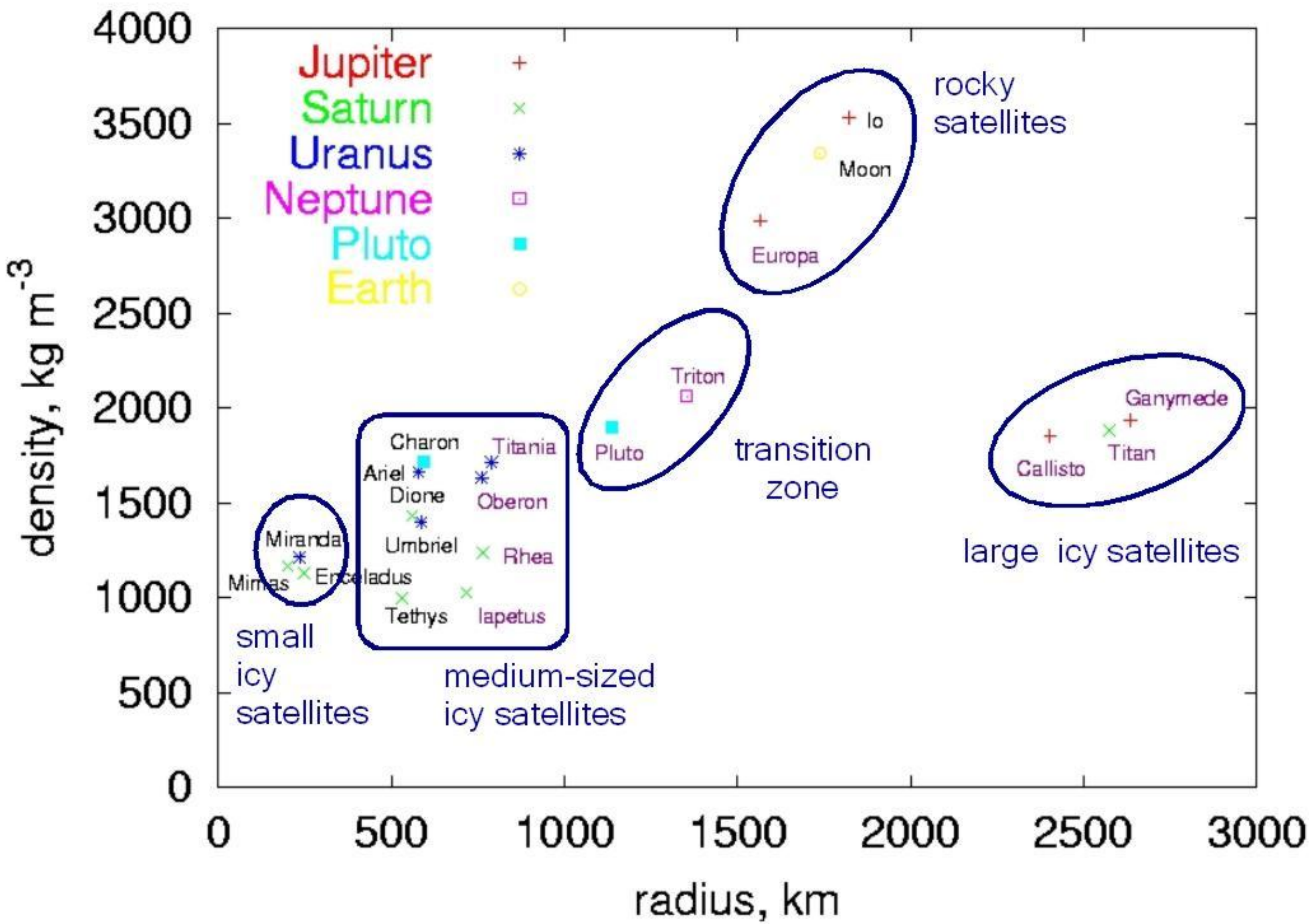



POOR
PLUTO
MathiasPedersen.com

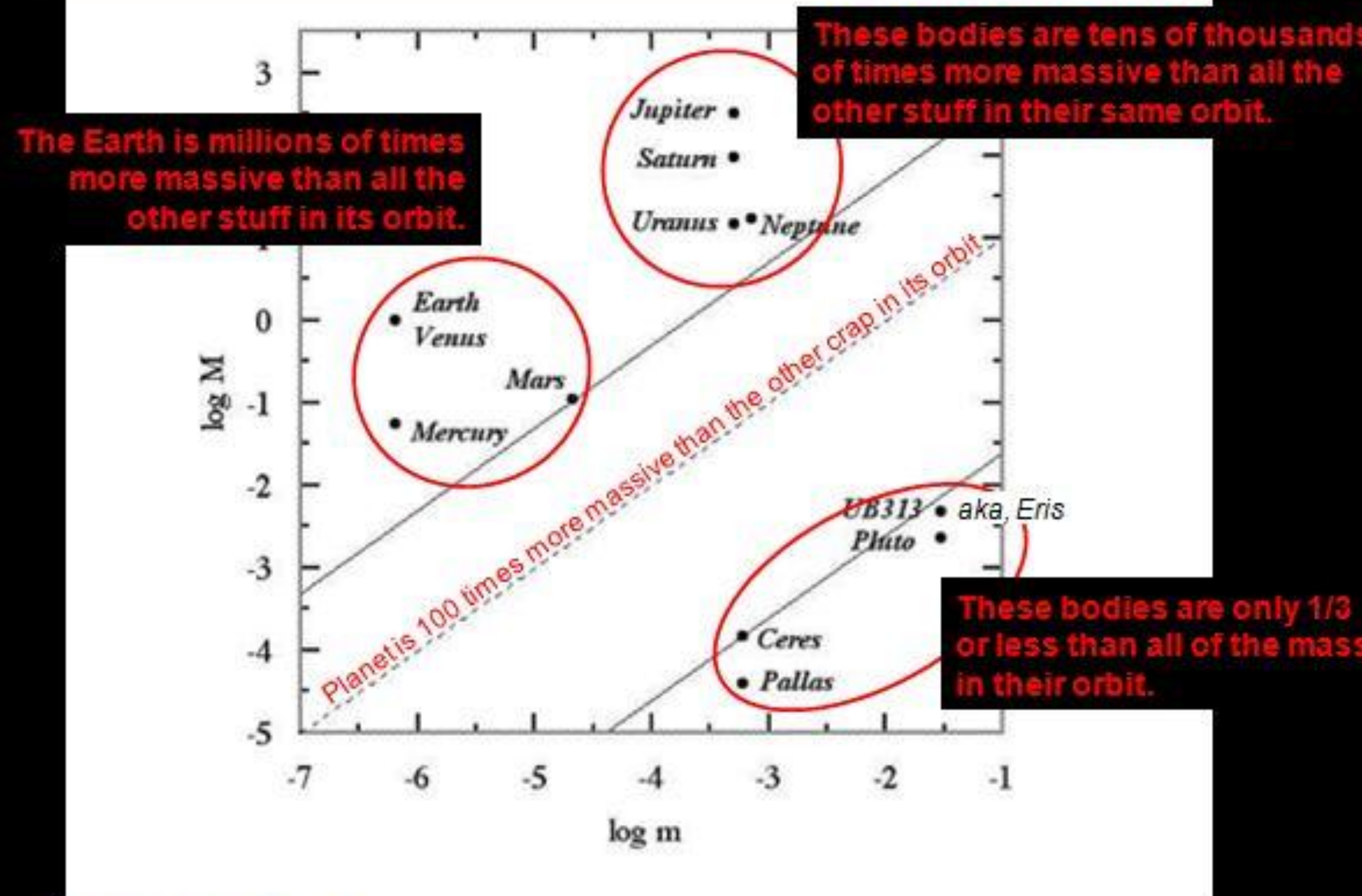
The Case Against Pluto I



The Case Against Pluto II



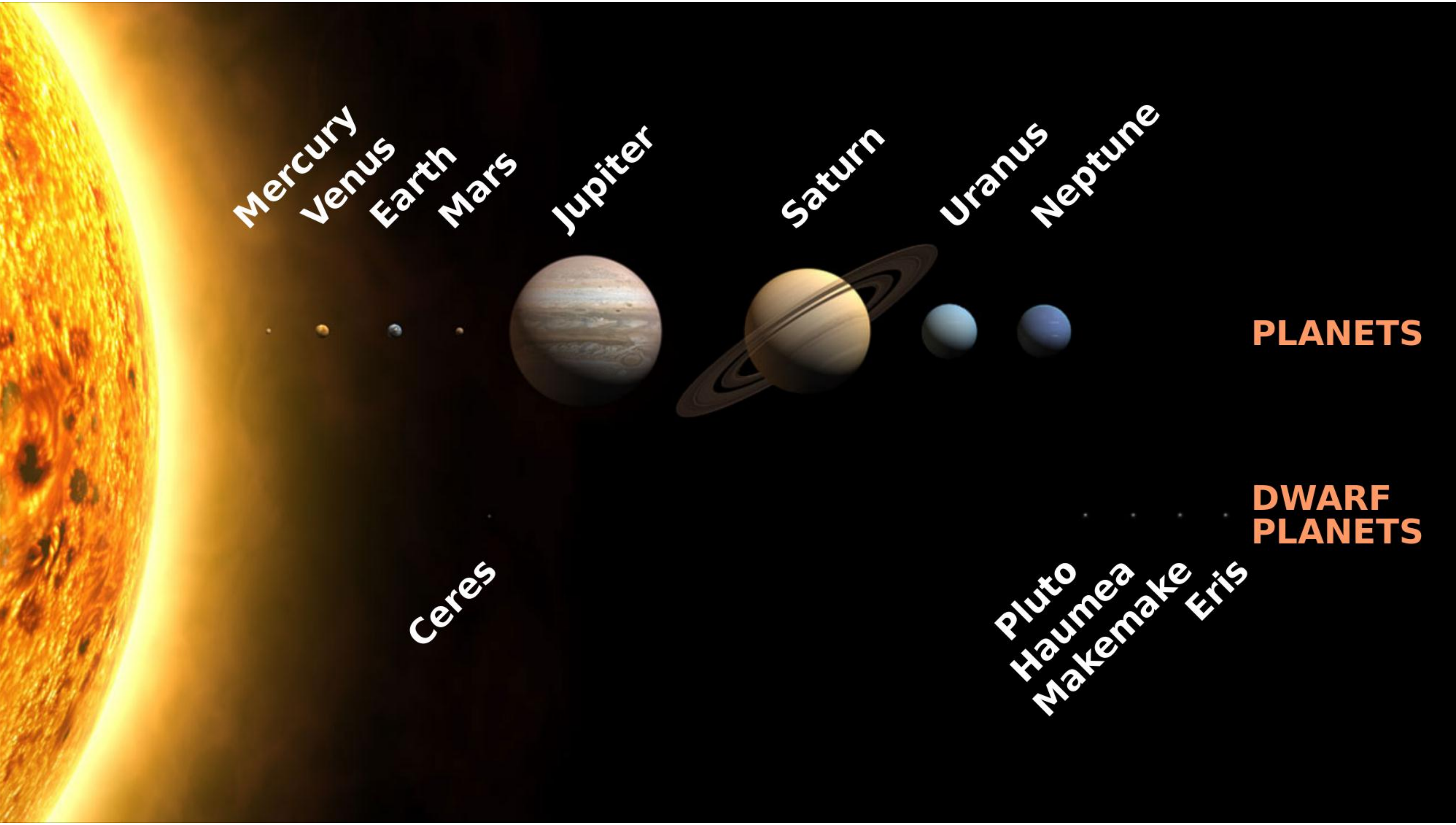
The Case Against Pluto III



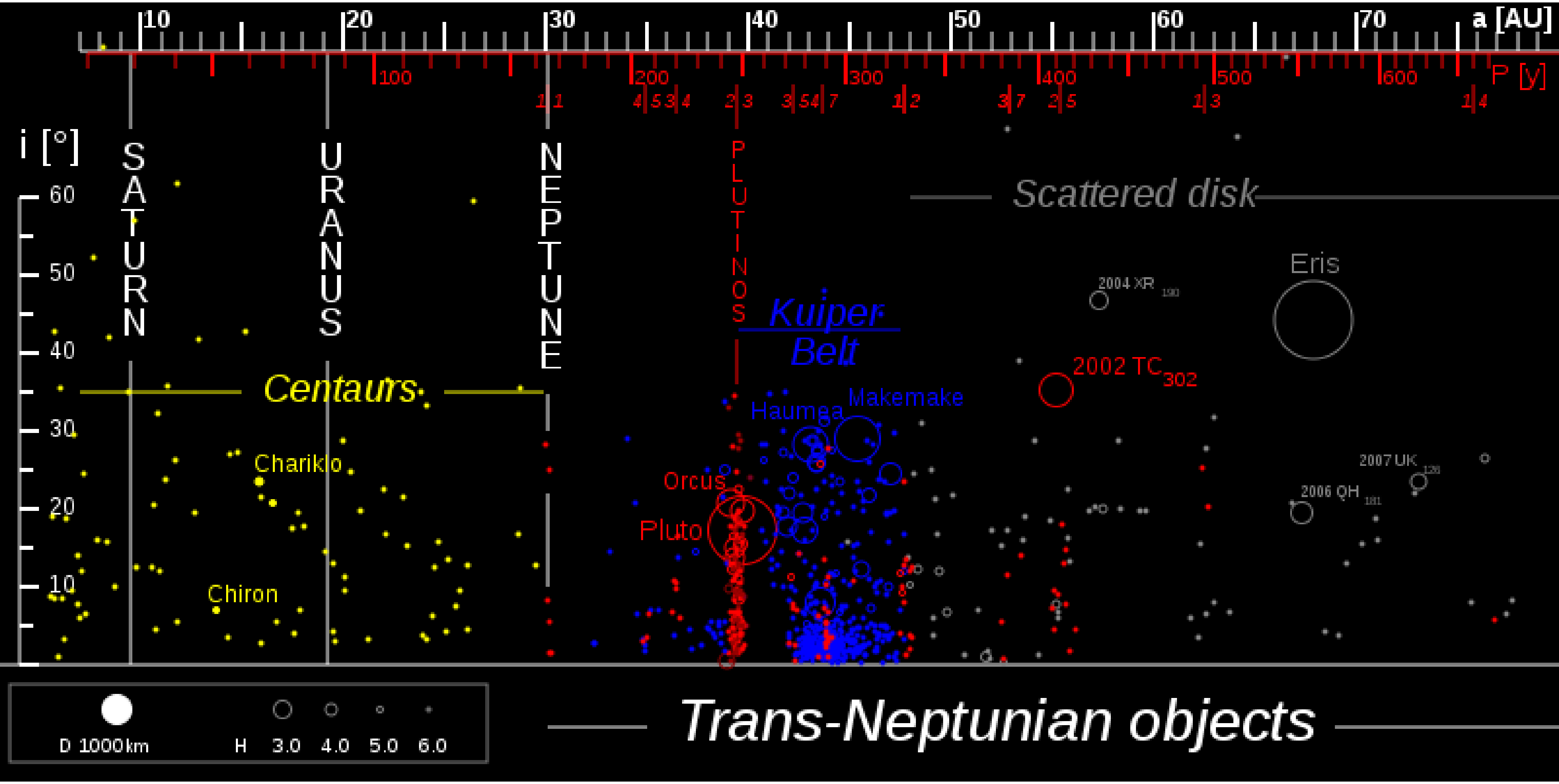
DWARF PLANETS

Have not "cleared" out the neighborhood around their orbits.

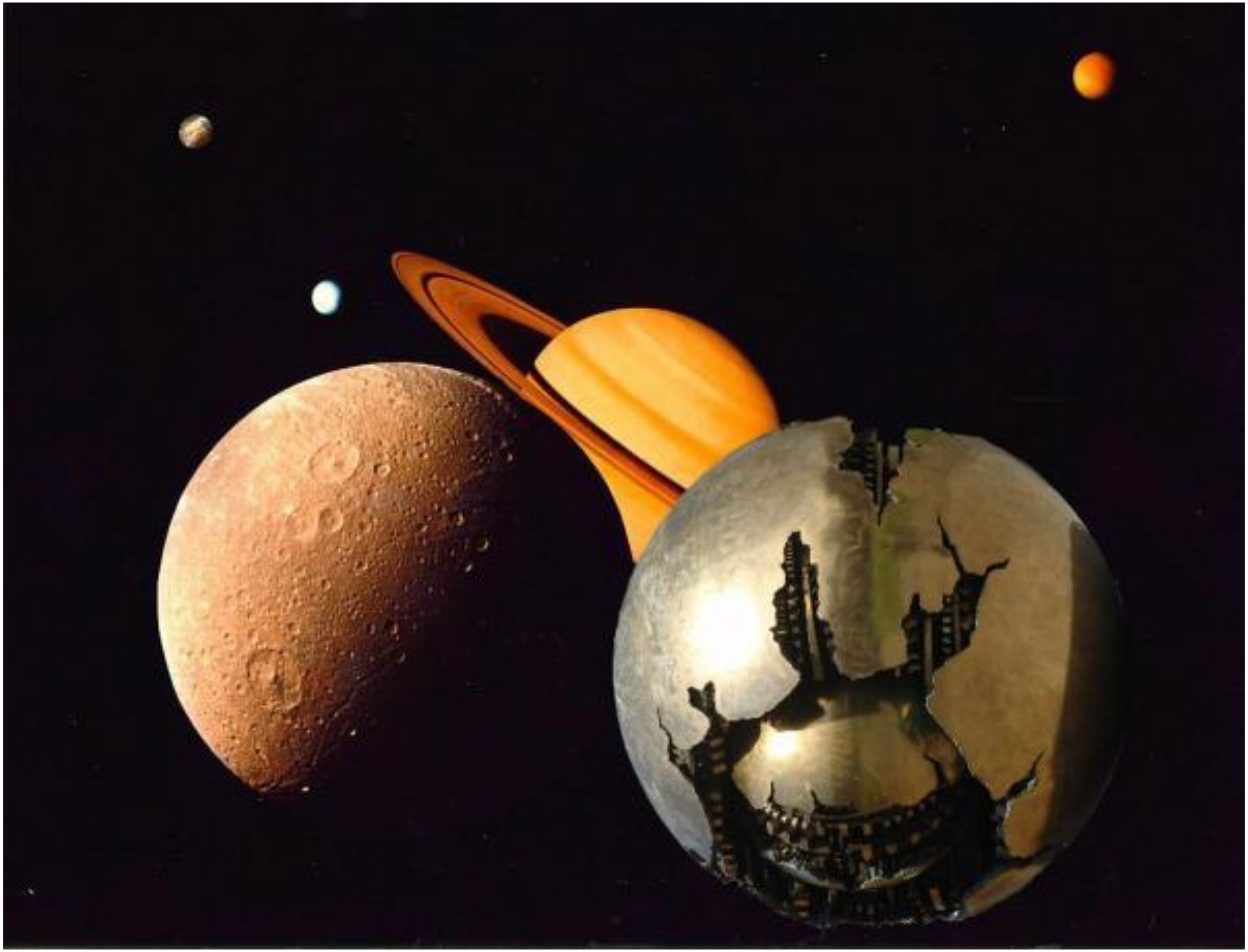
Normal and Dwarf Planets



Trans-Neptunian Objects



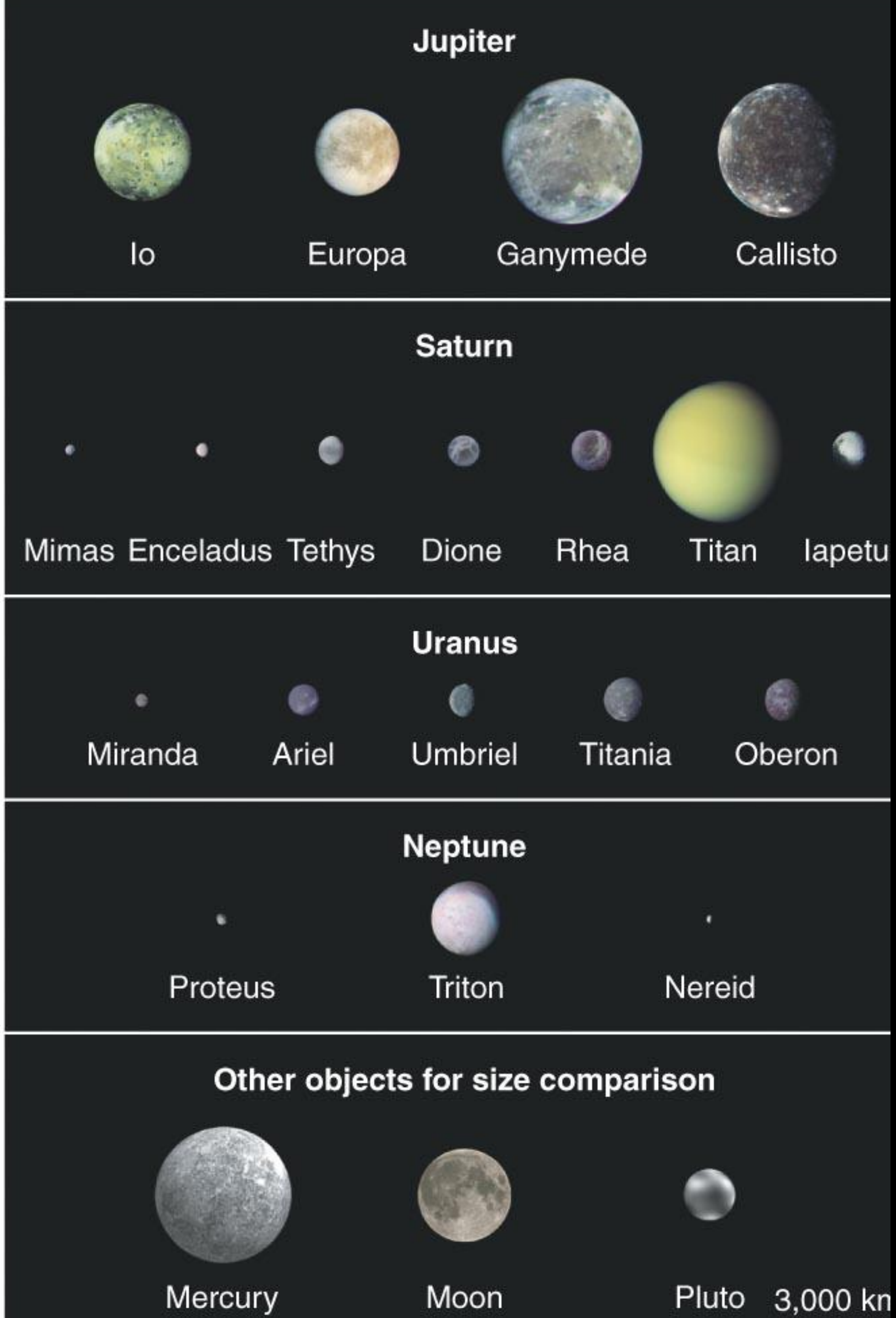
Satellites



Many moons of the giant planets are very distinctive "worlds" in their own right.

Some have atmospheres and also geological activity, others are heated by tidal effects or from radioactivity in their cores.

As many as a **dozen** might have water kept liquid under pressure below a rocky and icy surface. Tiny Enceladus is only 500 km across yet it has geysers that spurt water into space (an interior ocean?)



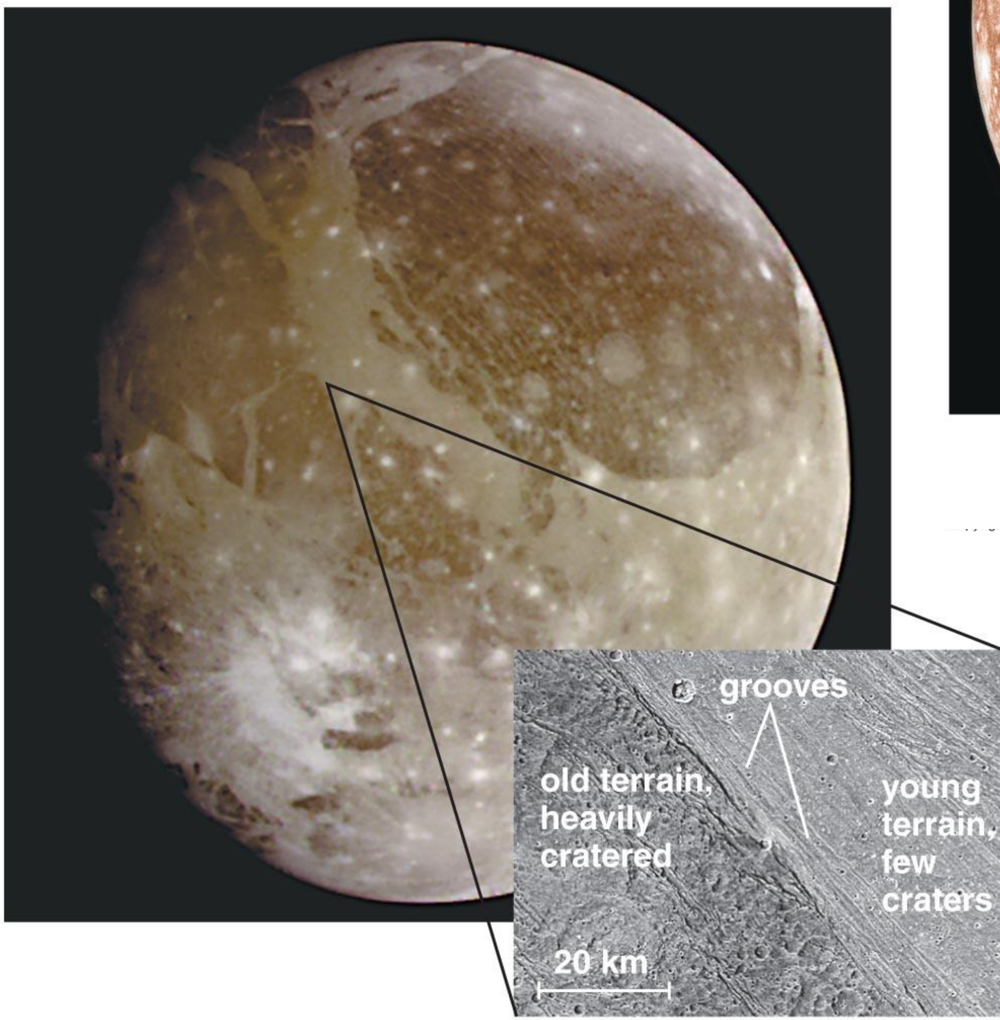
Terrestrial Planet Geology

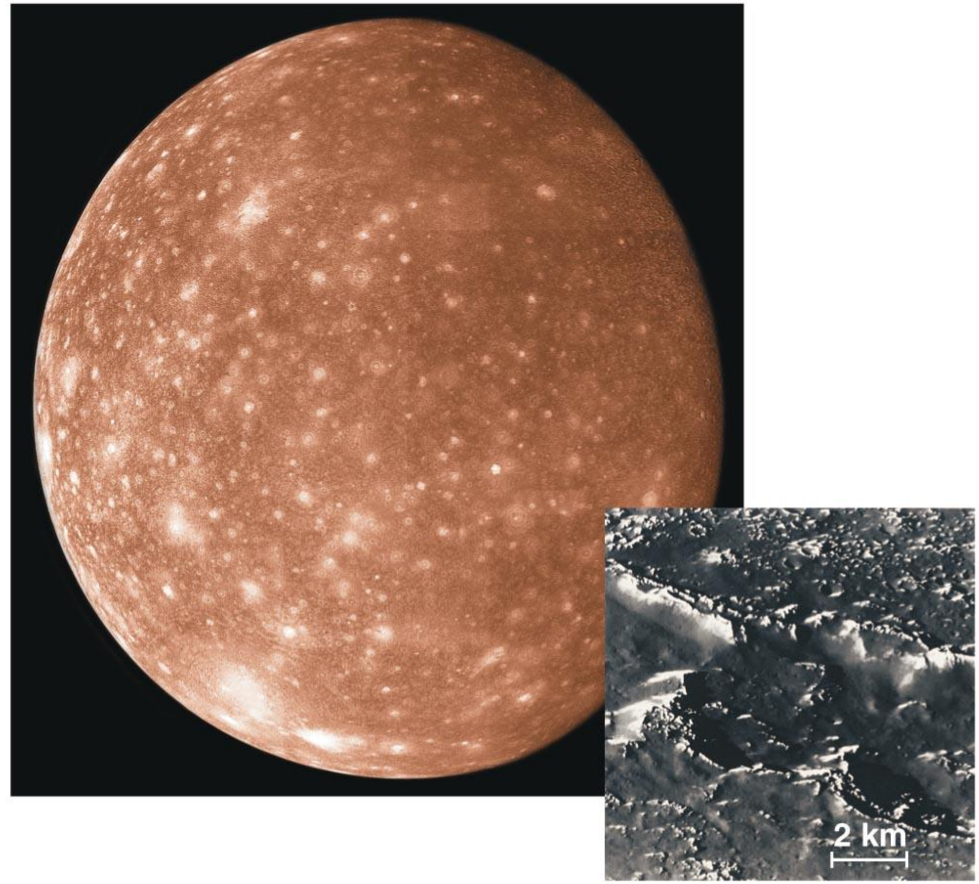
- Internal heat, primarily from radioactive decay, can cause volcanic and tectonic activity.
- Only large planets retain enough internal heat to stay geologically active today.
- Example: Mars (photo above) probably retains some internal heat. If it had been smaller, like Mercury, it would be geologically “dead” today. If it had been larger, like Earth, it would probably have much more active and ongoing tectonics and volcanism.

Jovian Moon Geology

- Tidal heating can cause tremendous geological activity on moons with elliptical orbits around massive planets.
- Even without tidal heating, icy materials can melt and deform at lower temperatures than rock, increasing the likelihood of geological activity.
- Together, these effects explain why icy moons are much more likely to have ongoing geological activity than rocky terrestrial worlds of the same size.
- Example: Ganymede (photo above) shows evidence of recent geological activity, even though it is similar in size to the geologically dead terrestrial planet Mercury.

Ganymede, the largest moon in the solar system, with cratered surface ice.





Callisto is very heavily cratered, but may have a deeply buried ocean.

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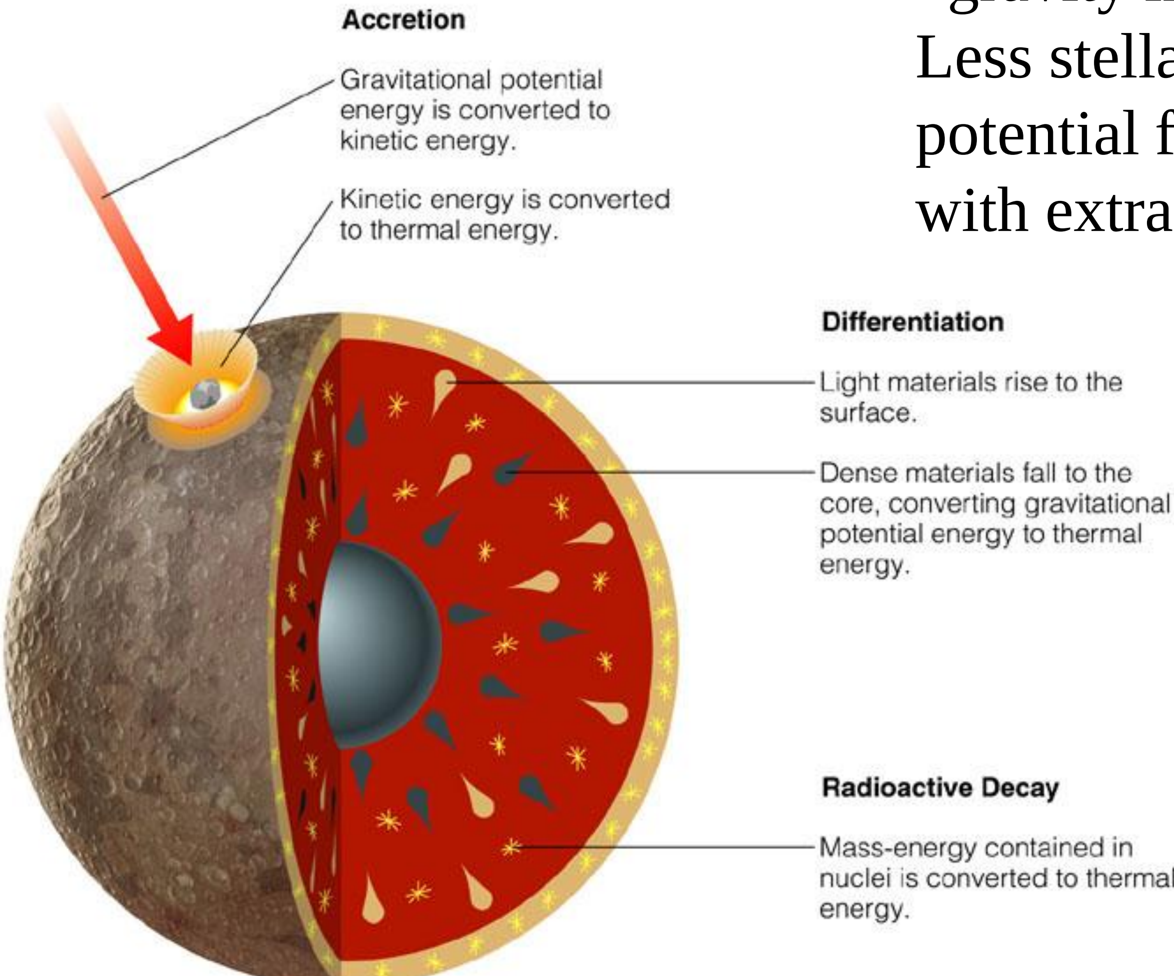
Life needs energy…

Implies proximity to a star, but perhaps energy can come from:

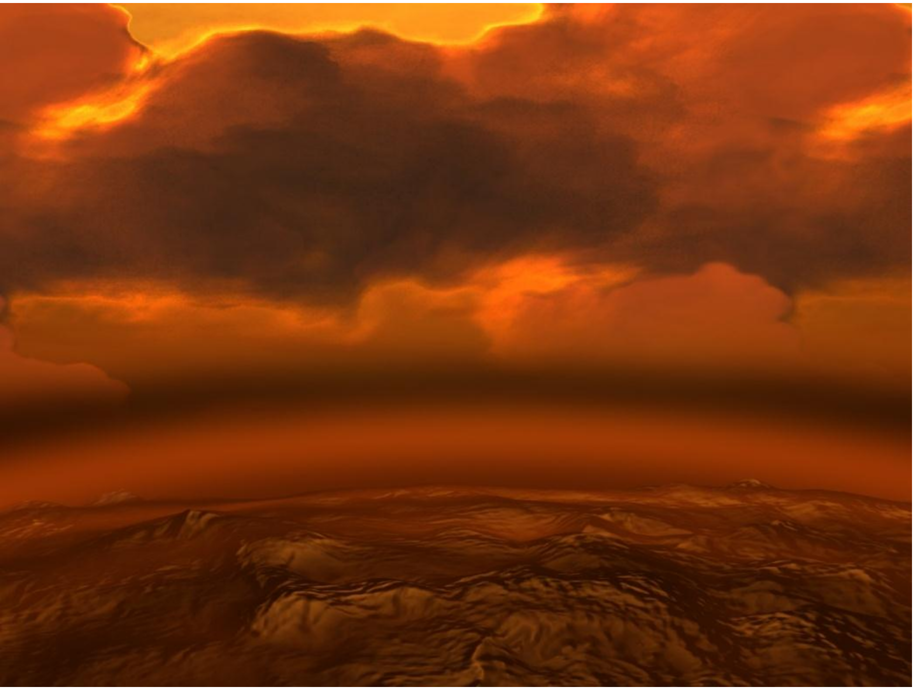
- Internal heat (radioactivity)
- Tidal heating (squeezing by gravity in elliptical orbits)

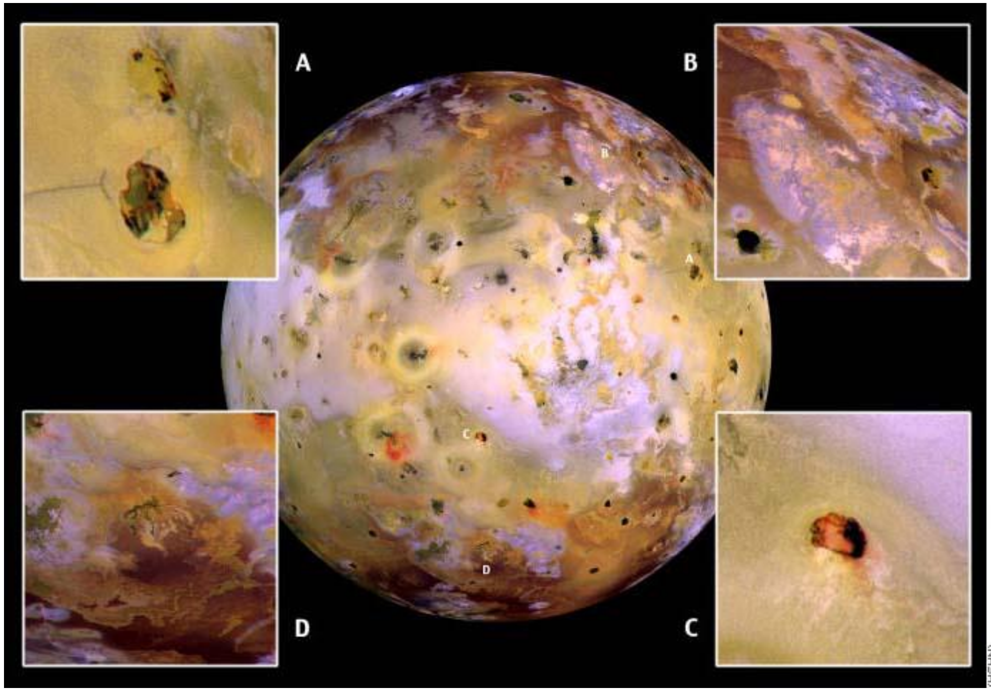
Less stellar energy but also the potential for thick atmospheres with extra greenhouse heating.



Real estate in form of cryogenic biospheres
GREATLY EXCEEDS
Real estate in form of terrestrial biospheres

Could there be life in even more extreme environments?

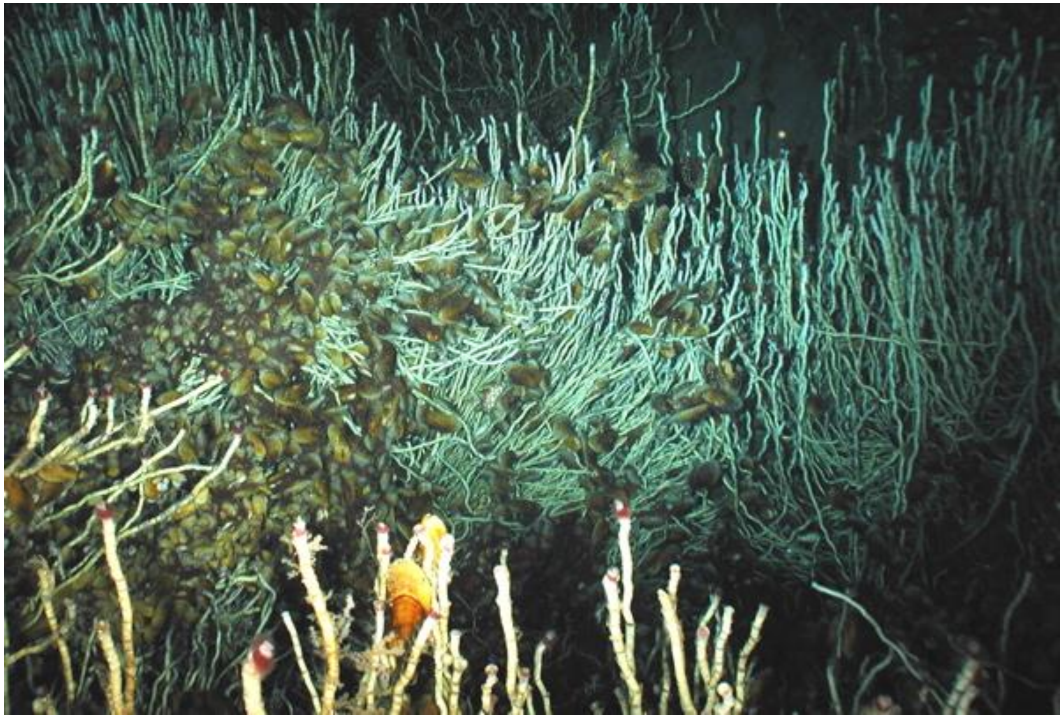




Biochemistry floating in the temperate upper regions of Venus' toxic atmosphere?

Biochemistry based on the highly active sulfur-based reactions on Io's surface?

Remember, life on Earth can happily handle extremes…

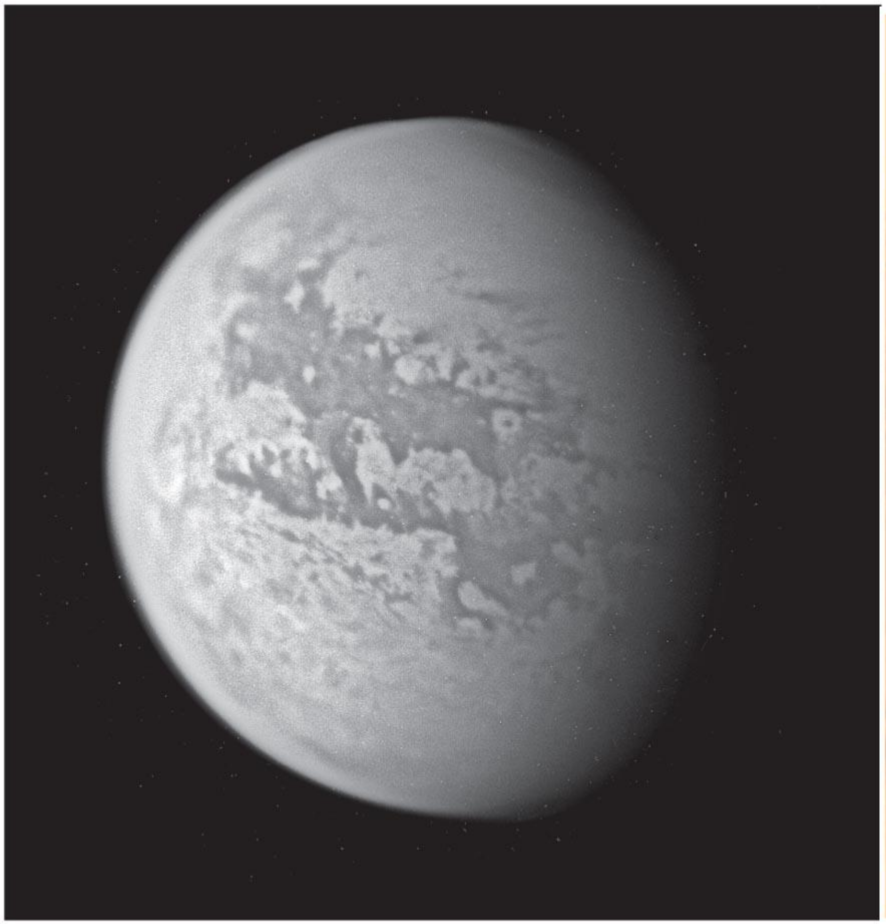


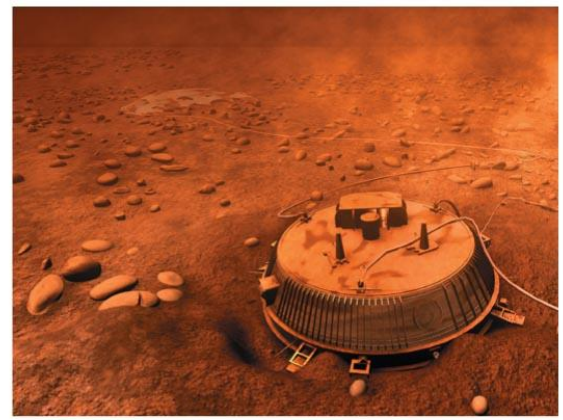
Hundreds of degrees, 100 atmospheres, and highly toxic chemistry.

Entire ecosystems that do not use photosynthesis; life that's independent of a star's energy?

Titan

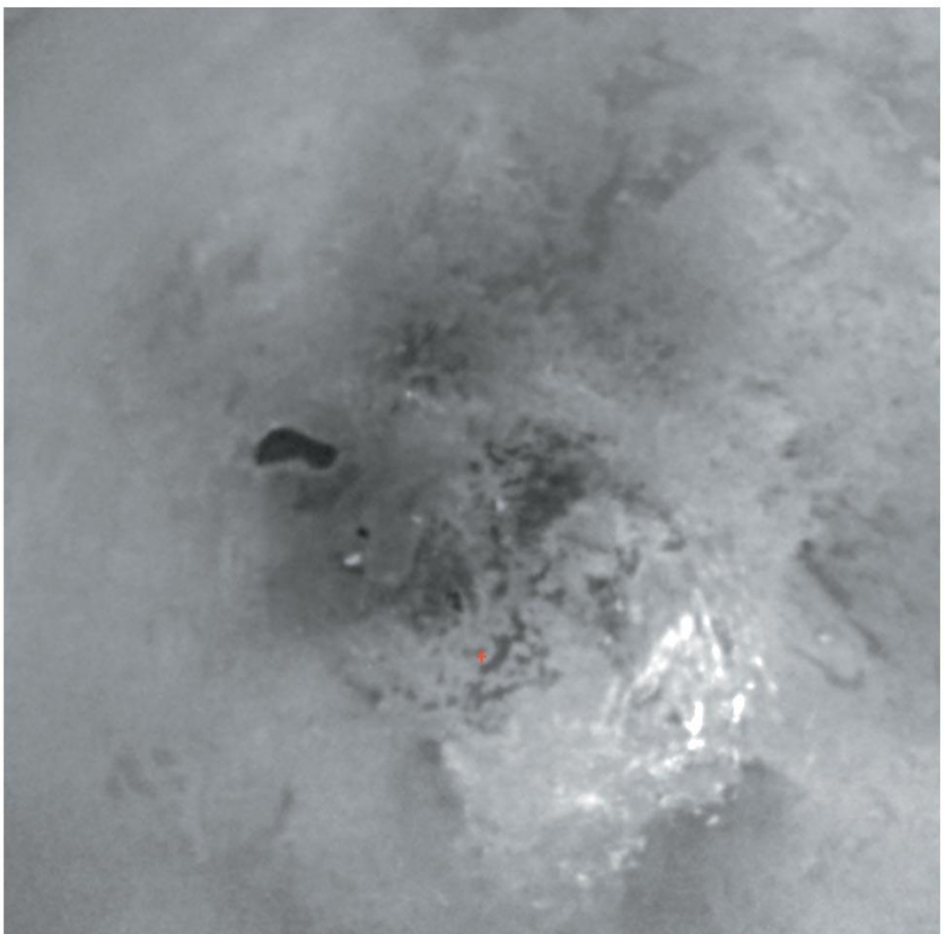
A large moon of Saturn with a nitrogen atmosphere thicker then Earth's, active geology, and weathering.

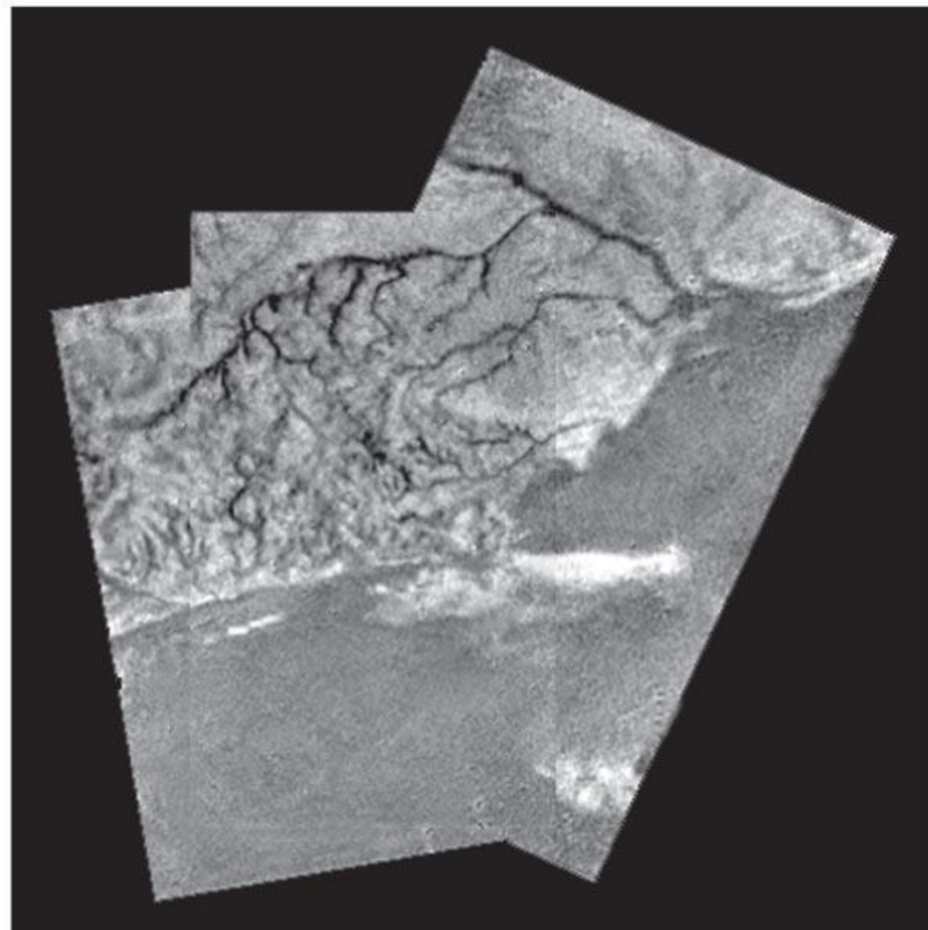




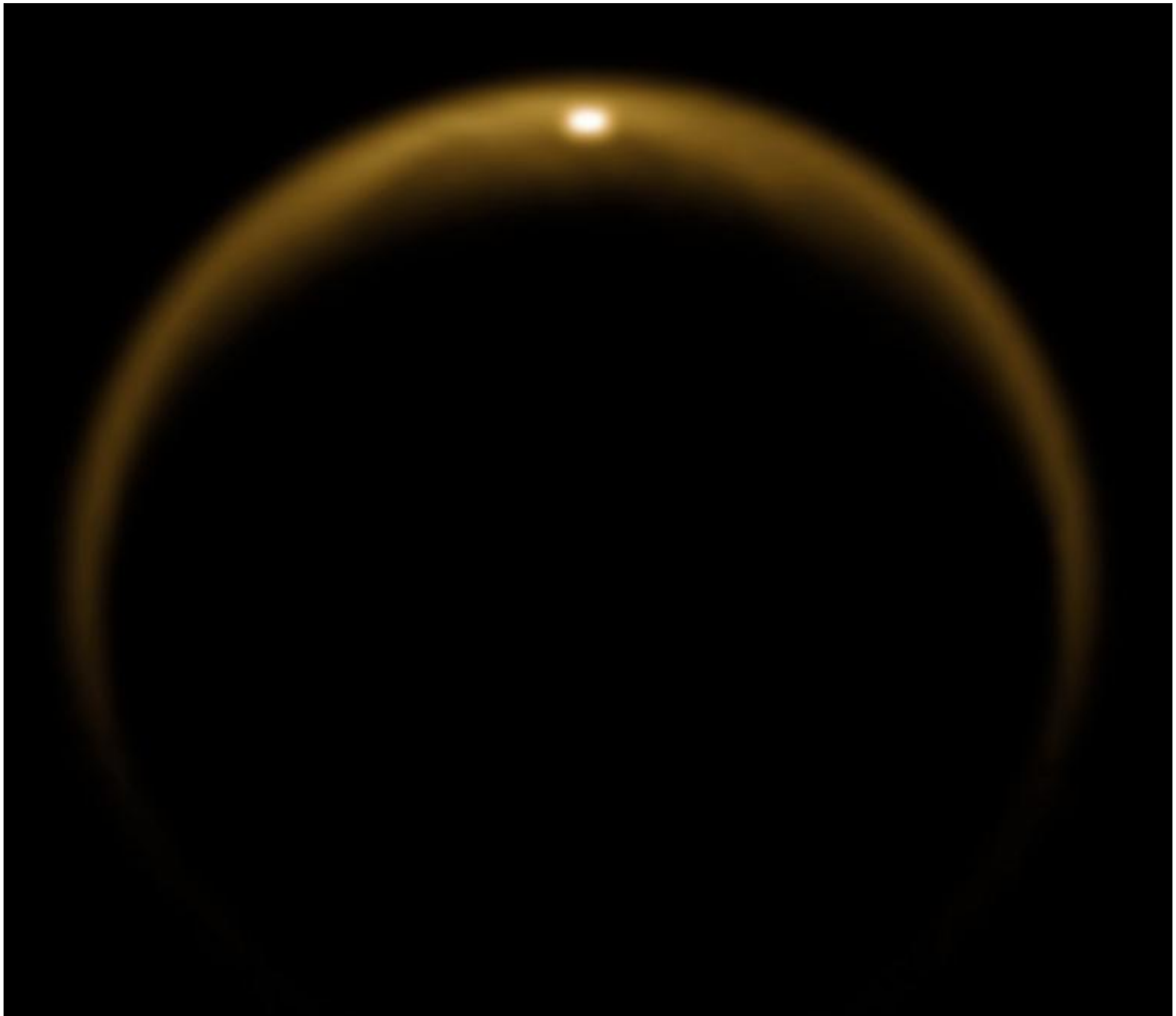
A view from the Huygens lander, sent in late 2005.

But it is nothing like the Earth. The lakes and the erosion features are mostly ethane and methane – complex hydrocarbon chemistry.



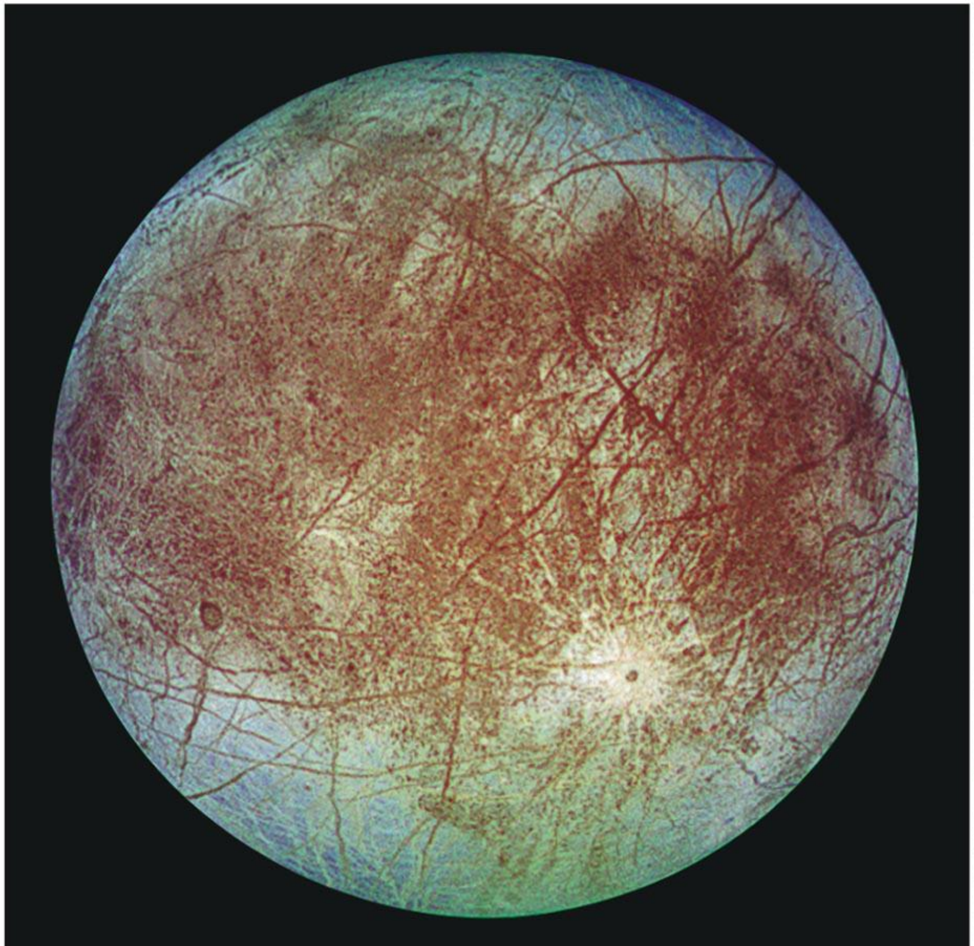


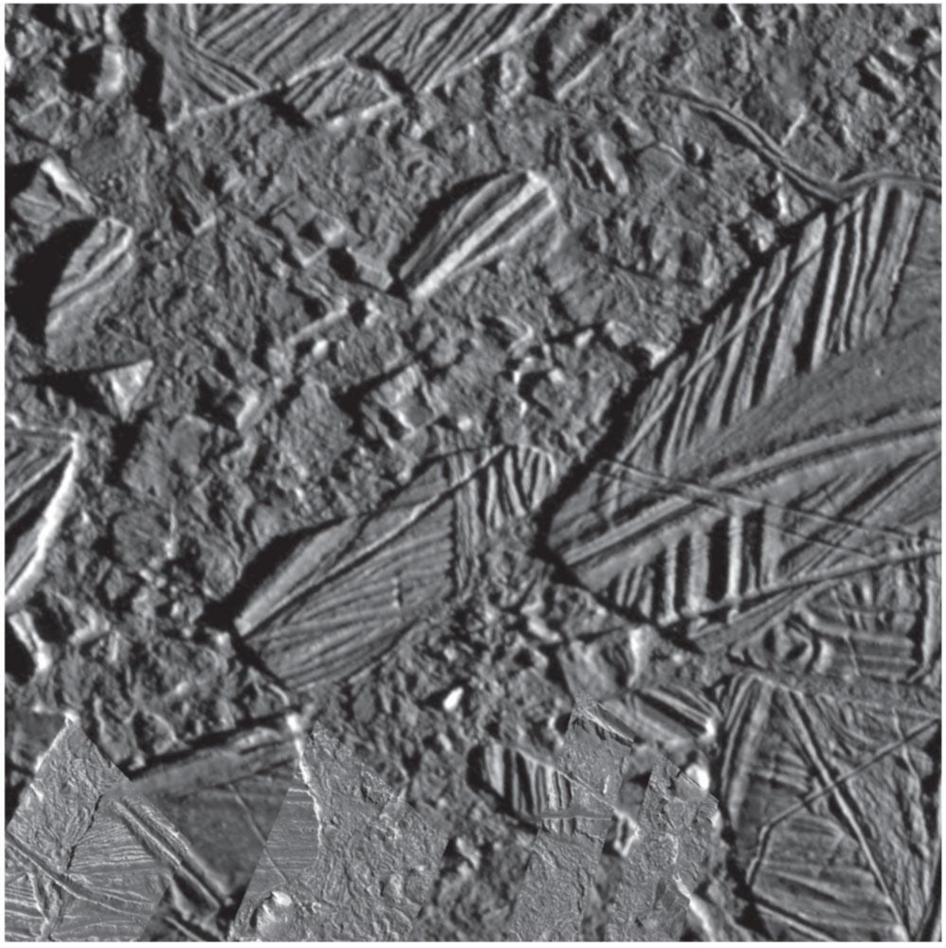
Sunlight glinting off a lake on Titan, the first image of specular reflection from liquid on another world .

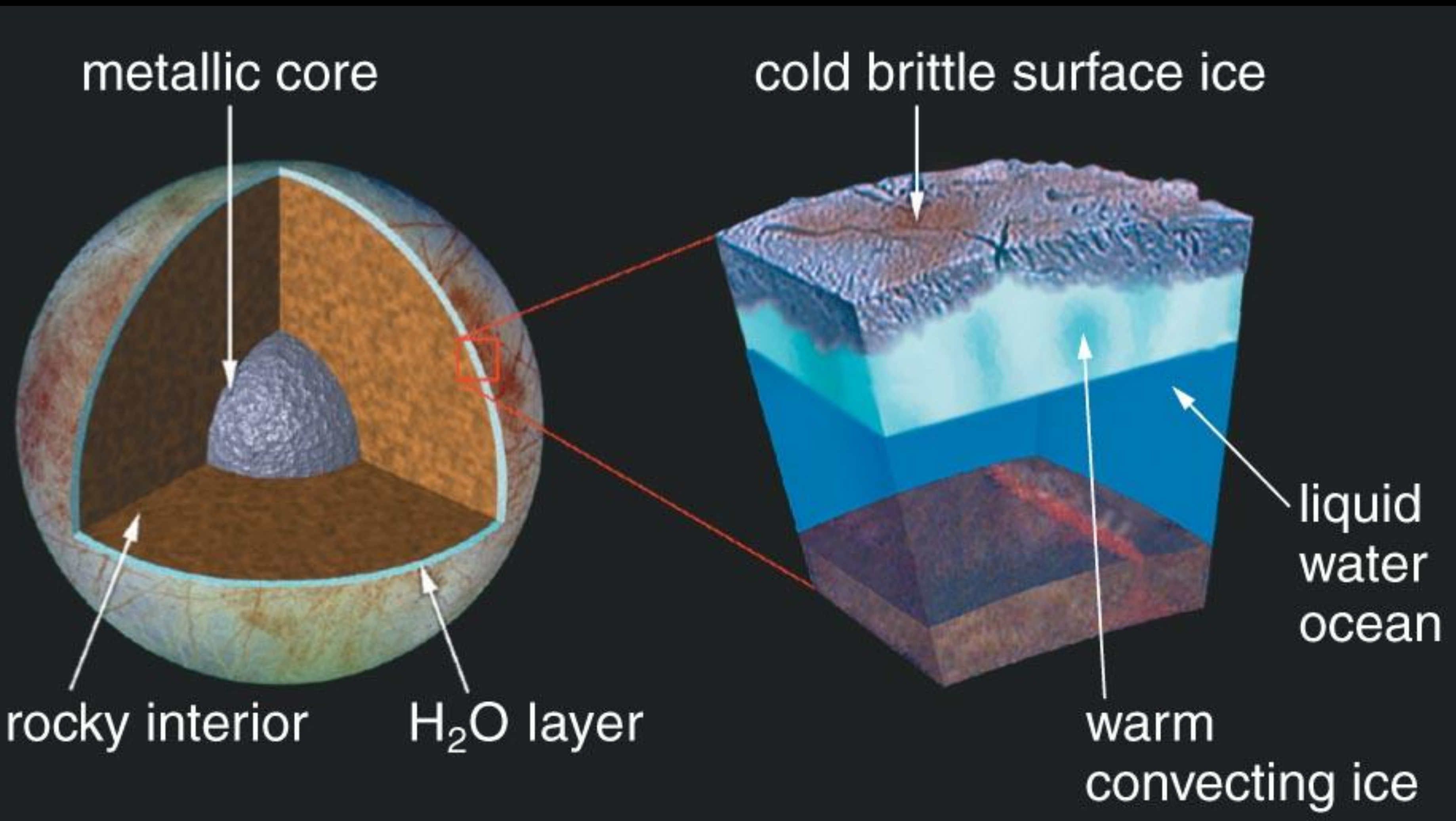


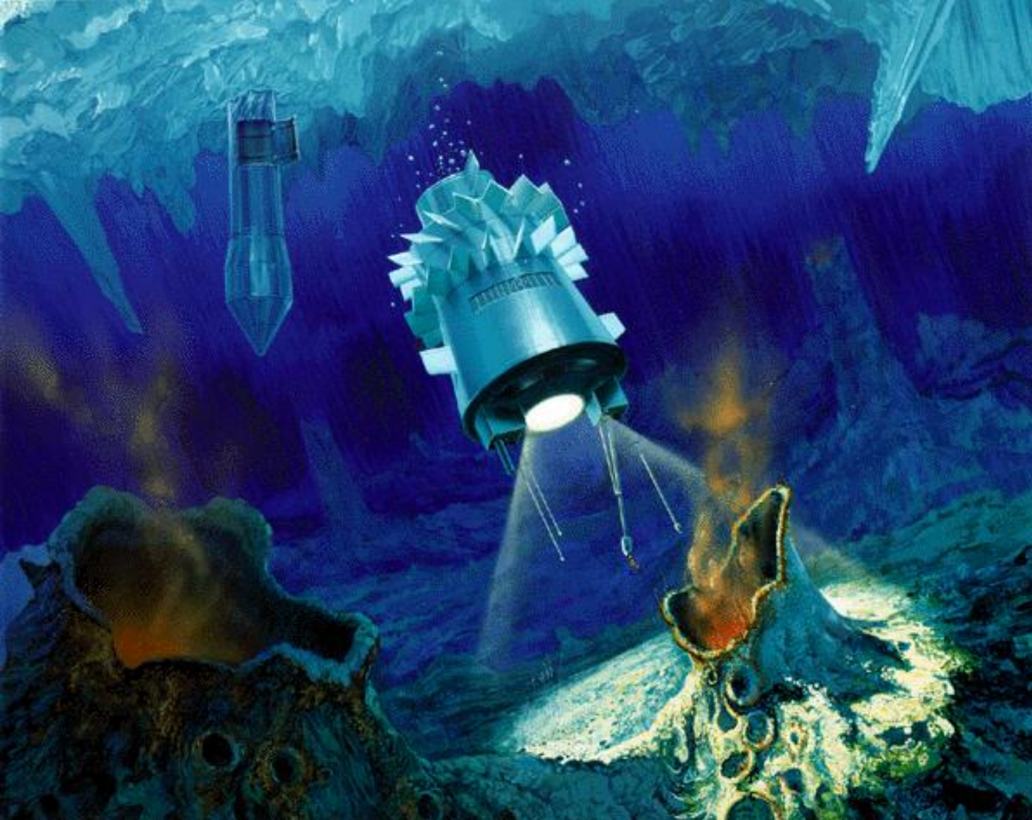
Water Worlds

Jupiter's moon Europa is the closest thing in the solar system to a water world like the Earth. An icy crust covers an ocean.

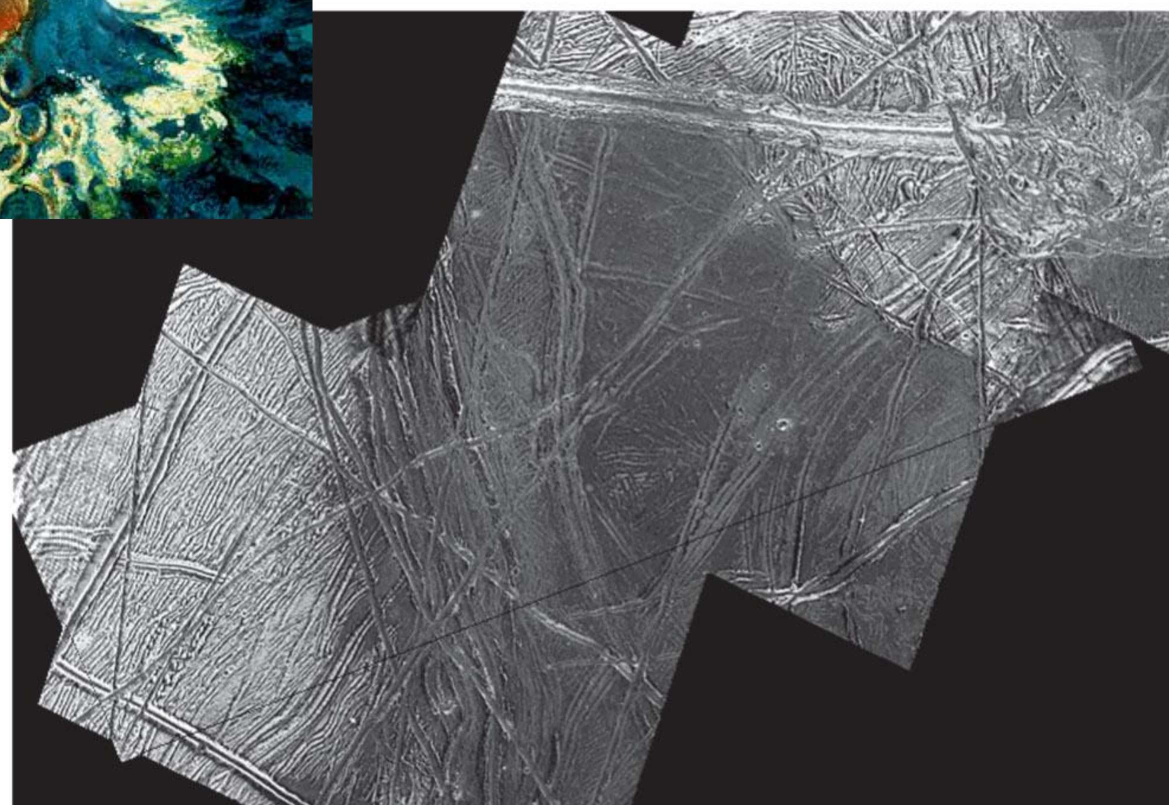





metallic core
cold brittle surface ice
liquid
water
ocean
rocky interior
H_2O layer
warm
convecting ice



An unfunded mission would land on the ice pack, use heat from a nuclear reactor to melt through it, and release a hydrobot to explore.



There may be places where the crust is thin and water wells up, spreads over the surface, and freezes.

Enceladus

- NASA's Cassini spacecraft has observed plumes of material escaping from Saturn's small icy moon, Enceladus.
- The plume is mostly water vapor, with tiny ice particles and other gaseous molecules mixed in (e.g. CO_2, CH_4, C_2H_6).
- The plume supplies ice particles to one of Saturn's nearby rings.
- Some ice particles contain salt, which may indicate they originate in an ocean deep below the icy crust.

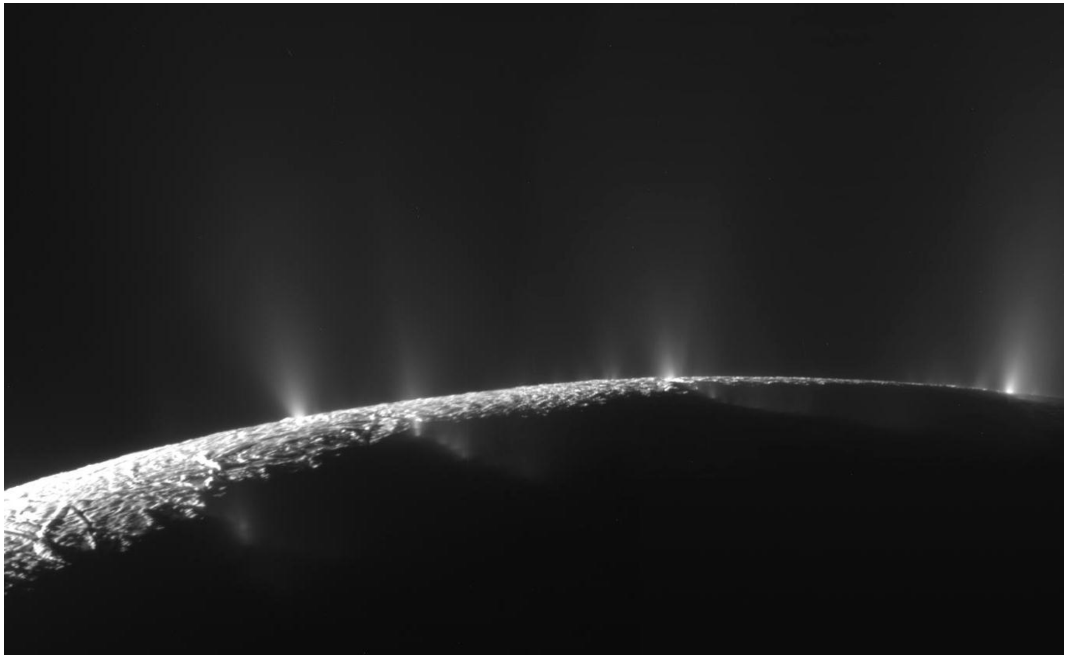
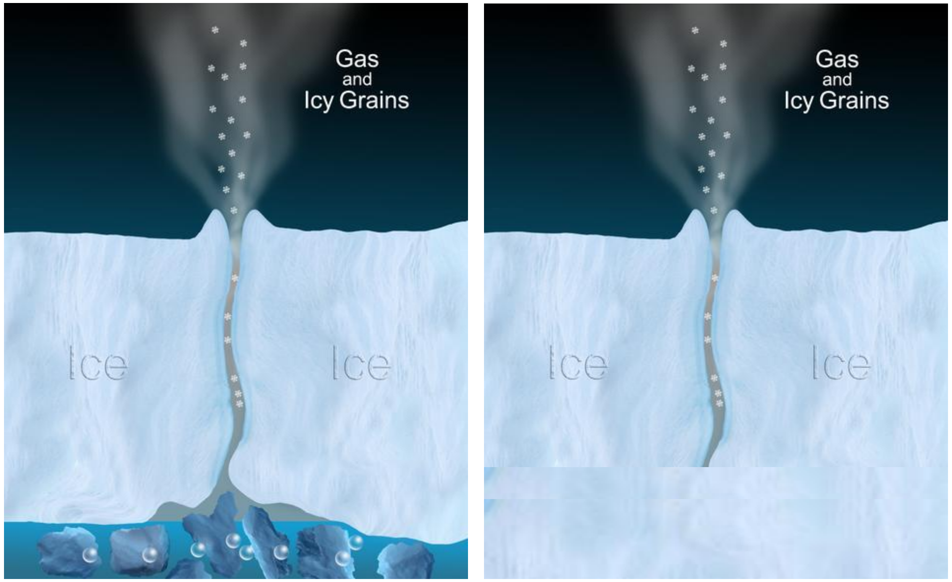


Image mosaic of Enceladus taken by Cassini, showing individual plumes of gas and ice escaping from the surface. The plumes extend 100's of km into space from the ~500 km diameter moon.

Geysers

- Plumes may be material escaping through surface cracks from an internal salty ocean or lake.
- Alternatively, ice along cracks may sublime or melt, which is followed by escape of water vapor and icy particles.
- Many scientists find the salty ocean idea most convincing, but others like combinations of alternative explanations.



Left: Enceladus may have a salty subsurface ocean that releases material to space through cracks in the moon's icy shell. Right: The walls of icy cracks in the surface may melt or sublime, venting gas and icy particles to space.

A Living Moonlet?

- Enceladus is surprisingly active for such a small body - likely a consequence of tidal heating.

- Future flybys of Enceladus by Cassini may help to resolve whether Enceladus joins the growing “club” of solar system bodies believed to have oceans.

- If Enceladus has an ocean, then it contains all of the ‘ingredients’ known to be important for life: liquid water, molecular building blocks, and energy.

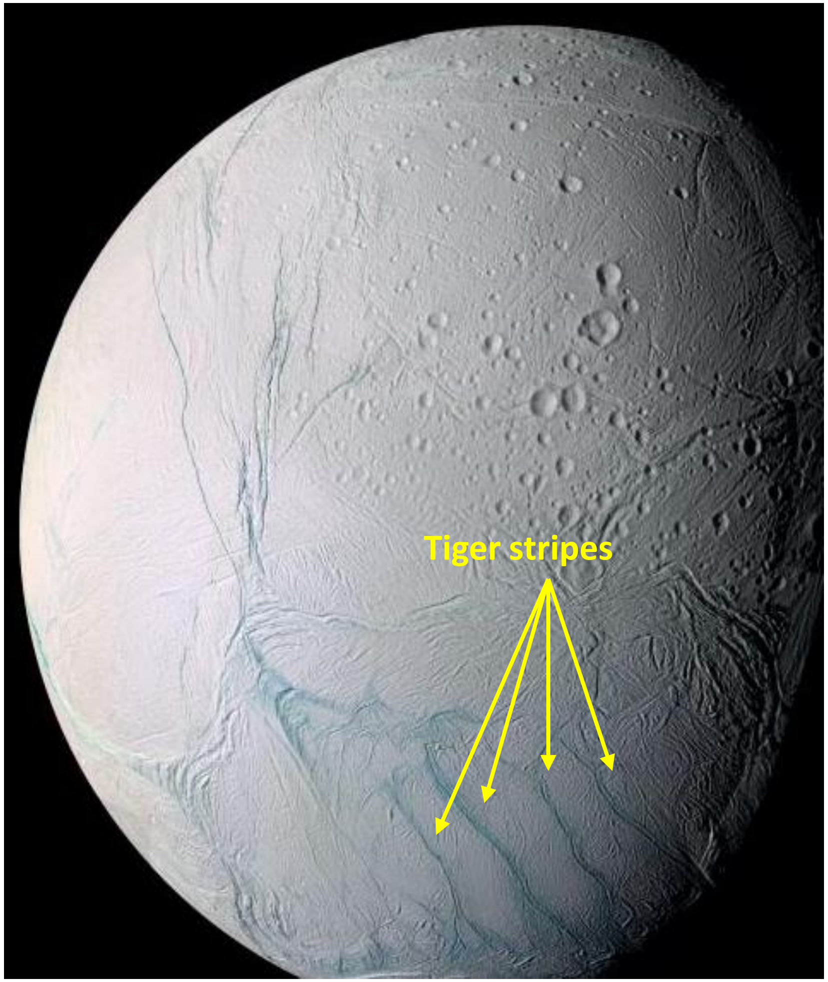
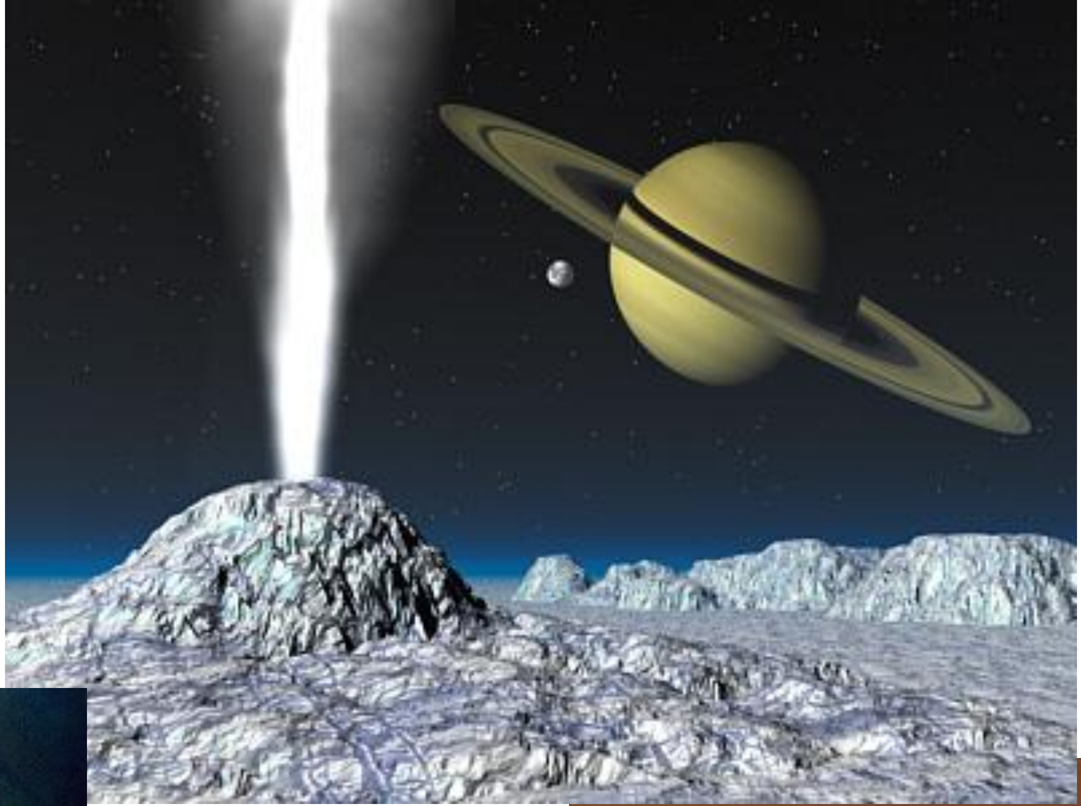


Image of Enceladus showing the ‘tiger stripes’ region in the southern hemisphere, where the plumes originate

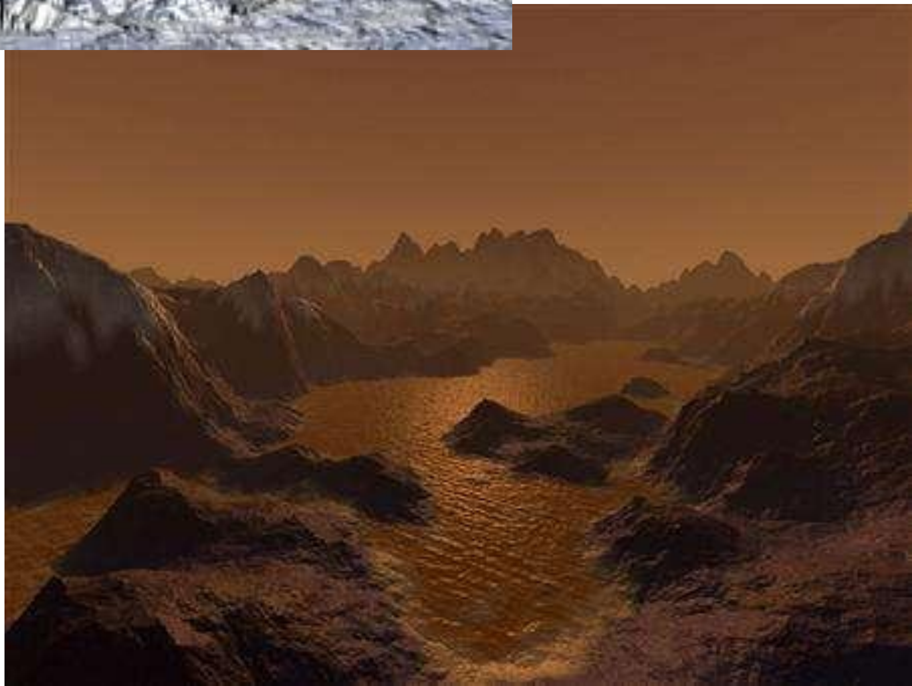
Until next gen missions land there, we can only imagine and visualize other worlds.



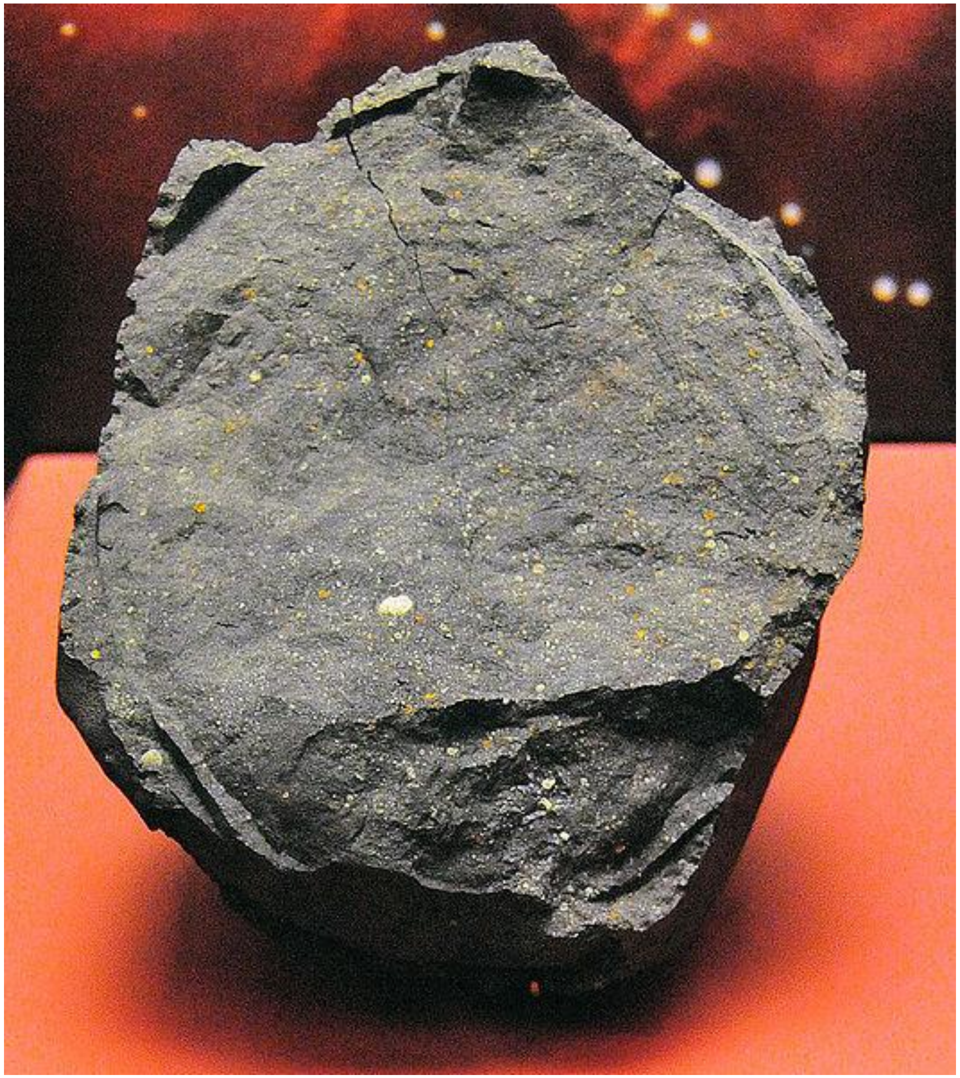
Enceladus

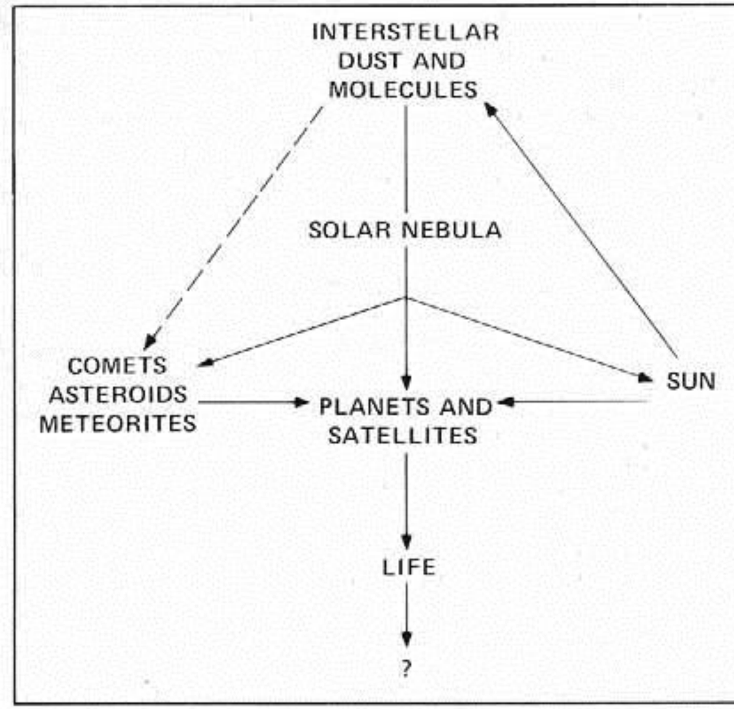
Europa

Titan



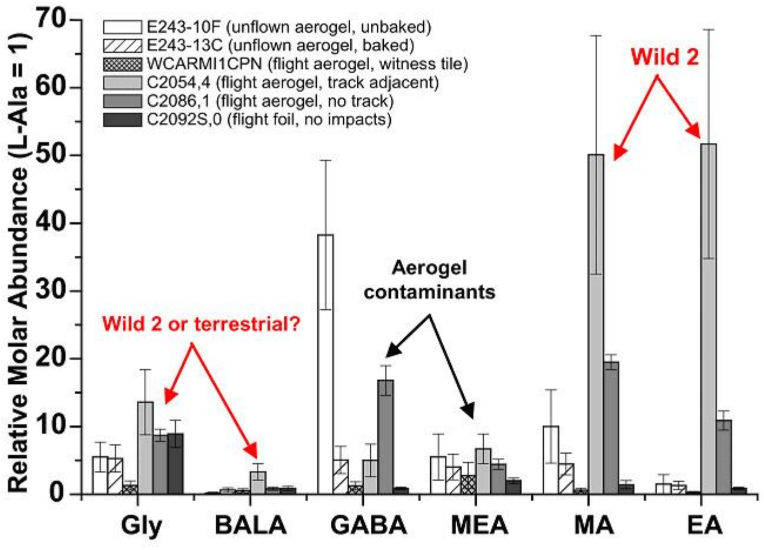
Small Bodies





Small bodies in the Solar System play an important role in chemical evolution. The Murchison meteorite had over 100 amino acids.

Stardust mission returned samples from the comet Wild-2, which contained amino acids. Also, comets probably delivered to the Earth most of its inventory of water very early in the history of the Solar System.



DEEP IMPACT!

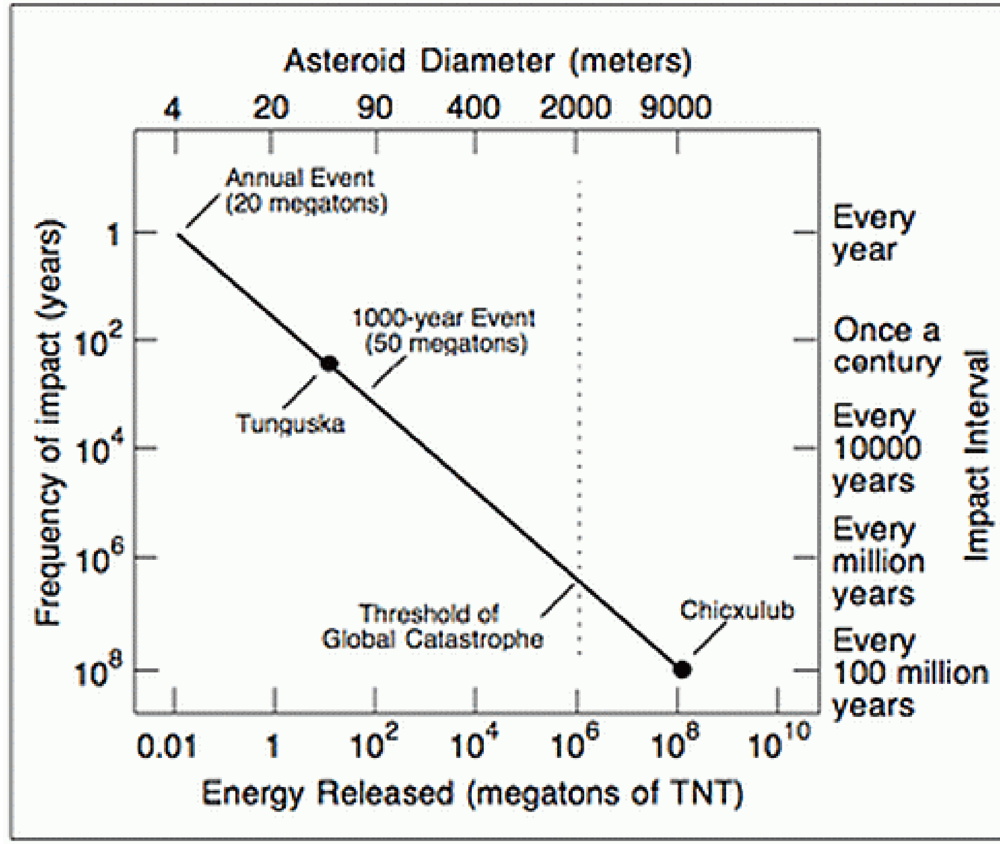
Cosmic Intruders

Asteroids and comets arrive randomly from deep space.

There are many more small impactors than large ones.

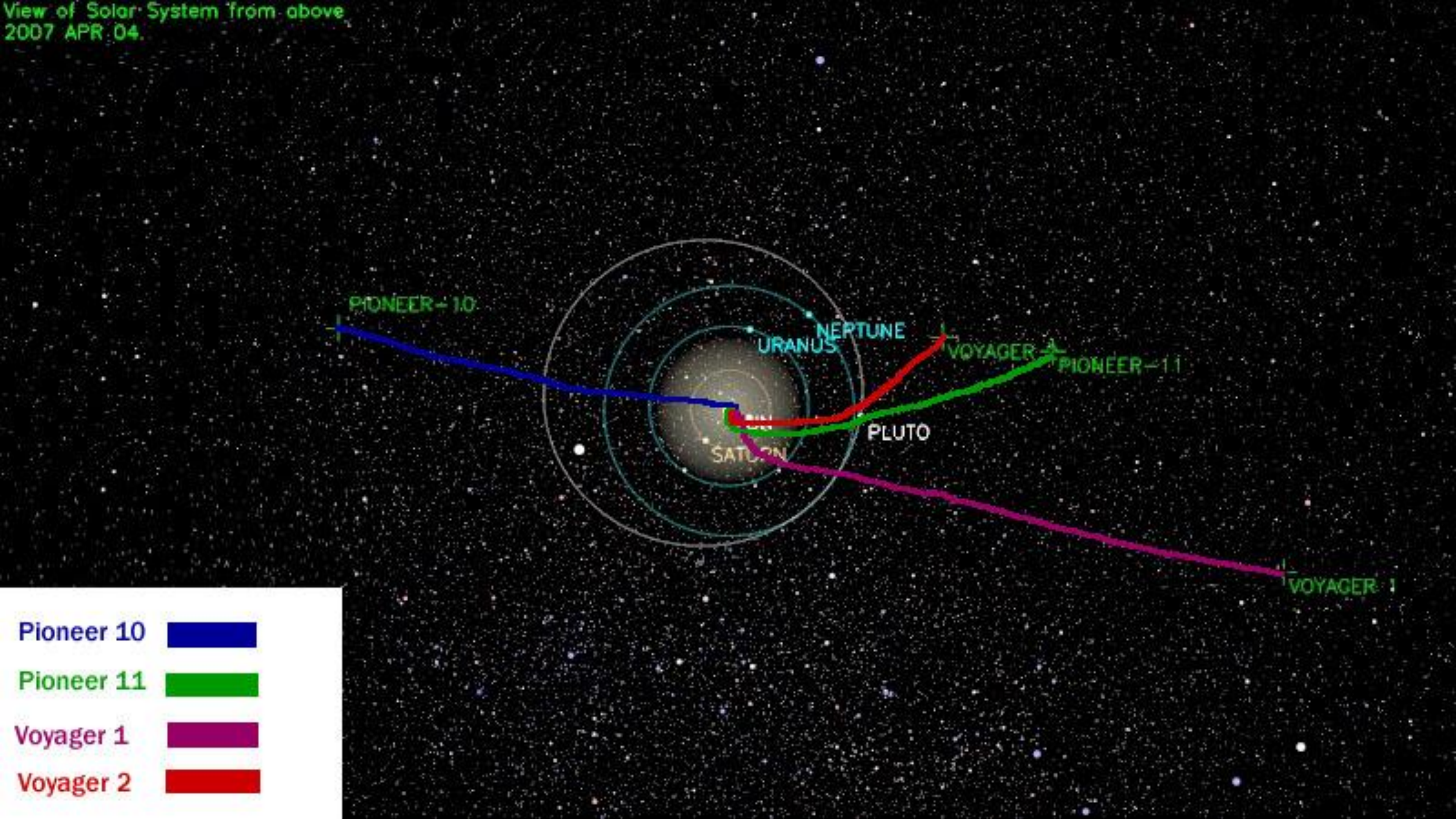
Most burn up harmlessly in Earth's upper atmosphere.

Rare large intruders can be a cause of mass extinction.



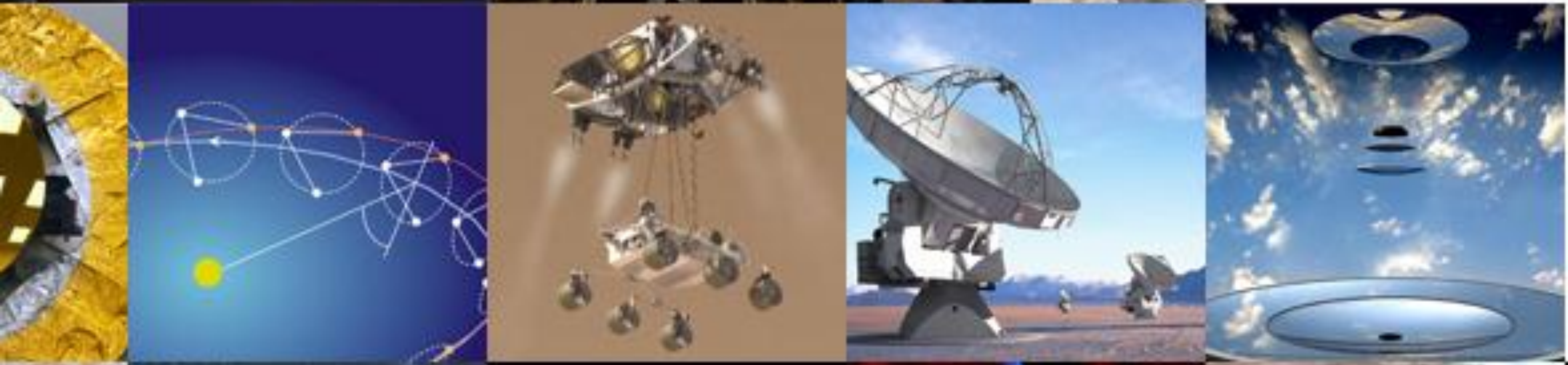
Chelyabinsk, Russia
February 15, 2013

55 feet, 10,000 tons
500 kilotons energy



Our most distant emissaries have now left the Solar System.
Voyager 1 is the most distant, over 11 billion miles from Earth.
But even at this speed, the nearest star is ~50,000 years away.

Astronomy
State of the Art



With Chris Impey
of the University
of Arizona