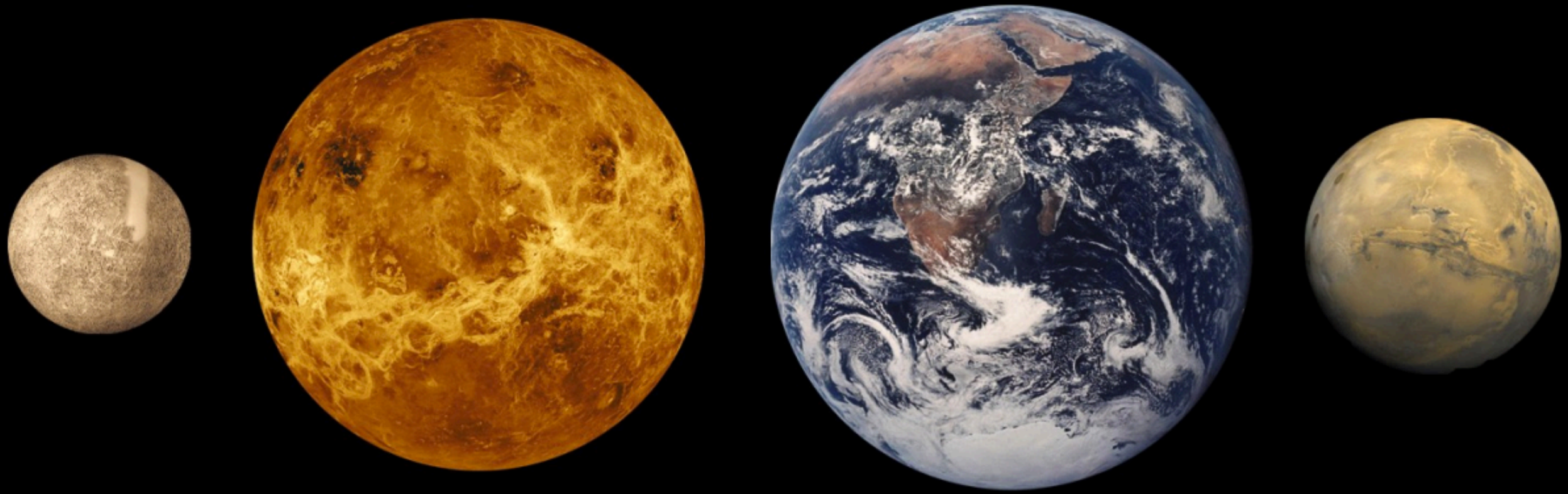


Terrestrial Planets

Astronomy 101: Exploring the Night Sky

January, 2018

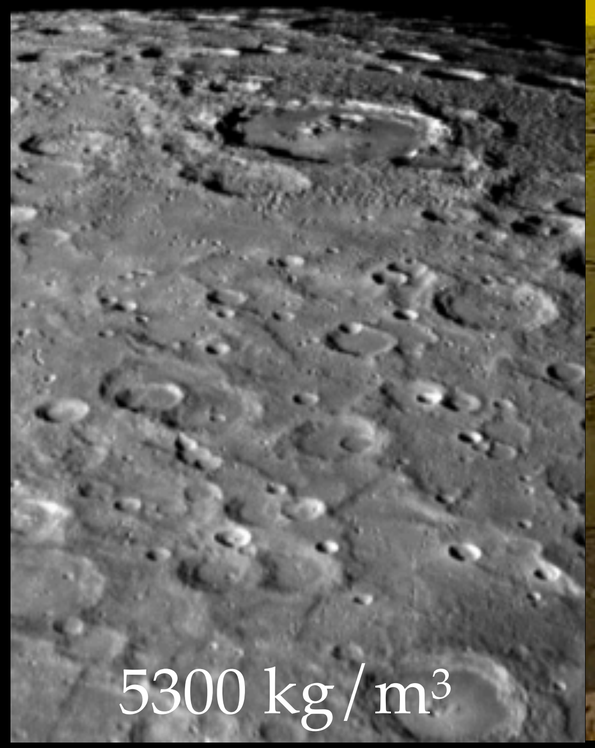
Overview

Comparison

Object	Semimajor Axis (AU)	Orbital Period (y)	Mass (Earth masses)	Radius (Earth radii)	Gravity	Natural Satellites	Rotation Period (d)	Avg Density (g/cm^3)
Mercury	0.39	0.24	0.055	0.38	0.38	0	59	5.4
Venus	0.72	0.62	0.82	0.95	0.91	0	-243	5.2
Earth	1	1	1	1	1	1	1	5.5
Mars	1.52	1.9	0.11	0.53	0.38	2	1	3.9

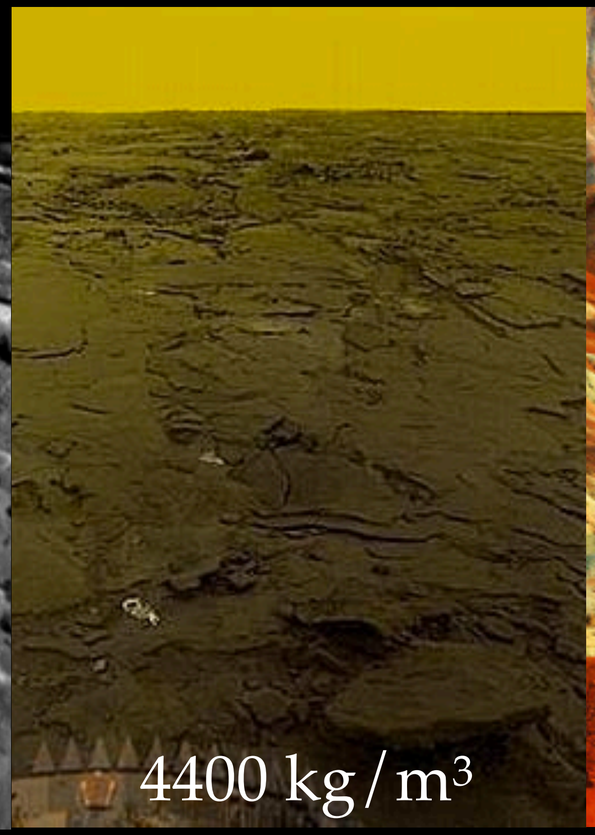
The Rocky Planets

Mercury



5300 kg / m^3

Venus



4400 kg / m^3

Earth

4400 kg / m^3

Mars

3800 kg / m^3

The differences between planets follows a pattern that helps us understand our solar system. For example, consider the UNCOMPRESSED densities.

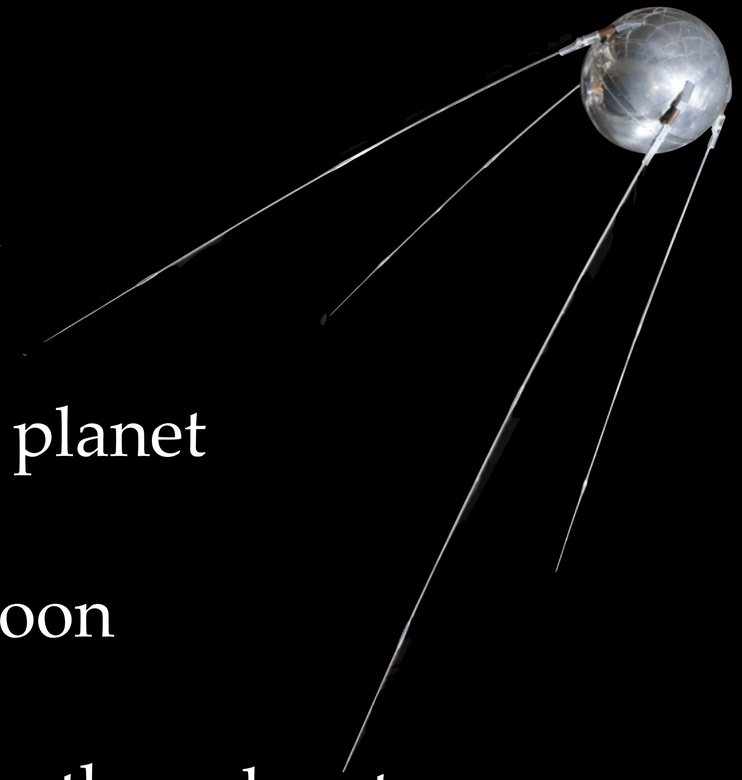
Exploration

The Space Race

Following WWII, the USSR and the USA fought a battle of competition (the Cold War) - a race to dominate world politics, economics and technology.

Technology progressed at a rapid pace and amazing feats of engineering and exploration were accomplished - at the cost of peace, and the constant threat of nuclear war.

The Space Race



Sputnik (USSR - 1957) - First artificial satellite in orbit

Mariner 2 (NASA - 1962) - First probe to visit another planet

Lunar Orbiter 1 (NASA - 1966) - First orbiter of the Moon

Venera 4 (USSR - 1967) - First atmospheric probe of another planet

Apollo 11 (NASA - 1969) - First humans to land on the Moon

Venera 7 (USSR - 1970) - First probe to land on another planet

Important Missions - Moon

Apollo 8 demonstrated that it was possible to send people to the Moon - humans occupying a spacecraft orbited the Moon and safely returned to Earth.

Apollo 11, carrying Neil Armstrong, Michael Collins, and Buzz Aldrin, successfully landed on the Moon.

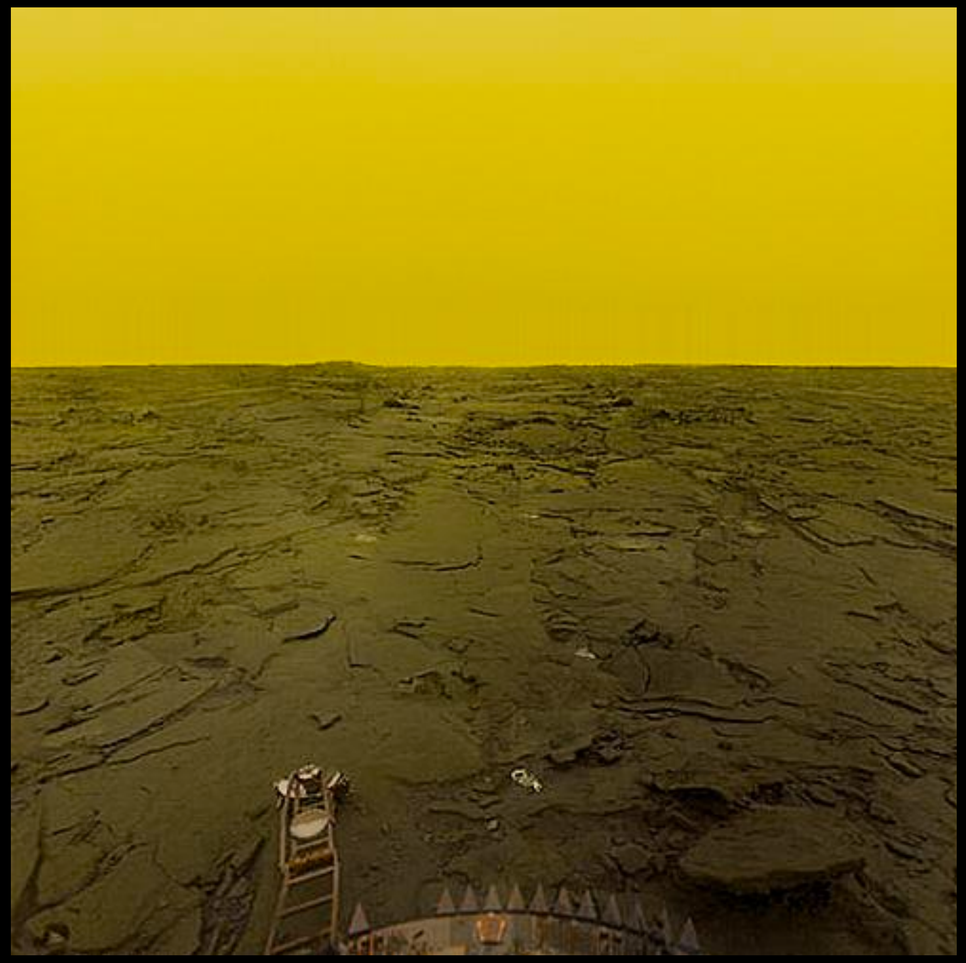
Apollo 12, 14, 15, 16 and 17 all landed on the Moon and returned.

Iconic image of the Earth from the orbit of the Moon

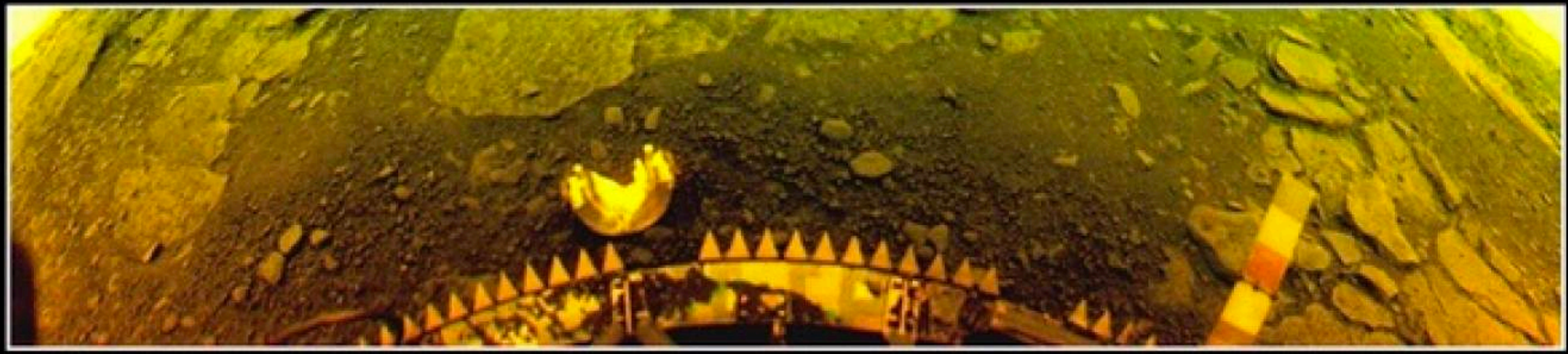
Important Missions - Venus

Venus was the first planet to be visited by probes because it was hoped that the atmosphere beneath the upper clouds might be livable/breathable.

The USSR's Venera series (1969-1983) included 8 landers that gave us the first up-close pictures of an alien world.



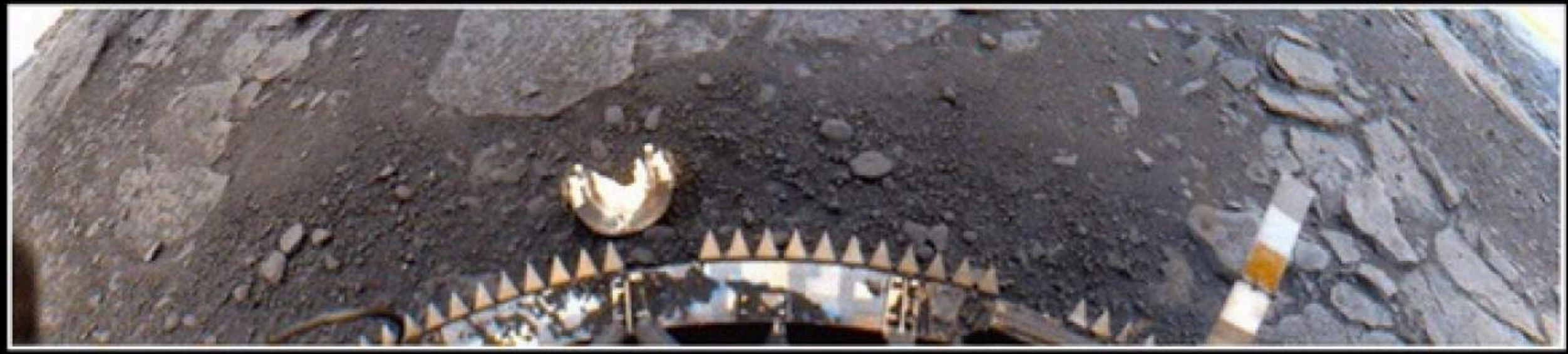
What they found was volcanic rock and a temperature that melted the craft.



Color as seen on the surface of Venus

Venera 13

Color with atmospheric effects removed



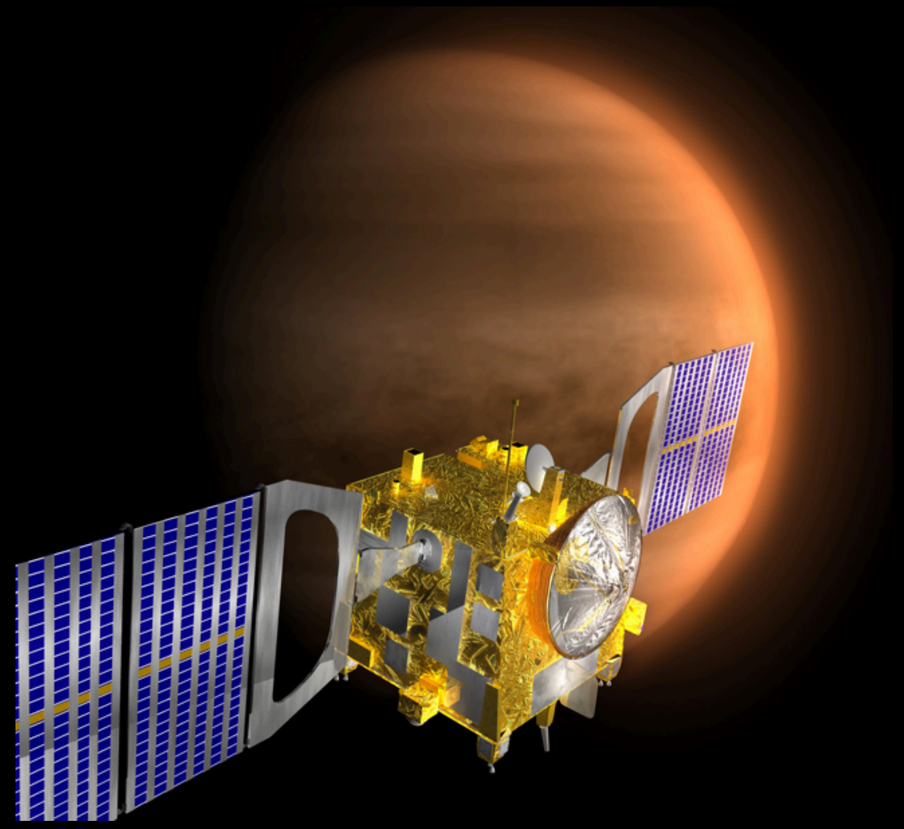
USSR Academy of Sciences / Brown University

Important Missions - Venus

NASA's Magellan (1990-1994) and the EU's Venus Express (2006-2015) have given us the most detailed information we have of the planet.

Detailed atmospheric studies, magnetic field measurements, and cloud-penetrating RADAR scans of the surface were produced by these missions.

Much of what we know of Venus has only been learned in the last 30 years!

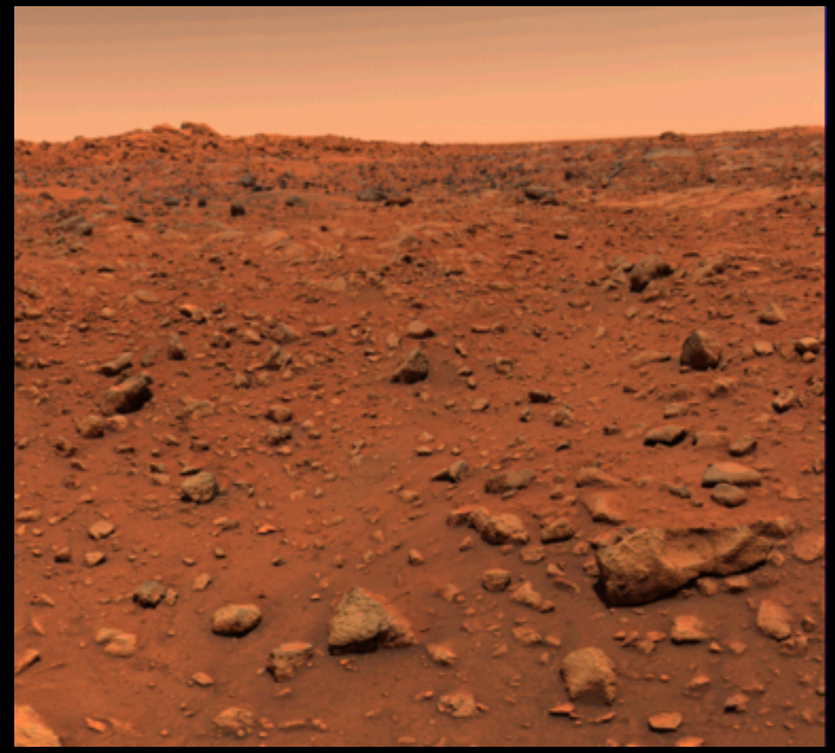


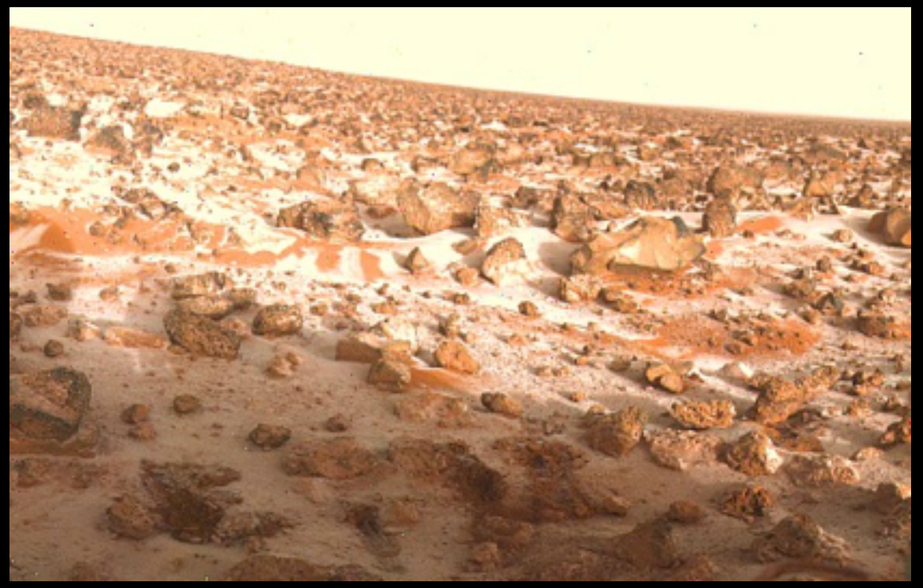
Important Missions - Mars

Viking 1 (1976) and Viking 2 (1976) were the first successful landers on the planet, giving us an up-close image of the surface.

They found dusty plains covered with rocky debris.

The rust colour of the rock due to a high iron content in the soil.





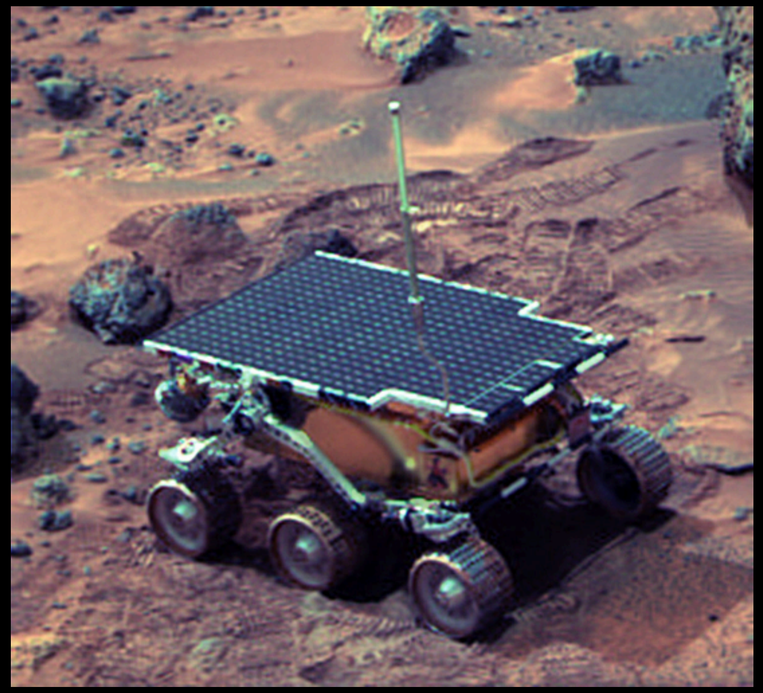
Important Missions - Mars

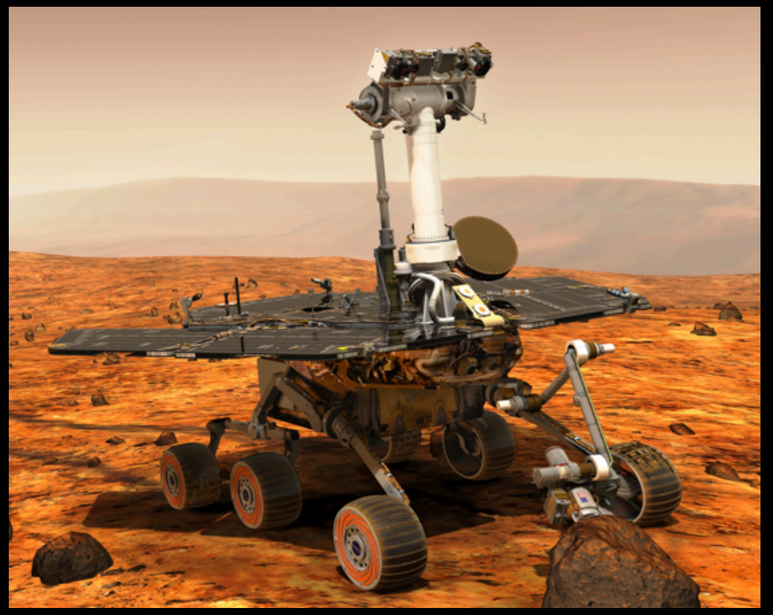
Sojourner landed with the Pathfinder mission (1997) - the first vehicle to roam on another planet.

Spirit and Opportunity (2004) were much larger and meant to focus on evidence of water.

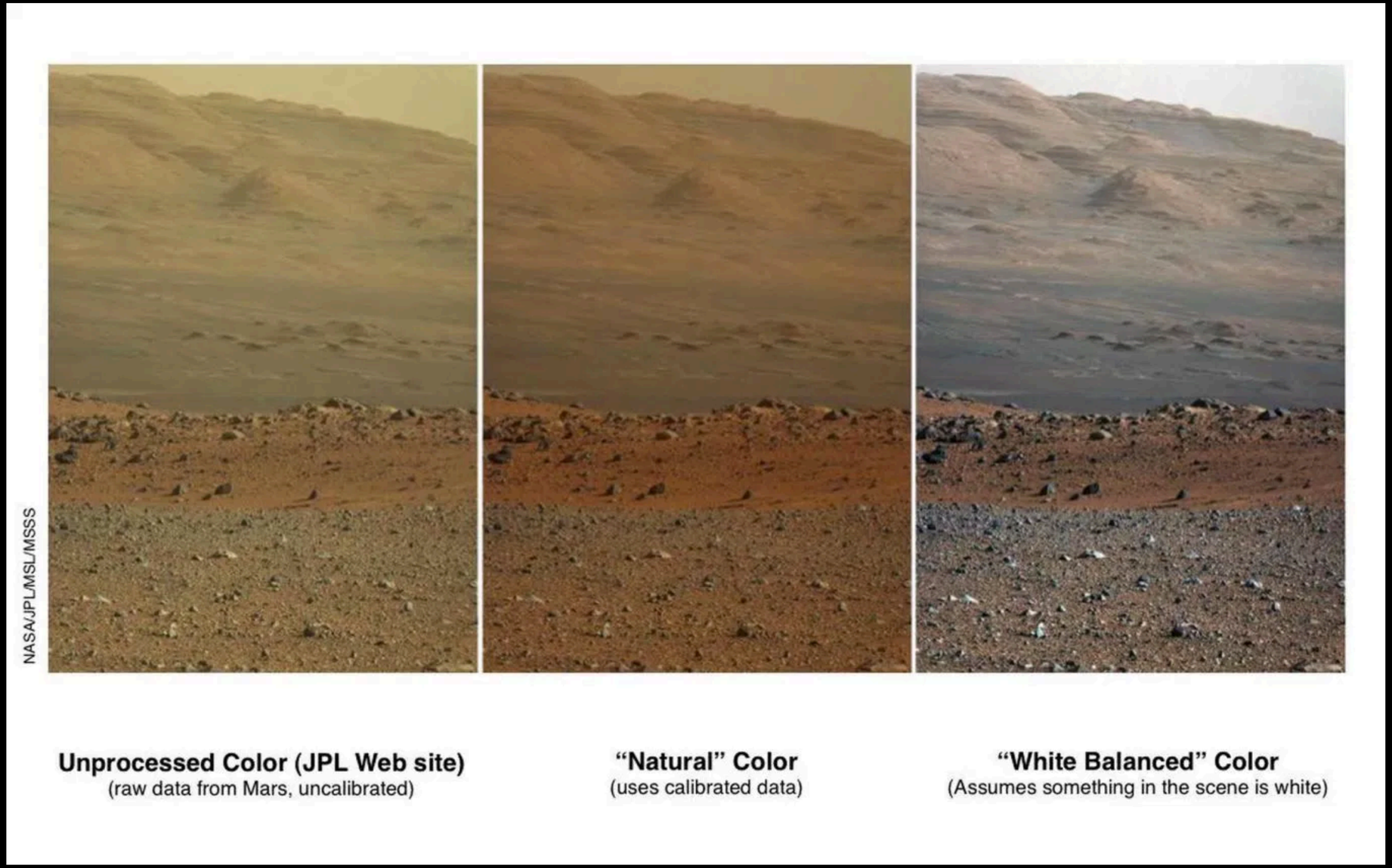
~~Opportunity is still active, 14 years later, despite its original 90 day intended mission.~~

RIP Opportunity





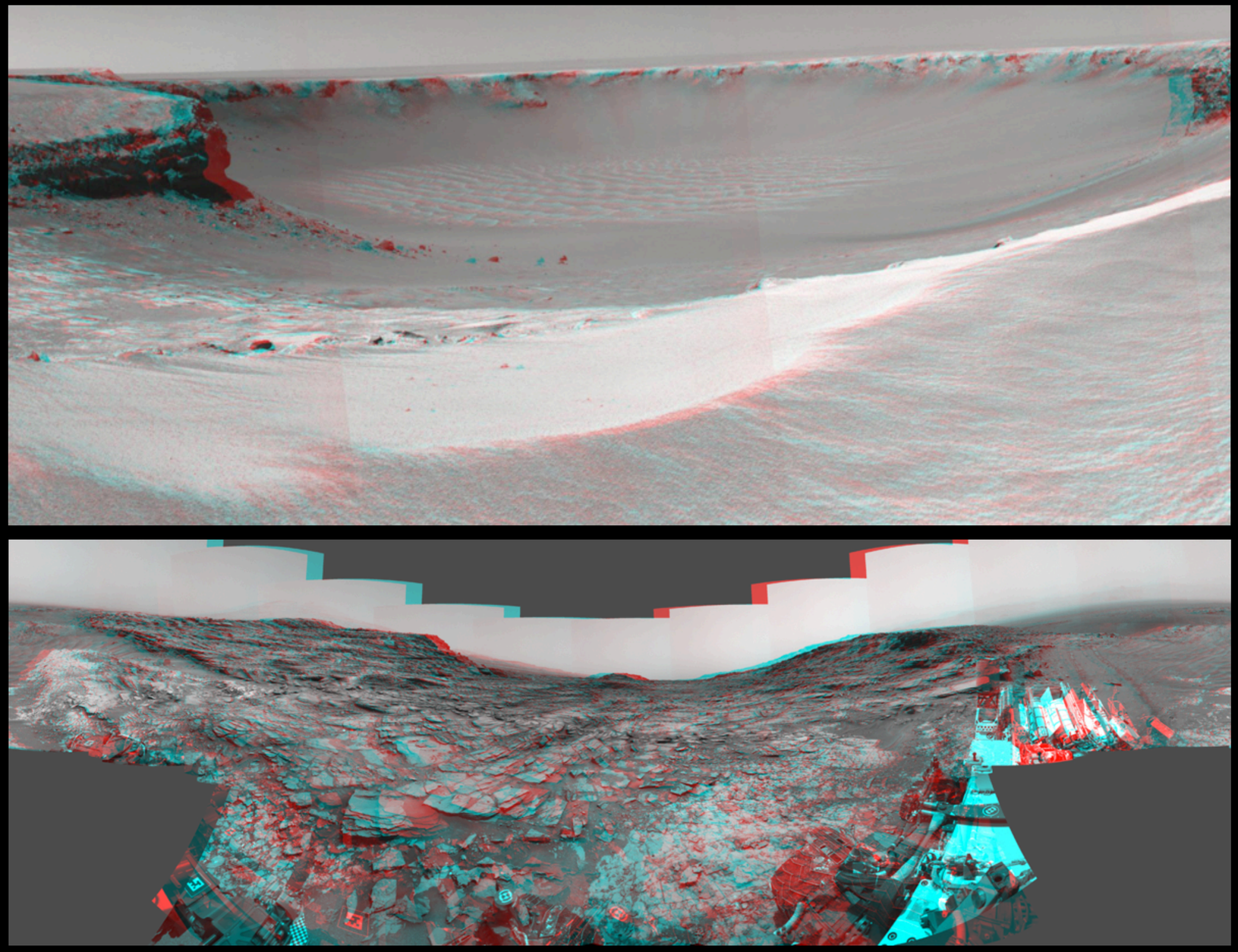
Images of Mars



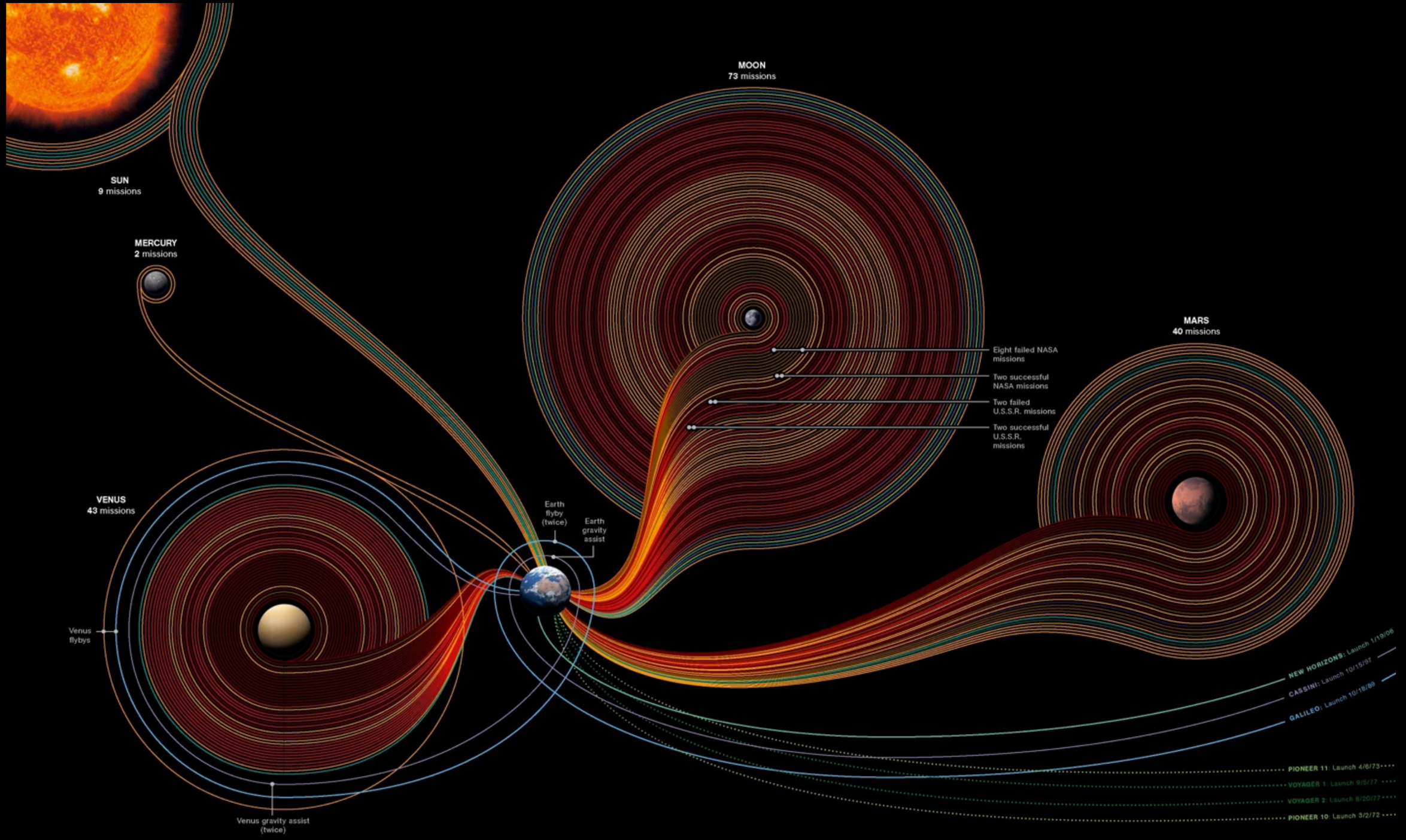
Images of Mars

Thousands of images have been taken in stereoscopic 3D.

Find some anaglyph 3D glasses and you can see Mars in 3D for yourself!

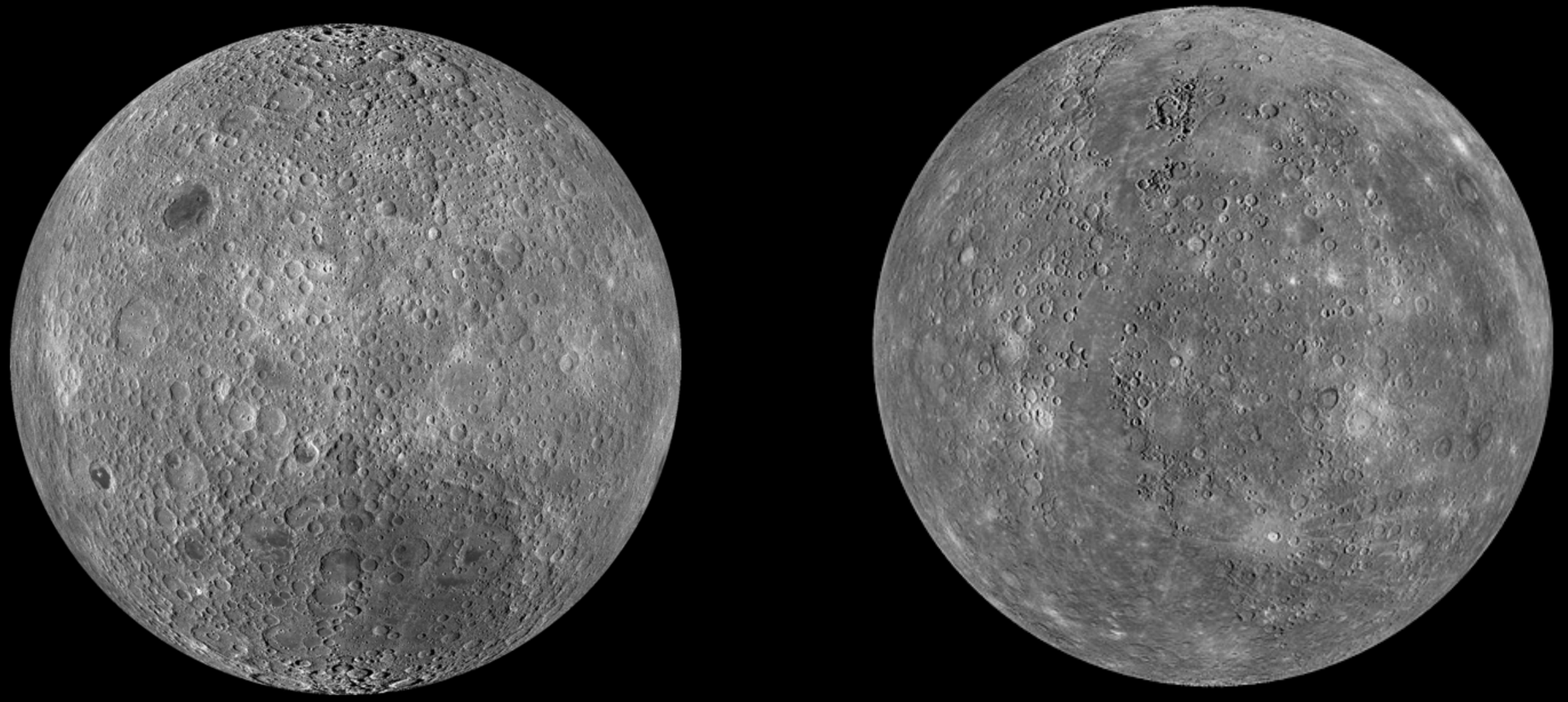


https://mars.nasa.gov/mars3d/


SUN
9 missions
MERCURY
2 missions
MOON
73 missions
Eight failed NASA missions
Two successful NASA missions
Two failed U.S.S.R. missions
Two successful U.S.S.R. missions
MARS
40 missions
VENUS
43 missions
Earth flyby (twice)
Earth gravity assist
Venus flybys
Venus gravity assist (twice)
NEW HORIZONS: Launch 1/19/06
CASSINI: Launch 10/15/97
GALILEO: Launch 10/18/89
PIONEER 11: Launch 4/6/73
VOYAGER 1: Launch 9/5/77
VOYAGER 2: Launch 8/20/77
PIONEER 10: Launch 3/2/72

Mercury

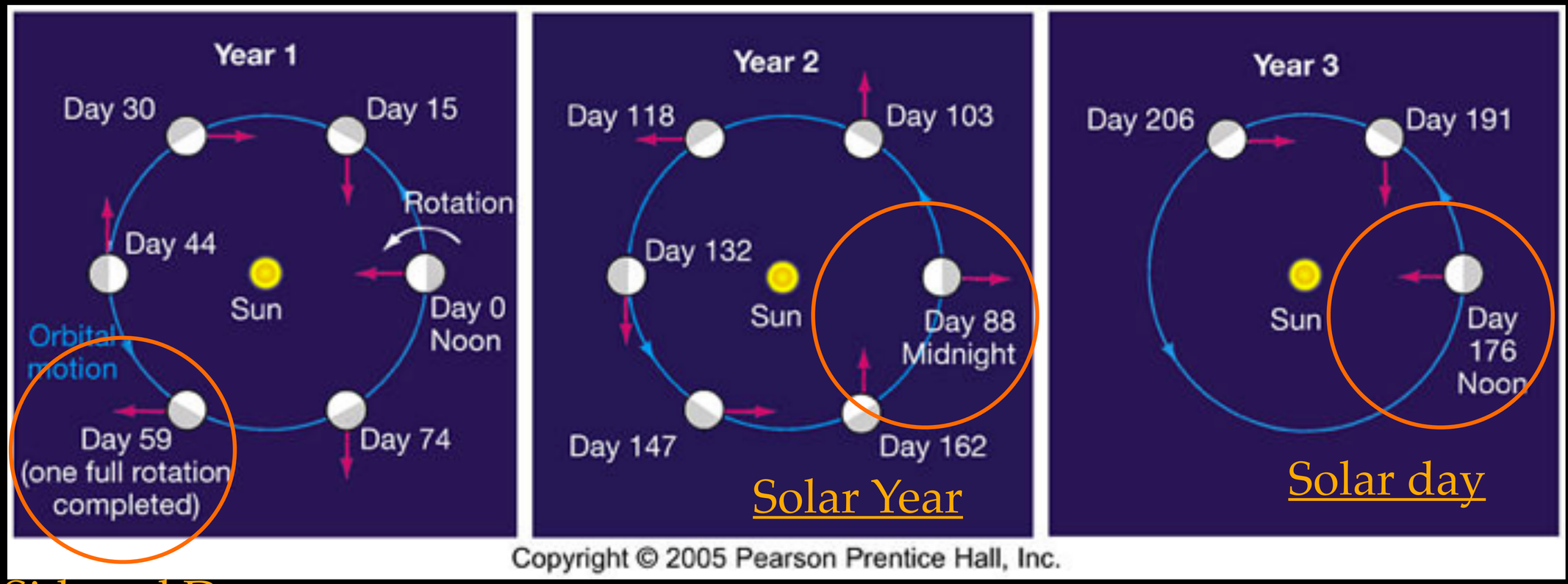
Comparison to the Moon



Side-by-side, it is difficult to distinguish between the Moon and Mercury.

Orbital Oddities

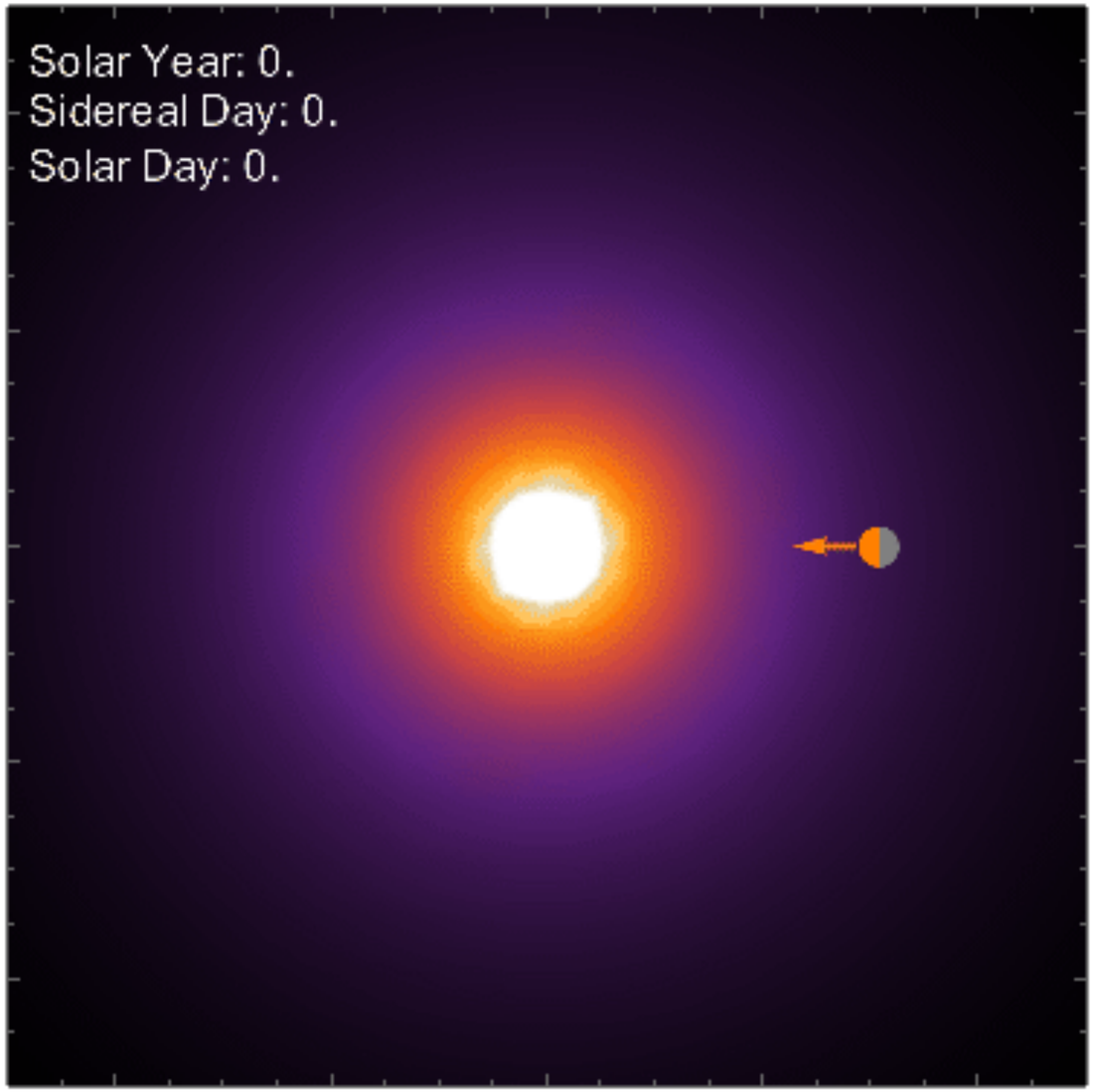
Originally thought to be tidally locked, RADAR scans with Arecibo found the sidereal rotational period to be 59 Earth days, exactly 2/3 of its solar year

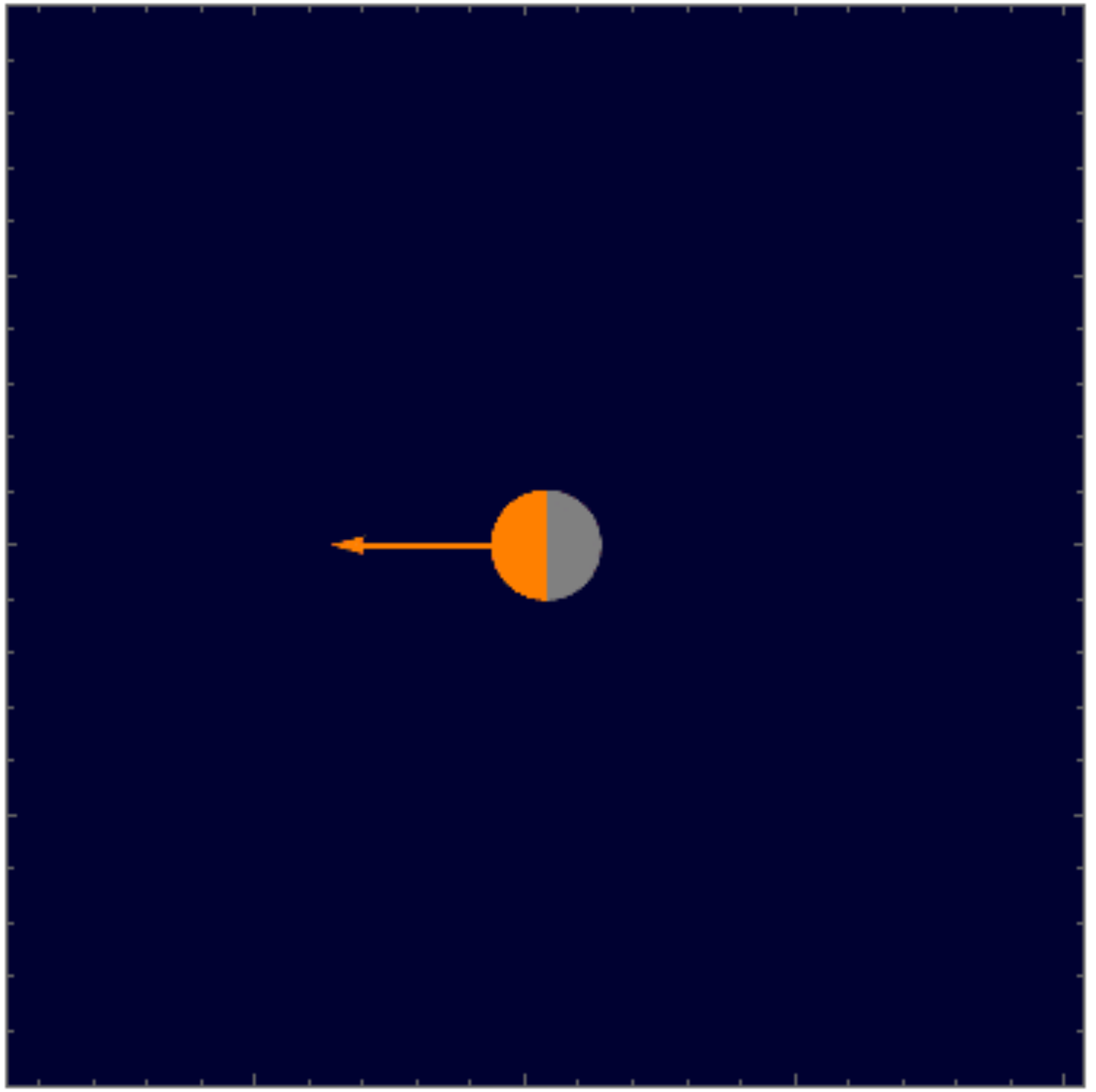


Sidereal Day

Solar Year

Solar day


Solar Year: 0.
Sidereal Day: 0.
Solar Day: 0.

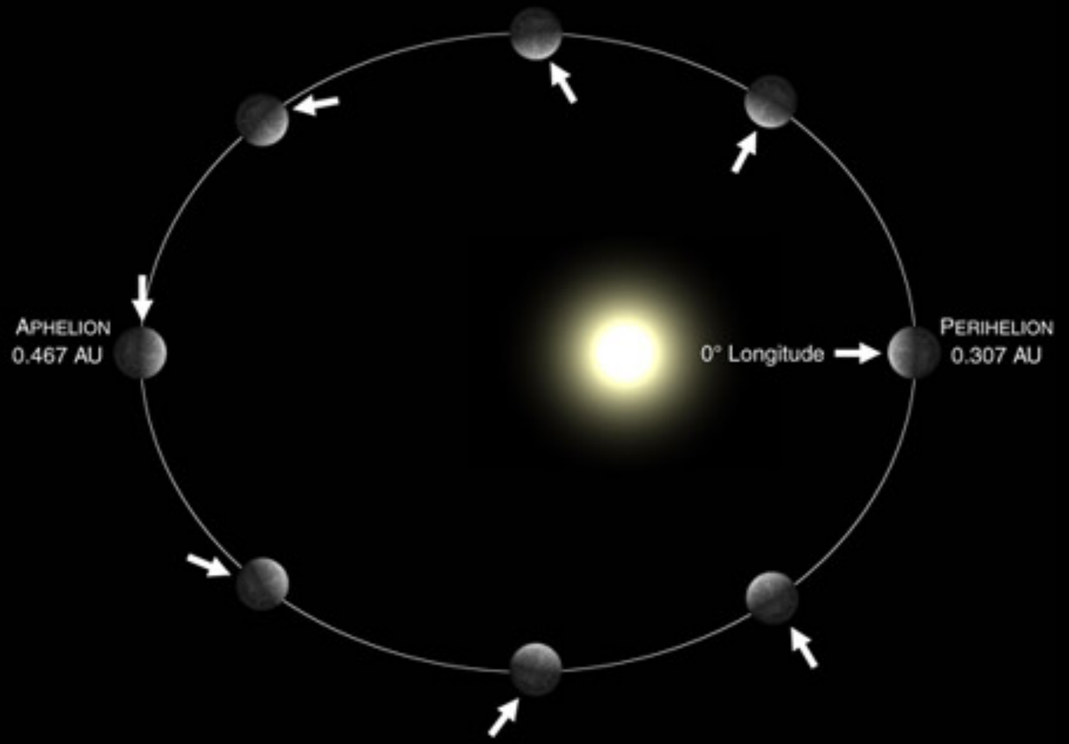


Orbital Resonances

The Moon has a 1:1 orbital resonance meaning 1 sidereal rotation = 1 orbital period. (TIDAL LOCK)

Mercury has a 3:2 orbital resonance.
3 sidereal rotations = 2 solar orbits
which also equals 1 solar rotation

The cause is the same as the Moon: the Sun's gravity locked the rotation in an integer ratio.



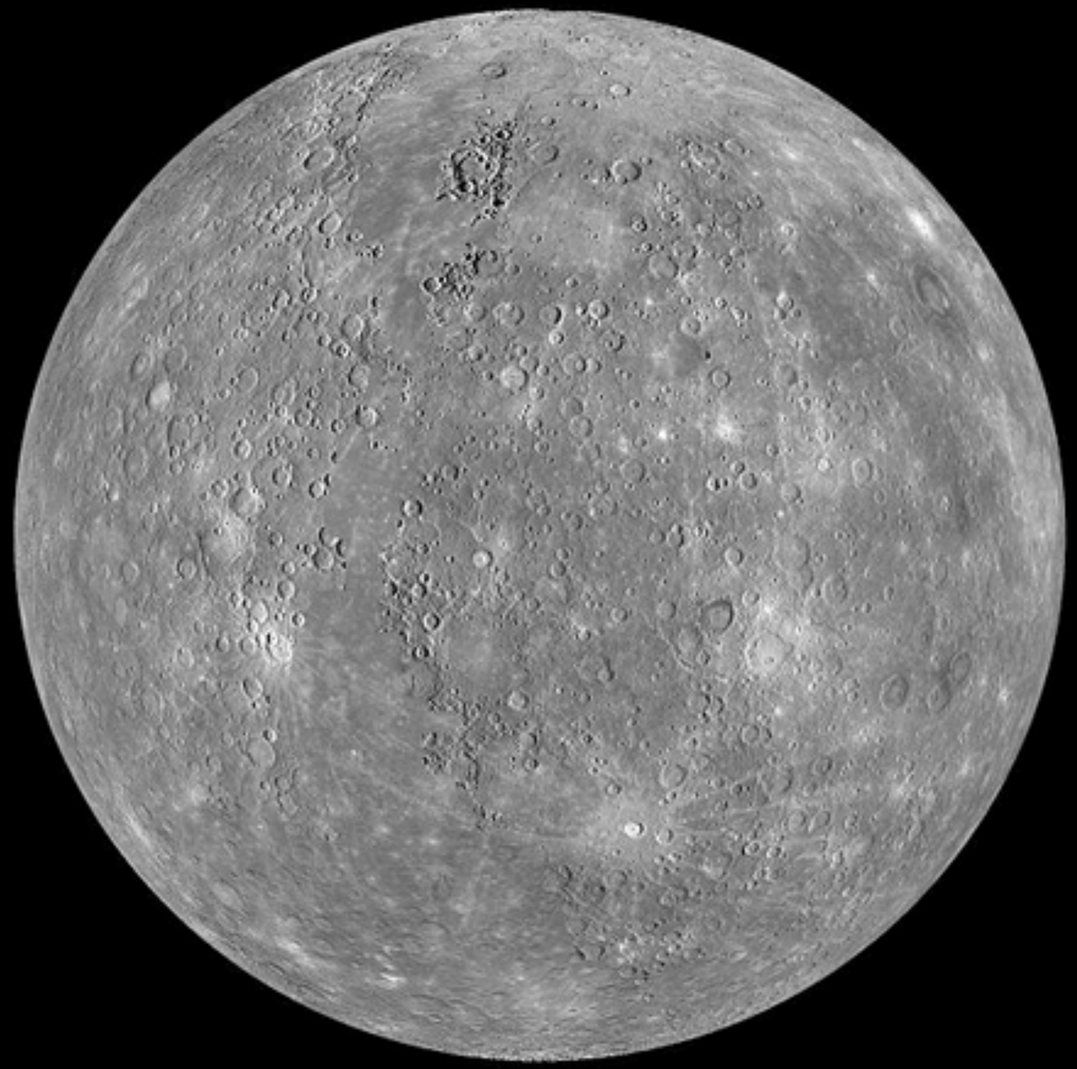
Due to Mercury's large eccentricity, it can only reside in a 3:2 resonance and will never reach a 1:1 resonance.

Geography

Fewer craters than the Moon, with plains cover ~40% of the planet.

Extrapolating from the bombardment timeline from the Moon, the plains were formed 4B years ago.

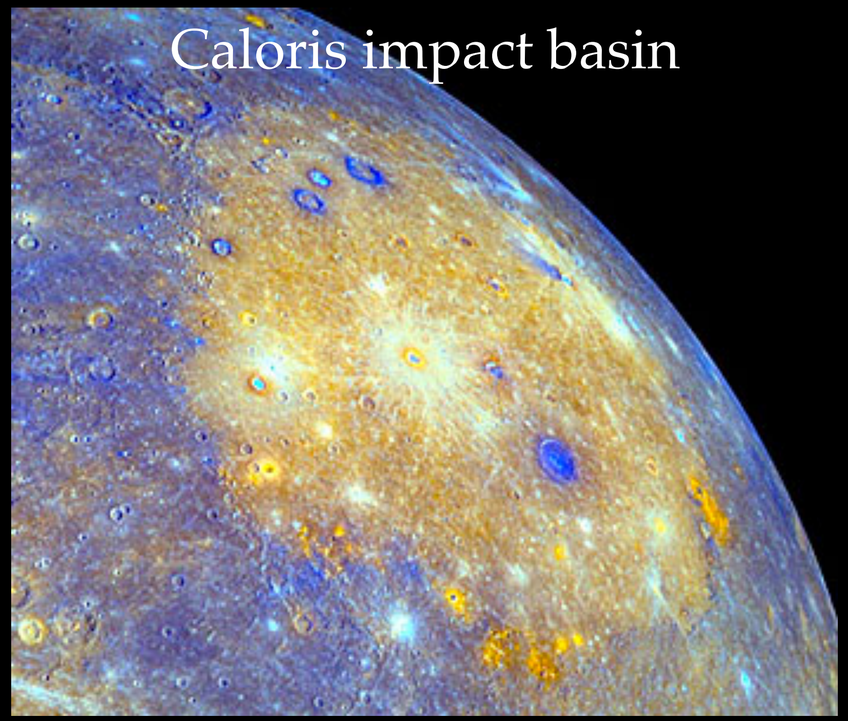
Craters have smaller ejecta patterns due to the larger gravity.

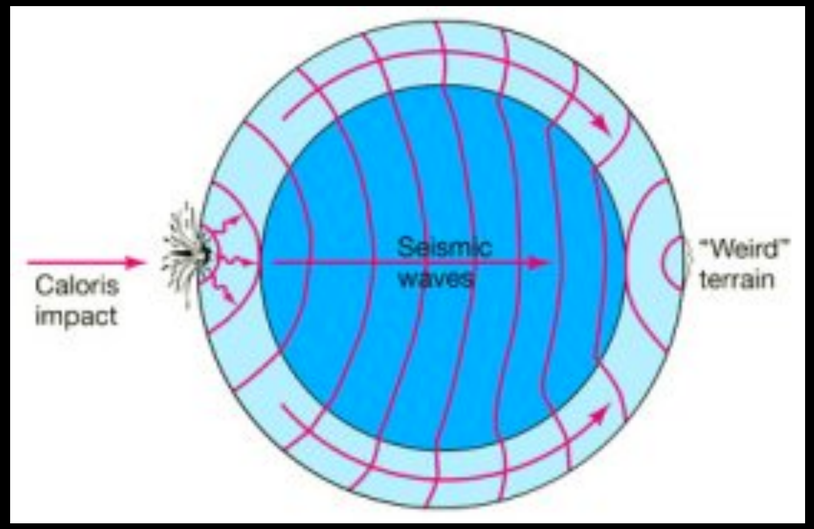


Caloris Basin

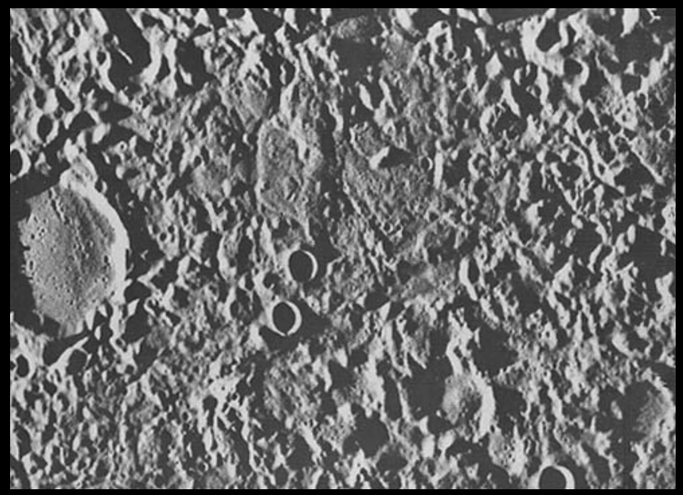
The most distinctive feature is a giant impact crater called Caloris Basin.

Caloris impact basin





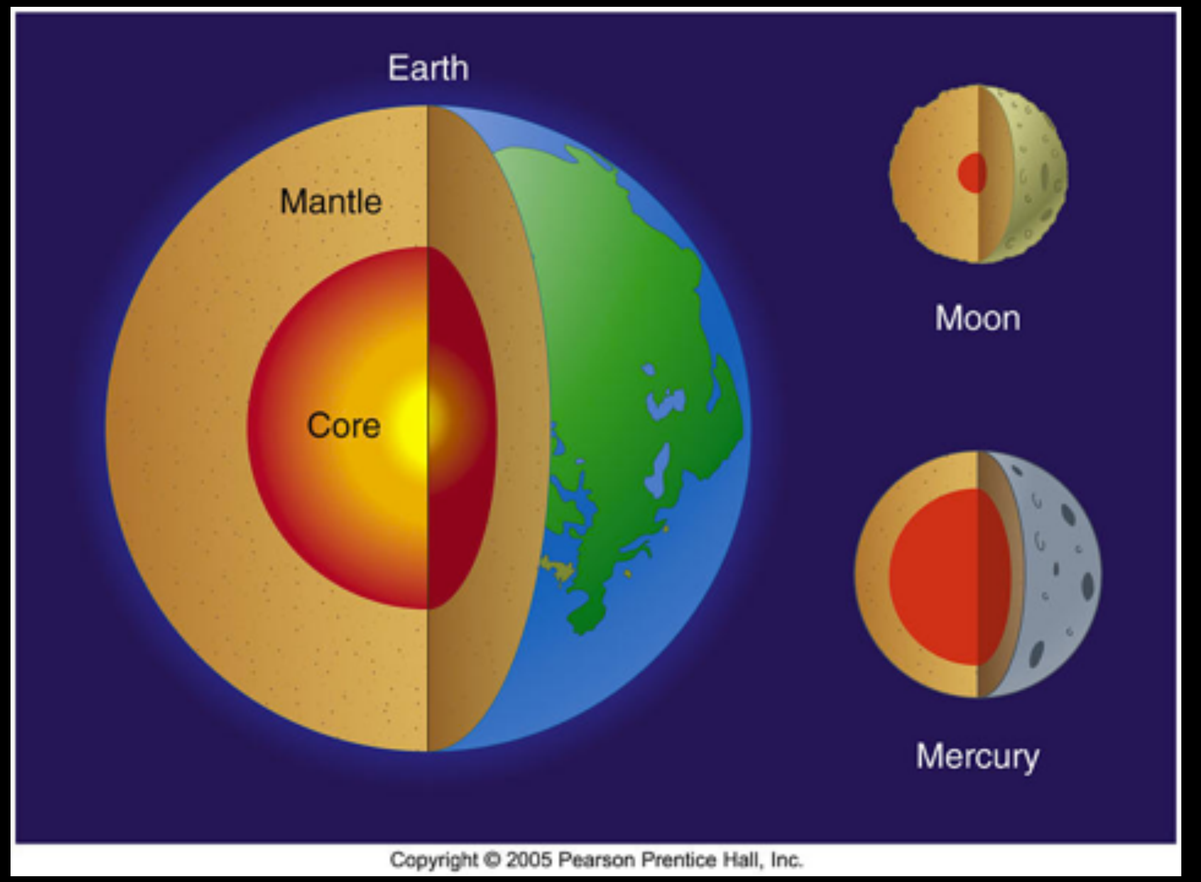
Caloris antipodal point



The seismic waves collided on the opposite side and caused a wrinkling.

Geology

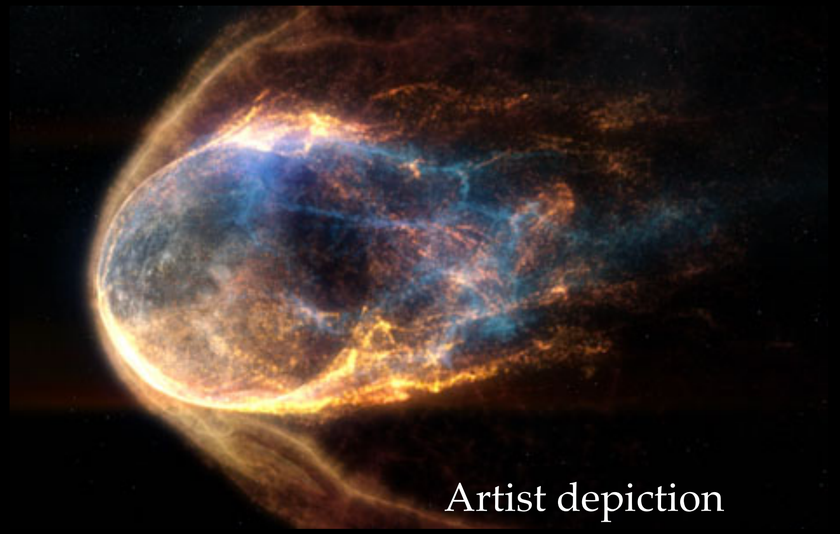
Study of the surface by Messenger reveals evidence of a core that makes up a larger fraction of the planet than Earth's.



The highlands and plains have similar colouring, indicating that the surface has a similar elemental composition as the core.

Atmosphere and Magnetic Field

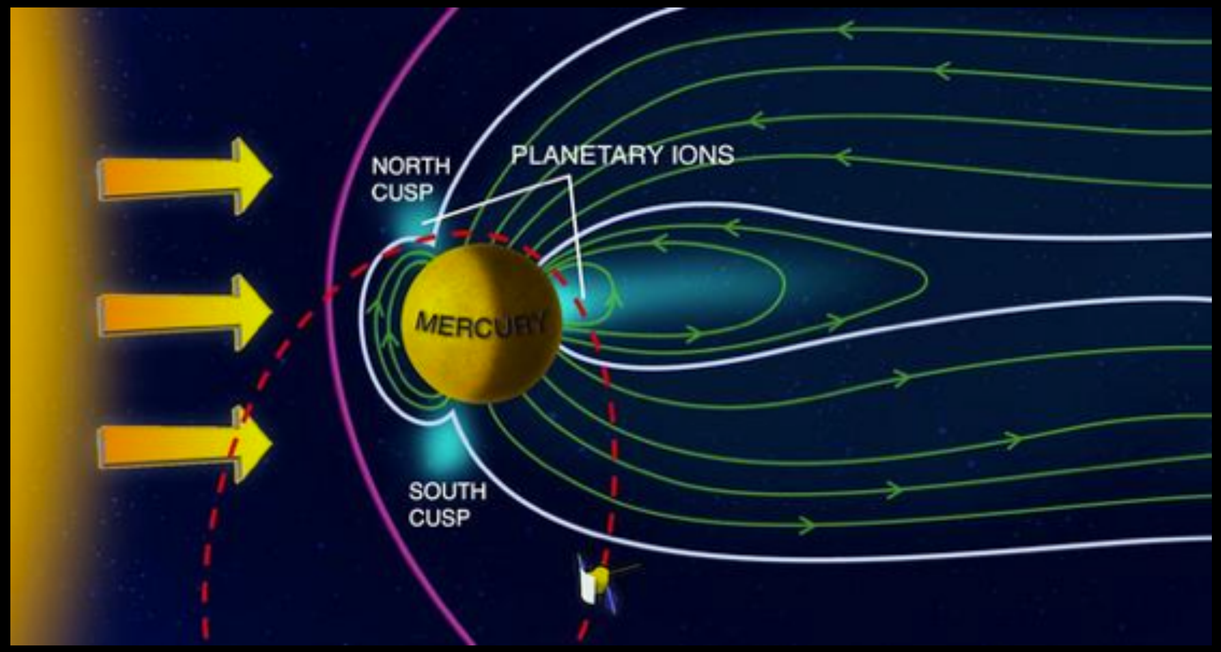
Mercury periodically captures solar winds but otherwise has no appreciable atmosphere.



Artist depiction

MESSENGER measured a small magnetic field, but much larger than should exist for a slowly rotating planet.

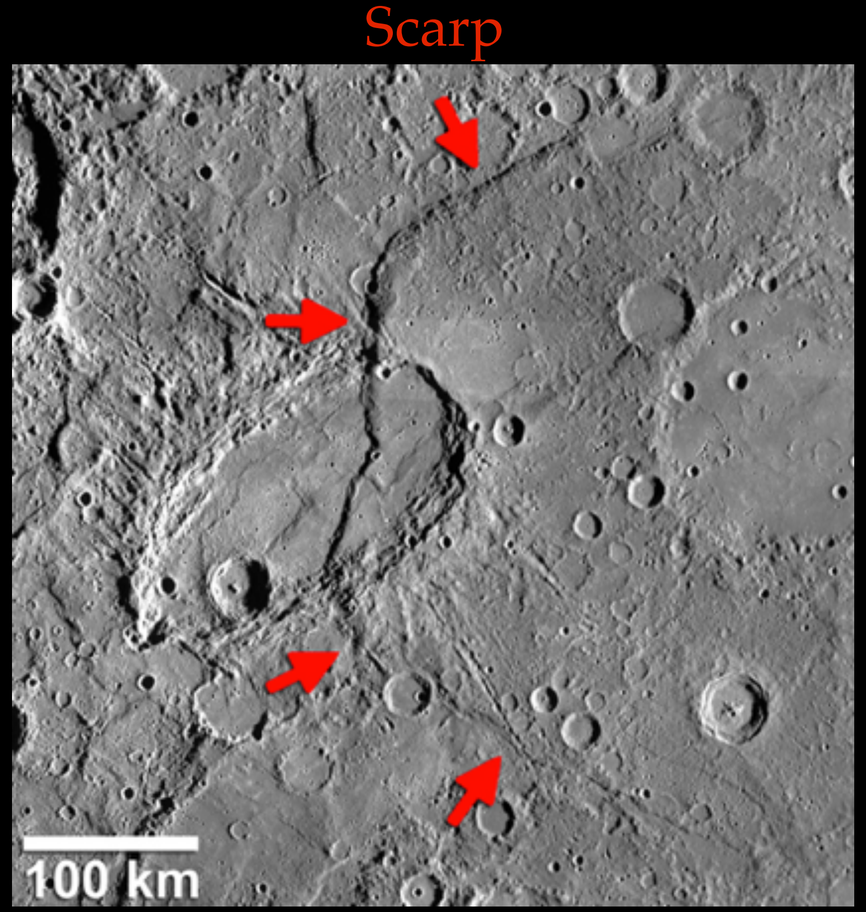
Best explanation: residual magnetism from when it rotated faster, fossilized in the iron content of the planet.



Geological History

Mercury cooled more slowly due to proximity to the Sun.

As the crust formed, it was thinner and allowed more volcanic activity, which smoothed out the surface (fewer craters).



Eventually planet cooled and shrank, creating scarp that cover the planet as wrinkles in the crust. This tight crust prevented further volcanic activity caused by later large impacts.

Venus

Comparison to Earth

Similar in size, density and chemical composition.

Primary differences are atmospheric and surface conditions.

USSR/Russian, EU and American probes have all visited Venus and contribute to our understanding of the planet.

So far, only USSR/Russia has landed on Venus.

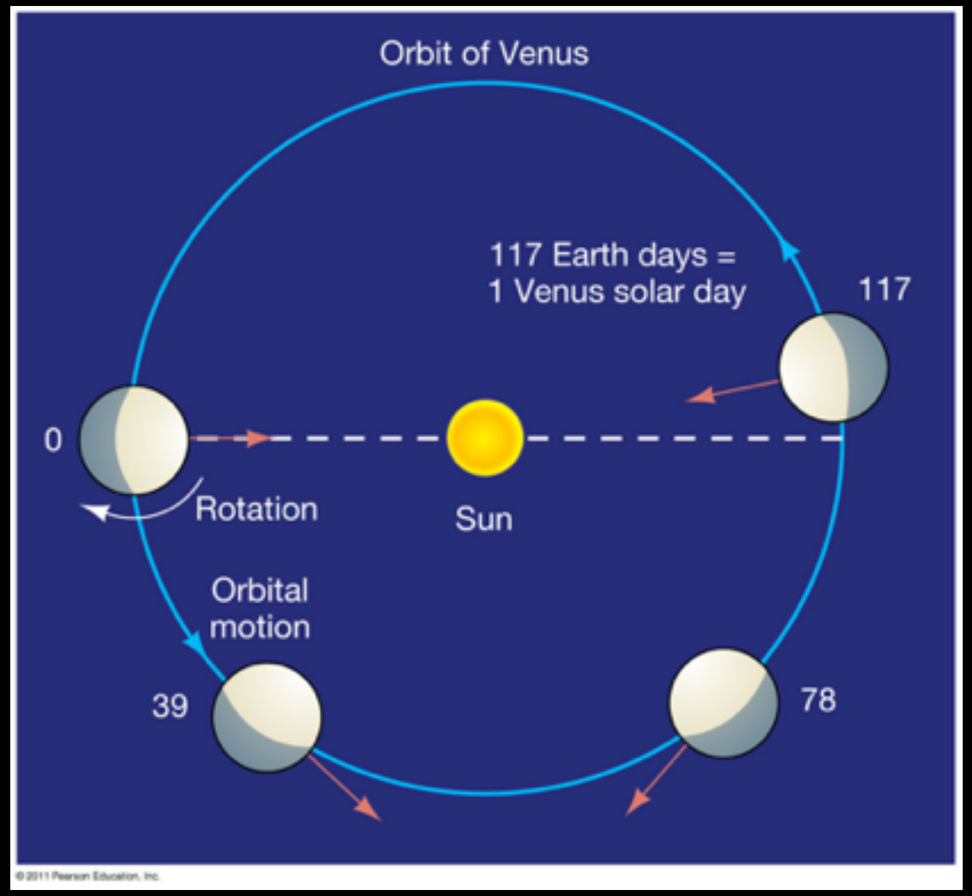
Retrograde Rotation

A negative sidereal day means it is rotating in retrograde - against the rotation of the rest of the solar system.

Prograde rotation causes the sidereal day to be shorter than the solar day.

Retrograde rotation causes the solar day to be shorter than the sidereal day.

In contrast, its solar year is 225d, so there are just under 2 solar days per solar year.

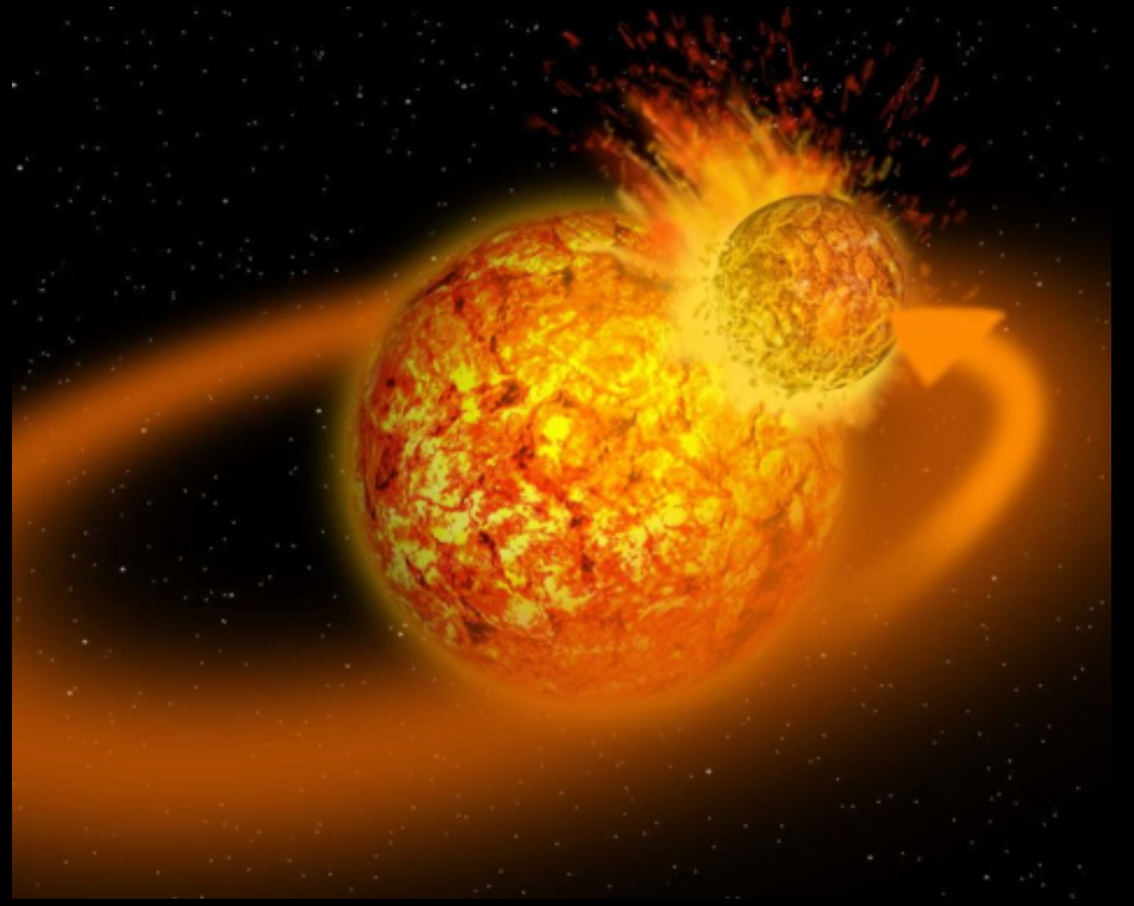


Conservation of Angular Momentum

Conservation of Angular Momentum suggests that all planets should rotate in a prograde sense.

This suggests that Venus was not formed entirely by accretion of smaller objects.

Likely two very large (Mars sized?) objects collided at just the right angle to produce the retrograde rotation.

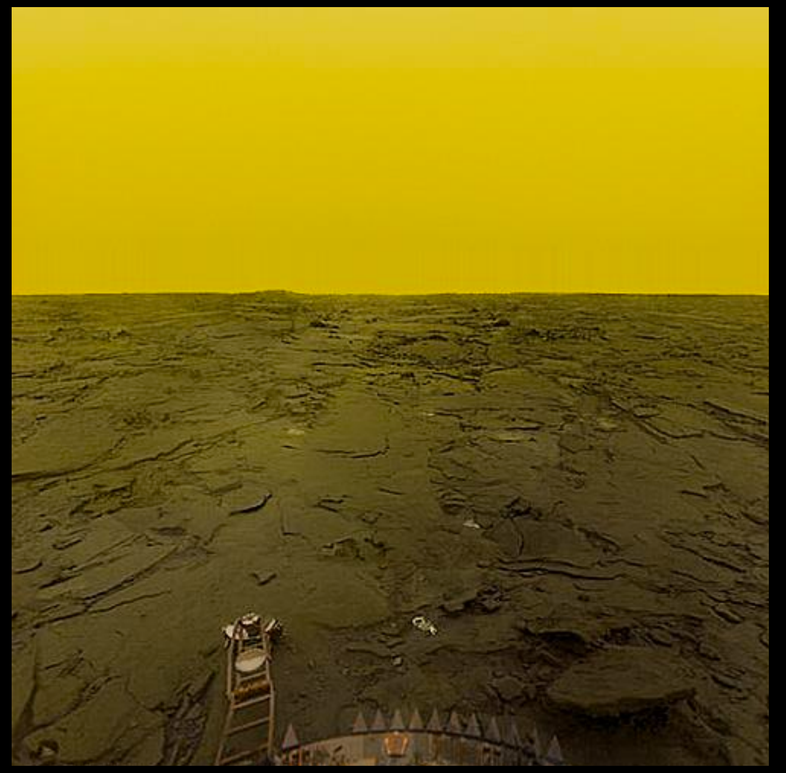


VENERA Missions

The Russian VENERA series of missions landed on Venus multiple times.

Images of the surface show volcanic flagstones and signs of atmospheric weathering.

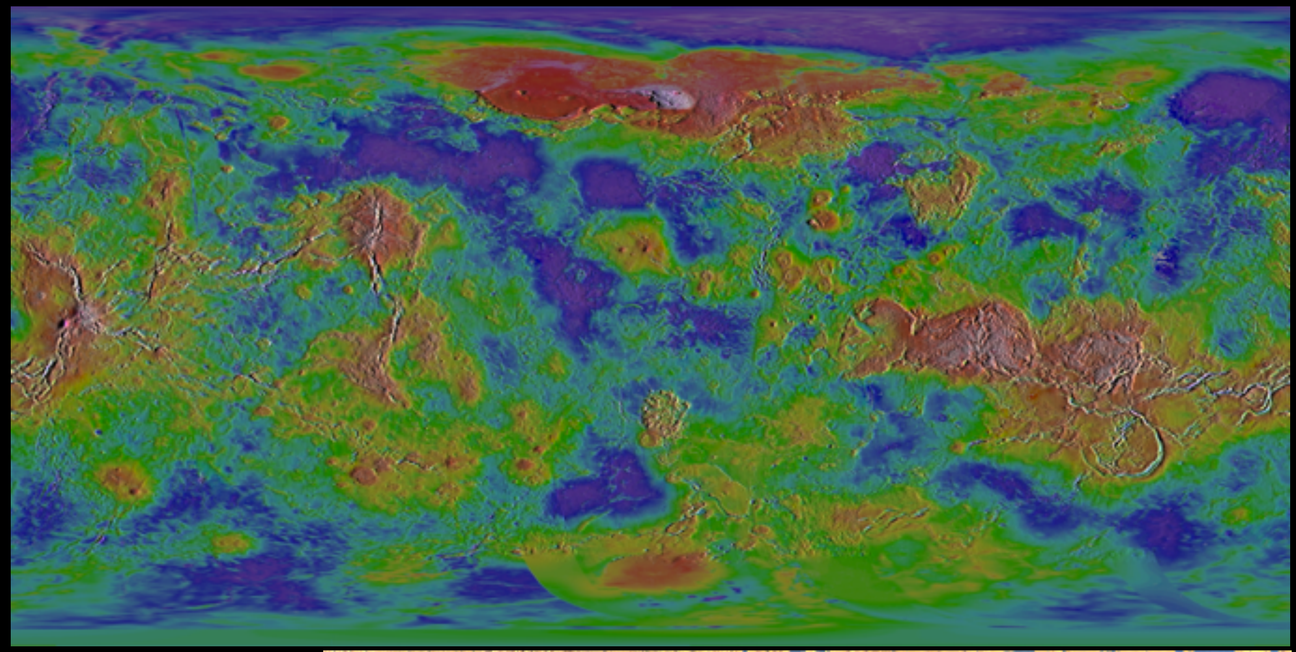
Temperature exceeds 400^{o}C, and critical components of all landers melted within 1h.



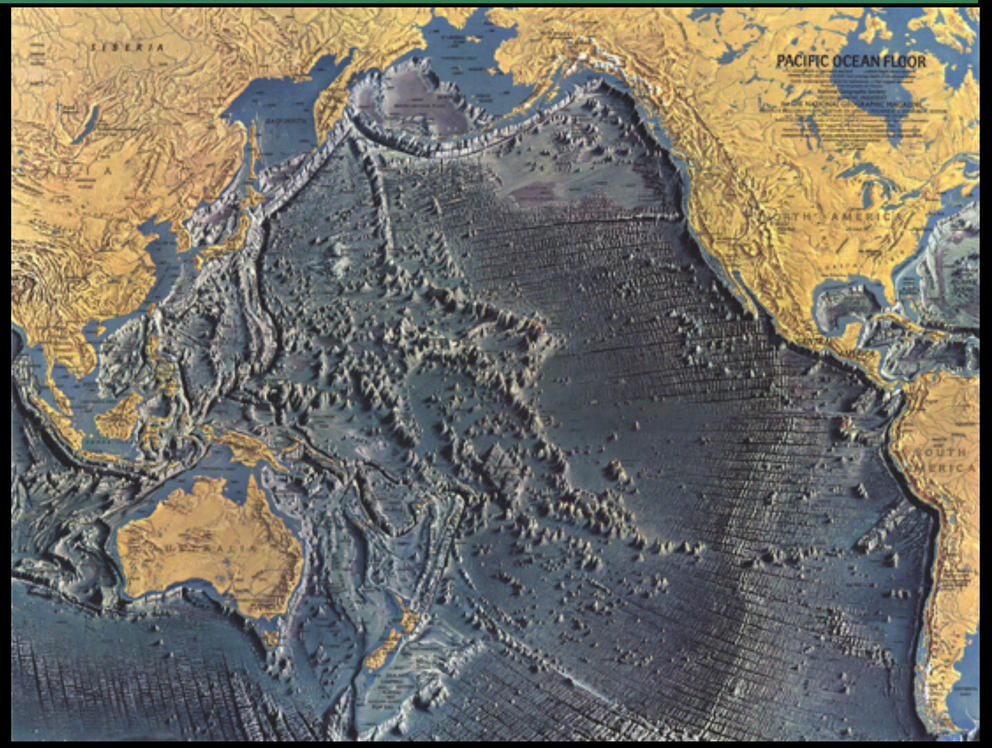
Beware - some people have added weather patterns/clouds to the VENERA images that were not part of the originals.

Geography

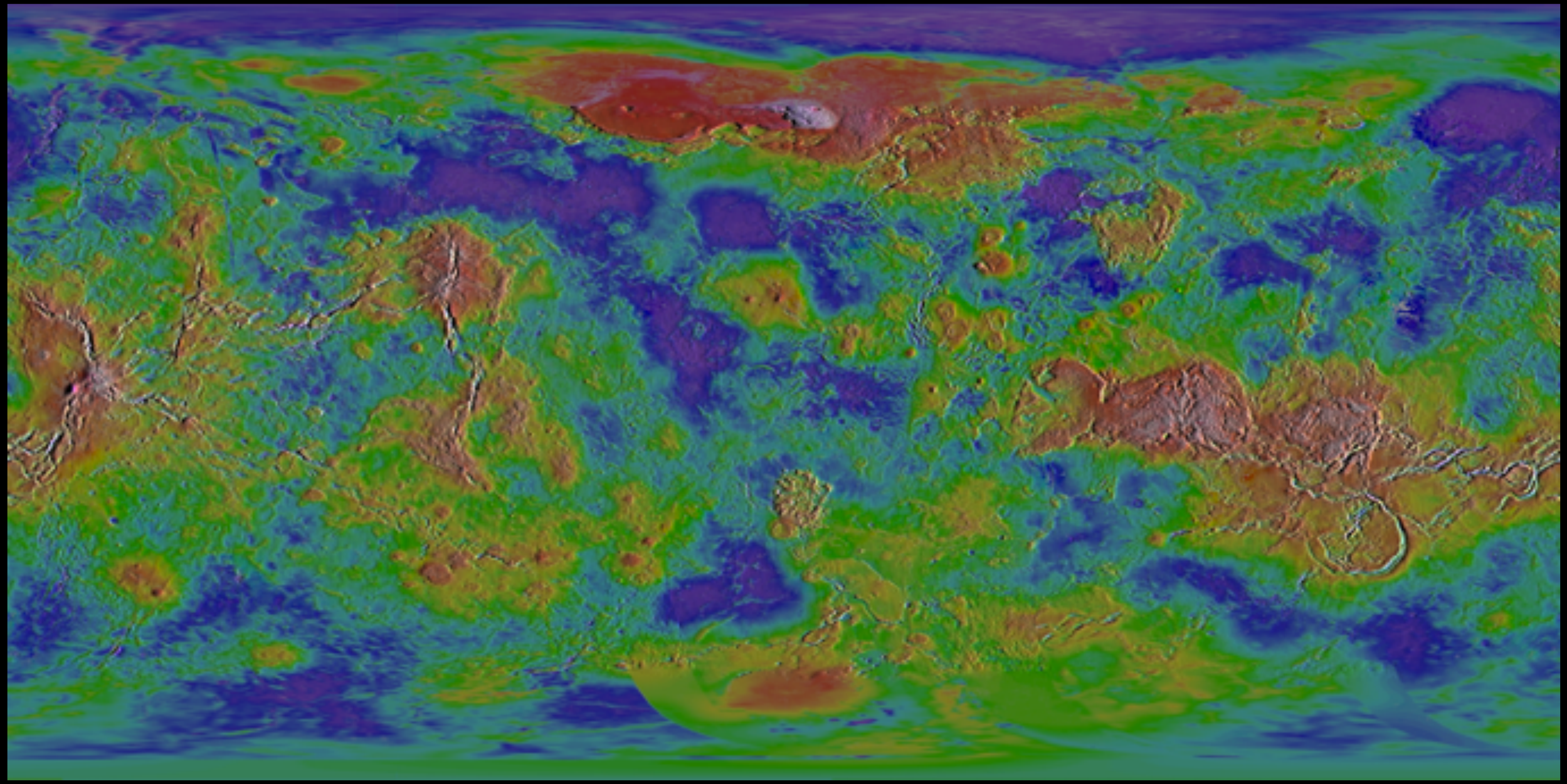
Surface features are named after women in history / mythology / science.



Two primary “continents”, and there appears to be cracking near the equator that are similar to regions of tectonic activity on Earth.

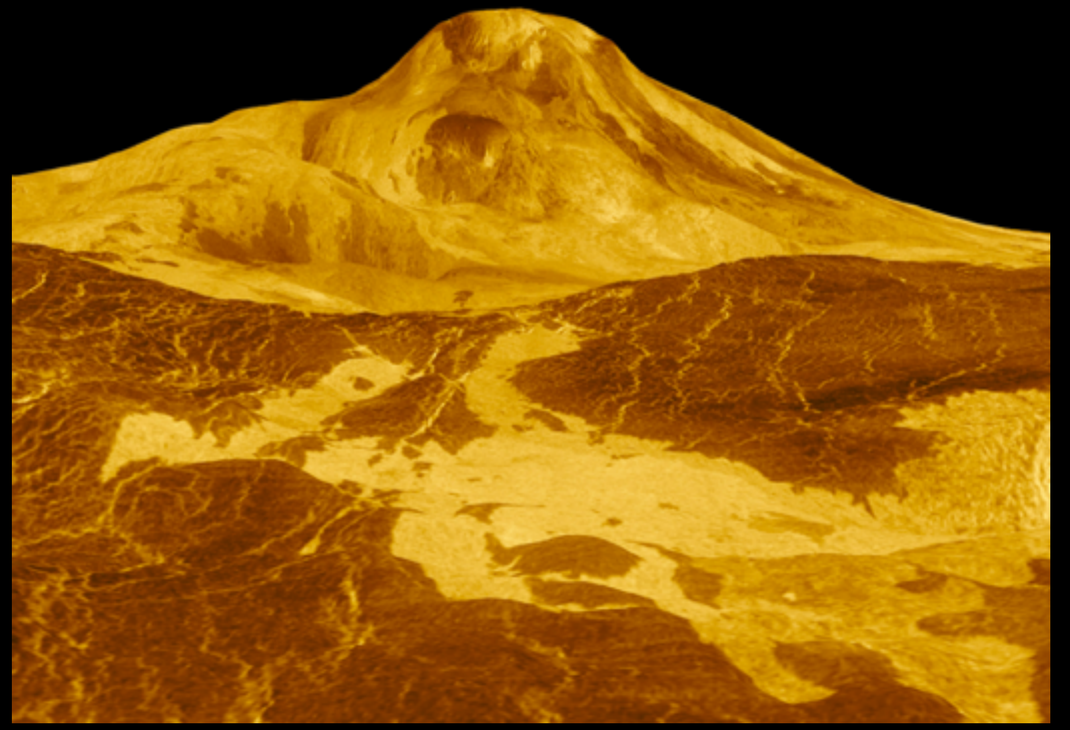


No active surface motion observed, however.



Volcanism

The surface of Venus is dominated by lava flows, volcanic peaks and other volcanic features.



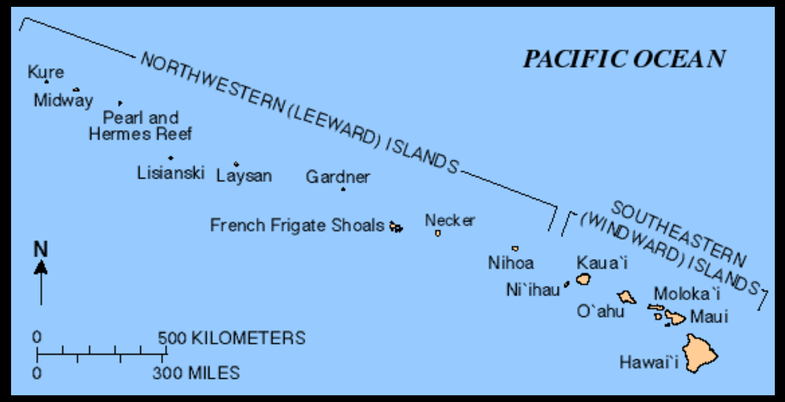
Largest volcano is Maat Mons, 8km high.

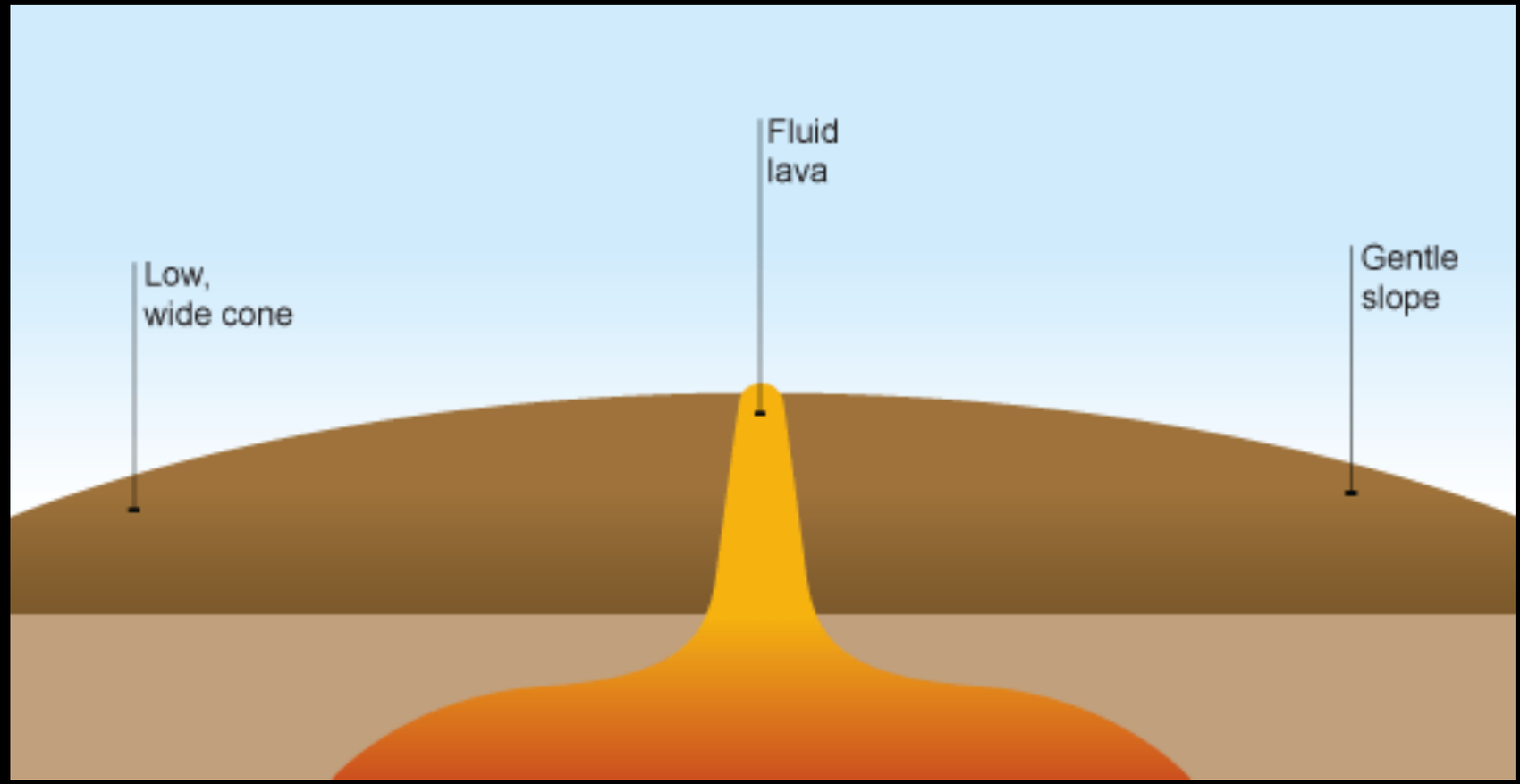
The structure of all the volcanoes indicate that they are shield volcanoes produced by hot-spots rather than tectonic spreading.

The giant size indicates their age, and further rejects the tectonic theory.

Shield Volcanos

Built up over a long period of slow, gentle eruptions. If the source of lava were to move (i.e. tectonic activity), then a new volcano would start elsewhere (e.g. Hawaii).



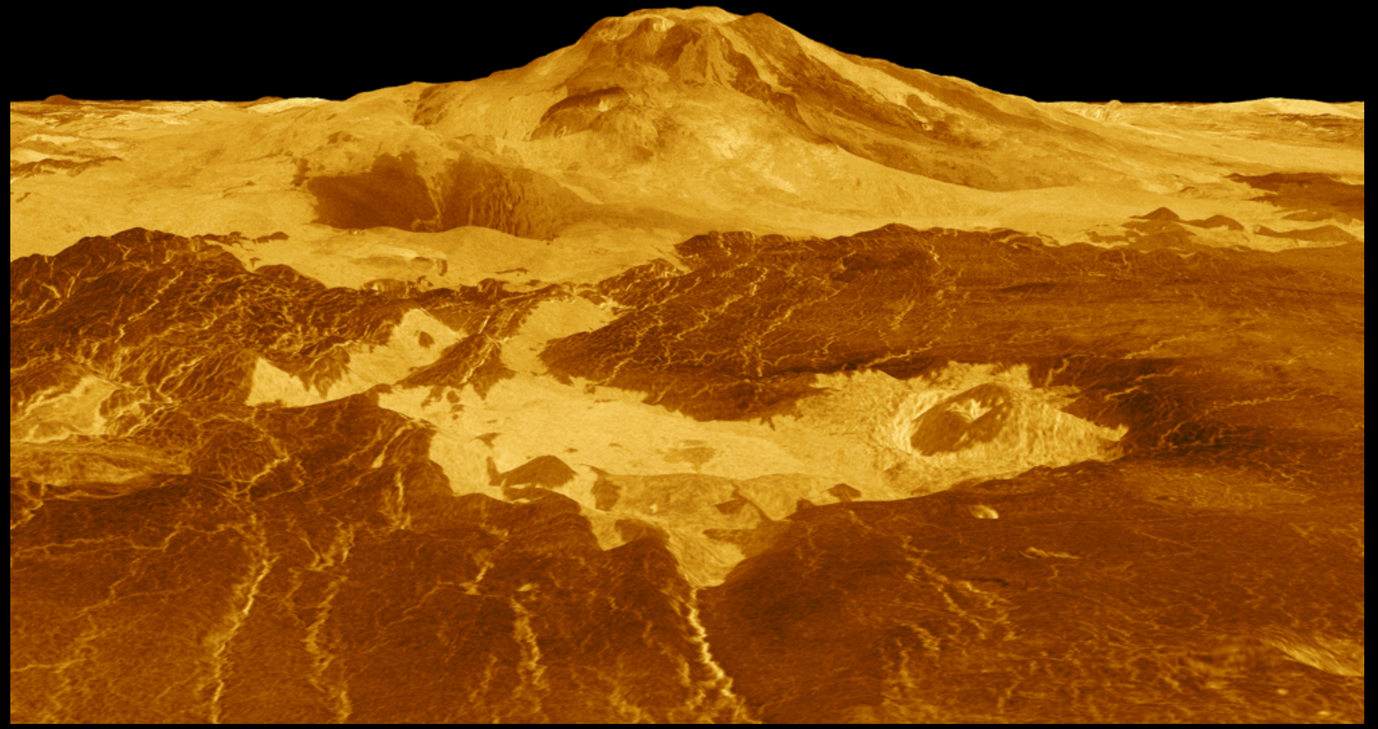


Age of Volcanism

Young lava flows tend to be rough, which reflects radio/radar waves well.

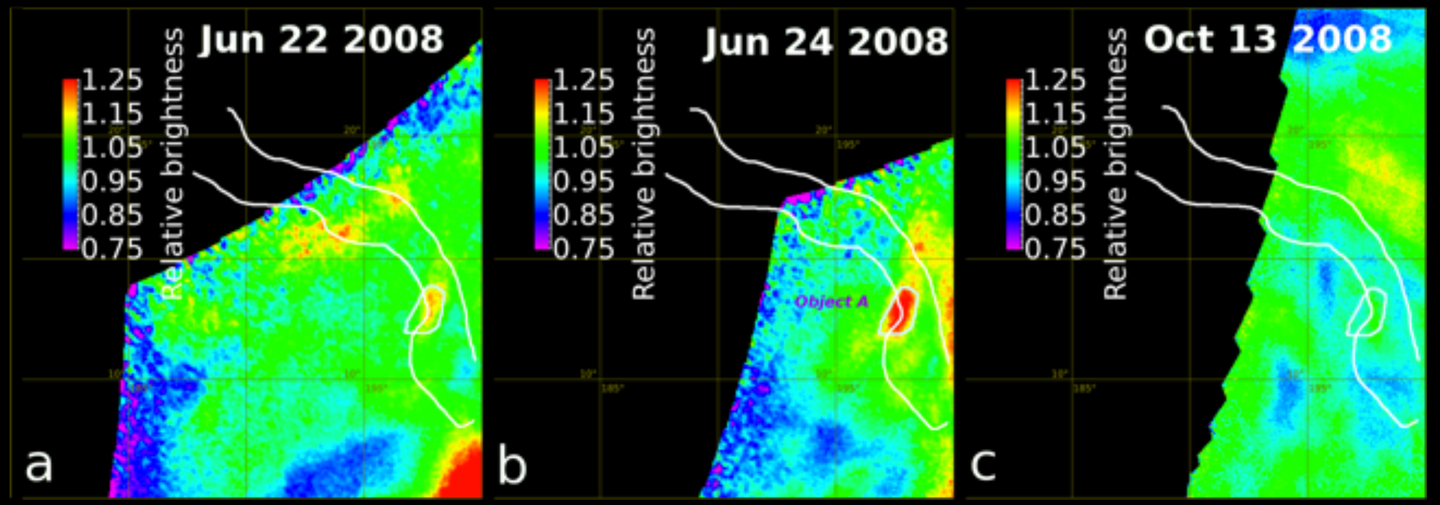
Light coloured regions indicate younger land, darker is older.

In addition, sulfur dioxide levels in the atmosphere fluxuate, and there are radio energy bursts consistent with lightning.



This is evidence of ongoing volcanism, however no eruptions are seen!

Catastrophic Volcanism

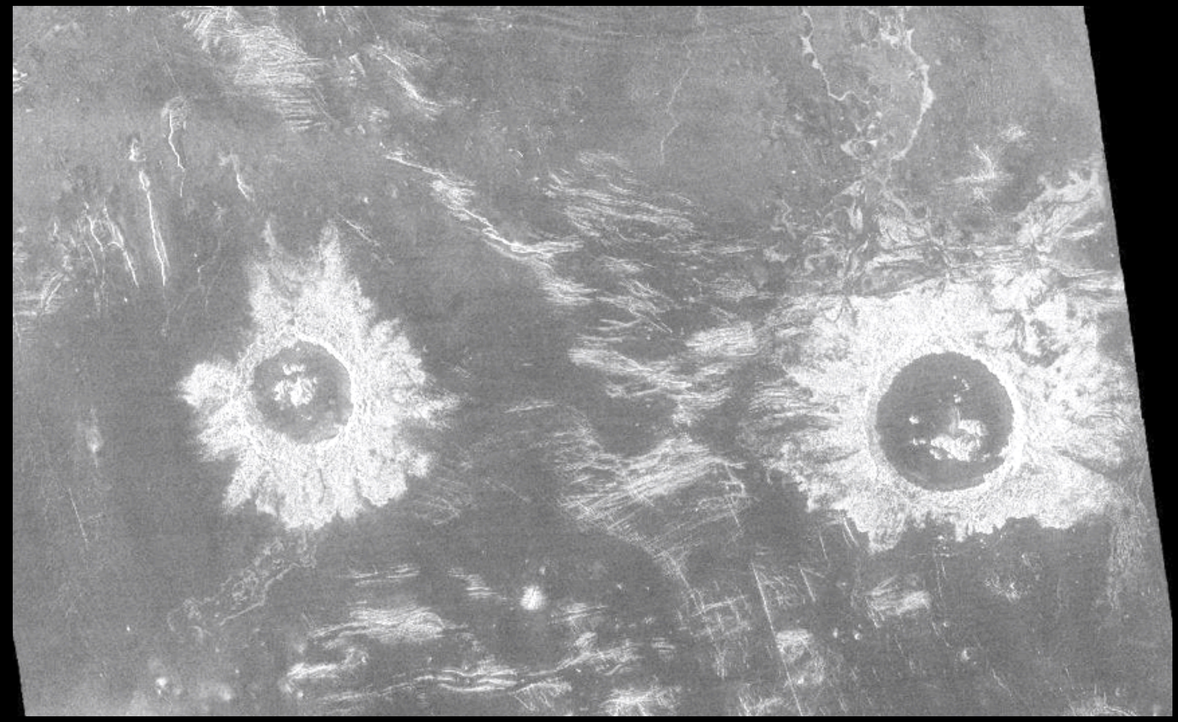


Best evidence so far comes from Venus Express.

Observed moving hotspots in the proximity of a known lava flow.

Surface of Venus shows very little impact cratering - crater density suggests surface is 200-300M years old.

Suggests heat builds up inside, resulting in periodic catastrophic volcanic activity.

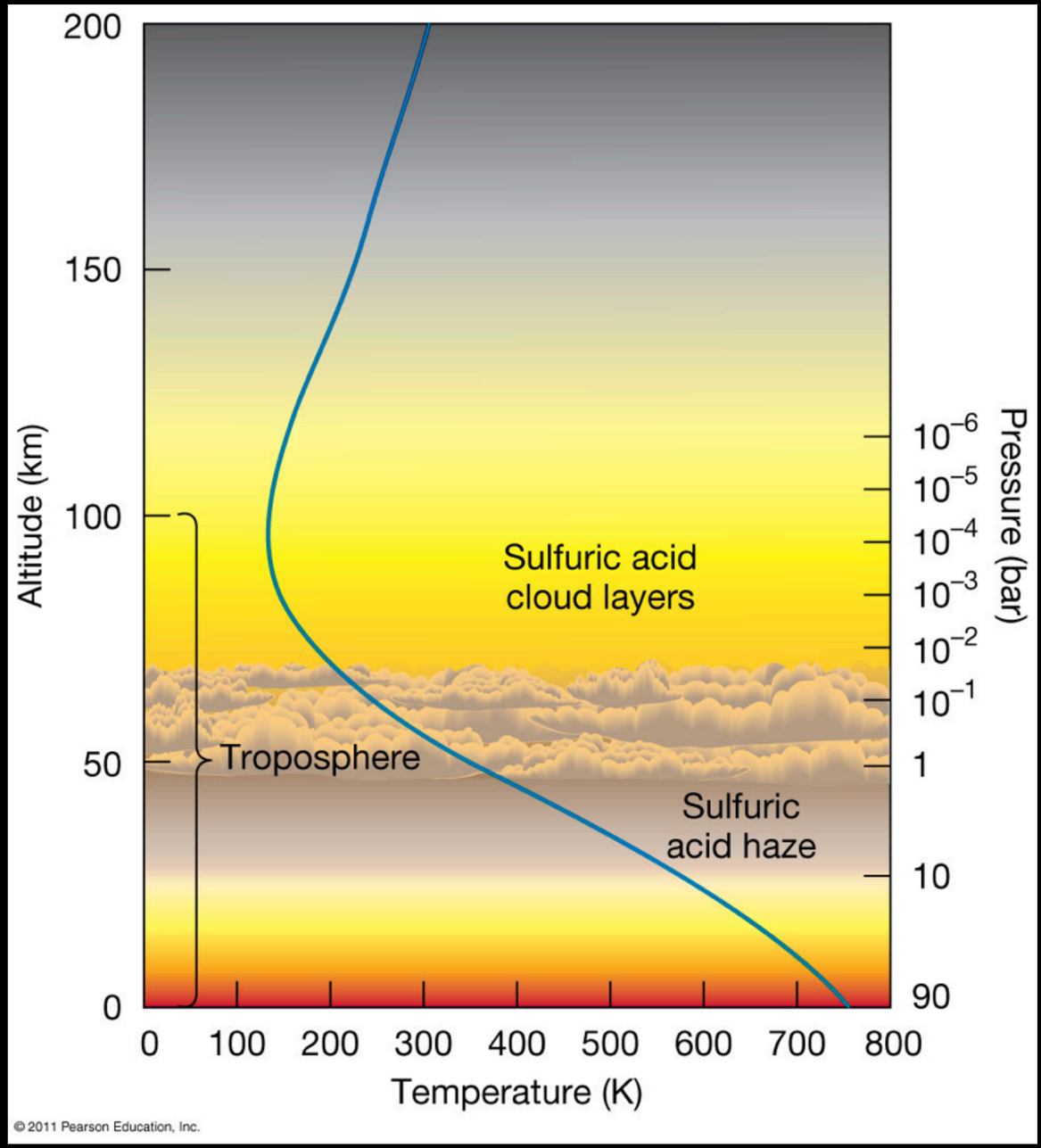


Atmosphere

Venus atmosphere contains 90x more mass than Earth's.

Mostly CO_2 (96%), with 3.5% nitrogen and small amounts of sulfur compounds.

Estimated that the amount of carbon in Venus atmosphere is similar to the total carbon now stored in Earth's crust, as e.g. limestone.



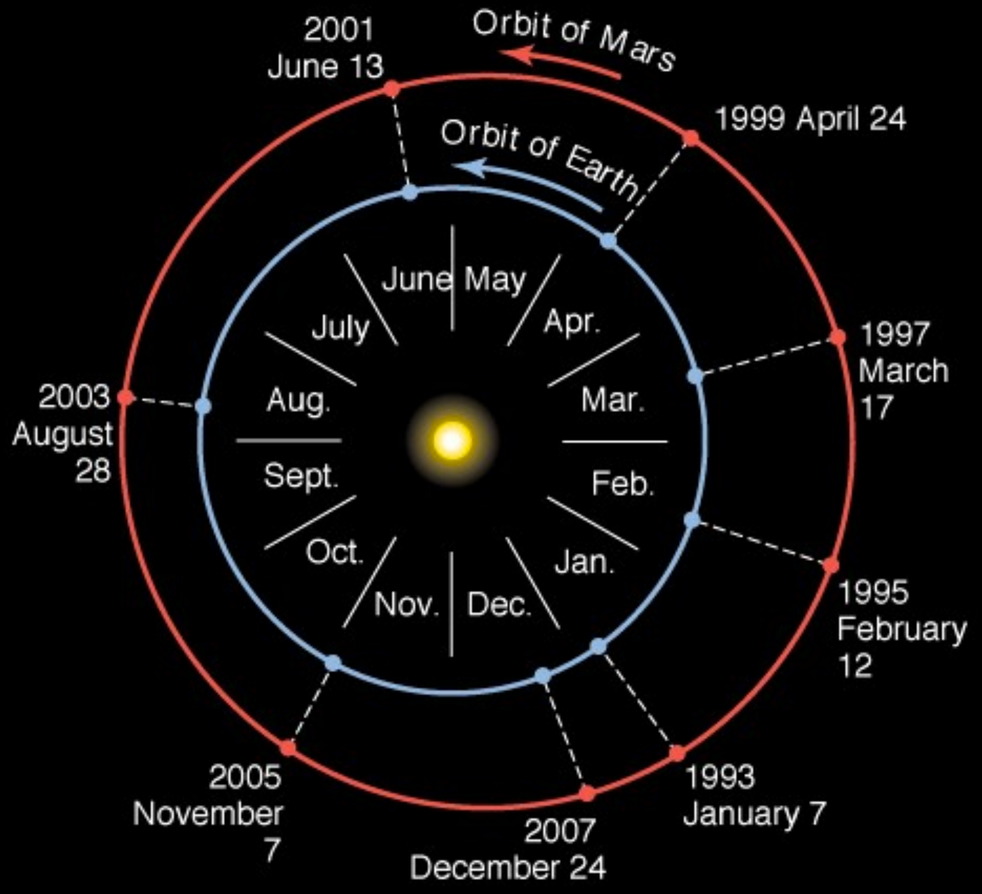
Mars

Mars Orbit & Rotation

Earth's aphelion lines up with Mars's perihelion, resulting in a 0.37 AU distance at opposition every so often.

This allows excellent viewing of the planet.

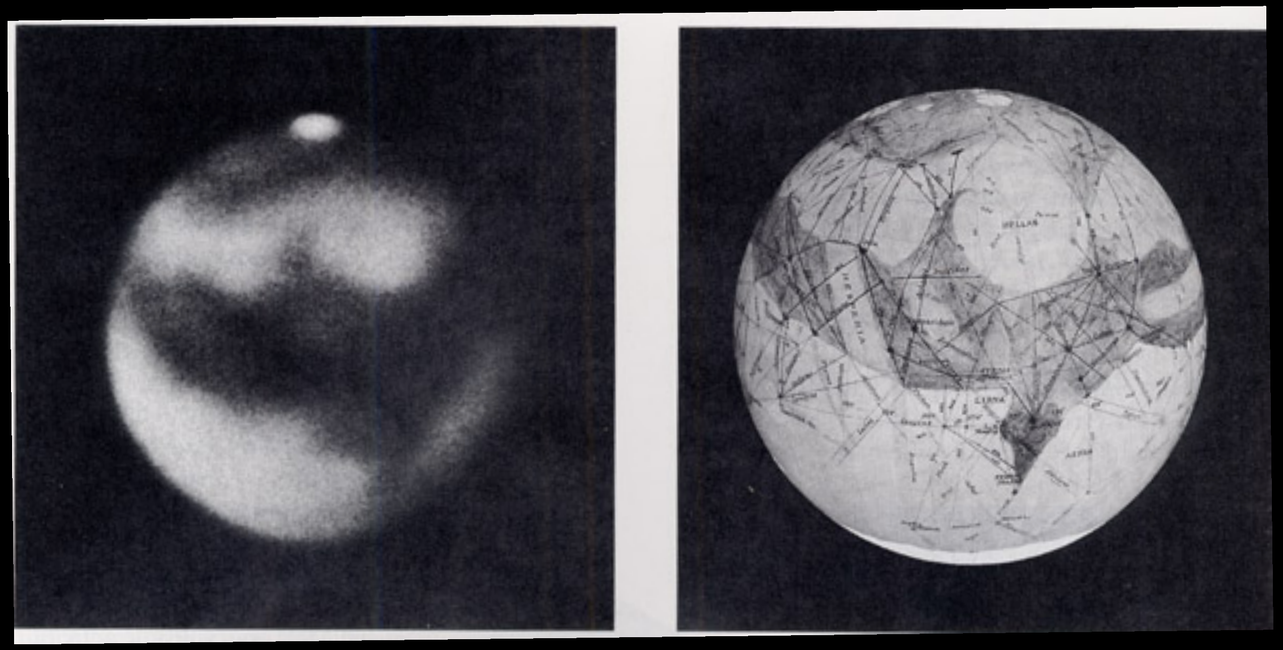
In contrast, Venus is never in opposition: when Venus is closest to Earth, it is silhouetted against the Sun.



Early Observations

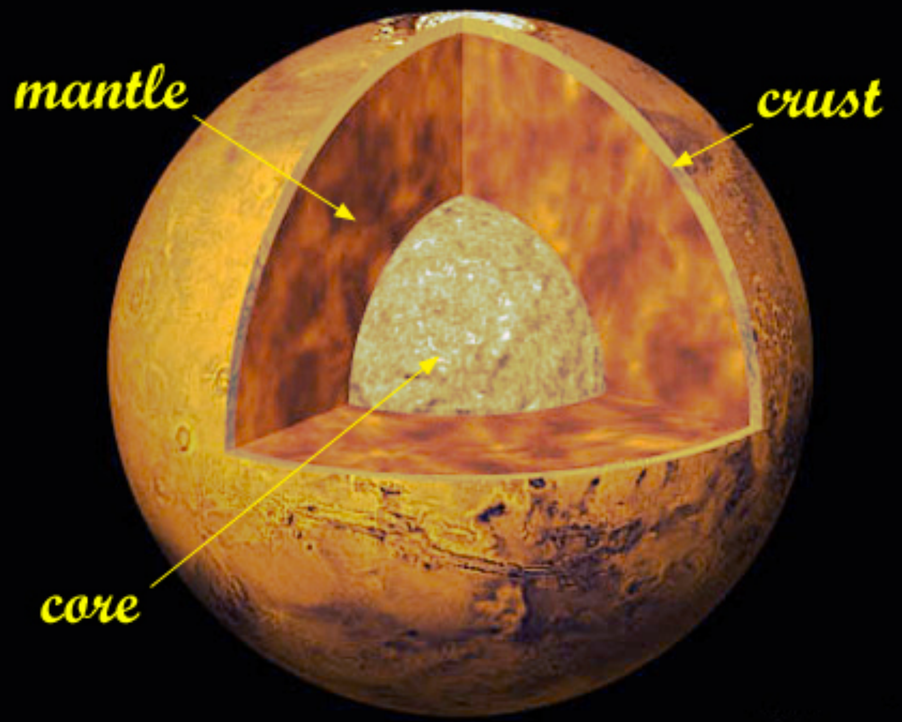
In 1877, new telescope technology combined with a close opposition of Mars resulted in detailed views of the planet.

An Italian astronomer, Schiaparelli, noticed “canali” (channels/grooves) which were mistranslated as canals.



English media ran with the stories of observed canals on Mars, suggesting the presence of water, life, countries, etc...

Mars's Interior



Mars doesn't have a sizeable magnetic field.

This indicates that the planet is mostly solidified now with little convection.

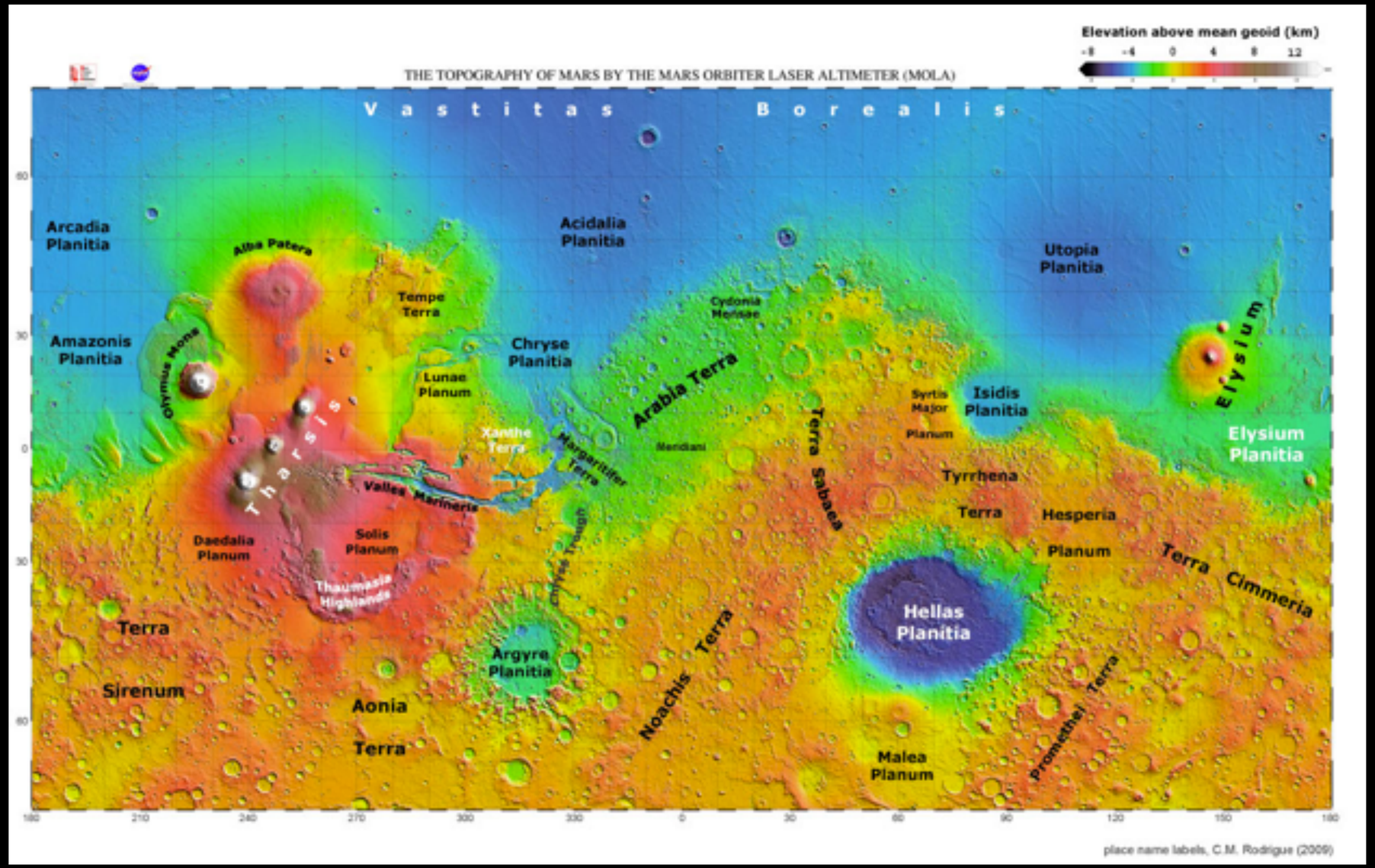
However, there are pockets of magnetism frozen into surface rock indicating that there likely was a liquid layer at one point, along with a magnetic field.

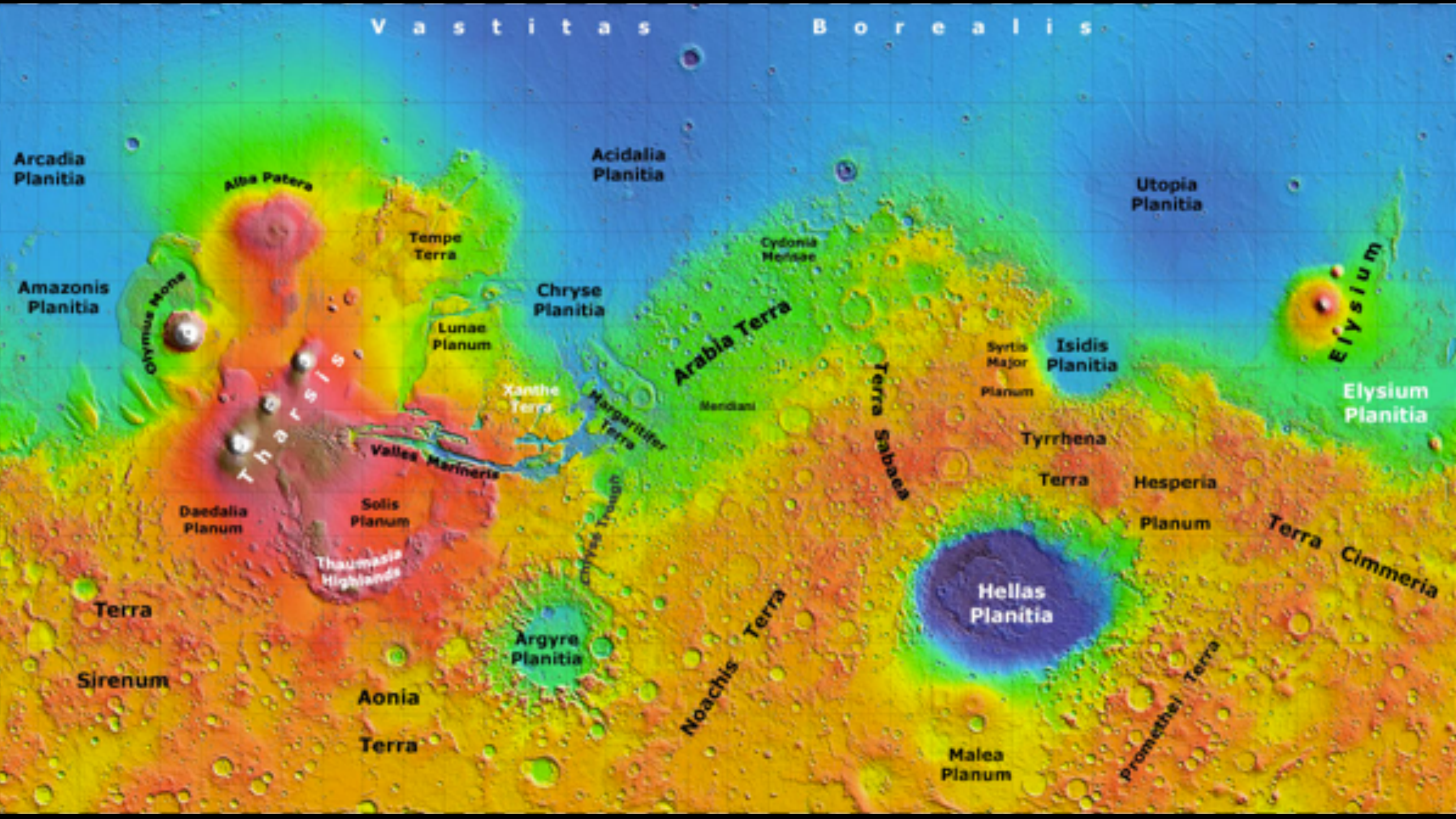
Because Mars is smaller, it likely lost its heat quicker and solidified faster.

Geography

Mars has been mapped in 3D down to the 1m level!

This is approx. the same resolution as Google Earth.



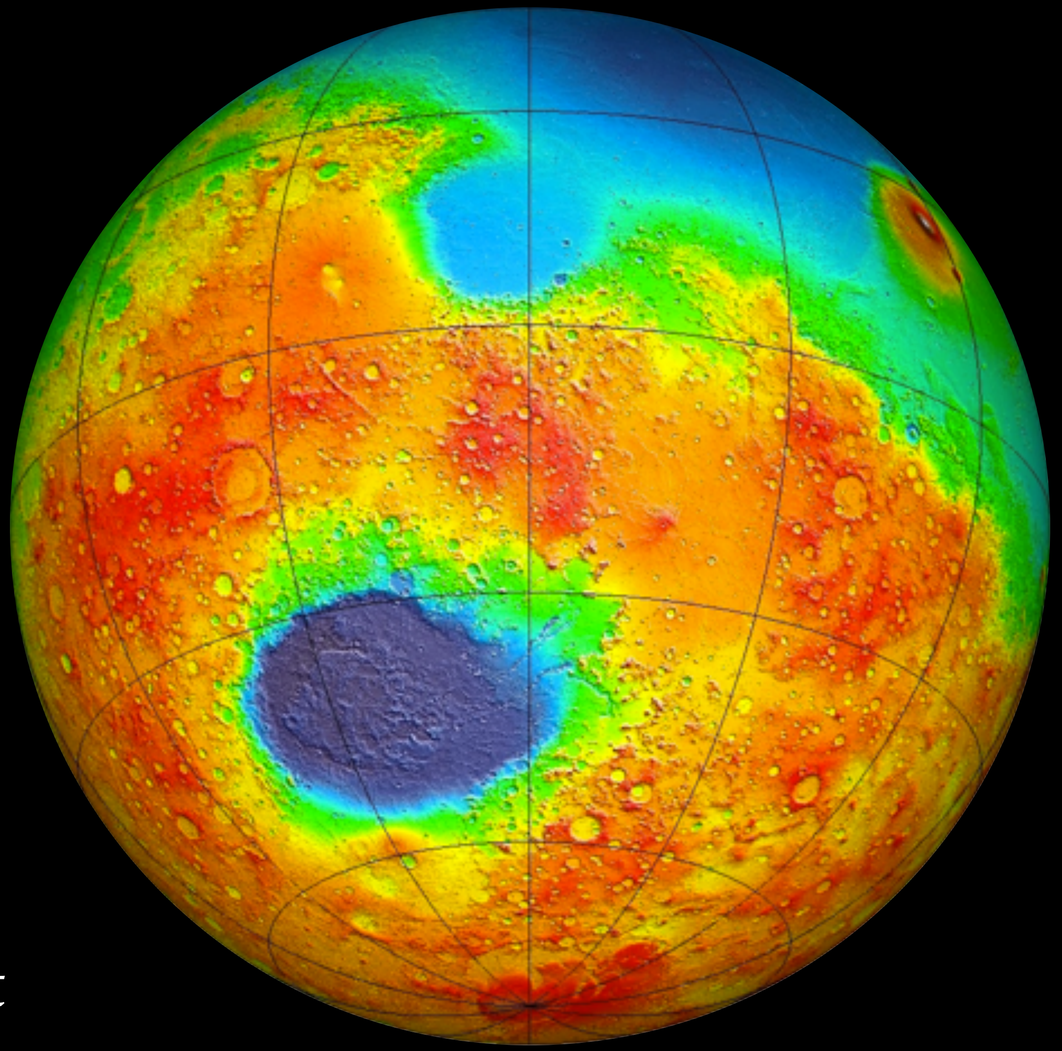

Vastitas Borealis
Arcadia Planitia
Alba Patera
Acidalia Planitia
Utopia Planitia
Tempe Terra
Cydonia Mensae
Amazonis Planitia
Olympus Mons
Chryse Planitia
Lunae Planum
Arabia Terra
Elysium
Syrtis Major Planum
Isidis Planitia
Xanthe Terra
Margaritifer Terra
Meridiani
Terra Sabaea
Elysium Planitia
Valles Marineris
Tyrrhena Terra
Hesperia Planum
Daedalia Planum
Solis Planum
Thaumasia Highlands
Terra Cimmeria
Hellas Planitia
Terra
Argyre Planitia
Noachis Terra
Sirenum
Aonia Terra
Malea Planum
Prometheï Terra

Impact Features

The most obvious impact crater is Hellas Basin in the Southern Hemisphere.

It is 2300 km across and has an elevation of -7 km in some places (below average elevation for the planet).

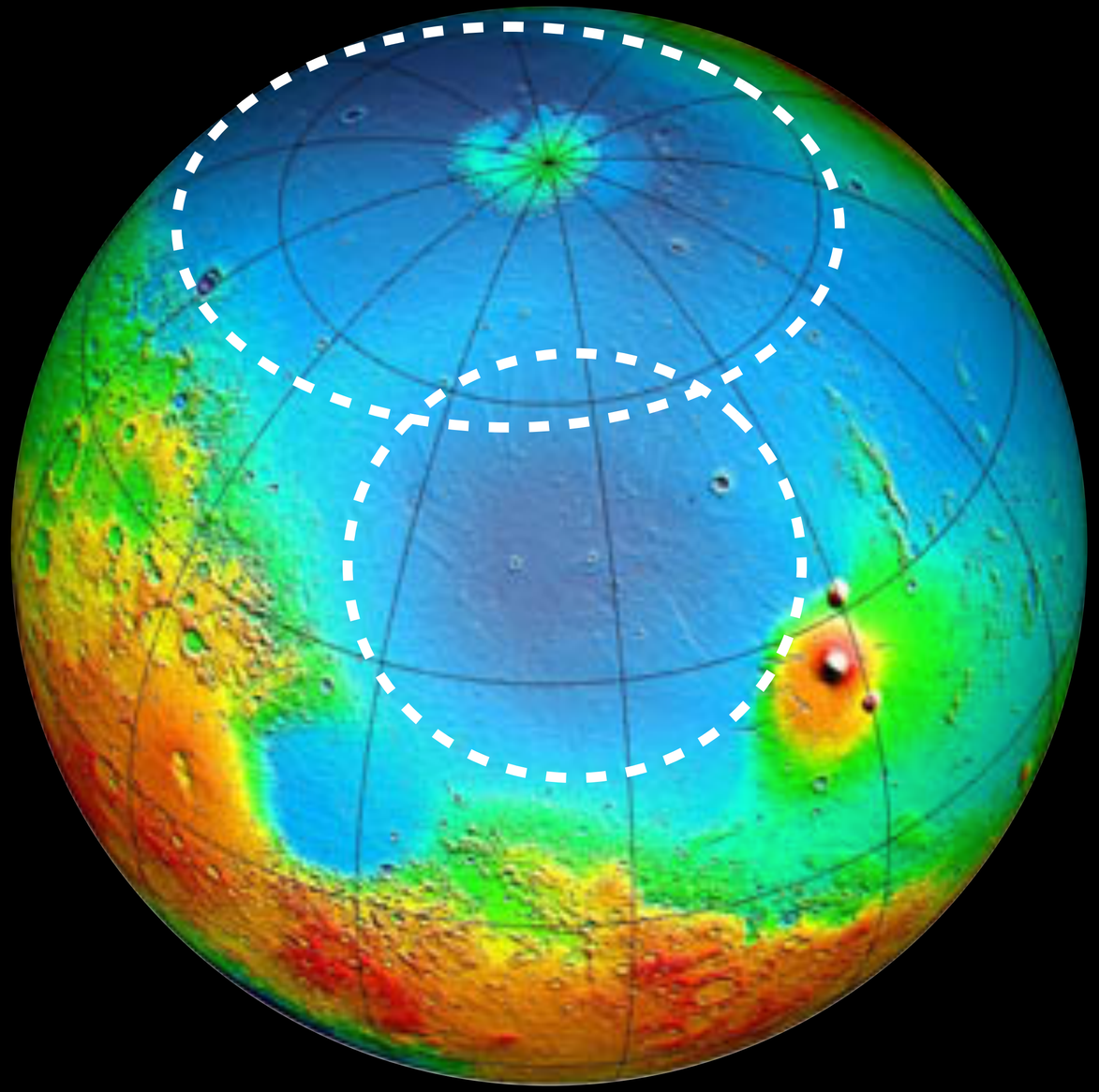
In contrast, the crater from the impact that caused the last mass extinction is 180 km across.



Impact Features

The two largest impact craters in the solar system are in the Northern Hemisphere of Mars.

Borealis Basin (north pole) is not confirmed as an impact feature, but shows many signs of being one. It is 10 000 km across.

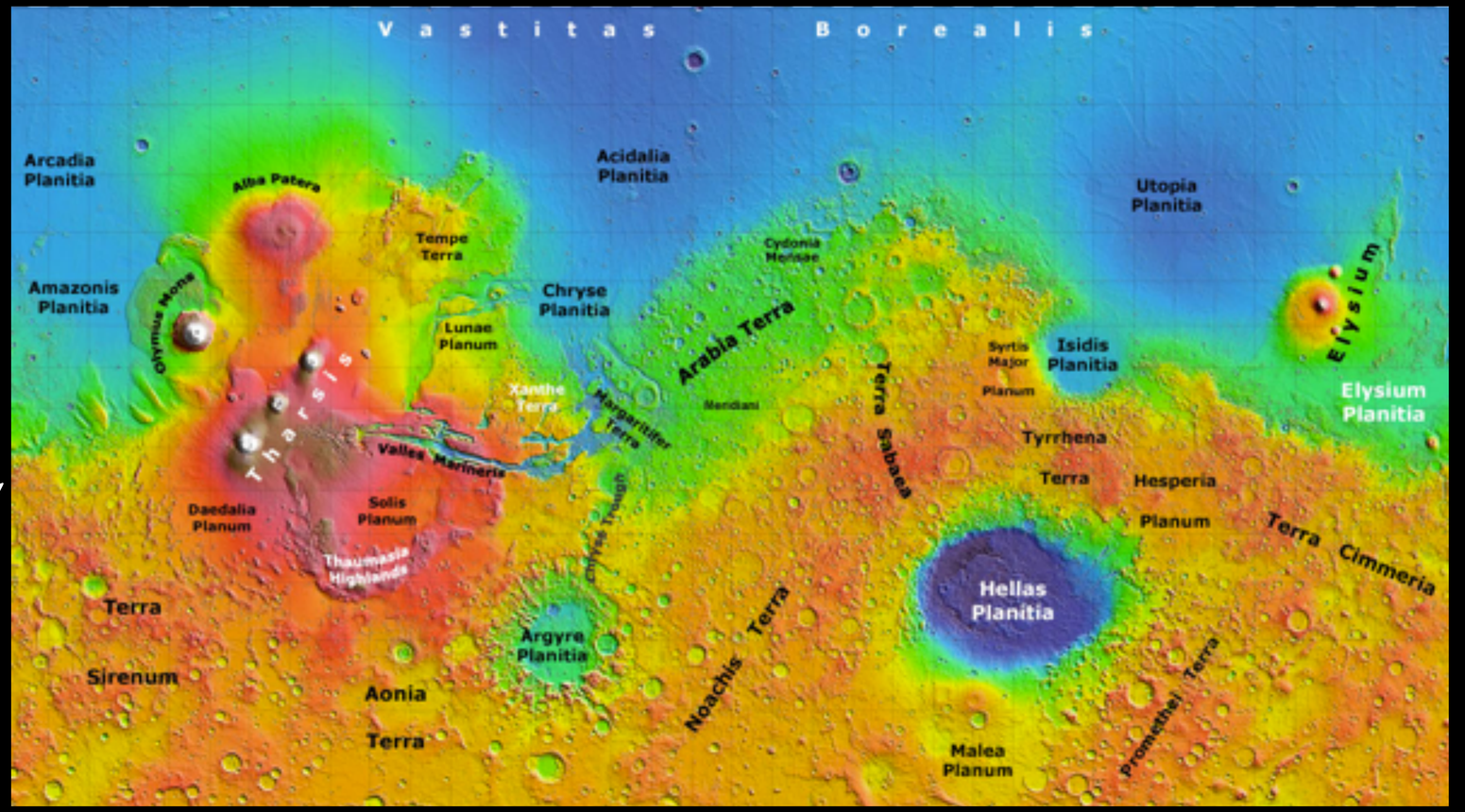


Utopia Planetia is a confirmed impact feature, with a crater size of 3300km

Cratering

Mars has few small craters.

Mars has many large craters,
and does not have
a sufficient atmosphere to
burn up small objects.

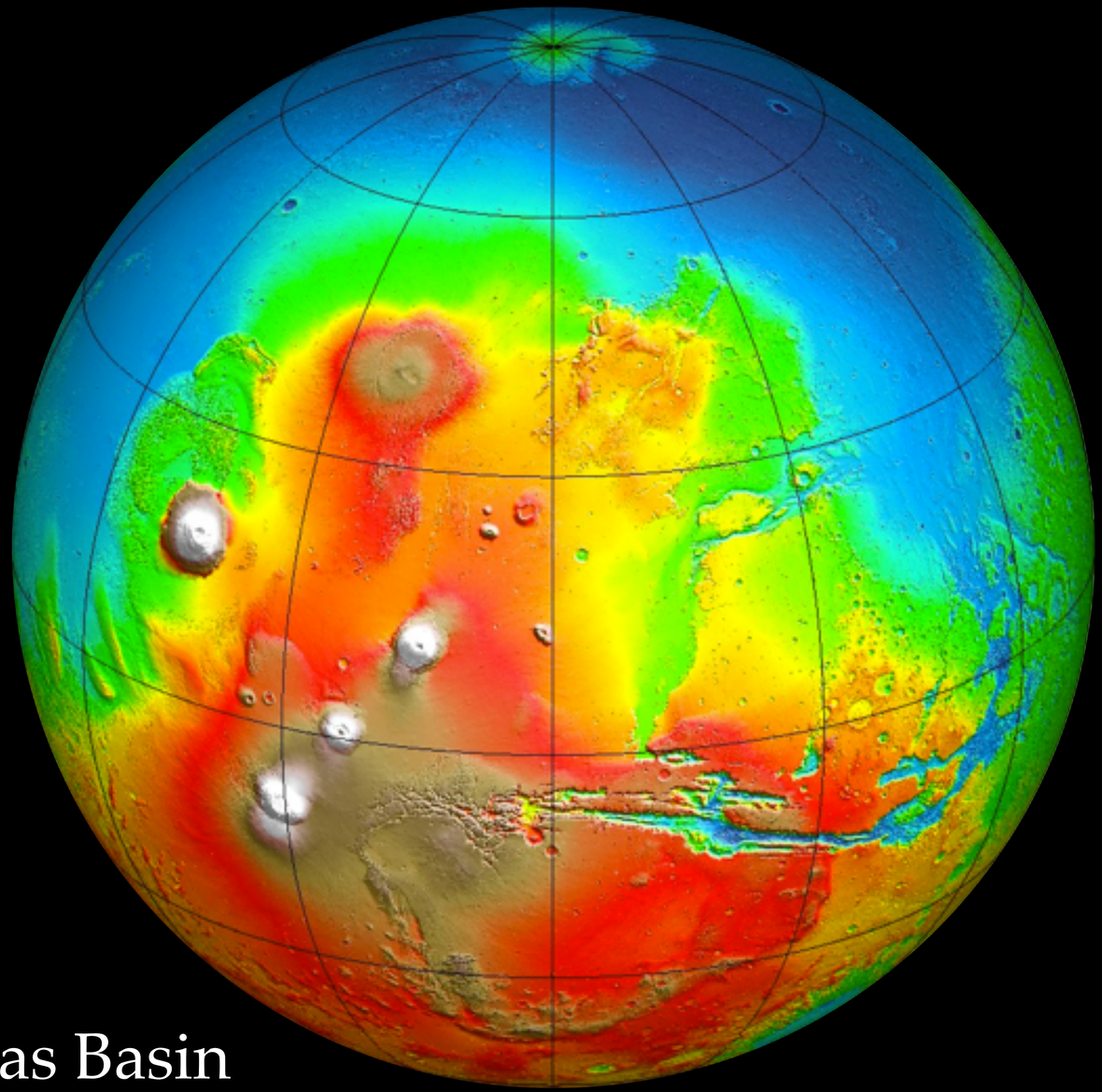


The conclusion is that erosive effects have covered up the small craters.

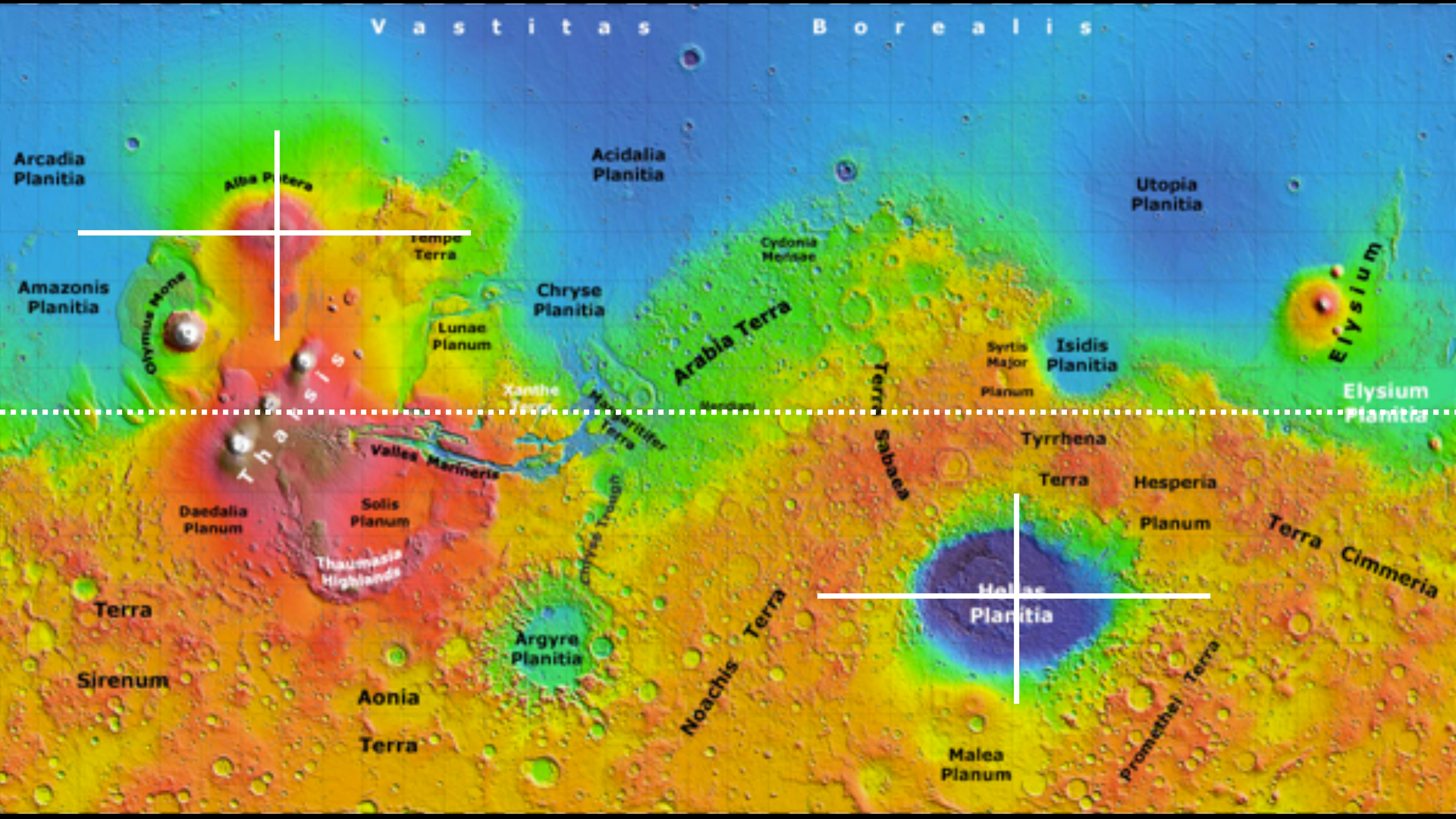
Volcanism on Mars

Largest volcano in the solar system is Olympus Mons: 25km high, 700 km across. (Everest is 8km high)

Nearby are the three volcanoes of the Tharsis Bulge, which are similarly large.



These points lie approx antipodal to Hellas Basin and other large impact craters, suggesting a possible link.


Vastitas Borealis
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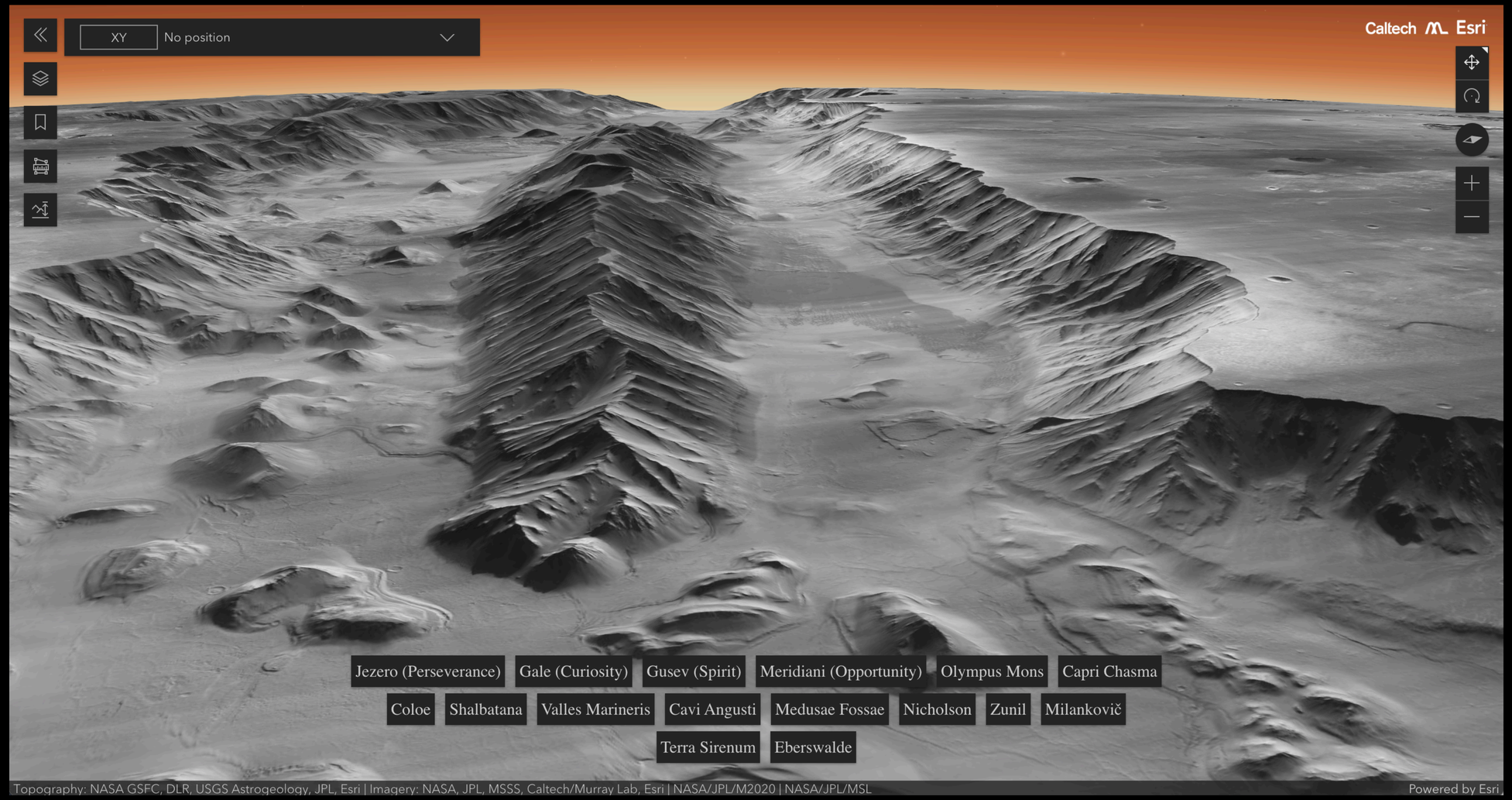
Syrtis Major Planum
Isidis Planitia
Elysium
Elysium Planitia
Xanthe Terra
Tharsis
Valles Marineris
Terra Sabaea
Tyrrhena Terra
Hesperia Planum
Terra Cimmeria
Daedalia Planum
Solis Planum
Thaumasia Highlands
Chryse Trough
Hellas Planitia
Terra Sirenum
Argyre Planitia
Noachis Terra
Aonia Terra
Malea Planum
Prometheus Terra

Mars can be viewed in 3D!



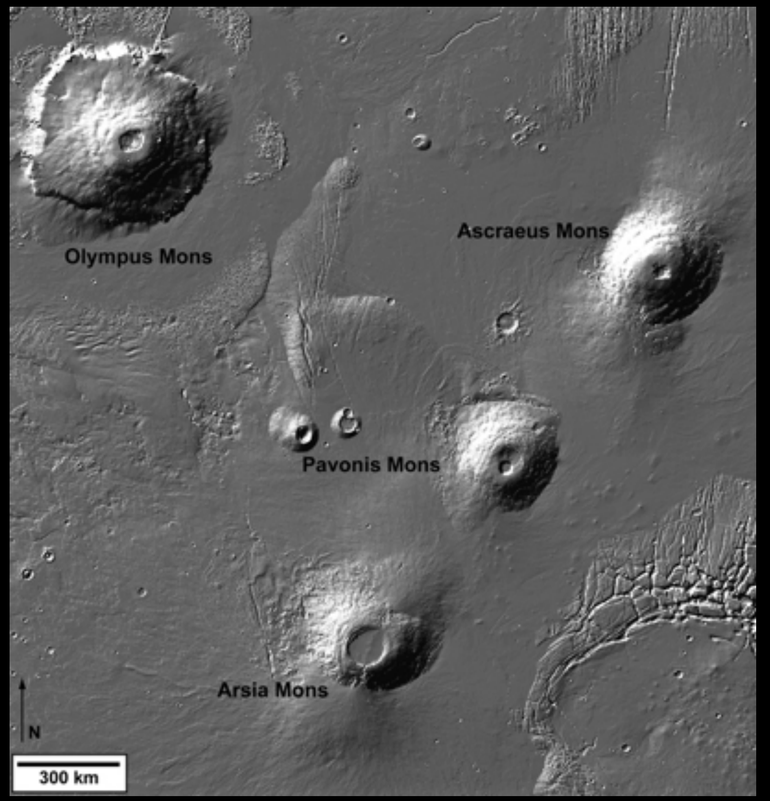
https://murray-lab.caltech.edu/CTX/V01/SceneView/MurrayLabCTXmosaic.html

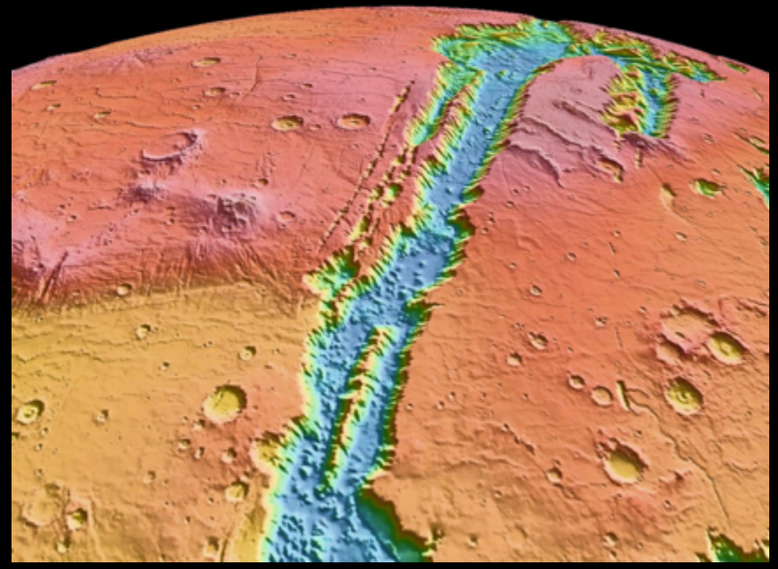
Volcanism on Mars

Volcanoes are particularly large on Mars because of the lower gravity - less gravity to pull lava down, results in larger build up at the top.

All volcanoes are shield volcanoes, and there is no sign of tectonic activity.

The large Valles Marineris canyon (4000 km long, 120 km across, 7 km deep) appears to be caused by something other than tectonic spreading.



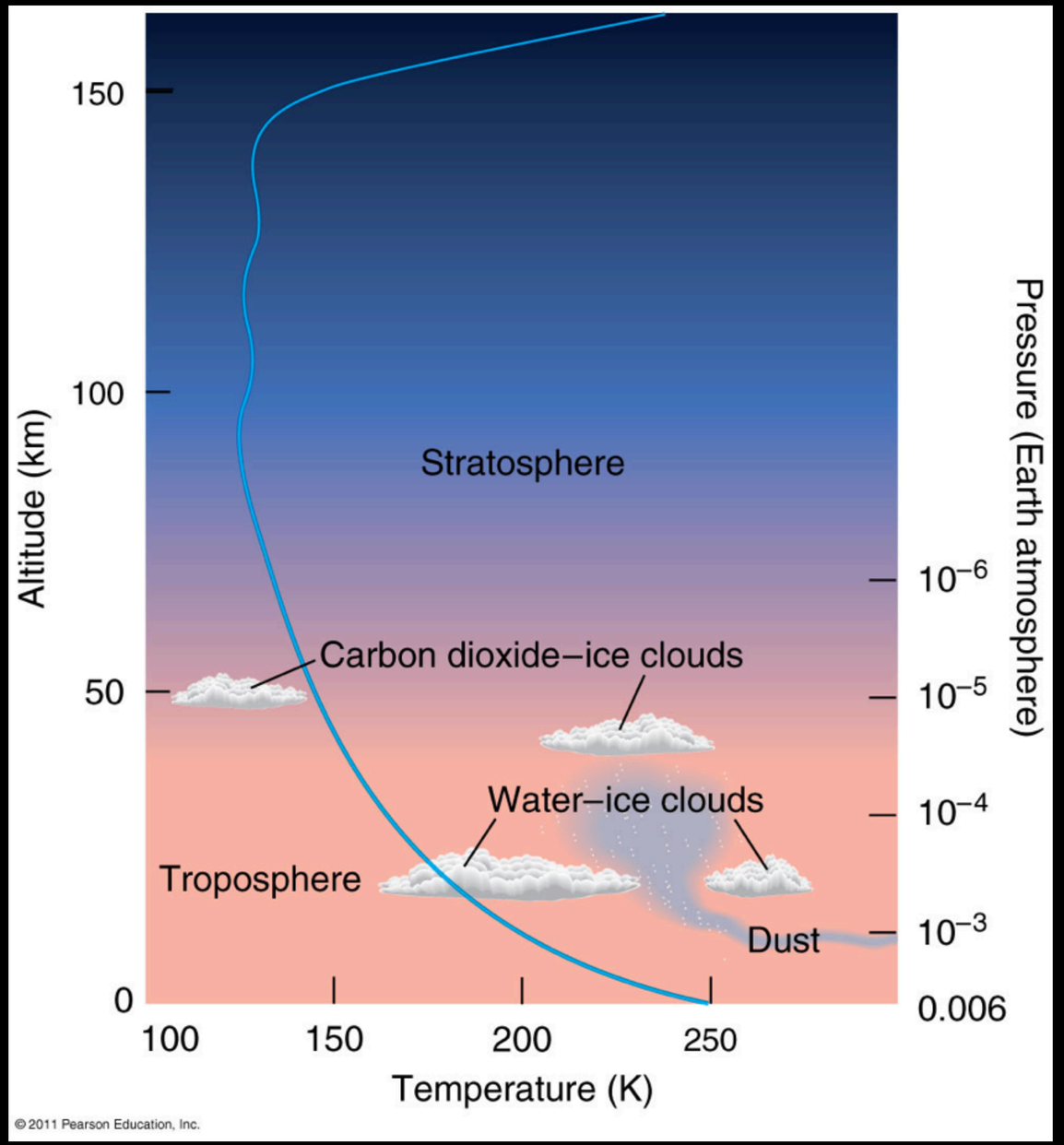


Atmosphere and Climate

95% CO_2, 3% N_2 atmosphere, with
1/150 the atmospheric pressure of Earth.

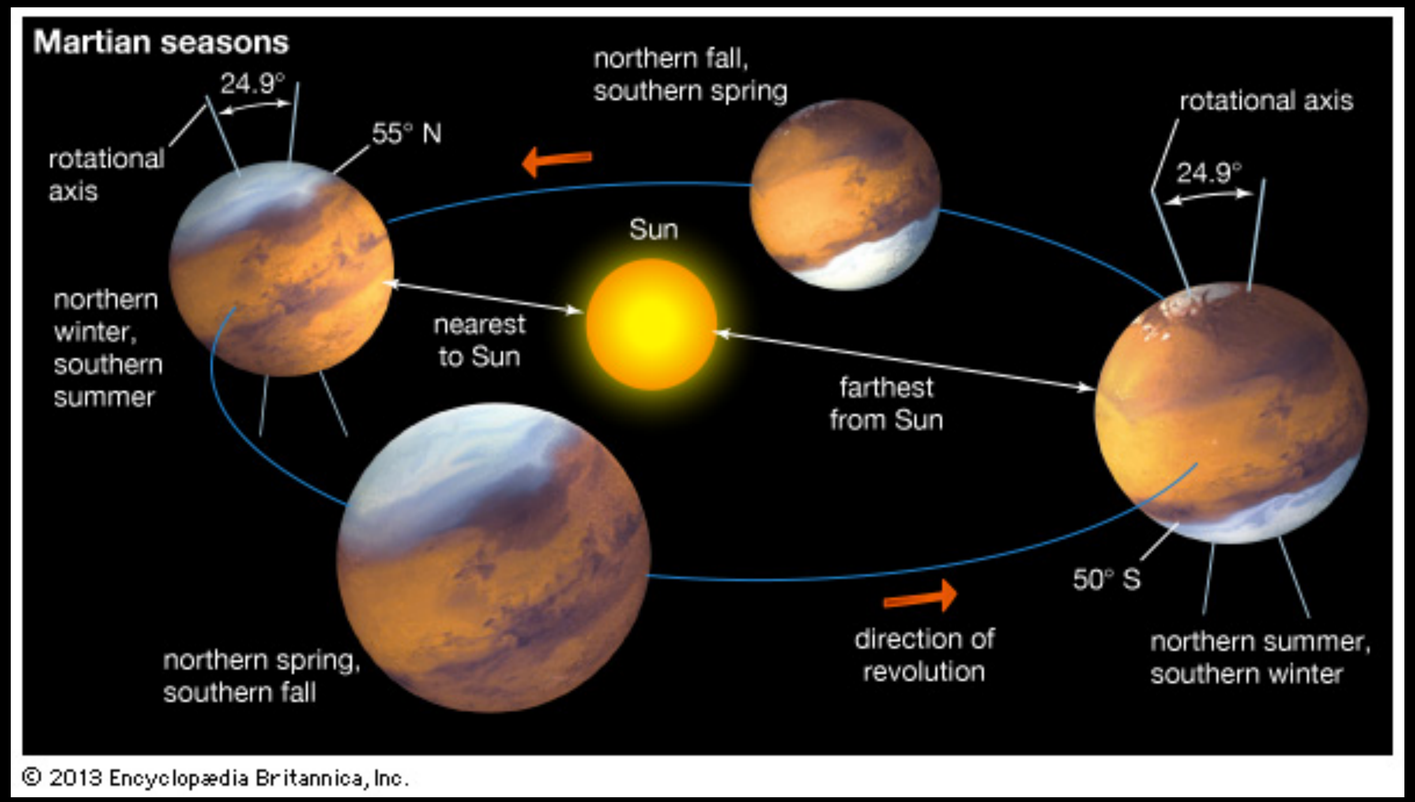
Water-ice clouds exist up to 30 km up,
and CO_2 ice clouds exist at 50 km.

Temperature can reach as high as 30°C
in mid-summer, but is mostly sub-zero.



Atmosphere and Climate

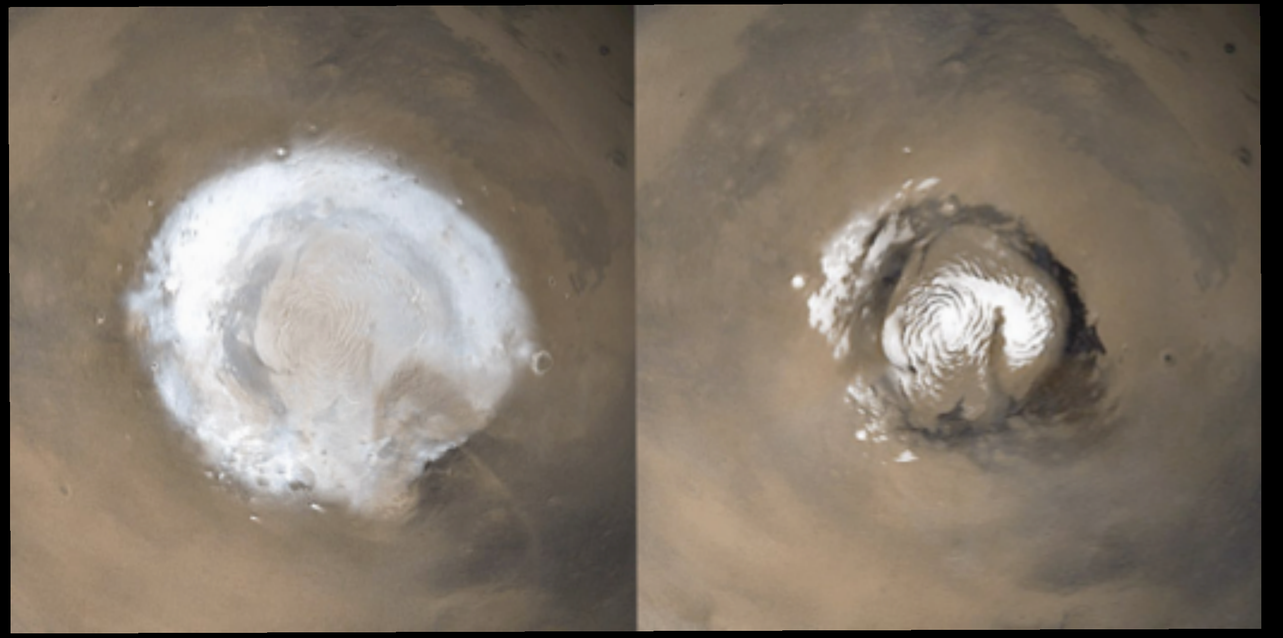
Mars has a similar axial tilt to Earth, and has a moderate eccentricity that results in about 32% difference in sunlight at perihelion and aphelion.



The axial tilt and the major axis line up, resulting in combined weather effects that produces extreme seasonality.

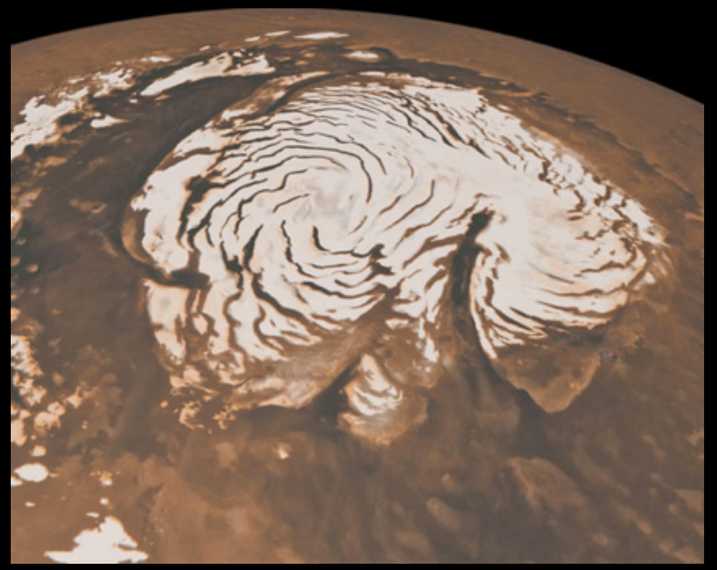
The most visible of the effects is on the polar ice caps.

Ice Caps



The polar caps are primarily solid CO_2 (“dry ice”): The summer temperatures rise above the freezing point for CO_2, and the cap melts down to a Residual Cap made of significant amounts of water-ice.

The winter ice cap is typically 4000 km diameter for the South and 3000 km diameter for the North.



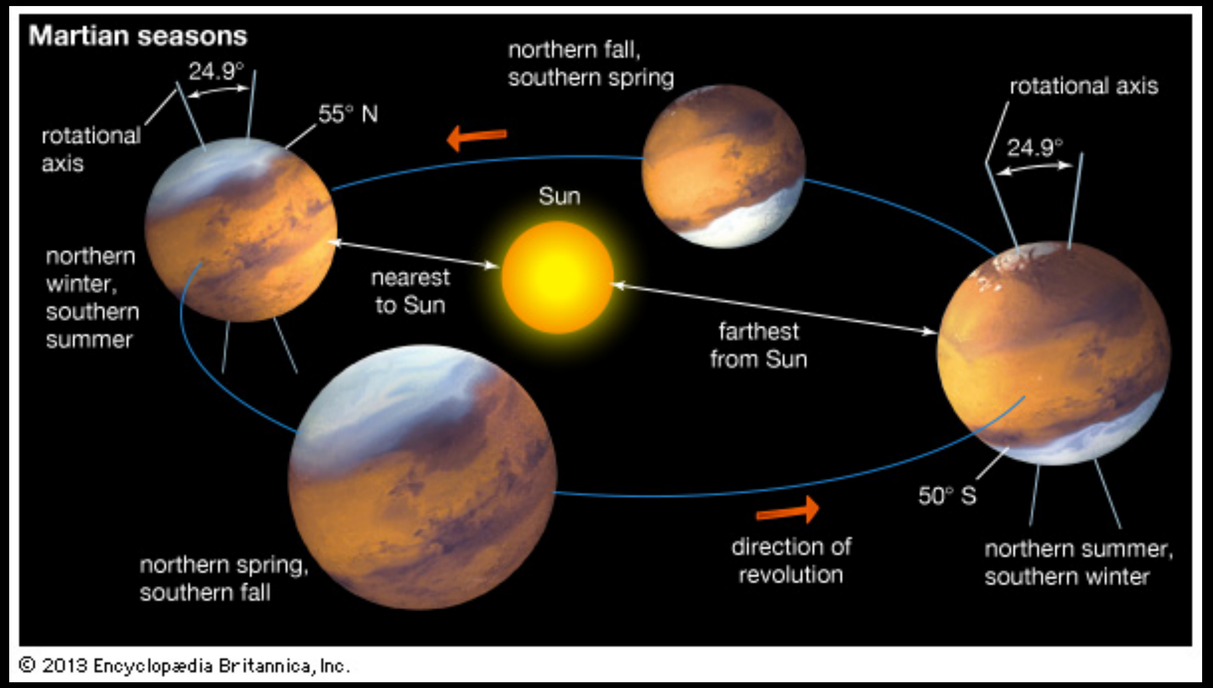
Ice Cap

The ice caps store approximately 30% of the entire atmosphere of the planet.

As the caps melt, they produce winds that result in dust storms that can last for months at a time.

These dust storms result in atmospheric erosion on the rocks, and fill in small craters over time.

Question: Mars's southern residual cap is only 350 km across, while the northern residual is 1000 km across. Which of these best explains the residual cap size difference?



a. Northern axial summer is near Mars's aphelion

b. Northern axial summer is near Mars's perihelion

c. Northern axial winter is near Mars's aphelion

d. Northern axial winter is near Mars's perihelion

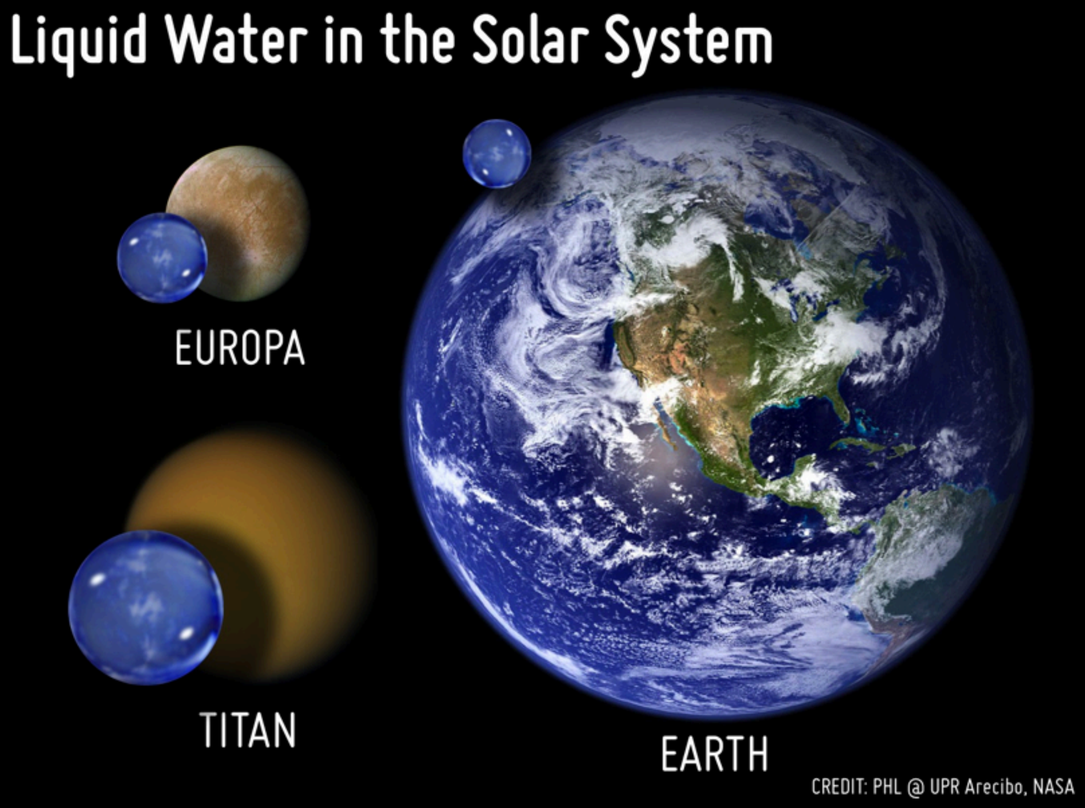
Water on Terrestrial Planets

Presence of Water

Earth obviously has lots of water.

Kuiper Belt objects are made up in large part by water-ice.

The moons of the Jovians contain large quantities of water.

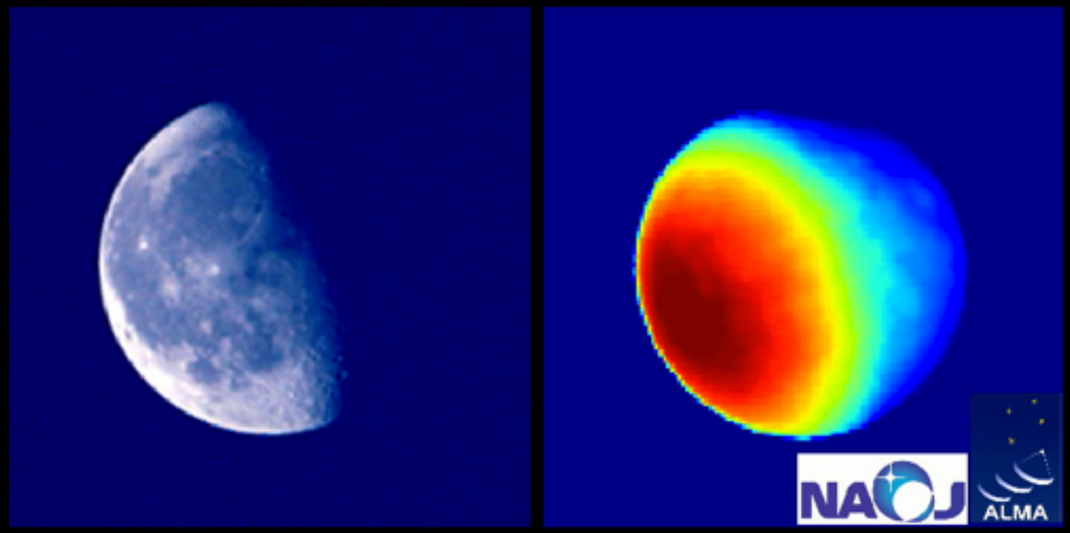


Even asteroids in the asteroid belt show the presence of water.

So where is the water in the inner solar system, other than on Earth?

Lunar Water

Recall that the Moon has a very similar chemical composition to the surface of the Earth, and was formed in proximity to Earth.



Should whatever resulted in water on Earth also have resulted in water on the Moon?

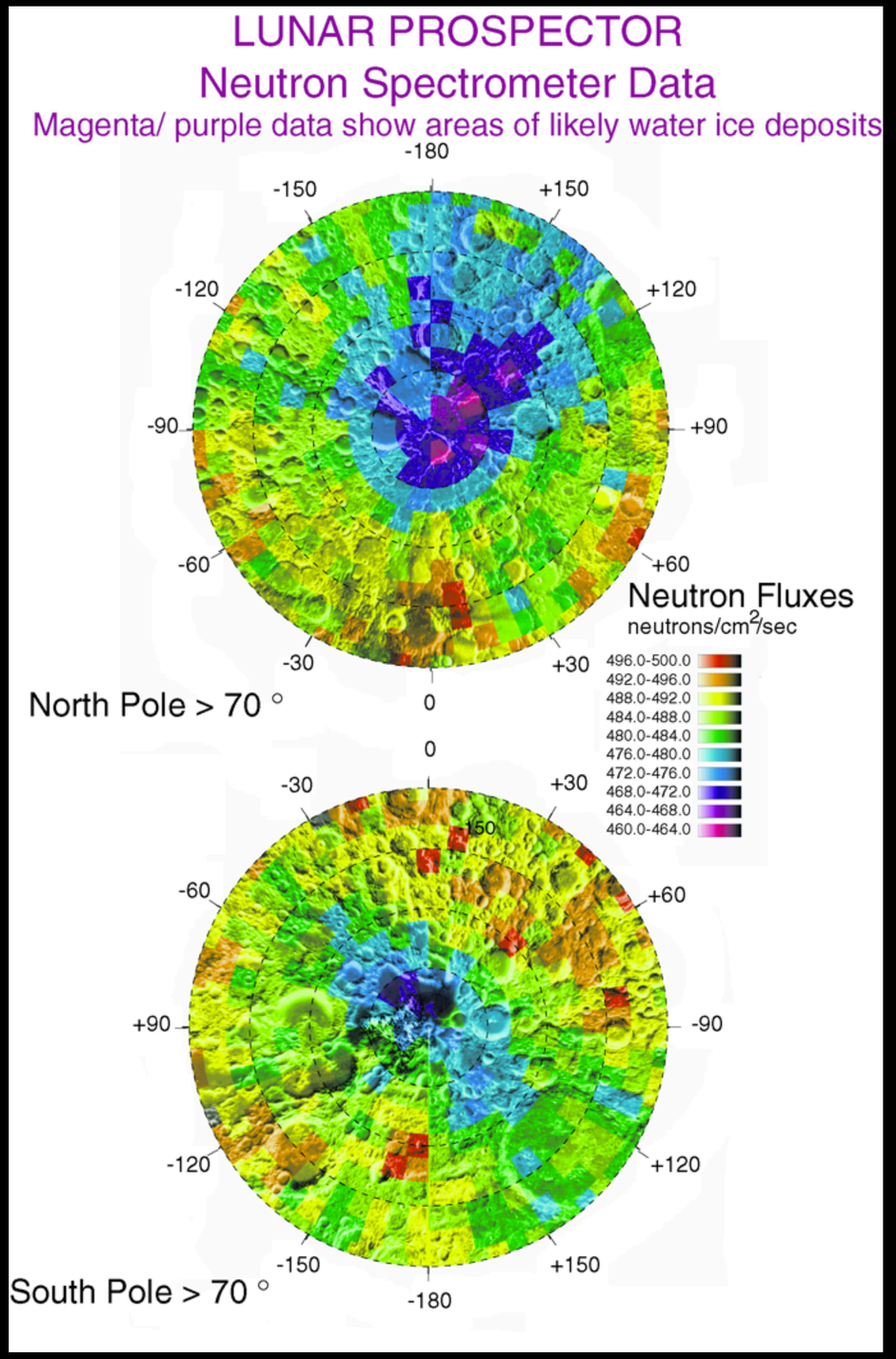
Daytime temperatures reach >100^{o}C,
which is believed to have baked all water out of the surface rock

Lunar Water

Lunar Prospector scanned the poles in 1996 and found indications of reduced density, indicative of the presence of water-ice.

Believed to be sub-surface deposits.

Lunar Prospector then crashed into the surface to try to release some as gas.



NASA's Revenge

After the failure of Prospector, NASA sent LCROSS with a similar mission.

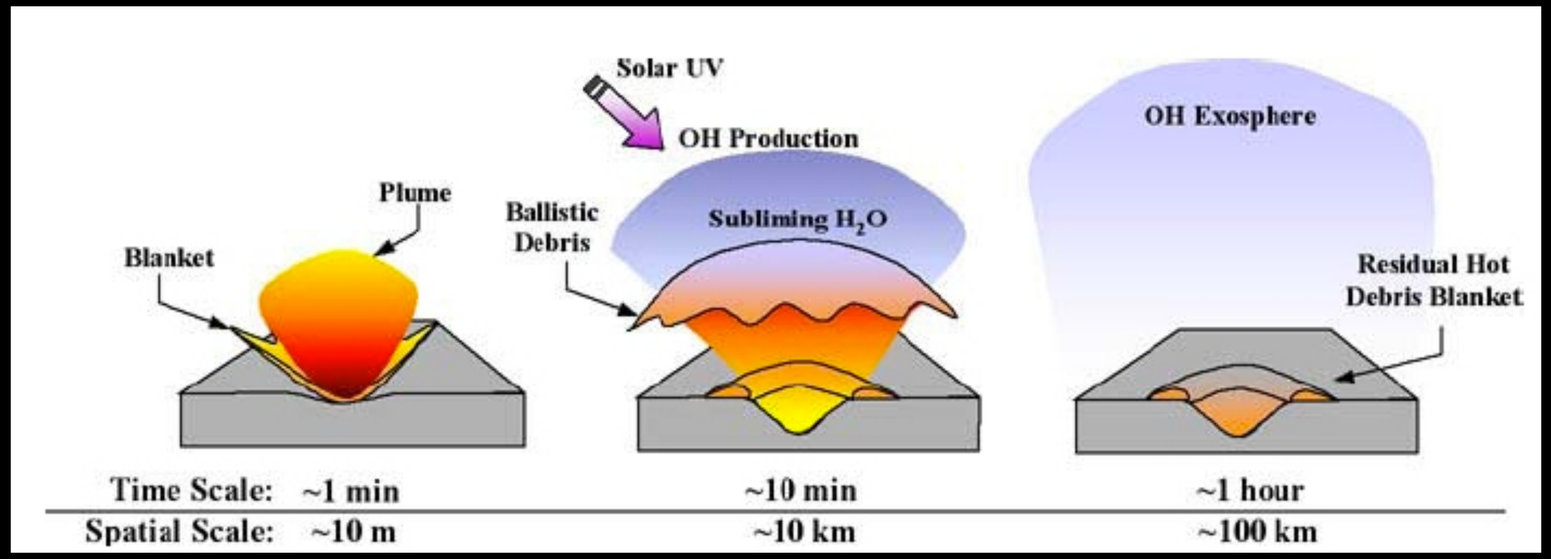
The rocket used to get to the Moon was then launched into the Cabeus crater with the LCROSS observer following behind.

From 1000 km away, spectroscopic readings of the cloud confirmed the presence of water.

Then LCROSS crashed, too.

Water on the Moon

Solar UV light sublimated the water released, which remained around the Moon while the dust/rock settled down.



LCROSS showed 1/100 000 concentration of water, which is important since it costs up to $20000 to transport 1 kg of water to moon.

Water on Venus

The temperature of Venus is too hot for liquid water, but the atmosphere shows 0.0002% water composition (Earth has 0.4%).

In addition, spectroscopic studies of the solar wind's effect on Venus shows a trail of hydrogen and oxygen ions leaving the planet.

With no ozone layer, the UV light from the Sun splits the water molecules, which are then too light to remain on the planet.

This process is also happening on Earth, but much, much slower.

Water on Mars

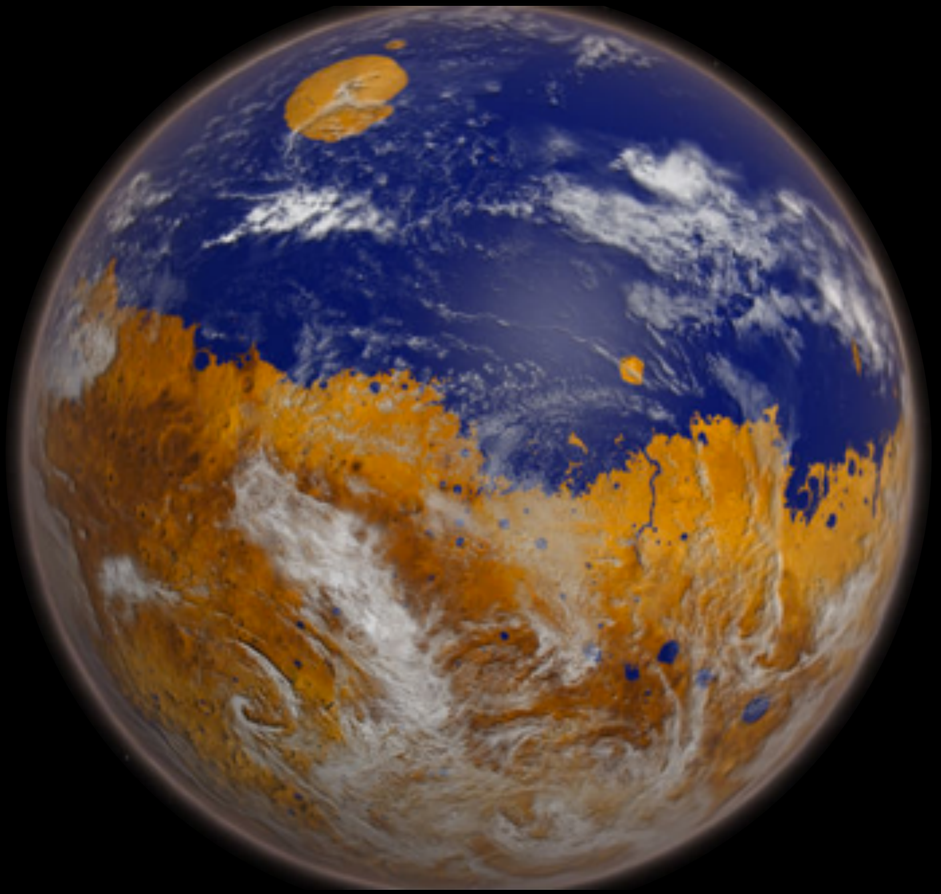
Mars is a good candidate for the presence of water, due to its proximity to the asteroid belt, and its further distance from the Sun (lower temperature).

So why doesn't Mars look more like Earth?

Was there ever a liquid water cycle, like Earth?

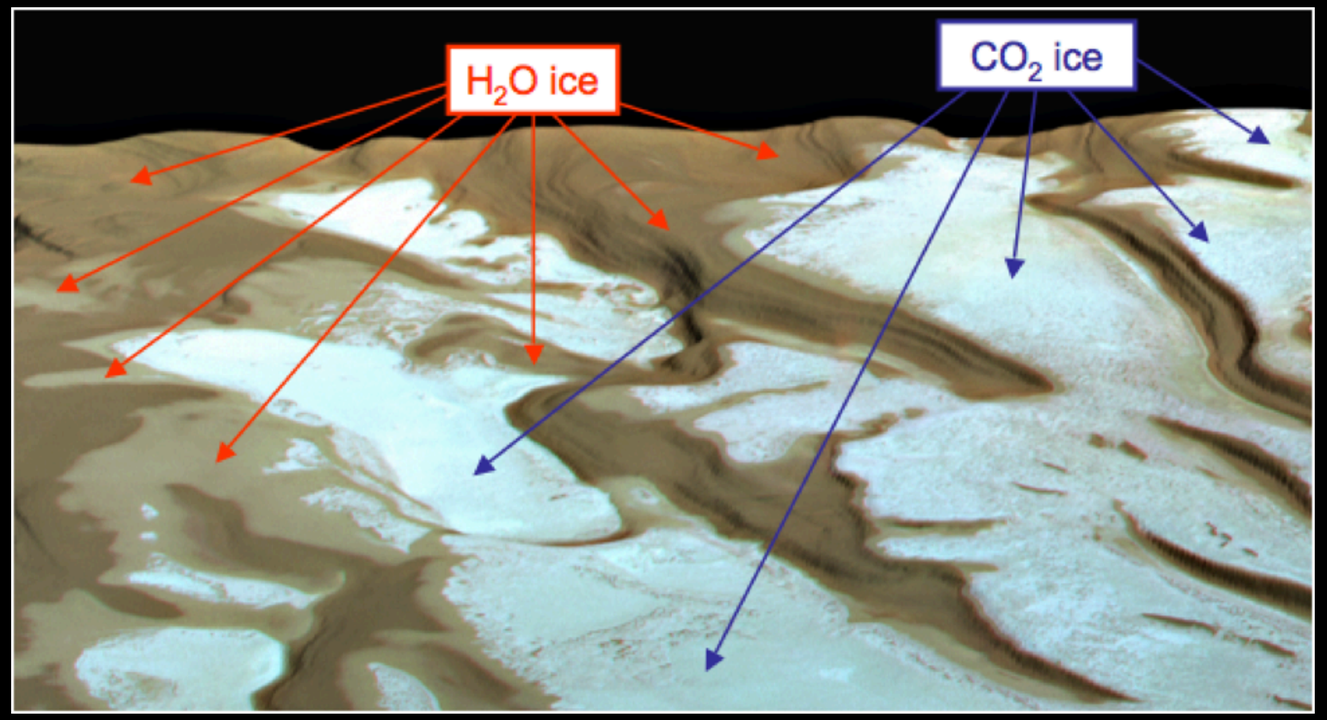
If there was more water, where is it now?

No LIQUID water has been found on Mars yet, but water-ice has been confirmed.

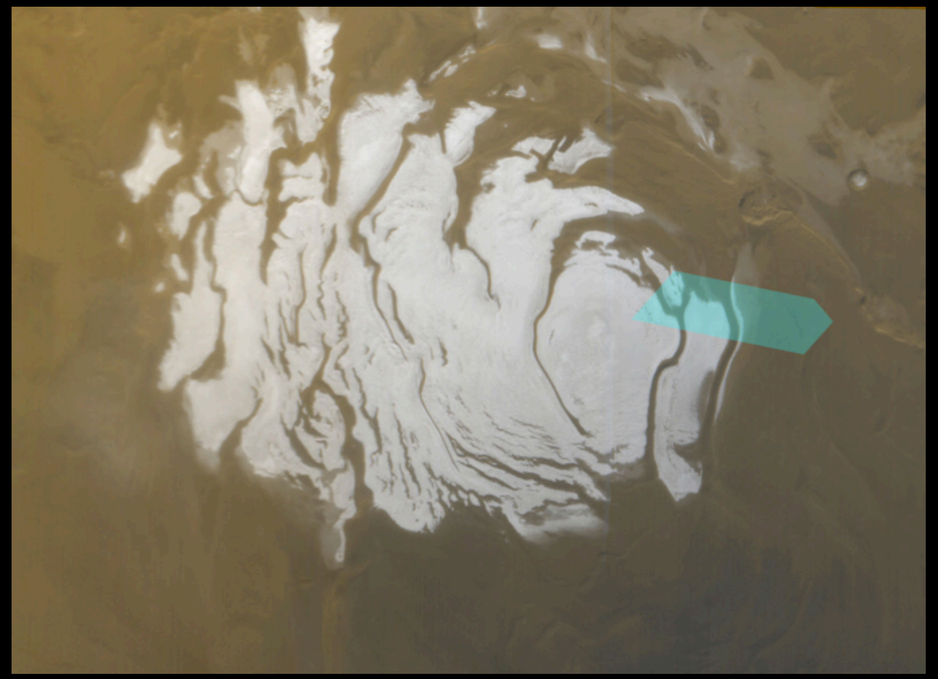


Water on Mars

The Northern residual polar cap is comprised of a thick layer of water-ice. The Southern pole was originally shown to be CO_2.



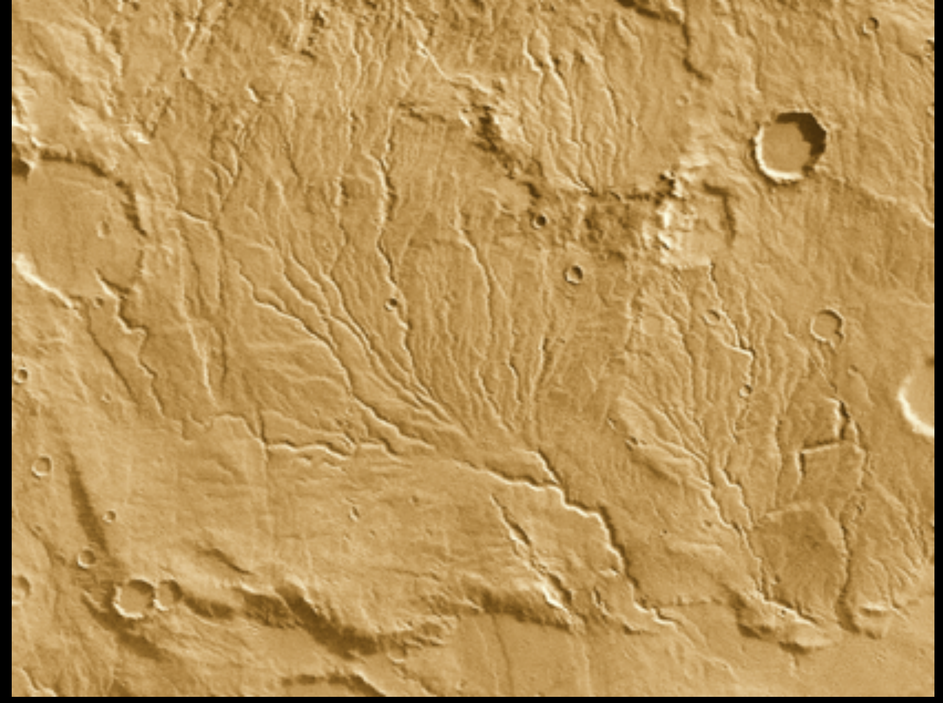
Mars Express and Oddyssey each scanned the South polar cap and found evidence of large water-ice deposits beneath a layer of residual solid CO_2.



Liquid Water on Mars

Multiple places on Mars show the presence of runoff channels, which strongly resemble the collecting stream patterns of water systems on Earth.

A water cycle is not necessary to explain runoff channels, which could be produced by periodic ice melting - if water ice existed/exists in the region.



Mars

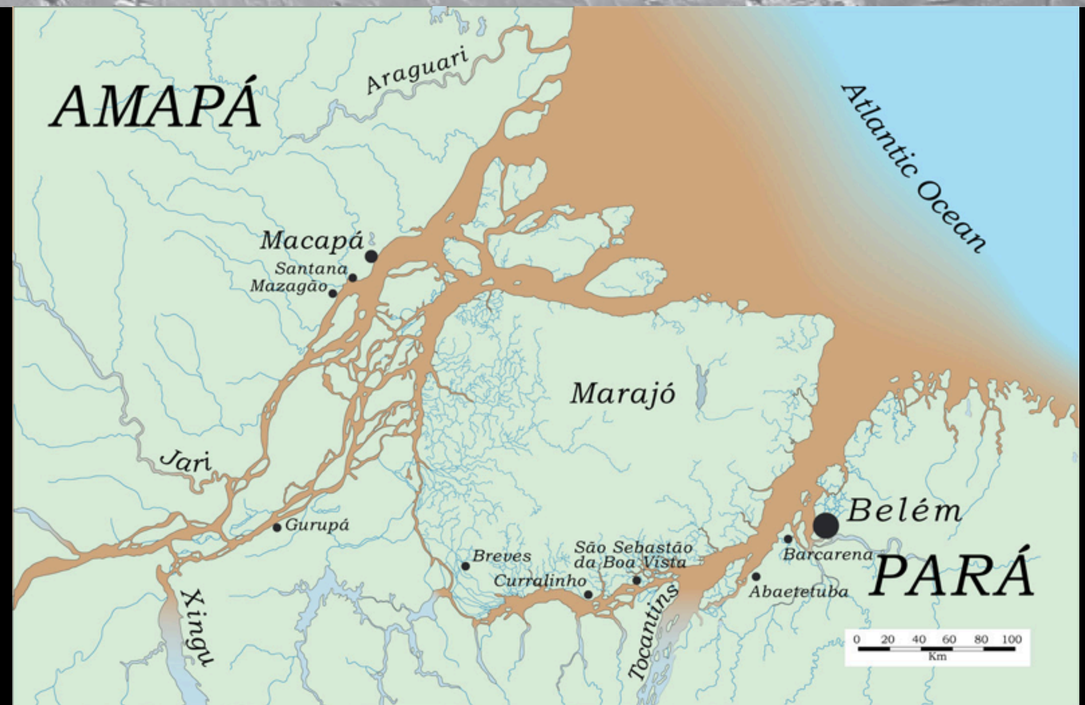
Northern Alberta

Liquid Water on Mars

Outflow channels also exist, which are indicative of much larger flows of water.

Compare this image of Mars to the mouth of the Amazon river.

Crater densities place the age of this runoff channel to be 3B years, and it carried 100x as much water as Amazon.

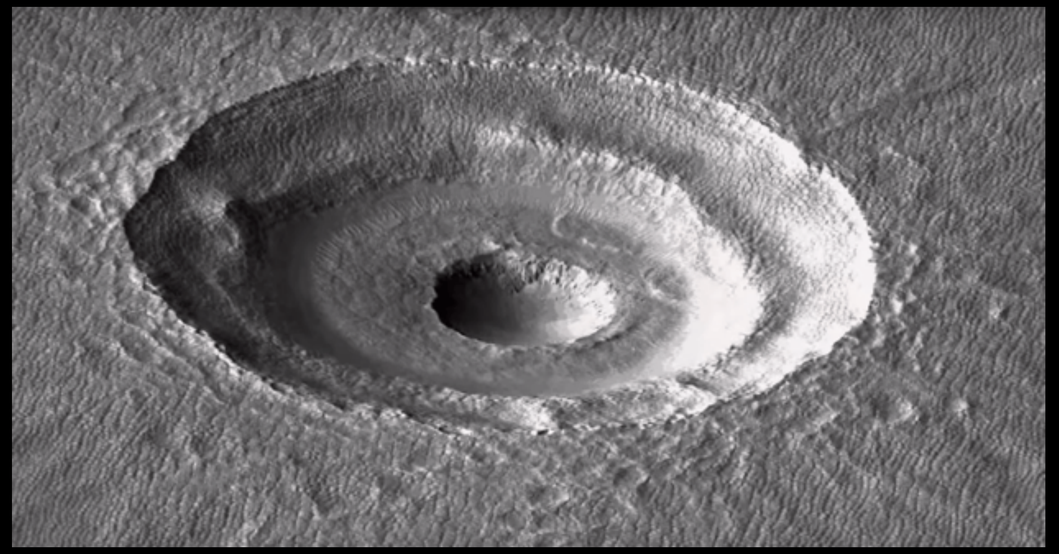


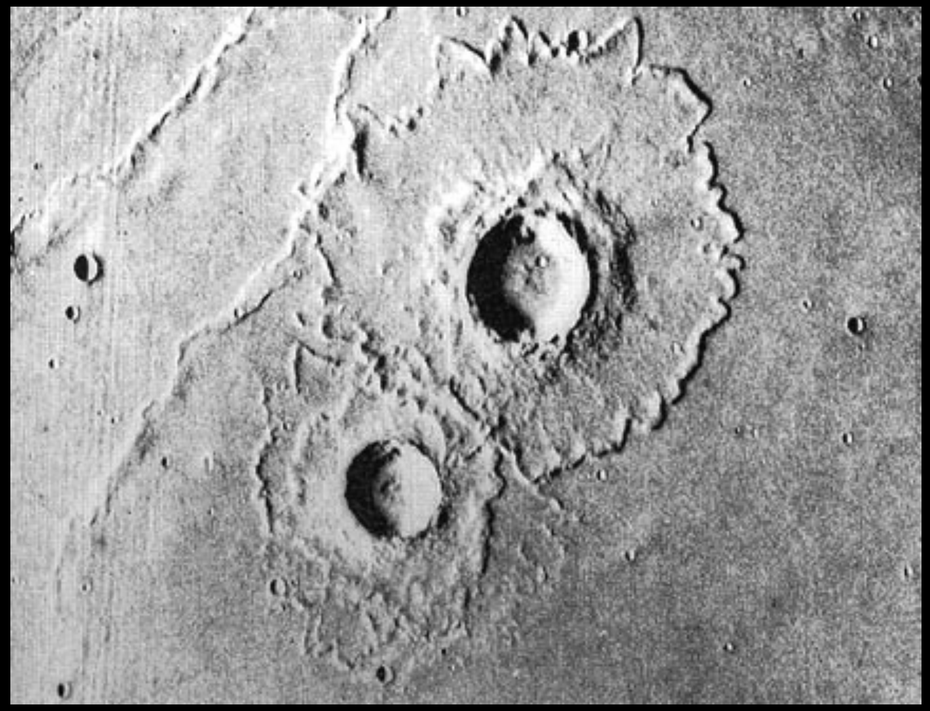
Other Evidence of Liquid Water

Terracing in craters suggests some type of liquid filled the crater at some point, and caused the collapse of the walls.

Impact craters show outrushing of water that caused sediment to flow.

These suggest the presence of large quantities of water below the surface of Mars.



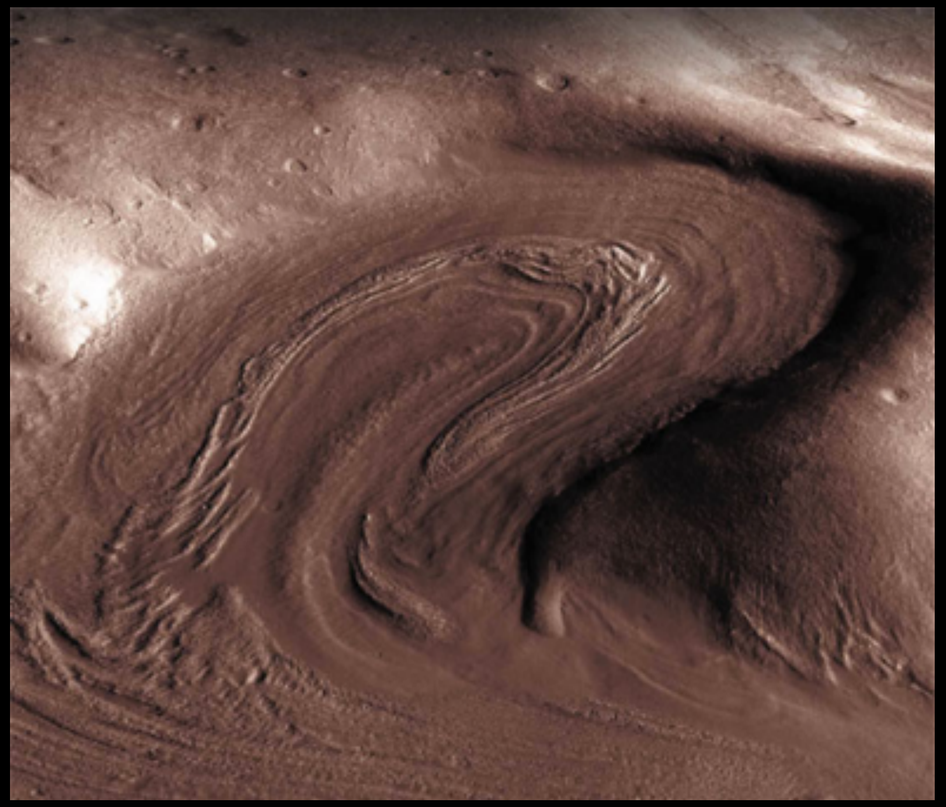


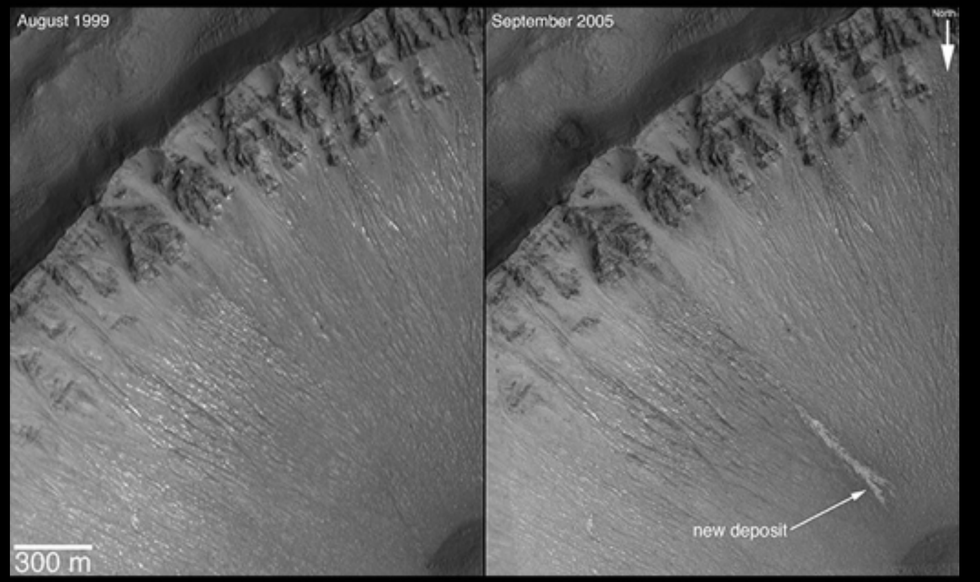
Other Evidence of Liquid Water

Mars Reconnaissance found structures that are similar to glacial melts on Earth, where large bodies of ice rapidly melt.

Cratering in the region suggests that they could be as young as 100M years.

Images of the surface show the possibility of flowing water that froze to the sides of crater walls. (Could be CO_2)





Evidence Against Liquid Water

There is no direct evidence for current surface liquid water, and water vapour forms a small portion of atmosphere.

On Earth, everywhere there is water, there are deposits of carbonates.

Rock samples analyzed by landers show insufficient carbonate deposits to suggest long term surface water, considering the CO_2 atmosphere.

Climate Evolution - The Greenhouse Effect

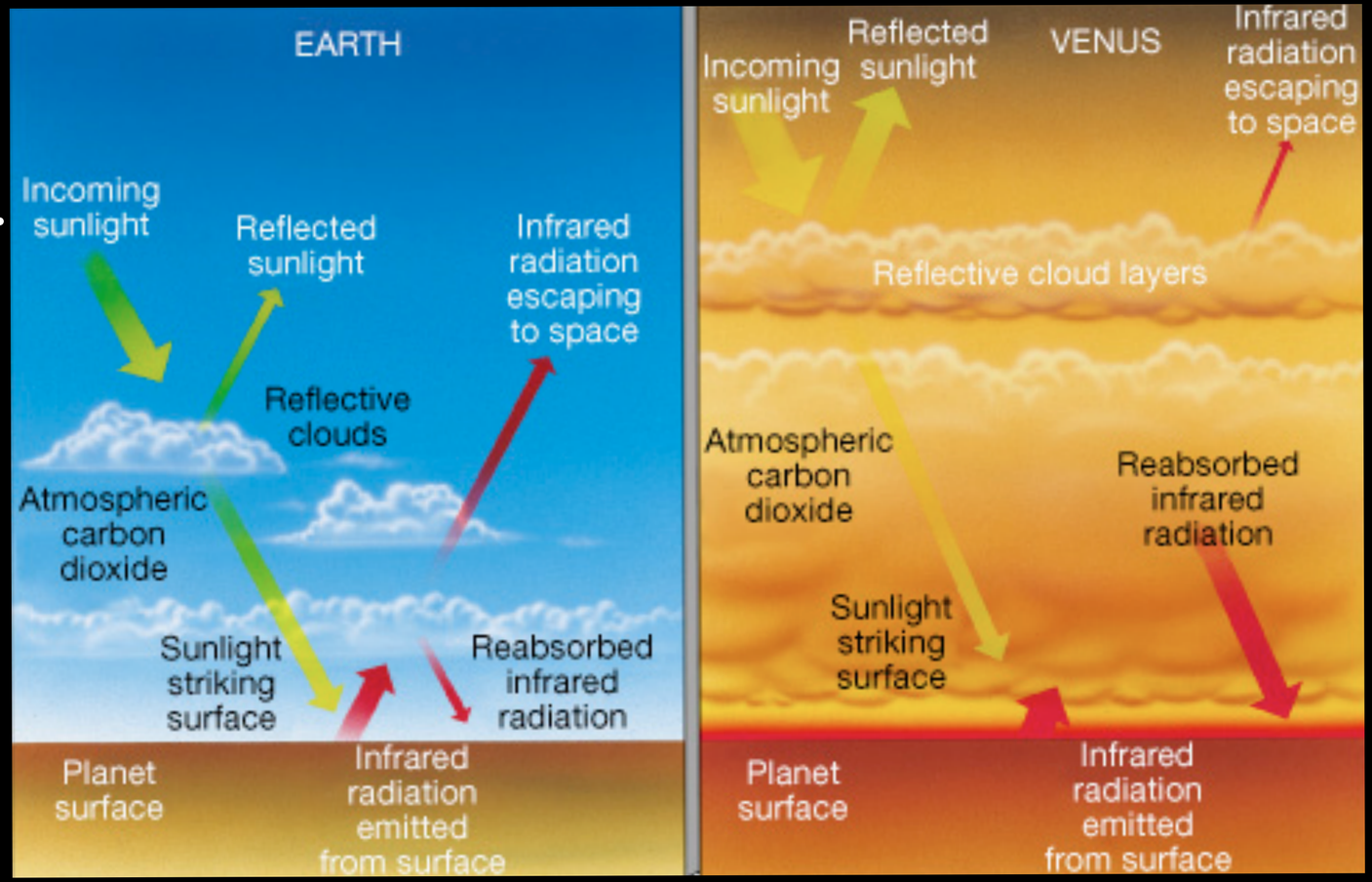
The Greenhouse Effect

Venus is evidence of a planetary-scale greenhouse effect.

Venus has a slow rotation and reflects 70% of the solar radiation.

Yet the dark side of the planet is approximately the same temperature as the day side.

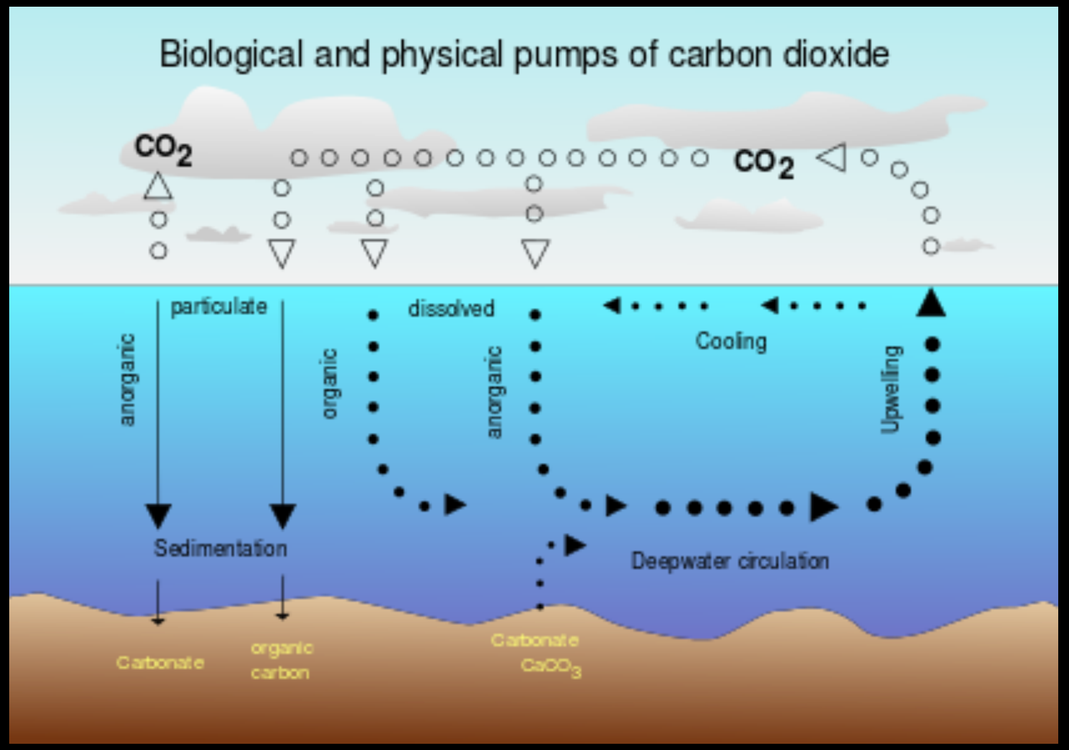
Greenhouse effect stores heat in the atmosphere and transfers it.



Venus Climate Evolution

Venus and Earth likely started out similarly: same composition, same initial outgassing.

Venus is 30% closer to the Sun, so received twice as much solar radiation, preventing the water from condensing.



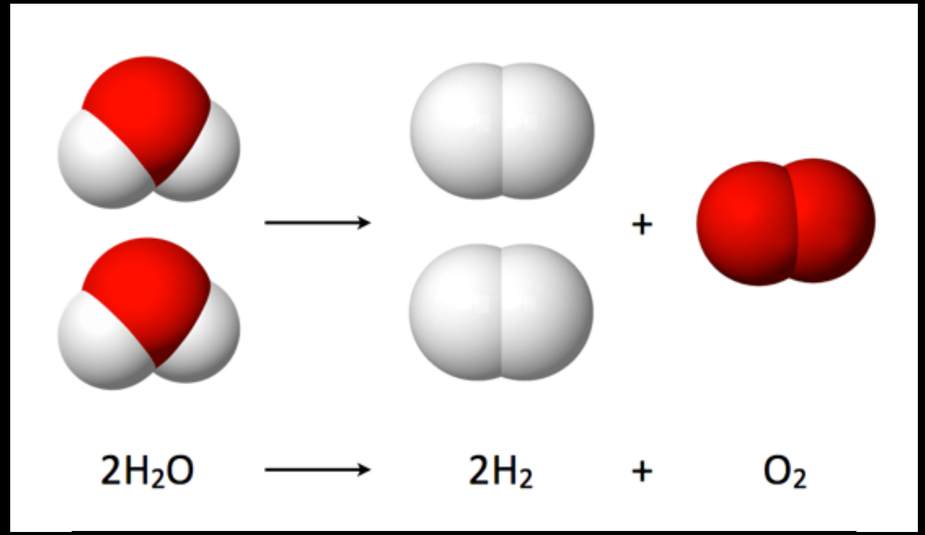
Without liquid water to dissolve the atmospheric CO_2, the planetary greenhouse effect continued to keep the planet warm.

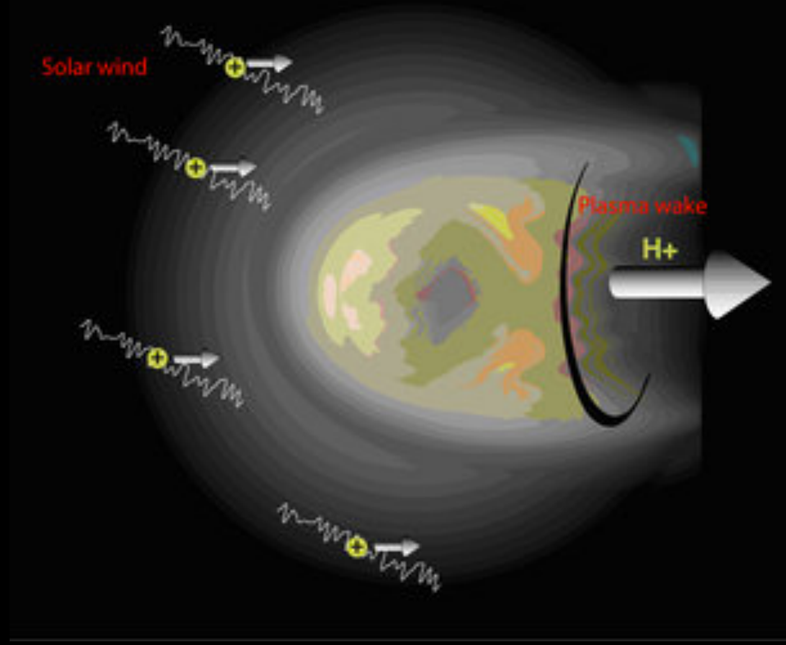
Runaway Greenhouse Effect

This would happen on Earth if CO_2 levels rose too much: UV light breaks apart H_2O to form H_2 and O_2, and H_2 is too light to stay on Earth.

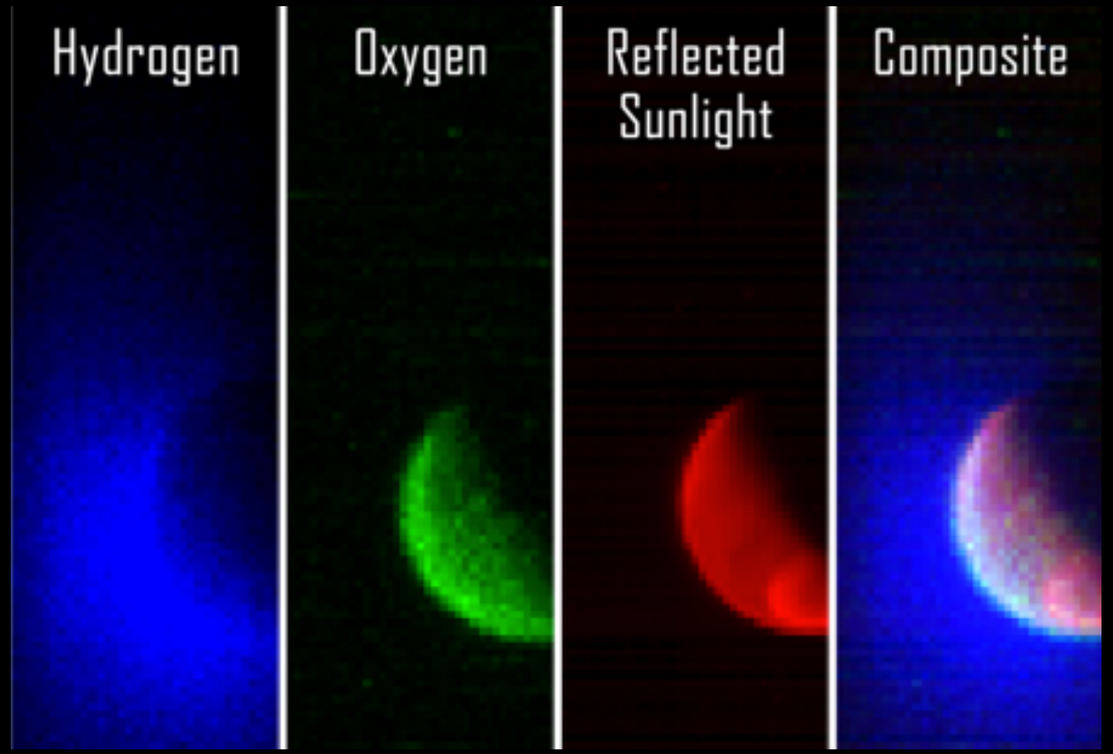
The ESA Venus Express mission observed ongoing losses of hydrogen from Venus, suggesting that this process continues on Venus even now.

This is a feedback loop, progressively worsening.





Mars Climate Evolution



Mars also shows evidence of hydrogen losses. It is a much smaller planet, and it loses hydrogen much easier than Earth or Venus.

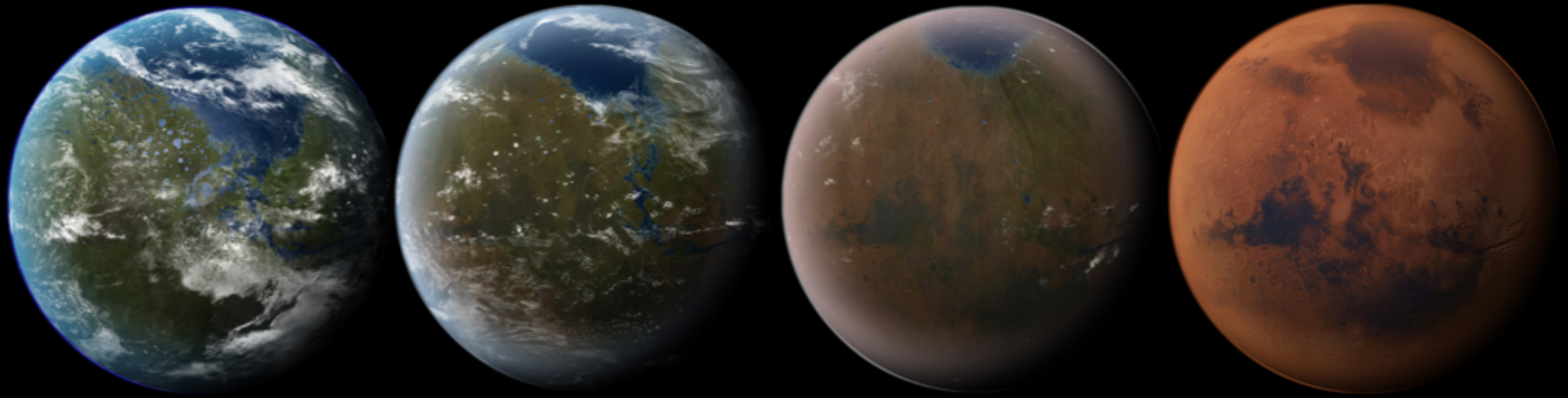
The similar chemical composition of Mars suggests it outgassed a secondary atmosphere very much like Earth/Venus.

The Greenhouse Effect would have kept Mars warm enough for liquid water to form on the surface.

Mars Climate Evolution

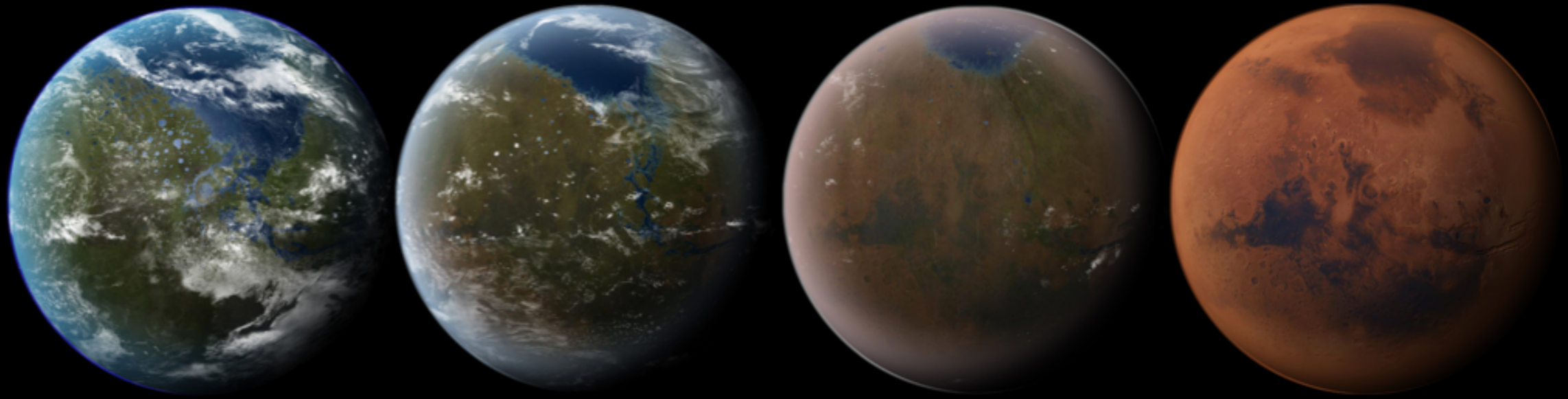
However, the water would have started absorbing CO_2 out of the atmosphere and acted to cool the planet down (reducing greenhouse).

As the planet cools, the water freezes out of the atmosphere and reduces greenhouse effect even further.



Mars Climate Evolution

With the low air pressure and cold temperatures, UV light would have slowly sublimated all the solid surface water.



Mars Climate Evolution

Large impacts 3B years ago would have caused widespread volcanic activity that rapidly reheated the surface of Mars.

This produced the outflow channels and glacial melts that were observed.

Eventually, the planet cooled again, and the freeze out process continued.

This is known as the REVERSE GREENHOUSE EFFECT. It is also a feedback/runaway process - once it starts, it won't stop.