such as He and N_2 are expected to yield the most reliable values of temperature.

The He and N_2 data of Fig. 2, orbit 17 (solar zenith angle, $\simeq 88°$) lead to scale heights of about 57 km and 8.4 km, respectively, which correspond to a temperature of 230 K. The CO_2, CO, and O data indicate similar temperatures but are not considered as reliable. The He and N_2 data for orbits 3, 4, and 5 (solar zenith angle, $\simeq 69°$) when the periapsis was near 180 km (above exobase altitude of ~170 km) (*6*) give a temperature of about 400 K.

These temperatures support the concept of a relatively "cool" upper atmosphere as deduced most recently from the temperatures inferred from Mariner 5 (*7*) and Mariner 10 (*3*) airglow measurements as well as those suggested by theoretical models of the ionosphere (*8, 9*). A rather strong decrease in temperature with increasing solar zenith angle also is observed, leading to a temperature gradient three times larger than predicted by a global thermosphere model (*10*).

The CO_2 density and gas temperature decrease with increasing solar zenith angle. If we assume that the global circulation model of Dickinson and Ridley (*10*) is valid, then we can compare our measurements made near the evening terminator with those of the BNMS (*11*) made near the morning terminator, since the model invokes cylindrical symmetry about the sun-planet axis. Thus, comparing our temperature of 230 K and CO_2 density of 1.1×10^9 cm^{-3} at 150 km and a solar zenith angle of 88° with the BNMS temperature of 253 K and CO_2 density of 6×10^9 cm^{-3} at the same altitude and a solar zenith angle of about 60°, we see that both the density and temperature decrease with increasing solar zenith angle. If this comparison is feasible then a kinetic pressure imbalance is present which must be balanced by a dynamical pressure resulting from horizontal flow from day to night as suggested originally by Dickinson and Ridley (*10*).

H. B. NIEMANN, R. E. HARTLE
W. T. KASPRZAK, N. W. SPENCER
NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771
D. M. HUNTEN
University of Arizona, Tucson 85721
G. R. CARIGNAN
University of Michigan, Ann Arbor 48109

References and Notes

1. L. Colin and D. M. Hunten, *Space Sci. Rev.* **20**, 451 (1977).
2. S. C. Liu and T. M. Donahue, *Icarus* **24**, 148 (1975); N. D. Sze and M. B. McElroy, *Planet. Space Sci.* **23**, 736 (1975).
3. S. Kumar and A. L. Broadfoot, *Geophys. Res. Lett.* **79**, 2529 (1974).
4. H. G. Mayr, I. Harris, R. E. Hartle, W. R. Hoegy, *J. Geophys. Res.* **83**, 4411 (1978).
5. The ^{36}Ar measurement can be obscured by HCl, a possible contaminant in the instrument, which yields mass peaks at 35, 36, 37, and 38 amu with relative peak heights of 12, 100, 4, and 33 percent, respectively. The limited time for which these mass peaks have been sampled did not allow a proper magnitude determination of the peak heights.
6. The exobase (base of the exosphere) is defined as the altitude where the mean free path of the atoms and molecules is equal to the local scale height, that is, the logarithmic decrement of density with altitude.
7. D. E. Anderson, Jr., *J. Geophys. Res.* **81**, 1213 (1976).
8. S. J. Bauer and R. E. Hartle, *Geophys. Res. Lett.* **1**, 7 (1974).
9. S. Kumar and D. M. Hunten, *J. Geophys. Res.* **79**, 2529 (1974).
10. R. E. Dickenson and E. C. Ridley, *Icarus* **30**, 163 (1977).
11. U. von Zahn, D. Krankowsky, K. Mauersberger, A. O. Nier, D. M. Hunten, *Science* **203**, 768 (1979).
12. We thank everyone who helped to make this experiment possible, especially J. Cooley and S. Way and the Engineering Group and the Data Analysis Branch (lead by P. Smith) at the Goddard Space Flight Center. At the University of Michigan we thank the engineering teams (led by B. Kennedy and J. Maurer) and at NASA Ames Research Center we thank the personnel of the Pioneer Venus Project (under the direction of C. Hall.)

16 January 1979

Venus Thermosphere and Exosphere: First Satellite Drag Measurements of an Extraterrestrial Atmosphere

Abstract. *Atmospheric drag measurements obtained from the study of the orbital decay of Pioneer Venus 1 indicate that atomic oxygen predominates in the Venus atmosphere above 160 kilometers. Drag measurements give evidence that conditions characteristic of a planetary thermosphere disappear near sundown, with inferred exospheric temperatures sharply dropping from approximately 300 K to less than 150 K. Observed densities are generally lower than given by theoretical models.*

Atmospheric drag measurements obtained from the orbital decay of Earth satellites have been used since the beginning of the space age to determine upper atmosphere density from which composition and temperature are inferred. The atmospheric characteristics derived from those satellite drag measurements have formed the basis of a number of standard upper atmospheric models of the earth (*1*). From the present study of the orbital decay of Pioneer Venus 1 (orbiter) comes the first detection of atmospheric drag from a spacecraft orbiting another planet (*2*). In this report we discuss the determination of atmospheric densities from satellite orbital decay, and then describe an atmospheric composition model that is consistent with the observed variation of density with altitude. Finally, we use a model with variable exospheric temperature to study the nature of the diurnal variation of the upper atmosphere of Venus. The measurements were all obtained near 18.4°N latitude between 7 December 1978 and 1 January 1979 at altitudes of 150 to 190 km.

The density ρ_A (in grams per cubic centimeter) at a distance 1/2 H^* above periapsis (position of closest approach to planet surface), where H^* is the estimate of density scale height at periapsis (in centimeters), can be determined from the following equation if one assumes nominal Pioneer Venus 1 values of orbital eccentricity (0.84) and semimajor axis (39,600 km) (*3*).

$$\rho_A = \frac{4.35 \times 10^{-14}\,\Delta T}{\sqrt{H^*}}\,\frac{m}{C_D S} \qquad (1)$$

where ΔT is the change of orbital period per revolution caused by atmospheric drag, in seconds per revolution; m is the mass of the spacecraft, in grams; C_D is the coefficient of drag; and S is the effective cross-sectional area, in square centimeters. In practice, densities are determined by numerical integration through an atmosphere (*4*). The densities are evaluated above periapsis at the "effective" altitude of the drag effect to minimize errors associated with assumed value of H^*. With this technique, an error of 25 percent in H^* results in only a 1.2 percent error in the density a half scale height above periapsis.

The value of m, C_D, and S were approximately 361.7 kg, 3, and 6.15×10^4 cm^2, respectively. The mass of Pioneer Venus 1 decreased from 361.9 to 361.5 kg because of the expenditure of fuel in orbital maneuvers. The C_D value of 3 was determined after we considered experimental results consistent with values close to 3 as well as theoretical extremes of 2 and 4. The effective satellite cross section was constant at periapsis. Within 50 km altitude of periapsis where drag effects can be relevant, this cross section ranged from 6.06×10^4 to 6.20×10^4 cm^2.

The orbital elements, used to determine the change of orbital period (ΔT), were computed by a differential correction orbit determination program applied to S-band Doppler data received by the Deep Space Network (*5*). In order to isolate the atmospheric drag effect, which is concentrated near periapsis, changes in the orbital period due to other phenomena were taken into account. During the data interval discussed here, Pioneer Venus 1 did not enter shadow and thus the solar radiation force effects on the orbital period were second order and very small ($\sim 10^{-2}$) second per revolution). Second-order solar gravitational effects were more significant ($\sim 10^{-1}$ sec/rev) but were accurately calculated. The calculated effects of solar radiation and solar gravitational perturbations were subtracted from the total change in period from one apoapsis to the next to yield the change in period due to atmospheric drag. It was found that the major phenomenon causing changes in orbital period was atmospheric drag. The orbital decay per revolution that was caused by these drag effects ranged from -0.72 ± 0.02 to -8.32 ± 0.06 second. Care was taken to avoid the effects of maneuvers. In some cases large standard deviations occurred where full revolution fits could not be used because of maneuvers or lack of tracking data (see error bars on Figs. 1 and 2).

The final parameter required to solve Eq. 1 is H^*, the density scale height at periapsis. Appropriate values of H^* were determined by taking into account the altitudinal variation of density which was consistent with the drag measurements obtained during the period when the altitude of periapsis was being rapidly decreased (8 through 16 December). The corresponding observed atmospheric densities (in grams per cubic centimeter) are shown on the right of Fig. 1.

Composition models were generated consistent with the observed altitudinal variation of atmospheric density, an exospheric temperature of 350 K being assumed (*6*). Conditions at 45 km were assumed to be the conditions at the temperature minimum in the Dickinson-Ridley terminator model (solar zenith angle 90°) (*7*). The $n(O)/n(CO)$ ratio was assumed to equal one at the turbopause (*6*). For a 124-km turbopause, the resulting profiles of $n(O)$, $n(CO)$, and $n(CO_2)$ (per cubic centimeter), which fit the observed density variations, are shown by the dashed lines on the left of Fig. 1, and the resulting total density (in grams per cubic centimeters) is shown by the solid line on the right.

This drag model gives a mixing ratio of $n(O)/n(CO_2)$ of 0.023 at 124 km where the eddy diffusion coefficient is estimated to be 10^7 cm^2/sec. This 124-km turbopause model gives the following number densities at 144 km: $n(CO_2) = 3.5 \times 10^9$, $n(O) = 1.8 \times 10^9$, and $n(CO) = 4.7 \times 10^8$. On the other hand, if the turbopause is assumed to be 144 km, the following number densities are required at 144 km

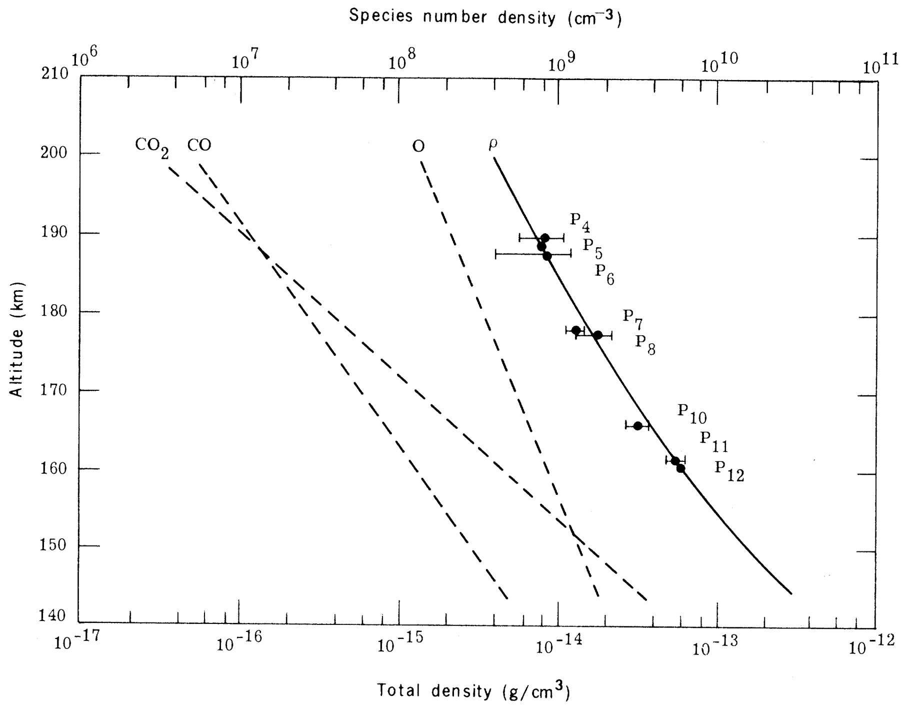

Fig. 1. Variation of density (solid line, bottom scale) and composition (dashed lines, top scale) of the Venus upper atmosphere model with exospheric temperature of 350 K, turbopause at 124 km, and mixing ratio of O/CO_2 of 0.023 and of O/CO of 1 at the turbopause. Tracking error bars ($1\ \sigma$) are shown for the drag data points when errors exceed 2 percent. The *P* numbers represent the daily periapsis number from 8 to 16 December 1978.

to fit the observed total densities: $n(CO_2) = 2.5 \times 10^9$, $n(O) = n(CO) = 1.5 \times 10^9$. If one assumes a 144-km turbopause, the eddy diffusion coefficient exceeds 10^9 because of the low densities. For the range of assumed turbopauses between 124 and 144 km, in order to fit the observed density profile atomic oxygen must be the major species above 160 km and the mixing ratio $n(O)/n(CO_2)$ at 144 km is between 0.5 and 0.6. Mixing ratios are insensitive to assumed constant values of C_D, m, or S. If the assumed exospheric temperature is lowered, the required mixing ratio at 144 km increases. Decreases of density with time during this 8-day interval could result in an overestimate of scale height and mixing ratios, but data clustered near 188 km, 177 km, and 161 km do not show evidence of such a temporal variation. Furthermore, a comparison of preliminary measurements of the orbiter neutral mass spectrometer of $n(CO)$ and $n(CO_2)$ from 7 and 8 December 1978 (*8*) indicate that if the density of CO plus CO_2 is substracted from the drag-determined total density, the oxygen values deduced near 179 km are within 25 percent of the 124-km turbopause drag model and within 10 percent of the 144-km turbopause drag model.

The high mixing ratio at 144 km may be the result of a low turbopause or circulation toward the nightside causing a buildup of atomic oxygen (*7, 9*) similar to the winter enhancement of atomic oxygen in Earth's atmosphere (*10*). A low turbopause altitude and a correspondingly low eddy diffusion coefficient would allow hydrogen to reach higher concentrations in the exosphere than has been observed unless a very effective nonthermal escape mechanism exists (*11*). An effective nonthermal escape mechanism for hydrogen could imply a major depletion of H_2O over geologic time (*12*). The high atomic oxygen concentrations may lead to significant exospheric cooling through vibrational and rotational excitation of CO_2 and may partially account for the cool exosphere (*7*).

The arguments of Bauer and Hartle (*13*) indicate that previously observed electron densities are not inconsistent with high concentrations of atomic oxygen when compression of the ionosphere by the solar wind is taken into account. Observations of 1304 and 1356 Å emissions are also not inconsistent with the high atomic oxygen concentrations (*14*).

It is of interest to compare total observed densities with various atmospheric models. The Kumar-Hunten model for 350 K (*6*) gives total densities which are a factor of 15 greater at 160 km and a factor of 4 greater at 190 km than indicated by the drag-measured densities. However, that model is consistent with the atomic oxygen concentrations we have calculated. The NASA model 1 (*15*) is higher by a factor of 4.5 at 160 km and

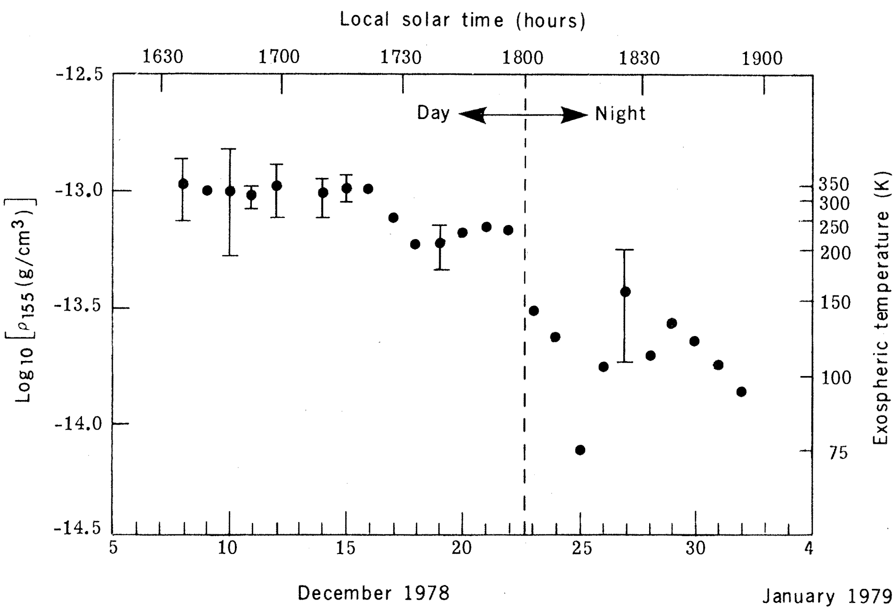

Fig. 2. Variation of atmospheric density normalized to 155 km and inferred exospheric temperatures based on the model of Fig. 1. Tracking error bars (1 σ) are shown when errors exceed 2 percent.

3.9 at 190 km than the observed densities. The Dickinson-Ridley terminator model (solar zenith angle, 90°) (*6*) is 0.8 of the drag model near 160 km. The Mayr model (*9*) is a factor of 4 denser than the drag model at 160 km.

During the period 17 December 1978 through 1 January 1979, the effective altitude of measurement remained within 4 km of 155 km. As a result, during this period vertical structure could not be investigated. However, by normalizing all the data to an altitude of 155 km, temporal variations could be studied. To normalize the data to a fixed altitude, the exospheric temperature of the 124-km turbopause model was allowed to vary.

The resulting atmospheric densities and inferred exospheric temperatures consistent with the drag measurements are shown in Fig. 2. The date and corresponding local solar time of the measurements are also shown. The effect of 16 tracking errors is indicated. The most remarkable feature in this figure is the sharp drop in densities and inferred temperature between 22 and 23 December at exactly the local solar time of the evening terminator. After the sharp drop (over only 6 minutes of local solar time) inferred exospheric temperatures remained below 200 K and averaged 118 K. If one considers that the boundary condition temperature at 115 km was 149 K, this low mean temperature at 155 km would not suggest a rise in temperature with altitude characterisitc of a planetary thermosphere or, in other words does not give evidence of a nighttime thermosphere. Apparently dynamical, chemical, and radiation processes on Venus are not capable of maintaining a significant positive temperature gradient above 115 km after sundown.

Solar activity variations may play an indirect role in varying nighttime conditions. A sharp drop in solar proton peak speed from 730 to 380 km/sec occurred between 22 and 25 December (*16*) during the period of largest change in atmospheric density and inferred temperatures. During that period densities at 155 km dropped by a factor of 8.7. Furthermore, on the basis of provisional 10.7 cm solar flux received at Earth, minimum values in the direction of Venus should have occurred on 25 December, the day of minimum inferred exospheric temperatures. Although solar activity variations may indirectly affect the nightside of Venus, the sustained low densities and inferred temperatures are indicative of the diurnal variation.

The "nighttime" (1802 to 1901 local solar time) average temperature of 118 K inferred from the drag data is in good agreement with Lyman α measurements of exospheric temperature from Mariner 5 which indicate a temperature of 150 $\pm$ 50 K at solar zenith angles greater than 90° (*17*). On the dayside, all of the inferred exospheric temperatures determined from the drag data exceeded 200 K and the average value for the period 8 through 22 December was 297 K, in agreement with preliminary estimates of 275 to 350 K exospheric temperature from various Pioneer Venus experiments (*18*).

These first satellite drag measurements have thus yielded substantial new information concerning the nature of the upper atmosphere of Venus. The high atomic oxygen concentrations detected may be indicative of a low eddy diffusion coefficient. A low eddy diffusion coefficient suggests that the low hydrogen concentrations in the Venus exosphere must result from nonthermal escape of hydrogen. This in turn could cause large depletions of H_2O over geologic time. The low exospheric temperatures on Venus may also be partially due to the higher atomic oxygen concentrations providing increased excitation and radiative cooling of CO_2. Our evidence indicates that dynamical, chemical, and radiation processes on Venus are not capable of maintaining a nighttime thermosphere. The disappearance of the thermosphere apparently occurs very near the evening terminator. There are indications that the neutral upper atmosphere may respond significantly to solar activity and solar wind variations.

G. M. KEATING
R. H. TOLSON
NASA Langley Research Center, Hampton, Virginia 23665
E. W. HINSON
Old Dominion University Research Foundation, Norfolk, Virginia 23508

References and Notes

1. For example, U.S. Standard Atmosphere, 1962; U.S. Standard Atmosphere Supplements, 1966; and COSPAR International Reference Atmospheres.
2. G. Keating, *Space Sci. Rev.* **20**, 520 (1977).
3. D. King-Hele, *Theory of Satellite Orbits in an Atmosphere* (Butterworths, London, 1964), p. 123, equation 7.27.
4. J. A. Mullins, G. M. Keating, D. S. McDougal, E. J. Prior, *NASA Tech. Note D-3432* (1966).
5. The orbital elements were supplied by R. Jacobson of Jet Propulsion Laboratory, Pasadena, Calif.
6. S. Kumar and D. M. Hunten, *J. Geophys. Res.* **79**, 2529 (1974).
7. R. E. Dickinson and E. C. Ridley, *Icarus* **30**, 162 (1977).
8. Information supplied by H. Niemann of Goddard Space Flight Center.
9. H. G. Mayr, I. Harris, R. E. Hartle, W. R. Hoegy, *J. Geophys. Res.* **83**, 4411 (1978).
10. G. M. Keating, J. A. Mullins, E. J. Prior, *Space Res.* **11**, 987 (1971); G. M. Keating, E. J. Prior, J. S. Levine, J. A. Mullins, *ibid.* **12**, 765 (1972); A. E. Hedin, H. G. Mayr, C. A. Reber, N. W. Spencer, *J. Geophys. Res.* **79**, 215 (1974).
11. S. C. Liu and T. M. Donahue, *Icarus* **24**, 148 (1975).
12. N. D. Sze and M. B. McElroy, *Planet. Space Sci.* **23**, 763 (1975).
13. S. J. Bauer and R. E. Hartle, *Geophys. Res. Lett.* **1**, 7 (1974).
14. G. J. Rottman and H. W. Moos, *J. Geophys. Res.* **78**, 8033 (1973); D. J. Strickland, *ibid.*, p. 2827.
15. Anonymous, "Models of Venus atmosphere," *NASA Spec. Publ. 8011* (1972).
16. Proton wind speeds were supplied by J. Wolfe of Ames Research Center.
17. D. E. Anderson, Jr., *J. Geophys. Res.* **81**, 1213 (1976).
18. *Avia. Week Space Technol.* (1 January 1979), p. 38.

19. We thank the following people for their contribution to this experiment: R. Jacobson, Jet Propulsion Laboratory, for providing and interpreting tracking and orbit data; J. Cowley and J. Dyer, Ames Research Center, for assistance in the early postencounter phase; J. W. Nicholson, Old Dominion University, for analysis support; and A. Seiff, Ames Research Center, for helpful review comments.

16 January 1979