

In situ observations of waves in Venus's polar lower thermosphere with Venus Express aerobraking

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Waves are ubiquitous phenomena found in oceans and atmospheres alike. From the earliest formal studies of waves in the Earth's atmosphere to more recent studies on other planets, waves have been shown to play a key role in shaping atmospheric bulk structure, dynamics and variability^{1–4}. Yet, waves are difficult to characterize as they ideally require *in situ* measurements of atmospheric properties that are difficult to obtain away from Earth. Thus, we have incomplete knowledge of atmospheric waves on planets other than our own, and we are thereby limited in our ability to understand and predict planetary atmospheres. Here we report the first ever *in situ* observations of atmospheric waves in Venus's thermosphere (130–140 km) at high latitudes (71.5°–79.0°). These measurements were made by the Venus Express Atmospheric Drag Experiment (VExADE)⁵ during aerobraking from 24 June to 11 July 2014. As the spacecraft flew through Venus's atmosphere, deceleration by atmospheric drag was sufficient to obtain from accelerometer readings a total of 18 vertical density profiles. We infer an average temperature of $T = 114 \pm 23$ K and find horizontal wave-like density perturbations and mean temperatures being modulated at a quasi-5-day period.

Atmospheric total mass densities in Venus's lower thermosphere are inferred from accelerometer measurements made on board the Venus Express (VEx) spacecraft on its polar and highly eccentric orbit ($e = 0.84$) with pericentre near 75° N at the terminator and 130–134 km altitude during the aerobraking phase from 24 June to 11 July 2014. This was the first and only aerobraking experiment carried out by the spacecraft, shortly before contact was lost on 28 November 2014. At each of the 18 consecutive days, one density profile extending about 3° in latitude on both sides of the pericentre (point of closest approach) was obtained. A summary of all density measurements is shown in Fig. 1a as a function of spacecraft latitude. Each line in the figure represents densities measured during one flyby. Overall, the densities are largest near the pericentre latitude (75° N) owing to the lowest altitude of the spacecraft there, and they decrease away from that latitude owing to the increasing spacecraft altitude. In a hydrostatic isothermal atmosphere, the density change with altitude z is given by

$$\rho(z) = \rho(z_0) \exp\left(-\frac{z - z_0}{H}\right) \quad (1)$$

where $\rho(z)$ and $\rho(z_0)$ are densities at altitudes z and z_0 (the pericentre altitude), and H is the atmospheric scale height, which for simplicity we assume to be constant with height. In such an idealized case, $\rho(z_0)$ represents the largest density during any flyby, although in our data we find densities to not always be largest at

pericentre owing to strong background perturbations which are visible in Fig. 1.

We may compare our densities to a commonly used empirical Venus upper atmosphere model, VTS3 (ref. 6), which was produced from nearly two years (1978–1980) of continuous *in situ* composition measurements at 142–250 km altitude by the Pioneer Venus Orbiter Neutral Mass Spectrometer (PV-ONMS)⁷. Although these observations were made near the equator (16° N) covering all local times (and all solar zenith angles), Venus's upper atmosphere was assumed to be forced primarily by solar heating, and the PV-ONMS observations were extrapolated to polar latitudes by assuming the same solar zenith angle dependence identified at low latitudes from local time changes to apply when moving at any fixed local time from equator to pole. Our observations allow us to assess the validity of this assumption.

For each flyby, we produced an individual hydrostatic density fit, ρ_{fit} , which satisfies equation (1) and represented a least mean square fit to observed densities, ρ , of that flyby. For each density profile, we determined the combination of $\rho(z_0)$ and H values that produced the optimal ρ_{fit} profile. The dashed red lines in Fig. 1a show two examples of such hydrostatic fits. As a result of producing these fits, we obtained 18 individual values of scale height, one per flyby, with a mean value of $H = 2.9 \pm 0.6$ km. Although temperatures are not directly measured by our experiment, we may use the derived scale heights with the definition $H = kT/(mg)$ to infer temperatures, T , for every flyby (k being the Boltzmann constant, $g = 8.49 \text{ ms}^{-2}$ the acceleration due to gravity and m the mean molecular weight). We have no direct measurements of m from VEx, but may estimate these from the VTS3 model. Over the latitude and local solar time (LST) ranges of our observations (71.5°–79.0° N, 4.5–6.3 h LST) as well as the range of solar flux during the relevant dates ($F_{10.7, \text{mean}} = 130.7\text{--}134$, $F_{10.7, \text{daily}} = 93.4\text{--}200.7$), VTS3 predicts $m = 34.7\text{--}41.8$ atomic mass units (AMU), or an average of $m = 38.3$ AMU. From these inputs we obtain 18 temperature values, again one per flyby, with an average of $T = 114 \pm 23$ K. For the same locations and conditions, VTS3 temperatures range from 141 to 159 K, so our inferred temperatures are considerably lower than values from VTS3. Our derived T values assumed the same m for all flybys, which adds a further systematic uncertainty of $\pm 10\%$ to our temperatures but will not change the basic finding of our temperatures being lower than those of VTS3. Recent observations by the Venus Express SPectroscopy for the Investigation of the Characteristics of the Atmosphere of Venus (SPICAV) and Solar Occultation in the InfraRed (SOIR) instruments found thermosphere temperatures at high latitudes near 130–140 km of around 120 K (refs 8,9), consistent with our value. So, the VTS3 model apparently overestimates lower thermosphere temperatures at higher latitudes.

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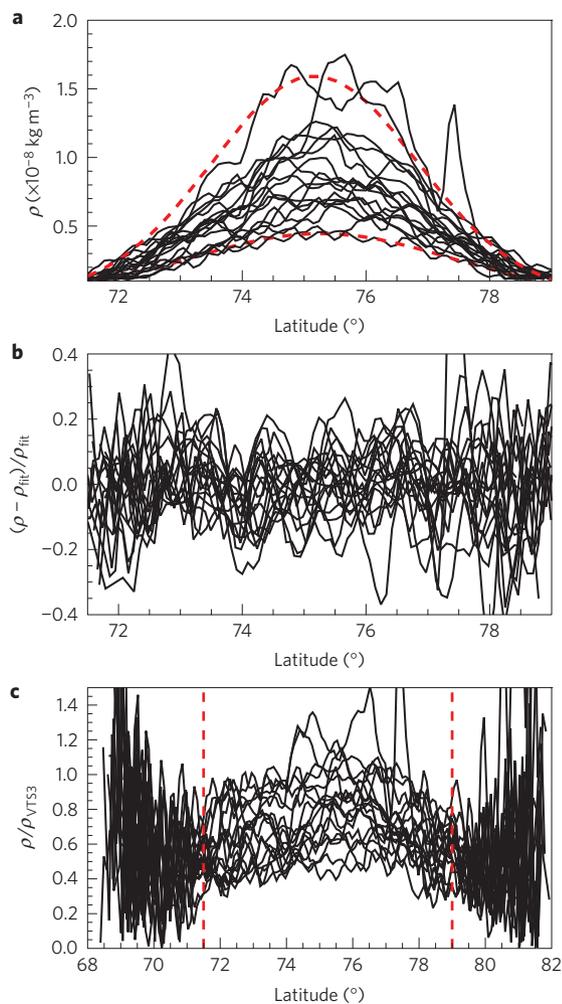


Figure 1 | Densities in Venus's upper atmosphere. **a**, Measurements along spacecraft trajectories for each of the 18 flybys during the aerobraking campaign of Venus Express from 24 June to 11 July 2014 at 130–140 km altitude. Red dashed lines are examples of best-fit background hydrostatic density profiles. **b**, Normalized perturbations around background values, illustrating a considerable abundance of atmospheric waves. **c**, Plot illustrating that the noise level of data outside of our chosen data window (below 71.5° N and above 79.0° N) increases considerably, justifying our chosen range of science data.

We may furthermore use the hydrostatic density profiles, ρ_{fit} , to extract the perturbations from the background densities in the atmosphere. This analysis assumes background densities to be close to the idealized hydrostatic fits, an approximation which is sufficiently accurate over the small vertical and horizontal range of sampled densities. Figure 1b shows normalized density perturbations, $(\rho - \rho_{\text{fit}})/\rho_{\text{fit}}$, to be of the order of 10%. They may be characterized as a fairly regular wave pattern (visible in Fig. 1a,b), and we therefore interpret these as signatures of atmospheric waves.

The overall variability of measured densities is also visible in Fig. 2, which shows all measured densities versus altitude. The red crosses show averages taken over bins spaced vertically by 2.5 km. The red line is a hydrostatic density curve with a slope defined by the previously obtained average scale height of $H = 2.9$ km. We centre the red line around the average density value at 133.5 km and find that it also passes fairly well through the other two average values (red crosses), thus capturing well the overall slope of the profiles and confirming the validity of our previously described approach in determining H from the ρ_{fit} profiles.

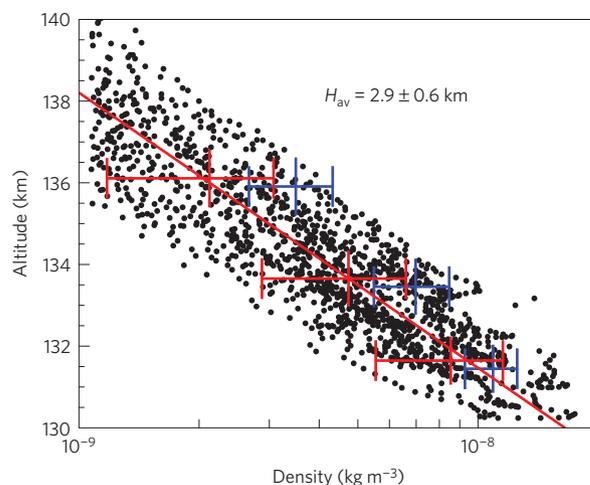


Figure 2 | Density profiles in Venus's lower thermosphere. Black symbols denote individual densities measured with Venus Express Aerobraking between 24 June and 11 July 2014, the red crosses are binned average values and their 1- σ variability within bins spaced vertically by 2.5 km. The red line denotes an average density profile with a slope (scale height H) determined from best hydrostatic fits for each flyby. Blue crosses are averages of individual densities from the VTS3 model⁶ extracted at the same locations as observed densities. The VTS3 averages are extracted within the identical bins as Venus Express measurements, but for clarity the blue crosses have been shifted downwards by 0.2 km in the figure.

Blue crosses in Fig. 2 are averages of densities from the VTS3 model that were sampled at the identical locations and conditions as those we measured, and illustrate that measured densities are smaller by around 22% near 130 km and 40% near 140 km with respect to those of VTS3. Linearly extrapolating this trend upwards to 180 km altitude would imply a discrepancy by a factor of around two there, in agreement with the discrepancy found by VExADE via Precise Orbit Determination at higher altitudes (176–186 km; ref. 10). This suggests scale heights in Venus's polar atmosphere to be systematically lower than predicted by VTS3 above around 100 km. This is consistent with our earlier finding of Venus's polar upper atmosphere being cooler than predicted by VTS3. The broader significance of these differences is that the assumptions of solar zenith angle symmetry underlying VTS3 are too simplistic for high latitudes, where other factors such as winds may lead to polar temperatures in the lower thermosphere being cooler than expected from solar forcing alone.

A second finding from Fig. 2 is that variability in the VTS3 model densities is lower than that of measured densities. Over the altitude range of Fig. 2, the average 1- σ variation of measurements (normalized to their background value) is 0.35; the corresponding value for VTS3 densities is 0.19. The local time changes, in particular, are responsible for most of the variability in VTS3, because the locations sampled in this study reach across the terminator, where the upper atmosphere is known to change considerably^{6,7}. The additional variability of our densities is caused by the density waves that we identified in Fig. 1.

To investigate these waves further, Fig. 3a,b shows normalized values, $(\rho - \rho_{\text{fit}})/\rho_{\text{fit}}$, for 30 June 2014 and 7 July 2014, respectively, as a function of distance to the closest approach point. We chose these two days as examples of stronger wave activity (Fig. 3a) and weaker wave activity (Fig. 3b). To quantify the amplitudes on each individual day, we fit the waves of every individual flyby with the sum of two wave trains, shown as dashed lines in Fig. 3a,b. The amplitudes and horizontal wavelengths of wave trains '1' and '2' are denoted by A_1, λ_1 and A_2, λ_2 , respectively, and we obtained a single

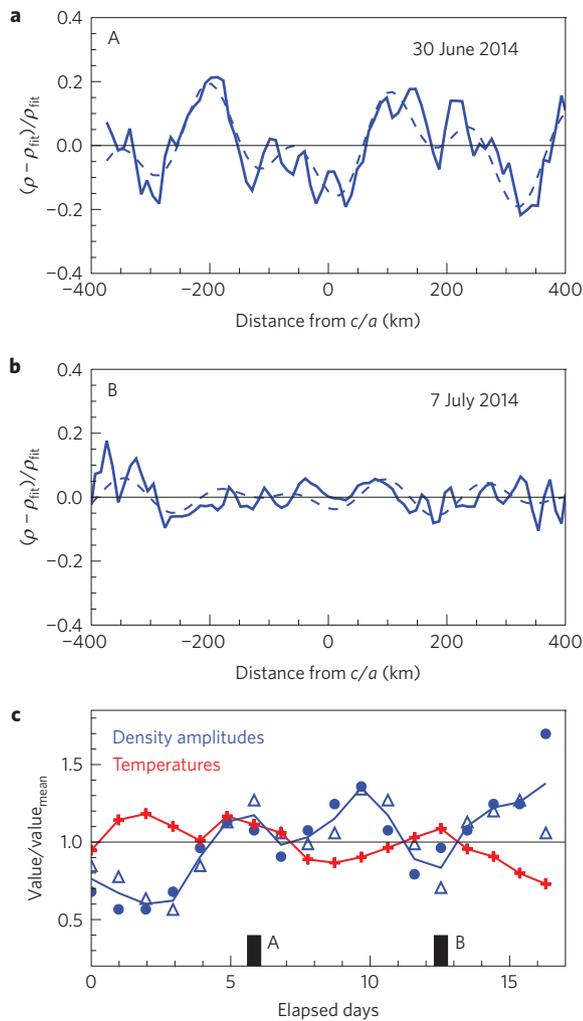


Figure 3 | Atmospheric waves on Venus. **a, b**, Wave-like perturbations are shown for two flybys on 30 June (**a**) and 7 July 2014 (**b**). Dashed lines are fits to the density perturbations with two wave trains. **c**, Points in blue are the normalized amplitudes, A/A_{mean} , of wave train 1 (dots) and 2 (triangles) versus days of observation. The blue line shows the average of these two amplitudes, indicating a 5-day modulation. Mean amplitudes over the 18 days are $A_{1\text{mean}} = 0.09$ and $A_{2\text{mean}} = 0.07$. Red crosses and the red line are normalized temperatures, T/T_{mean} , with the mean value $T_{\text{mean}} = 114$ K.

set of values for these at each flyby. Averaged over the 18 flybys, mean wavelengths are $\lambda_{1\text{mean}} = 275 \pm 70$ km and $\lambda_{2\text{mean}} = 126 \pm 30$ km and their mean amplitudes are $A_{1\text{mean}} = 0.09 \pm 0.04$ and $A_{2\text{mean}} = 0.07 \pm 0.03$, respectively. The similarity of $A_{1\text{mean}}$ and $A_{2\text{mean}}$ justifies our use of two wave trains. Although we attempted fitting three wave trains, the amplitudes of the third wave were considerably smaller.

Values of $A_1/A_{1\text{mean}}$ (blue dots) and $A_2/A_{2\text{mean}}$ (blue triangles) are shown in Fig. 3c as a function of time (days from 24 June 2014). Thick markers on the x -axis denote the days of observations shown in Fig. 3a and b. Clearly visible in Fig. 3c are periodicities in the density amplitudes of around five days, suggesting a modulation of the gravity waves by a 5-day oscillation in the atmosphere. Red crosses in the same panel are temperatures at each flyby, normalized to the average value $T_{\text{av}} = 114$ K. These show a periodicity of between three and seven days. Previously, cloud tracking near 65 km altitude from ground based telescopes and from spacecraft have been the primary method of detecting waves in Venus's atmosphere^{11,12}, alongside some measurements of thermal emissions

above (65–90 km)^{13,14}. These overall suggested the presence of a 4-day Kelvin wave at low latitudes and of a Rossby wave at a 5–6-day period at mid to high latitudes^{11,14}. More recently, radar tracking of the Magellan spacecraft revealed the presence of a 9-day oscillation near the equator (11° N) at 164–184 km altitude². The latter was interpreted as possibly originating from nonlinear wave-wave interaction between two planetary waves occurring near the cloud top². The modulation of gravity waves by planetary waves was shown to be important on Earth in explaining planetary wave periodicities detected in the thermosphere/ionosphere¹⁵, and our findings suggest the same occurs on Venus. Our observation of a high latitude 5-day modulation of gravity wave amplitudes at 130–140 km may thus be linked to the previous detection of a high latitude quasi-5-day oscillation at 65–90 km (refs 13,14). The planetary wave may have interacted nonlinearly with the gravity waves near 65–90 km, modulating their amplitudes and enabling the 5-day periodicity to be carried into the thermosphere.

Unlike the density perturbations, the temperature oscillations in Fig. 3 are not signatures of modulated small-scale temperature waves but periodic changes of the mean temperature itself with an amplitude of $\sim 20\%$ (~ 22 K). Because we are sampling temperatures within a narrow longitude range (220°–242°) this oscillation could either represent the reappearance of a warmer region advected around the planet by a super-rotating atmosphere, or it may be interpreted as a planetary wave. The upward propagation of planetary waves into the thermosphere is strongly affected by zonal wind speeds, being prevented from passing through a level where the zonal wave phase and mean zonal wind speed are equal. Zonal winds have been observed in the 90–120 km regime by means of Doppler shifts of the CO₂ 10 μm emission line (from 110 ± 10 km; ref. 16) as well as CO sub-mm absorption lines (from 90–115 km; ref. 17). Dynamics in that regime are found to be highly variable, transitioning from a region near the cloud top (65 km) dominated by retrograde super-rotating zonal (westward) (RSZ) flow ($v \leq 100$ m s^{-1}) to subsolar to anti-solar (SS-AS) circulation ($v \leq 150$ m s^{-1}), which is thought to become important in the thermosphere above ~ 150 km (refs 16–18). The exact balance of the RSZ and SS-AS components changes with time and altitude, and is unknown above ~ 130 km altitude. Although previous studies have shown that some Rossby waves can propagate vertically into the lower thermosphere^{11,19}, the variability of zonal winds and our inability from the limited data set to better characterize the horizontal structure and possible propagation speed of the temperature oscillations prevents us from assessing whether or not we are seeing a planetary wave in the temperatures. The other possible explanation is that of long-lived temperature structures being advected around the planet by zonal winds. At 75° latitude a 5-day periodicity is produced by a ~ 23 m s^{-1} zonal wind, indicating a weak RSZ speed, consistent with some of the ground-based observations^{16,17,20}.

Figure 4 is a visualization of the atmospheric gravity waves versus latitude and longitude, the contours being the normalized wave perturbations, $(\rho - \rho_{\text{fit}})/\rho_{\text{fit}}$. Figure 4a shows the observations, with superimpose black lines representing the spacecraft trajectories. Figure 4b–d are wave fits—the sum of both wave trains (b) and wave trains 1 (c) and 2 (d) individually. Although the underlying observations were carried out at different longitudes, they were also made on different days, so the longitude variations can also be regarded as time variations. By comparing Fig. 4a and b, we see that the wave fits capture the overall observed structures well. From Fig. 4c we cannot identify phase propagation of wave 1, but Fig. 4d suggests that wave 2 may exhibit a moderate southward phase propagation. The dashed and dotted lines illustrate two possible options of linking wavefronts and thus determining phase speeds. These suggest meridional speeds of around 0.1 m s^{-1} (dotted lines) and 0.5 m s^{-1} (dashed lines).

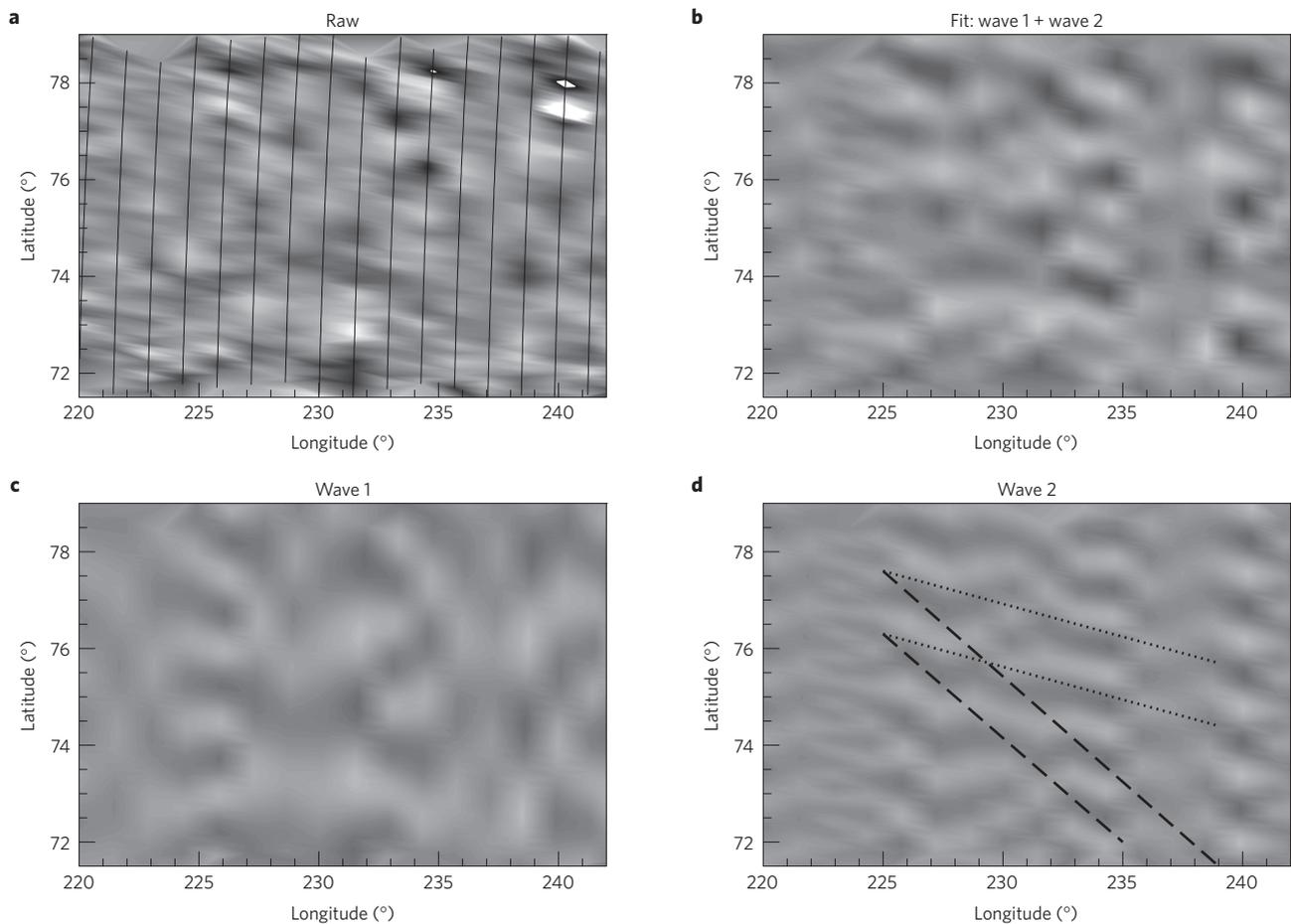


Figure 4 | Maps of density waves in Venus's lower thermosphere. **a**, VExADE observations. **b–d**, Best fits with two wave trains '1' and '2' (**b**), shown individually in **c** and **d**, respectively. Solid lines in **a** are the VEx trajectory paths mapped onto the surface. The dotted and dashed lines in **d** illustrate possible southward phase propagation of wave 2 at meridional speeds of 0.1 m s^{-1} and 0.5 m s^{-1} , respectively.

Despite the ambiguity in the meridional phase speed, the value is not likely to exceed the larger of both, so wave 2 is apparently quasi-stationary.

The Venus Express Visible and Infrared Thermal Imaging Spectrometer-Mapper (VIRTIS-M) remotely observed $4.3 \mu\text{m}$ emissions from 110 to 140 km altitude and discovered wave structures with horizontal wavelengths of around 90–400 km and meridional propagation speeds of around 30 m s^{-1} (ref. 21). Both our λ_1 and λ_2 values are comparable to those values, but the phase propagation speed of wave 2 is apparently much lower. Given our limited latitude window and 1-day time resolution of observations, during which time a 30 m s^{-1} wave will have propagated by 24° latitude, we cannot capture the phase propagation of the waves identified by VIRTIS-M. The apparent randomness of the phase of wave 1 in Fig. 4c is not inconsistent with waves found by those observations; we may thus have sampled *in situ* the same waves identified remotely by VIRTIS-M. Our findings illustrate the significant influence of Venus's cloud top layer on its lower thermosphere, emphasizing the importance of understanding vertical coupling in Venus's atmosphere.

Methods

Methods and any associated references are available in the [online version of the paper](#).

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Author contributions

I.C.F.M.-W. carried out the density wave extraction and analysis shown in Figs 2–4, and jointly with S.B. led the scientific interpretation of the results. S.B. and J.-C.M. performed the analysis of raw accelerometer readings using the GINS software to obtain density values. S.B. carried out the error analysis which led to Fig. 1. H.S. led the implementation of the VExADE experiment in the mission planning and made important scientific contributions in the interpretation of the data. I.C.F.M.-W. wrote the paper with significant contributions from all the authors in interpreting the results and editing of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

Methods

The VEx inertial measurement package contains three Honeywell QA-2000 accelerometers which provide 8 Hz velocity increment data. The measured acceleration, in the absence of thrusts and after removal of angular accelerations and with solar radiation pressure being negligible for altitudes below 150 km, is due to atmospheric drag. Details pertaining to the derivation of densities from accelerometer measurements have been previously presented^{22,23}. We processed the 8 Hz accelerometer data with the Geodesy by Simultaneous Numerical Integration (GINS) software, which calculates satellite orbits by taking into account all gravitational and non-gravitational forces acting on the satellite¹⁰. This data processing produced atmospheric densities at 1 Hz sampling.

The uncertainty in derived densities is the sum of a systematic part of 10% due to the uncertainty in the satellite drag coefficient, $C_D = 2.60 \pm 0.26$ (ref. 24), and a variable noise and bias part due to the accelerometers. The systematic error does not affect analyses of relative variations such as wave perturbations. The uncertainty due to the computed drag area and mass of the spacecraft is negligible thanks to accurate knowledge of its attitude and mass. The (formal) noise of the accelerometers, after 16-point smoothing and differencing the velocity increments

one second apart, is 0.001 m s^{-2} ($1-\sigma$). A signal-to-noise ($1-\sigma$) ratio of one is reached on average at 139 km altitude, which corresponds to profiles of about 80 s duration.

Another way of evaluating the validity range of the VEx densities is by means of comparison with a model. The VEx-to-VTS3 density ratios were computed for each profile. The density ratios start to present a typical noise behaviour for altitudes consistent with those calculated applying the formal accelerometer noise (see Fig. 1c).

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