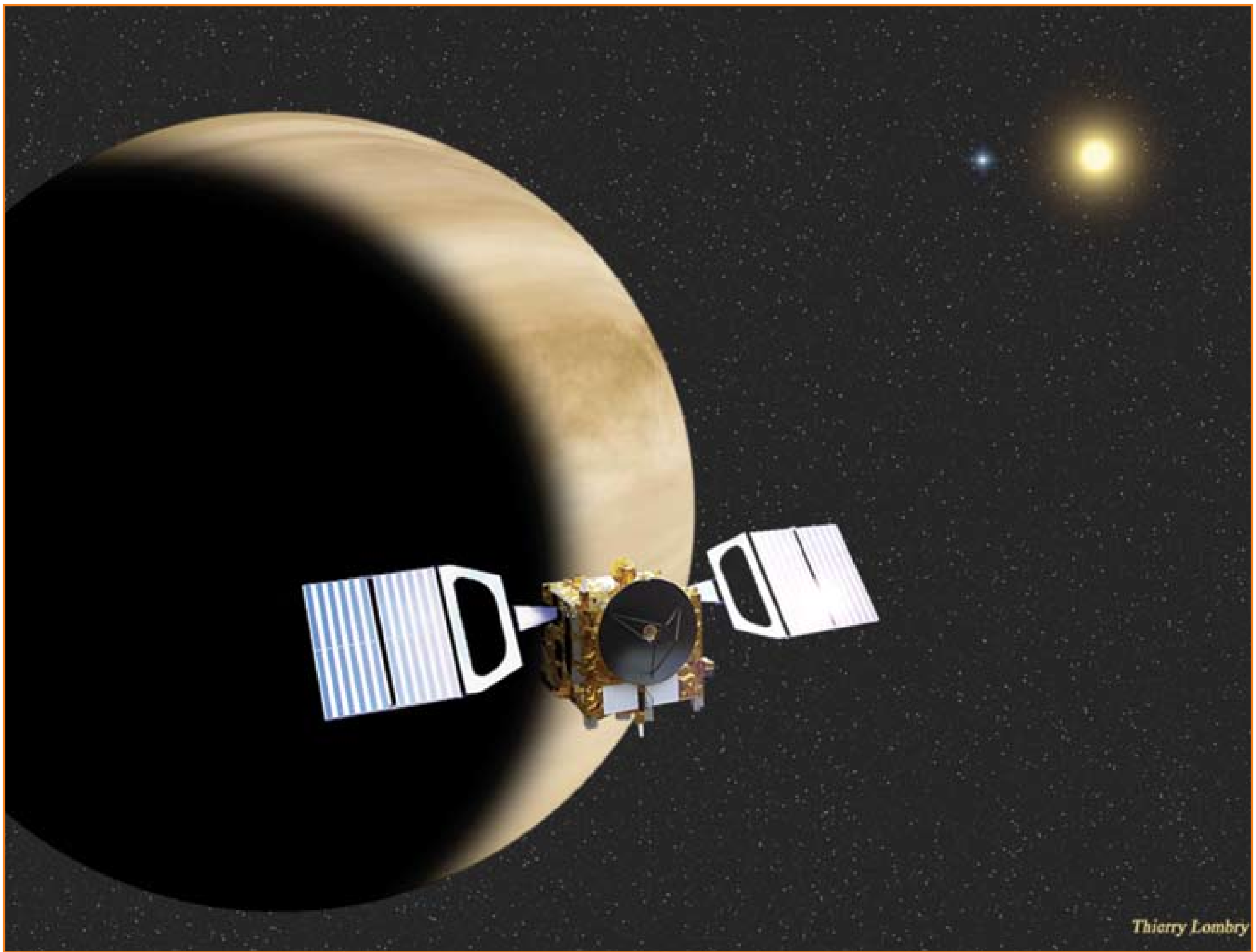
Venus: Not evil, jus



1: Artist's impression of Venus Express in orbit. After passing low over the north pole, the spacecraft is sweeping out to a distance of several Venus radii over the south pole as it follows its highly elliptical 24-hour orbit. The instruments face the planet, while the communications dish looks out towards the Earth; the planet Mercury can be seen in the distance, near the Sun. The Venus Express spacecraft is similar to the Mars Express design, but with fewer solar panels and a smaller radio dish because it is closer to both the Earth and the Sun.

The Venus Express mission, currently orbiting Earth's nearest planetary neighbour, has just had its mission extended until the end of 2012 by the European Space Agency (ESA). In December 2010 it will be joined by the Japanese Venus Climate Orbiter, which has similar goals of understanding the atmosphere and climate. In this article Fred Taylor looks at what has been learned so far and what remains mysterious about our nearby twin, with its torrid weather and its global warming issues.

A visit to another planet is among the sweetest dreams of humankind. If we cannot go ourselves, then a surrogate is next best; if a human cannot go then an intelligent and versatile machine is nearly as good. What we find is not always what we would have wished. Venus is a good example of this: our Earth-sized neighbour, long believed to be home to a moist, tropical climate (Arrhenius 1918), turns out to have surface temperatures high enough to melt metal. Since this was discovered nearly 50 years ago, it has become fashionable to call Venus Earth's "evil twin", although of course Venus did not act with the intent to make things uncomfortable for Earthlings, just as it is hardly the Earth's fault that we are making it a little more like Venus every day with our emissions and other activities. But why, when all the indications were that conditions on Venus should be more Earth-like, did it follow such a different evolutionary path?

In seeking answers to such questions, we are fortunate to live in the time when interplanetary travel has become possible at last. At first it was just the large confederations – the US and the USSR – that had the drive to do it, but a generation later the largest and richest national group, the Europeans, finally has an extensive

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t a bit unfortunate

2: Venus then and now. Early speculation about the climate on Venus, including (left) the classic work by Arrhenius (1918), determined on quite sensible grounds that it was likely to resemble the tropical regions of the Earth. The reality uncovered by spacecraft at the planet is, however, more like (right): a dry, sulphur-rich atmosphere and a hot, barren surface.

planetary exploration programme which has come together in the last decade or so. Just as our planet seems to be running out of resources, we have new worlds to explore and the human spirit has found a new peak to scale.

The European programme includes missions operating at Mars and Venus; past successes at comet Halley and Saturn's cloudy moon, Titan; a new comet mission (Rosetta) in flight; and an ambitious Mercury orbiter (BepiColombo) under construction. Plans are well advanced to place a European rover on the surface of Mars, and to develop, with NASA, a new outer planets flagship mission. By design, the programme is a fascinating mix of fast, practical, targeted missions such as Mars and Venus Express, and extravaganzas such as Rosetta and BepiColombo that never had a prayer of fitting into the agency's modest (by NASA standards) budget and have had to suffer seemingly endless delays and ever-diminishing goals. Meanwhile, Giotto, Huygens and the two "Expresses" (all but the Titan probe built in the UK, incidentally) have delivered fundamental data on the most famous comet and the properties, especially of the atmospheres and climates, of the three most Earth-like bodies in the solar system.

Venus Express

Venus Express has the distinction of being the first European mission to our planetary neighbour, and the first mission for twenty-odd years to investigate the hot, cloudy Venusian atmosphere. That there was such a long period of neglect of such an important and mysterious planetary environment is all the more remarkable since we know that Venus is afflicted by the same greenhouse warming phenomenon that is generating widespread concern about the future climate of the Earth. However, this void represented a great opportunity for ESA when it decided in 2004 to seek a follow-on to the agency's successful Mars Express mission. One of the proposals received in response to the announcement of opportunity argued successfully that Venus is close by and easy to reach with a small spacecraft on a modest launch vehicle, and it presents urgent scientific challenges that modern instruments can readily address at reasonable cost.

The science case for Venus focused on differences with the Earth, and why neighbouring planets with nearly the same size and mass have evolved so differently. Venus rotates very slowly, generates no internal magnetic field, and has an atmosphere a hundred times denser than our own. The high surface pressure generates the searing temperatures (450 °C, much hotter than an oven) that unfortunately prevent, for now, the exploration of the surface using long-lived landers and rovers, as has been so successfully done on Mars. The circulation of the Venusian atmosphere exhibits puzzling large-scale behaviour, including implausibly high wind speeds and exotic "dipole" phenomena at the poles, as well as deep-atmosphere meteorology that seems Earth-like in some ways but different in detail. Theory and models suggest that the differences in the interiors, surfaces, atmospheres and near-space environments are more a matter of evolutionary paths followed than of original differences, but this remains to be confirmed and elucidated by experimental evidence.

Money could be saved by using spares or copying designs from Mars Express (figure 1; Svedhem *et al.* 2009). The main changes needed for Venus were related to the much hotter thermal environment resulting from greater proximity to the Sun and a highly reflective, cloudy planet. On the other hand, fewer solar cells were needed to power the spacecraft and its payload, and a smaller communications dish was adequate to cover the shorter distance to the receiving station on Earth. ESA set up a brand new 35 m dish at Cebreros near Madrid to track Venus Express and receive the data from its seven instruments. These instruments were also mostly spares and copies of devices developed for other missions, carefully selected and sometimes modified to address the most information-rich wavelengths for remote sensing of Venus from orbit. The cost up to arrival at the planet was held down to less than €200m, about the price of a big Hollywood movie and less than a fifth of the comet and Mercury probes, which started sooner but are still far from delivery of results.

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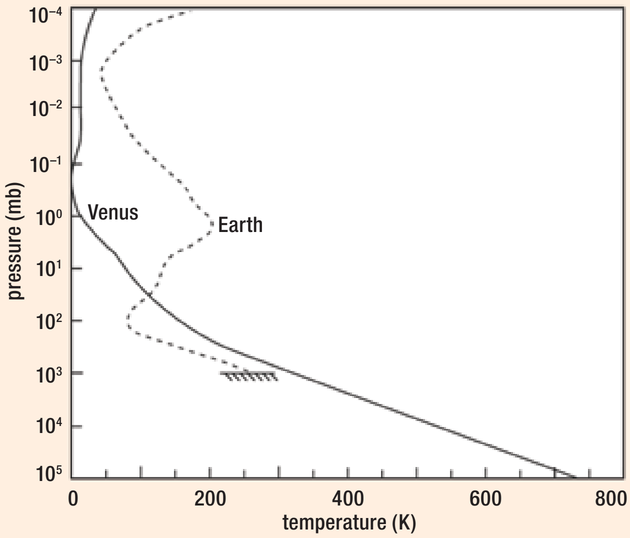
Construction of Venus Express began at Astrium (formerly British Aerospace, now part of the European EADS consortium) in Stevenage in January 2003 and the spacecraft was completed by September of the following year. Such a rapid development period justifies the name (although, to be pedantic, "express" really means "specific" not "fast"). The launch took place on a Russian Soyuz-Fregat rocket in November 2005, first into Earth orbit, then a second burn at just the right place and time to send it on to Venus. The short and flawless flight was over by April the next year, and the spacecraft has been in its elliptical orbit over the poles of Venus for more than three years now. Data collection is scheduled to continue until the end of 2012, which will allow joint operations with the Japanese Venus Climate Orbiter that arrives in December next year. A full description of both missions, including their instrumentation and objectives, can be found in the two special issues of *Planetary and Space Science* listed at the end of this article.

Atmospheric temperature and climate on Venus

Although we are only half way through the operational part of the mission, special issues of journals such as *Nature* and *Journal of Geophysical Research* have presented results and it is possible to make a preliminary summary of what advances have been made in our understanding of Venus's surface and atmosphere. A striking new theme, after years of musing over how surprisingly different Venus is from Earth (figure 2), is the realization, stimulated by the new data and a reassessment of the old, of how similar the two planets are in fact. Figure 3 gives an example. When a typical temperature profile for each atmosphere is plotted on the same scale of log pressure as a proxy for altitude, the similarity is striking. The main differences that stand out are the "bulge" in the Earth's stratosphere, due to the heating of the ozone layer, a feature which is not found on Venus, and the downward extension on Venus to pressures higher than 1 bar, the mean surface pressure on Earth. The gradient of temperature versus height in the lower atmosphere in both cases is, in agreement with expectation, close to the adiabatic lapse rate, which simple theory (see Taylor 2006) tells us is just the acceleration due to gravity divided by the heat capacity of the air. These constants are about the same on both planets and give a value for the gradient of about 10 °C per kilometre. Thus, because the surface on Venus is about 45 km below the pressure level found at the surface of the Earth, it cannot help but be 450 K hotter. Mystery solved.

However, this does not tell us why Venus has so much more atmosphere than the Earth. A clue is given by the nitrogen abundance, which is fairly similar on both planets – actually about three times higher on Venus, a modest difference compared to the corresponding factor for carbon dioxide of about 300 000. N_2 is much more stable chemically than CO_2, suggesting that perhaps the atmospheres were much more comparable in mass originally than they are now. If so, what happened to the Earth's CO_2? The answer lies, literally, in the soil, or more precisely in the carbonate rocks that make up structures like coral atolls and the white cliffs of Dover. The minerals in these rocks form when CO_2 dissolves in water and reacts with other elements, especially calcium, helped by shellfish and other aquatic life forms. One estimate (Kasting 1988) is that the Earth's total inventory of carbonate rocks is equivalent to the removal of enough atmospheric CO_2 to raise Earth's surface pressure to around 60 bars. At the beginning of this process, our planet would have been nearly as hot as Venus is today.

3: A Venus temperature profile measured by Pioneer Venus Orbiter OIR, and an Earth temperature profile measured by Nimbus 7 SAMS, both in February 1980. (SAMS was the Oxford department's fourth Earth-observing space instrument, while OIR was its first planetary experiment, and the first UK hardware to go to another planet.)



Venus was unable to remove its atmospheric CO_2 because of a shortage of liquid water (and shellfish). Why, though, is Venus so dry? Probably it was not always that way. Venus Express measurements show significant levels of water vapour in the atmosphere, and liquid water chemically combined with H_2SO_4 in the clouds. Interestingly, the ratio of "heavy" water (HDO) to the ordinary kind (H_2O) is more than two orders of magnitude greater on Venus than on Earth. The best explanation for this is that Venus has lost large quantities of water – possibly an ocean's worth – by dissociation and escape of hydrogen and oxygen, involving fractionation occurring between the heavy and light isotopes of hydrogen. Direct sampling by Venus Express of the "tail" behind Venus, produced by the solar wind impinging on the atmosphere, show ions of H and O streaming away into space to this day. What's more, they seem to be about in the ratio of 2:1, consistent with water as the source molecule. Earth has not lost so much water, although it loses some, partly because of its extra distance from the Sun, but mainly because of its protective magnetic field. Why does Venus not have a field like the Earth's? This is one of the things we still do not understand.

Magnetic fields, particles and lightning

The magnetometer on Venus Express has made a close-up, detailed search for any sign of a planetary magnetic field from the interior of Venus, but so far in vain. If there is one, it must be very weak, suggesting that the assumption that Venus is like the Earth on the inside may be wrong. Part of the difference may be the hard "lid" formed by the hot, dry surface; there are no signs on Venus of the plate tectonics that shape the Earth's surface with large-scale convective motions beneath. Venus is slightly smaller than Earth and the difference may be important; its relatively slow rotation may also be a factor (although the researchers who model planetary interiors and field generation say not). Forming closer to the Sun than Earth, Venus may have a somewhat different mix of metals such as nickel and volatiles like sulphur in its iron core. Finally, the missing field may be temporary: at times in its history, particularly during field reversals, the Earth is known to have had periods where magnetically it was as dormant as Venus appears to be now.

There is plenty for the magnetometer to measure, however. The solar wind interaction with the electrically conducting ionosphere near the top of the atmosphere deflects the supersonic solar wind around the planet so that a bow shock is formed. The ionopause separates the thermal plasma of the ionosphere from the hot magnetized plasma of the magnetosheath confined inside the bow shock. The importance of the loss of ionized gas to space has already been mentioned in connection with the loss of water from the planet. The ions themselves can be measured by direct sampling by the plasma instrument, ASPERA, in and around the magnetic field environment mapped out by the magnetometer.

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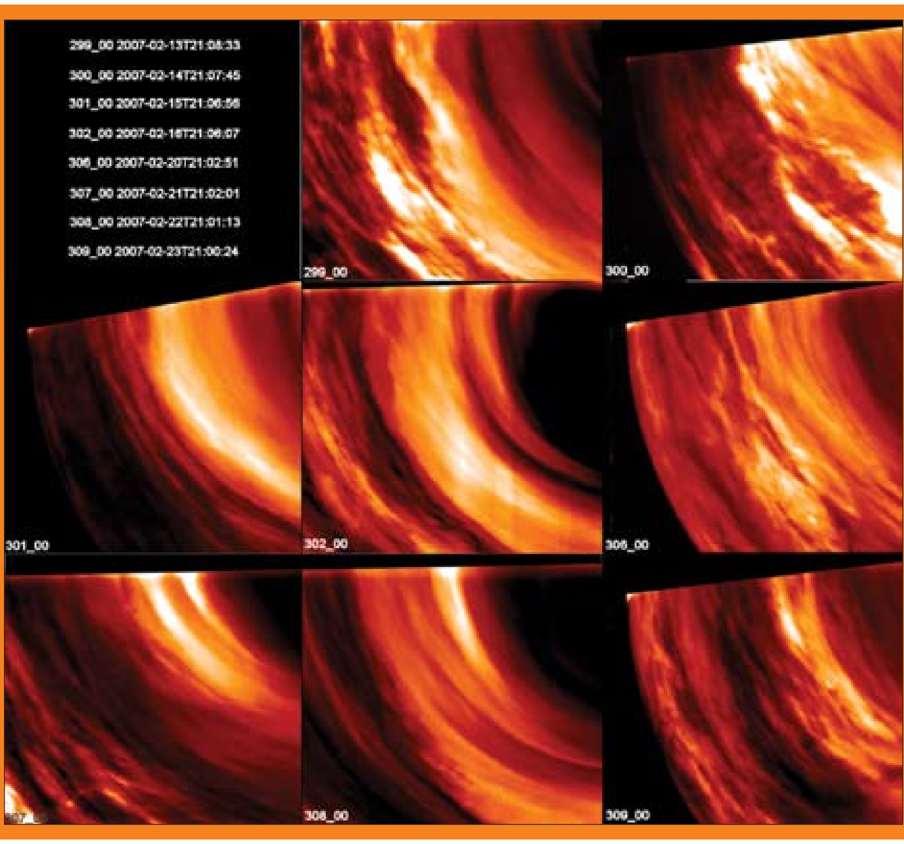
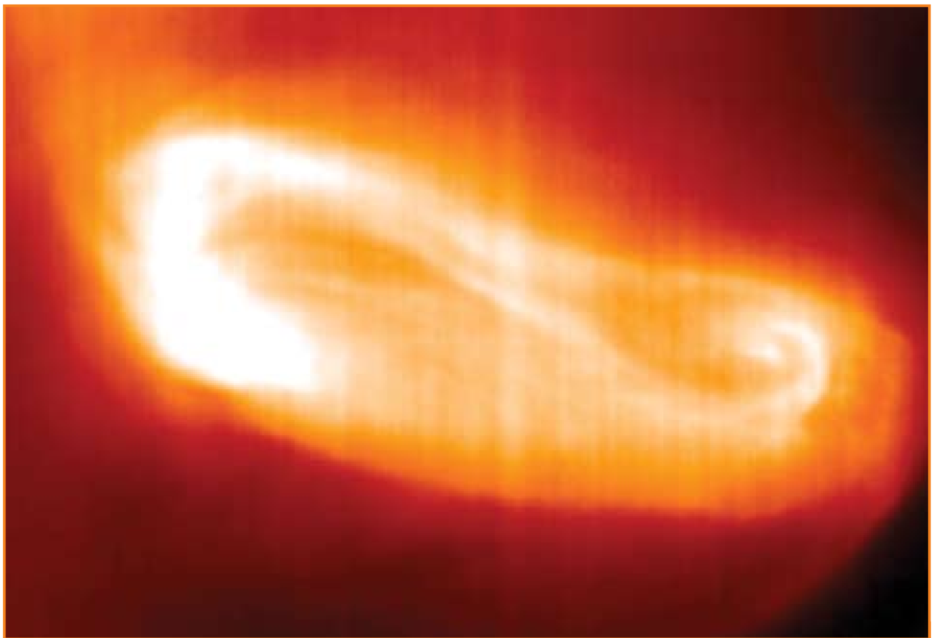


4: Night side images at 2.3 μm wavelength taken in eight orbits within 10 consecutive Earth days in February 2007. The contrast seen results from cloud layers at an altitude of about 50 km above the surface. The south pole is just outside the image, to the upper right-hand side. The patterns suggest a complex and variable meteorology, with mostly laminar flow surrounding the dark polar collar, and more chaotic convective motion near the equator where solar heating is greatest.

The magnetometer is also capable of detecting signals arising from lightning in the atmosphere, propagating in the whistler mode, and has been used to locate where and when these occur across the planet. While these data have been sufficient to convince many that Venus has lightning activity comparable to the Earth's, others point out that there has yet to be an optical detection of lightning on the night side of Venus, despite searches by the cameras on Venus Express and other spacecraft. The existence of lightning on Venus remains controversial, therefore.



5: The double eye of the south polar vortex, imaged at 5 μm wavelength by the VIRTIS instrument on Venus Express shortly after arrival at the planet. This feature is about 2000 km across.

Atmospheric dynamics and meteorology

After the global mean climate and its evolution, the biggest questions about Venus centre on the dynamics and circulation of the atmosphere. Near the cloud tops, winds blow around the equator at speeds in excess of a hundred metres per second. Structure can be seen in the clouds themselves if they are observed in reflected sunlight through an ultraviolet filter, due to the presence of an absorber mixed in with the sulphuric acid droplets. What this might be is still mysterious; possibly a mixture of sulphur compounds produced and destroyed in the chemical cycles that form and dissipate the cloud particles in the hot atmosphere below. (Some have suggested microbial life forms that thrive in the aqueous, energy-rich cloud-top environment where temperatures and pressures are similar to those in the Earth's biosphere, but needless to say this postulate is neither proven nor widely accepted.) The markings trace a variety of meteorological systems in the atmosphere, ranging from turbulent behaviour near the equator, through predominantly laminar behaviour at mid-latitudes, to a bright polar collar and high-level cloud cap at the poles. Wave motions on all scales are also seen; the giant "Y" shape seen through telescopes from Earth turns out to be the Venusian equivalent of the phenomenon known to terrestrial meteorologists as a trapped equatorial Kelvin wave.

The clouds look quite different in infrared images (figure 4). In these the thermal emission from the hot lower atmosphere is the source, so the clouds are back-illuminated and seen in transmission, which highlights the deep, thick clouds rather than the upper cloud tops seen in reflected sunlight. Their motions show that the winds fall off with height, and also towards the poles, but at different rates, so that above about 60° of latitude the atmosphere is in a state close to solid-body rotation. This is the polar vortex, a region of rapidly rotating, descending air, fed

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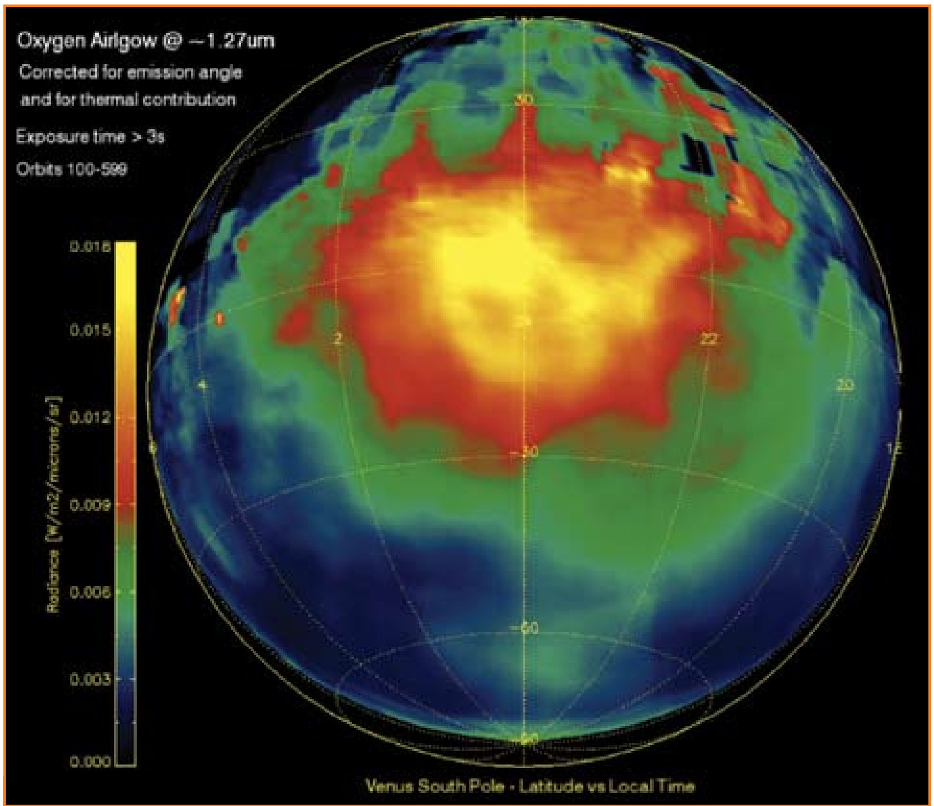
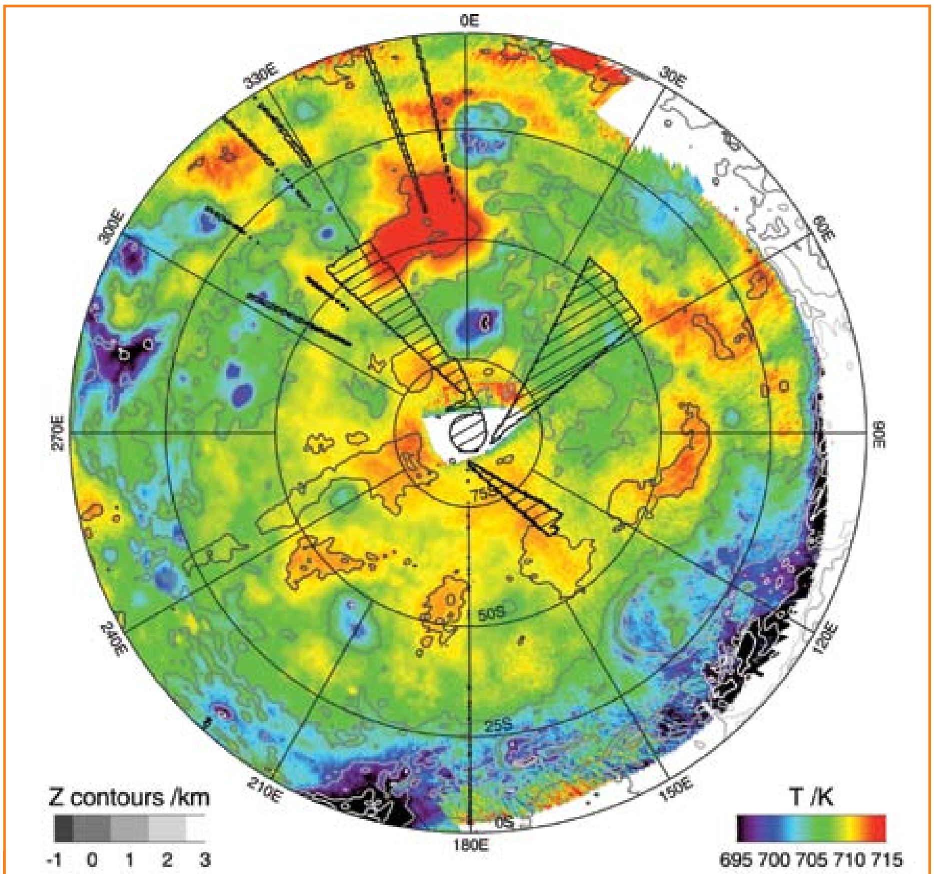


6: The night side of Venus, showing the oxygen airglow emission at 1.27 µm wavelength centred over the anti-solar point (i.e. the equator at midnight). The source is fluorescence emitted when oxygen atoms produced on the day side recombine into molecular oxygen after migrating to the night side, in what is apparently a subsolar to antisolar atmospheric circulation regime.



7: Venus surface thermal emission imaged at 1 µm wavelength by VIRTIS, centred at the south pole. The measured temperatures range from 442 °C (715 K), red to 422 °C (695 K) blue; higher temperatures correspond to lower altitudes, and vice versa. See Muller *et al.* (2008) for a preliminary interpretation in terms of the geology of the surface.

with angular momentum from the high equatorial winds propagating towards the pole in the slow equator-to-pole overturning known as the Hadley circulation.

The mysterious polar vortices

It has been known since the Pioneer Venus mission in the 1970s that the polar vortices on Venus are permanent and more intense than the equivalent phenomena on Earth or Mars. Also, the cloud structure at the centre of the vortex was found to have a curious double eye structure, that led to the name "polar dipole". Venus Express has now revealed this structure to be a pair of giant, coupled vortices rather than a simple analogue of the much smaller terrestrial hurricanes that were originally pictured (figure 5). The resemblance of the S-shaped pattern formed by the compound vortex to the "strange attractor" formed in the world's first computerized climate model, by Edward Lorenz at MIT in the early 1960s, has been noted. It also turns out that a theoretical analysis of the wave modes expected to develop at the poles under Venus-like conditions shows they are dominated by a wavenumber-2 instability. This, together with the evidence for the Hadley cell and for zonal super-rotation help us to feel comfortable after all with the polar dipole and its behaviour, which caused so much head-scratching in the 1980s when it was first observed.

As with theories of the hot climate, it is easy to oversimplify, however. Continued tracking of the southern dipole has revealed not only variations in its rate of rotation and meandering away from the pole, as observed at the north by Pioneer 30 years ago, but also tremendous additional complexity in its shape and movements (see the ESA website for movies that display these), including a disconcerting period when the "dipole" coquettishly became a tripole for a while. (While the Venus scientific community was searching for a new name, a German colleague put the native English speakers to shame by pointing out that "dipole" was never correct, it should have been "bipole".)

While the existence of the vortex and other evidence shows an equator-to-pole circulation in the lower part of Venus's atmosphere, remarkable results from airglow observations (figure 6) show that the upper part of the atmosphere has a contrasting subsolar to antisolar regime. The former is characteristic of a rapidly rotating planet like Earth or Mars; the latter of a slowly or non-rotating planet where the rotational poles are not well defined and the circulation is symmetric around the planet–Sun axis instead. Venus turns 243 times more slowly than Earth, and is now seen to have both regimes, stacked one on top of the other and mixed together in the middle. Combined with the convective–laminar–polar regimes in the meridional direction, discussed above, this defines a general circulation for

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8: Most of the next-generation Venus missions planned by Russia, the US, Japan and Europe involve a combination of orbiter/relay satellites, floating platforms, and landers or drop sondes. This artistic impression shows the European Venus Explorer (EVE).

Venus's extensive atmosphere that is at least as complex as the Earth's and with intriguing similarities and differences.

Although Venus Express is mainly about studying the atmosphere and climate, it has also made some unique observations of the surface of the planet. Shrouded in cloud layers that are permanently opaque everywhere at visible wavelengths, Venus has lifted her veil to instruments observing in spectral "windows" recently discovered in the near-infrared part of the spectrum. The images are formed from the heat radiation from the surface, after it passes through the clouds. At these wavelengths the clouds scatter the radiation but do not absorb much, so they make the image somewhat fuzzy but do not block it altogether. Higher regions like mountain tops are cooler than the plains beneath, just as on Earth, and appear as dark features. The very high mountains have something analogous to terrestrial snow caps covering the peaks; it is a mystery what the condensate might be as it is, of course, still far too hot for water ice. Suggestions for substances that condense at the right temperature have included the metal tellurium, and pyrite, otherwise known as Fool's Gold, either of which would make for spectacular scenery as viewed by thermally insulated future astronauts, but there are plenty of other candidates.

Prior to Venus Express, the NASA Magellan radar-mapping mission had revealed literally millions of volcanic constructs of various kinds on Venus. Many of these show vast, pristine-looking flows of lava extending in some cases hundreds of kilometres away from the source. However, it has remained unclear which volcanoes are active now, with all that implies for the activity in the interior and the contribution of more carbon dioxide and water, as well as other gases such as sulphur dioxide, to the atmosphere. Certainly the amounts of SO_2 seen by Venus Express suggest a lot of current volcanism, and a major role in cloud formation and a big effect on climatic conditions.

Surface observations like those in figure 7 show not only height-related temperature features but could also reveal relatively hot recent lava flows, if any exist that are large enough and fresh enough to generate sufficient signal. Unfortunately for the volcano search, there are also differences in surface emissivity between mineral types that produce similar signals and the two are hard to distinguish. It had been planned to search for additional evidence for volcanism using the high-resolution Planetary Fourier Spectrometer to detect accompanying plumes of volcanic gases such as sulphur dioxide, but unfortunately that instrument malfunctioned *en route* to Venus before any data could be taken. Of course, mapping different minerals on the surface is also a prime goal for the mission and some progress has been made with that.

Since the mission began, the European teams have worked closely with scientists from the US and Russia, who have a long history of Venus exploration, and with a team from Japan. The Japanese are preparing their own mission to Venus, with launch early next year and arrival in December 2010. The Venus Climate Orbiter has scientific objectives similar to Venus Express, but will address them with a different set of instruments in a different orbit, equatorial instead of polar. The combination should be powerful, and will give Venus scientists plenty to get their teeth into until the next cohort of missions arrives, probably sometime around 2018.

The current orbiter missions have fairly comprehensively covered the objectives that are susceptible to study by remote sensing, as this article has summarized. The next steps will require measurements inside the atmosphere and on the surface. The top priorities will include measuring the atmospheric composition in detail, especially the isotopic ratios in noble gases and other species that hold precious clues to the history of the planet. Then there is sampling the cloud layers; we still know very little about the composition of the deep clouds, their microphysical properties, or the chemical cycles that maintain them. Direct observation and sampling of active volcanoes on the surface will be a key part of understanding the cloud properties and composition. Finally, the motions of the atmosphere, inside the complex polar vortices for example, need to be traced directly using floating platforms and small drop sondes; only so much can be done with remote observations of cloud patterns and movements.

At the moment, it looks likely that the next steps will include an orbiter/balloon/probe combination called Venera-D from the Russians, and one or more of several options, most of them featuring balloons or deeper "submarines" floating in and below the clouds, from the Americans. These may be joined by a similar venture from this side of the Atlantic, the European Venus Explorer. The EVE mission (figure 8) consists of a platform floating at an altitude of 50–60 km, a descent probe and a lander with a lifetime of 30 minutes on the surface provided by Russia (or possibly a horde of microprobes provided by the UK), and a polar orbiter to perform science observations and relay data from the balloon and descent probe. The minimum lifetime of the balloon is seven days, required to be sure of completing one full circle around the planet, tracked by Earth-based VLBI and Doppler measurements. The Japanese space agency JAXA may provide a small water-vapour-inflated balloon to be deployed at 35 km altitude and communicate directly to Earth.

No-one is talking about astronauts just yet. ●

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Further information

European Venus Explorer team http://www.aero.jussieu.fr/EVE/mission.htm
Venus Express at ESA http://sci.esa.int/science-e/www/area/index.cfm?fareaid=64
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