The Exploration of Venus by Spacecraft

A summary of knowledge about Venus gained from spacecraft missions,
with comparisons to Earth
and an examination of the questions
the newly arrived Venus Express spacecraft was designed to answer

Prepared for the 2006 BDAS Astronomy Course

by
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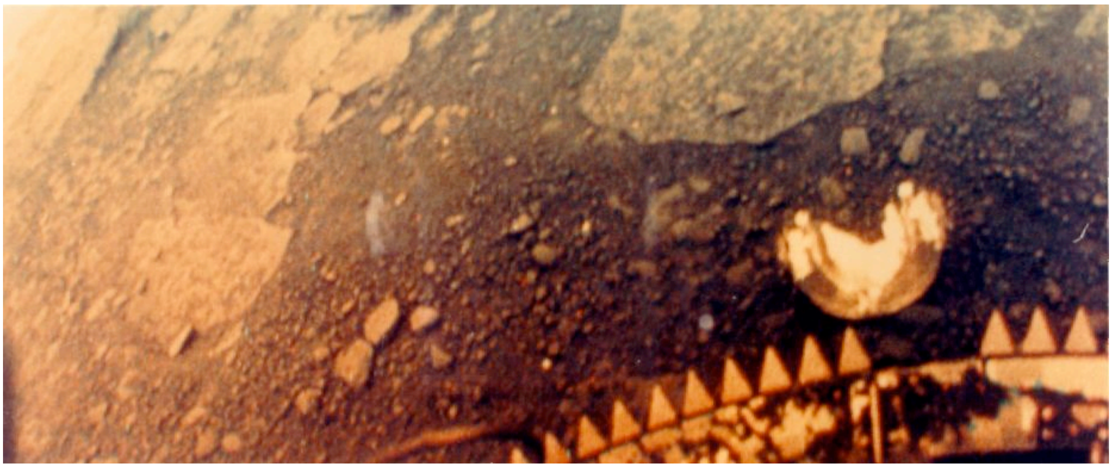
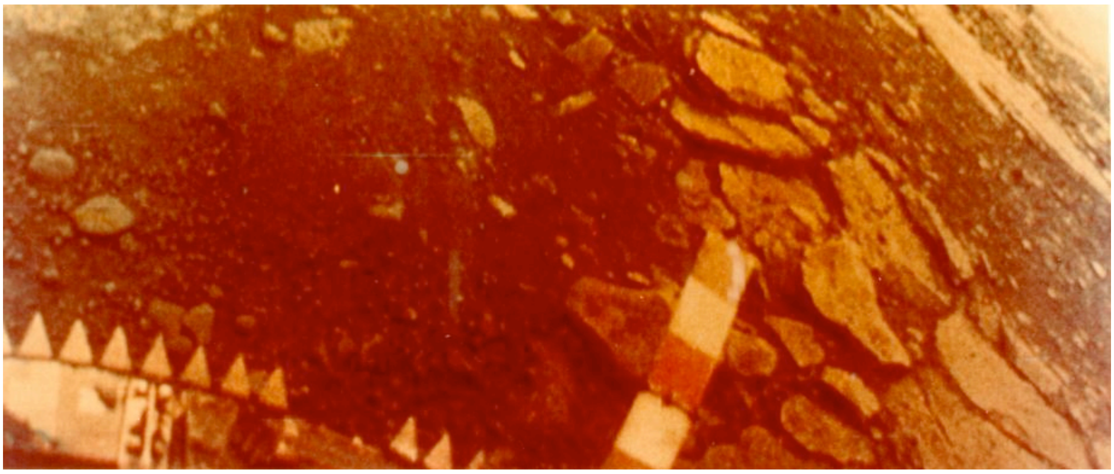
18th April 2006





First colour images received from Venus. Venera 13 landed on a surface strewn with basalt rocks in 1982
Soviet Space Program

Acknowledgement of sources

This document makes extensive use of text and images from ESA's Venus Express Home Site:
http://www.esa.int/SPECIALS/Venus_Express/

Other material has been added from a variety of sources. In particular:
Wikipedia Venus Spacecraft:
http://en.wikipedia.org/wiki/Category:Venus_spacecraft
Don P Mitchell, The Soviet Exploration of Venus
http://www.mentallandscape.com/V_Venus.htm
NASA Planetary Photo Journal
http://photojournal.jpl.nasa.gov/index.html
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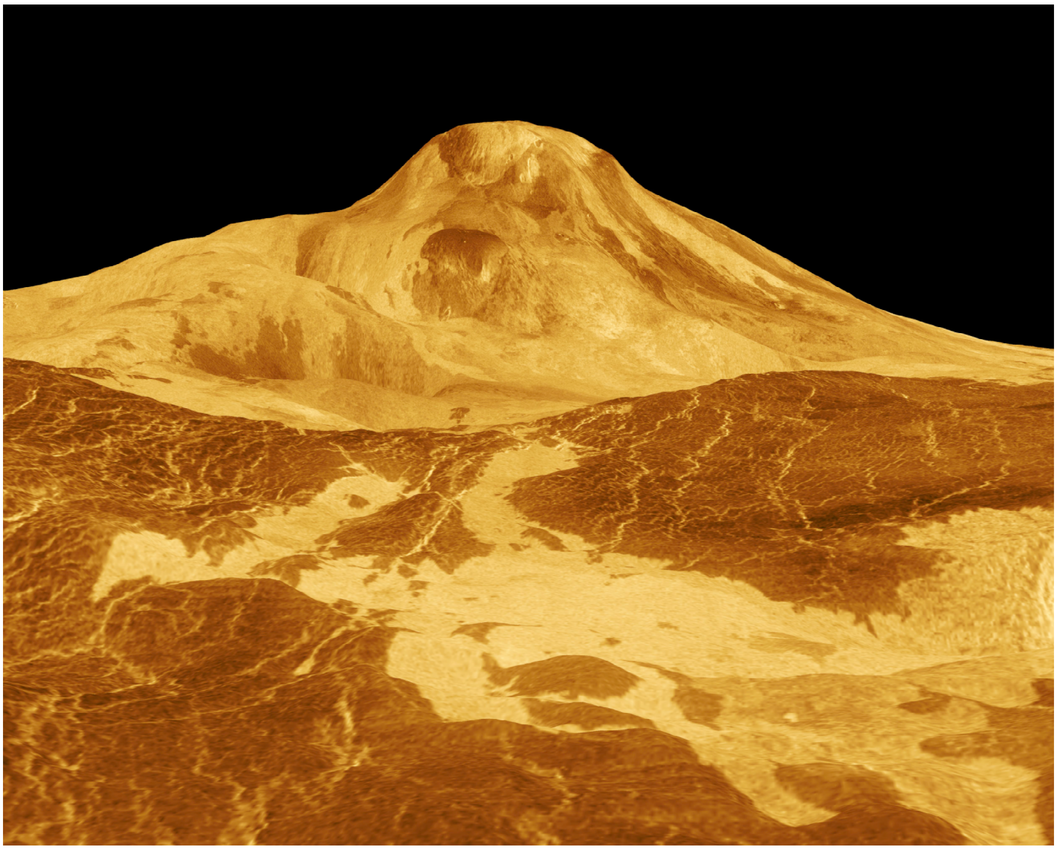
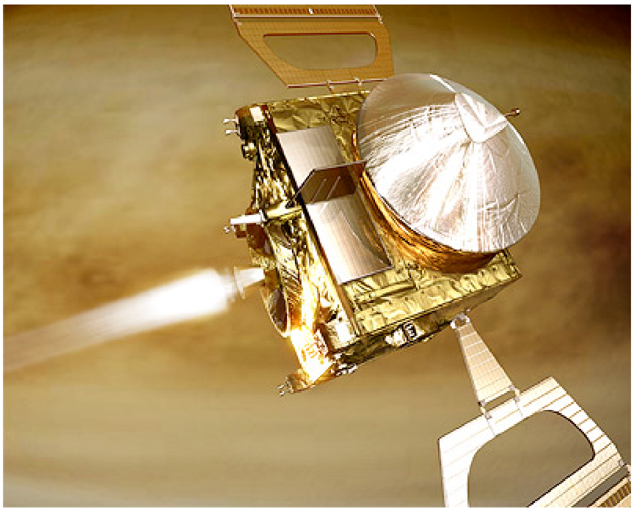


3D perspective view of Maat Mons, an 8.5 km high volcano on Venus. The image has been generated from Magellan Orbiter radar data obtained between 1990 and 1994. The vertical scale is exaggerated. The colours are simulated. The colours used to represent the data are based on images taken by the Soviet Venera 13 and 14 spacecraft. NASA. Planetary Photo Journal.

Part 1. Spacecraft Explorers



Venus Express arrives at Venus. Artist's impression. ESA

The Venus Express spacecraft successfully entered Venus orbit on 11th April 2006. It arrived packed with instruments designed to answer many of the questions generated by previous missions to Venus.

In 1960, before the launch of spacecraft to other parts of the Solar System, Earth and Venus appeared to be sisters. They had similar masses and densities. Their radii were almost the same. Both condensed from the same region of the nebula from which the Solar System formed. Both solidified from a molten state about four and a half billion years ago. Scientists speculated that the two planets were following similar evolutionary paths. Because its orbit was a little closer to the Sun, Venus was predicted to be at warmer, more primitive stage, perhaps similar to Earth, for example in Carboniferous times, 300 million years ago. Beneath Venus's dense cloud cover, scientists expected to find warm oceans and steamy jungles. The first Venus landers were equipped with detectors for measuring ocean swell, in case they descended over water.

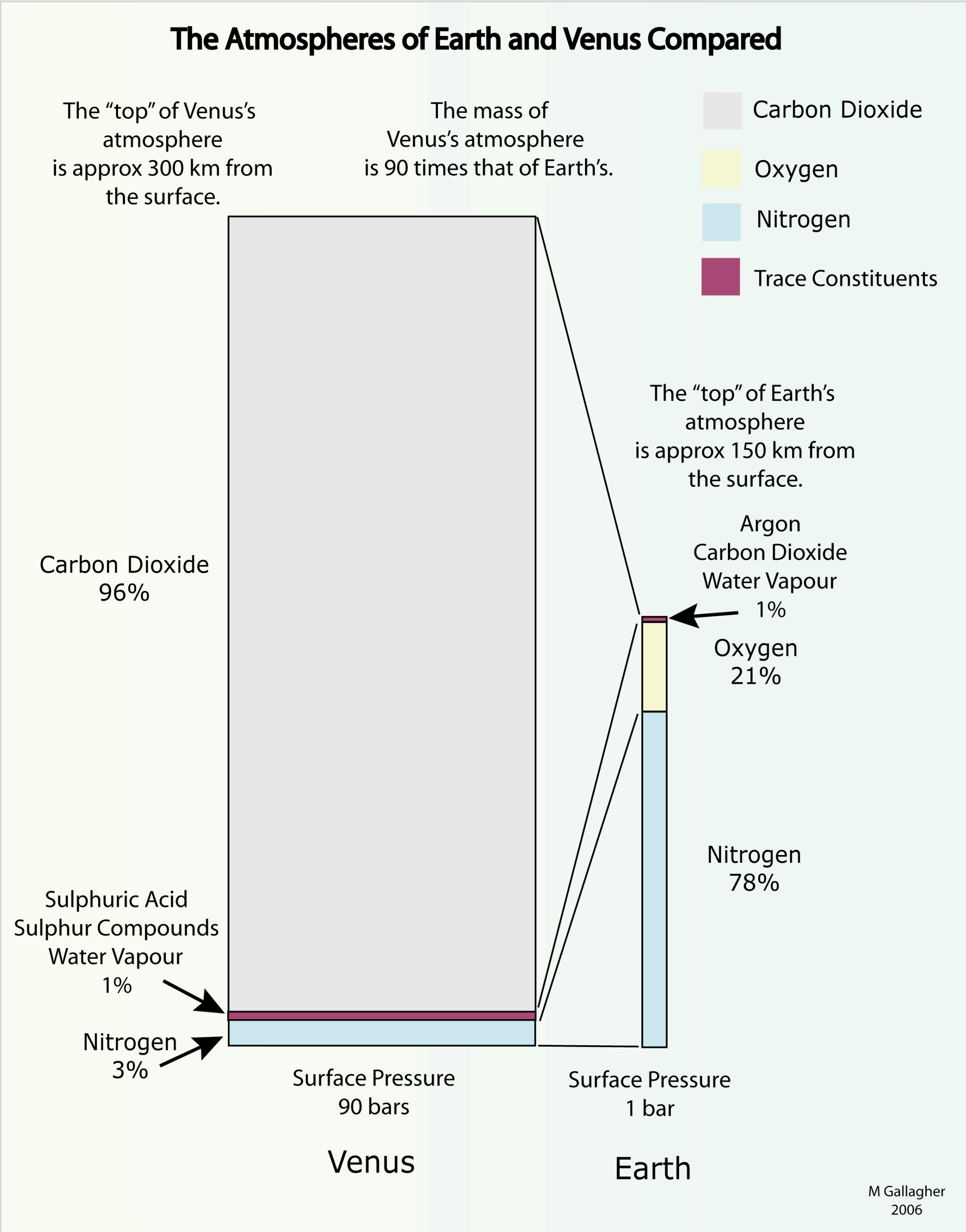
It was only when spacecraft began returning data from Venus that we began to realize just how different the two planets are. Details of the missions that have made discoveries at Venus are summarized in the table below:

Spacecraft that have returned data from Venus		
Spacecraft	*Year*	*Details*
Mariner 2 Flyby	1962	Radiometer scans revealed that Venus has cool clouds and an extremely hot surface.
Venera 3 Atmospheric Probe	1963	Communications failed. Crash landed on Venus.
Venera 4 Atmospheric Probe	1967	Transmitted atmospheric data. Landed on Venus, but transmissions failed during descent.
Mariner 5 Flyby	1967	Shed new light on the hot, cloud-covered planet and on conditions in interplanetary space.
Venera 5 Atmospheric Probe	1969	Transmitted atmospheric data. Crushed 26 km from surface
Venera 6 Atmospheric Probe	1969	Transmitted atmospheric data. Crushed 11 km from surface
Venera 7 Lander	1972	Landed on Venus. Survived for 23 minutes before succumbing to heat and pressure.
Venera 8 Lander	1972	Landed on Venus. Survived for 50 minutes before

		succumbing to heat and pressure.
Mariner 10 Mercury mission Venus gravity assist flyby	1974	Ultra-violet camera filters uncovered details in the clouds of Venus that surprised most researchers.
Venera 9 Orbiter and Lander	1975	Landed on Venus and sent back the first images of a rock strewn surface. Survived for 53 minutes before succumbing to heat and pressure.
Venera 10 Orbiter and Lander	1975	Landed on Venus. Corroborated Venera 9 findings. Succumbed to heat and pressure after 65 minutes.
Venera 11 Flyby and Lander	1978	Landed on Venus. Survived for 95 minute. Imaging system failed.
Venera 12 Flyby and Lander	1978	Landed on Venus. Survived for 110 minutes. Recorded evidence of lightning.
Pioneer Venus Orbiter	1978 to 1992	Collected and mapped surface and atmospheric data over 14 years. Observed at multiple bandwidths. Measured composition of the atmosphere. Analyzed affect of the solar wind on the atmosphere. Carried out surface radar imaging. Measured magnetic field strengths. Collected and transmitted data from the multiprobes.
Pioneer Venus Multiprobe	1978	One large and three small atmospheric probes measured composition, particle sizes, the distribution of sources and sinks of radiative energy, temperature, pressure, turbulence and wind velocity while descending through the atmosphere. Each probe was deliberately targeted to a different part of the planet. One of the probes continued to send data for an hour after impact.
Venera 13 Flyby and Lander	1981	Landed on Venus. Returned the first colour images of Venus' surface. Discovered tholeiitic basalt, similar to that found in Earth's mid-ocean ridges.
Venera 14 Flyby and Lander	1981	Landed on Venus. Returned colour images. Discovered leucite basalt in a soil sample.
Venera 15 Orbiter	1983	Together with Venera 16, mapped the northern hemisphere from the pole down to 30 degrees from north.
Venera 16 Orbiter	1983	Collaborated with Venera 15 to map the northern hemisphere from the pole down to 30 degrees from north.
Vega 1 Venus Flyby and probe	1985	On the way to Halley's comet, the Vega 1 spacecraft released a lander and a balloon probe at Venus. The lander malfunctioned. The balloon probe returned measurements of temperature, pressure, wind speed and aerosol density for nearly two days.
Vega 2 Venus Flyby and probe	1985	On the way to Halley's comet, the Vega 2 spacecraft released a lander and a balloon probe at Venus. The lander transmitted data from the surface for 56 hours. The balloon probe returned measurements of temperature, pressure, wind speed and aerosol density for nearly two days.
Magellan Orbiter	1990 to 1994	Completed extensive radar imaging, radar ranging and gravity mapping surveys. Radar imaging and surface elevation data was assembled to create a topographical map covering almost the entire surface.
Galileo Jupiter Mission Flyby of Venus	1990	Used Venus for gravity assist, on the way to Jupiter. Multiple-wavelength imagery captured unprecedented cloud detail.
Hubble Space Telescope	1990 to 2006	From time to time, the Hubble Space Telescope has monitored the weather on Venus.
Cassini Saturn Mission gravity flybys of Venus	1998, 1999	During two passes of Venus, gravity assists for its journey to Saturn, radio experiments detected no instances of lightning. Test images were captured by the craft's Visual and Infrared Mapping Spectrometer on the second pass.

Part 2. Summary of Current Knowledge of Venus

The Atmosphere



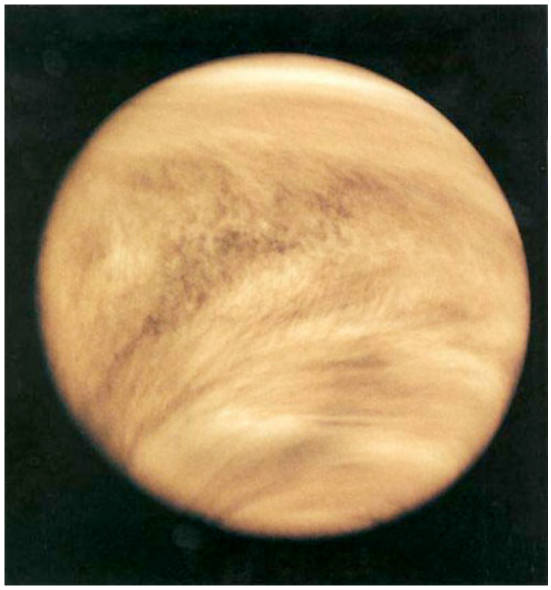
Venus's atmosphere is 90 times more massive than Earth's. Carbon dioxide is by far the major constituent. On Earth, the major constituents are nitrogen and oxygen. Venus's impenetrable cloud cover consists of sulphuric acid and other sulphur compounds and solid particles of unknown composition. Earth's sparse cloud cover consists mostly water aerosols condensed on dust nuclei.

Atmospheric pressure at the surface of Venus is 90 times higher than on Earth – equivalent to the pressure at a depth of 2 km in the ocean.

Its dense cloud cover reflects back into space about 80% of the solar radiation that strikes Venus. Earth’s atmosphere, in contrast, reflects back only 40%.

Venus’s atmosphere traps solar radiation as heat. The surface temperature is 465 °C, high enough to melt lead. Venus has the hottest surface in the Solar System, generated by a run-away greenhouse effect.

The first spacecraft landers could not survive on the surface. They were crushed by the dense atmosphere, corroded by sulphuric acid clouds and cooked by the extreme temperatures.



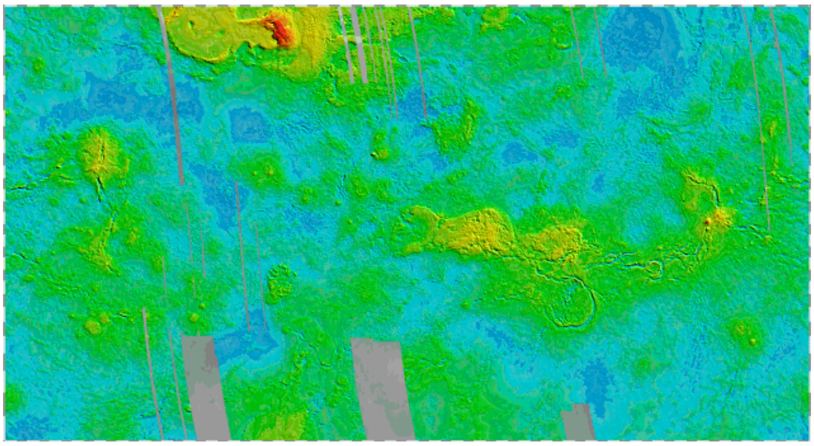
Mariner 10, UV light image of Venus cloud tops
NASA

The Surface

Venera 9 and 10 returned these images from Venus’s surface.
Soviet Space Program

Venera 9 and Venera 10 were the first landers tough enough to operate on the surface. They sent back images and data indicating that Venus is strewn with basaltic rocks, similar to those over much of Earth’s surface.

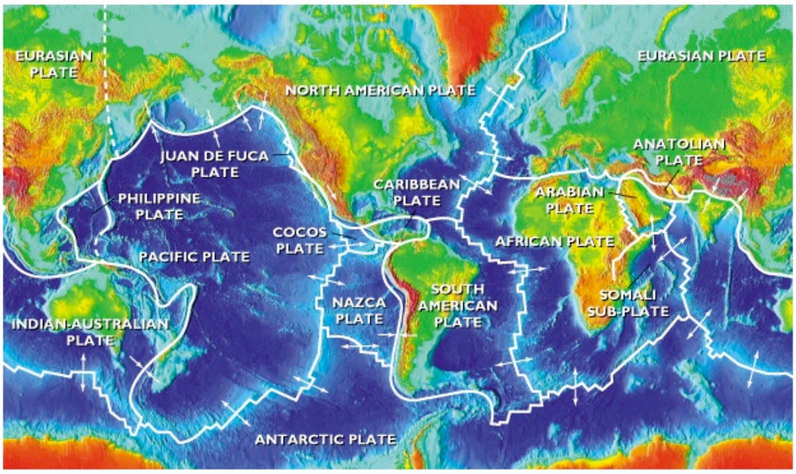
Oceans cover 80% of Earth and land masses the remainder. The radar scanner on Magellan has returned detailed images of most of Venus’s surface. From that and other data, we know that Venus has only landforms. Around 70% of the surface consists of gently rolling uplands. About 20% is made up of very flat lowlands. The remaining 10% consists of continent-sized highlands.



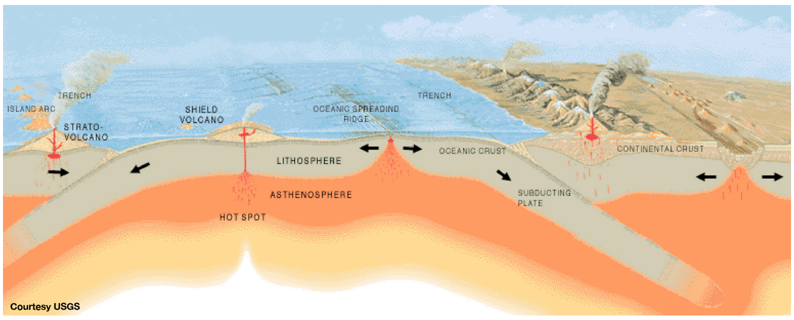
Topographic map of Venus, derived from Magellan data. NASA

Tectonic activity and volcanism

Tectonics is the movement of a planet's crust caused by convection currents in its molten interior. Earth's crust is divided into two types of tectonic plate: thick, granitic, continental plates and thin, basaltic, oceanic plates. On Earth, tectonic processes continuously create oceanic plate along mid-ocean ridges. The expanding oceanic plates collide with continental plates, driving continental drift, raising mountains and triggering earthquakes.

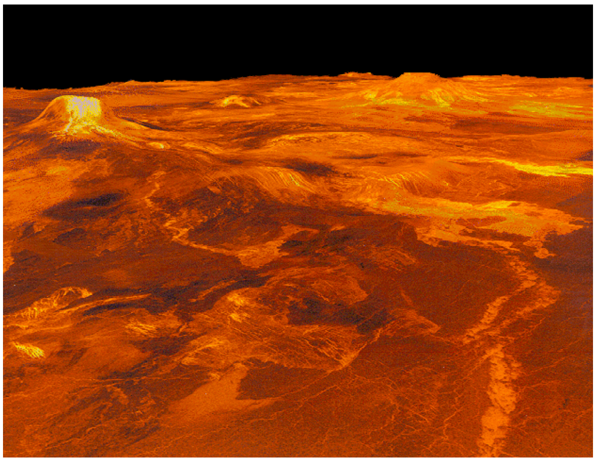


Earth's Tectonic Plates. Dr Steve Gao



Mid-Ocean Ridge production of oceanic plate and subduction at continent margins. NOAA.

Venus seems to have just a single plate that covers the whole planet. Tectonic forces have deformed that plate. We don't yet know whether Venus's crust is thick or thin, or to what extent tectonic forces move it today.

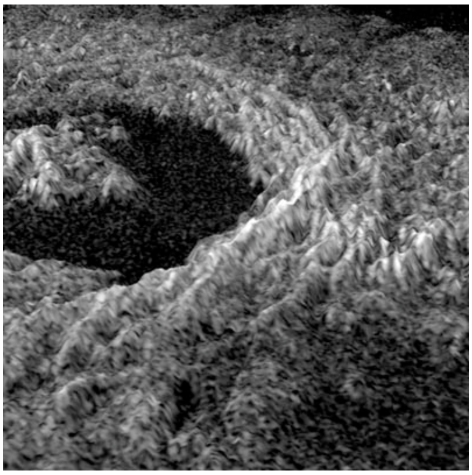
 

Left: Global image of Venus obtained by the Magellan Radar Scanner. Right: 3D perspective of Western Eistla Regio taken by the Magellan Radar Scanner. NASA images.

Volcanic activity has shaped Venus's crust. Early on in the planet's history, volcanism laid a thick layer of crust over a liquid mantle, just as on Earth. There are signs of many different kinds of volcanism - volcanic plains, volcanic rises and classic cones such as we find on Earth. There are lava flows that extend for hundreds miles. We don't yet know whether volcanism is still occurring on Venus today.

A lack of small impact craters

Many impact craters dot the surface of Venus. Unlike other Solar System bodies, however, there are almost no craters less than two kilometres in size. Does the dense atmosphere pulverize smaller meteorites before they meet the surface?



Golubkina crater on Venus. Magellan, NASA

A newly laid surface

Surprisingly, the oldest craters seem to be less than 500 million years old. Perhaps on Venus, internal energy builds up inside the planet until a global eruption engulfs and resurfaces the planet. Perhaps such a resurfacing occurred around 500 million years ago.

Earth appears never to have experienced such a massive disruption. Plate tectonics and volcanism continually dissipate internal energy before it builds up to globally catastrophic levels.

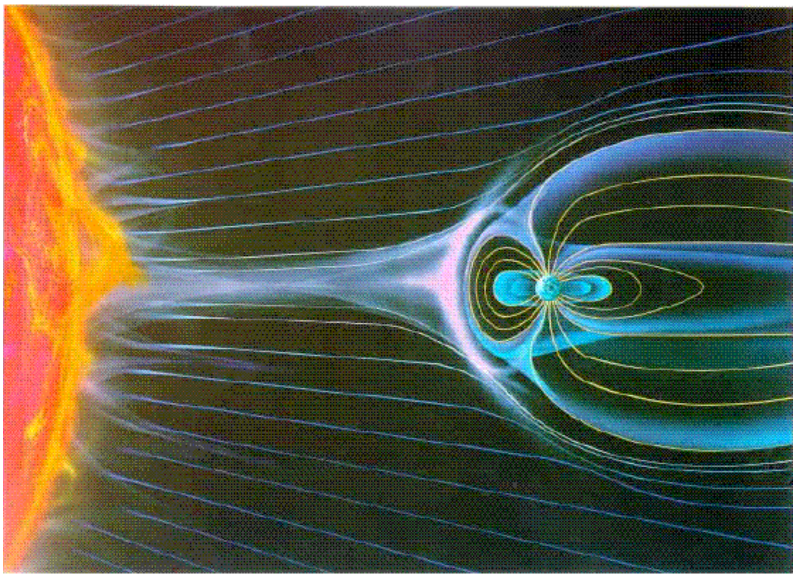
A short year, retrograde rotation and a very long day

Being closer to the Sun, Venus orbits the Sun more quickly than Earth. A Venusian year has only 225 days.

Most Solar System bodies rotate on their axis in the same direction that they orbit the Sun - from west to east. Venus is an exception. It rotates backwards - its rotation is said to be retrograde. On Venus, the Sun rises in the west and sets in the east.

As well as being retrograde, the rotation of Venus is very slow – one rotation or Venusian day takes 243 Earth days. A Venusian day is longer than a Venusian year.

Absence of a global magnetic field



Earth's Magnetosphere shields the atmosphere from bombardment by the Solar Wind. Artist's impression. Not to Scale. K Endo. NGDC

Movement in the Earth's metallic core, driven by the planet's relatively fast rotation, generates a strong, global, magnetic field. This creates a magnetic shield, the magnetosphere, which protects Earth's atmosphere from Solar Wind bombardment.

Venus lacks a global magnetic field. Its atmosphere is exposed to the effects of the Solar Wind. Scientists have yet to determine why a magnetic field is absent on Venus. Perhaps the core is no longer fluid. Perhaps Venus's rotation is too slow for a field to be generated.

Puzzling wind systems and polar vortices

In the middle atmosphere, at the top of the cloud belt, high velocity winds circumnavigate the planet in four days. There is almost no wind at the surface or at the top of the atmosphere. A massive vortex circulates above each pole, drawing upper atmospheric gases down to the surface. We do not have enough data to explain and model these phenomena.

Divergent evolutionary pathways

Venus and Earth must have been quite similar bodies in the early Solar System. The divergent paths along which they have evolved are of major interest to planetologists. Combining knowledge of Earth with what we learn about Venus will help us understand the factors that have produced such dramatically different internal structures, surfaces and atmospheres.

Part 3. Venus Express Mission Objectives

Venus Express has been launched to answer various questions raised by analysis of data from previous missions. Venus Express is an orbiter, designed specifically to study the planet's atmosphere. Surprisingly, however, mission scientists expect that the craft will also return copious information about the surface, the geology and the interior of the planet.

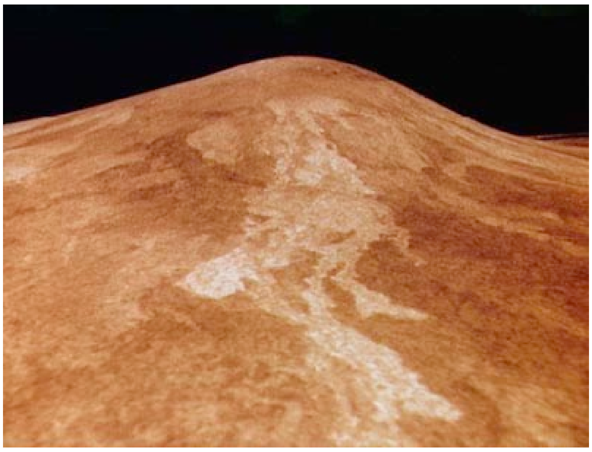
Surface Processes

Venus Express will carry out experiments designed to answer questions such as:

- Are there surface gas emissions that indicate active volcanoes?
- Do the surface and the atmosphere exchange material? Does a carbon dioxide cycle occur on Venus? Is there a water cycle? How do the sulphuric acid and sulphur compound cycles transfer material?
- On Earth, the oceans and the atmosphere are strongly coupled. Are the surface and the atmosphere of Venus similarly related?
- Do seismic events propagate mechanical waves through Venus's atmosphere?

Volcanoes and venus-quakes

Data returned by previous missions indicates that Venus is one of the most geologically active planets in the Solar System. It has a young surface. There are no signs of past history older than 500 million years. The planet appears to have been completely resurfaced not long ago by some massive disruption of the crust. Some surface features seem to have formed only recently. Is Venus still internally active?



Larva flow erupted from the volcano.
Sif Mons on Venus. Magellan, NASA

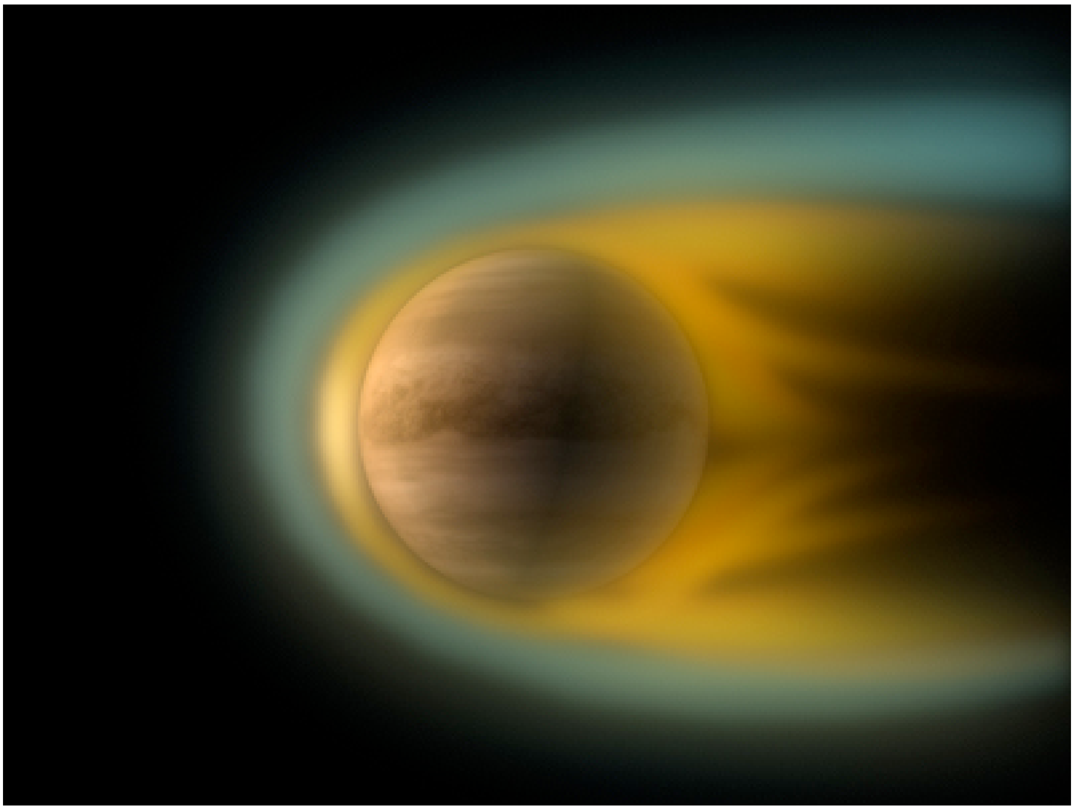
Venus Express is designed to test such hypotheses. It will search for signs of volcanic activity by analyzing the gases in the lower atmosphere. Changing abundance of sulphuric acid and sulphur dioxide may indicate the presence of volcanic activity. Temperature variations at particular locations could confirm and pinpoint the activity.

Venus's atmosphere is dense enough to transmit pressure waves that result from seismic jolts. Venus Express can detect variations in temperature and pressure caused by seismic waves propagating through the atmosphere. Venus Express may be able to use such waves to identify seismically active regions, determine the rate of seismic activity, and even determine the position and magnitude of the strongest venus-quakes.

The effect of the Solar Wind in the absence of a global magnetic field

The atmospheres of Venus and Earth must initially have had similar amounts of hydrogen, oxygen, water vapour and other volatiles. The two atmospheres have since evolved very differently. Venus Express will help determine whether significant components of Venus's atmosphere were lost to space as a result of the Solar Wind or whether they have combined to form surface material.

Venus has only a weak, local magnetic field induced by the solar wind. Its atmosphere is unprotected from the Solar Wind. Does the Solar Wind drive gas and water vapour from Venus's atmosphere? Is the Solar Wind the main factor that has caused Venus's atmosphere to evolve so differently from Earth's?



In the absence of a global magnetic field, Venus's atmosphere is blasted directly by the Solar Wind. Artist's impression. ESA

No water has been detected on the surface and very little water vapour has been detected in the atmosphere of Venus. Were massive amounts of hydrogen lost to space in early epochs? Was oxygen was lost to space, or has some massive process bound it with surface material?

Why does Earth have so much water and Venus so little? Was there once a primordial ocean on Venus and was it later vapourised and lost?

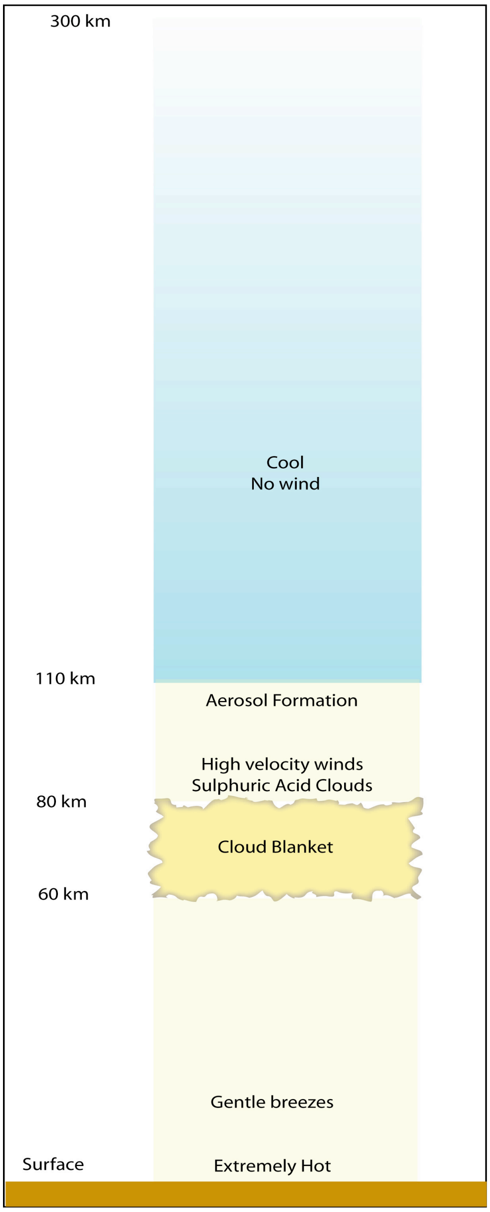
Venus Express will make the first global study of how atmospheric escape processes work on Venus. This will improve our understanding of how Venus's atmosphere has evolved and help us understand our own atmosphere.

Cloud blanket

Sixty kilometres above the surface there is a 20 km thick cloud blanket. This dense, yellowish, un-broken layer completely envelops the planet and prevents Earth-based observatories and orbiter missions from seeing the surface in visible light.

From previous missions, we know that the upper part of the cloud layer is mostly tiny droplets of sulphuric acid. The chemical processes occurring in the lower clouds are still unknown. Large solid particles floating in the lower clouds were first observed by Pioneer-Venus. Their origin is still unknown.

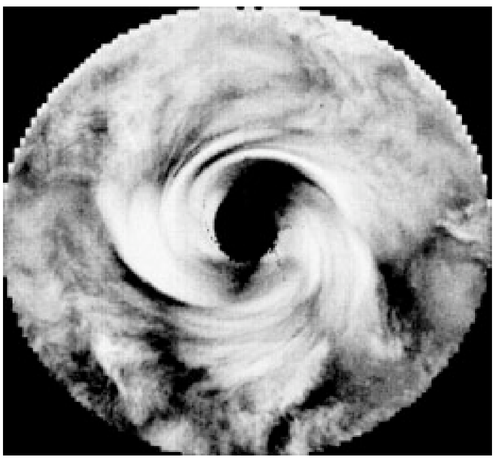
The Venus Express remote-sensing instruments will determine the constituents of the clouds, how the clouds are structured, how they form and evolve and how their opacity varies.



Venus Atmosphere Profile
M Gallagher

High-velocity winds and polar vortexes

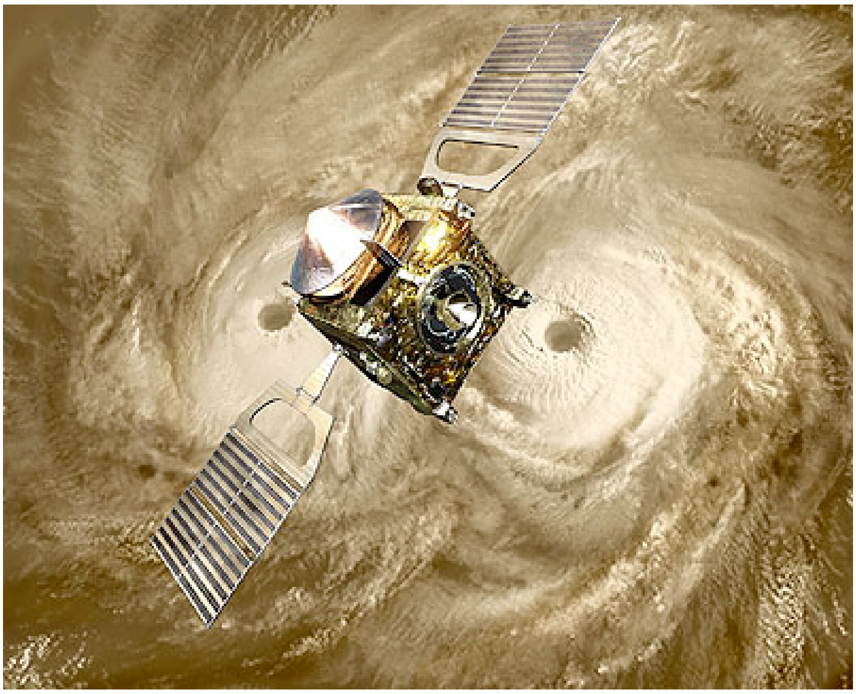
At the level of the cloud tops, the atmosphere rotates rapidly. Wind speeds reach 360 kilometres per hour and travel round the planet in four days. The speed of the winds progressively decreases to a gentle breeze at the surface. What drives the super rotation of the cloud top winds? What causes the different wind zones?



Vortex above the north pole of Venus
Pioneer Venus Orbiter NASA

Enormous vortices rotate over both poles and transport upper atmospheric gases down to the surface. So far, only the north-pole vortex has been observed in any detail. It has a peculiar double 'eye' shape. A collar of cool air surrounds it. It completes a full rotation in three Earth days.

Is the super-rotation of the cloud top winds linked to the rotation of the polar vortices? How does the global atmospheric circulation on Venus work? So far, no model has been developed to simulate the dynamics of the atmosphere of Venus. Venus Express scientists hope to gather the required data.



Artist's impression. Venus Express over the two-eyed north-pole vortex. ESA

Lightning?

Ground observatories and spacecraft have observed flashes in Venus's atmosphere, and detected localised emissions of radio waves. Does lightning cause them? The answer is hotly debated. Sulphuric acid droplets can become highly electrically charged, and could produce lightning. Does lightning affect chemical processes in Venus's atmosphere? Scientists still have little understanding of how the atmospheres of the inner planets become electrically charged and then discharge. Venus Express may help us improve our understanding.

Aerosol Formation

In the middle atmosphere, 60 to 110 kilometres above the surface, carbon monoxide is one of the more abundant trace gases. It is formed by dissociation of carbon dioxide by ultraviolet solar radiation. Photo-dissociation of sulphur dioxide also forms sulphuric acid molecules that combine to form cloud aerosols. Trace amounts of oxygen and water vapour are present in the middle atmosphere. Studying the chemical cycles of these gases will help us understand the formation of the clouds below.

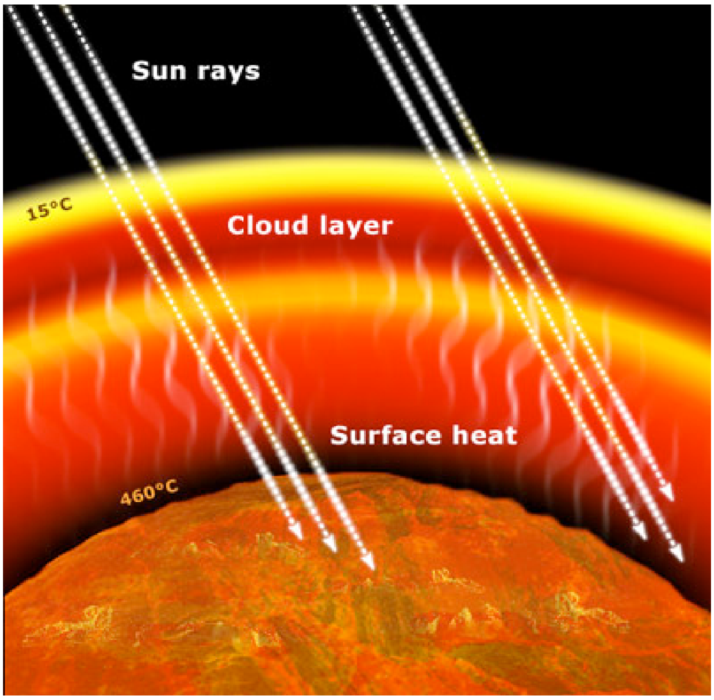
An upper atmosphere, cooler and stiller that expected

At the top of the atmosphere, there are still more mysteries. The temperatures in the upper atmosphere are surprisingly low, considering Venus's closeness to the Sun. They range from 30°C on the dayside, down to –160°C on the night side. Why is the upper atmosphere so cool?

Elsewhere in the Solar System, high-velocity winds are generated by upper-atmospheric temperature differences similar to those on Venus. Why are such winds absent in Venus's upper atmosphere?

Greenhouse effect and heat transfer

Venus's is host to the most powerful greenhouse effect in the Solar System. The greenhouse agents sustaining it are carbon dioxide, water vapour and sulphuric acid aerosols. Only 20% of incident radiation actually heats the atmosphere and the surface. But the atmosphere blocks that heat from re-radiating back into space. A staggering 500°C temperature difference between the surface and the cloud-tops is the result. Do other gases contribute to this effect?

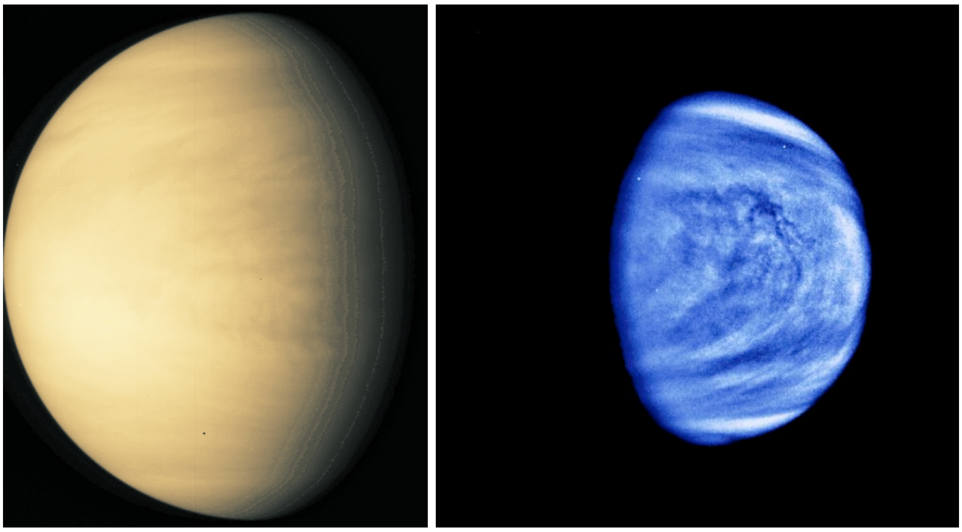


Greenhouse effect on Venus. ESA.

How is heat transported from the surface to the cloud layer 60 km above? Is the transfer facilitated by radiation, by turbulence or by atmospheric convection?

Ultraviolet markings

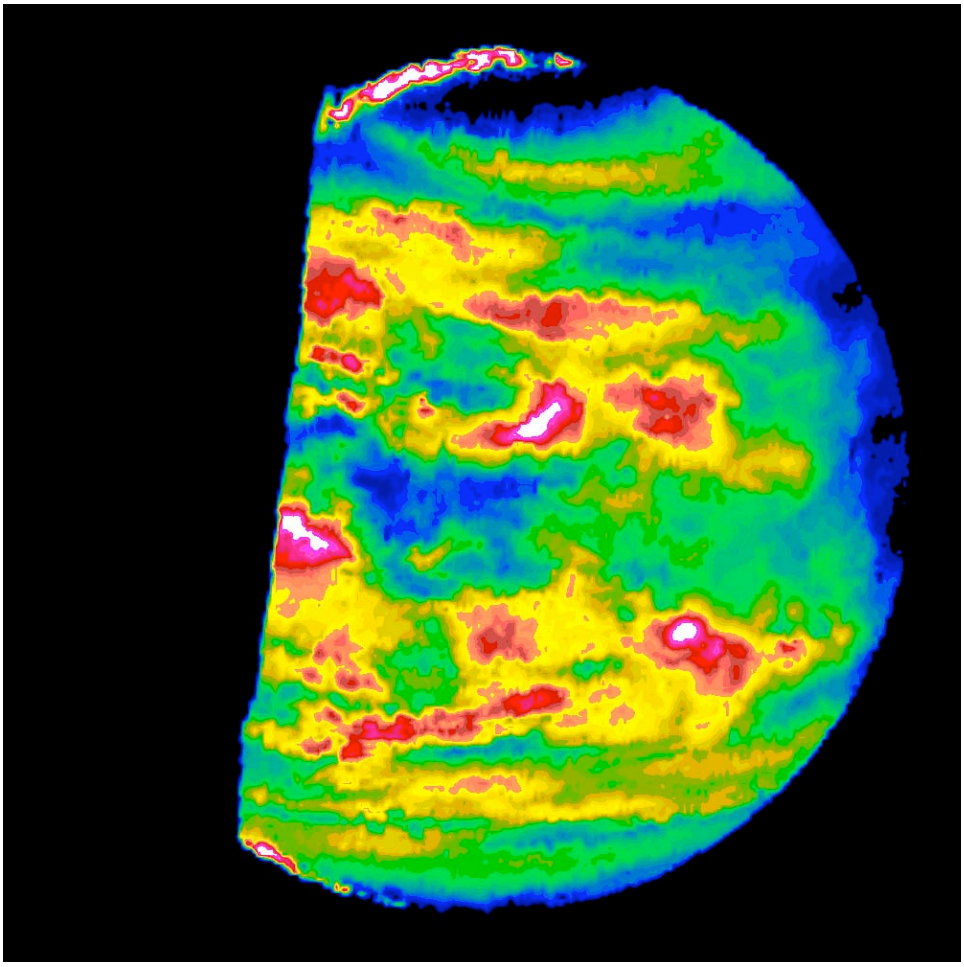
In the upper clouds, areas visible only in ultraviolet light mysteriously absorb a disproportionately high portion of incident solar radiation. What is the origin of these ultraviolet markings? Why is their absorption power so high?



As it sped past, en route to Jupiter, the Galileo spacecraft trained an array of instruments on Venus. Top left: visible light image. Top right: High band pass violet filter image. NASA images.

Atmospheric mixing

When observed in visible light, the atmosphere of Venus appears bland. When observed in infrared and ultraviolet light, Venus's clouds are seen to be complex, turbulent mixtures. What are the processes driving the mixing. Are enormous cumulus-type clouds continually forming and effecting the mixing?

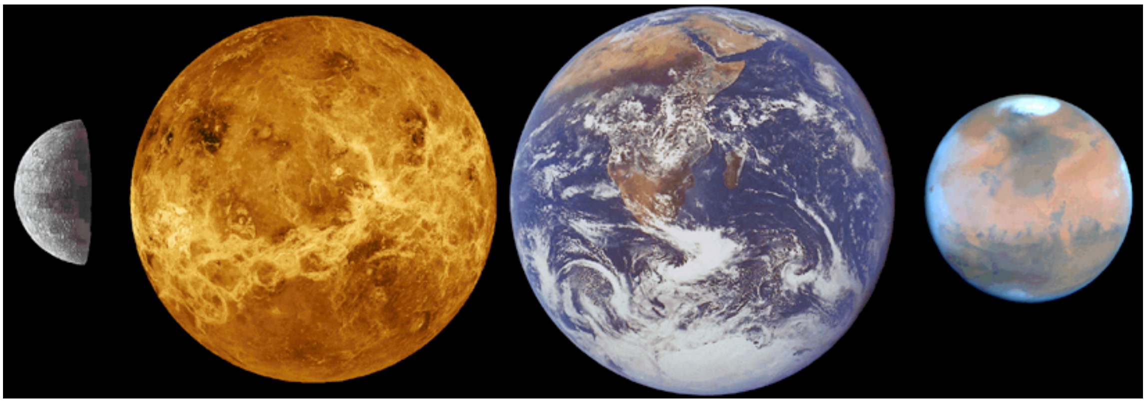


Complex structure in the night-side atmosphere of Venus. Galileo infrared image. NASA.

A better understanding of long-term climate change

The Venus Express mission will greatly increase our knowledge of local and global weather processes on Venus. It will help us to understand why the weather systems on Venus and Earth have followed such divergent evolutionary paths. It will assist us with the prediction and control of long-term climate change.

Venus compared to Earth



From the left: Mercury, Venus, Earth, Mars. NASA.

The four inner Solar System planets, Mercury, Venus, Earth and Mars have rocky surfaces. Venus, Earth and Mars have atmospheres, clouds and weather systems. Venus and Earth have almost identical sizes and densities. Extensive studies via spacecraft, however, have shown just how widely different the two planets are. Some of their similarities and differences are summarized in the table below.

Property	***Venus***	***Earth***
Mass	4.87 x 10^{24} kg	5.98 x 10^{24} kg
Radius	6,052 km	6,378 km
Density	5,250 kg/m^3	5,520 kg/m^3
Surface gravity at equator	8.9 m/s^2	9.8 m/s^2
Av. distance from Sun	108 million km	150 million km
Orbit period (year)	224.7 Earth days	365.2 days
Orbit inclination	3.4°	0° (Refernence plane)
Moons	None	The Moon
Rotation period (day)	243 Earth days (retrograde)	23 hours 56 minutes
Obliquity of axis	178°	23.5°
Global Magnetic field	None. Only localised fields induced in surface material by Solar Wind.	Global core generated field. Extensive magnetosphere shields atmosphere from Solar Wind.
Albedo (reflectivity)	0.76	0.37
Atmosphere	96% CO_2 , 3% N_2	78% N_2 , 21% O_2, 1% Ar
Surface pressure	90 bar	1 bar at sea level
Mean surface temperature	465 °C	15 °C
Cloud	Dense, unbroken layer 60 to 80 km above surface. Sulphuric acid and sulphur compounds, water vapour and solids. Poorly understood.	Zero to full cover, depending on weather, extending from surface to an altitude of 20 km. Water vapour condensed on dust nuclei.
Winds and weather.	Poorly understood. High velocity winds at top of cloud layer, Polar vortices. Little wind at the surface or at the top of atmosphere.	Complex diurnal and seasonal weather patterns. Jet streams, polar vortices. At times, destructive storms at surface, dust storms, wind erosion. Rain, hail, snow, run-off via rivers to oceans, water erosion., evaporation. A vigorous water cycle.
Crust	Single tectonic plate, Current tectonic activity unknown	Tectonically active. Multiple oceanic and continental plates.
Vulcanism	Young surface of volcanic origin. Full range of volcanic landforms. Current activity unknown.	Tectonics related volcanically active areas on continents and in oceans.
Surface types	Uplands 70%, lowlands 20%, highlands 10%	Oceans 80%, continents 20%
Highest point on surface	Maxwell Montes, 17 km	Mount Everest, 8.8 km
Rock types	Basalt rock, altered materials	Basalt, granite, altered materials

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