~30° in the southern hemisphere. The equator is well below the center of the images.

There is a distinct tendency for the equatorial region to be brighter than other latitudes (see Fig. 3, a to c). There is also a tendency for the western limb to be brighter than the eastern limb, before orbit 90 or so, and for the eastern to be brighter than the western thereafter, suggesting that at any given time the brightest emission occurs about 30° in longitude beyond the antisolar meridian toward the morning terminator. ("Morning" and "evening" are used on the basis of the observed retrograde circulation of the cloud tops.) Occasional isolated bright patches are seen in both hemispheres; one example appears as a band sweeping across the upper part of Fig. 3b. The overall signal level fluctuates from orbit to orbit, with the brightest signals being seen on orbits 94 and 114; this suggests temporal fluctuations superimposed on the spatial variations.

We conclude on the evidence of the night airglow observations reported here that the overall circulation of the Venusian thermosphere is temporally irregular and, in addition, its convergence on the nightside is largest near the equator at all longitudes and ~30° beyond the antisolar meridian at latitudes between 60°N and 60°S.

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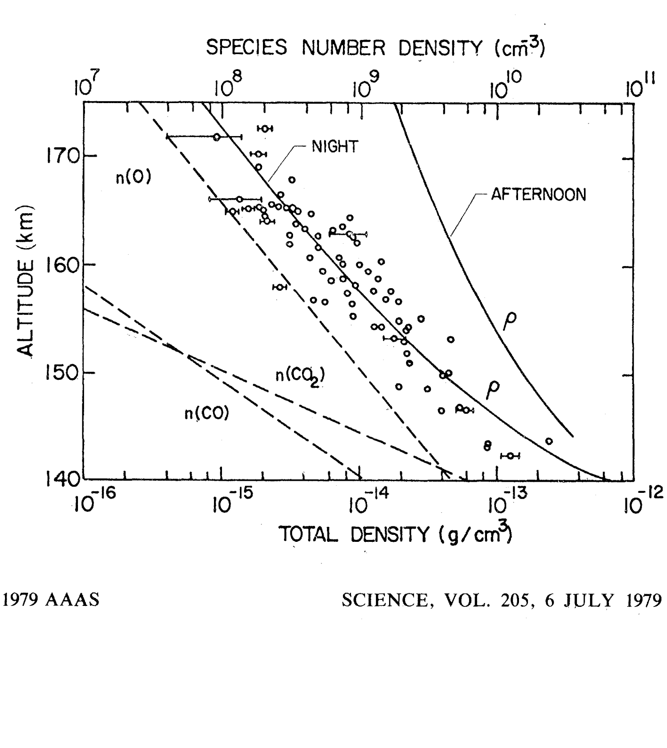
Short-Term Cyclic Variations and Diurnal Variations of the Venus Upper Atmosphere

Abstract. *Measurements of satellite drag obtained from the orbital decay of the Pioneer Venus orbiter on the nightside of Venus indicate an atomic oxygen atmosphere near 155 kilometers (an order of magnitude less dense than expected) with nighttime inferred exospheric temperatures averaging as low as 110 K. Densities at these altitudes decrease sharply from day to night, contrary to the predicted nighttime oxygen bulge. This decrease may be indicative of an unexpectedly weak transport across the evening terminator or a very strong heat sink at night that is possibly related to vertical eddy heat transport. Large periodic oscillations in density and inferred exospheric temperature are detected with a period of 5 to 6 days. We have subsequently discovered temperature variations of the same period in the stratosphere, which are tentatively interpreted as planetary-scale waves that may propagate upward producing the periodic variations in the thermosphere and exosphere. The peak-to-peak amplitude of the temperature oscillations associated with these waves apparently increases with altitude approximately as follows: 1 K (70 kilometers), 3 K (90 kilometers), 40 K (155 kilometers). Inferred nighttime exospheric temperatures are found to be asymmetric relative to midnight, minimizing on the morning side. The possibility of superrotation of the thermosphere and exosphere is discussed.*

From the orbital decay of the Pioneer Venus orbiter, atmospheric densities on Venus have been determined at altitudes ranging between 140 and 175 km near a latitude of 18°N. The method by which densities are determined near periapsis from changes in the orbital period caused by atmospheric drag was discussed in (*1*). In the present report we discuss a study of the vertical structure of the nighttime thermosphere and exosphere, the results of which verify the atmospheric model [see (*1*)] that indicated nighttime exospheric temperatures below 150 K. We then study temporal variations identifying (i) a very sharp density decrease from day to night contrary to predictions, (ii) the existence of a large amplitude periodic variation in the exosphere with a period of 5 to 6 days, (iii) preliminary evidence of a 5-day temperature wave in the stratosphere interpreted as a planetary-scale wave which may be the cause of the oscillations in the exosphere, and (iv) a significant asymmetry with respect to midnight of the diurnal variation. Some of the implications of these results, including the possible coupling between the upper and lower atmosphere of Venus, are discussed.

Shown on the right of Fig. 1 is the observed altitudinal variation of densities on the nightside of Venus over the period 1 January through 1 April 1979. Densities were obtained nearly every day except for days when large tracking errors occurred. It may be seen that conditions are highly variable. The observed mean altitudinal variation near 155 km is consistent with a density scale height of 7 km. The model developed in (*1*) from altitudinal variations of dayside density data gave, for any density, correspond-

Fig. 1. Variation of nighttime density (ρ) (solid line labeled "night," bottom scale) and composition (dashed lines, top scale) with altitude based on the model described in (*1*) and an exospheric temperature of 110 K. The "afternoon" density profile from (*1*) is also shown. Tracking error bars are shown for drag measurements of density when errors exceed 10 percent. Measured densities are shown between periapsis pass 28 and 118 (local solar times 7:00 p.m. to 4:00 a.m.).



ing composition and temperature profiles. The model is in fair agreement with dayside temperatures and composition measured by the neutral mass spectrometer aboard the Pioneer Venus orbiter (*2*). The solid line labeled "night" in Fig. 1 is the model prediction of the variation of density with altitude for the very low densities on the nightside. Thus the model in (*1*) fits satisfactorily both the day and night data. The corresponding nighttime model composition is shown by the dashed lines in Fig. 1 with atomic oxygen as the major species over the altitude interval of the measurements. Thus the nighttime density measurements are essentially measurements of atomic oxygen variations. The nighttime density and composition profiles correspond to an exospheric temperature of ~ 110 K compared to the 118 K reported for the first hour of darkness in (*1*). The very cold nighttime temperatures reported in (*1*) are therefore confirmed by the low scale heights shown here.

The Dickinson-Ridley model (*3*) predicts an increase in total density from day to night over the altitude range of the measurements (*4*) due to transport of atomic oxygen to the cooler nightside resulting in a buildup of a nighttime atomic oxygen bulge similar to the winter atomic oxygen (*5*) and helium bulges (*6*) on Earth. On the contrary, a comparison of the afternoon profile in (*1*) (labeled "afternoon" in Fig. 1) and the nighttime profile indicates that densities (principally atomic oxygen) at these altitudes drop sharply from day to night. Nighttime densities near 155 km are about a factor of 20 lower than the estimates in the Dickinson-Ridley model. This drop in densities may be principally related to the exospheric temperatures being much lower at night (~ 110 K) than predicted by the Dickinson-Ridley model (~ 170 K to 270 K) although it may also be related to the possible atomic oxygen bulge at lower altitudes being flatter than expected.

In order to study temporal variations of density and inferred temperature, we normalize measured nighttime densities to 155 km, the mean altitude of measurement, using the model in (*1*). Figure 2 shows that there is a large oscillation in density and inferred temperature. The variation does not correlate with measured variations in solar wind velocity (*7*) or with variations in solar decimetric flux we deduced for Venus.

The vertical lines at the top of Fig. 2 represent the approximate time of maxima for the 5- to 6-day oscillation, and the tick marks on the top scale indicate a constant period of oscillation that best fits the data. Analysis of the amplitude, phase, and period of the inferred exospheric temperature oscillation does not indicate statistically significant variations with altitude. Average peak-to-peak oscillations in density are greater than a factor of 2 near 155 km, corresponding to ~ 40 K exospheric temperature oscillations. Because the periapsis remained on the dayside only briefly before it entered the nightside, statistically significant results have not yet been obtained about such an oscillation on the dayside, although the possibility of such a variation has been pointed out (*8*). A harmonic analysis of the nighttime data also reveals lower amplitude periodic variations of approximately 4, 5, 10, and 16 days.

These cyclic variations in the thermosphere (*9*) and exosphere might be caused by planetary-scale waves propagated upward from lower in the atmosphere. We investigated this possibility using simultaneous temperature measurements obtained at lower altitudes by the Venus radiometric temperature experiment (VORTEX), an infrared remote sensing experiment on the orbiter (*10*). Figure 3 shows preliminary evidence for planetary-scale temperature waves with a period of approximately 5 days. Figure 3B shows the wave at cloud top level (11.5 μm), at ~ 70 km (13.1 μm), and at ~ 80 km (13.7 μm); in Fig. 3A the wave near 90 km (14.7 μm) observed by the infrared experiment is compared with the exospheric temperature wave obtained from drag measurements near 155 km. As the wave propagates (presumably) upward from 70 km to 90 km, its peak-to-peak amplitude increases from about 1 K to 3 K. A phase shift of about π rad is seen from 70 to 80 km and of about 3 $\pi/2$ rad from 80 to 90 km. Since the infrared measurements near 90 km and drag measurements near 155 km were obtained on opposite sides of the planet, the phases for the two waves could be essentially the same. The temperature wave might be caused by disturbances that essentially rotate with the stratosphere. The fact that the period appears to be longer than that of the cloud tops observed in the ultraviolet (~ 4 days) is significant. Perhaps the waves originate in deeper levels than the ultraviolet markings, where the rotation rate is slower.

Shown in Fig. 4 are 11-day running means of exospheric temperature as a function of local solar time. Symmetry with respect to midnight might be expected for an essentially nonrotating upper atmosphere. On the contrary, inferred exospheric temperatures are found to be lower in the morning than in the evening. If the atmosphere were rotating in the direction of planet rotation, minimum exospheric temperatures would be expected in the early morning hours similar to what is observed on Earth. Indeed, that is what we see on Venus. Superrotation (*11*) of the thermosphere

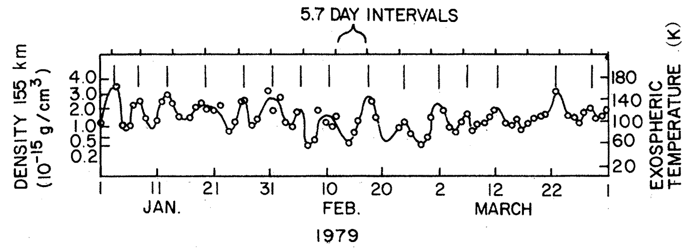


Fig. 2. Temporal variation of nighttime atmospheric density normalized to 155 km according to the model in (*1*), and the corresponding inferred exospheric temperatures. The vertical lines give the approximate time of maxima of the 5- to 6-day oscillation. The scale at the top of the figure indicates the constant period of oscillation that best fits the data.

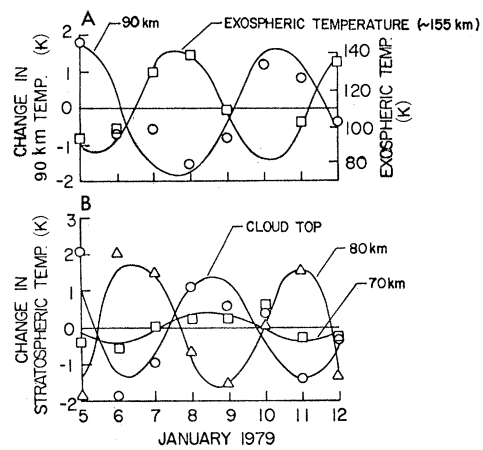


Fig. 3. Comparison of temperature waves measured by VORTEX and by the orbiter atmospheric drag experiment (OAD). (A) Temperature variations obtained near 90 km (circles) by VORTEX are compared with exospheric temperature variations determined from atmospheric drag near 155 km (squares). (B) Temperature variations measured by VORTEX are shown at cloud top (circles), ~ 70 km (squares) and ~ 80 km (triangles) levels. The VORTEX measurements were obtained between latitudes 33° and 38°N and longitudes 2° and 12°E, whereas the OAD measurements were obtained near latitude 18°N and longitudes 211° to 221°E. Standard deviations of these VORTEX measurements, due principally to atmospheric variations, range from ~ 0.2 to 1 K.

and exosphere could also explain qualitatively the lack of evidence of a significant atomic oxygen bulge and the existence of 5- to 6-day oscillations. If the thermosphere rotates rapidly, the net buildup of atomic oxygen on the nightside should be considerably less than for an essentially nonrotating atmosphere (*12*). Of course, the 5- to 6-day oscillation could be the result of the upper atmosphere near 155 km rotating every 5 to 6 days. This possible superrotation could be simply an extension of the atmospheric rotation near cloud tops which is approximately one revolution every 4 days (*13*, *14*). Thus the rotation rate might decrease with altitude from about 100 m/sec near 65 km to 70 m/sec near 155 km. But the recently observed high polar temperatures near 80 km indicate zonal winds essentially cease near 80 km if the wind is cyclostrophically balanced (*10*, *15*). Alternatively, zonal winds might build up in the thermosphere from processes similar to those that cause the superrotation in Earth's thermosphere (*16*). However, the very sharp drop in exospheric temperature near the evening terminator could rule out superrotation at satellite altitudes.

Figure 5 shows a comparison of the exospheric temperature distribution obtained from drag measurements [taken from Fig. 4 and (*1*)] and the temperature distribution predicted for the nonrotating atmosphere by the Dickinson-Ridley model (*3*). According to that model, the principal heat source at night is adiabatic heating. Clearly, the observed sharp drop in temperature near the terminator was not predicted. Apparently the transport across the terminator is overestimated, resulting in an overestimate of adiabatic heating, or there is an extremely effective heat sink on the nightside. Superrotation would appear to make the problem more difficult to solve by increasing transport across the evening terminator. However, the Dickinson-Ridley model does not include the possible effects of eddy heat transport. Dickinson (*17*) has indicated that if cooling by eddy mixing is more effective than heating due to frictional dissipation of small-scale motions, very cool exospheric temperatures of the order of 100 K (as noted in Fig. 5) could be obtained.

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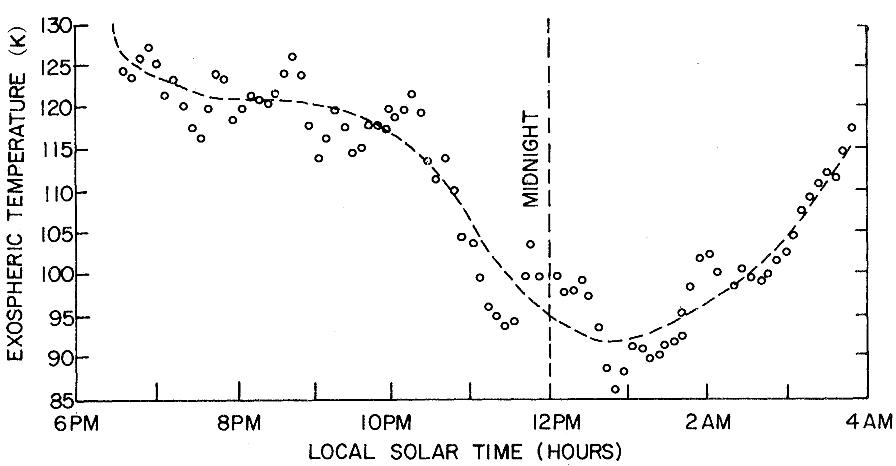

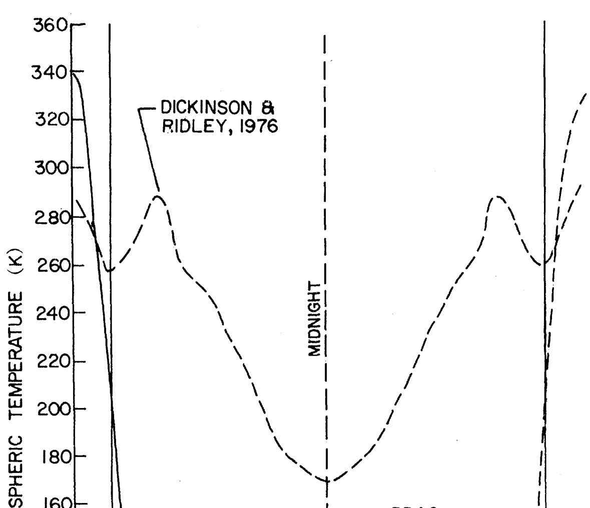

Fig. 4 (above). Variation of 11-day running means of inferred exospheric temperatures obtained from drag measurements with local solar time. Fig. 5 (left). Comparison of diurnal variation of inferred exospheric temperatures obtained from drag measurements with the diurnal variation predicted by the Dickinson-Ridley model (*3*).

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