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Venus as a more Earth-like planet

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Venus is Earth's near twin in mass and radius, and our nearest planetary neighbour, yet conditions there are very different in many respects. Its atmosphere, mostly composed of carbon dioxide, has a surface temperature and pressure far higher than those of Earth. Only traces of water are found, although it is likely that there was much more present in the past, possibly forming Earth-like oceans. Here we discuss how the first year of observations by Venus Express brings into focus the evolutionary paths by which the climates of two similar planets diverged from common beginnings to such extremes. These include a CO_2-driven greenhouse effect, erosion of the atmosphere by solar particles and radiation, surface–atmosphere interactions, and atmospheric circulation regimes defined by differing planetary rotation rates.

Venus, Earth and Mars—the three terrestrial planets with atmospheres, grouped close together in the inner solar system—have many features in common. Earth and Venus, in particular, are nearly the same size and seem to have been quite similar in the epoch when they formed and cooled, probably with large inventories of CO_2 in Earth's atmosphere and liquid water oceans on the surfaces of Venus (and Mars). Today they have very different conditions on their surface as a result of evolutionary processes that we try to understand by measuring and modelling the common processes, aided by data from space missions designed to probe the planets and their environments. Earth and Venus have roughly the same amount of CO_2; on Earth it is bound in carbonates in the crust, whereas on Venus it exists mostly as gas. The extreme climate at the surface of Venus, driven by this excess of CO_2 in the atmosphere, reminds us of pressing problems caused by similar physics on Earth.

More than 30 spacecraft have made the trip to Venus since the Americans sent Mariner 2 in 1962—the first successful man-made mission to another planet. The Soviet Venera and Vega and the American Pioneer Venus missions in 1967–92 were particularly influential in establishing a basic description of the physical and chemical conditions prevailing in the atmosphere. They showed the venusian atmosphere to be filled with corrosive gases and thick clouds, extraordinarily active, with high winds and complex cloud formations sculpted by meteorological systems that seemed to defy categorization by terrestrial analogy, and a vast double-eyed vortex over each pole. Now the European Space Agency has sent its first mission to our nearest planetary neighbour, to investigate how the global atmospheric circulation, the cloud chemistry, surface–atmosphere physical and chemical interactions including volcanism, atmospheric escape processes and the global energy balance and the 'greenhouse' effect at the surface all act together to produce a climate apparently defiantly different from Earth's[1].

Venus Express

The Venus Express design is based on the successful Mars Express spacecraft—a 600-kg, three-axis-stabilized platform with a body-fixed communications antenna[2]. It was launched by the Russian Soyuz-Fregat launcher from Baikonur, Kazakhstan, on 9 November 2005 and is the first mission dedicated to atmospheric and plasma investigations of Venus since NASA launched its Pioneer Venus orbiter and probes more than a quarter of a century ago. It arrived at Venus on 11 April 2006 and became fully operational in June of that year, deploying a new generation of instrumentation[2] and using new modes of observation[3]. The core of the payload is composed of optical instruments including spectrometers and spectro-imagers (Fig. 1 and Table 1), which make the first systematic use of the spectral windows between 1 and 3 μm for three-dimensional imaging of the atmosphere all the way down to the surface[4]. Solar, stellar and Earth radio occultation is used for vertical profiling of atmospheric properties. The highly elliptical polar orbit combines global nadir observations of extended duration of the southern hemisphere with close-up snapshots of the equatorial and northern latitudes[3].

Middle and lower atmosphere

These first observations covering a range of depths in Venus's atmosphere at high spatial resolution have revealed, in addition to

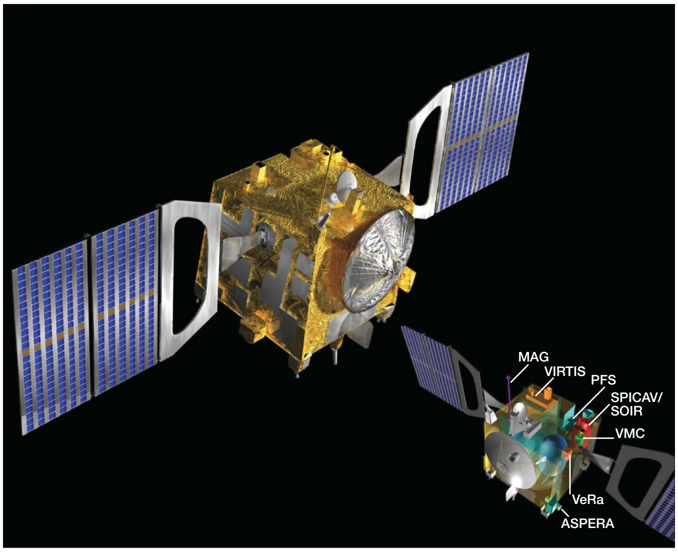

Figure 1 | The Venus Express spacecraft. The inset shows the positions of the seven scientific instruments in a semi-transparent view. The optical instruments for remote sensing are mounted below the upper platform; all apertures are aligned with the $+z$ axis (pointing towards the top of the image). The magnetometer (MAG) on its 1-m-long boom can be seen on the upper platform, while the two ASPERA sensors are mounted on the bottom platform (only one can be seen in this view). PFS, Planetary Fourier Spectrometer; VeRa, Venus Radio Science Experiment; VMC, Venus Monitoring Camera.

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Table 1 | The scientific payload of Venus Express

Name (acronym)	Description	Measured parameters
ASPERA-4	Detection and characterization of neutral and charged particles	Electrons 1 eV–20 keV; ions 0.01–36 keV/q; neutral particles 0.1–60 keV
MAG	Dual sensor fluxgate magnetometer, one sensor on a 1-m-long boom	**B** field 8 pT–262 nT at 128 Hz
PFS	Planetary Fourier Spectrometer (currently not operating)	Wavelength 0.9–45 μm; spectral resolving power about 1,200
SPICAV/SOIR	Ultraviolet and infrared spectrometer for stellar and solar occultation measurements and nadir observations	Wavelengths 110–320 nm, 0.7–1.65 μm and 2.2–4.4 μm; spectral resolving power up to 20,000
VeRa	Radio Science investigation for radio-occultation and bi-static radar measurements	X- and S-band Doppler shift, polarization and amplitude variations
VIRTIS	Ultraviolet–visible–infrared imaging spectrometer and high-resolution infrared spectrometer	Wavelength 0.25–5 μm for the imaging spectrometer and 2–5 μm for the high-resolution channel; resolving power about 2,000
VMC	Venus Monitoring Camera for wide-field imaging	Four parallel channels at 365, 513, 965 and 1010 nm

These instruments are expected to produce more than 2 terabits of data during the design lifetime of four Venus sidereal days (about 1,000 Earth days). Venus Express is operating in an elliptical polar orbit with a period of 24 h and an apocentre altitude of 66,000 km. The pericentre altitude is maintained between 250 and 400 km approximately over the north pole. q is elementary charge.

localized 'weather' phenomena, the overall organization of the atmospheric circulation. Three broad regimes are clearly present in the middle and lower atmosphere, with convective and wave-dominated meteorology in the lower latitudes and an abrupt transition to smoother, banded flow at middle to high latitudes[5]. The latter terminates at about 30° from the pole, where the cold polar collar discovered by earlier missions lies. This encloses a vast vortex-type structure several thousand kilometres across with a complex double 'eye' that rotates every 2.5–2.8 Earth days. Simultaneous observations in the ultraviolet and thermal infrared spectral ranges show correlated patterns, indicating that the contrasts at both wavelengths, although representing different atmospheric levels, are driven by the same circumpolar dynamical regime[5,6]. Spectroscopic observations indicate marked changes in the temperature and cloud structure in the vortex, with the cloud top in the polar collar located at an altitude of 70–72 km, about 5 km or one scale height higher than in the eye. Night-side observations in the transparent spectral windows showed that the vortex structure and circulation exist at as least as great a depth as the lower cloud deck at 50–55 km, although its 'dipole' appearance seems to be confined to the cloud-top region[6]. The edge of the polar collar at 50–60° latitude apparently marks the poleward limit of the Hadley circulation, the planet-wide overturning of the atmosphere in response to the concentration of solar heating in the equatorial zones (Fig. 2a). Indirect evidence of such meridional circulation is provided by monitoring of the latitude distribution of minor constituents, especially carbon monoxide, as dynamical tracers in the lower atmosphere.

The mesopause on Venus at 100–120 km altitude marks another transition between different global circulation regimes, this time in the vertical. The predominance of zonal super-rotation in the lower atmosphere below the mesopause is replaced by solar to antisolar flow in the thermosphere above, as revealed by non-LTE (non-local thermodynamic equilibrium) emission in the spectral band of O_2 at 1.27 μm that originates from the recombination of oxygen atoms in descending flow on the night side (Fig. 2b). The observed emission patterns are highly variable, with the maximum at about the anti-solar point and the peak altitude at about the mesopause[7]. A mesospheric temperature maximum is observed on the night side[8], produced by adiabatic heating in the subsiding branch of the thermospheric solar to anti-solar circulation.

Sequences of ultraviolet and infrared images have been used to measure the wind speeds at different altitudes by tracking the motions of contrast features in the clouds. Zonal winds at the cloud tops (~70 km) derived from the ultraviolet imaging are in the range $100 \pm 10\ \mathrm{m\,s^{-1}}$ at latitudes below 50° (ref. 5), in good agreement with the earlier observations[9,10]. The new data, which penetrate the bright upper haze obscuring the main cloud at middle latitudes, find that the cloud-top winds quickly decline poleward of 50°. The infrared observations[6] sound the dynamics in the main cloud deck at ~50 km altitude on the night side, finding strong vertical wind shear of about $3\ \mathrm{m\,s^{-1}\,km^{-1}}$ below 50°, and no shear poleward of this latitude, when compared with the higher-altitude ultraviolet-derived winds. The wind velocity profiles on Venus are found to be roughly, although not exactly, in agreement with those predicted by the cyclostrophic

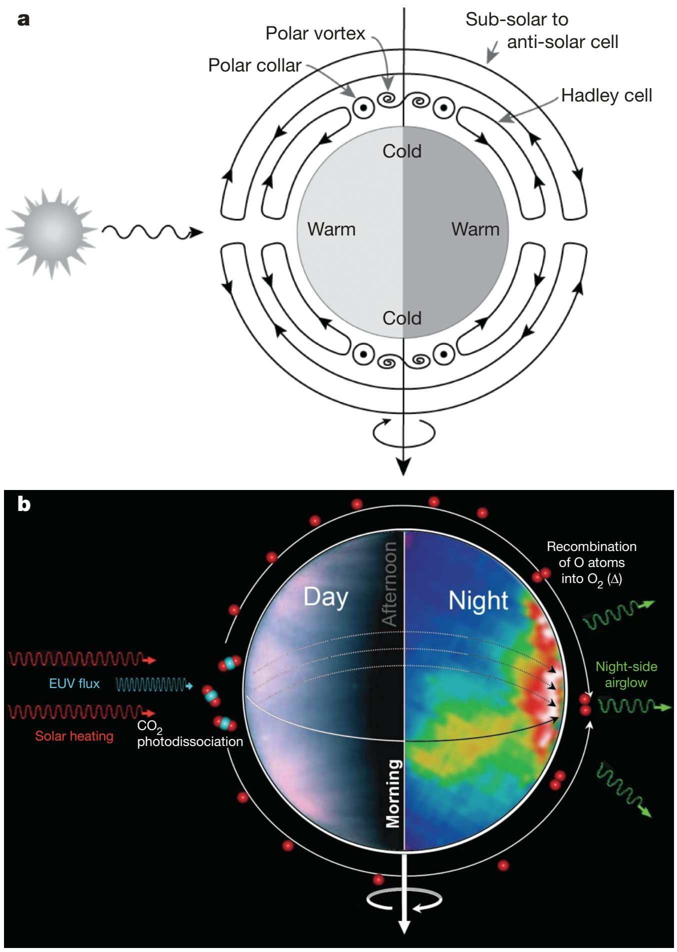

Figure 2 | Schematic view of the general circulation of Venus's atmosphere. **a**, The main feature is a convectively driven Hadley cell, which extends from the equatorial region up to about 60° of latitude in each hemisphere. The trend is polewards at all levels that can be observed by tracking the winds (at about 50–65 km altitude above the surface), so the return branch of the cell must be in the atmosphere below the clouds. A cold 'polar collar' is found around each pole at about 70° latitude; the Hadley circulation evidently feeds a mid-latitude jet at its poleward extreme, inside which there is a circumpolar belt characterized by remarkably low temperatures and dense, high clouds. Inside the collar a thinning of the upper cloud layer forms a complex and highly variable feature, called the 'polar dipole' in earlier literature describing poorly resolved observations, which appears bright in the thermal infrared[6]. Because in general terms thinner-than-average or lower-than-average cloud is often associated with a descending air mass, and vice versa, the vortex may represent a second, high-latitude circulation cell, resembling winter hemisphere behaviour on Earth. **b**, Above about 100 km altitude the circulation regime on Venus changes completely to a sub-solar to anti-solar pattern. Oxygen airglow emission at 1.27 μm reveals the recombination of oxygen atoms into molecular oxygen while descending to lower altitudes in the anti-solar region. Additional evidence of this circulation is given by the upper-atmosphere temperature profiles, which show a pronounced temperature maximum on the night side that is due to compressional heating in the downward branch of the circulation cell[8].

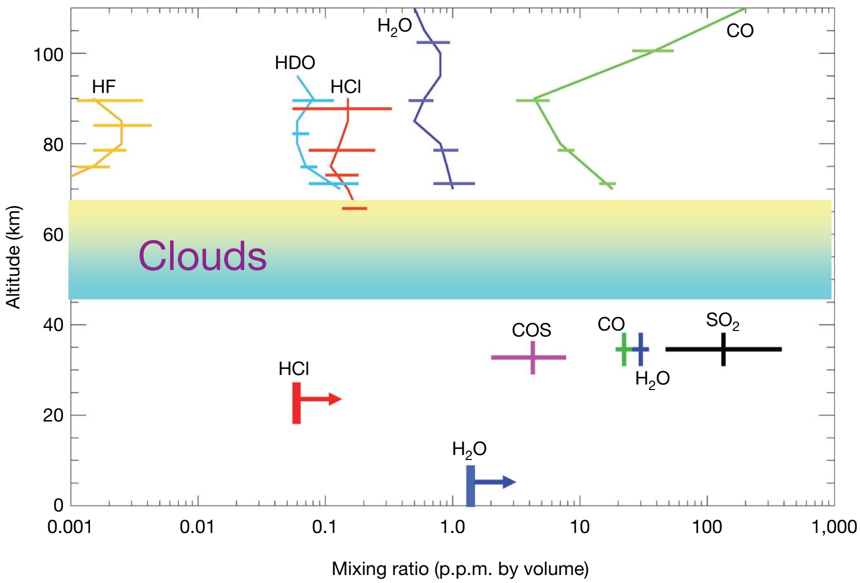

Figure 3 | Atmospheric composition from the Venus Express observations. The colours mark different trace gases. The vertical profiles of H_2O, HDO, CO, HCl and HF above the clouds have been derived from SPICAV/SOIR solar occultation measurements[8]; the abundances of H_2O, CO, SO_2 and COS below the clouds are derived from VIRTIS spectra. The error bars in mixing ratios indicate the minimum and maximum detections over all latitudes, and the error bars in altitudes for the lower atmosphere indicate the width of the weighting functions used for deriving the altitude. The bars with arrows in the lower atmosphere show the expected sensitivity of the Venus Express measurements for which data analysis is still in progress.

approximation[9], which postulates a balance of pressure gradient and centrifugal force in a purely zonal flow. This is, as expected, in contrast with Earth, where so-called geostrophic balance generally applies, dominated by the Coriolis forces produced by the relatively rapid rotation of Earth.

Figure 3 summarizes the results so far of composition measurements by Venus Express[8]. In the deep atmosphere, the most remarkable result is the distribution of CO, which shows a larger systematic latitudinal variability than the other minor species observed, including water vapour. With a large source high in the atmosphere from the photolysis of CO_2 and sinks in the clouds and near the surface, and a lifetime measured in weeks, CO turns out to be an excellent tracer of the general circulation. VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) global maps show a well-defined maximum in the abundance of CO at a latitude of about 60°, near the outer edge of the cold collar, which probably marks the poleward extent of the Hadley cell (Fig. 2a). The other species seem to be much more uniformly distributed over the globe in the deep atmosphere but may be variable at the $\leq$10% level. The clouds show tremendous variability, with a variety of meteorological systems in several different layers, and distinct regions in which different mean particle sizes predominate. There are, for instance, distinctly larger particle sizes in the clouds in the polar region, although no definite departure from the composition of sulphuric acid and water has been detected.

Upper atmosphere and plasma environment

The absence of an internal magnetic field for Venus means that the solar wind interacts directly with the upper atmosphere, leading to a different distribution of the energies and densities of electrons, ions and energetic neutral atoms from that around Earth[11,12] (Fig. 4). Venus Express measurements are taken at solar minimum, thus complementing the Pioneer Venus plasma studies that were acquired during solar maximum. Photoelectrons with a typical energy of 22–28 eV are measured *in situ* when the satellite dips into the ionosphere while passing the pericentre at 250–350 km. Below this altitude the vertical distribution of electron density is sounded by radio occultation[13], suggesting a stable bottom of the ionosphere at 120 km. The electron density peaks at about 4×10^5 cm^{-3} at about 140 km altitude, and a very dynamic topside ionosphere is observed.

Simultaneous measurements of the vertical profiles of hydrogen-bearing species in the upper atmosphere and plasma *in situ* monitoring have begun to characterize the escape processes that have been responsible for the depletion of water on Venus over the planet's history. Earlier measurements established a D/H ratio ~150 times the terrestrial value in the lower atmosphere[14], which is consistent with the long-term loss of much larger amounts of hydrogen—presumably from water—from Venus compared with Earth. Still higher values of D/H, up to twofold higher, are now being found above the clouds by SPICAV/SOIR (Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus/Solar Occultation at Infrared), which has also uncovered strong variability in both H_2O and HDO content[8]. This unexpected behaviour has been

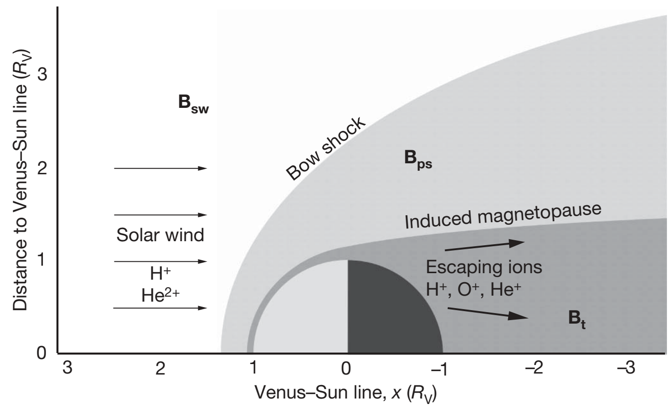

Figure 4 | The plasma environment of Venus as determined by Venus Express. All parameters noted in the figure are measured on a regular basis by the magnetometer and the ASPERA instrument, in three distinctly different regions: the unperturbed solar wind (sw), the plasma sheath (ps) and the induced magnetosphere/tail (t). The boundaries determined by the two instruments are shown approximately to scale. Oxygen ions are observed at high concentrations around the terminator and at lower concentrations well into the tail, indicating escape from a specific source region. He^+ shows similar behaviour, whereas H^+ is observed much more evenly distributed around the planet[11]. The figure shows cylindrical coordinates; the *x* axis is aligned with the Venus–Sun line. R_V, radius of Venus.

tentatively explained by a combination of fractionation in the condensation of ice particles and atmospheric transport, which would imply that species bearing hydrogen and deuterium are already fractionated in the mesosphere right beneath the region from which escape occurs.

ASPERA-4 (Analyser of Space Plasmas and Energetic Atoms 4) has established for the first time the composition of the escaping planetary ions, finding that, after H^+, the main escaping ion is O^+. This is in contrast with Mars, where the escaping plasma consists of approximately equal amounts of O^+, O_2^+ and CO_2^+, and it results from the higher gravitational acceleration at Venus, which tends to retain heavier components such as CO_2^+. High fluxes of escaping He^+ are also detected[11]. Oxygen and hydrogen ions are formed by the dissociation of neutral atmospheric species, including water, by solar ultraviolet radiation, which are then blown away towards the outer reaches of the Solar System (Fig. 4). This happens at a faster rate on Venus than on Earth, not just because Venus is closer to the Sun but also because it lacks the magnetic field that protects Earth from the flux of energetic charged particles from the Sun. These loss processes must have removed large amounts of water from Venus during the first billion years or so after the formation of the Solar System. A detailed quantification of the loss rates enables a more accurate estimate of how much water Venus has lost over its entire history, and by the end of the mission we should know better whether the planet once had an ocean as extensive and deep as Earth's.

Lightning

For a long time the existence of lightning on Venus has been controversial. Whistler-mode waves, which can be considered reliable evidence of lightning, were detected by the Venus Express magnetometer during more than 10% of the pericentre passes[15]. This corresponds to a lightning rate at least half that of Earth. Frequent lightning represents a significant energy input that has important implications for the chemistry in the lower and middle atmosphere on Earth, and this now seems likely to be true for Venus also.

Venus is more Earth-like

The overall sense of the results from the first year of operation of Venus Express is that the differences, particularly in climate, between Venus and Earth are much less mysterious than previously thought after the early phase of spacecraft exploration. They are consistent with theoretical ideas and interpretations suggesting that the two planets had similar surface environments in the past and that they evolved differently, with Earth's oceans converting most of its atmospheric CO_2 to carbonate rocks, and Venus losing most of its water to space. Both processes can now be seen to be still going on. The high zonal winds and near-equatorial turbulence on Venus, as well of course as the high surface temperatures, result from the depth of the atmosphere and huge inventory of greenhouse gas retained by Venus. The slow rotation of Venus, as well as possibly being responsible for the lack of magnetic field that makes erosion of the atmosphere by the solar wind so effective, permits the Earth-like Hadley cell component of the atmospheric circulation to extend closer to the poles, where it breaks down in spectacular fashion to form mid-latitude jets and polar vortices that are larger and more energetic than Earth's but are in many respects quite similar.

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Acknowledgements We thank R. Hueso and J. Bailey for the provision of graphics and data for Fig. 2b, and E. Marcq, C. Tsang, P. Drossart and J.-L. Bertaux for providing data for Fig. 3.

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