Modern Astronomy: Voyage to the Planets

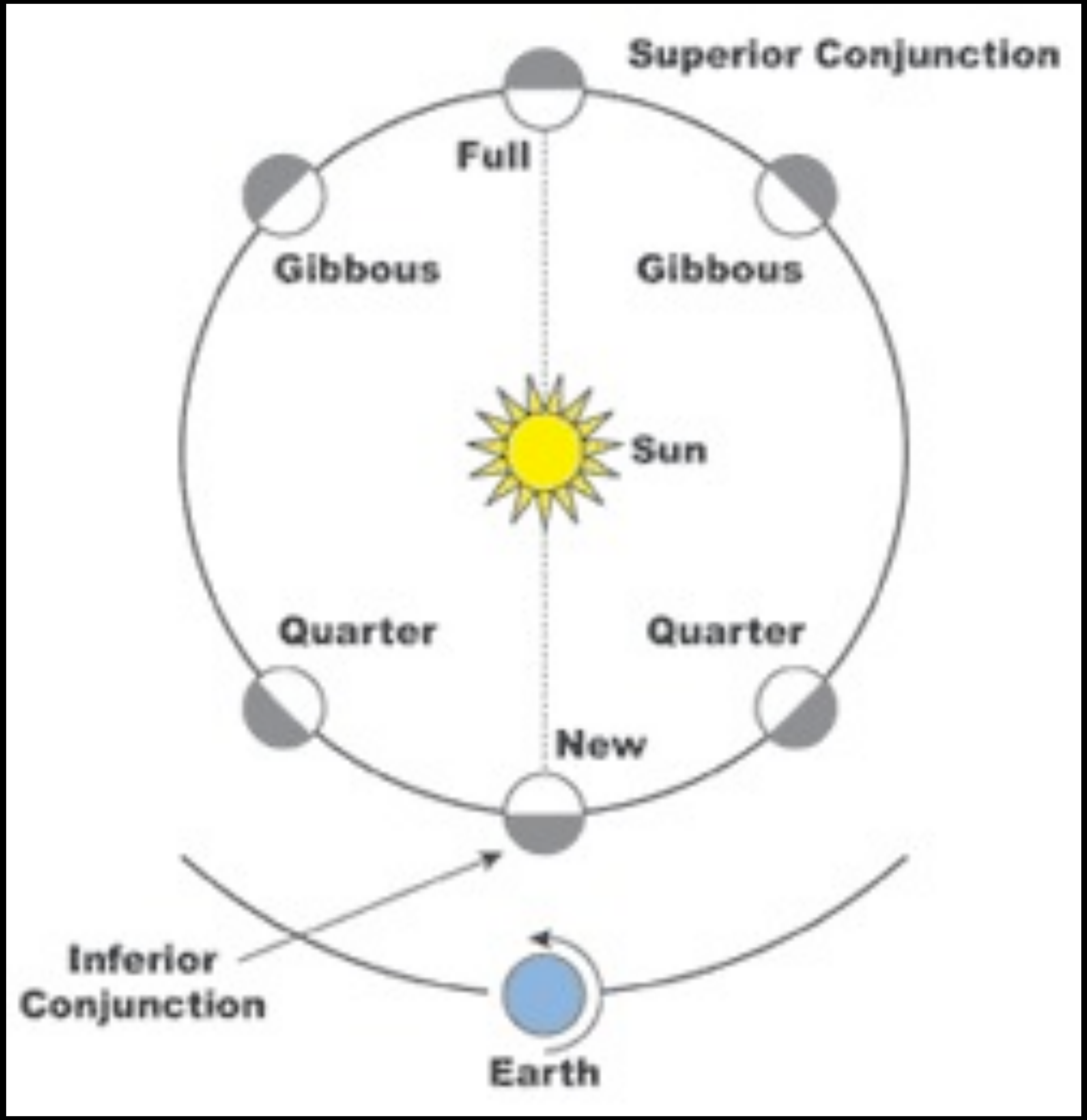
Lecture 3

Mercury and Venus

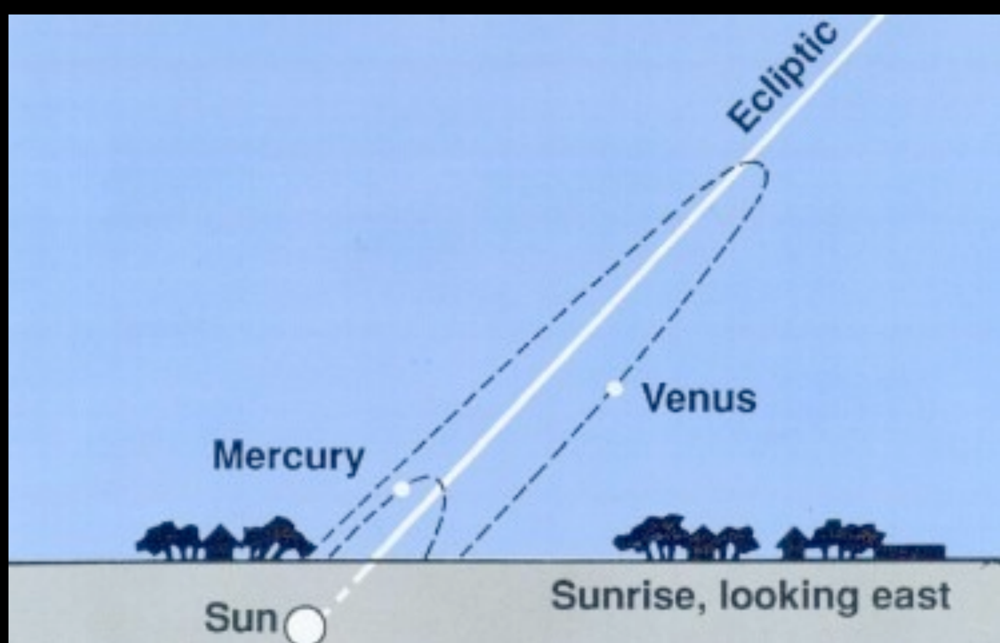
the inner planets

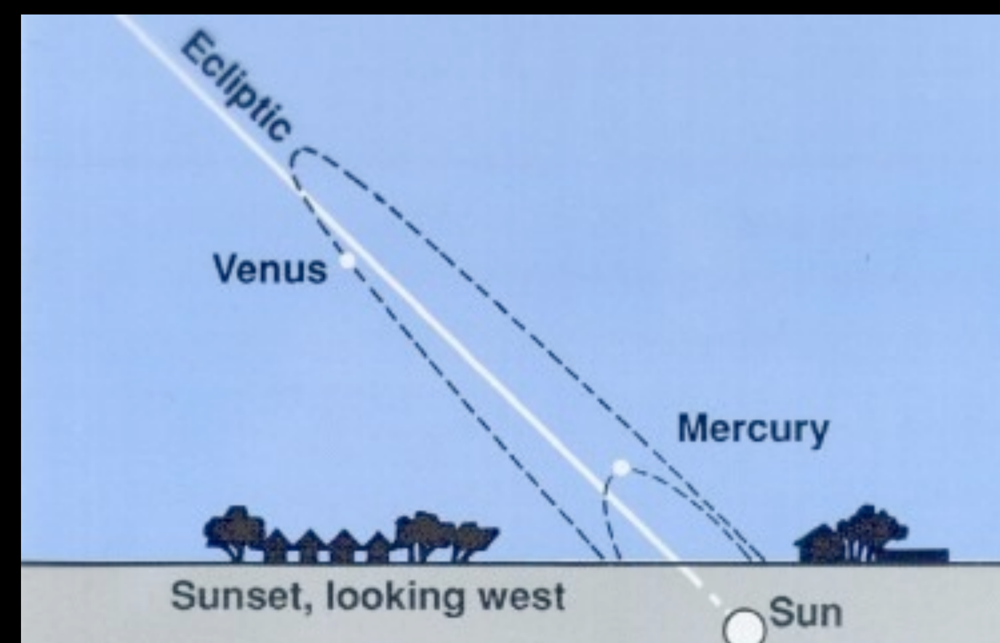
University of Sydney
Centre for Continuing Education
Spring 2011

This week we'll look at the *inferior planets*, Mercury and Venus. Because they orbit closer to the Sun than the Earth, we never see them very far away from the Sun., and they show a full range of phases.



The furthest Venus ever gets from the sun (its *maximum elongation*) is 47°; for Mercury it is 28°.





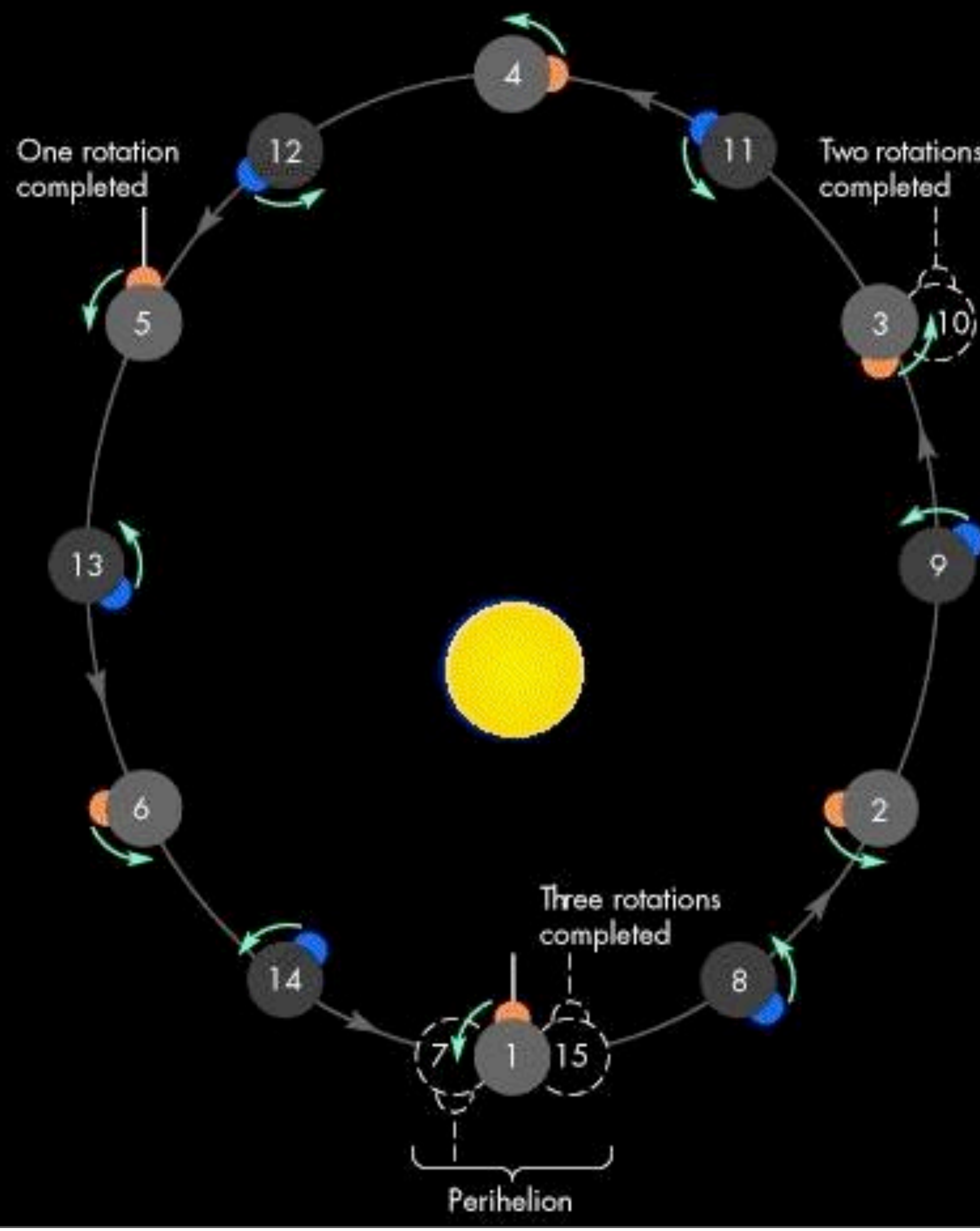
Mercury's successive positions during March of 2000. Each picture was taken from the same location in Spain when the Sun itself was 10 degrees below the horizon and superposed on the single most photogenic sunset.

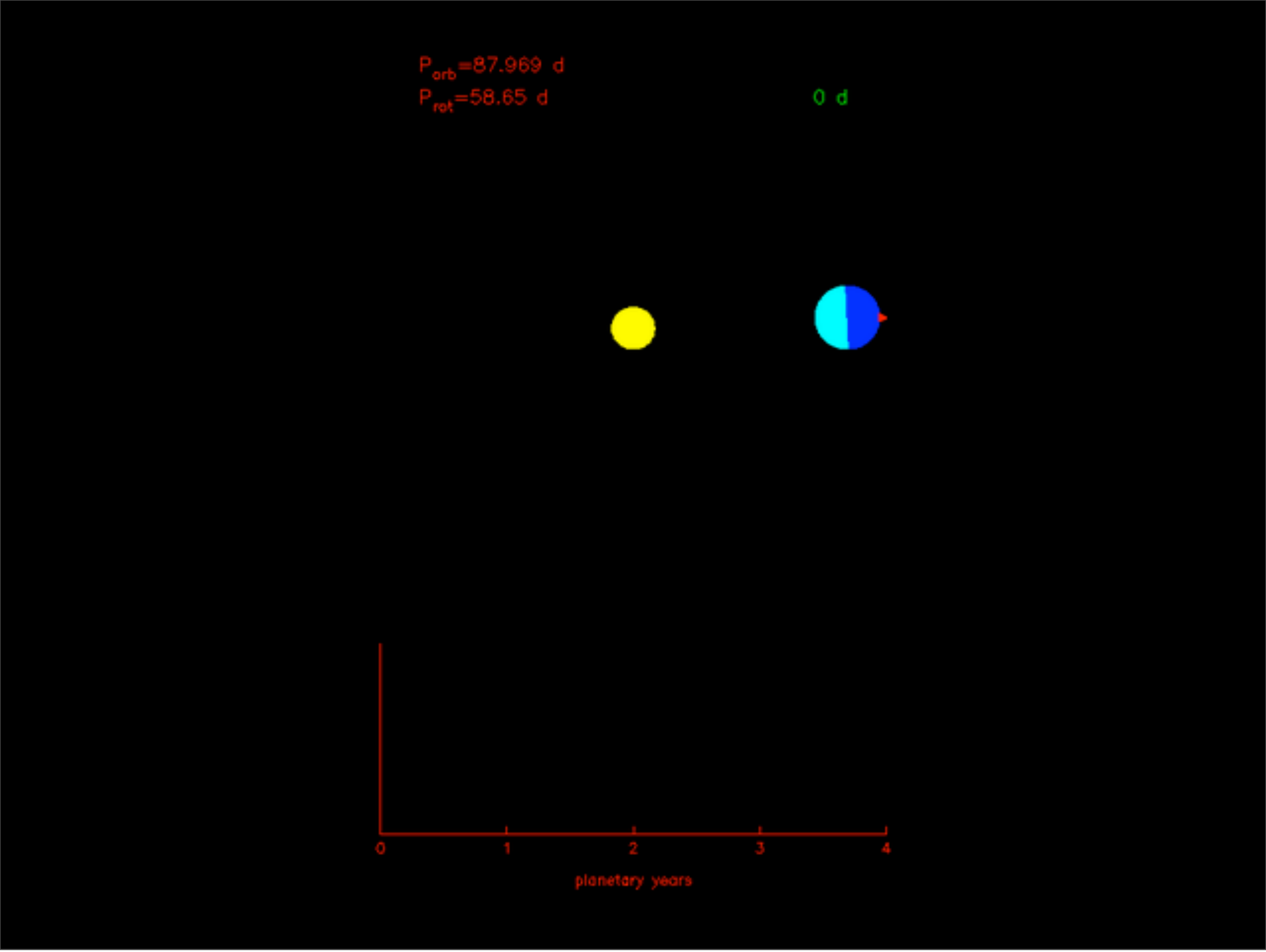
Mercury

Basic data

	Mercury	Mercury/Earth
Mass	0.3302×10^{24} kg	0.0553
Radius	2440 km	0.383
Mean density	5.427 g/cm^3	0.983
Gravity	3.70 m/s^2	0.378
Semi-major axis	57.91×10^6 km	0.387
Period	87.969 d	0.241
Orbital inclination	7.0^o	-
Orbital eccentricity	0.2056	12.311
Rotation period	1407.6 h	58.78
Length of day	4222.6 h	175.94

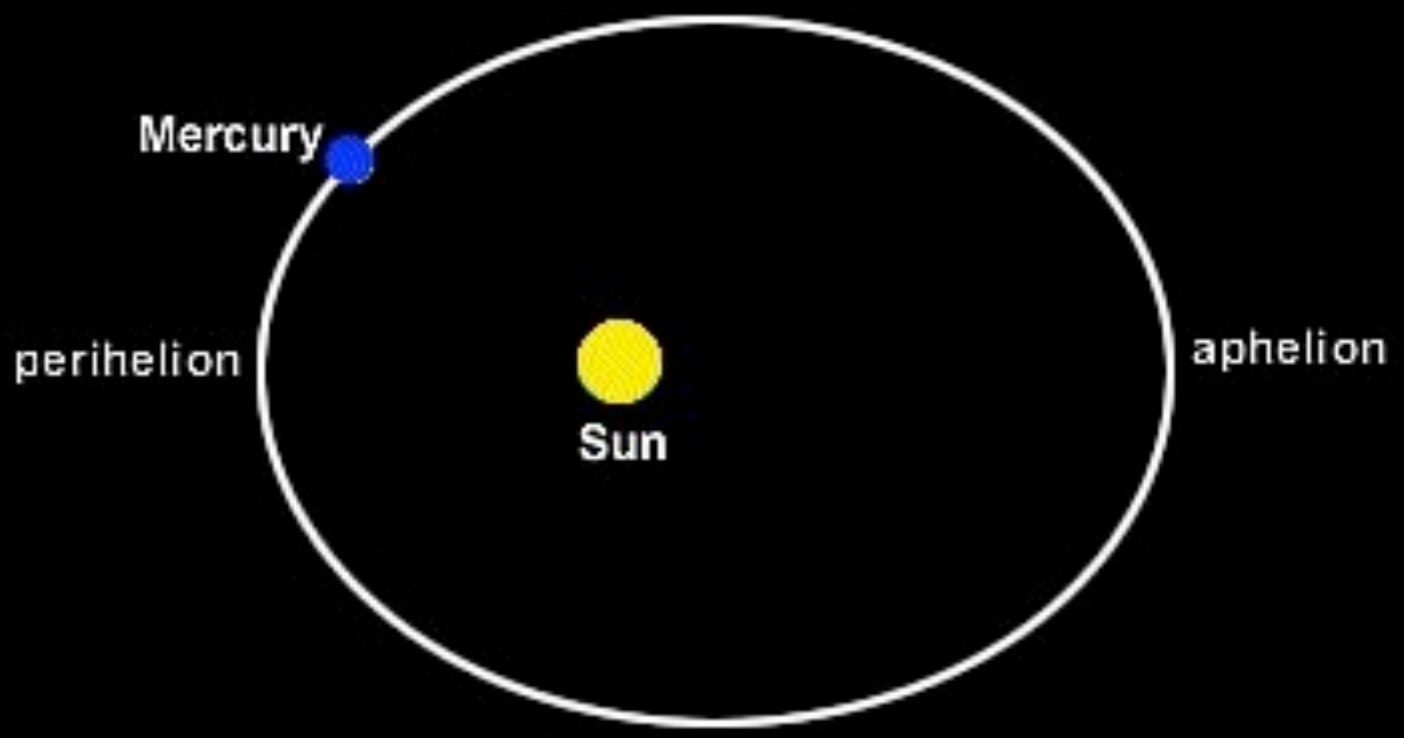
Mercury's period of rotation (58.7 days) is exactly two-thirds of the orbital period (88.0 days, the Mercurian year). This 3:2 resonance means that the *solar day* on Mercury – the time between noon and noon – is 176 (Earth) days long, twice the length of the year!




P_orb=87.969 d
P_rot=58.65 d
0 d
0
1
2
3
4
planetary years

Mercury's orbit is the most elliptical of any planet except Pluto. Its distance from the Sun varies from 46 million km at perihelion to 70 million km at aphelion, a difference of more than 50%. This means that the intensity of sunlight on the surface varies by about a factor of two.

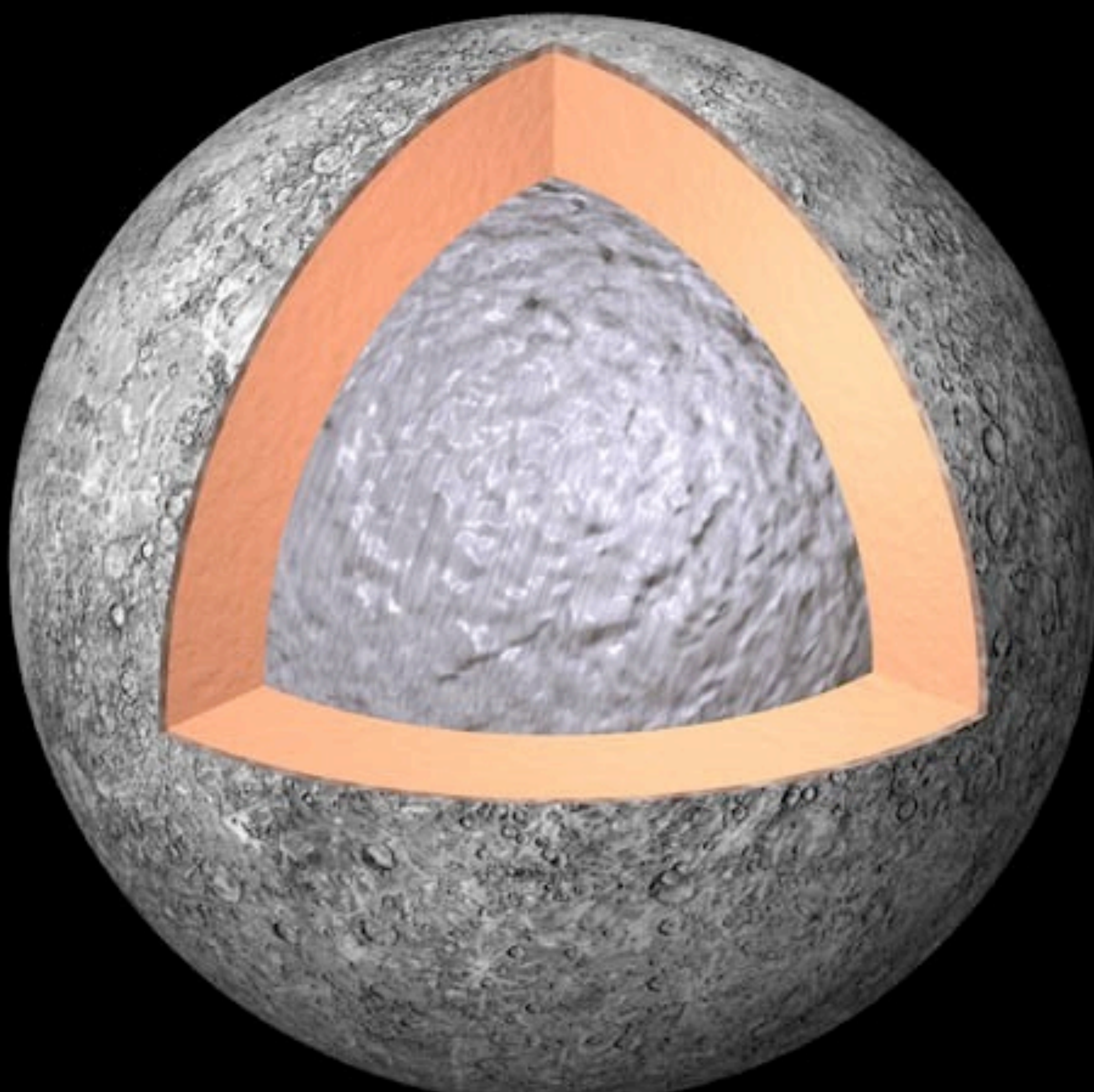
The 3:2 resonance means that the same region of the planet faces the Sun every *second* perihelion, with the region on the opposite side of the planet facing the Sun in alternate years. So Mercury has two "hot poles".



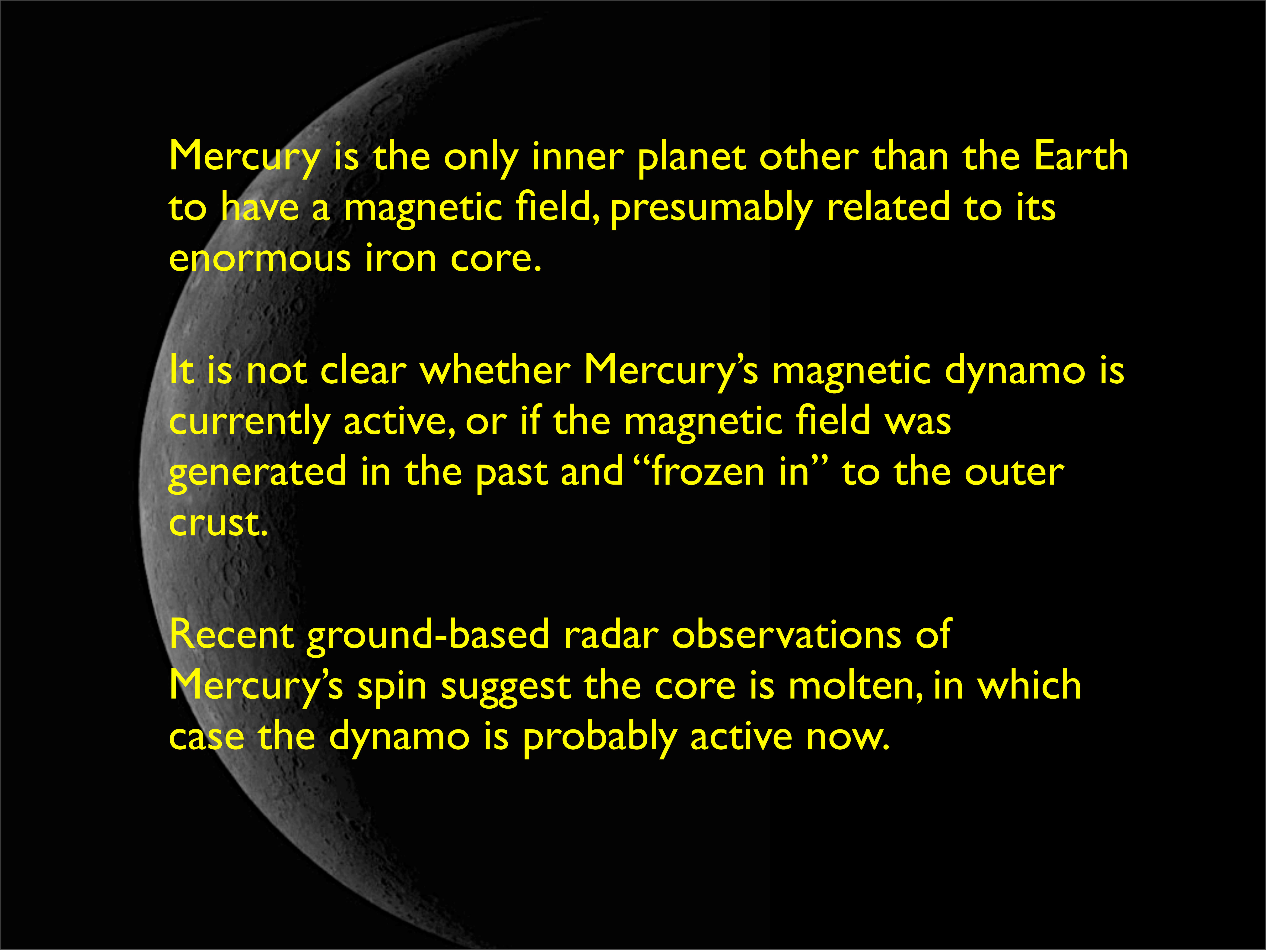
A night temperature low of 90 K (–180°C) was measured by Mariner's infrared radiometer just before dawn on Mercury. The maximum daytime temperature in late afternoon was 460 K (190°C).

This temperature difference between night and day is enormous. But at times, when Mercury makes its closest approach to the Sun, the range can reach 650 K (380°C): greater than on any other planet in the Solar System.

Mercury is extremely dense: despite its small size (only slightly larger than the Moon), it is nearly as dense as the Earth. This implies that about 70% of its mass must be made of iron, probably in a large core about 75% of the planet's radius.



Cutaway view of the possible structure of the interior of Mercury. The core is much larger in proportion than Earth's, about 1800 km in radius. The silicate outer shell is only 500–600 km in thickness.



Mercury is the only inner planet other than the Earth to have a magnetic field, presumably related to its enormous iron core.

It is not clear whether Mercury's magnetic dynamo is currently active, or if the magnetic field was generated in the past and "frozen in" to the outer crust.

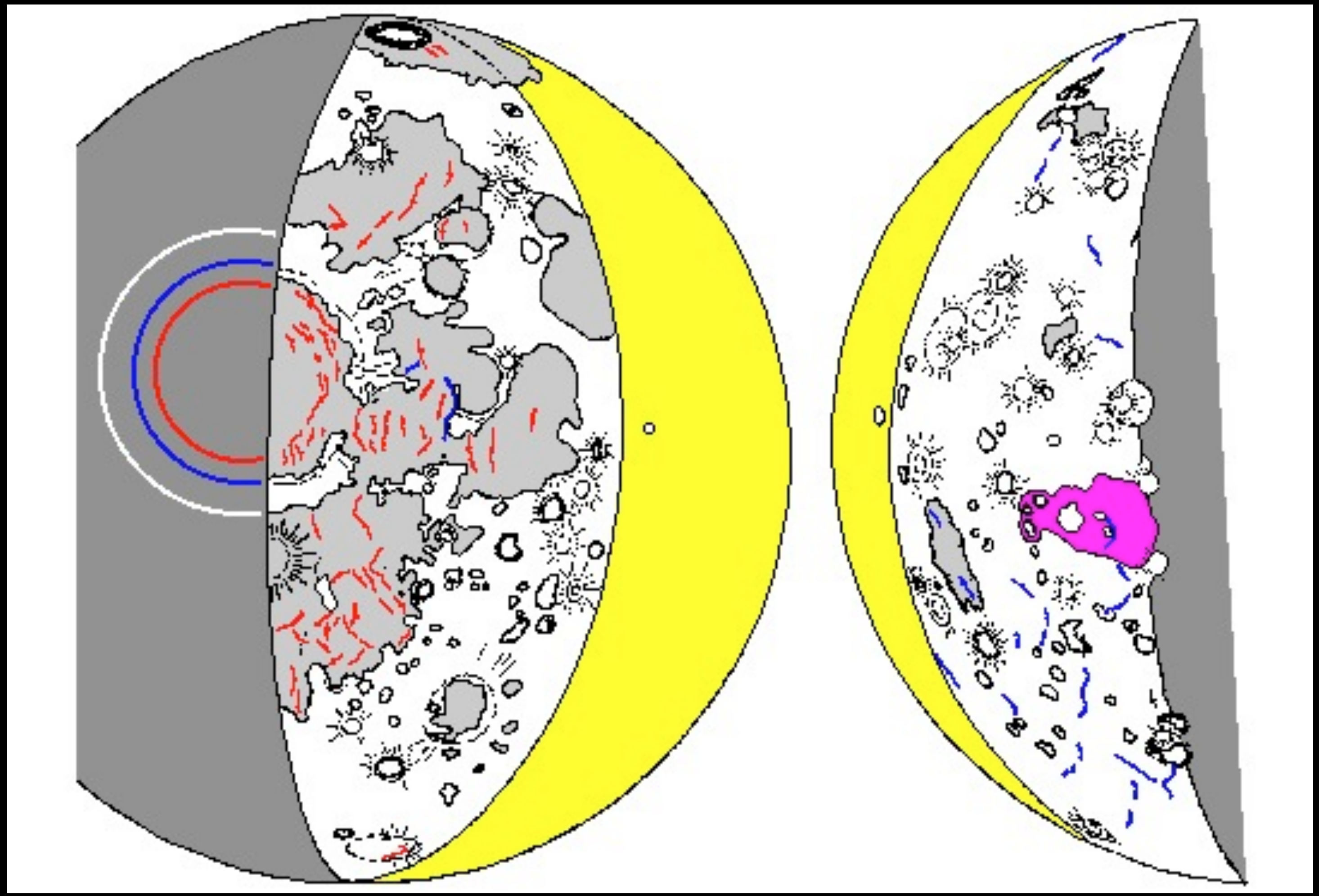
Recent ground-based radar observations of Mercury's spin suggest the core is molten, in which case the dynamo is probably active now.

Only two spacecraft have visited Mercury. Mariner 10 made three flybys in 1974–1975. Only 45% of the surface was photographed.

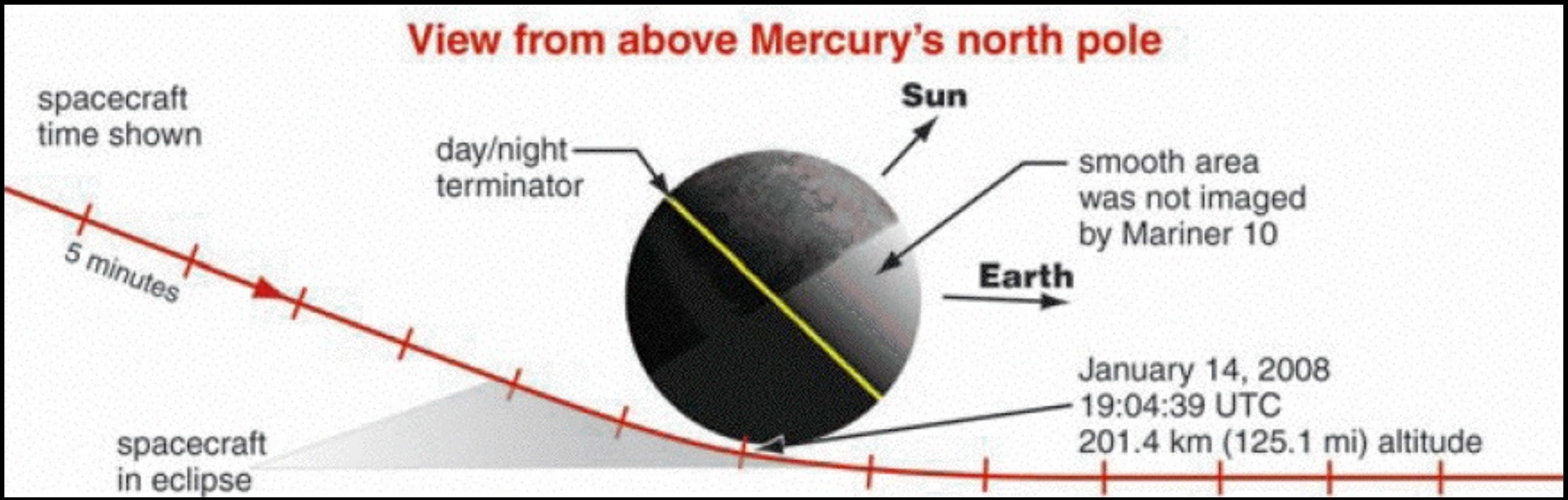
NASA launched the MESSENGER mission to Mercury in August 2004. It made three Mercury flybys in January and October 2008 and September 2009, and entered Mercury orbit in March 2011.

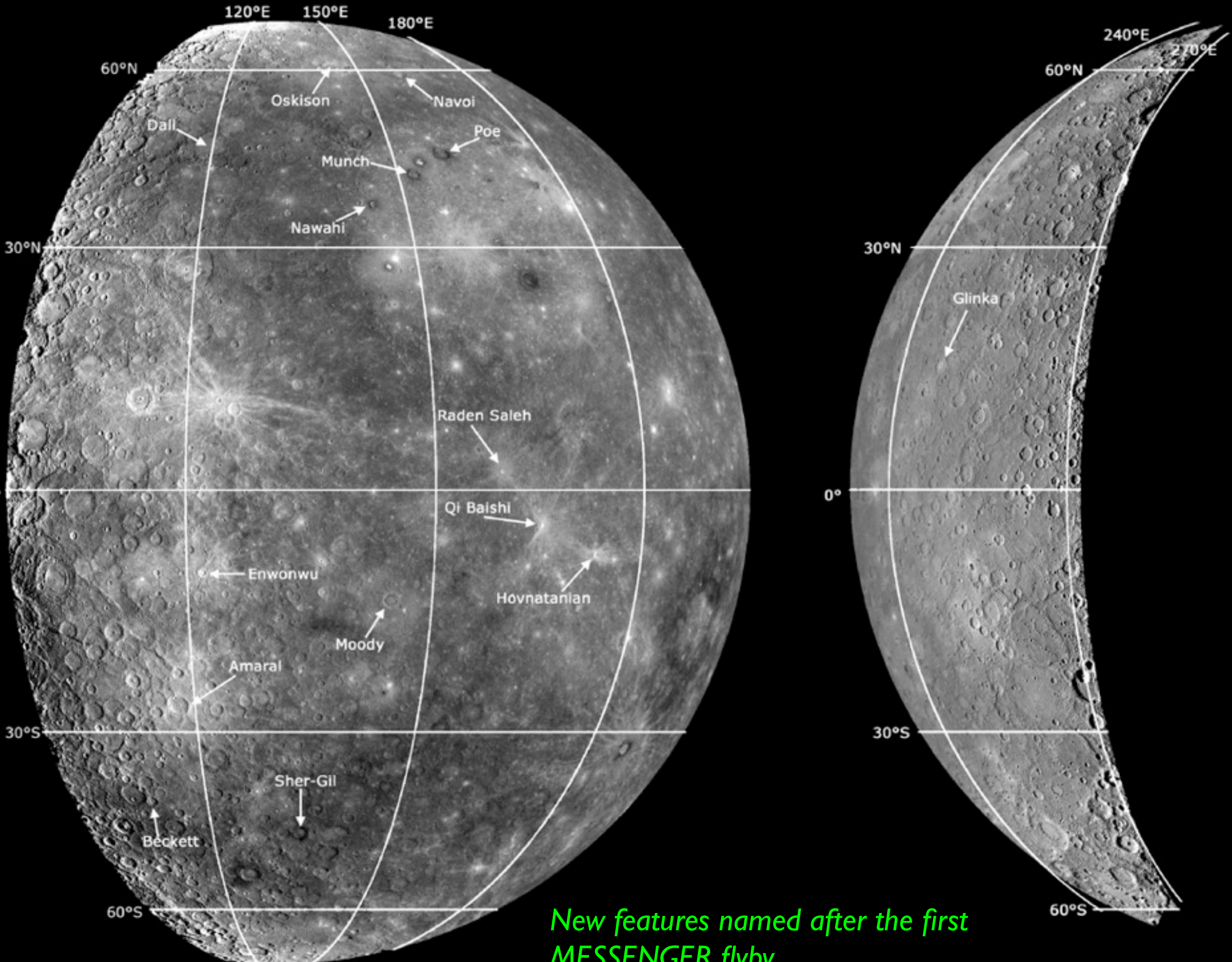
ESA plans two Mercury orbiters called BepiColombo, for launch in 2014, arriving at Mercury in 2020.

Even though Mariner 10 flew past Mercury three times, Mercury's peculiar orbit meant that it saw almost exactly the same area each time, under the same lighting conditions. On the globe below, the grey area was on the night side, while in the yellow area the sun was too high so features could not be seen properly.



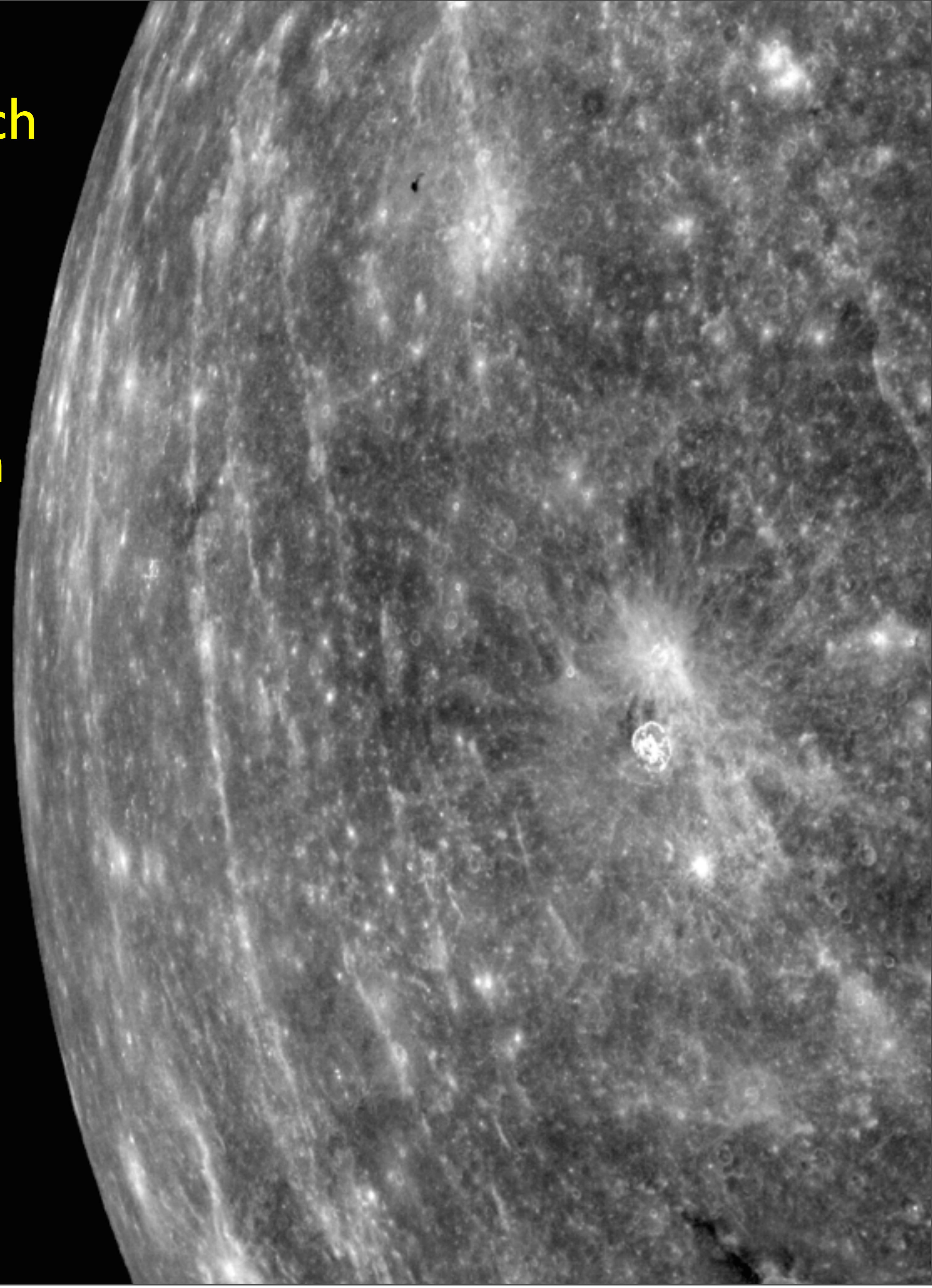
In its first flyby, MESSENGER imaged an additional 21% of the surface that had not been seen by Mariner 10, mostly as it left the planet. After the second flyby, about 90% of the planet has been imaged.





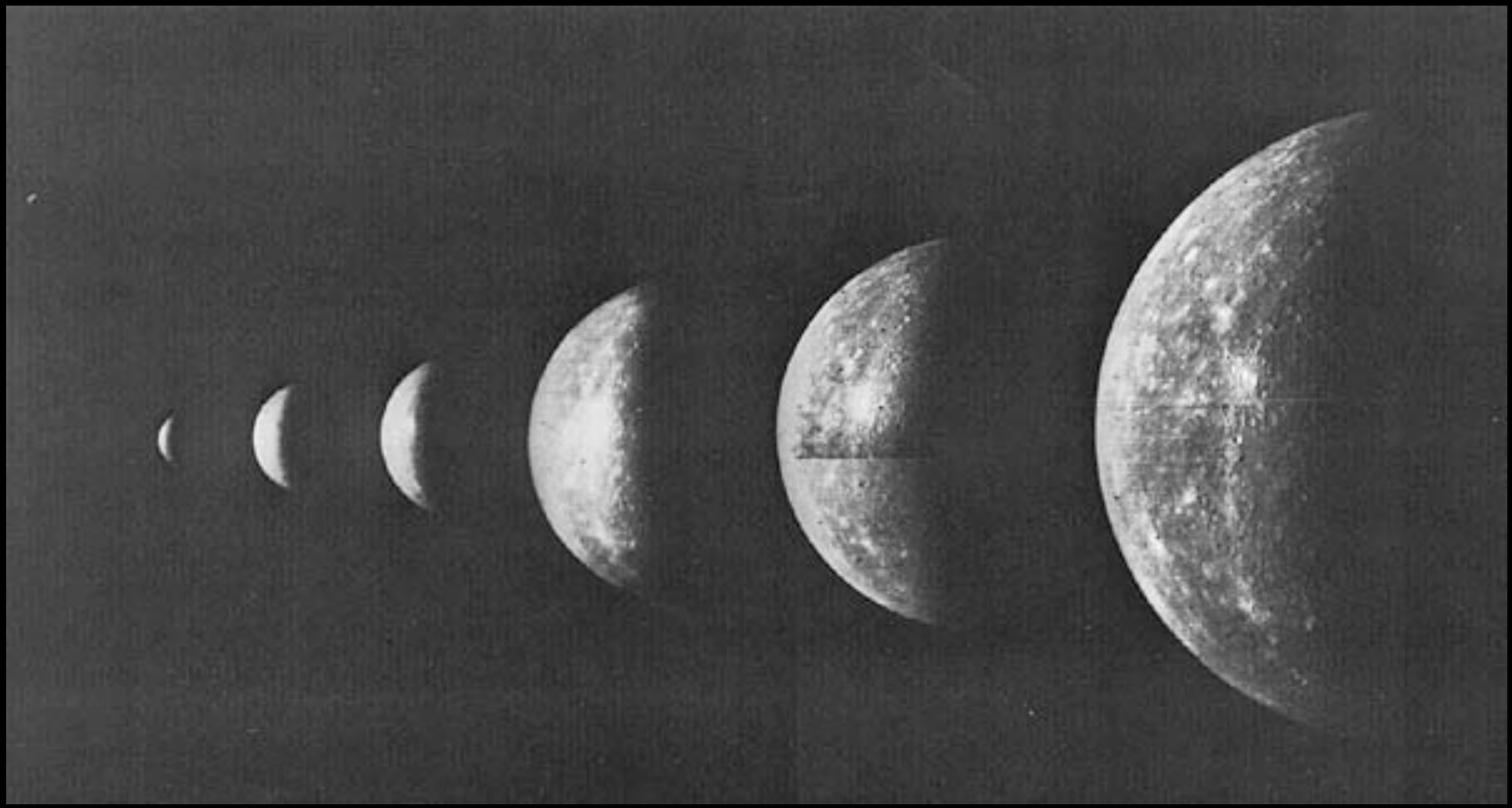
New features named after the first MESSENGER flyby

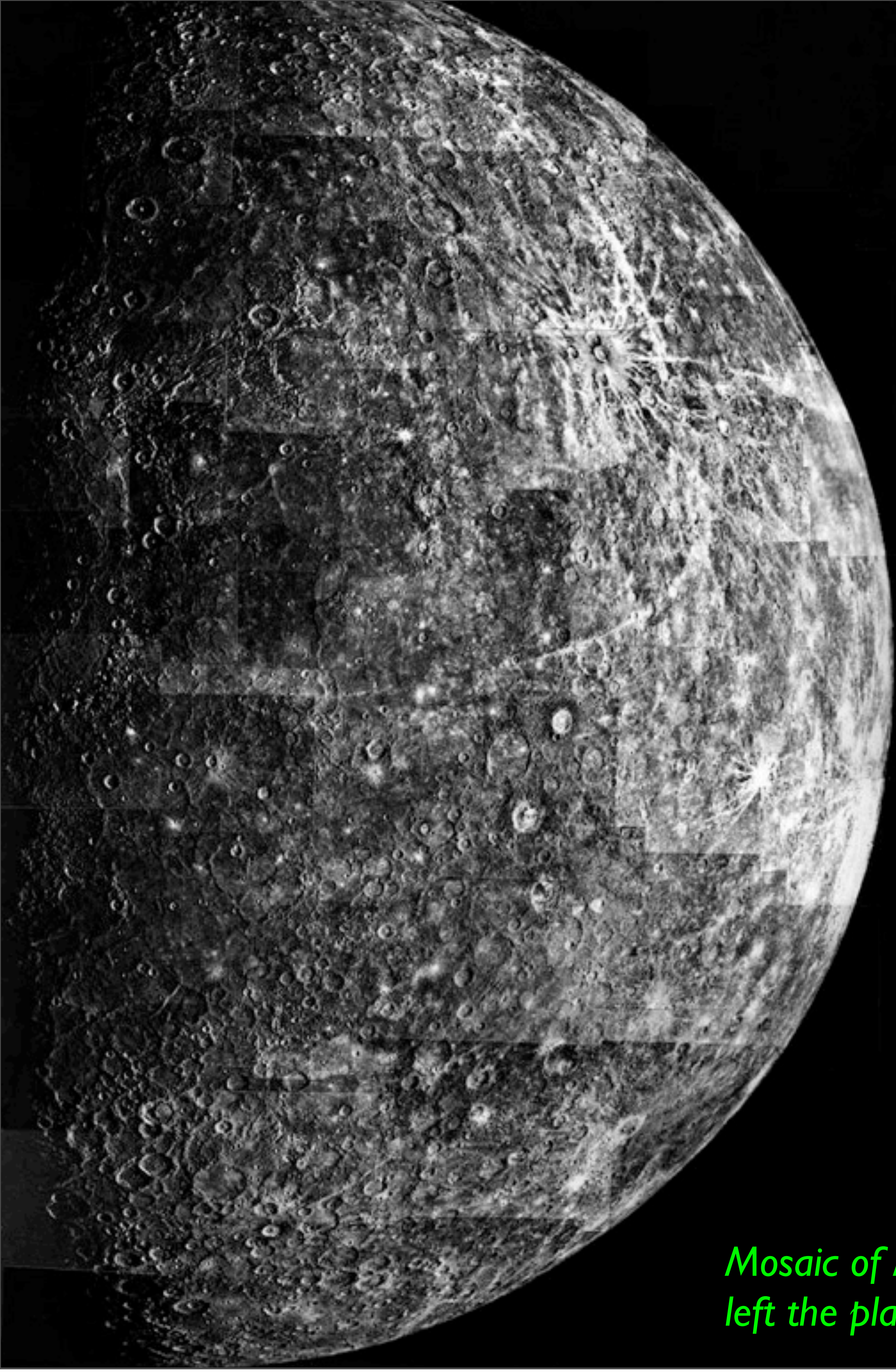
Since reaching orbit in March this year, MESSENGER has taken 40,000 images of the surface. The mission is scheduled to last 12 Earth months – two solar days on Mercury.



Surface

The Mariner 10 photos revealed a surface bearing a striking resemblance to the Moon: heavily cratered, with large flat circular basins similar to those on the Moon and Mars.





Impact craters cover most of the planet. The craters range in size from 100 meters (the smallest resolvable feature on Mariner 10 images) to 1,300 kilometers. Some are young with sharp rims and bright rays like the craters we saw on the Moon. Others are highly degraded, with rims that have been smoothed by the bombardment of meteorites.

Mosaic of Mariner 10 images as it left the planet

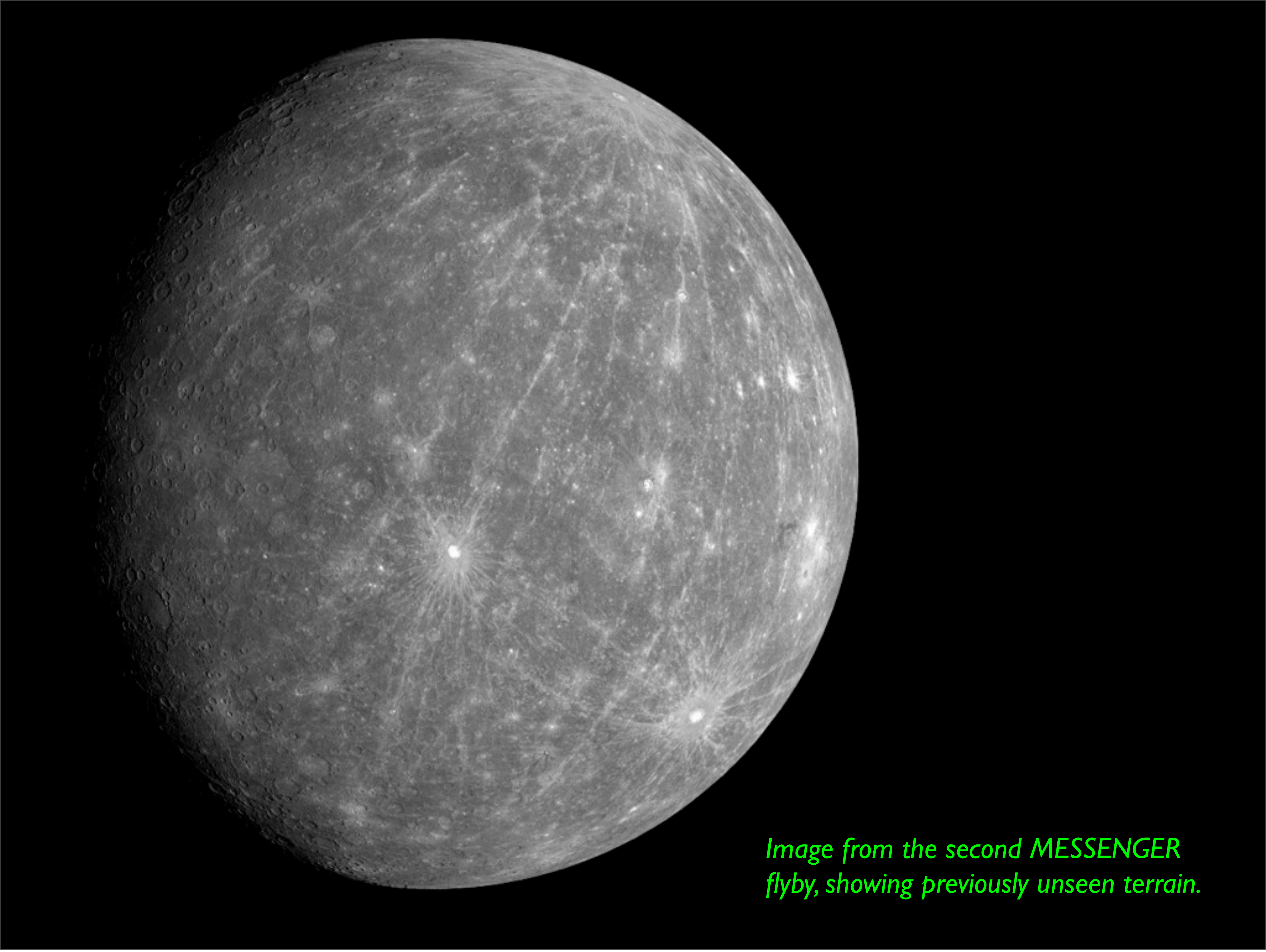
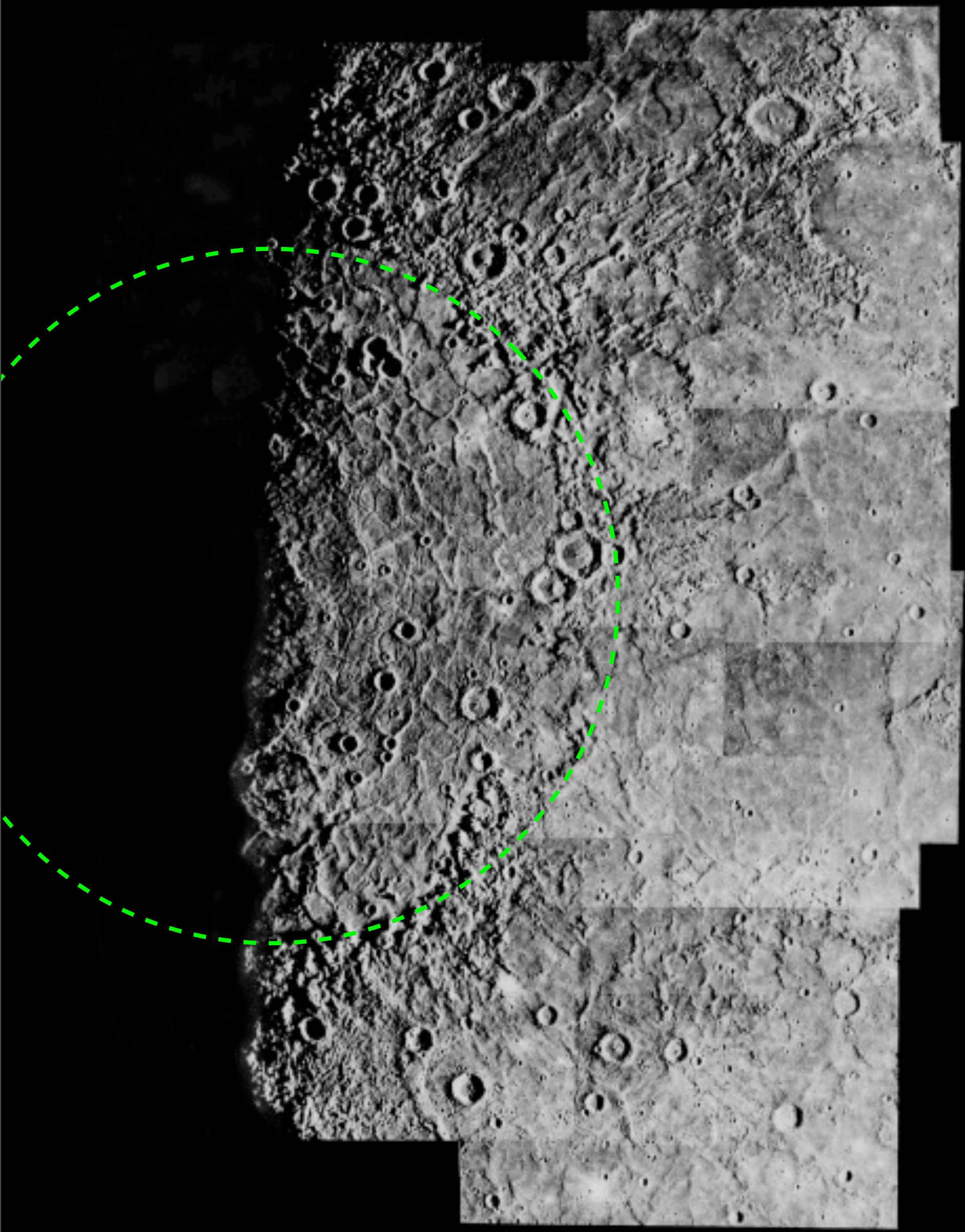


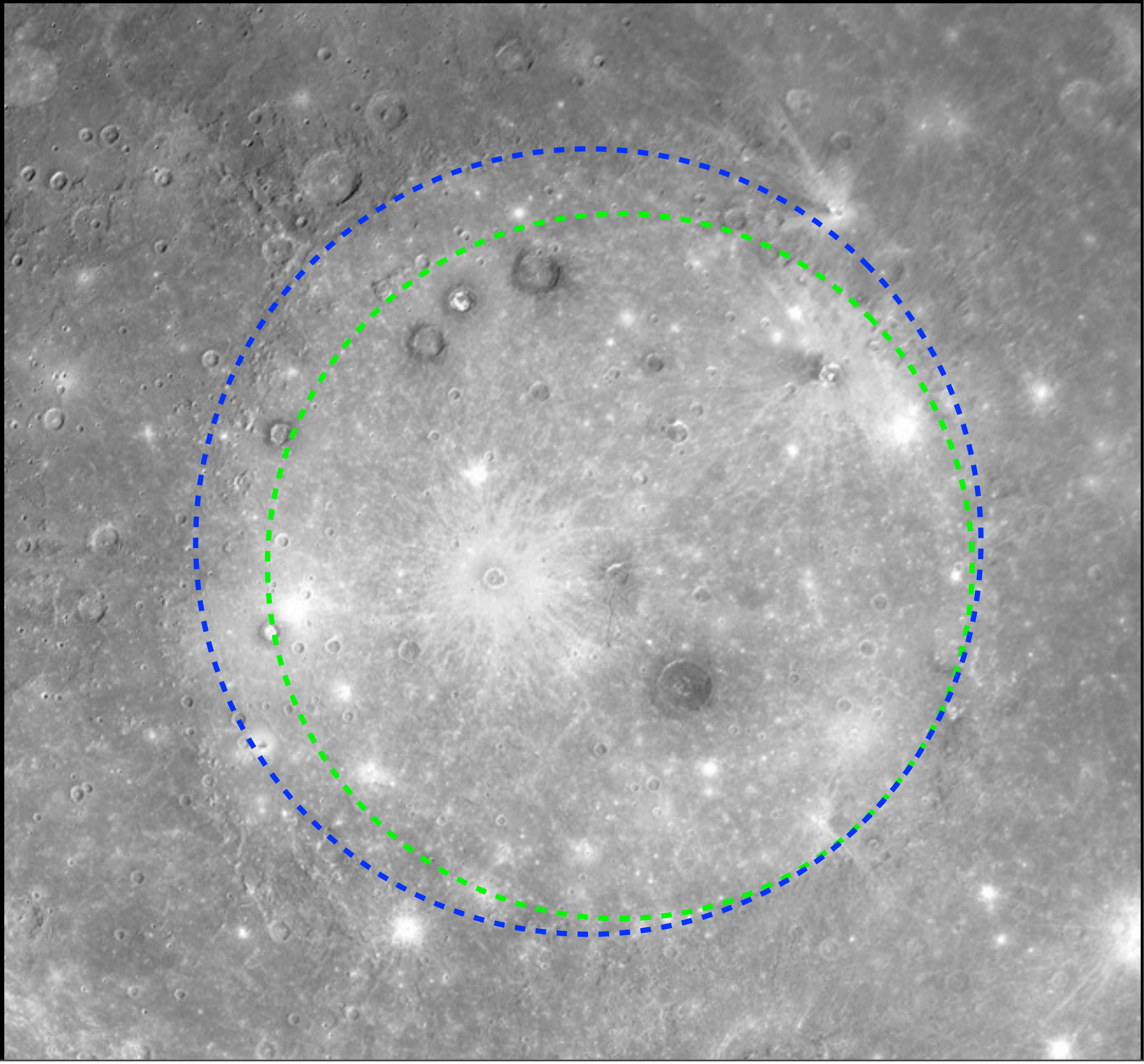
Image from the second MESSENGER flyby, showing previously unseen terrain.

The largest crater on Mercury is the *Caloris basin*. It is located near one of the two "hot poles", near 180° of longitude.



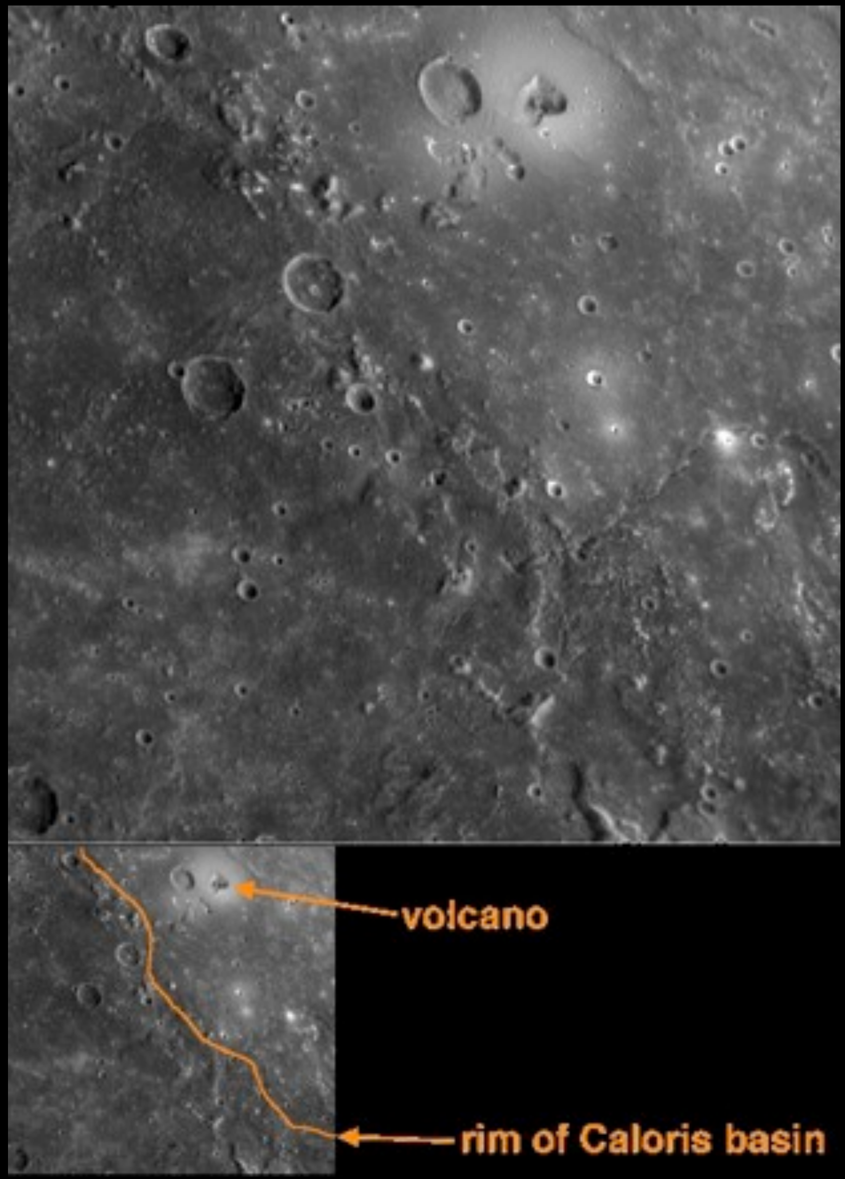
The Caloris basin must have resulted from the impact of an asteroid at least 100 km across early in the formation of the planet. Caloris is just north of the planet's equator and is surrounded by circular mountain ridges up to 2 km high. The diameter of the basin is 1300 km. Smooth plains between the rings may represent volcanism triggered by the impact.

MESSENGER saw the western half of the Caloris basin during its first flyby, and it turned out to be even bigger than assumed: 1550 km instead of 1300 km.

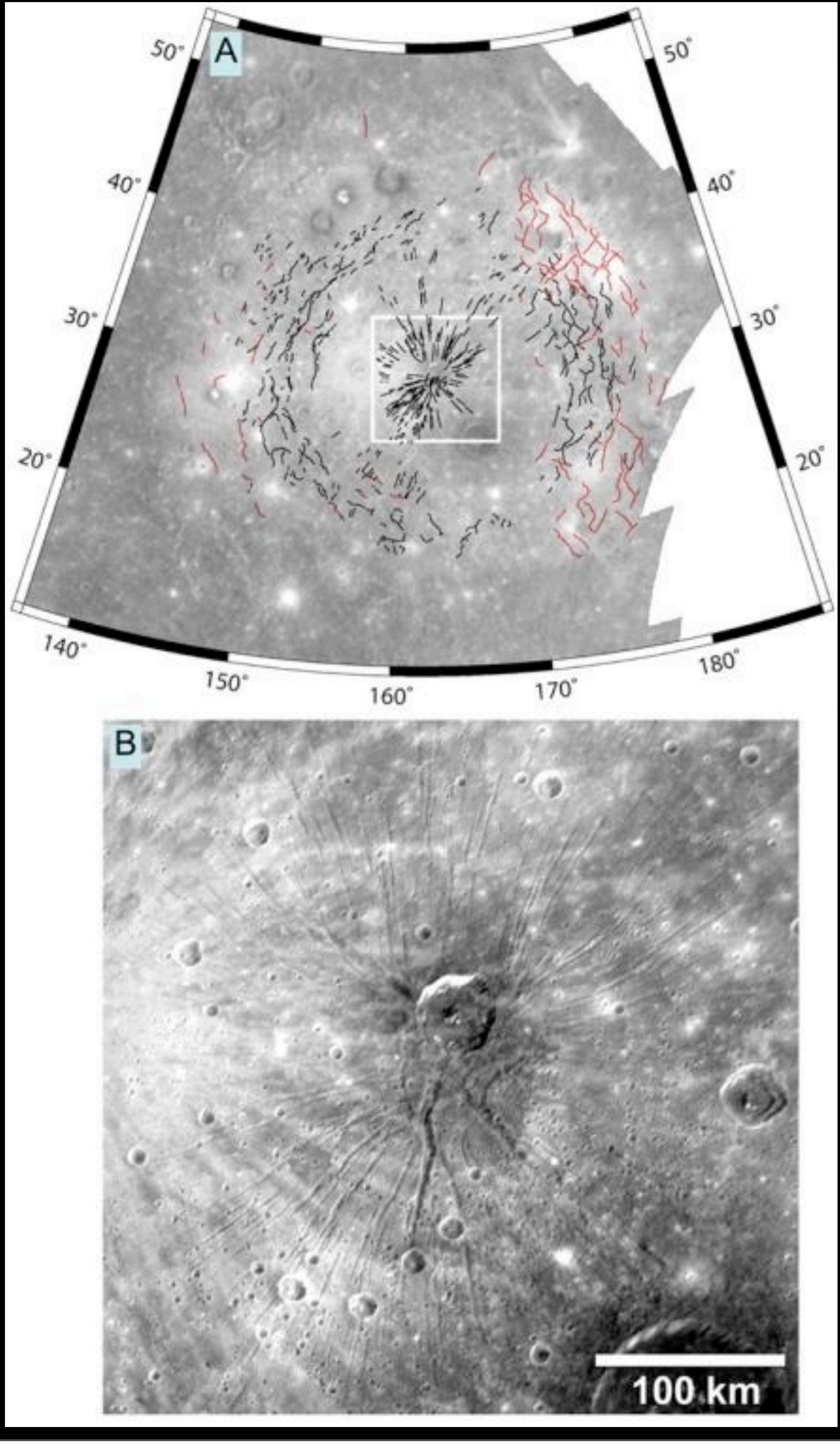


MESSENGER's view of the Caloris basin

By taking images in many different filters, MESSENGER made this false-colour image of Caloris, showing the variations in composition. The interior of the basin appears to be flooded with volcanic lava; the orange spots around the rim are probably volcanic features.



MESSENGER found a unique feature in the middle of Caloris initially dubbed "the Spider", but now officially called *Pantheon Fossae*. It consists of over a hundred narrow, flat-floored troughs radiating from a complex central region. There is a crater near its center, but it is not clear whether that crater is related to the original formation or was formed later.



On the exact other side of the planet to the Caloris Basin is a vast area of jumbled, peculiar terrain. It has been suggested that the immense shock waves produced by the impact of the body that produced Caloris were focused around the planet so that the resultant seismic disturbances broke up the surface, and that this is responsible for the chaotic appearance of this region.

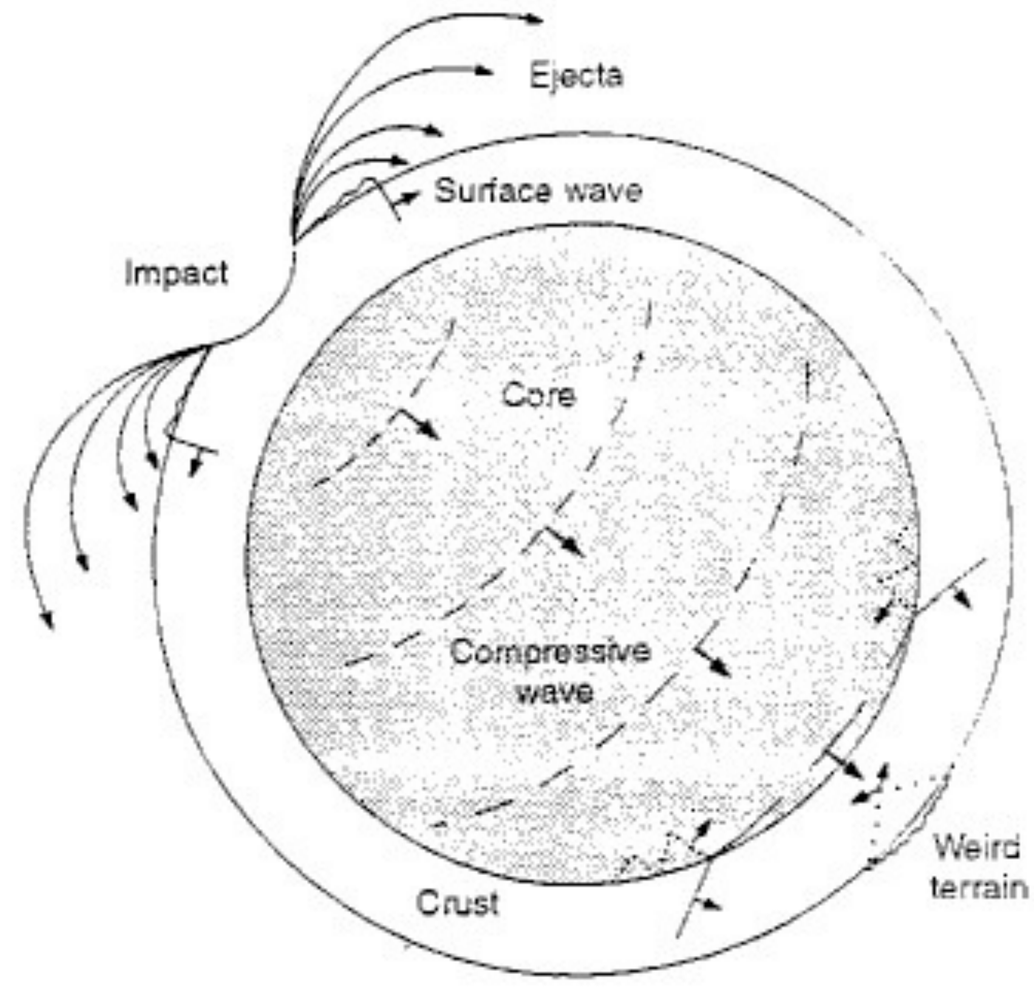
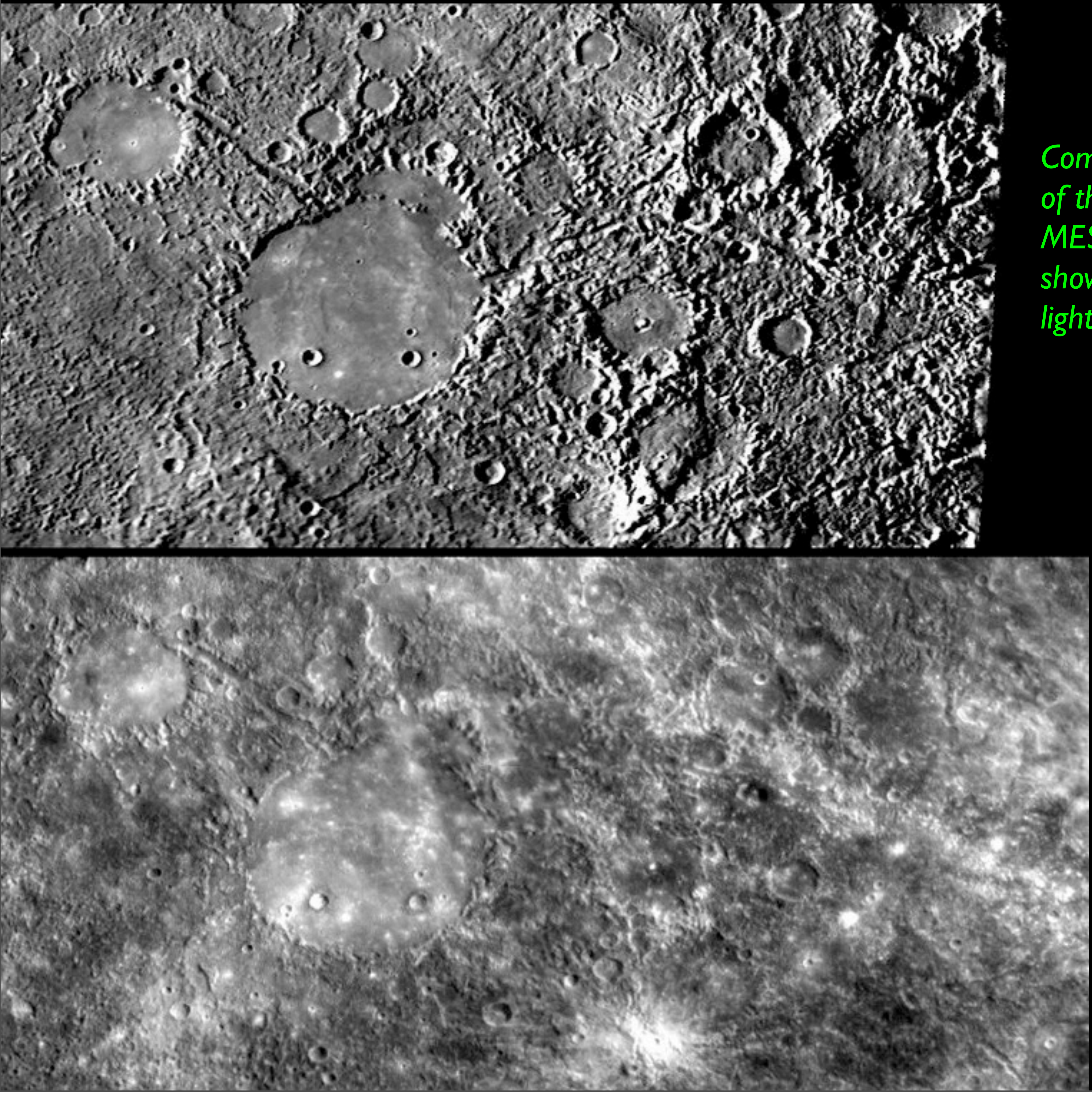
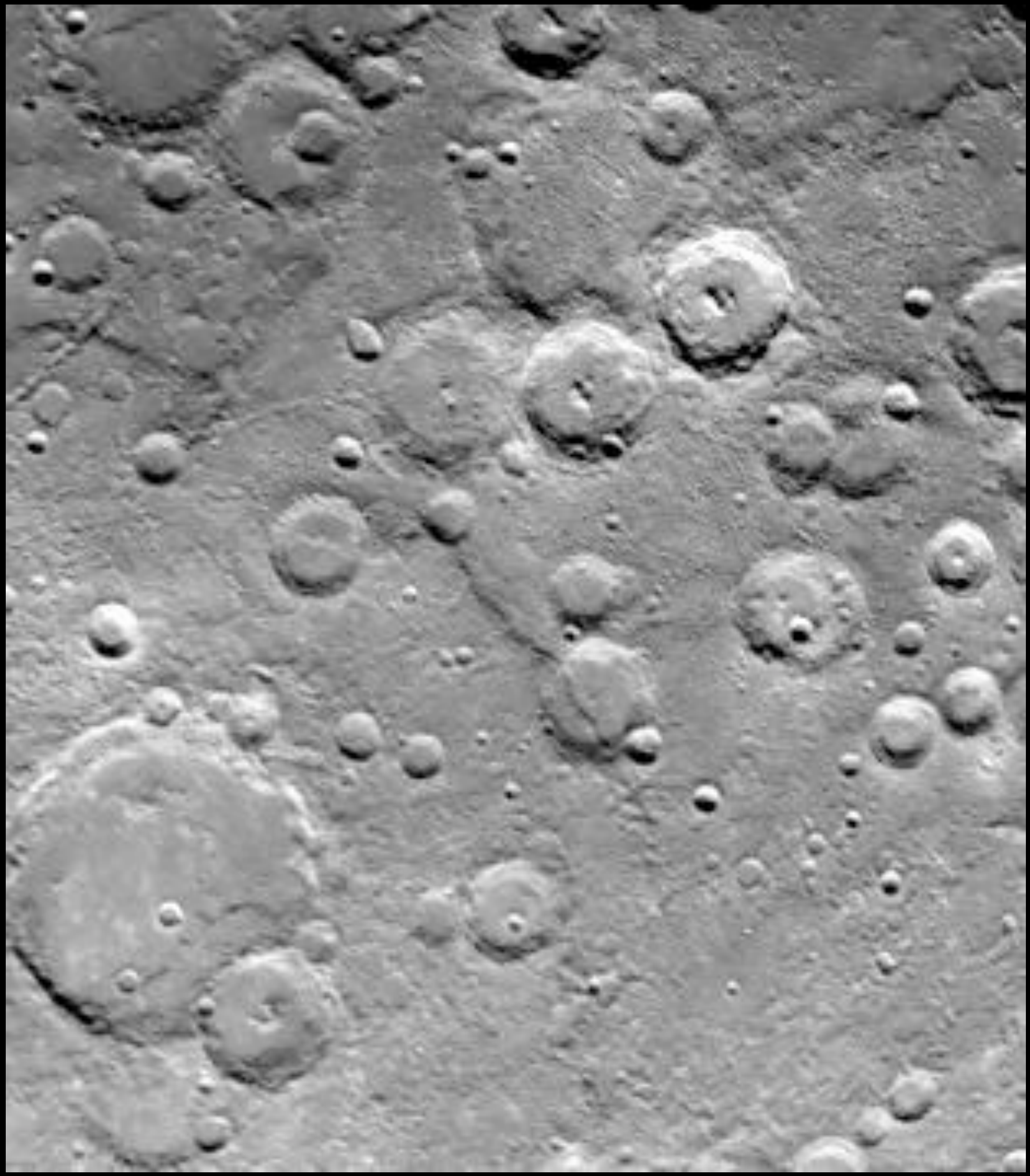


FIGURE 10 Diagrammatic representation of the formation of the hilly and lineated terrain by focused seismic waves from the Caloris impact. [From Schultz, P., and Gault, D. (1975). *The Moon* 12, pp 159–177.]

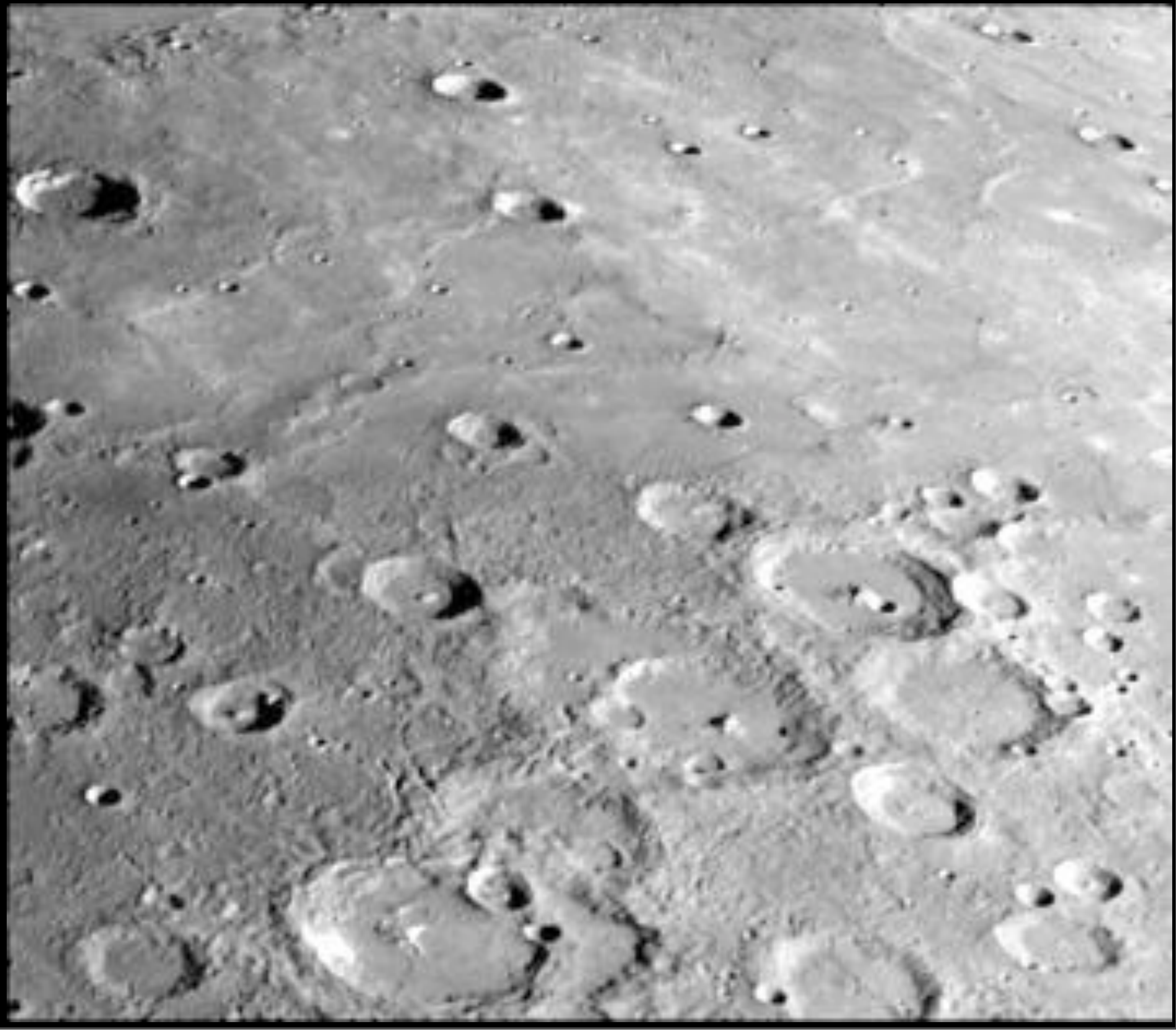


Comparison of Mariner's view of the weird terrain (top) and MESSENGER's (bottom), showing the effect of different lighting conditions

The heavily cratered regions are not as densely cratered as the Moon: the surface is not saturated with craters as the lunar highlands are.

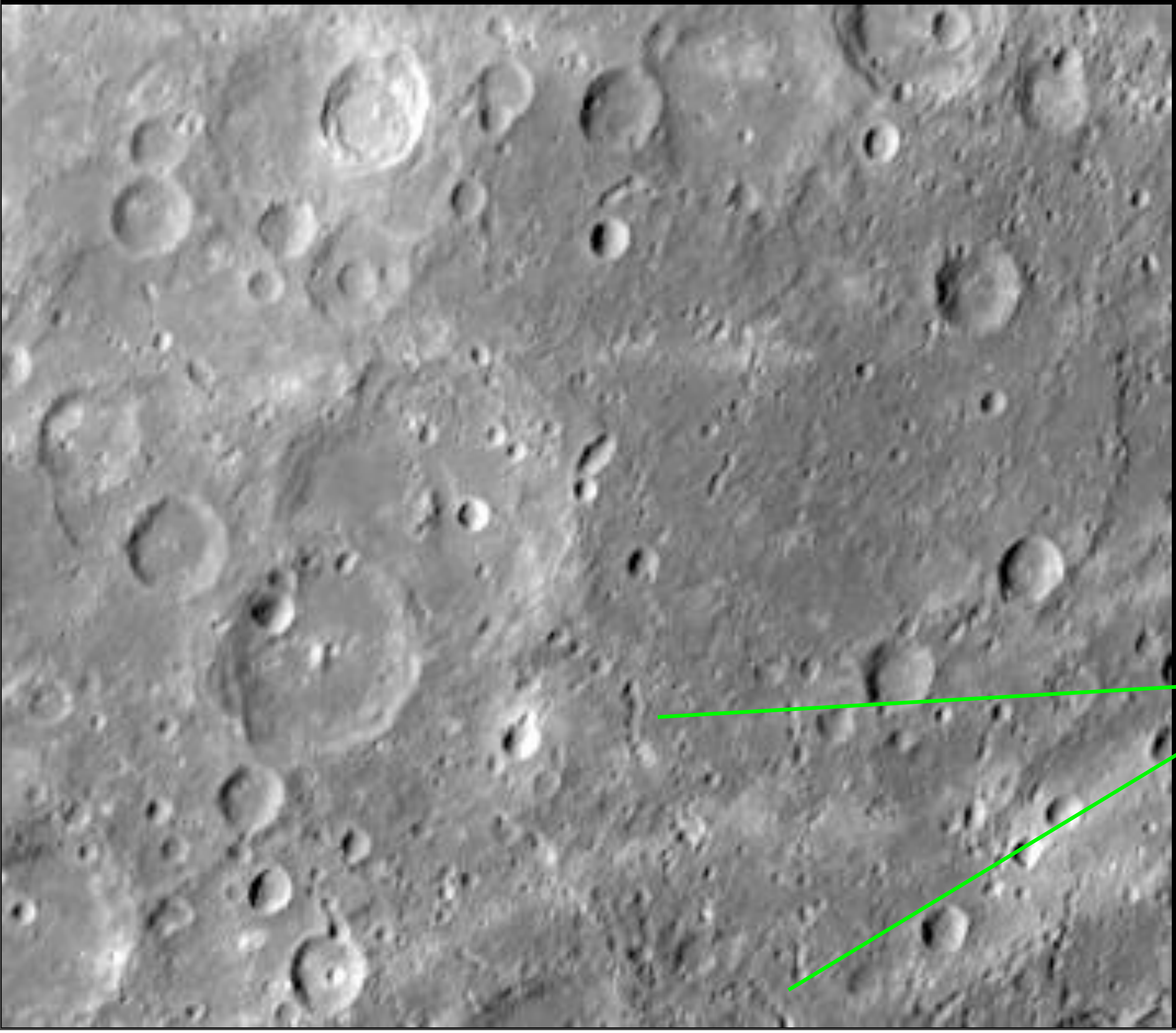


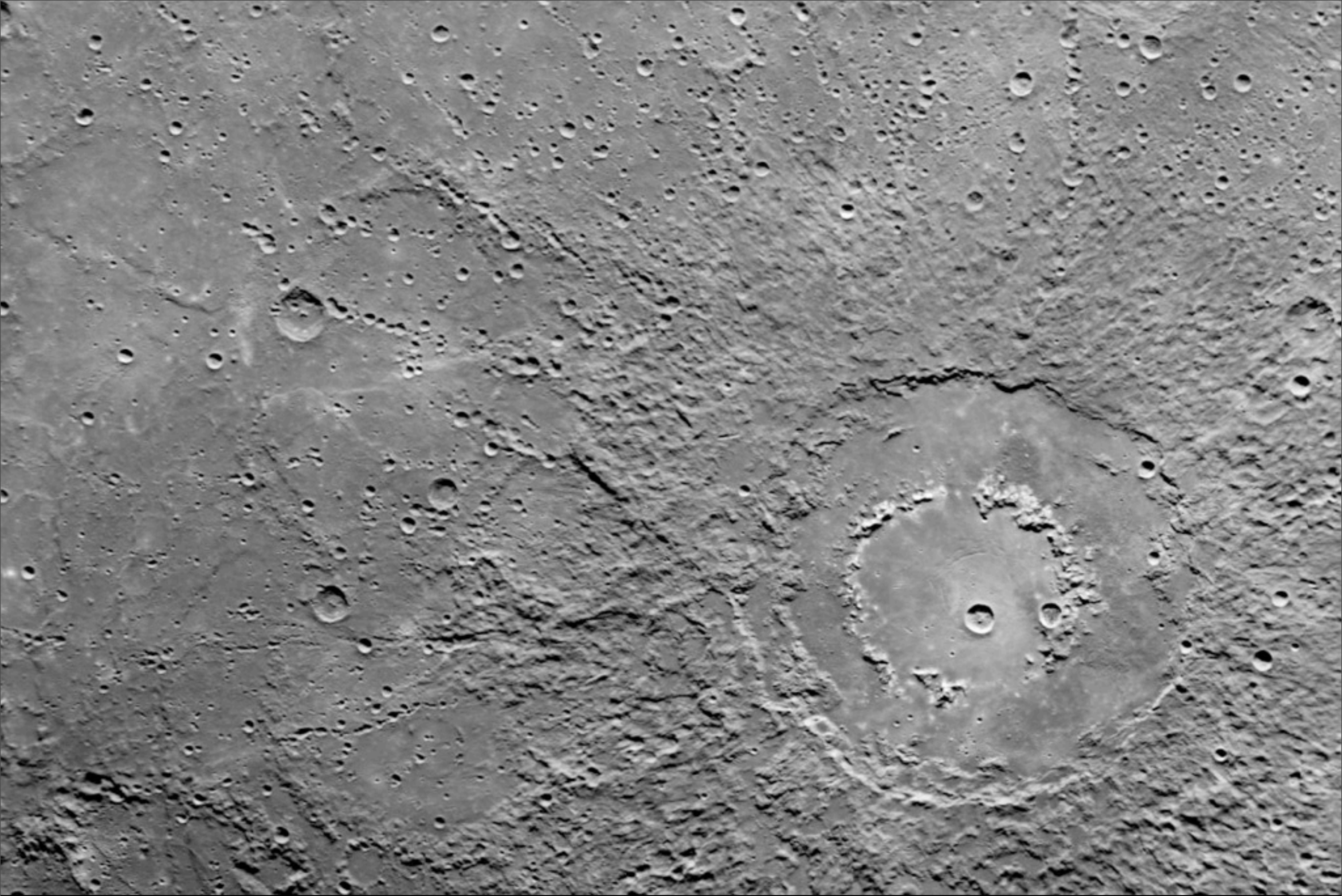
Around and between regions of heavy cratering are *intercrater plains*. Unlike the maria on the Moon, they are distributed among the heavily cratered regions instead of in broad basins, and they are much more highly cratered than the lunar maria. They don't lie obviously under or over the craters, implying the planet was resurfaced late in the accretion process.



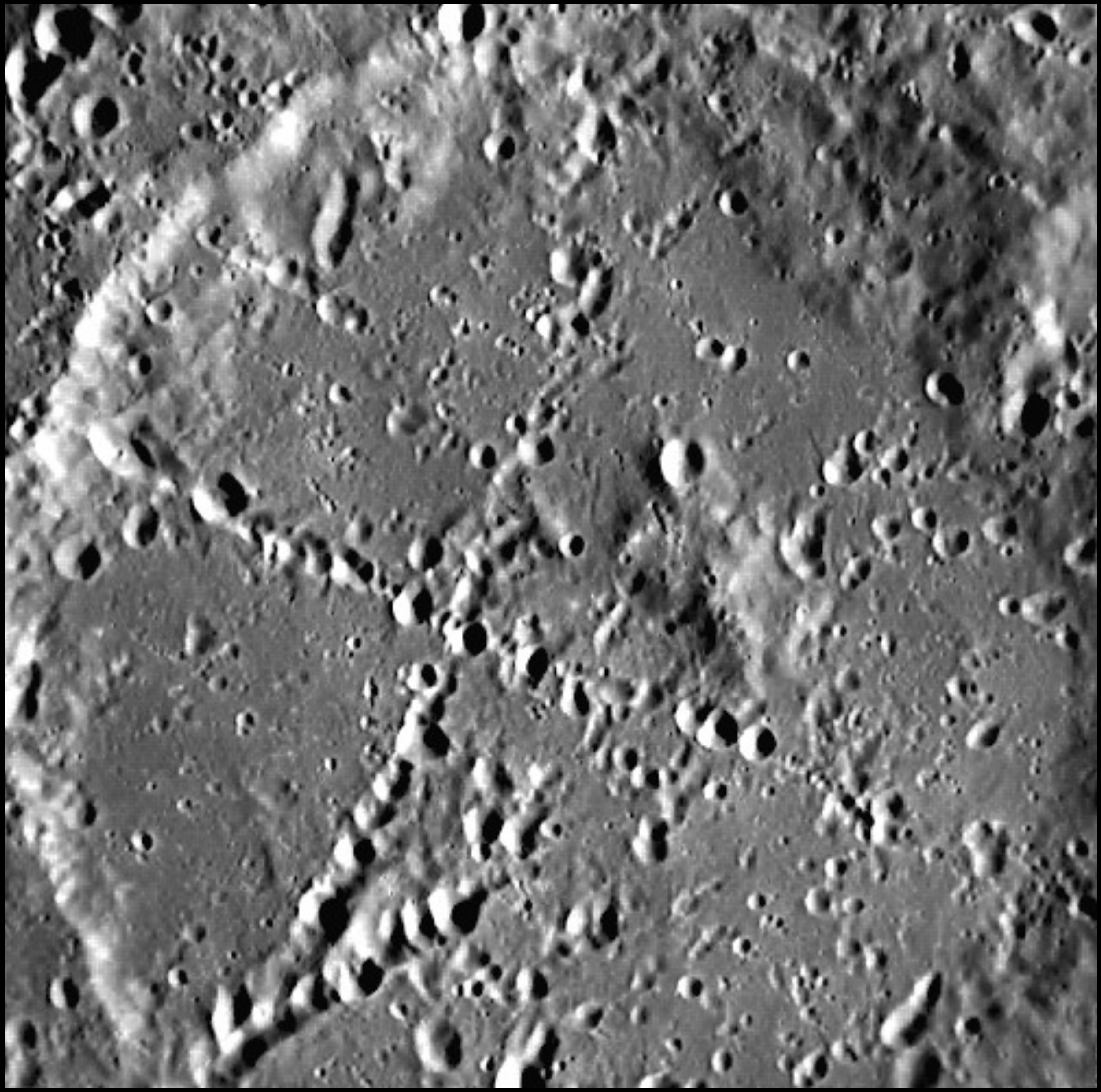
Heavily cratered terrain abutting a smooth plain, with a few young craters.

The intercrater plains are peppered with small craters, often in chains, which must be secondary craters formed by material ejected from a larger crater. These secondary craters are much more common than on the Moon, which is related to Mercury's stronger gravity (0.38g)





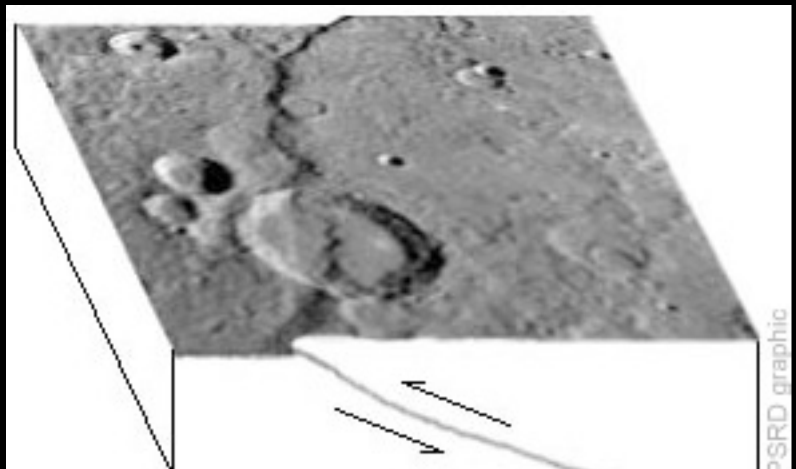
MESSENGER image of an unnamed double ring crater, showing multiple crater chains



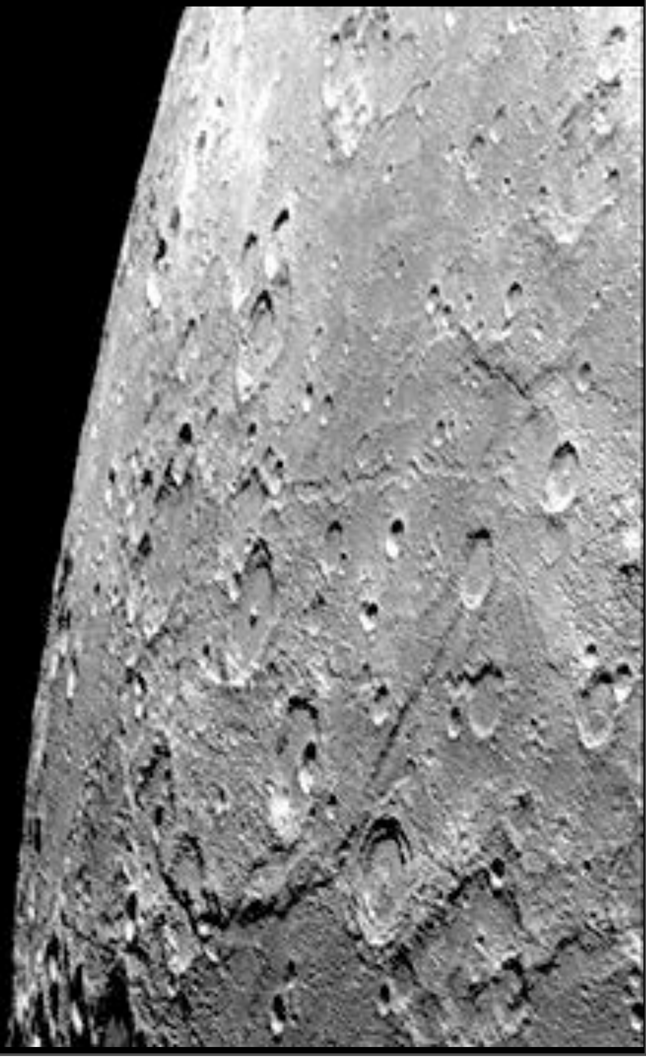
X marks the spot: two crossing crater chains

Mercury shows long linear features: *scarps* and *troughs*. The scarps are between 500–1000 m in height and can be several hundred km long. They are thought to have formed as the interior of Mercury cooled, causing the planet to contract slightly.

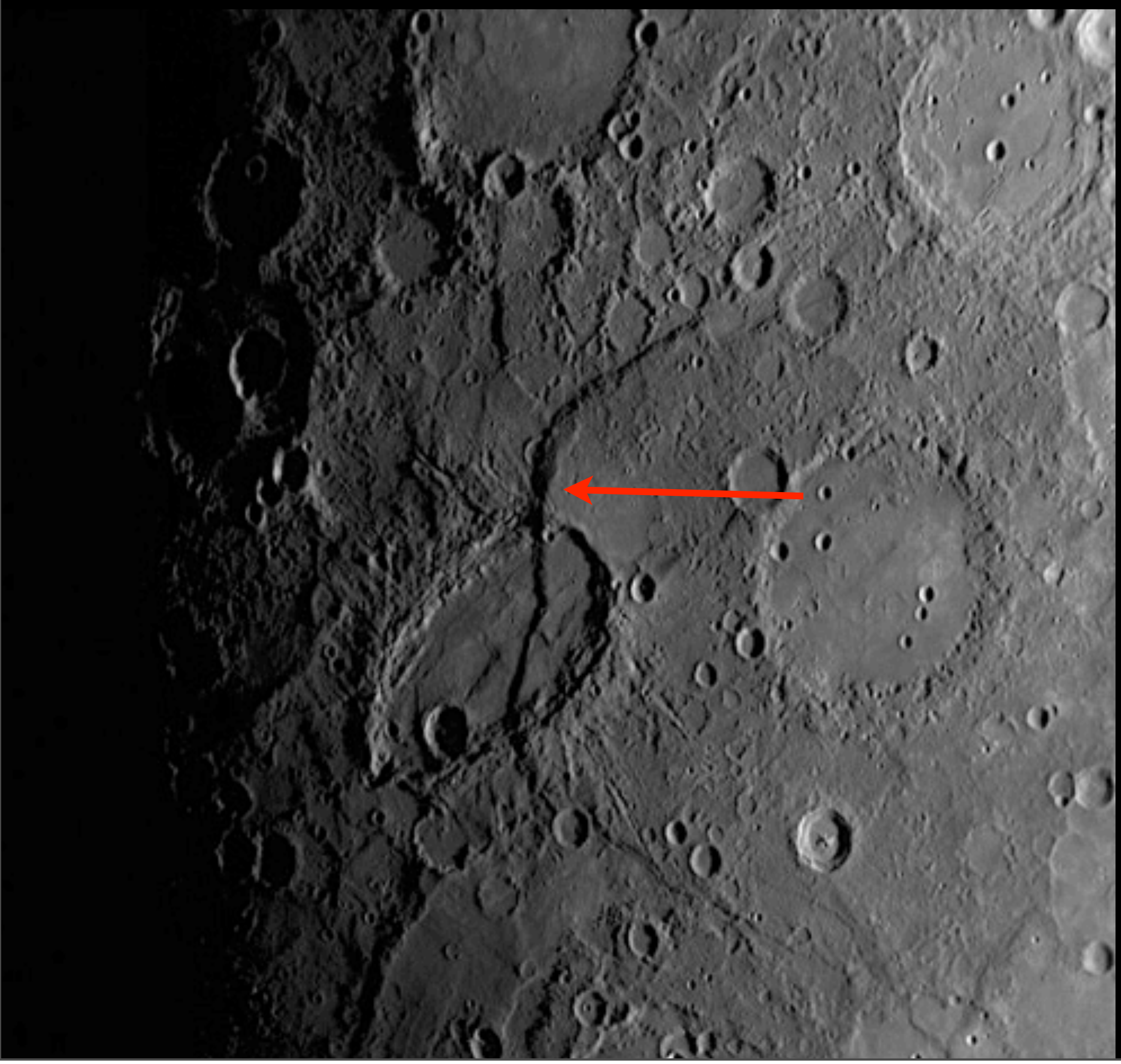
Discovery Rupes (left) and Hero Rupes (right). Below, a picture of how the ground may have shifted to produce the scarp.

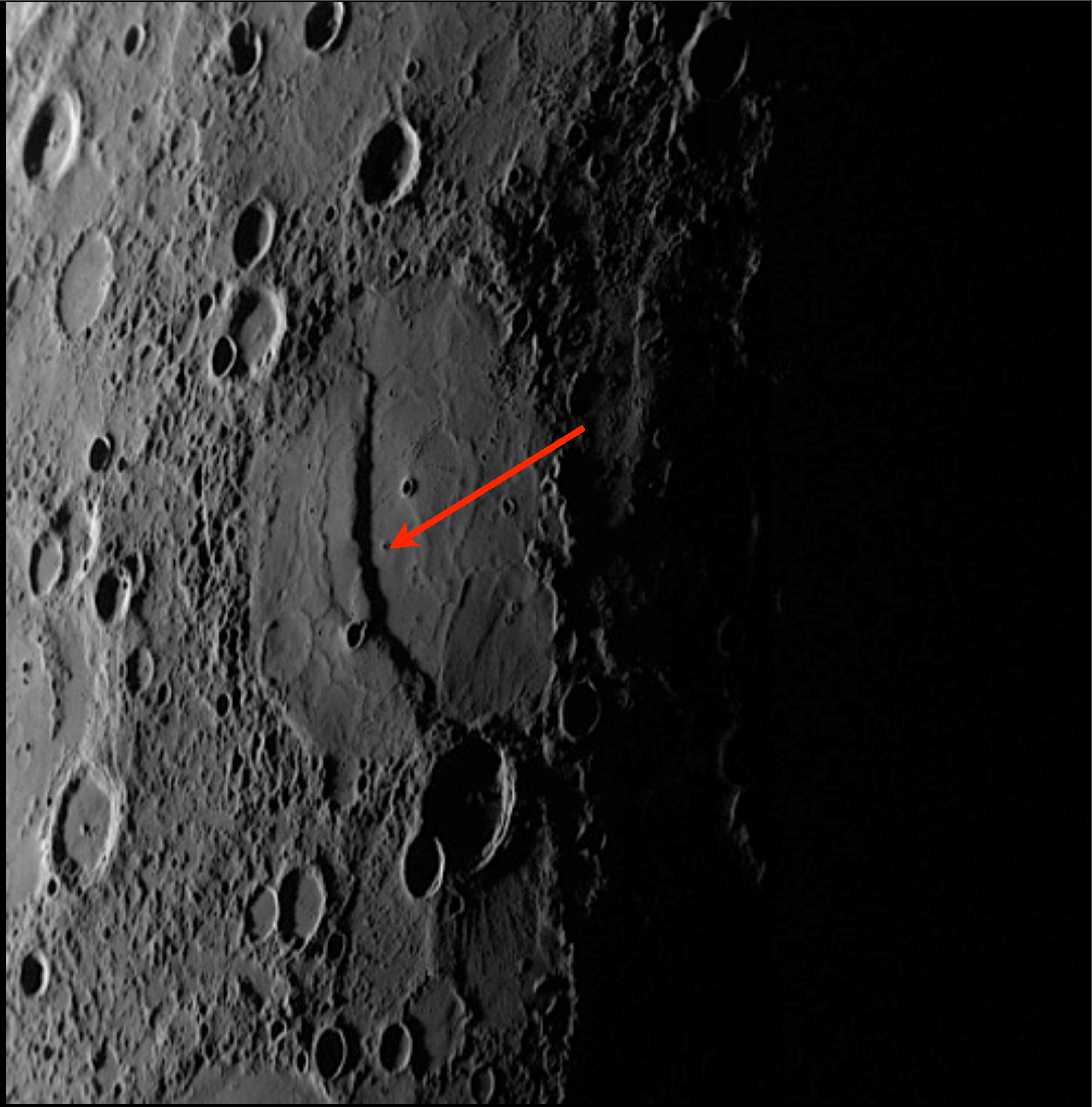


Discovery Rupes schematic



The fact that some scarps cut across craters, while others are partially obliterated by craters, suggest they were formed during the period of heavy bombardment.

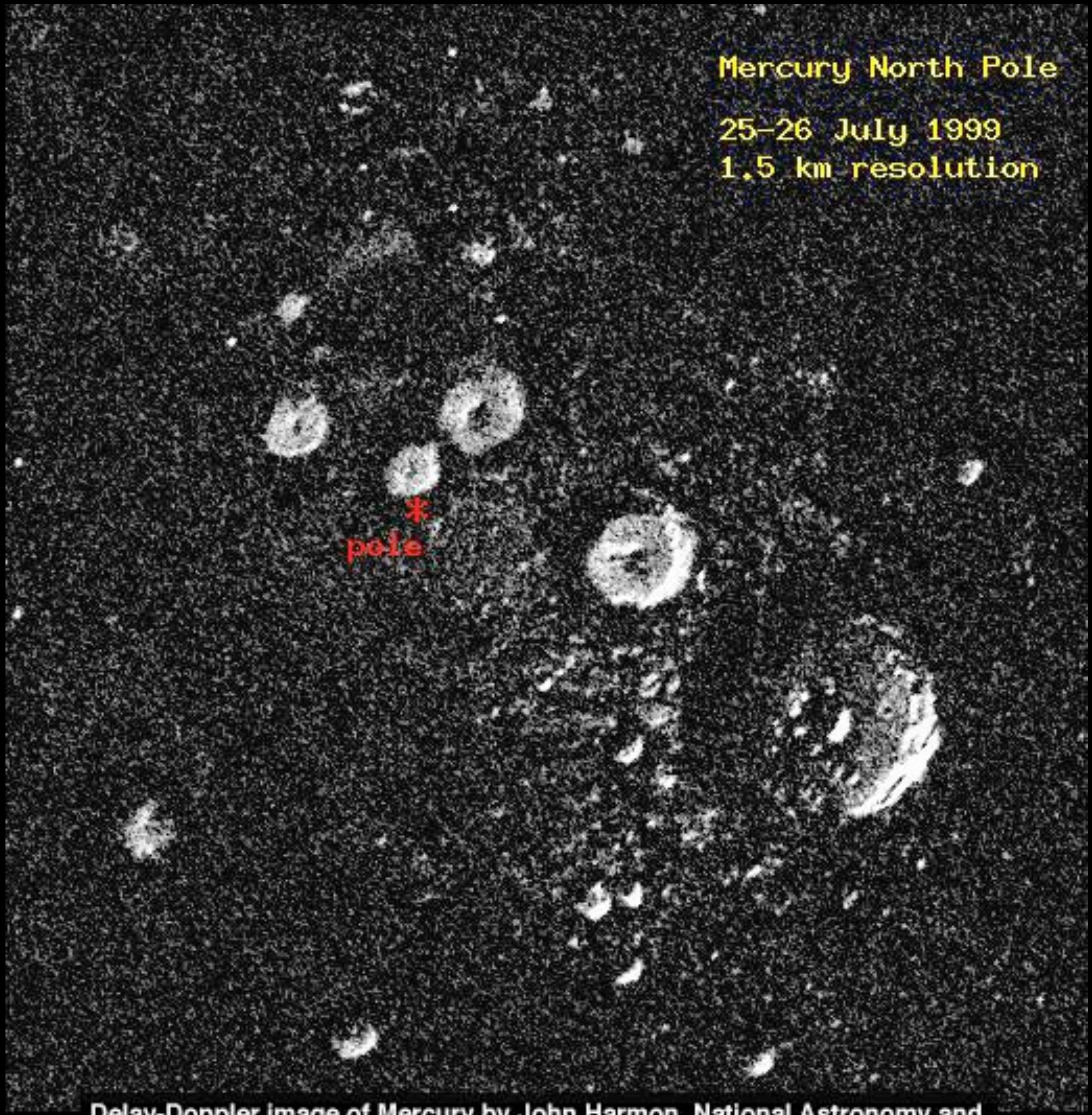




(above) The scarp bisecting the crater must have formed after the large crater filled with lava (almost burying a smaller crater)

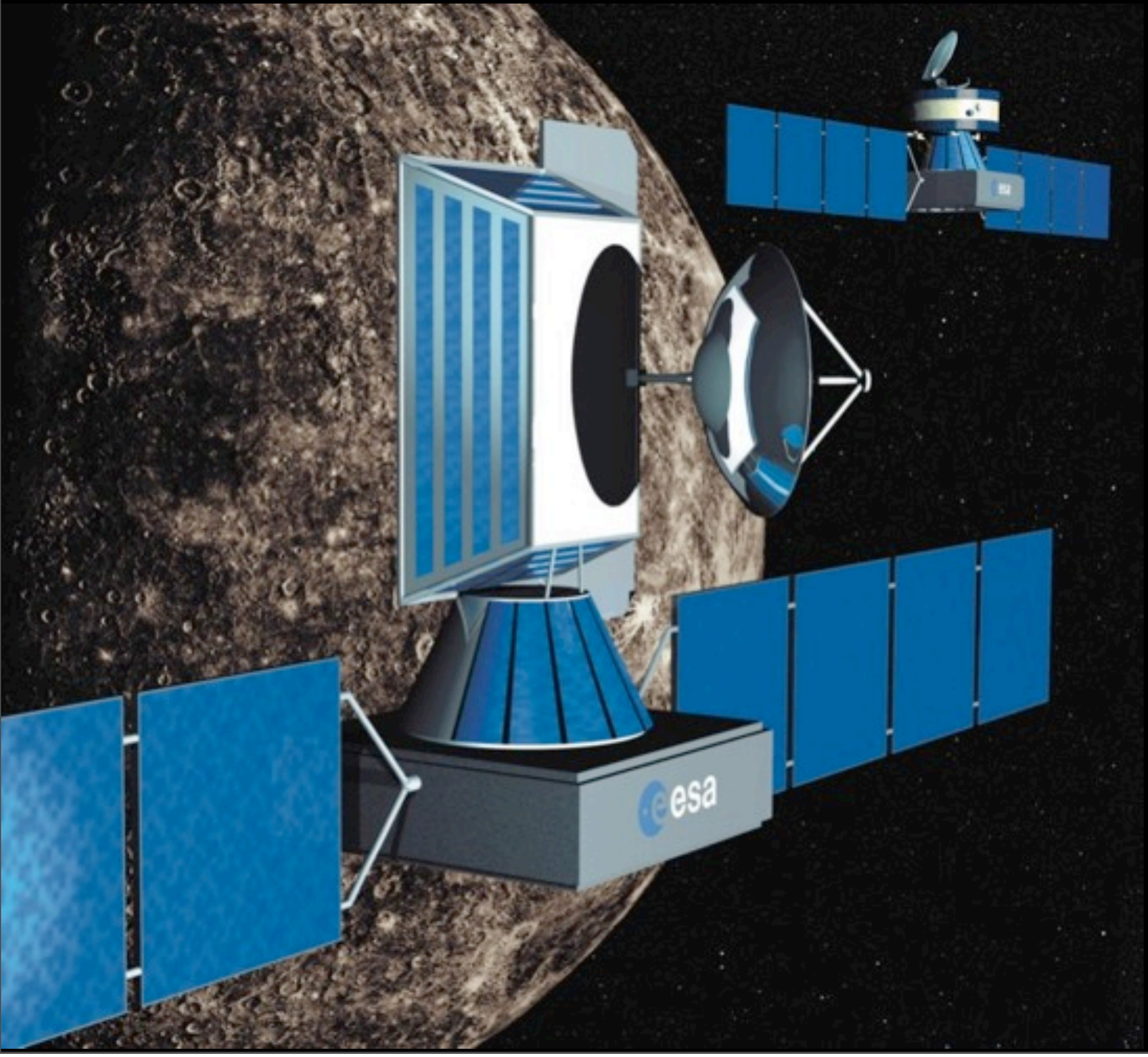
(left) Beagle Rupes is more than 600 km long and bisects an unusual elliptical crater, Sveinsdóttir crater; the scarp is almost a kilometre high.

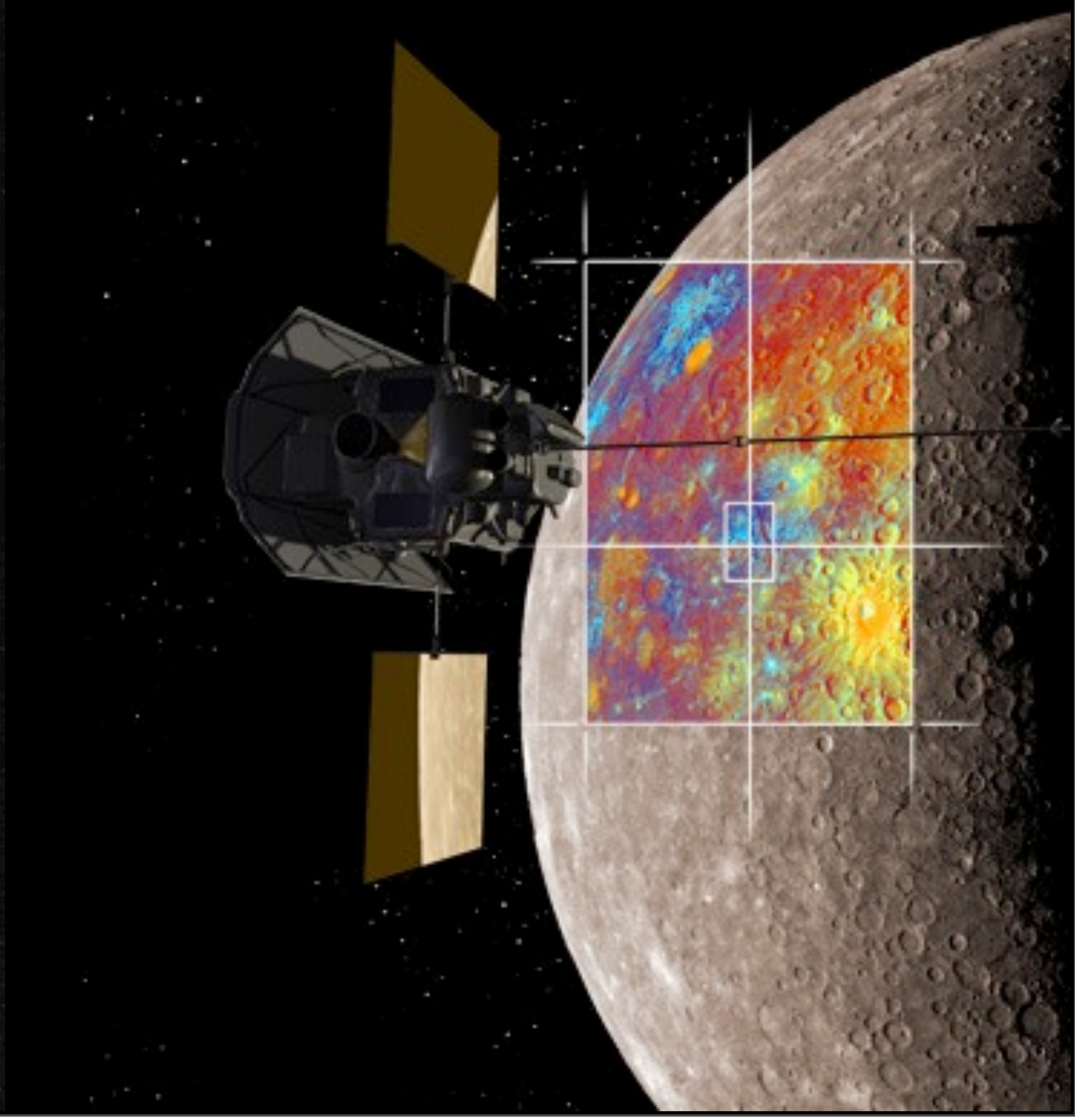
Earth-based radar observations show strong radar reflections from permanently shadowed craters near the north pole. These could represent deposits of ice inside the craters, possibly just below the surface.



Delay-Doppler image of Mercury by John Harmon, National Astronomy and Ionosphere Center, Arecibo Observatory, Puerto Rico.

There is still much we don't know about Mercury. We'll have to wait for MESSENGER to complete its mission, and for BepiColombo to arrive, to learn more.



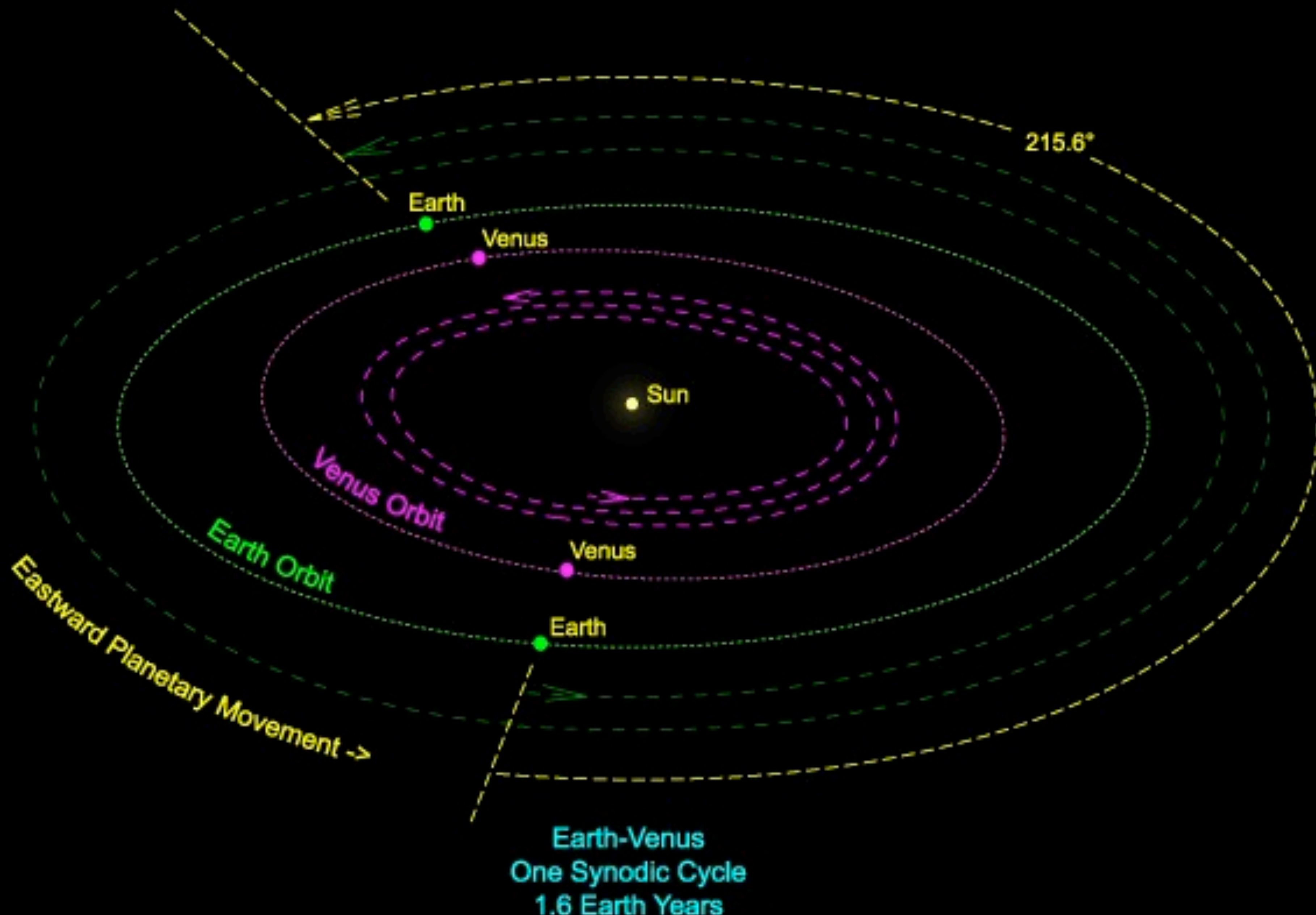


Venus

Basic data

	Venus	Venus/Earth
Mass	4.8685×10^{24} kg	0.815
Radius	6052 km	0.95
Mean density	5.243 g/cm^3	0.943
Gravity	8.87 m/s^2	0.907
Semi-major axis	108.21×10^6 km	0.723
Period	224.7 d	0.615
Orbital inclination	3.39°	-
Orbital eccentricity	0.0067	0.401
Rotation period	–243.686 d (retrograde)	243.686
Length of day	2802 h	116.75

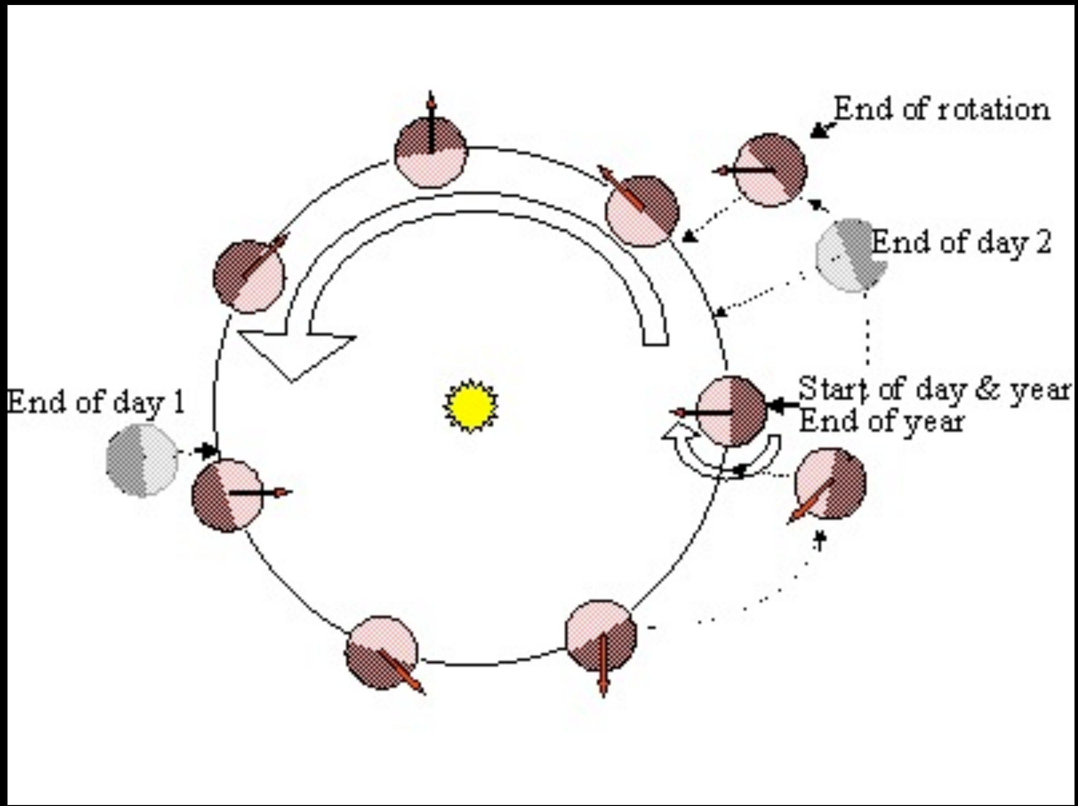
Venus' orbital period is almost exactly 5/8 of a year, so Earth and Venus are in a 5:8 resonance. This means that inferior conjunction occurs every 1.6 years, during which time Venus has covered 2.6 orbits. After eight years, the two planets are back to almost the same position (off by about 2°).

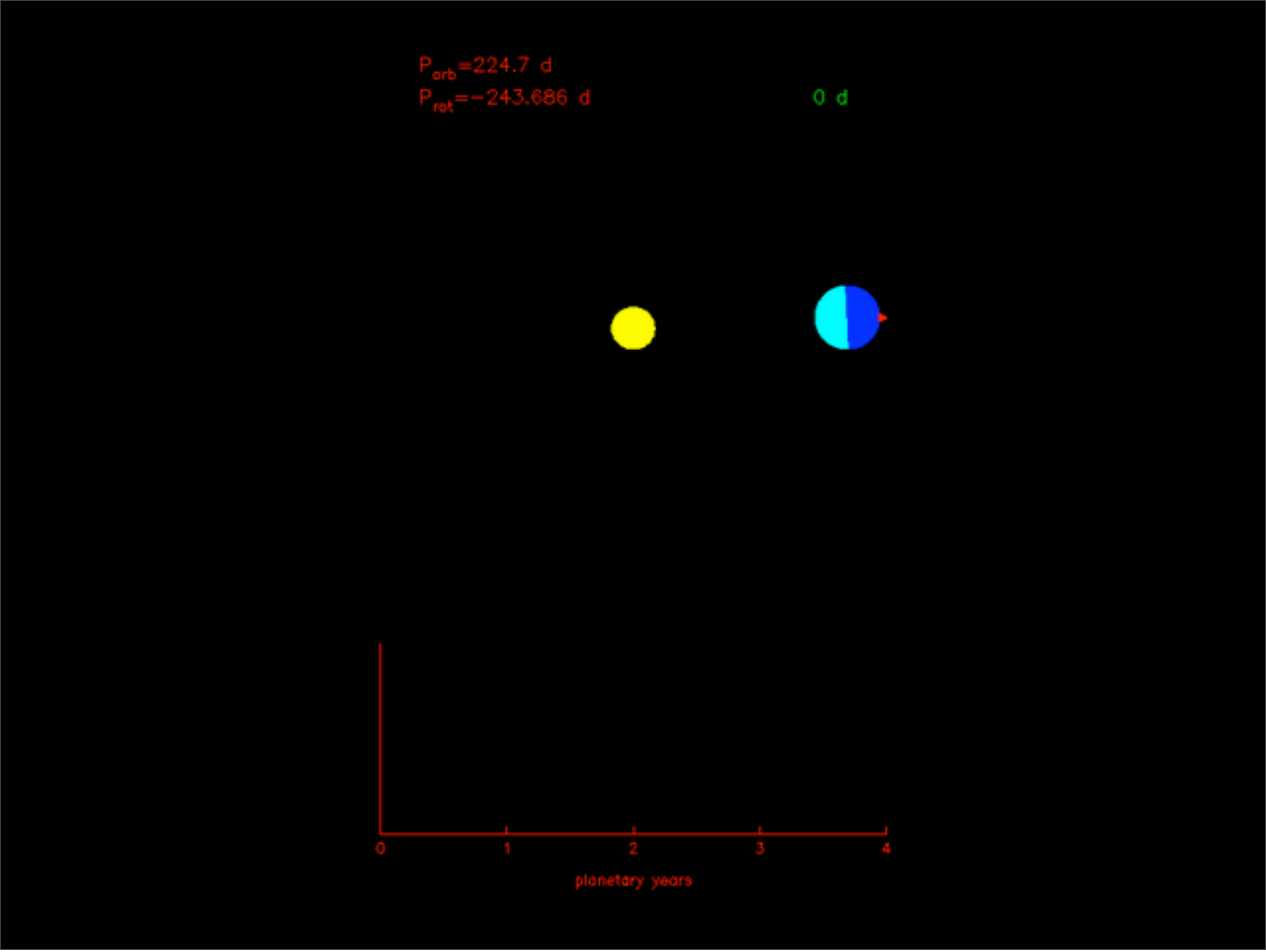


Venus' rotation period is 243 days in the opposite sense to its orbit: Pluto is the only other planet with retrograde rotation.

This means the solar day (the time between sunrise and sunrise) is 117 days.

To an observer on the surface, the sun rises in the west and sets in the east 59 (Earth) days later, so the sun rises and sets twice a year.





P_{orb}=224.7 d
P_{rot}=-243.686 d
0 d
0
1
2
3
4
planetary years

Aside: *Mathematical details for those who are interested*: The length of the day P_{day} is given by

$$P_{\rm day} = \frac{P_{\rm year} \times P_{\rm rot}}{P_{\rm year} - P_{\rm rot}}$$

where P_{year} is the length of the planet's year, and P_{rot} is the planet's rotation period. This is the same equation we came across when we were discussing the time between planetary conjunctions – the "beat period".

We can express this in a slightly more useful way by saying the number of days per year $N_{day}=P_{year}/P_{day}$ is given by the number of rotation periods per year minus 1:

$$N_{\rm day} = \frac{P_{\rm year}}{P_{\rm rot}} - 1$$

where negative P_{rot} represents retrograde rotation.

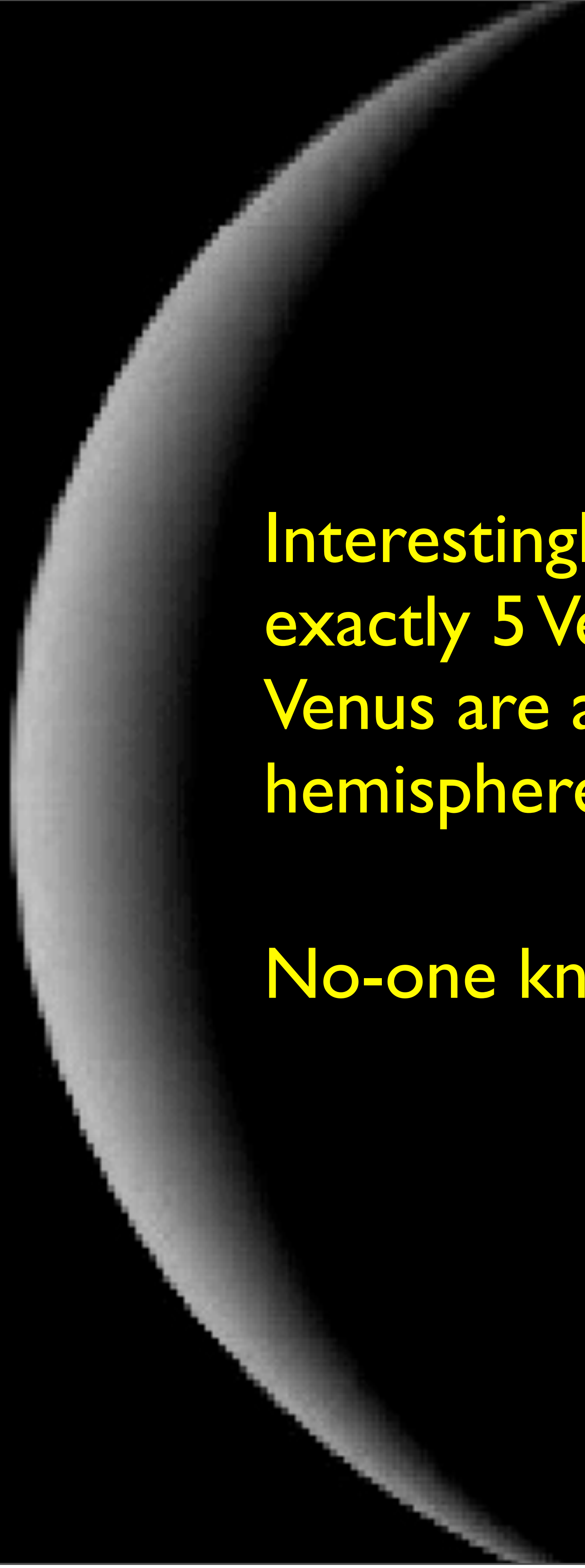
The Earth's rotation period is so much smaller than its year that we don't notice the difference between the length of the day (24h) and the length of the Earth's rotation period (23h56m), except that astronomers notice because the stars all rise 4m earlier every night. But when the rotation period is comparable to the year, the difference between the two is very pronounced indeed.

So for Venus, P_{year} = 224.7 d, P_{rot} = –243.686 d, so you can verify that N_{day} = –1.922, so the length of the day is P_{day} = 224.7/1.922 d = 116.9 d.

For Mercury, P_{year} = 87.969 d, P_{rot} = 58.785 d, so N_{day} = 0.496, or a day length P_{day} = 177.2 d.

So in fact Mercury is the only planet with a day longer than its year!

Note that if $P_{year} = P_{rot}$ (tidal synchronisation), the number of days per year is zero: the sun never rises and sets.



Interestingly the 584 day synodic period is almost exactly 5 Venusian days: so every time Earth and Venus are at inferior conjunction, the same hemisphere of Venus is facing us.

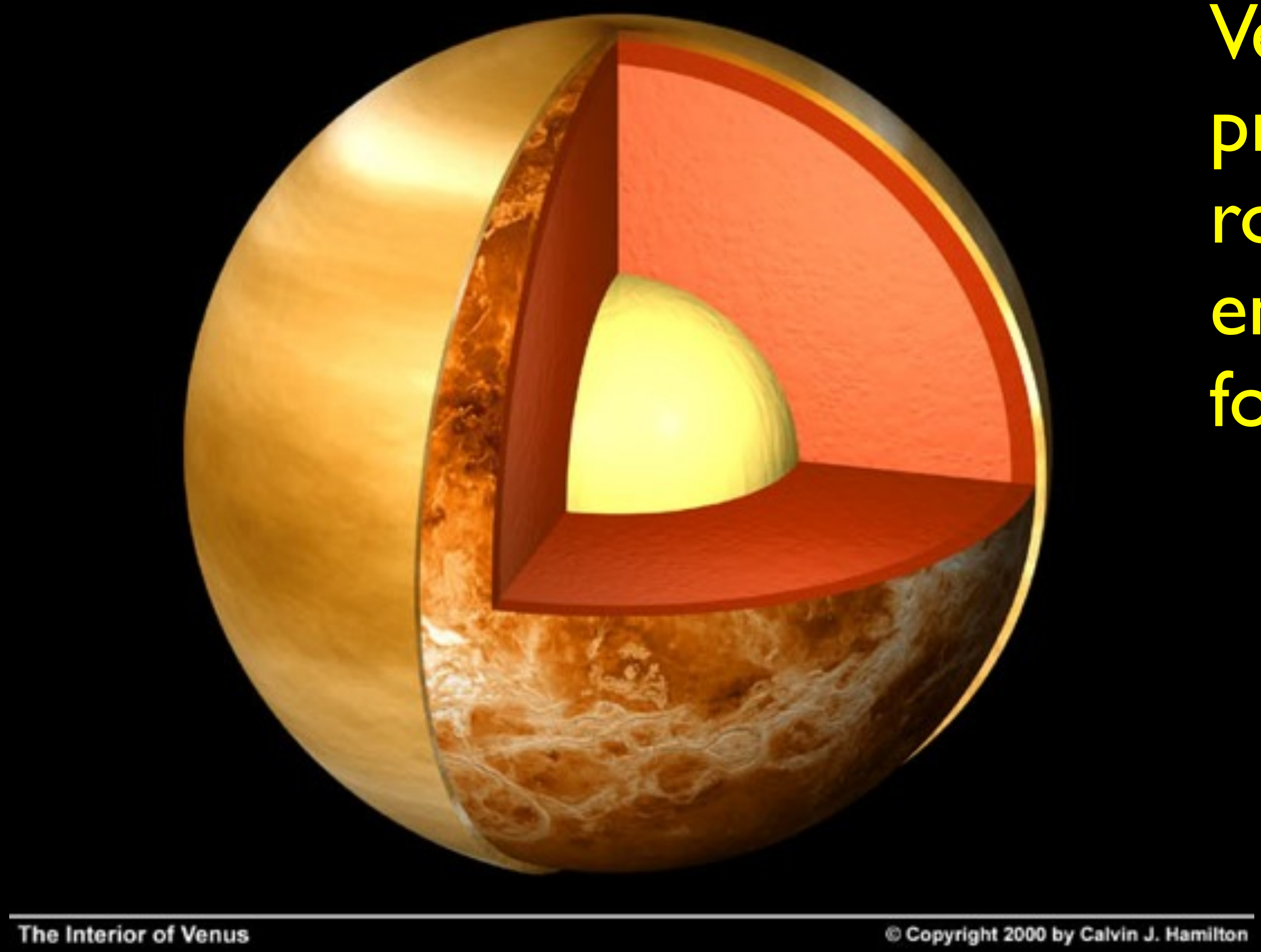
No-one know the reason for this sychronisation.

More spacecraft have visited Venus than any other planet, including three NASA Mariner missions, sixteen Soviet Venera orbiters and landers, the NASA Pioneer orbiter and probes, and more recently Galileo, Magellan and the European Venus Express, which arrived in 2006.

Venera 1	1961	Flyby (contact lost)
Mariner 2	1962	Flyby
Venera 4	1967	Probe
Mariner 5	1967	Flyby
Venera 5	1969	Probe
Venera 6	1969	Probe
Venera 7	1970	Lander
Venera 8	1972	Lander
Mariner 10	1974	Flyby
Venera 9	1975	Orbiter & lander
Venera 10	1975	Orbiter & lander
Pioneer Venus	1978	Orbiter & probes
Venera 11	1978	Lander
Venera 12	1978	Lander
Venera 13	1982	Lander
Venera 14	1982	Lander
Venera 15	1983	Orbiter
Venera 16	1983	Orbiter
Vega-1	1985	Flyby
Vega-2	1985	Flyby
Galileo	1990	Flyby
Magellan	1990	Orbiter
Messenger	2006,2007	Flyby
Venus Express	2006	Orbiter

The mean density of Venus is 5243 kg/m^3, very similar to Earth's, so it must also have an iron core.

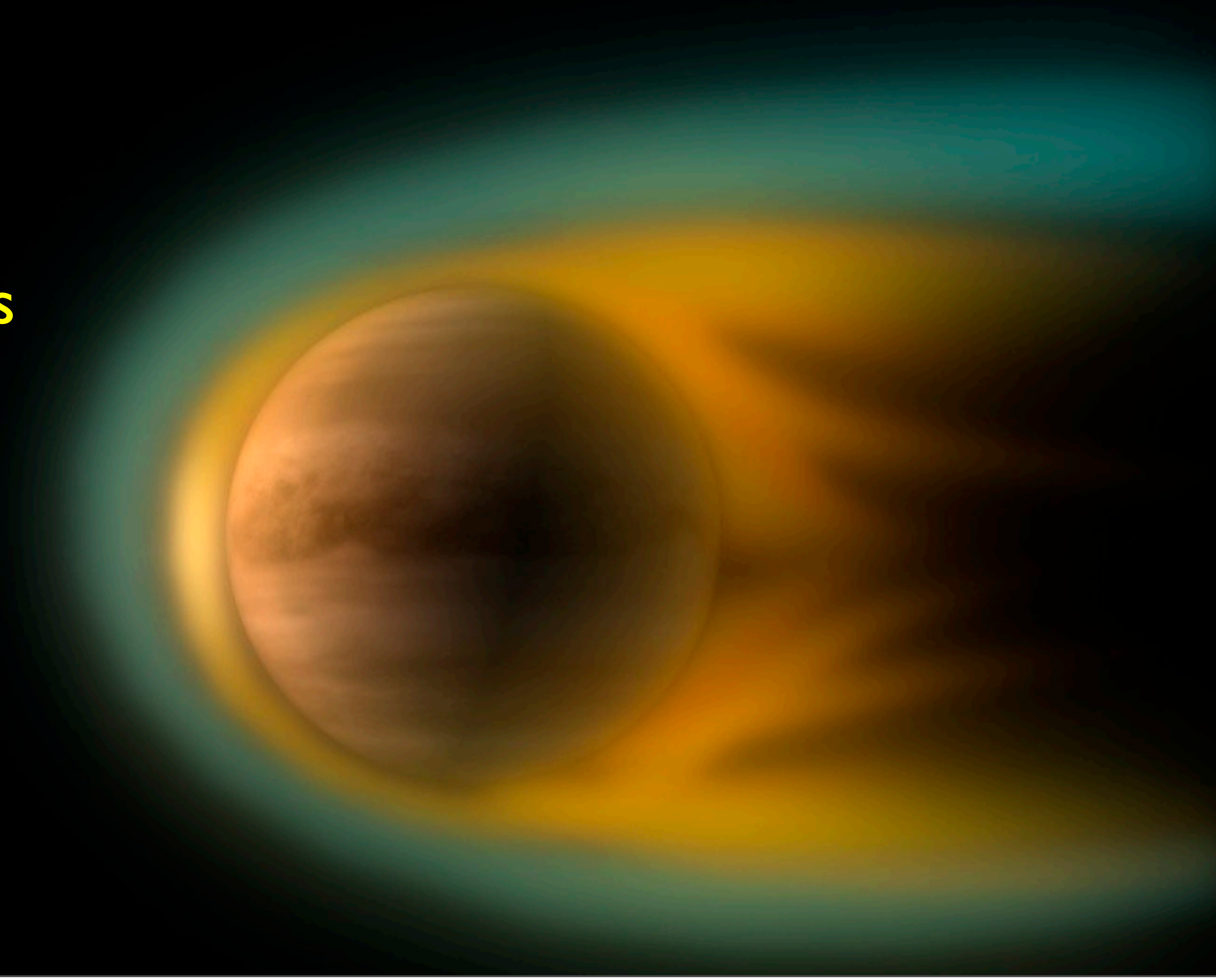
One of the outstanding questions about Venus' interior is: does Venus have plate tectonics?



Venus has no magnetic field, presumably because the slow rotation means there is not enough motion in core to form a planetary dynamo.

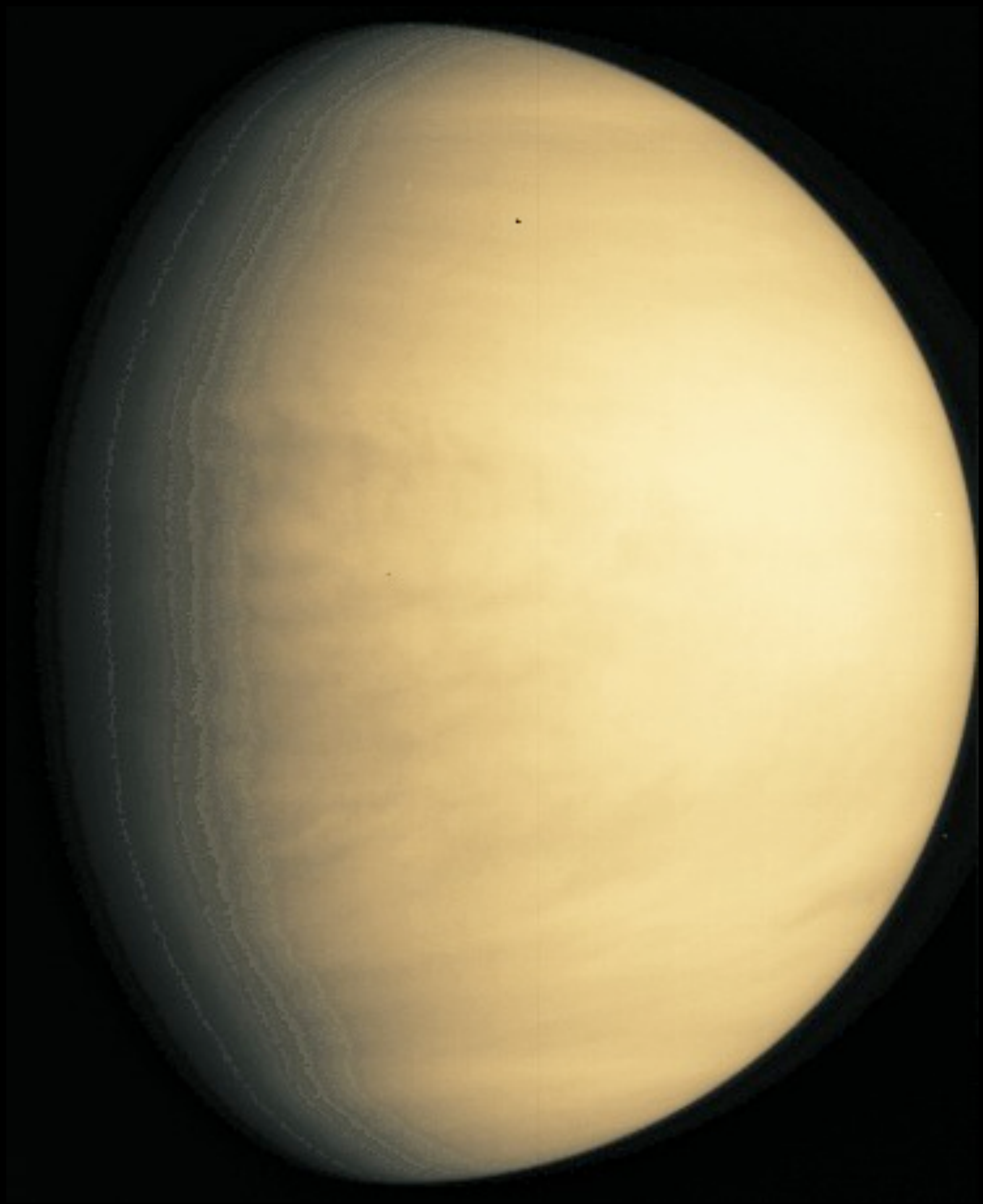
Cutaway view of the possible structure of the interior of Venus. The core is probably similar in size to Earth's, about 3000 km.

However, the interaction of the solar wind with Venus' ionosphere produces an "induced magnetosphere",. Charged particles from the Sun cause electric currents to flow in the atmosphere, which in turn produce a magnetic field around the planet. The solar wind particles eject gas from the atmosphere of Venus into space, forming an invisible comet-like tail behind the planet.

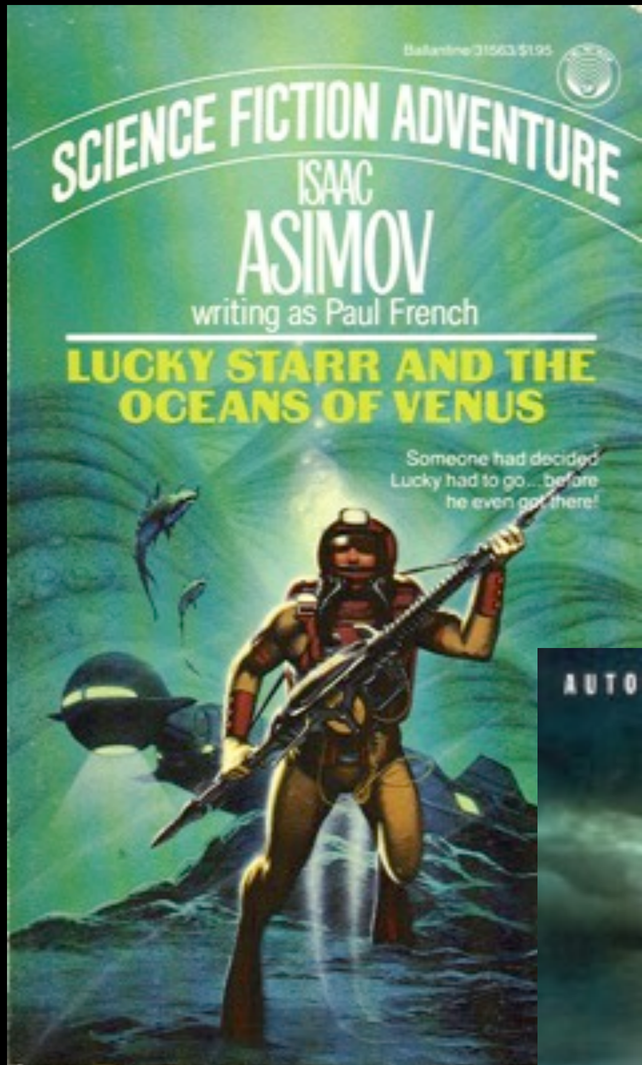


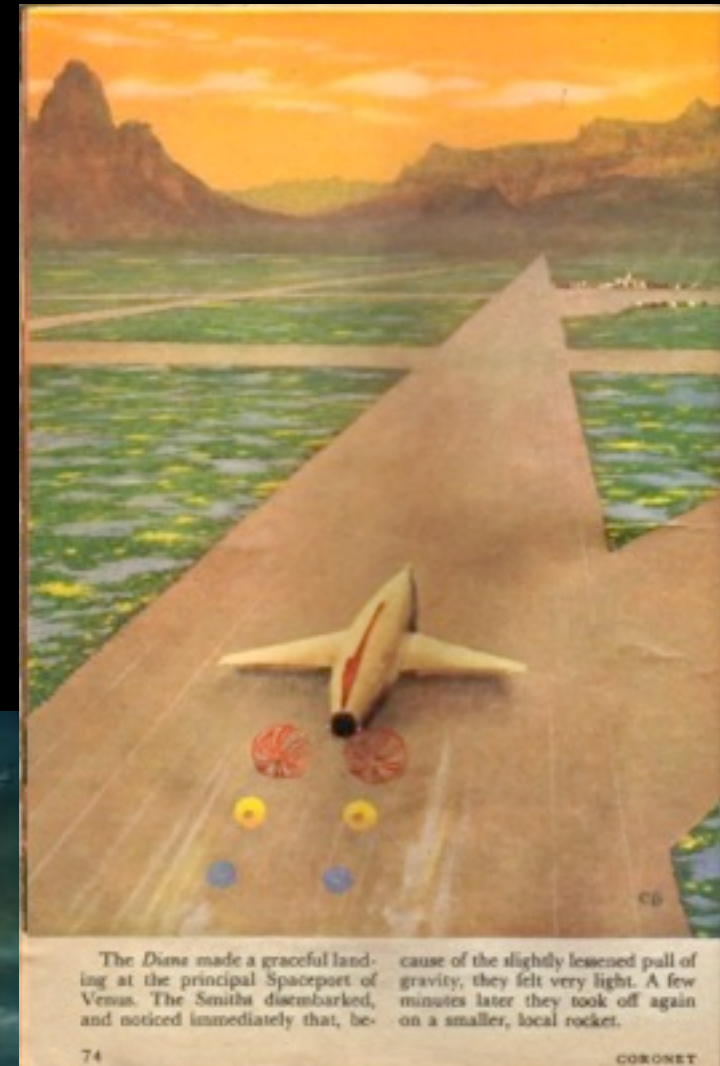
Atmosphere

Venus is completely covered by clouds. For many years this led to speculation that under the clouds Venus was



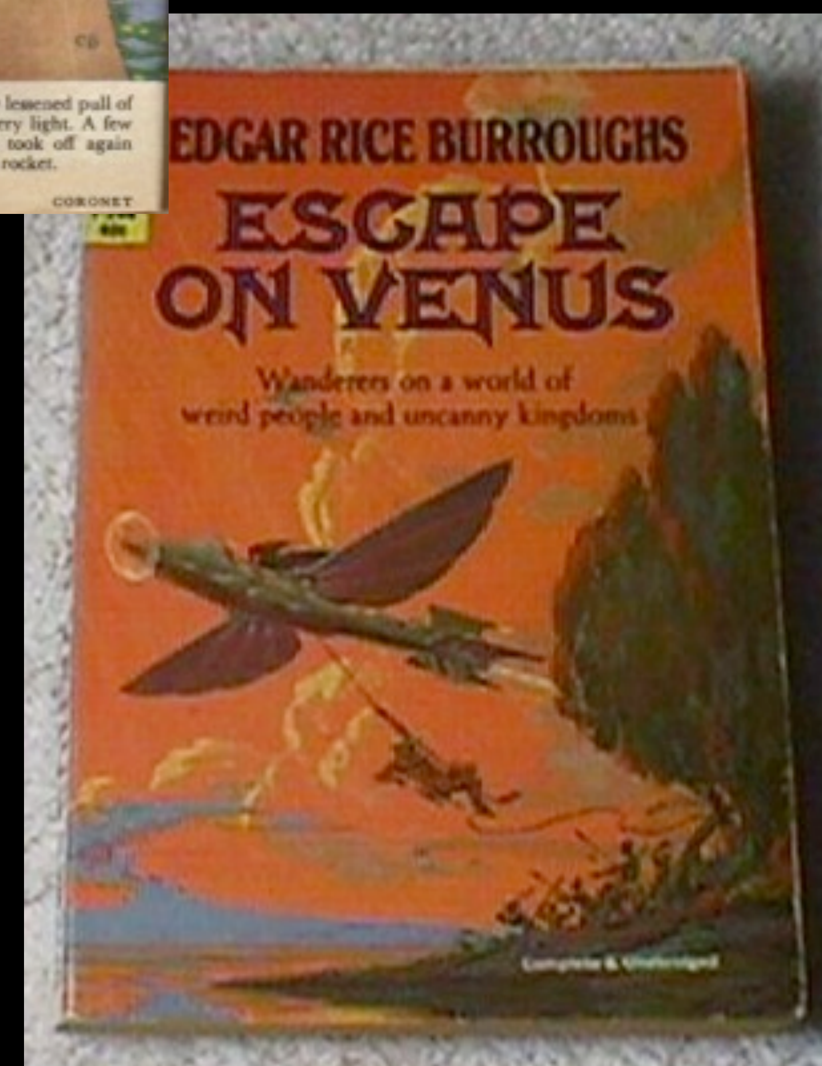
a wet planet, possibly even teeming with life, like the Carboniferous period in Earth's history.





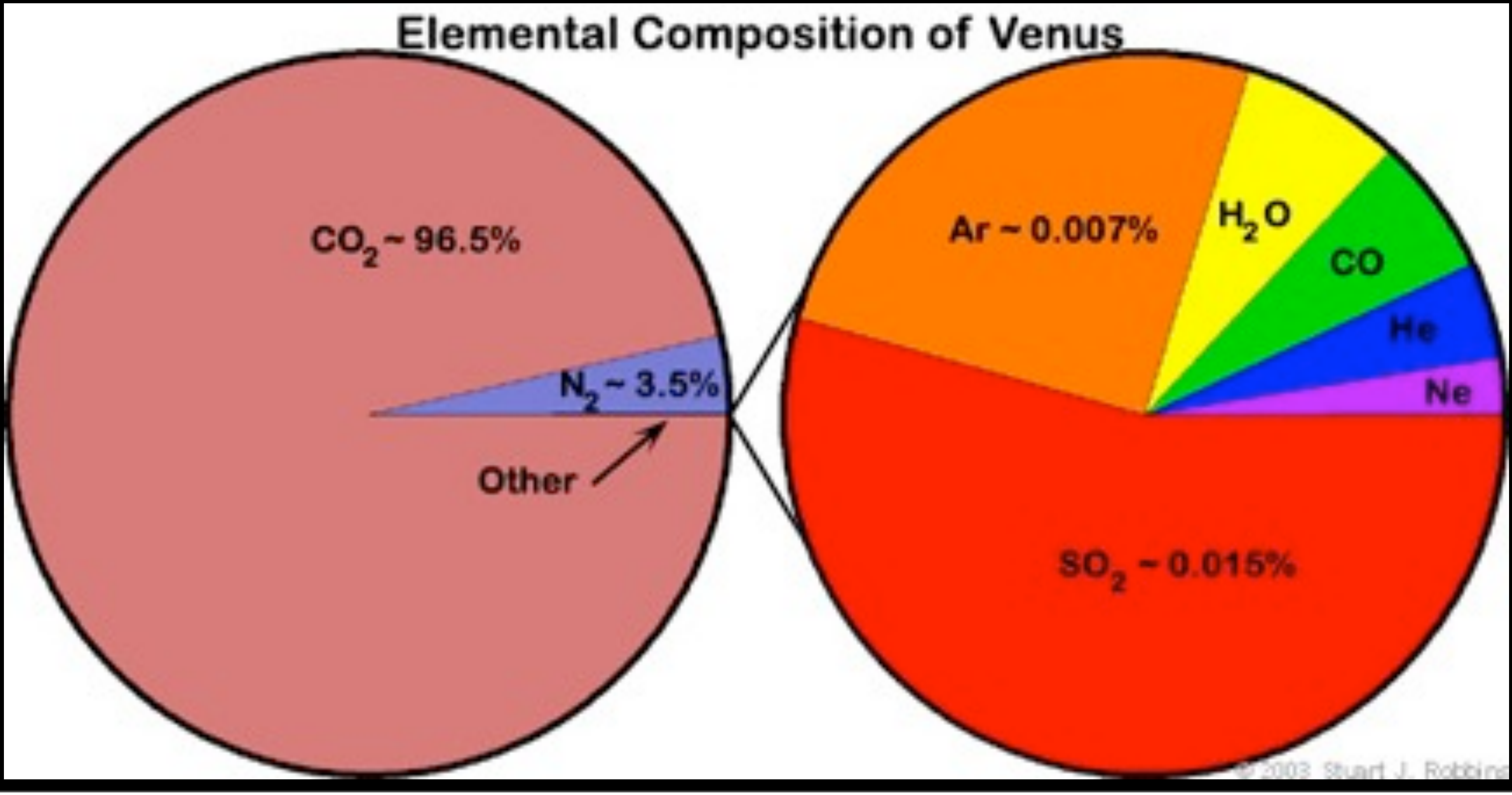
The *Diana* made a graceful landing at the principal Spaceport of Venus. The Smiths disembarked, and noticed immediately that, because of the slightly lessened pull of gravity, they felt very light. A few minutes later they took off again on a smaller, local rocket.

74 CORONET



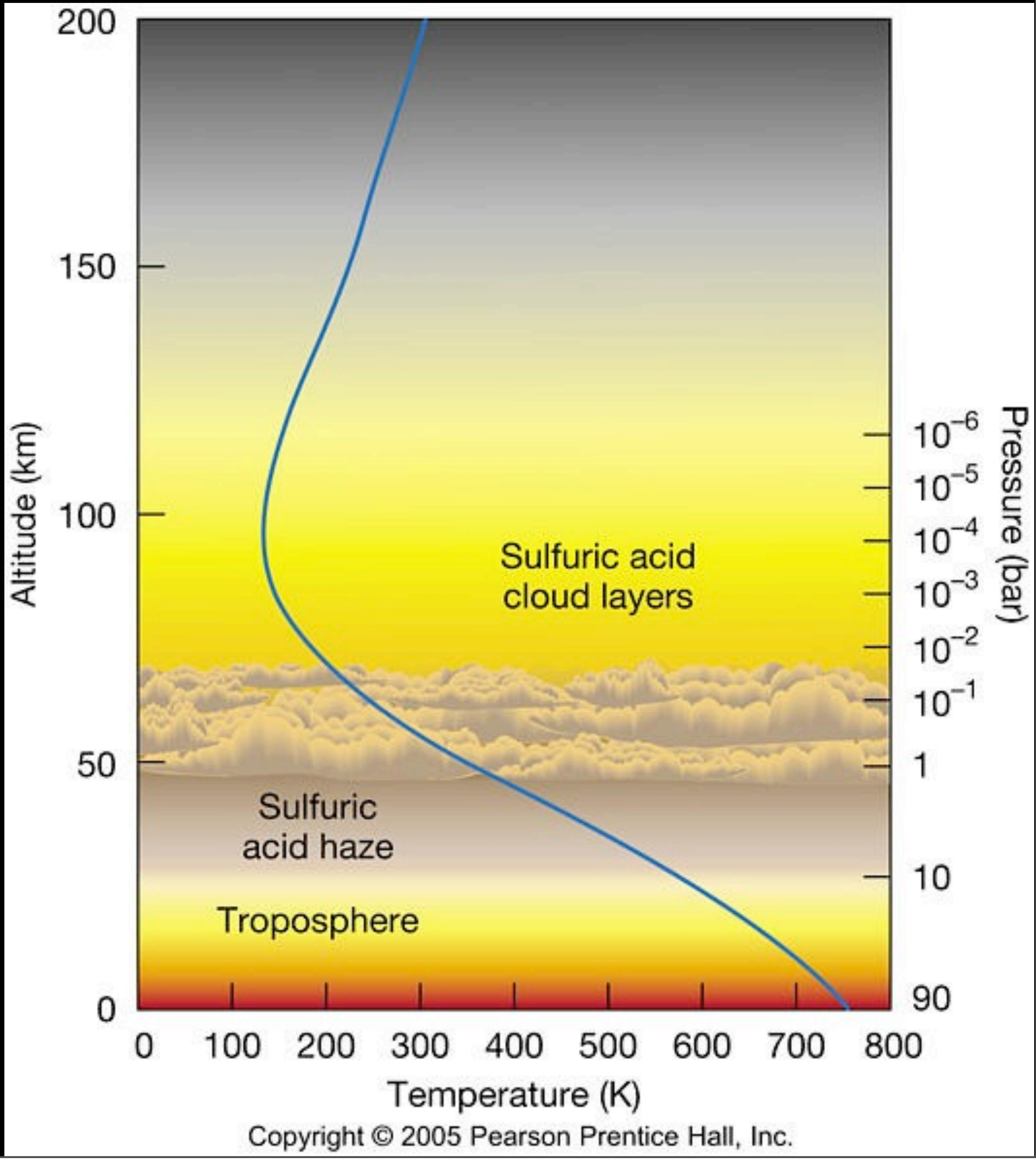
The reality is not nearly so idyllic.

The atmosphere on Venus consists of 96% CO_2, 3% N_2, and trace amounts of other chemicals. Deuterium (heavy hydrogen) is 150 times more abundant than on Earth. Argon and neon are also 50–100 more abundant on Venus.



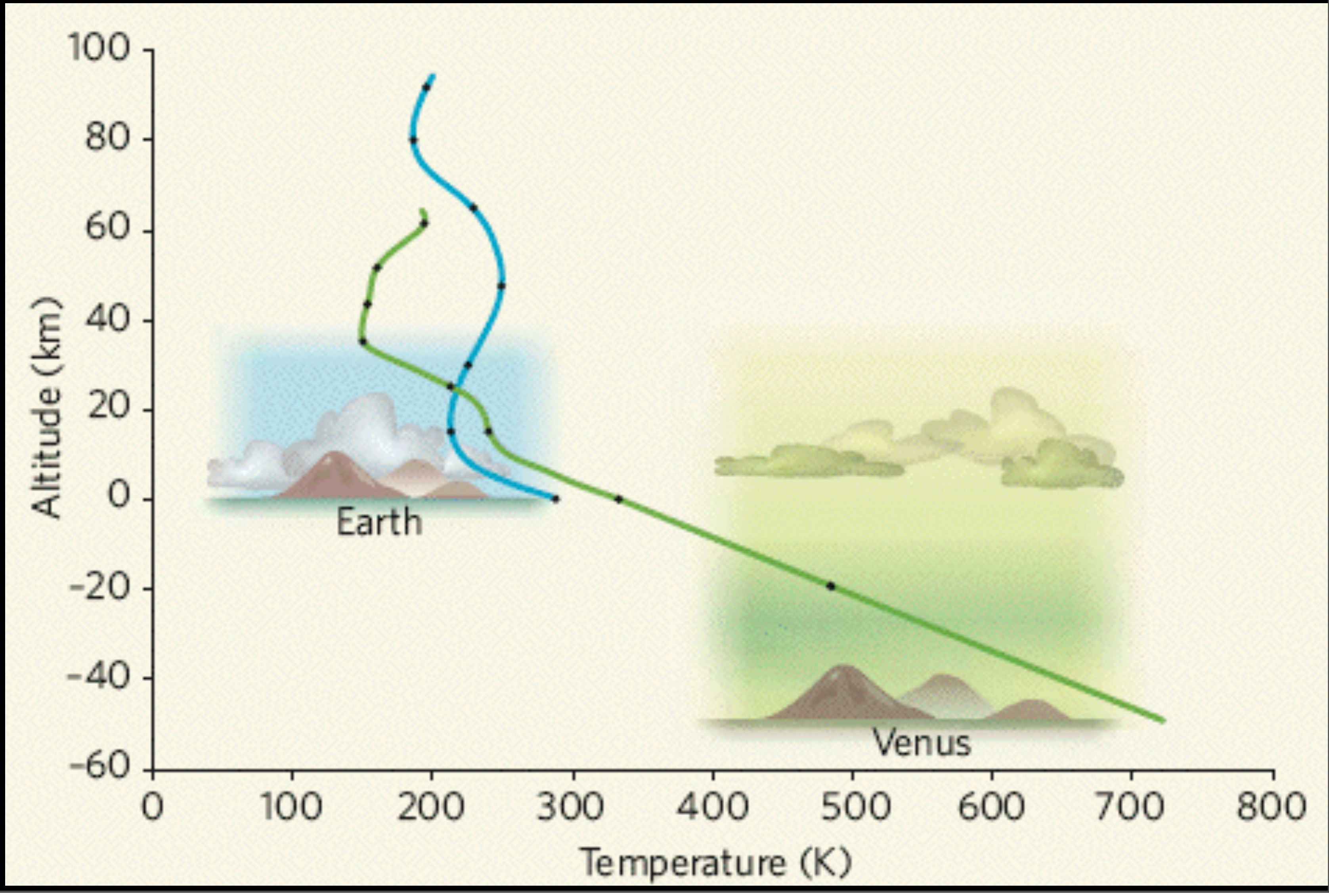
The clouds on Venus are not water vapour, but sulphuric acid. They are confined to a layer 20km thick, about 60km above the surface.

The average size of the cloud droplets is much smaller than in clouds on Earth, so the density of the clouds is much lower: it would seem more like fog than cloud, but fog without end.

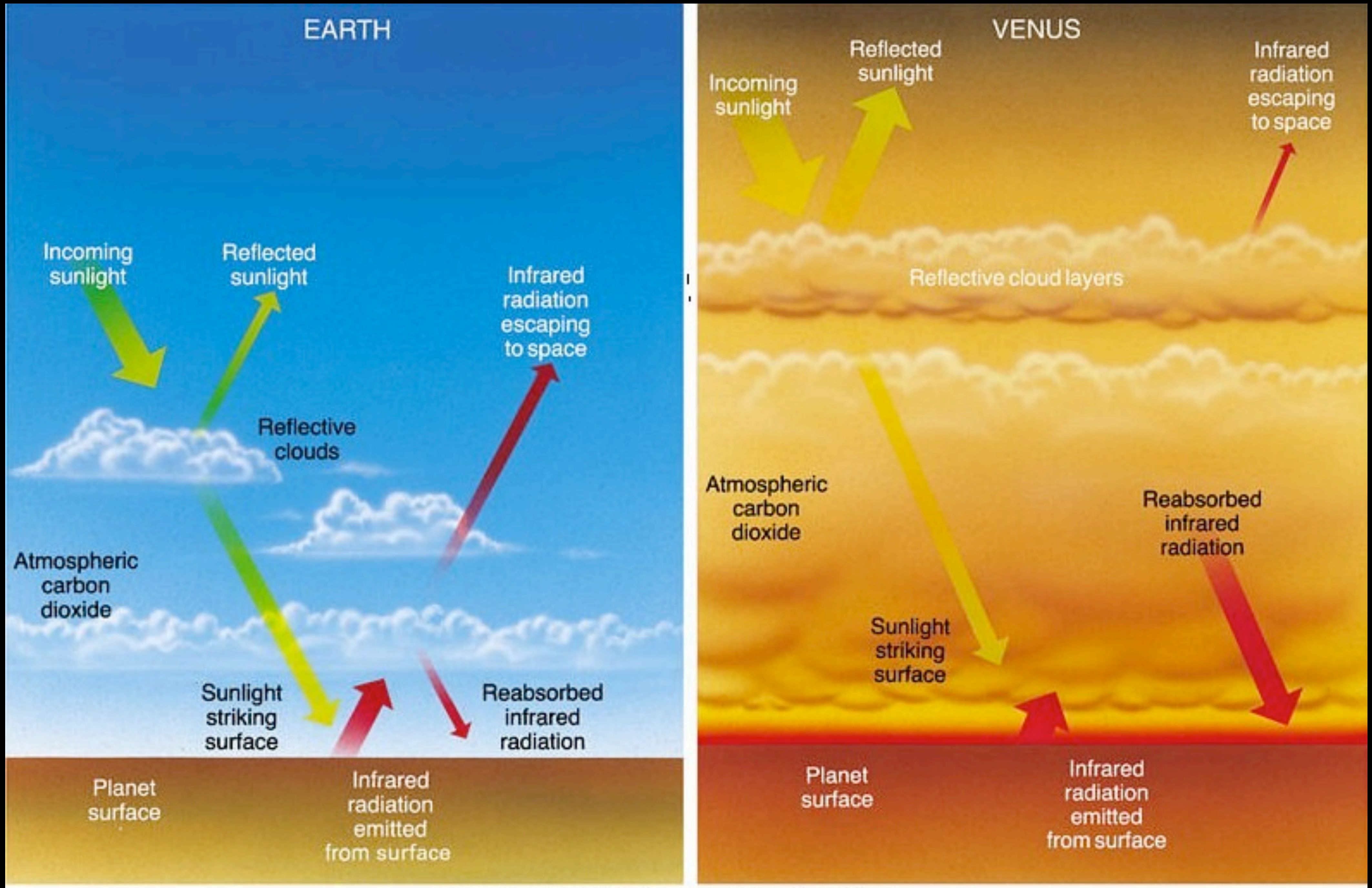


The pressure at the surface is 90 times the air pressure on Earth – the same pressure found at a depth of 1 km in Earth's oceans.

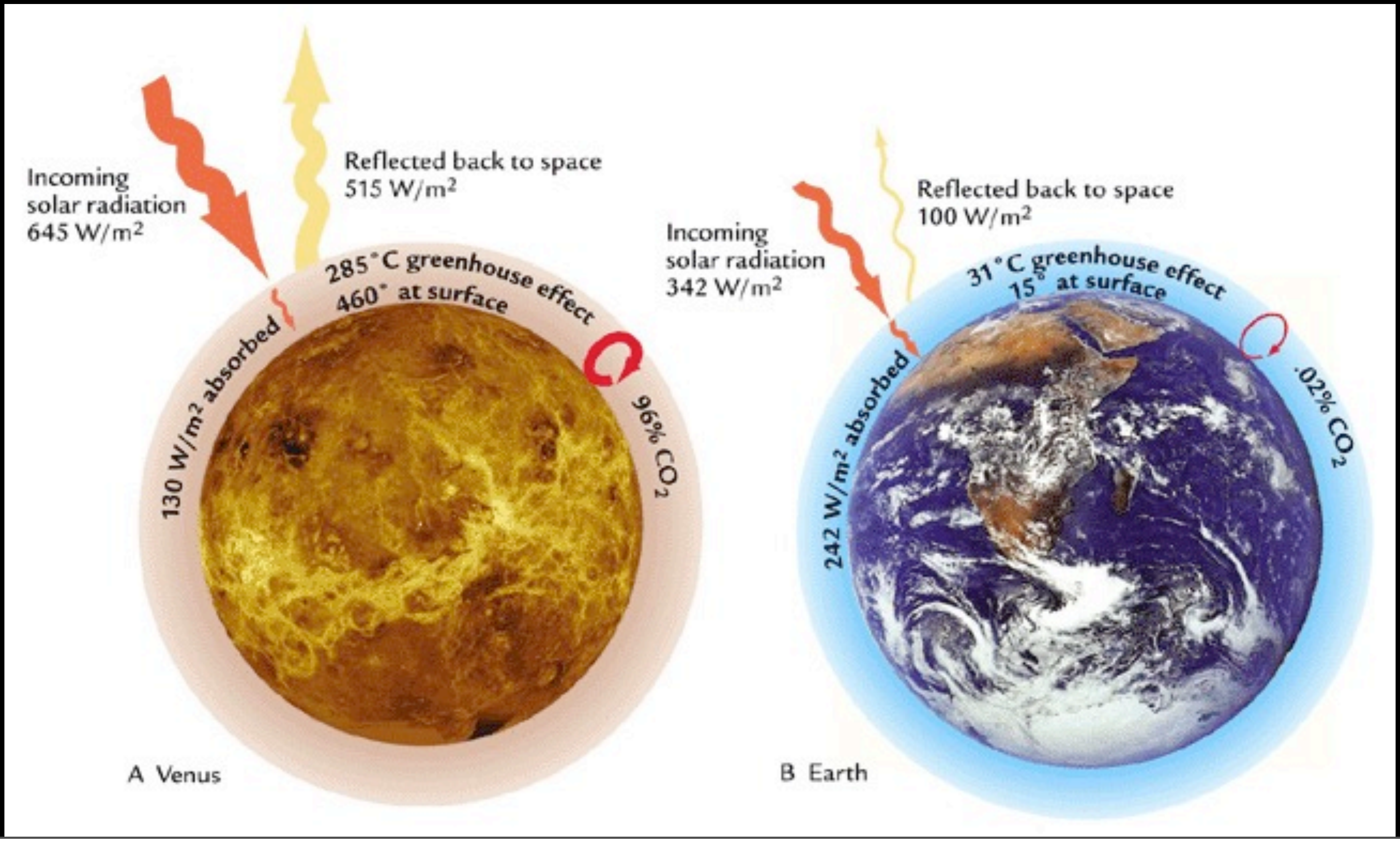
The temperature at the surface is 740 K (470° C), hot enough to melt lead.



The surface of Venus is so hot because of the *greenhouse effect*. Carbon dioxide in the atmosphere traps heat radiated from the ground, which is reabsorbed by the ground, raising the temperature still further.



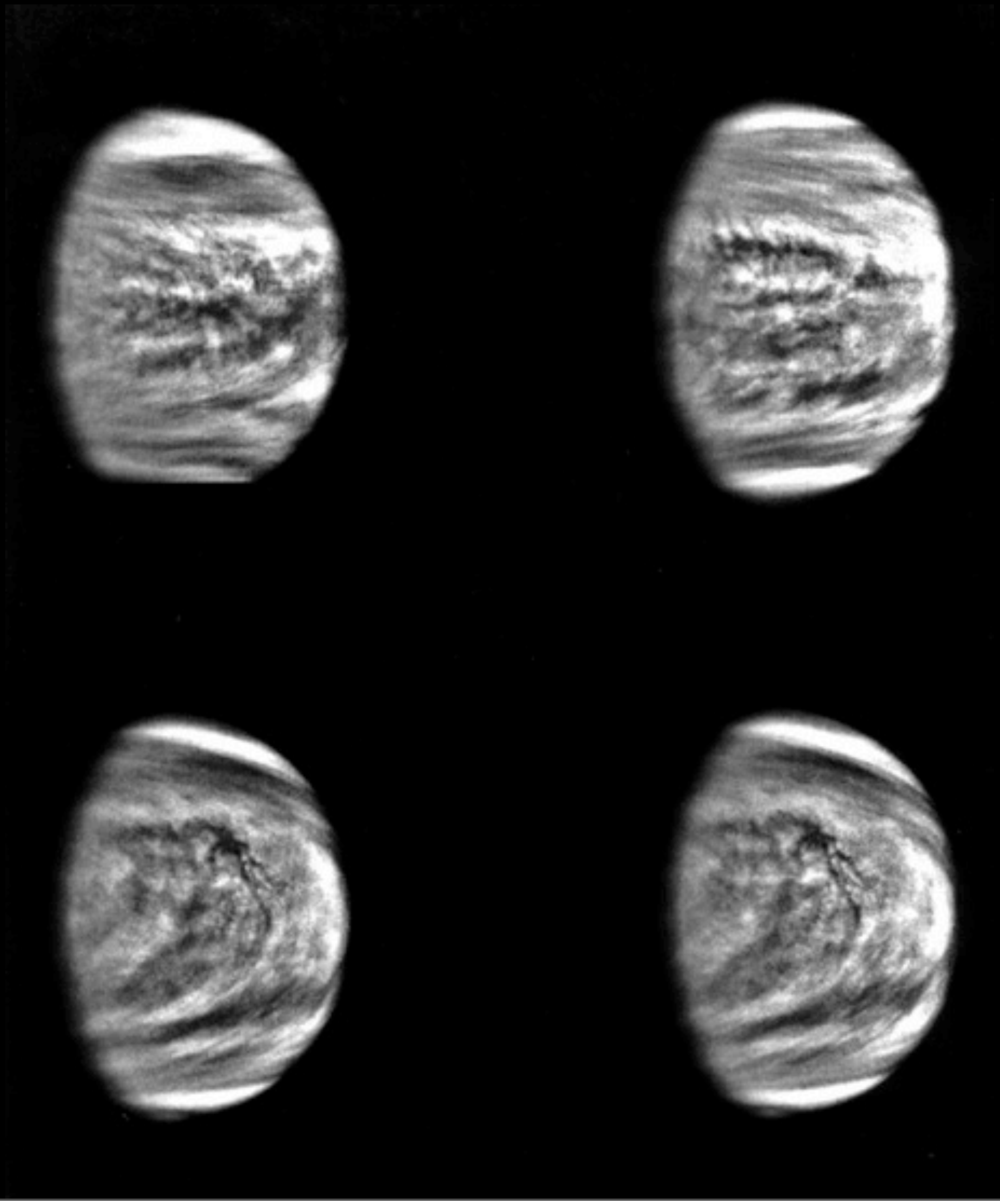
Venus actually reflects 70% of sunlight back into space, whereas Earth only reflects 30%, which means that Earth actually receives somewhat more sunlight at the surface than Venus, despite being further away. However, the actual surface temperature depends on the atmosphere. The small amount of CO_2 in Earth's atmosphere means it is about 30° warmer than its equilibrium temperature. Venus' atmosphere, however, raises the surface temperature by nearly 500° C.



Almost no features are visible in optical light on Venus: the planet-wide clouds are bright and featureless. Ultraviolet images, however, show swirls and streaks.

These dark patterns, from absorption by an unknown material, trace the motion of Venus' upper atmosphere.

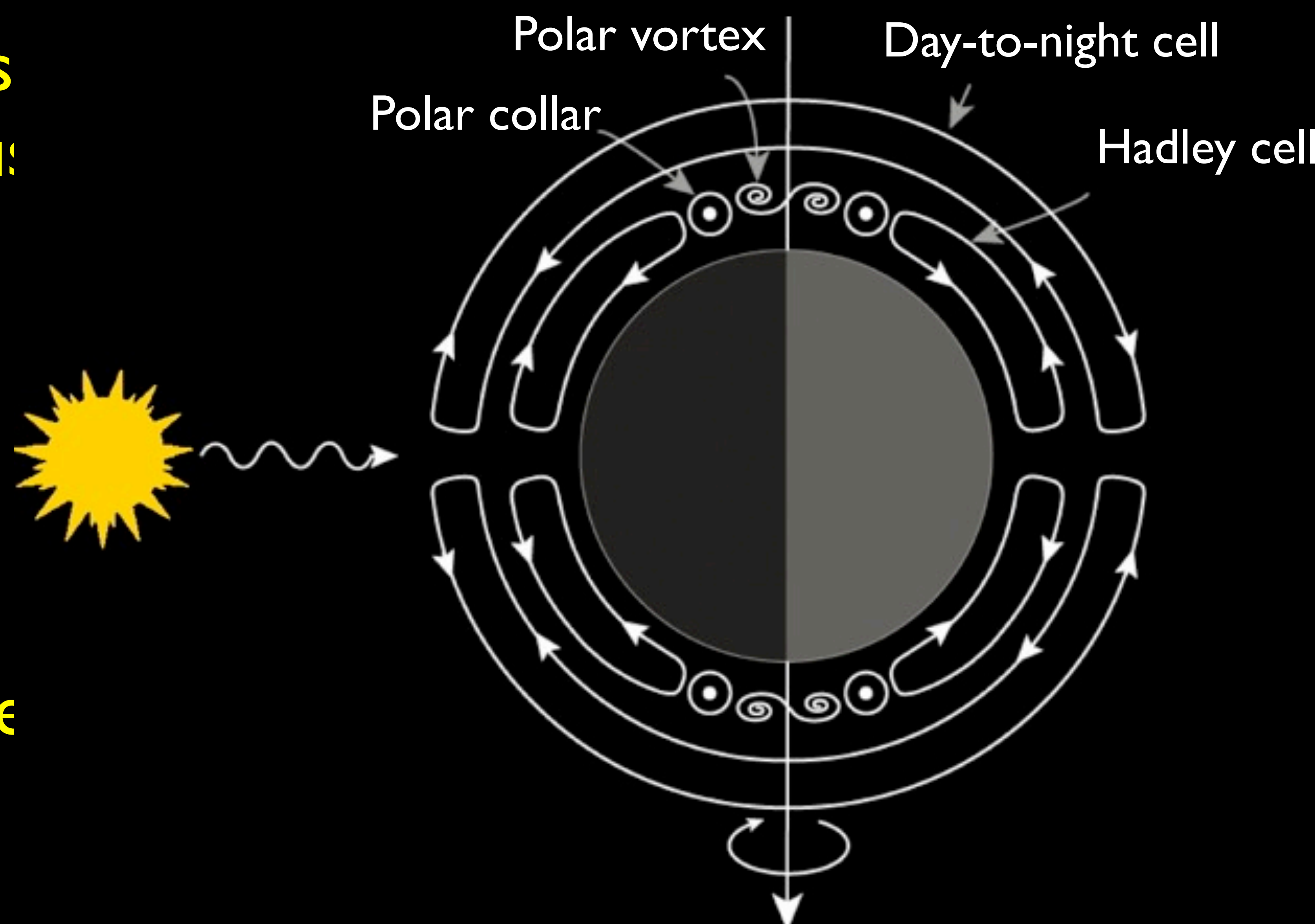
The upper atmosphere mover at speeds of 100 ms^{-1}, circling the planet in just four days.



Near the ground the atmosphere is much more sedate. The slow rotation of Venus means that there is almost no Coriolis deflection, so heated air at the equator rises and travels to the poles, where it cools and sinks.

The observed wind is all towards the pole, s the return stream mu be below the clouds.

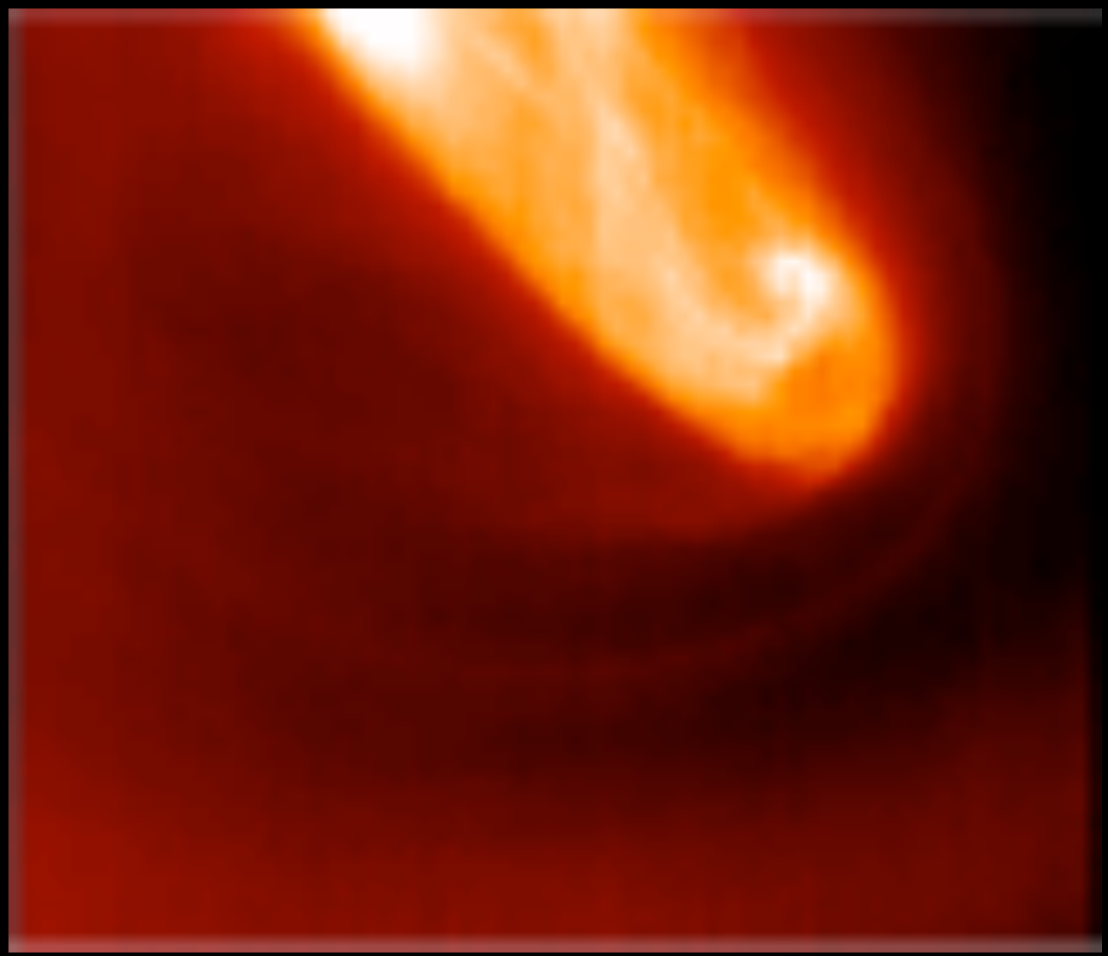
Given how slowly Venus rotates, its not clear what causes the "superrotation" of the upper atmosphere.



The sinking air at the pole is visible as a giant vortex, where air spirals down over the pole.

Polar vortex observed by Pioneer Venus.

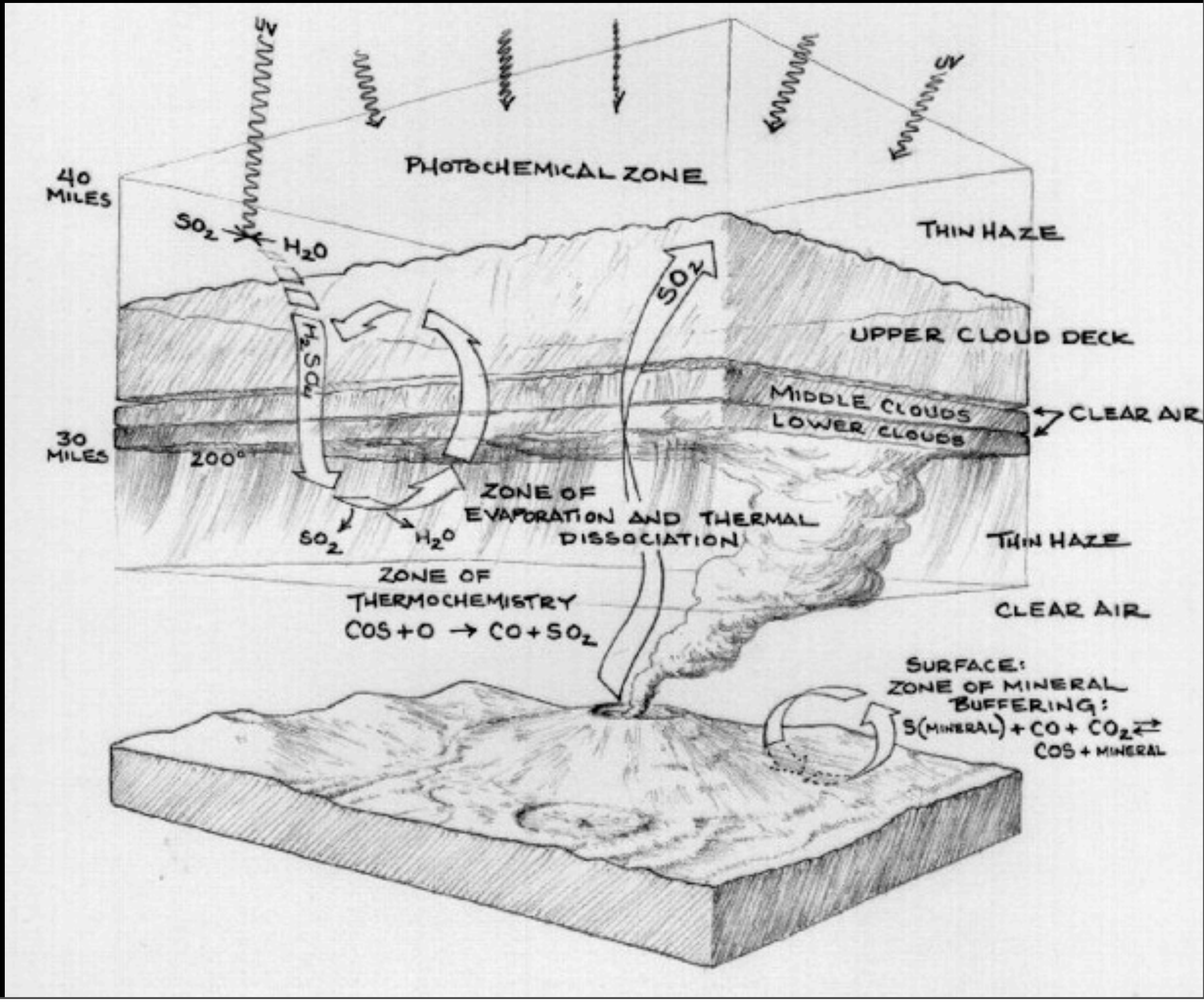
Venus Express found that the vortex at Venus' south pole has a mysterious double-eye feature. This polar vortex is bounded by a a 'polar collar', a wide (~1000km), shallow (~10km) river of cold air which circulates around the pole at about 70°



Close-up movie of the south polar vortex, seen in UV.

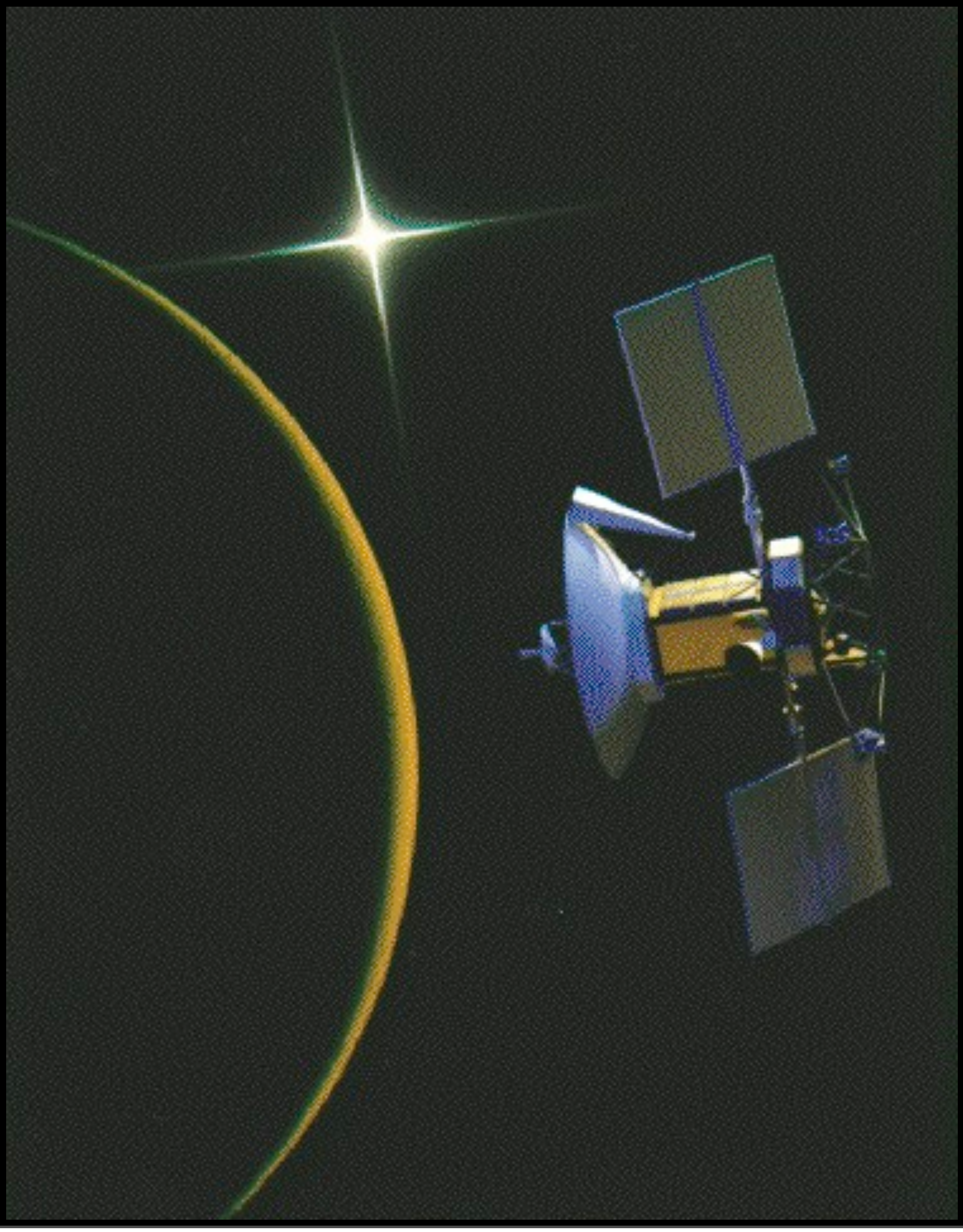
Venus has a complex *sulphur cycle*, similar to the water cycle on Earth. H_2SO_4 is formed when UV photons hit the atmosphere; these droplets condense to form the clouds, then start to fall. At an altitude of 50 km, the temperature is high enough for the drops to evaporate and dissociate. Rain on Venus never reaches the surface!

Below this, all sorts of chemical reactions are taking place, possibly including replenishment of atmospheric SO_2 by volcanoes.



Surface

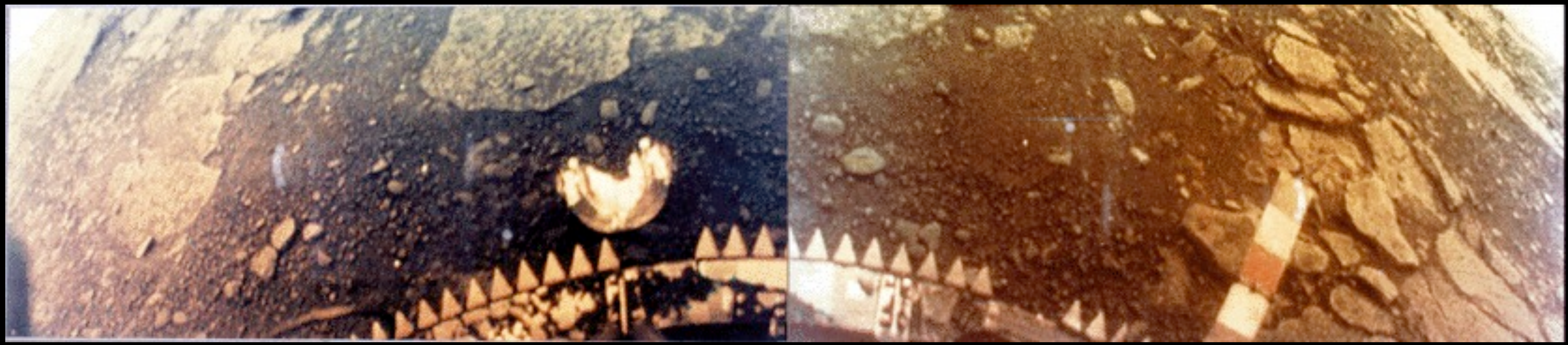
Because of the thick clouds, everything we know about the surface of Venus has come from radar measurements.



In particular, the Magellan mission, which mapped the surface of Venus from orbit from 1990–1994, has given us detailed information on the hidden surface.

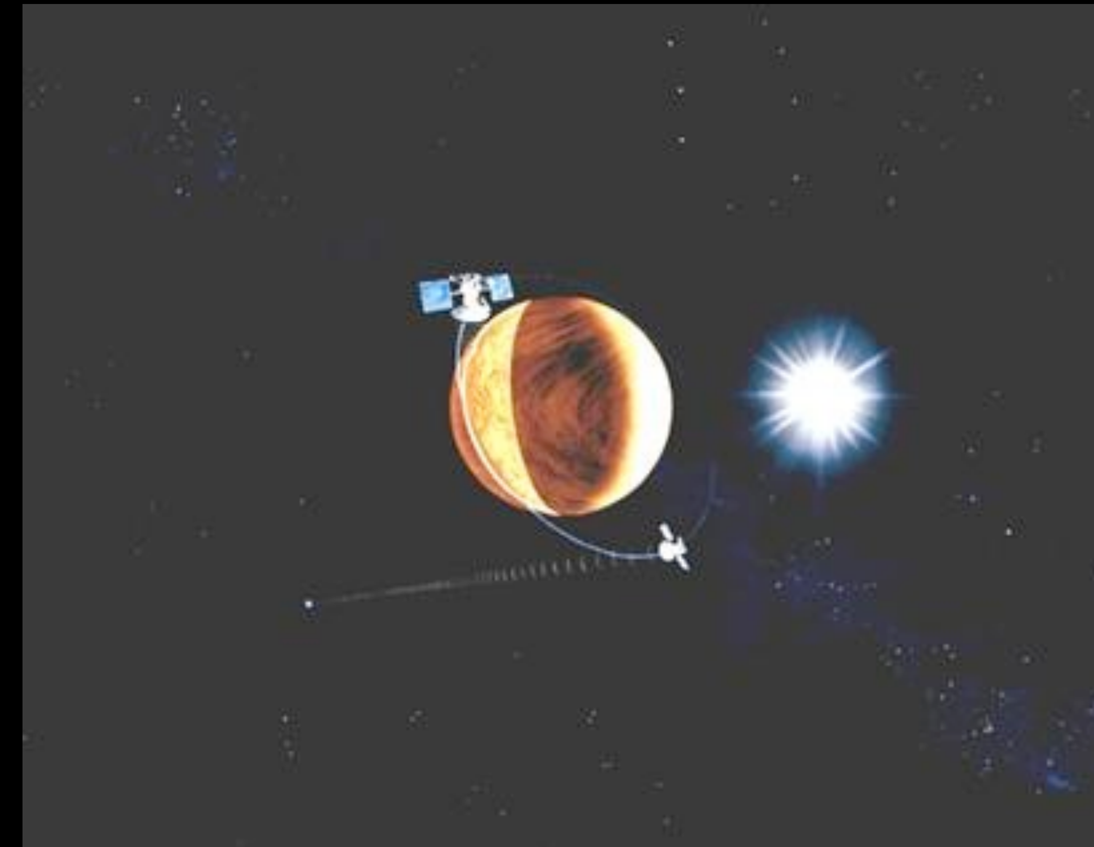
We do have a couple of views of the surface: the *Venera* probes sent back pictures from their landing sites; those on *Veneras 13* and *14* were even in colour.

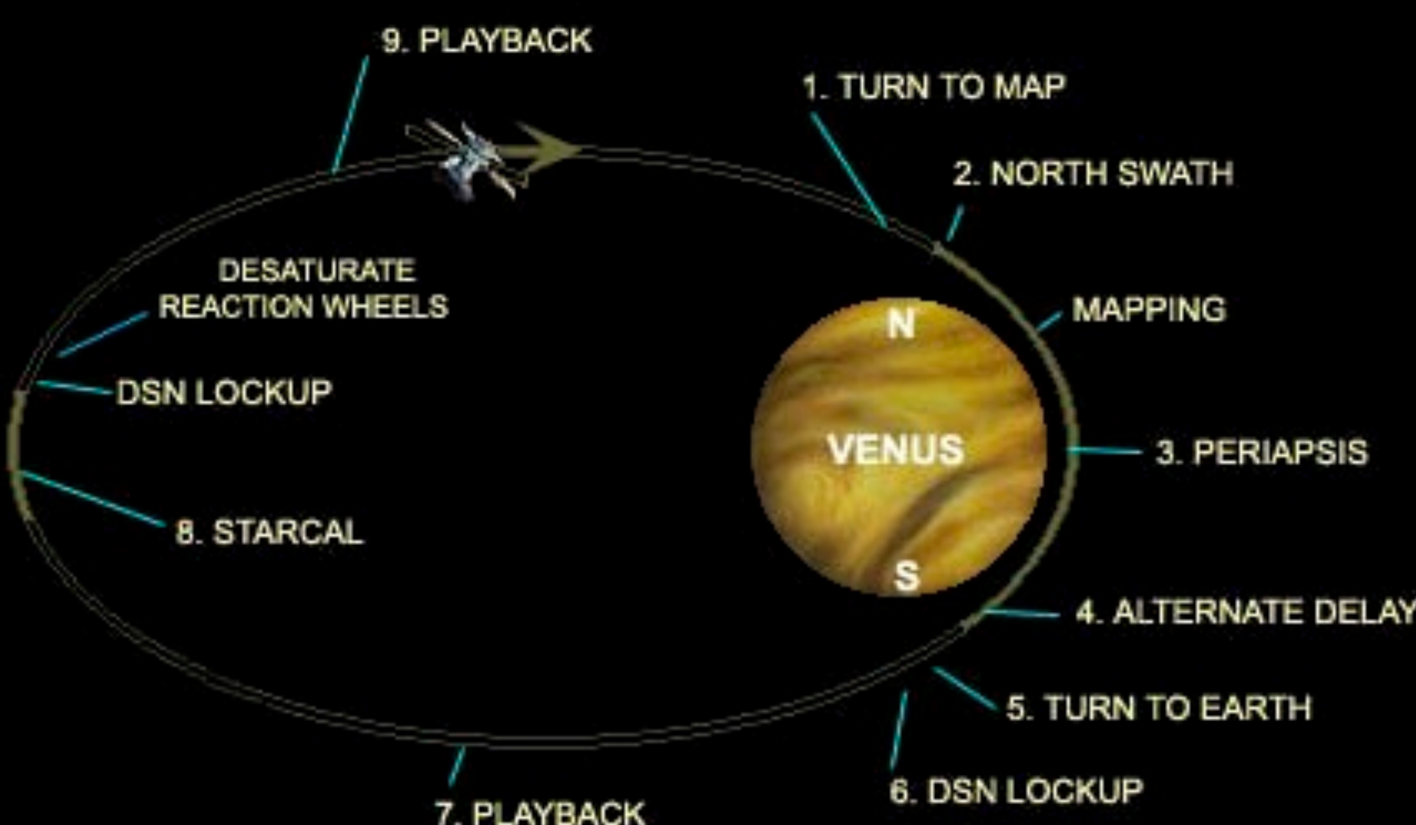
It showed a scene with a strong red tint. The rocks themselves are not red; but the thick atmosphere has removed nearly all the blue light, so on the surface of Venus, everything looks red.



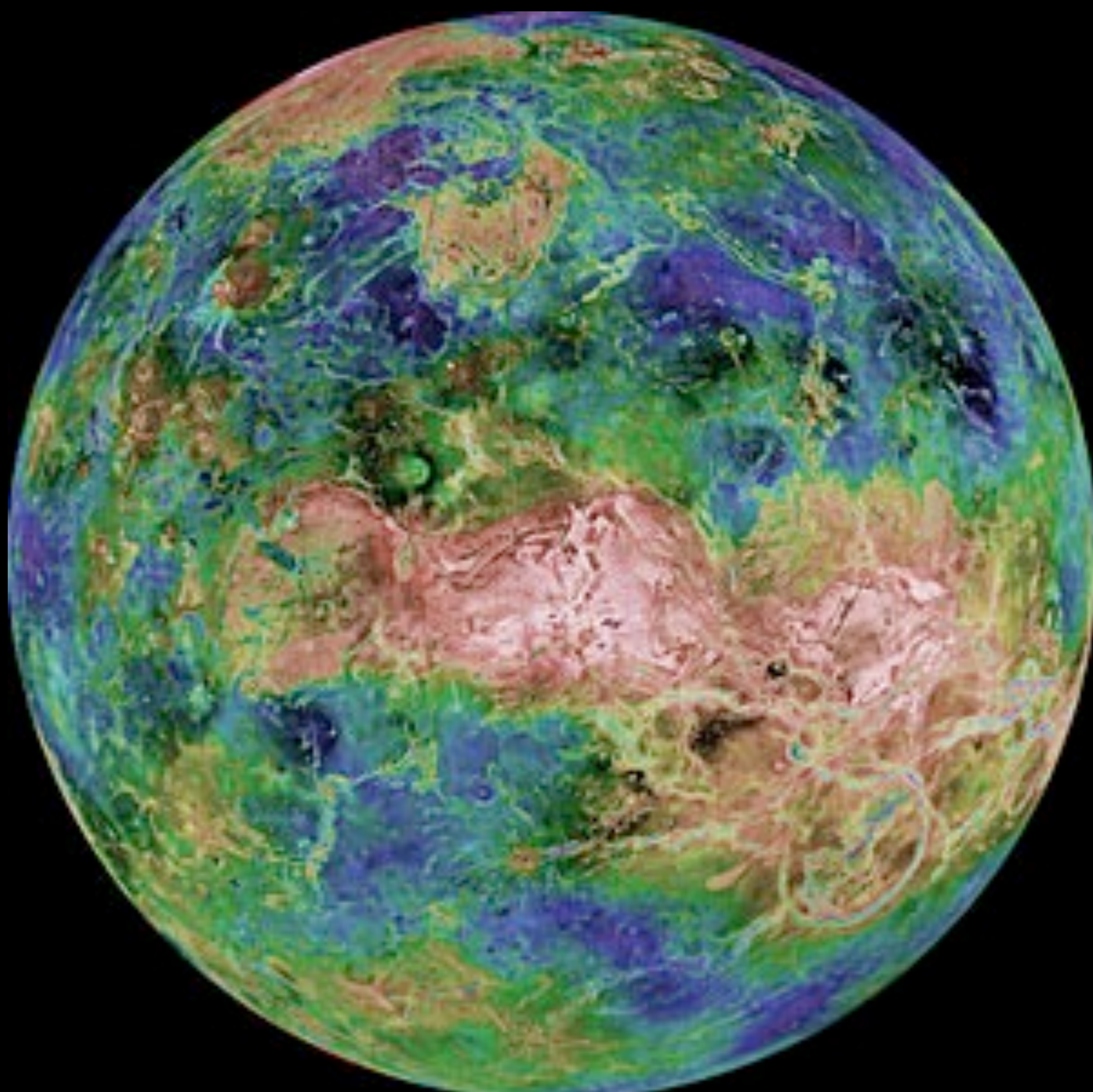
170 degree panorama taken by Venera 13 on 1 March 1982; part of the spacecraft and the camera lens are visible in the foreground.

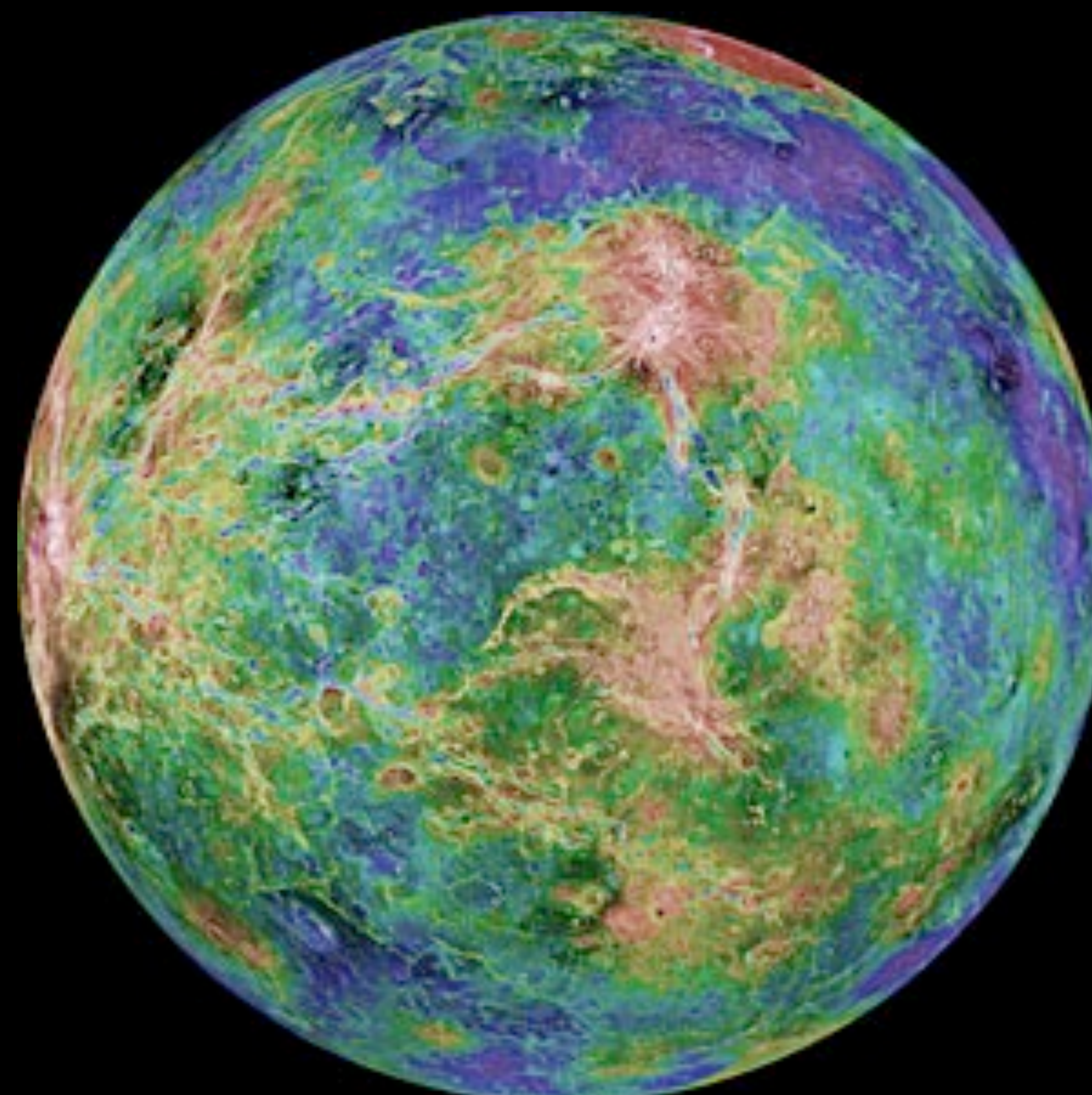
Magellan entered Venus orbit in August 1990. Its mission was to use radar to map the surface of the planet to a resolution of better than 1 km.



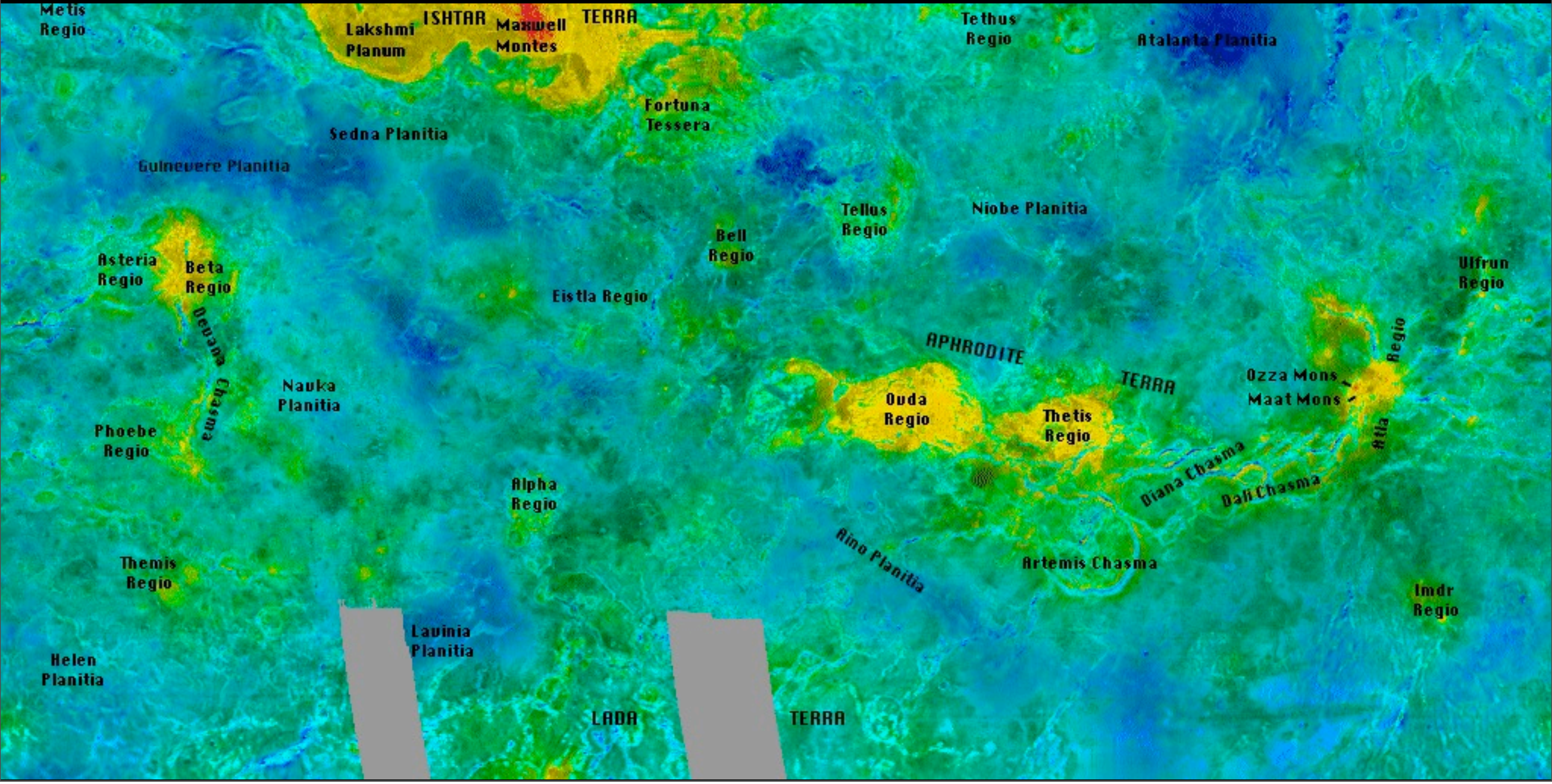


Magellan revealed a world dominated by volcanoes: almost 90% of the surface is occupied by volcanic landforms.

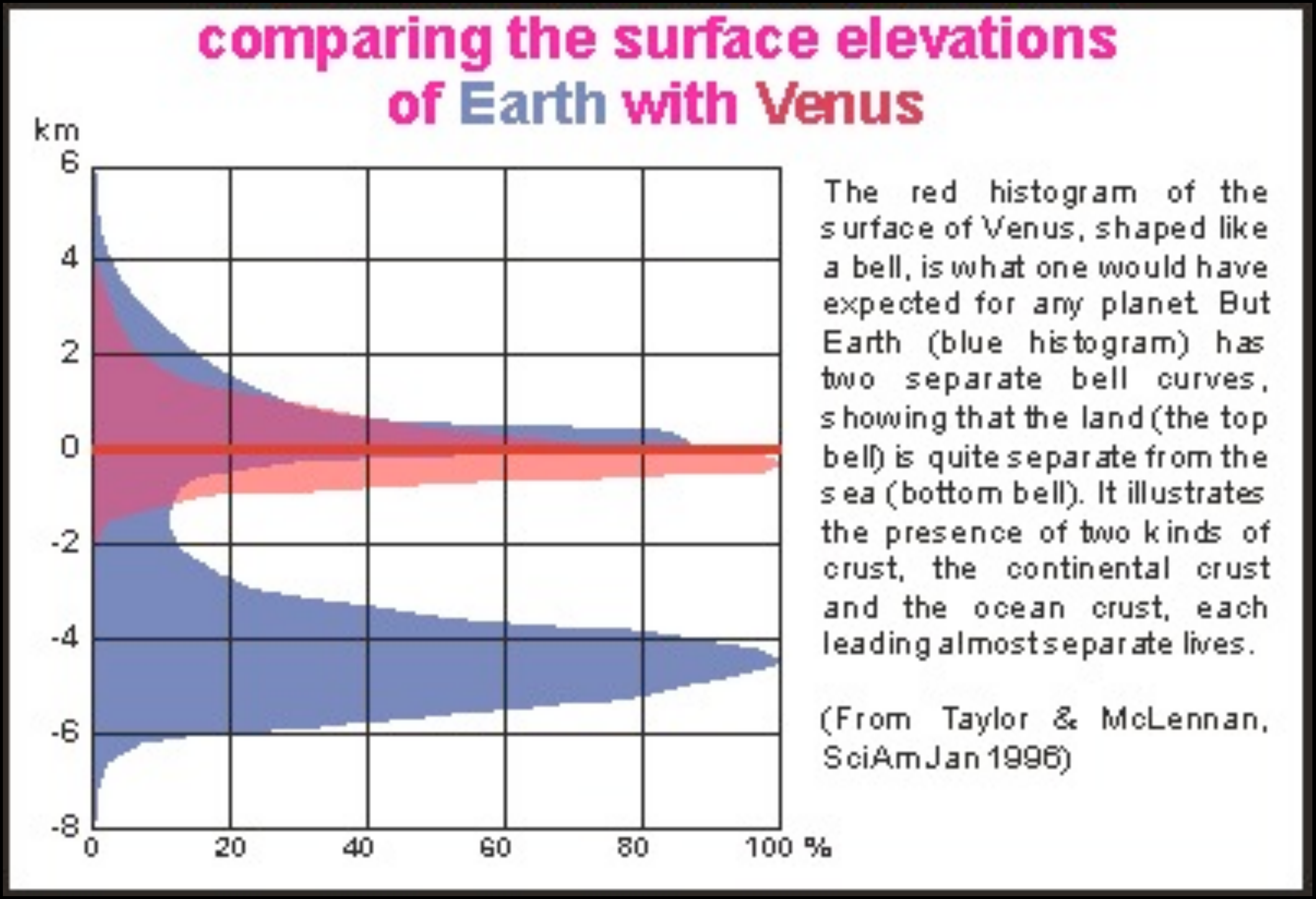




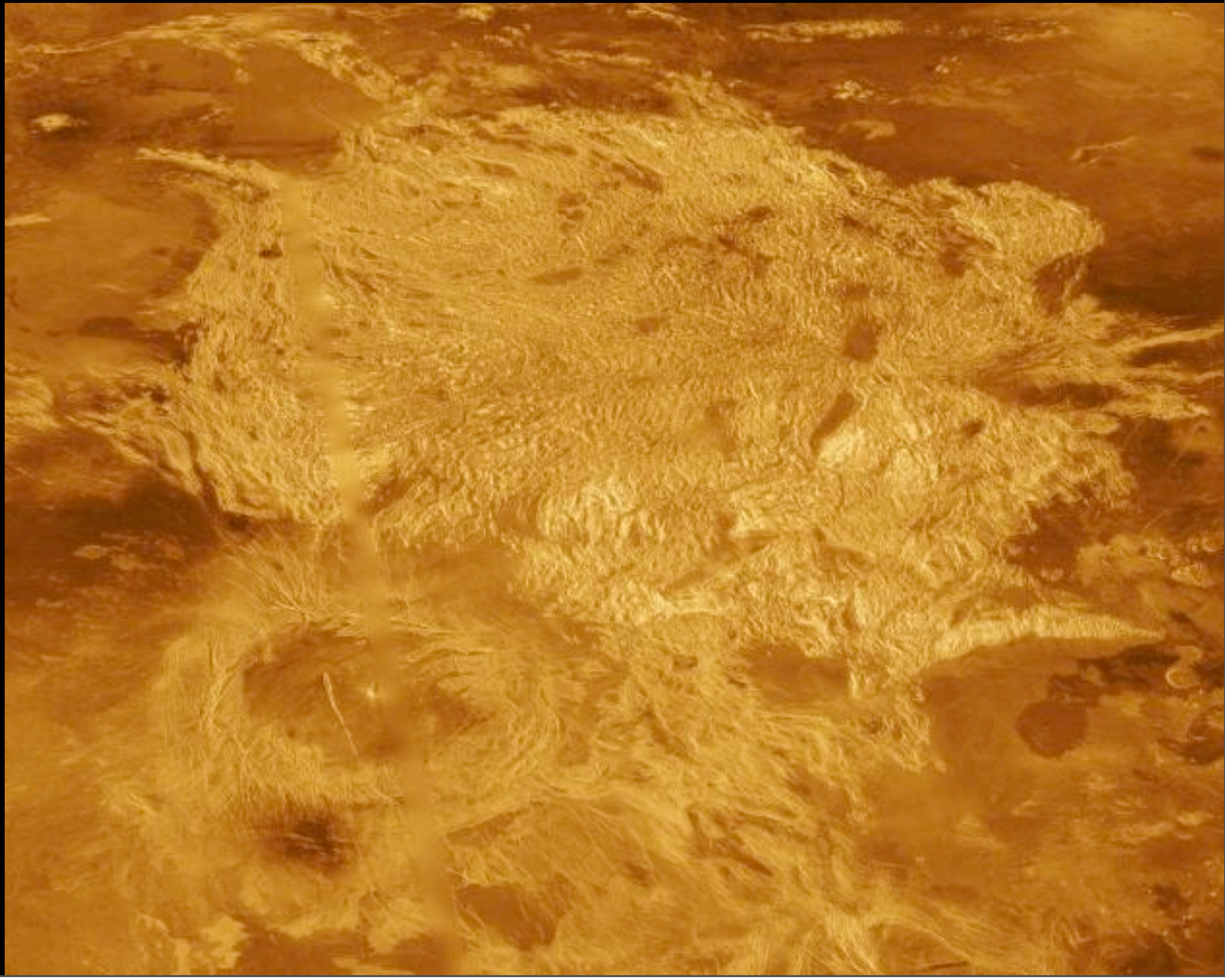
There are two "continents" – large regions several kilometres above the average elevation: *Ishtar Terra* and *Aphrodite Terra*. Ishtar is about the size of Australia, Aphrodite about the size of Africa.



A comparison of the surface elevations of Venus with those on Earth show that in fact the “continents” are not like the continents on Earth, which are quite distinct from the oceanic crust.

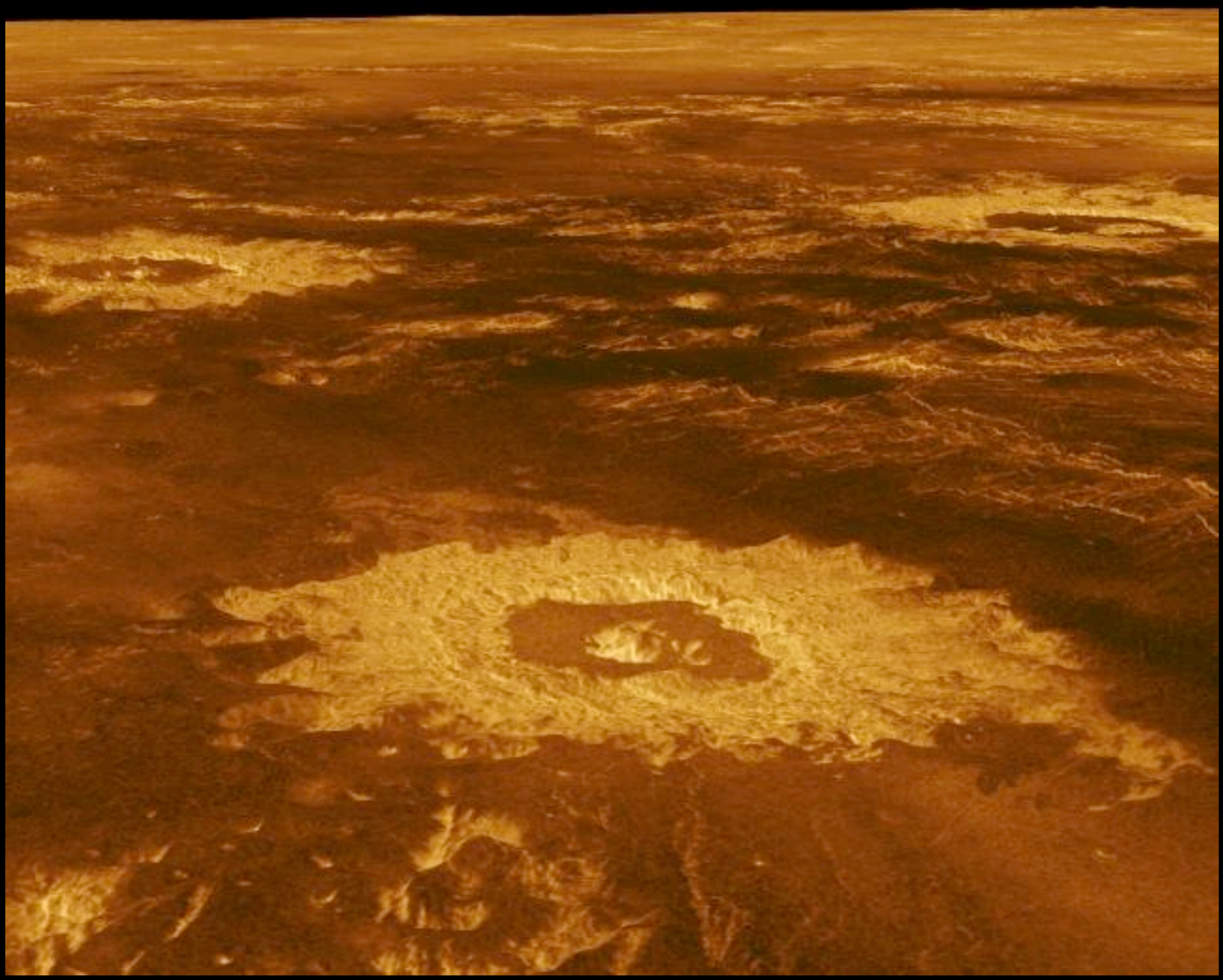


Highland regions above 2.5 km in height are unusually bright in radar images. It is not clear what causes the unusual radar reflectivity. One suggestion is that it might be deposits of iron pyrite (“fool’s gold”), which is unstable on the plains but would be stable in the highlands.



Perspective view of the radar-bright area of Alpha Regio. The radar-bright spot located centrally within Eve (the large ovoid-shaped feature south of the complex ridged terrain) marks the location of the prime meridian of Venus.

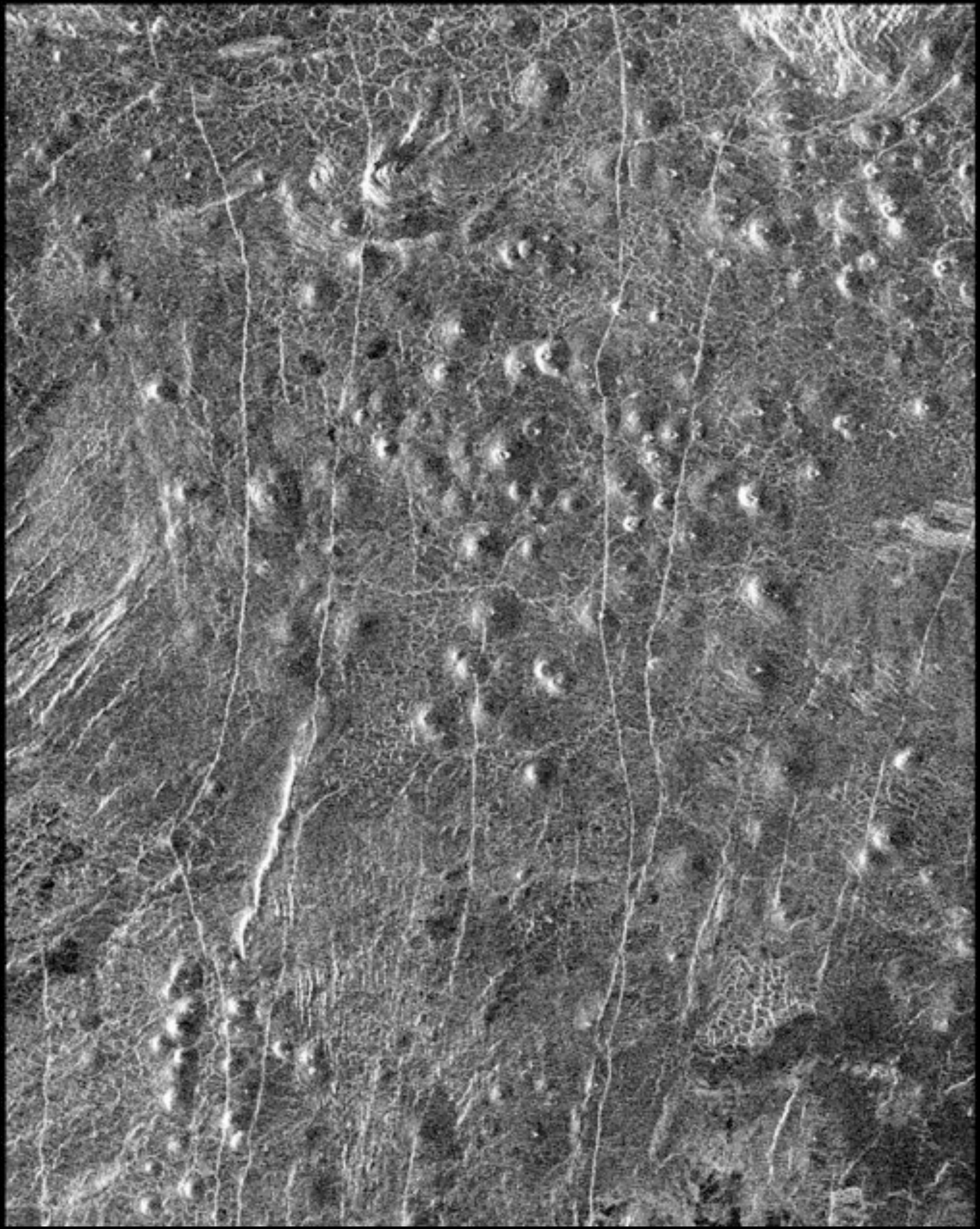
Much of Venus (more than 80%) is covered by vast low-lying areas of relatively featureless flows of lava.



Perspective view of Lavinia Planitia, showing craters on a smooth lava plain.

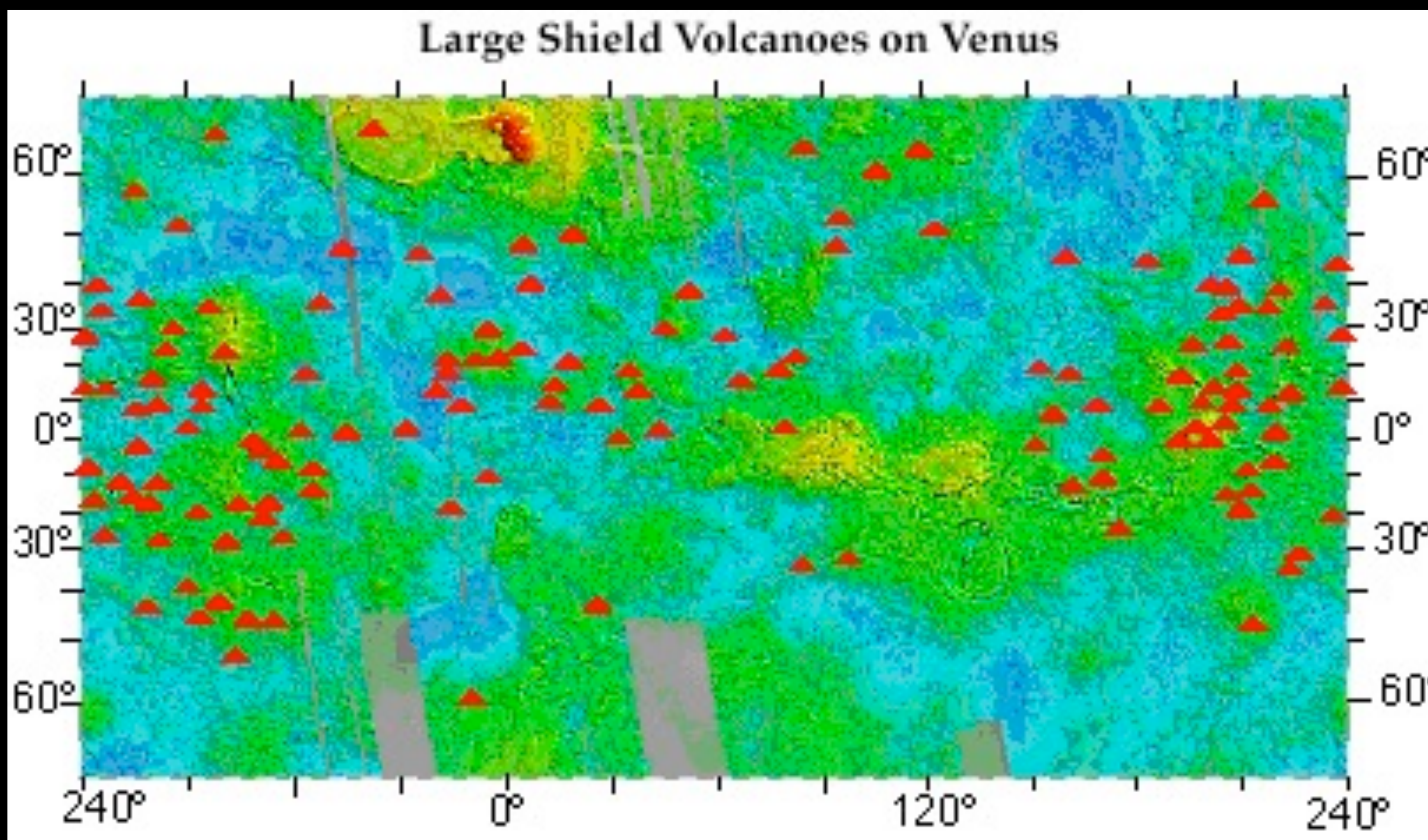
These plains are dotted with thousands of small shield volcanoes, built up gradually by repeated flows of runny lava. They usually occur in clusters, called *shield fields*.

The shield fields are widely scattered on Venus, but they mostly occur in the lowland plains. Many have also been partly buried by later lava plains.

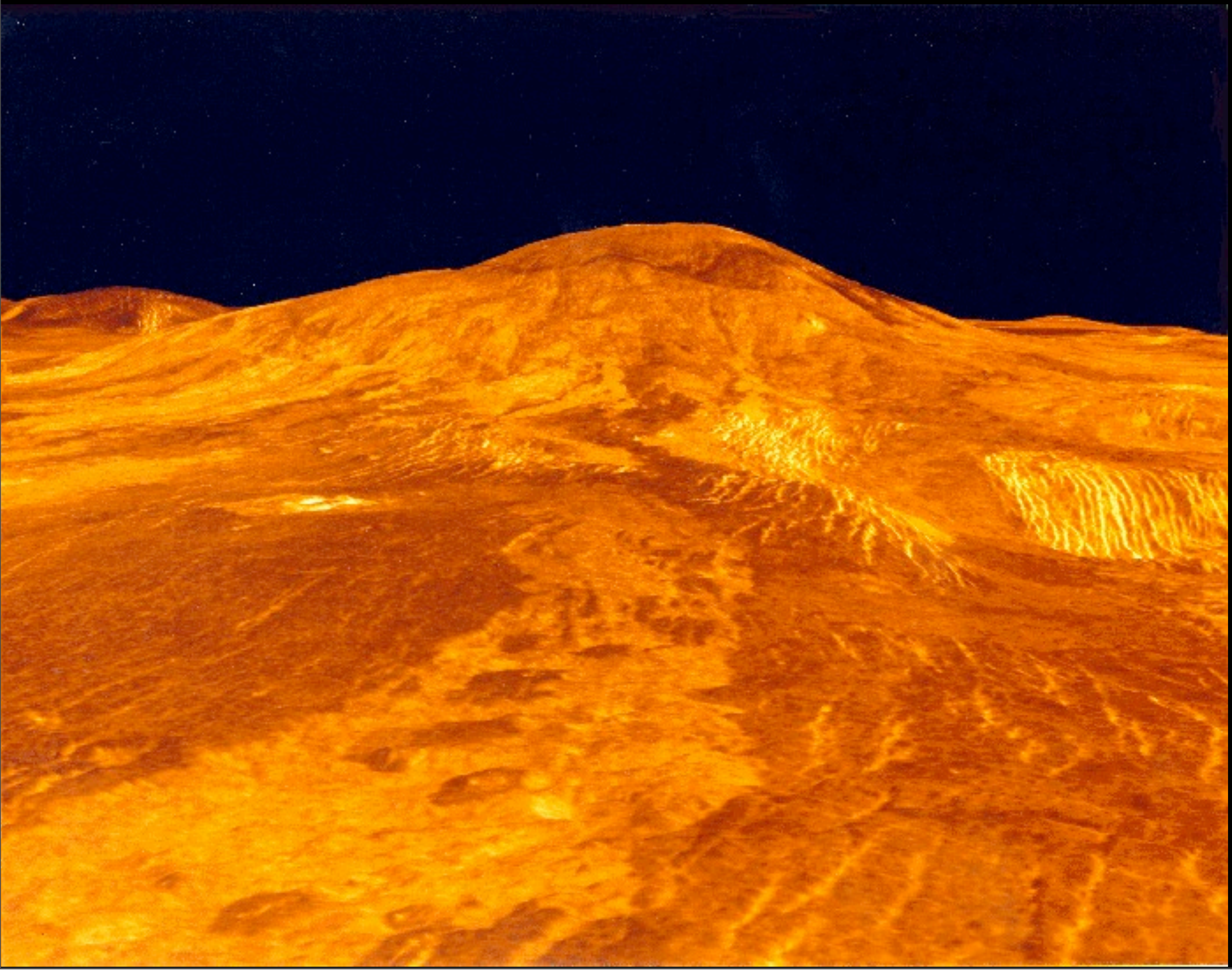


Region of the Tilli-Hanum Planitia, showing hundreds of small volcanoes ranging from 2–12 km in size.

There are also about 150 giant volcanoes, up to 700 km in diameter and up to 5.5 km in height. They are mostly in the upland regions, and are widely scattered over the planet, instead of being found in linear volcanic chains like on Earth. This suggests that Venus does not have active plate tectonics.

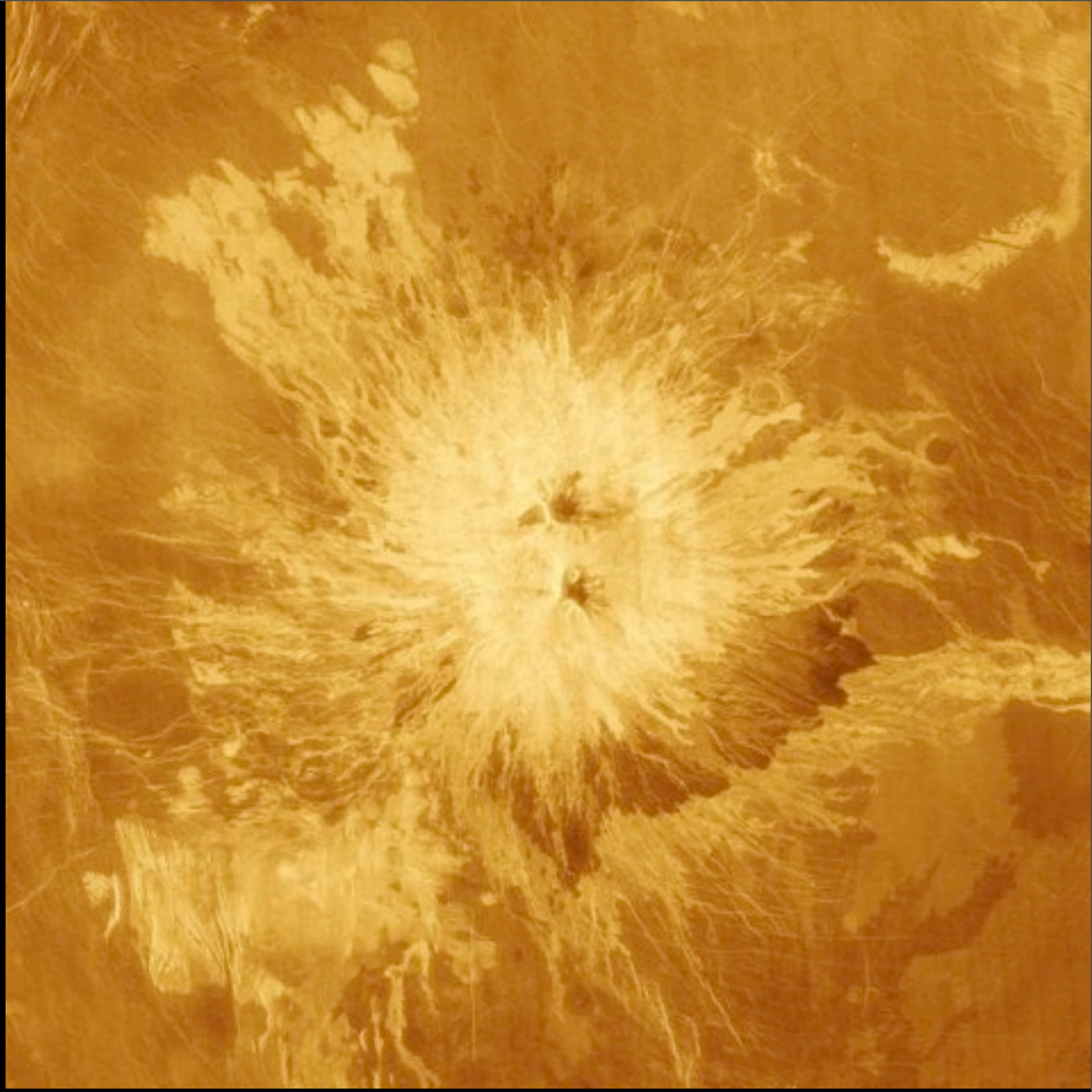


The volcano Sif Mons. is about 2 km high and nearly 300 km across. It lies near the equator in Western Eistla Regio. There appear to be recent lava flows at the front of the image: these flows are about 120 km long, which suggests that these lavas were also very fluid.



Perspective view of Sif Mons: this image has a vertical exaggeration of 23x.

Sapas Mons is a large volcano, 400 km across, in Atla Regio. Numerous lava flows overlap, and some appear to come from the flanks of the volcano instead of the summit.



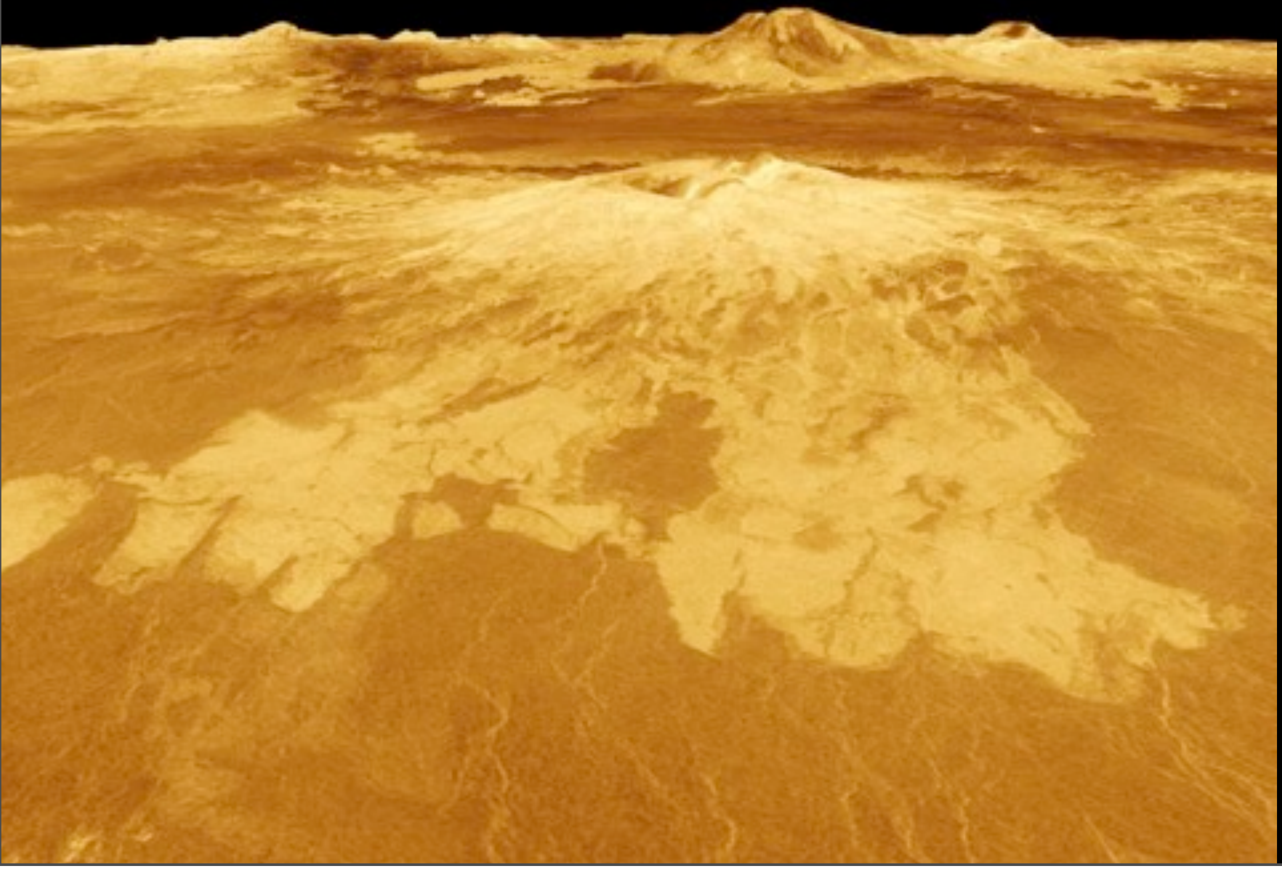
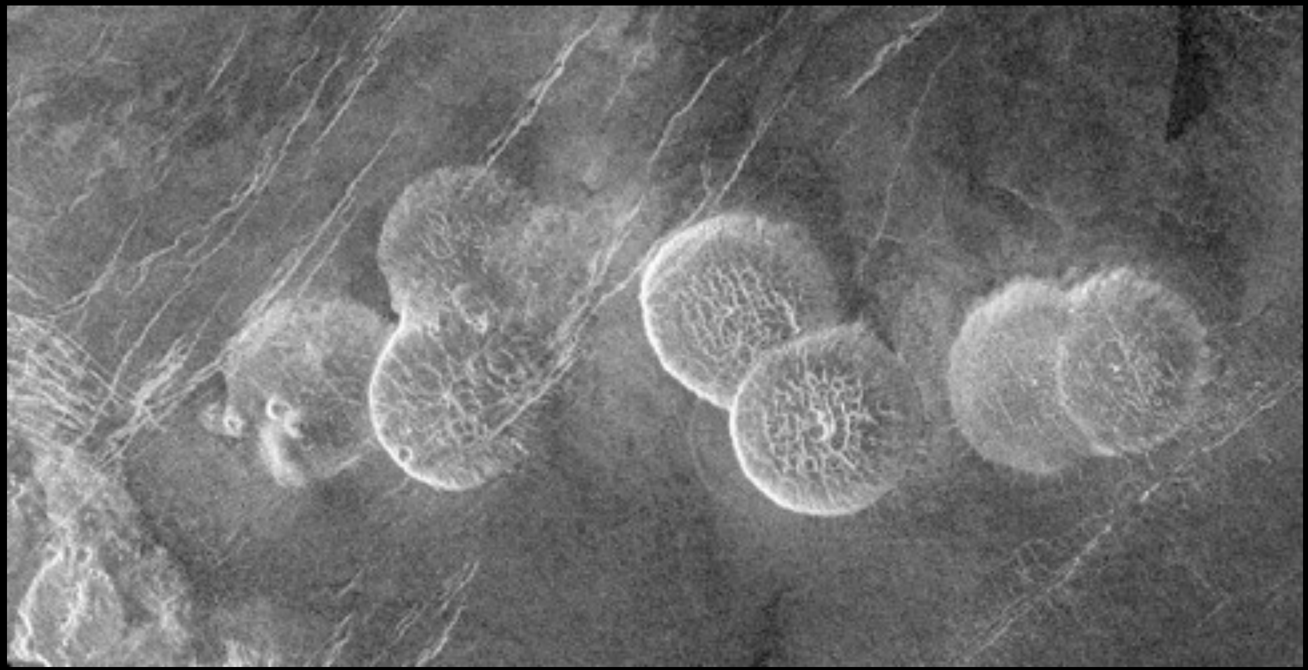


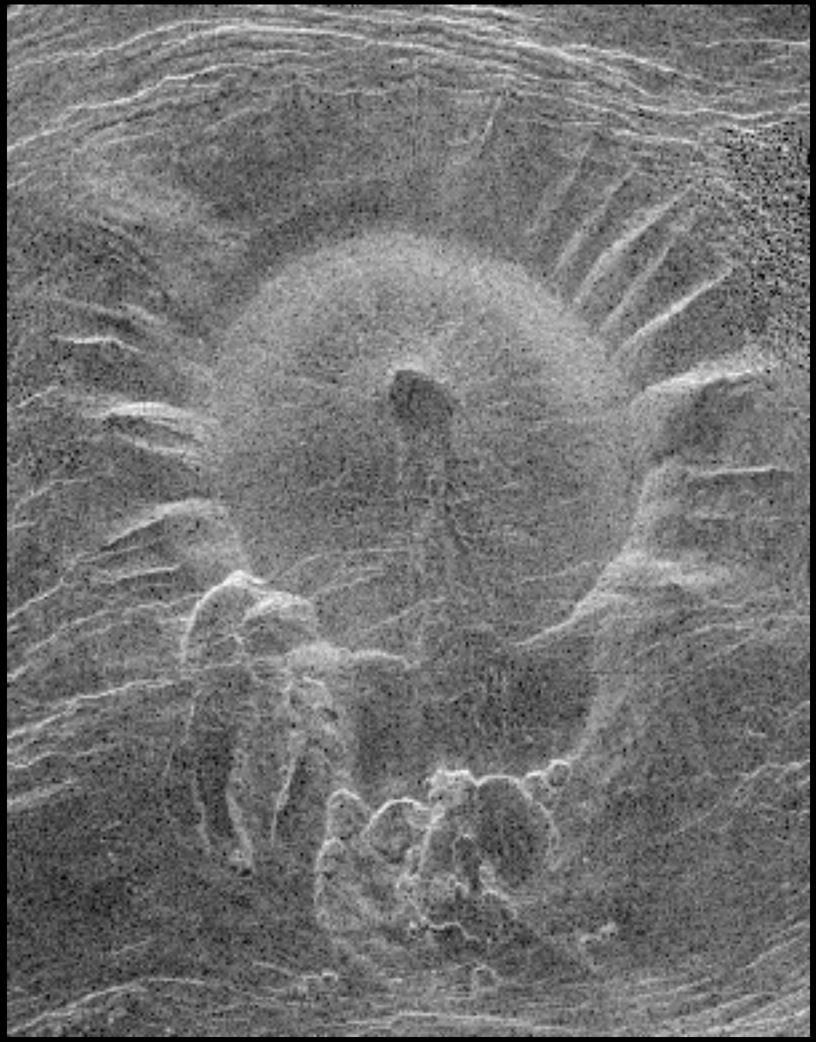
Image and perspective view of Sapas Mons.

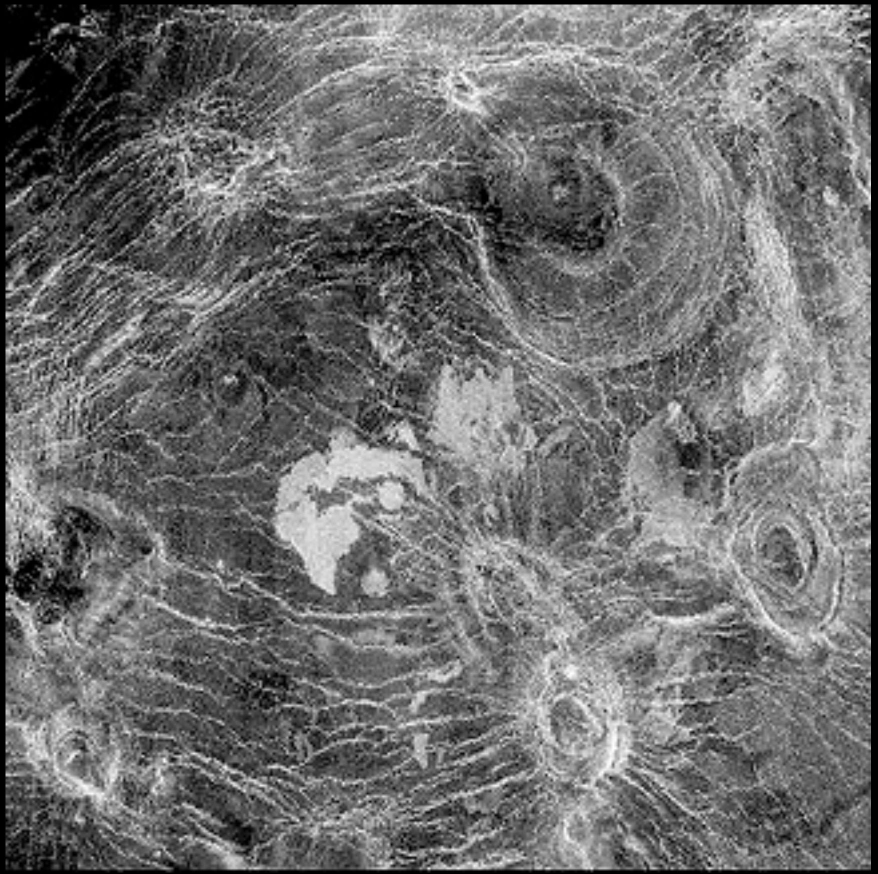
Pancake domes are steep-sided, flat-topped volcanoes. They are probably sites where more viscous lava squeezed up through the crust and piled up, instead of flowing away. Much smaller versions can be seen on Earth.

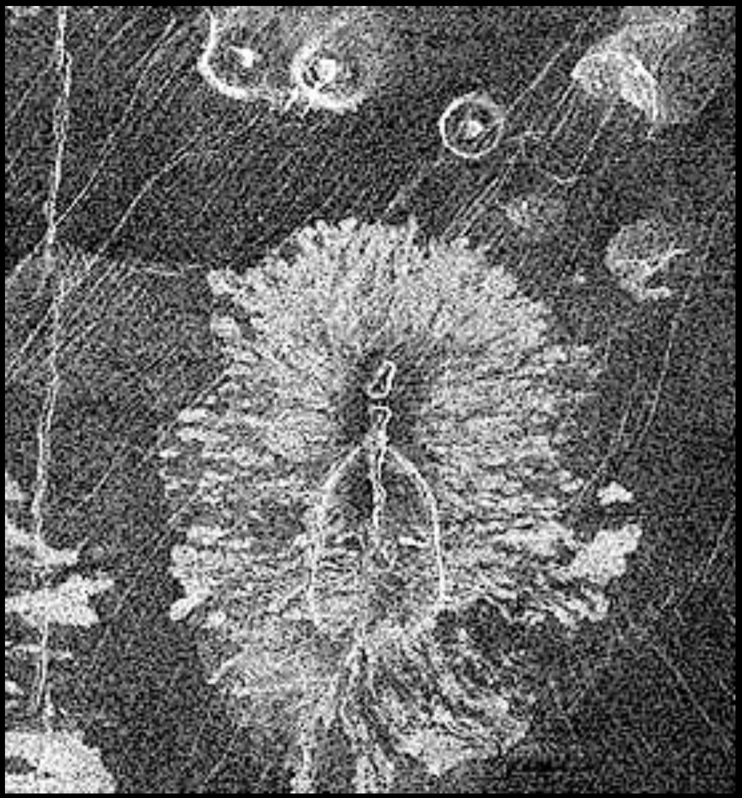


Pancake domes in Alpha Regio (left) and the Eistla region (right). The domes are 20–65 kilometers in diameter with broad, flat tops less than one kilometer in height. Much smaller domes can be seen on Earth, such as this dome formed by the 1912 eruption of Katmai in Alaska.

Some of Venus' other volcanic features look like nothing on Earth, presumably because the lava acts very differently under Venusian conditions: *ticks*, *arachnoids* and *anemonae*.







Coronae have patterns of circular rings; they can be as small as 80 km, or as large as 2100 km. They are thought to arise from upwelling in the mantle, which eventually subsided and cracked the crust, leaving the characteristic round fractures.

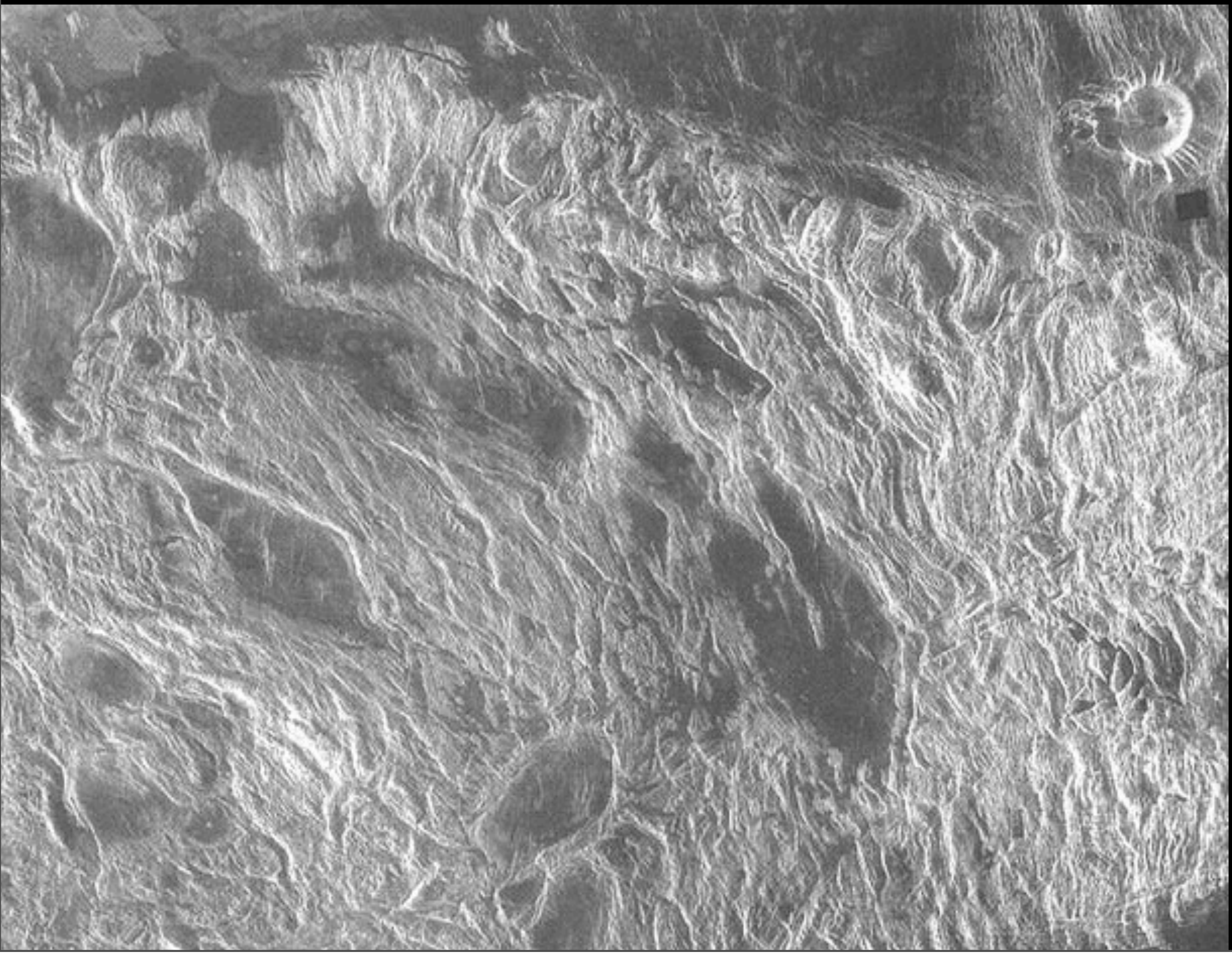
Aine Corona, located south of Aphrodite Terra, is 200km in diamater. Note the pancake domes to the north and inside the corona.

Venus also has *lava channels*, like rivers feeding the lava flood plains. These are typically a few kilometres wide and up to thousands of km in length. The longest, Baltis Vallis, is at least 6800 km in length.

These channels must have been formed by something with very low viscosity, which flowed for a long time.

This unusually long channel ranges from Fortuna Tessera in the north down to the eastern Sedna Planitia in the south. The channel is about 2 km wide and shows branches and islands along its length.

About 10% of the surface, including most of the elevated regions, consists of highly deformed areas called *tesserae*. These appear to be tectonic features, but for whatever reason, Venus does not have continent-sized plates which move relative to each other. Instead, the crust cracks and fractures more easily than on Earth.

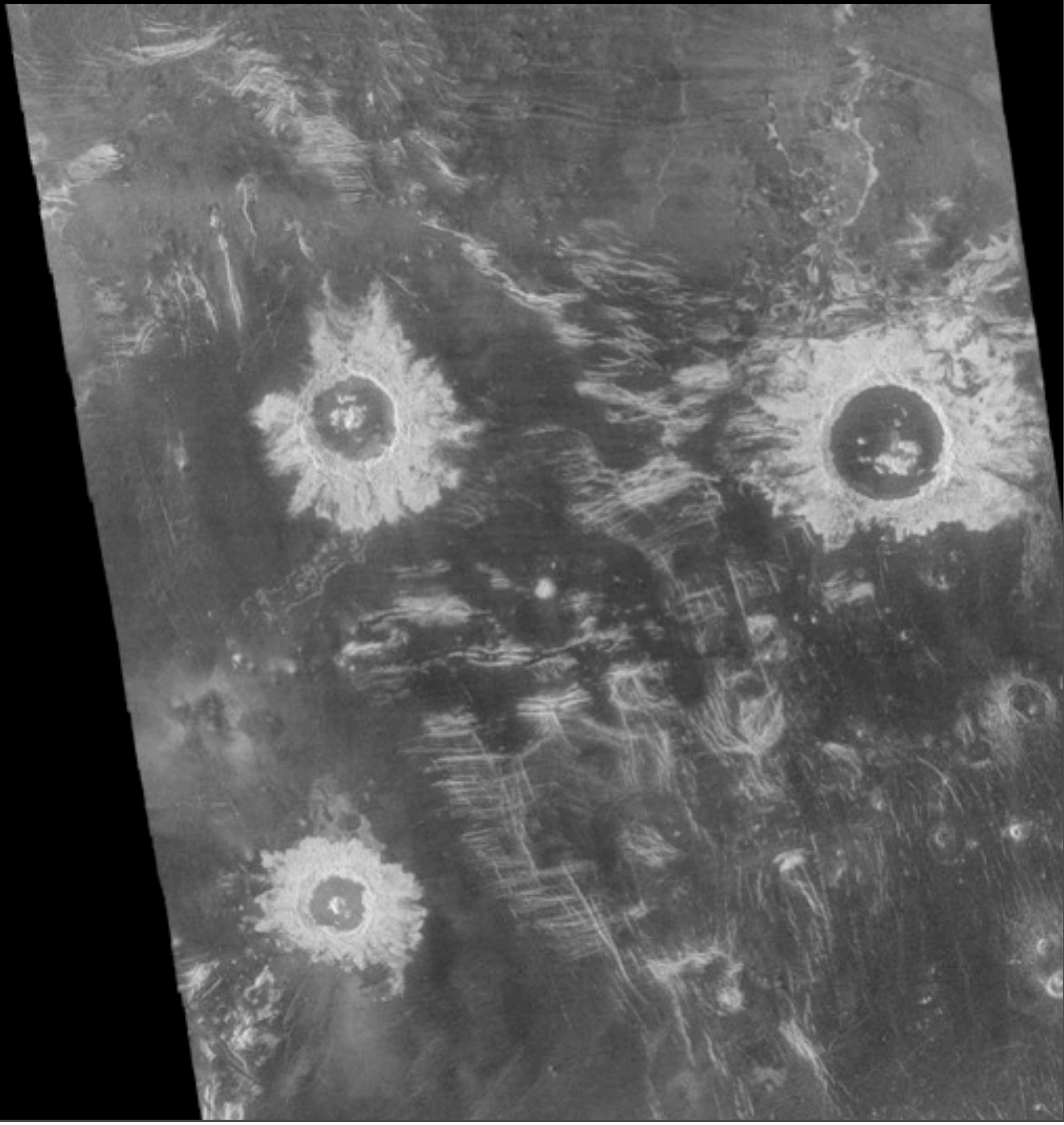


Tesserae are always covered on their edges by other features, indicating they are the oldest regions on the planet.

A portion of Alpha Regio, showing networks of intersecting ridges and troughs.

Venus also has impact craters, though many fewer than on Mercury, Mars or the Moon. There are no craters smaller than 1 km in diameter, because the thick atmosphere prevents the smaller meteors from reaching the surface.

The surface density of craters indicates most of the surface is only 600 million years old; but craters do not appear to be eroding. Where are all the older craters?

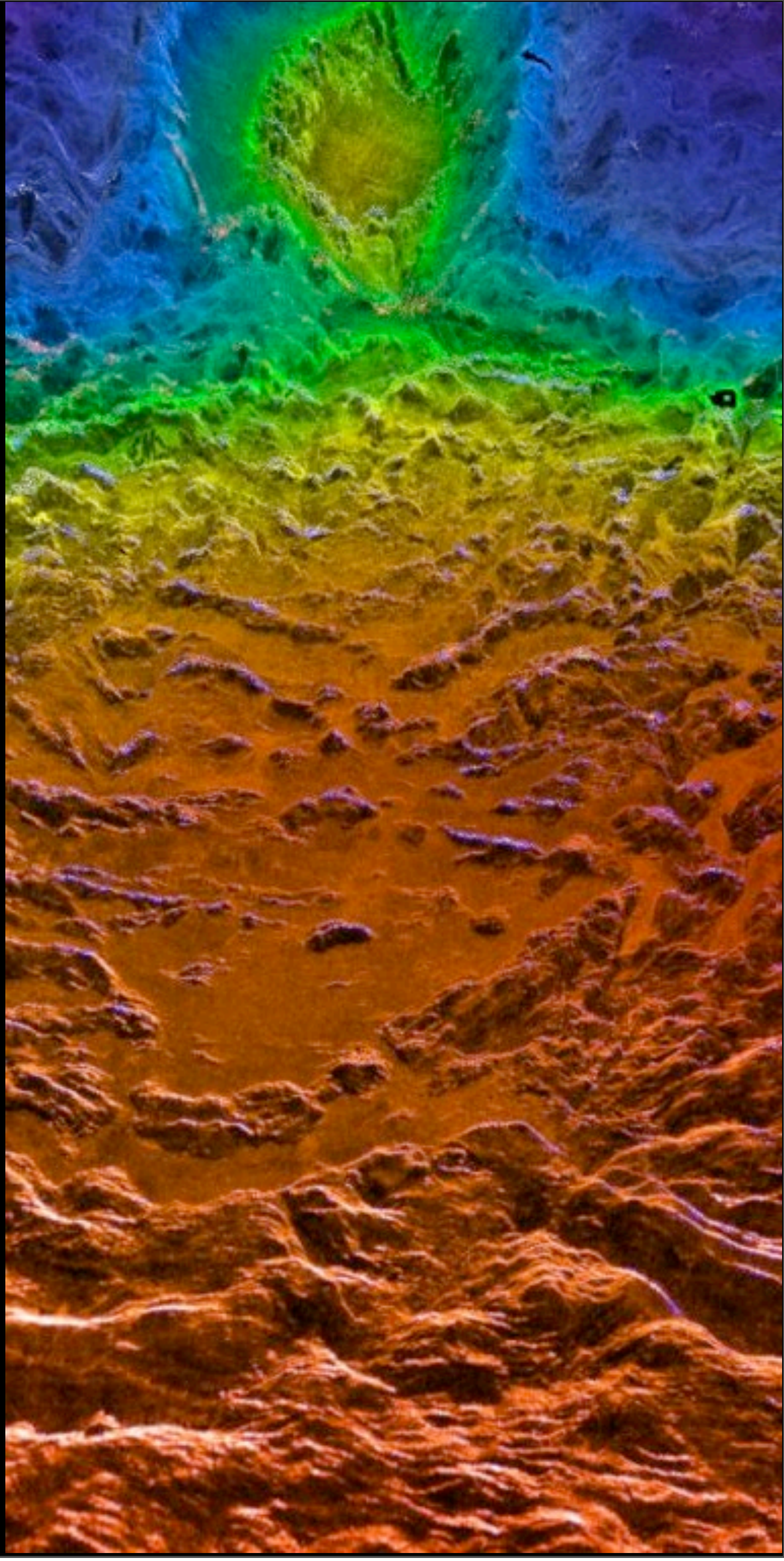


One possibility is that Venus' mantle continually kneads the crust, thickening and thinning it in a way that leaves it crater-free.

Another possibility is that Venus undergoes periodic *catastrophic resurfacing*. Perhaps heat builds up in the mantle, resulting in massive global volcanism. Or perhaps the crust becomes so cool and dense that it is unable to support itself on the mantle, so the entire crust sinks, turning the entire planet into a sea of magma.

The last such event would have taken place about 600 million years ago.

One possibility is that plate tectonics does exist on Venus, but because of the lack of water in the mantle, it is episodic instead of continuous. The global resurfacing event 600 million years ago was the last tectonic event.

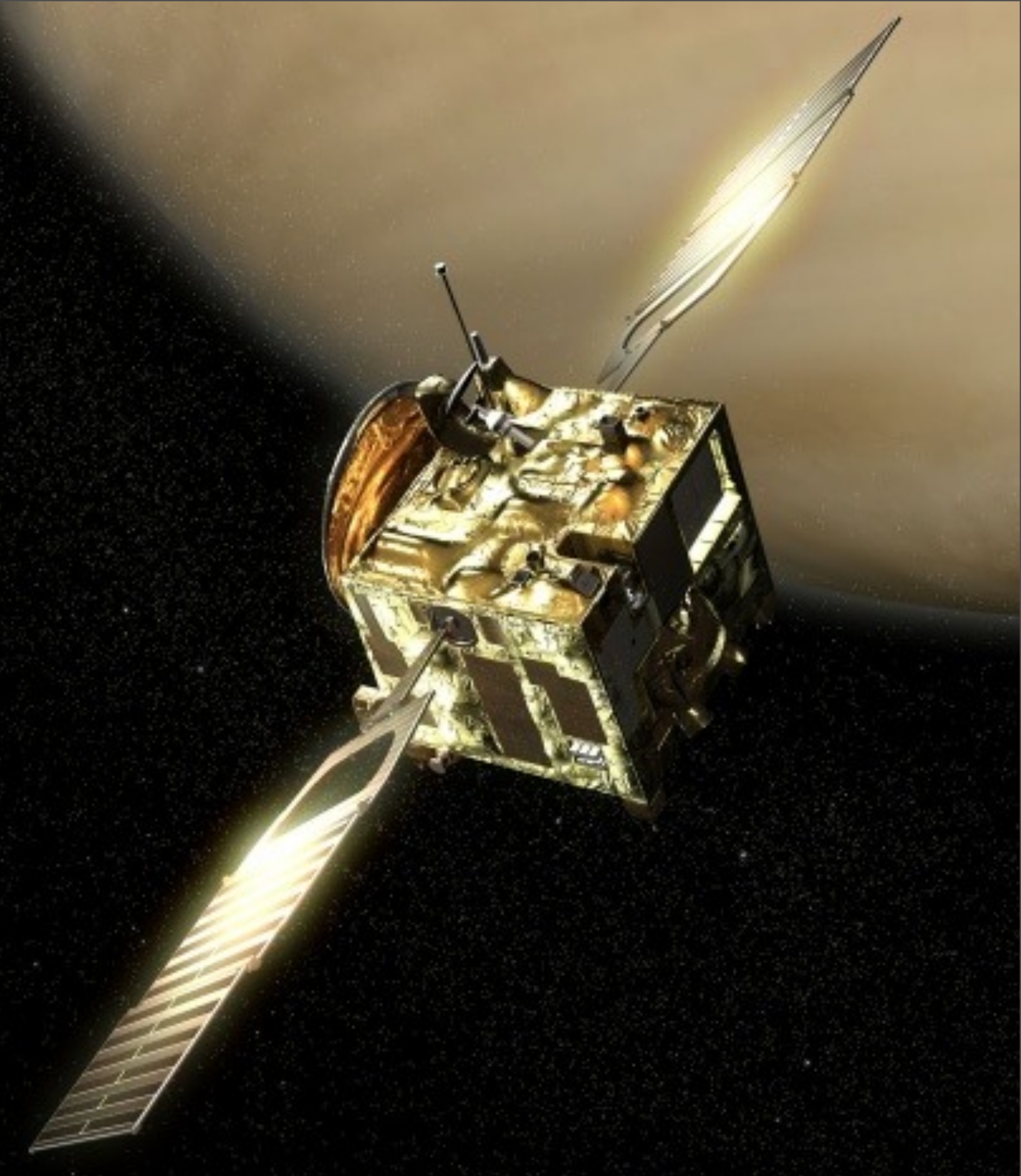


Perspective view of Venus looking westward across the Fortuna Tessera toward the slopes of Maxwell Montes. The tessera terrain of both Fortuna and the slopes of Maxwell is characterized by roughly parallel north-south trending ridges. The circular feature on the slopes of Maxwell is the crater Cleopatra, which has a diameter of approximately 100 km

Are any of Venus' volcanoes still active?

No signs of current activity have been found. But clouds of volcanic dust are invisible to radar!

Fluctuations in the amount of atmospheric SO_2 may indicate it is currently being injected by volcanoes.



Venus Express arrived at Venus in April 2006 to spend 3 years studying Venus' atmosphere. It has so far failed to detect any active hotspots, or any plumes of sulphur.

Venus is the closest planet to Earth, not only in distance, but in size, density and chemical composition. The two planets started out as twins: how did they end up so different?

Nitrogen and carbon dioxide are present in about the same amount on both planets. On Earth, CO_2 makes 96.5% of the massive atmosphere, whereas on Earth it is locked up in minerals in the crust. Water is the most abundant volatile compound on Earth, almost all of it in the oceans (which are 300 times more massive than the atmosphere). On Venus, however, water is present in only tiny amounts, all of it in the atmosphere.

Venus must once have had an ocean’s worth of water, but lost it. The hotter temperature evaporated the water, which increased the greenhouse effect, heating the planet still further. Once the oceans had boiled off and all the water was in the atmosphere, sunlight split the water vapour into hydrogen and oxygen. The light hydrogen gas escaped into space, while the oxygen remained and oxidised the crust.

Venus remains a reminder of what could go wrong.

Next week...

... we'll look at Mars, the red planet.

Further reading

There are not too many really up-to-date books about the inner planets. Doubtless there'll be more in a few years, when the MESSENGER results have been digested.

- **"Venus Revealed: A new look below the clouds of our mysterious twin planet"** by David Grinspoon (Helix Books/Addison-Wesley 1997) is an excellent description of the latest results on Venus, from one of the Magellan scientists. A very entertaining and informative read. There's also an interview with him at space.com http://www.space.com/scienceastronomy/venus_life_040826.html, discussing how Venus lost its water.
- The main MESSENGER website is at http://messenger.jhuapl.edu/index.php
- Definitely check out the animations about Mercury's orbit at http://btc.montana.edu/messenger/elusive_planet/around_sun.php (can also be reached from the "Education" link on the main MESSENGER page)
- There's a nice set of java applets on planetary science at "The Solar System Collaboratory", http://solarsystem.colorado.edu/. The module on the greenhouse effect allows you to play with the various factors that influence the temperature of the surface of a planet.
- There are beautiful relief maps of Venus, Mars and the Moon at Ralph Aeschliman's Planetary Cartography and Graphics http://ralphaeschliman.com/

Sources for images used:

All images of Mercury and Venus are from the NASA Planetary Photo Journal http://photojournal.jpl.nasa.gov, unless otherwise indicated. I have given the Planetary Image Archive (PIA) number for each image

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- Mercury background image: MESSENGER Encounters the Innermost Planet, PIA 11247 http://photojournal.jpl.nasa.gov/catalog/PIA11247
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- Rotation of Mercury: from Journey to the Cosmic Frontier by John D. Fix, Fig. 10.3, http://www.mhhe.com/physsci/astronomy/fix/student/chapter10/10f03.html
- Animations of rotations of Mercury and Venus: animations by HMJ, with thanks to Ian Johnston.
- Flash animation of a day on Mercury: from MESSENGER: Animations and Movies, http://btc.montana.edu/ceres/MESSENGER/animationpage.htm
- Diagram of Mercury's orbit: from MESSENGER: Around the Sun, http://btc.montana.edu/ceres/MESSENGER/around.htm
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- Mariner 10 composite approaching Mercury: from NASA's History Division SP-424 The Voyage of Mariner 10, Chapter 7, http://history.nasa.gov/SP-424/ch7.htm
- MESSENGER Flyby 2 mosaic: from http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?gallery_id=2&image_id=214
- Except where otherwise noted, all Mariner 10 images are from NASA Planetary Photojournal: Mercury, http://photojournal.jpl.nasa.gov/targetFamily/Mercury or the NSSDC Planetary Image Catalog: Mercury, http://nssdc.gsfc.nasa.gov/imgcat/thumbnail_pages/mercury_thumbnails.html
- Mariner 10 map of Mercury: from Mercury Transit on May 7, 2003: Mapping Mercury, http://www.astro.uni.wroc.pl/vt-2004/mt-2003/mt-mercury-mapping.html
- Caloris basin mosaic: PIA10383 http://photojournal.jpl.nasa.gov/catalog/PIA10383

- Caloris from MESSENGER: http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&search_type=and&image_id=394&keyword=67&search_cat=
- Caloris basin in colour: PIA10359 http://photojournal.jpl.nasa.gov/catalog/PIA10359
- The Spider; PIA11077 http://photojournal.jpl.nasa.gov/catalog/PIA11077
- Volcano in Caloris: PIA10942 http://photojournal.jpl.nasa.gov/catalog/PIA10942
- Formation of the weird terrain: from Astronomy 23/223: Mercury, www.mtholyoke.edu/courses/ mdyar/ast223/mercury/mercury_geol.pdf
- Weird terrain comparison: from http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&gallery_id=2&image_id=297
- Crater chains from MESSENGER: PIA10378 http://photojournal.jpl.nasa.gov/catalog/PIA10378
- 3-D view of Discovery Scarp, from "New Data, New Ideas, and Lively Debate about Mercury" by G. Jeffrey Taylor, http://www.psrd.hawaii.edu/Oct01/MercuryMtg.html
- Scarps from MESSENGER: PIA10939 http://photojournal.jpl.nasa.gov/catalog/PIA10939 and http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&gallery_id=2&image_id=287
- Radar detection of ice: from "New Data, New Ideas, and Lively Debate about Mercury" by G. Jeffrey Taylor, http://www.psrd.hawaii.edu/Oct01/MercuryMtg.html
- Image of Messenger: from the Messenger website, http://messenger.jhuapl.edu/. Image of BepiColombo: from ESA Space Science, http://www.esa.int/esaSC/120391_index_0_m.html
- Venus title image: computer generated picture of Magellan radar data, from Astronomy Picture of the Day 2002 March 30, http://antwrp.gsfc.nasa.gov/apod/ap020330.html
- Venus background image: from MESSENGER Bids Farewell to Venus, http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&gallery_id=2&image_id=158
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- Venus magnetosphere: from ESA News 11 April 2006 http://www.esa.int/esaCP/SEM2GQNFGLE_index_0.html#subhead4
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