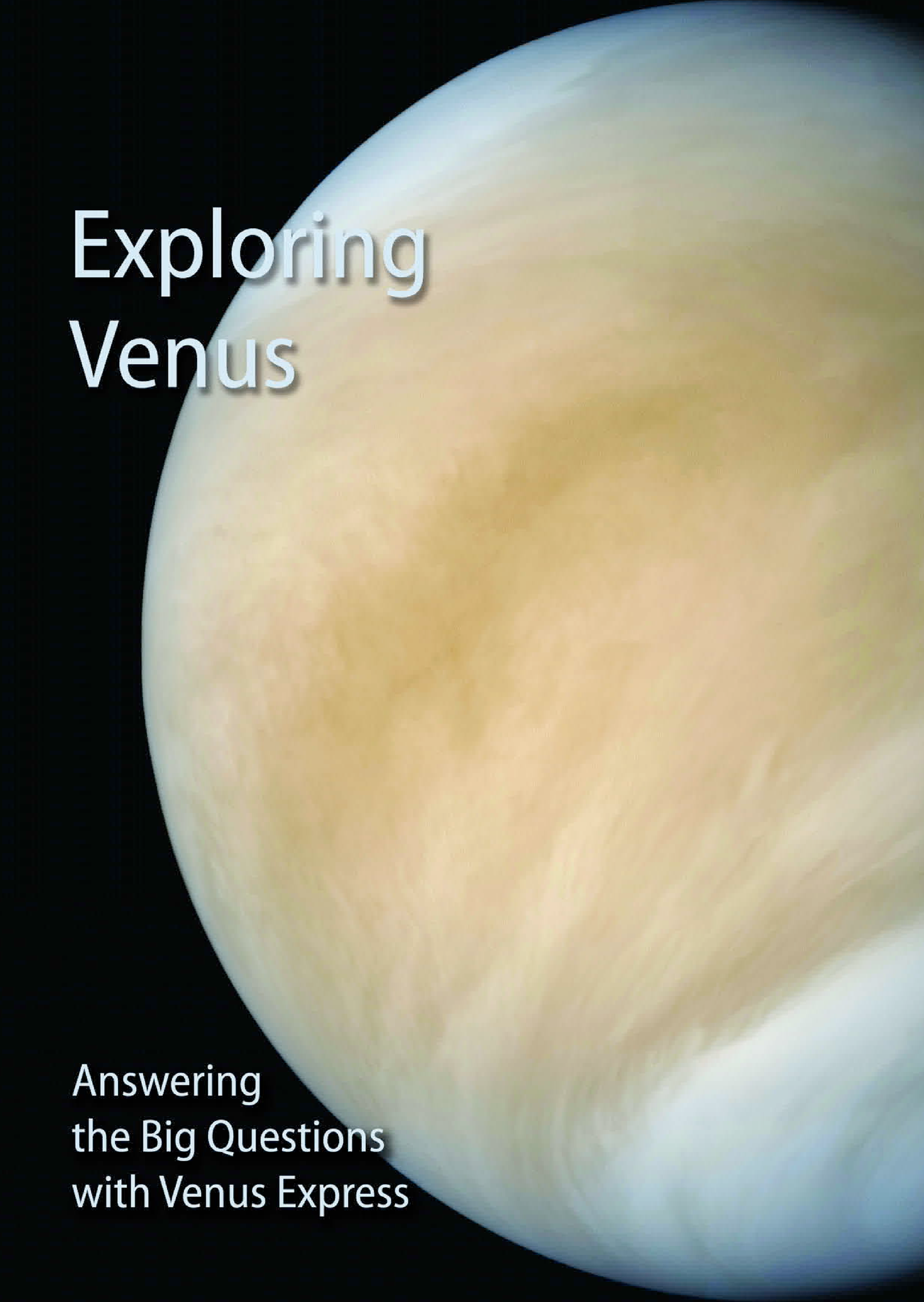
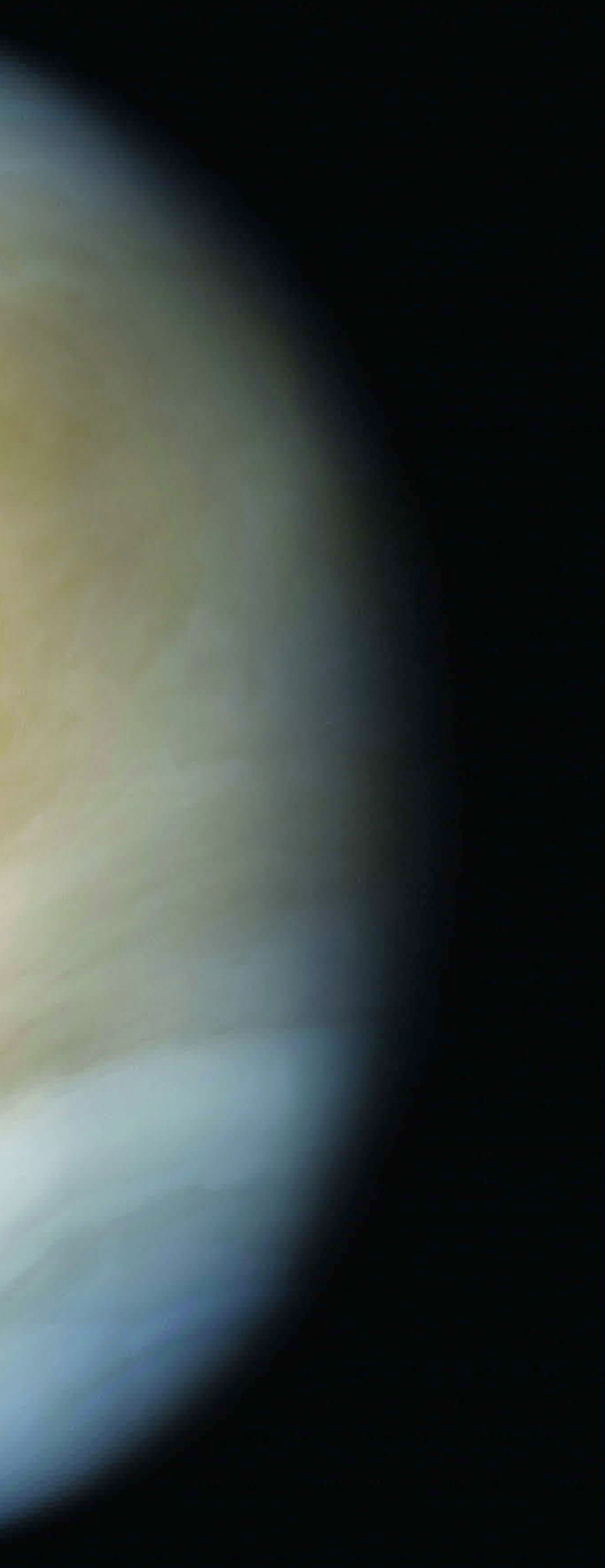
Exploring Venus



Answering the Big Questions with Venus Express



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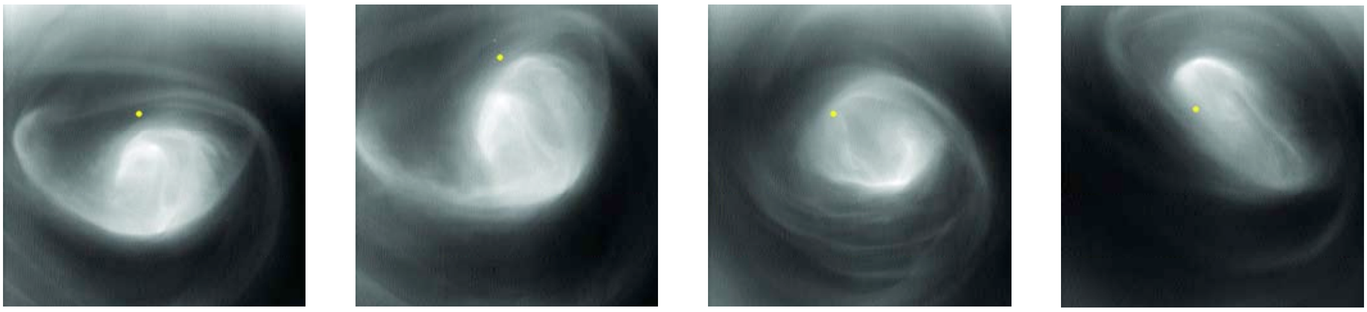
After being seemingly 'forgotten', with no visitors from Earth for more than 15 years, Venus is back in the limelight as one of the most exciting planets to explore, and ESA's Venus Express is keeping scientists busy interpreting new data.

Since arriving at Venus on 11 April 2006, ESA's Venus Express has provided a wealth of new data and is now keeping the scientists busy interpreting this information and modelling the results (see also *ESA Bulletin 124*, November 2007). With its design inherited from Mars Express, the Venus Express spacecraft has been performing very well during the two years in Venus orbit, in spite of being bathed in solar radiation four times more intense than at Mars and twice that at Earth.

Over 25 spacecraft have been previously targeted at Venus, but they have still left a great number of questions unanswered. Perhaps the most fundamental question is why Venus and Earth are so different today. Until even as late as the middle of the last century, it was generally believed that the



A sequence of images taken by the VIRTIS instrument at a wavelength of 5 micrometres shows the vortex at the south pole of Venus at an altitude of approximately 60 km. After the first image, the second, third and fourth are four hours, 24 hours and 48 hours later respectively. Each frame is about 2000 km across. The yellow dot marks the position of the pole (ESA/VIRTIS/INAF/Obs.deParis-LESIA/Univ.Oxford)

conditions on Venus were not too dissimilar from those of Earth and that possibly life existed there.

With the early missions of the 1960s, it became clear that no life could exist on the planet, at least not in the form that we know it. The surface has a temperature of over 450°C, hot enough to melt lead. The atmosphere is composed of 97% carbon dioxide and 3% nitrogen, at a pressure of 92 bar (about the same pressure as at a depth of 1 km under Earth's oceans). To add to these inhospitable conditions, the planet is covered in clouds of concentrated sulphuric acid.

The Grand Question

Perhaps the most important problem to understand is why Venus has evolved in such a dramatically different way compared to Earth, despite many similarities like size, mass and (likely) bulk composition. Most probably Venus has had a significant inventory of liquid water in the past, perhaps even as much as Earth, while today the amount of water is equivalent to a global ocean with an average depth of only 3 cm (3 km for Earth).

Data from the SpicaV/SOIR instrument show that the ratio of HDO to H_2O corresponds to a deuterium to hydrogen (D/H) ratio much higher than that on Earth (and the Solar System in general). This indicates that large amounts of hydrogen have escaped from the planet and left the heavier isotope deuterium in place. This lost hydrogen likely corresponds to the missing water.

How is this connected to the lack of a magnetic field and the time that the field disappeared? Is the lack of plate tectonics the key to the different evolution, or a consequence?

In the early days of the Solar System, the temperature must have been much lower. When and why did that change? Here are some of the results from Venus Express that could help us to answer these major questions.

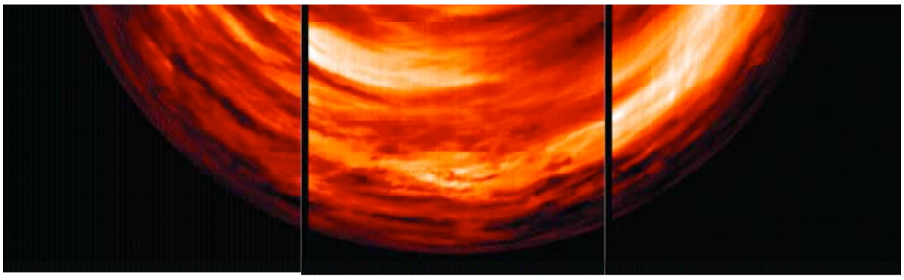
Venus's Atmosphere

The super-rotation of the atmosphere and the polar vortices are two of the major mysteries of the atmosphere. At the equator, winds reach over 100 m/s at an altitude of 60 km, and thus circle the planet in about four days. This is exceptionally fast, considering the long 243-day rotation period of the solid planet itself. Venus Express takes a few steps closer to solving these mysteries by mapping the atmospheric motion of the atmosphere in three dimensions and time. By measuring at infrared wavelengths of 1–3 micrometres, it is possible to probe different depths of the atmosphere and, thanks to the elliptical orbit with a pericentre over the north pole, it is possible to monitor the southern hemisphere for an extended time.

The sequence of four images demonstrates the highly variable character of the vortex at the south pole. It is not yet clear from where the driving force of this originates but it is obvious that there is a connection to the fast-rotating air masses at the mid and lower latitudes.

The next image shows a composite of a part of the southern hemisphere taken at a wavelength of 1.7 micrometres that shows the cloud structure at an altitude of about 45–50 km. By tracking features in several consecutive images of this kind taken at short time intervals, the wind speed can be estimated. By using different wavelengths, the wind speeds at different altitudes can be obtained. Elaborate models are used to take in many measured parameters, in particular

A false-colour composite of the southern hemisphere on the night side of Venus made by the VIRTIS instrument at a wavelength of 1.7 micrometres. It shows the structure of the clouds at an altitude of about 45–50 km. The south pole is just above the top of the central frame(ESA/VIRTIS/INAF/Obs.deParis-LESIA)



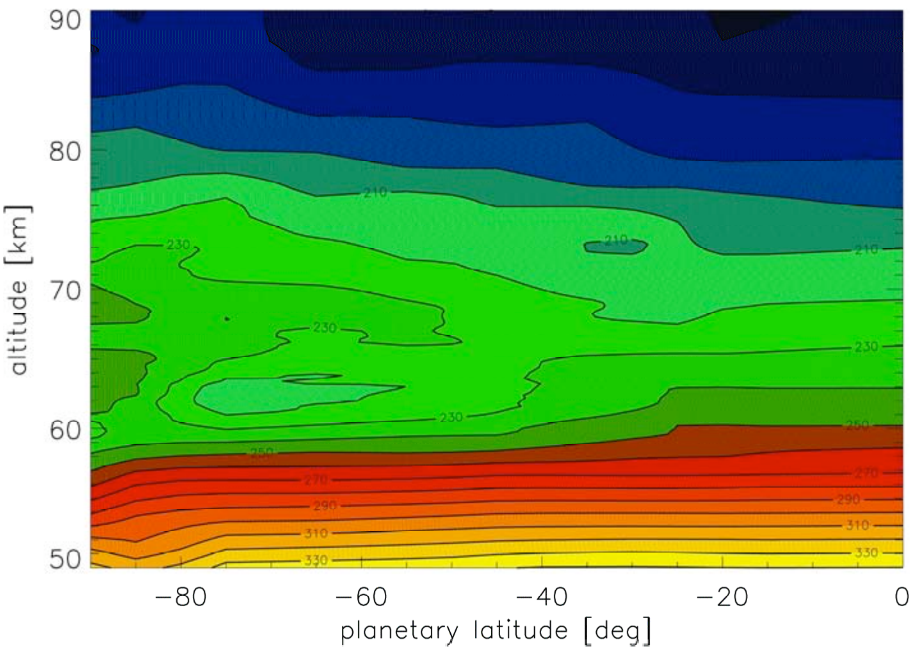
thermal profiles, and to try to reproduce these measured wind speed data.

The three-dimensional temperature distribution is very important for understanding the atmosphere. It is measured indirectly by three different methods, by the instruments VIRTIS, Vera and SpicaV, each focusing on different altitude ranges. The PFS instrument would have provided important additional data but, due to a malfunction, this instrument is not operational. The SpicaV instrument uses the stellar occultation technique to sound the temperature in the altitude range 100–140 km altitude

A warm layer at about 90 km altitude, close to the midnight position, has been discovered. This is believed to be caused by quickly downdrafting air that has been circulated from the sunlit side and migrated around the planet and being heated by compression while descending.

The Vera investigation uses a radio occultation technique through the telecommunication link to Earth to sound the temperature in the altitude range 40–90 km. This has revealed that the temperature in the lower atmosphere during the day and night is fairly similar around the planet for constant altitude. Between 60 degrees and 80 degrees northern latitude there is a thermal inversion in the tropopause at about 60 km altitude. This is a part of the 'cold collar', which marks the outer region of the polar vortex. This is likely to be caused by slowly downdrafting cold air making up the southern end of a 'Hadley cell'. This cell is a circulation pattern in the troposphere and mesosphere (below 90 km), with warm air rising in the equatorial region, transported polewards and descending to lower altitudes on cooling at these latitudes.

These two global circulation mechanisms, an East-West super-rotation combined with a meridional Hadley-type circulation below 100 km and a solar to anti-solar circulation above 100 km, co-exist and play a major role in the mixing of the different layers in the atmosphere.



Temperature in a cross-section of the atmosphere from the equator to the south pole in the altitude range 50 km to 90 km for the night side. The cold 'polar collar' that encircles the pole can be seen between 60° and 80° southern latitude at about 65 km altitude

Atmospheric Composition and Chemistry

Apart from the major gases carbon dioxide and nitrogen, there are a large number of minor gases in the atmosphere, at the level of a few hundred parts per million or less. Of these, the most important are sulphur dioxide (SO_2), carbon monoxide (CO), water vapour (H_2O and the related HDO), hydrogen chloride (HCl) and carbonyl sulphide (OCS). All these can be measured and mapped by Venus Express's SpicaV/SOIR and Virtis instruments.

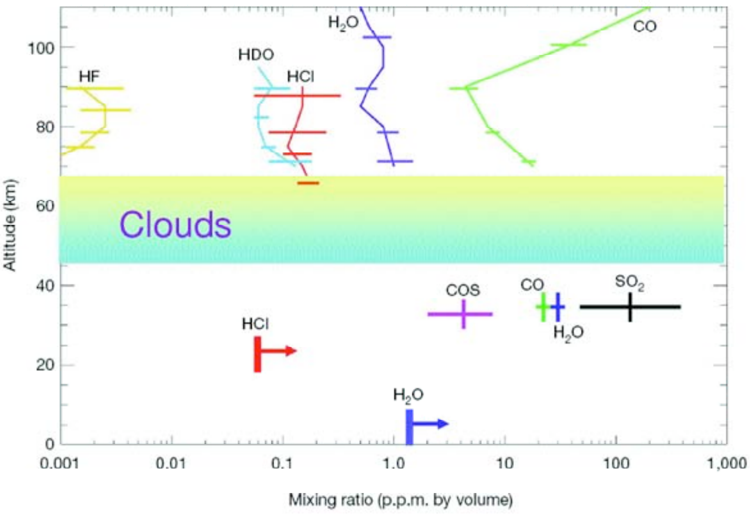
Recently, the hydroxyl radical (OH) was also detected by looking at the fluorescent light emitted by the excited molecule after having taken part in a chemical reaction. This very small amount of gas could be detected with VIRTIS by using limb-viewing geometry, where the amount of gas seen through a section of atmosphere at the limb appears to increase by up to a factor of 50 times as opposed to looking directly down to the surface of the planet. Hydroxyl is important because it is very reactive and normally has a short lifetime. The fact that we can see it means that there is a continuous production.

Nitrogen oxide (NO) and molecular oxygen (O_2) have been detected due to their fluorescent properties. Oxygen 'airglow' is fairly bright and can be observed also in nadir geometry and so images of its extension and dynamic behaviour can be used for general studies of the atmosphere at these altitudes (about 100 km).

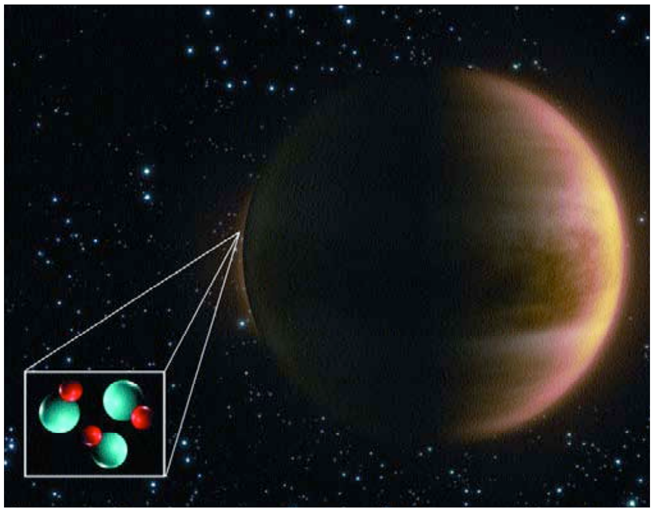
The oxygen comes from the CO_2 molecules on the sunward side of the planet that become dissociated into CO and O by the solar ultraviolet radiation in the upper mesosphere or lower thermosphere (about 100–120km). The oxygen atoms then travel around the planet to the anti-solar side where they descend and recombine with other oxygen atoms to form oxygen molecules (O_2). During the recombination the molecules become excited and they emit a photon with a characteristic wavelength of 1.27 micrometres. This is the 'airglow' observed.

Cloud Layer and Hazes

Venus is constantly covered by a thick global cloud layer at an altitude of 50–70 km. This cover is the reason that



Average abundance of the most important minor gases in the atmosphere. The horizontal bars are not error bars but the range that the data are spanning. Note that the sulphuric dioxide is very variable. The gases HCl and H_2O in the lower atmosphere have not yet been measured. The bars indicate the minimum detectable amount



An artist's impression of the detection of the airglow of hydroxyl (OH) molecules on the night side of the planet. The signal is enhanced by looking at the limb of the planet

Venus has an extraordinarily high albedo of 76%, meaning 76% of the incoming sunlight is reflected away from the planet by the clouds and does not contribute to the processes and the heating below. In visible light, almost no structure can be seen at the top of this cloud cover. In the ultraviolet light, however, an inhomogeneous distribution of an as yet still unknown absorber causes a significant amount of contrast that allows detailed studies of the top of the cloud layer. The VMC camera is well suited for this purpose with its wide field of view. Observations have shown a large temporal variation and that there are three distinctly distinguishable regions separated at latitudes of approximately 45 degrees and 70 degrees. VIRTIS data show that the cloud tops are located at about 70 km altitude except in the polar region, poleward of about 55 degrees latitude, where the cloud tops slowly drop to an altitude of 65 km at the pole.

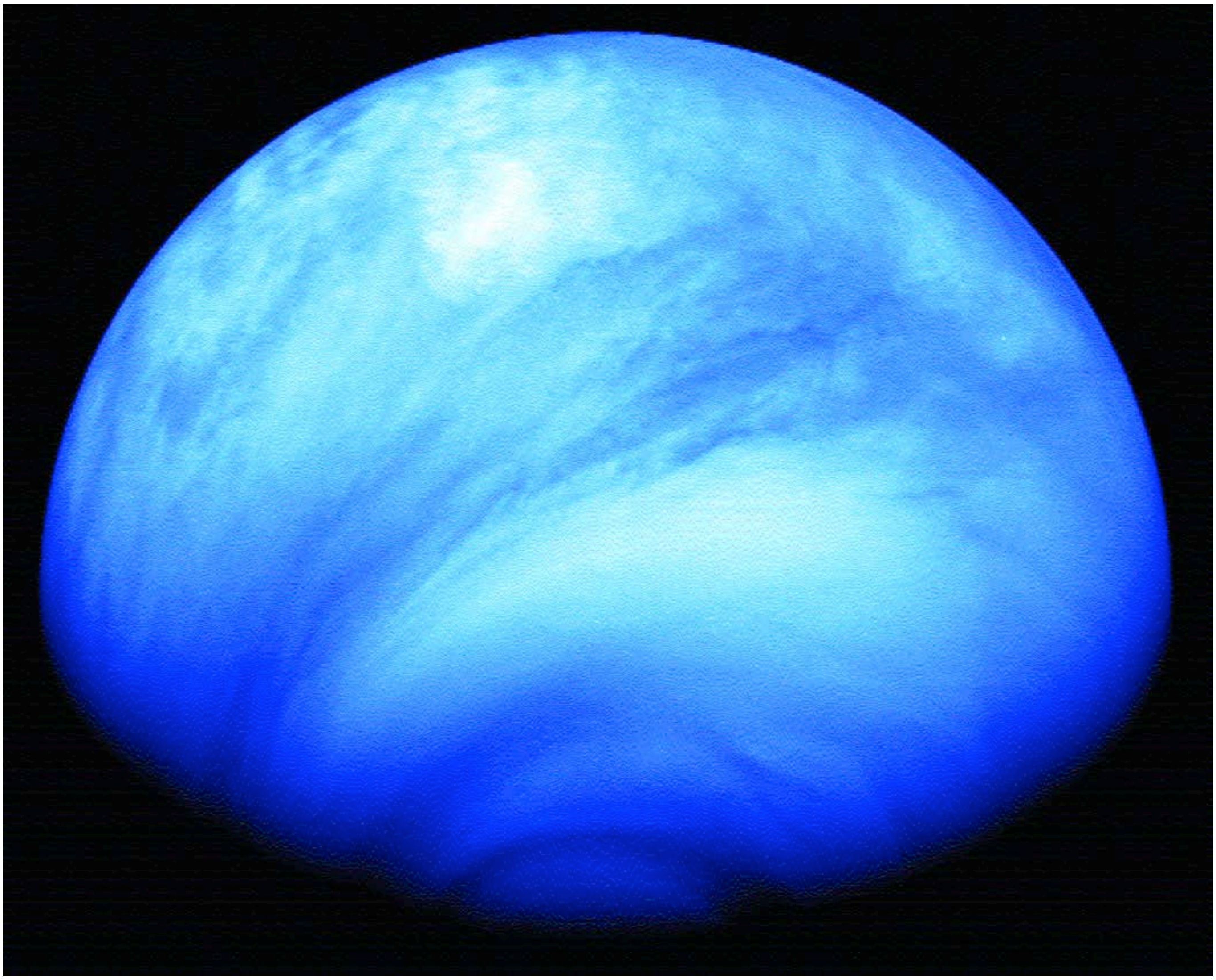
The sulphur cycle on Venus is very important since it includes also all the clouds and so has a major impact on the climate. The sulphur dioxide in the atmosphere is the source of the sulphuric acid in the cloud droplets. However, the sulphuric compounds on Venus have a lifetime of about 20 million years due to interaction with the surface. If there was no source to continuously supply sulphur dioxide to the atmosphere, the clouds would quickly disappear. The most likely mechanism for this supply is volcanic activity but no proof of existence of such activity has yet been found.

Data from the magnetometer give strong indications of the existence of lightning in the atmosphere. This is of great importance for the chemistry since lightning provides the extra energy required to synthesise many molecules. The frequency of the lightning appears to be similar to that of Earth but it has not yet been possible to estimate the energy of the individual lightning strikes. The lightning is not likely to occur between the clouds and the ground, but rather between clouds only.

The Surface of Venus

From crater statistics, based mainly on data from the Magellan mission, it has been possible to determine that the surface of Venus is very young, geologically speaking, at 700 million years ±200 million years. Furthermore, there seems not to be any difference in the age of the different regions of the planet and therefore it is believed that a dramatic resurfacing event took place more or less simultaneously over the planet. The duration of this event does not necessarily need to have been short, it could be tens of millions of years or more, but it has no known comparison in the Solar System. Like the other terrestrial planets (except Earth), there does not appear to be any plate tectonic activity. Therefore it is of great interest to get a better understanding of the surface properties of this planet.

Both VIRTIS and VMC are capable of peering through the thick atmosphere and the cloud cover by using the 1 micrometre spectral 'window' in the infrared region and to study the surface on the night side of the planet. However, the droplets in the cloud layer will blur the images and limit the spatial resolution attainable to about 50–100 km. These images are maps of surface brightness temperature and not images in reflected sunlight. They will be used for the search for regions of anomalously high surface temperature that could indicate the presence of volcanic activity or fresh lava fields. For comparison, synthetic maps based on Magellan altimetric maps together with an altitude to temperature conversion factor are used. This comparison also yields maps of surface emissivity



The sunlit side of Venus seen in ultraviolet light by the Venus Monitoring Camera from a distance of 30 000 km. The south pole is just below the lower end of the image and the equator is close to the upper limb running from left to right. The cloud structure in the equatorial region is dominated by turbulent regions, with convection cells forcing the air up or down in small packets. The mid-southern latitudes are characterised by long streaks in the clouds and clearly less convection while the polar region is dominated by the polar vortex (partly hidden behind the terminator) (ESA/MPS/DLR/IDA)

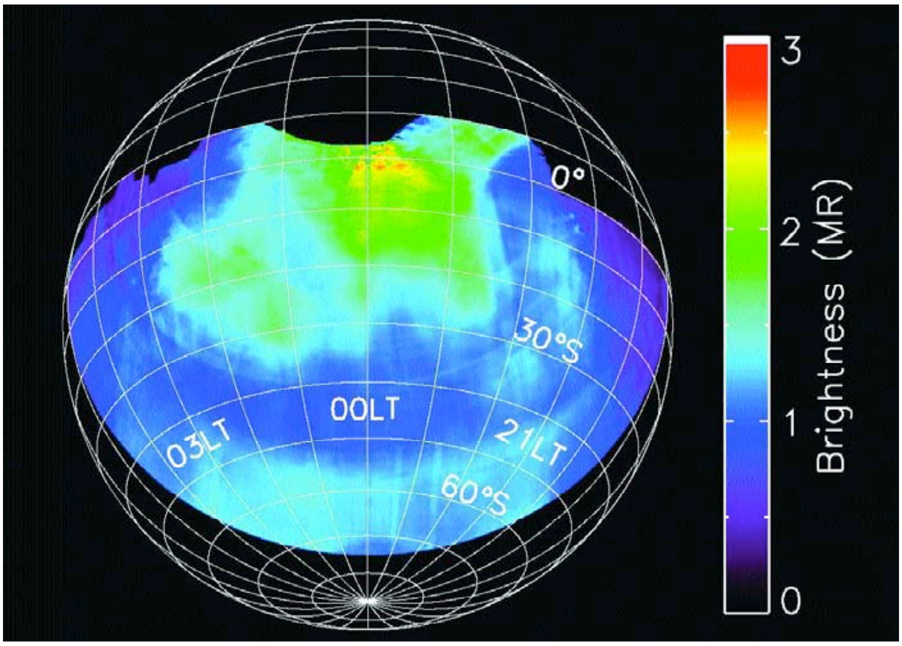
variations that are used for evaluation of different types of geological features.

Impact of the Solar Wind

Venus does not have an internal magnetic field to protect the atmosphere, unlike Earth, so the solar wind can interact directly with the upper atmosphere and erode the atmosphere in a very different way. It is important to understand how this process works and what the impact on the evolution of the atmosphere has been in the past and will be in the future.

The Aspera instrument characterises energetic ions, electrons and neutral particles with respect to mass, flux, direction and energy in situ along the orbit of the spacecraft down to the pericentre at 250 km altitude. It is also characterising the different regions and boundaries of the induced magnetosphere together with the magnetometer. Both instruments make reference measurements of the solar wind when the spacecraft is outside the influence sphere of the planet. The two instruments together have determined the position of the bow-shock and the induced magnetospheric boundary and their relation to the solar wind parameters. Presently, the solar activity is near its minimum and these data complement well the data taken by Pioneer Venus in the 1980s during the solar maximum.

An important finding by Aspera is the absolute number of escaping hydrogen, oxygen and helium ions. A particularly interesting find is that the ratio of escaping hydrogen to oxygen is 2.6, which indicates that water is a major source of these ions. If all of both components of water escaped, the ratio would be 2, but since the oxygen is much heavier it does not escape as easily as hydrogen. This may explain the difference of 0.6. An



A map of the oxygen airglow at 100 km altitude on the antisolar point. The maximum of the intensity is almost perfectly centred on the equator at local midnight. It is caused by oxygen atoms that combine to oxygen molecules and then fluoresce at infrared wavelengths

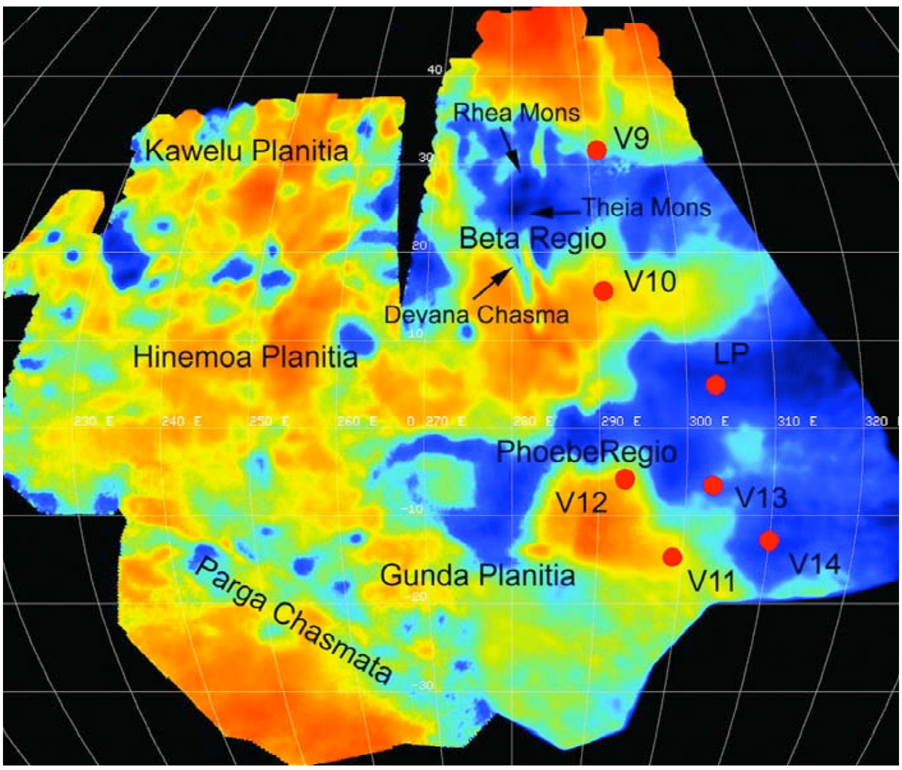
estimate of the present escape rate is a very important factor for understanding the evolution of water on the planet.

Climate and 'Greenhouse Effect'

The greenhouse effect is strongly dominated by the vast amount of carbon dioxide in the atmosphere. The enhancement due to carbon dioxide only, on the surface temperature, has been estimated to about 420K. However the water vapour, even if at a low abundance, enhances the surface temperature by 70K and the cloud cover as much as 140K if the albedo effect is not accounted for. There are still important uncertainties in these numbers since the absorption lines of most gases at Venus conditions are not well known. Related laboratory studies in support of the Venus Express investigations are in progress. The net effect of the cloud cover on Venus, just as on the Earth, is not yet fully understood. Both extended theoretical work and more data will be needed for a better understanding.

The carbon cycle is, or at least has been, very important since it relies on equilibrium between the carbon dioxide in the atmosphere and the carbonate rock in the crust. We do not know how much carbonate rock there is on or below the surface but, at the present-day temperature on Venus, most of the carbon should be in the form of carbon dioxide in the atmosphere. This is in contrast to Earth for example, where most carbon is contained in carbonates in Earth's crust, while the total inventory of carbon on Venus and the Earth has been estimated to be equal, or at least within a factor of two.

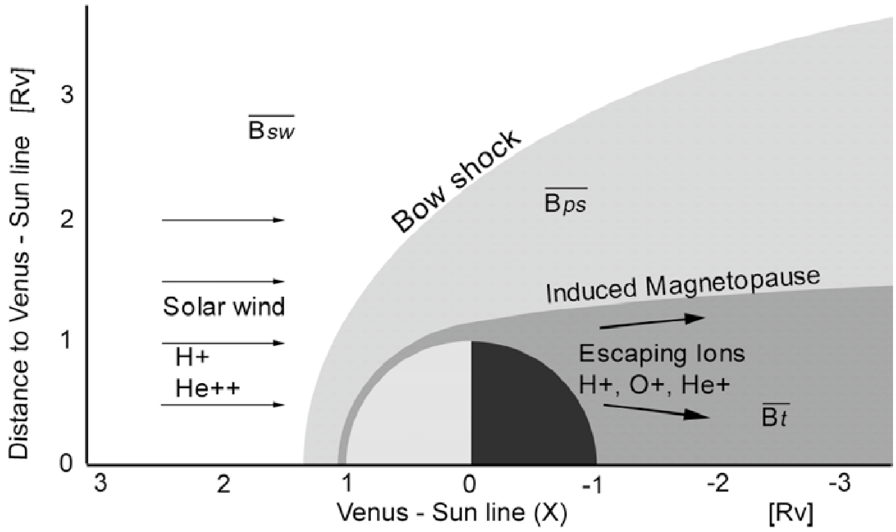
A composite of several images taken with the Venus Monitoring Camera. It shows the thermal radiation from the surface of the planet that is able to penetrate through the thick atmosphere, thanks to one of the spectral 'windows' at infrared wavelengths. The spatial resolution is limited due to strong scattering of the light while passing through the cloud layer. Orange-red areas indicate a high surface temperature (low elevation), while blue areas indicate a comparatively low surface temperature (high elevation). The red dots show landing sites of Russian Venera landers and the US Pioneer Venus Large Probe (ESA/MPS/DLR)



Conclusion

Perhaps the most likely answer to the 'Grand Question' is that the slight difference in distance to the Sun was the decisive factor. Due to this, the water on Venus started to evaporate creating a strong greenhouse effect that eventually cooked the carbon dioxide out of the rocks, so putting the planet in a 'runaway greenhouse state'. On Earth, the oceans converted the carbon dioxide already in the atmosphere into carbonate rocks to become sediments on the ocean floor and so stabilise Earth's climate. More data still has to be collected and analysed, but data from Venus Express processed so far are all compatible with this scenario.

It is not possible to get a complete understanding of how the climate works and evolves on one planet without having an understanding of it works on all planets in the inner Solar System. Understanding Venus is essential for understanding Earth. The coming years will see several studies focusing on comparing the different aspects of the evolution of Mars, Venus and Earth, in order to progress toward such a general understanding.



The plasma environment around Venus. The x-axis is pointing toward the Sun and the y-axis shows the distance to the Sun-Venus line (in radii of Venus). Venus has no internal magnetic field but, due to an interaction between the solar wind, the heliospheric magnetic field and the planet itself, an artificial protective bubble is set up around the planet. Due to the pressure of the solar wind, this bubble becomes deformed and very asymmetric and lets the solar wind come much closer than for example it does at Earth. The location of the boundaries called 'Bow shock' and 'Induced magnetopause' are found by both the magnetometer and the Aspera instrument. Planetary ions, notably hydrogen and oxygen (constituents of water), escape the atmosphere through the wake in the solar wind