Venus: Density of Upper Atmosphere from Measurements of Drag on Pioneer Orbiter

Abstract. *Measurements of the changes in orbital period of the Pioneer Venus orbiter have yielded estimates of the density of the upper atmosphere of Venus at altitudes in the range from 150 to 200 kilometers. At the lower limit of this range, the density on the dayside of the terminator exhibits a temporal variation of amplitude near 4 × 10^{-14} gram per cubic centimeter about a mean of approximately 1.4 ×10^{-13} gram per cubic centimeter. The variation appears oscillatory, with a 4- to 5-day period, but barely one cycle was observed. The density on the nightside of the terminator, sampled in the same 150-kilometer altitude range, fluctuates about a smaller mean of approximately 4 × 10^{-14} gram per cubic centimeter. The density between the altitudes of 150 and 200 kilometers, sampled only on the dayside of the terminator, imply a scale height of between 15 and 20 kilometers. The interpretation of this estimate is uncertain, however, in view of the measurements at the different altitudes having been made at different times and, hence, at different values of solar phase.*

The Pioneer Venus orbiter (PVO) has provided the first opportunity to exploit satellite-drag measurements to explore the atmosphere of another planet. Such measurements have been used with success in the past for the study of the upper atmosphere of Earth (*1*).

The atmosphere of Venus has been causing noticeable changes in the orbital period of the PVO since its periapsis was lowered on 7 December 1978 to an altitude of approximately 200 km (*2*). Subsequent decreases in the periapsis altitude, largely completed on 16 December, have since kept this altitude in the range 149 to 156 km.

The PVO is essentially a spinning cylinder (5 rev/min) with a set of thrusters that are occasionally used to adjust its orbit and spin. Most of the characteristics of the spacecraft and its orbit, pertinent for the inference of the density of the upper atmosphere, are given in Table 1.

The orbit of the PVO about Venus is determined from analysis of the tracking data that consist of the (two-way) Doppler shifts of the S-band radio signals transmitted to, and transponded by, the spacecraft (*3*). This analysis allows the orbital properties to be determined with substantially higher accuracy than indicated in Table 1. However, except in the determination of the (variable) orbital period, such accuracy is not required for our present purposes.

Because of the large eccentricity of its orbit, the PVO is sensitive to the air density only in the vicinity of periapsis which it samples approximately once per day. The main effects of this drag are to decrease the orbital period and the eccentricity; in the analysis given here, only the former is considered. These changes in orbital period are simply related to the density and scale height of the atmosphere at periapsis. With the variation of density with altitude approximated by an exponential, one obtains the following useful expression (*4*) for ΔP, the change in the orbital period due to air drag during one periapsis passage:

$$\Delta P = -6\pi\left(\frac{\pi}{2}\right)^{1/2} C_D \frac{A}{M} \rho H^{1/2} (GM_♀)^{-1/2} a^2 \left[\frac{(1+e)^3}{e(1-e)}\right]^{1/2} \simeq -4.6 \times 10^{13} \rho (H/10 \text{ km})^{1/2} \text{ g}^{-1} \text{ cm}^3 \text{ sec} \quad (1)$$

where, in addition to the quantities defined in Table 1, C_D denotes the drag coefficient, G the universal constant of gravitation, $M_♀$ the mass of Venus, and ρ and H the density and scale height, respectively, of the atmosphere at periapsis. In the third line of Eq. 1, we evaluate all quantities which remain virtually constant over the total span of the observations. We use $C_D = 2.4$ as a nominal value (*5*). Equation 1 indicates that from a single determination of ΔP we can infer only the product $\rho H^{1/2}$.

Each value of ΔP is inferred by comparison of the orbital period determined from data obtained before a periapsis passage with one determined from data obtained after such a passage. Each orbit determination utilizes data that span at most the interval from 1 hour after peri-

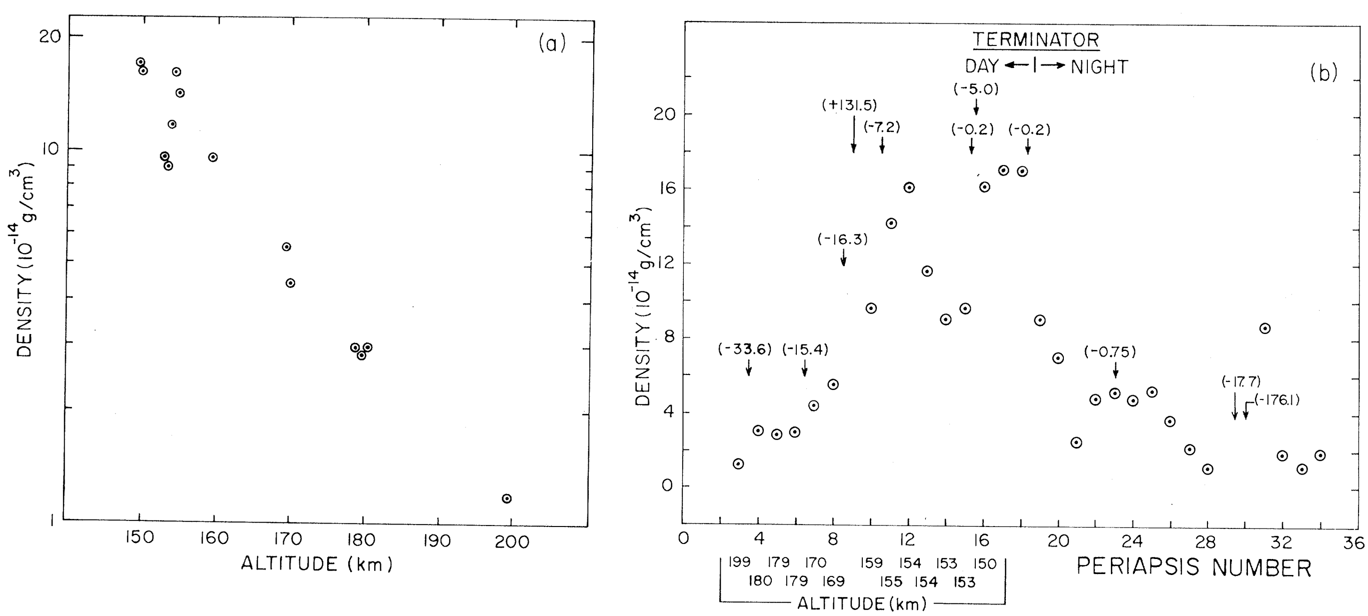

Fig. 1. (a) Density of the upper atmosphere of Venus as a function of altitude (*2*), inferred from the effects of drag on the Pioneer Venus orbiter. Only data obtained with periapsis on the dayside of the terminator are shown. See text for relevant factors used in conversion of estimated changes in orbital period to air density. (b) Density of the upper atmosphere of Venus shown as a function of time. The arrows signify the epochs of thruster activity; the numbers in parentheses above these arrows indicate the estimated change in orbital period, in seconds, due to the thrusting. See Table 1 for conversion of periapsis numbers to epochs and to values of Sun-Venus-periapsis angles (solar phase). The periapsis altitude is given below the periapsis number for the early orbits. During the later orbits, the altitude changed smoothly in the range 149 to 156 km.

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Table 1. Spacecraft and orbit characteristics. The symbol N is the number of periapsis passage; $N_0 = 3$ and corresponds to 7 December 1978, 14 hours 31 minutes 44 seconds. Each epoch is the Universal Time, Coordinated (U.T.C.) of the event as observed on Earth, minus the Earth-Venus light propagation time, τ; $\tau \cong 185 + 3.4\ (N - N_0)$ seconds. The Venus (body-fixed) coordinates for latitude and longitude are referred to the spin vector of Venus adopted by the Pioneer project [see (*12*)].

Spacecraft mass (M)	$\cong 362.17 - 0.03\,(N - N_0)$ kg
Spacecraft area projected onto the plane normal to the orbital velocity at periapsis (A)	$\cong 6 \times 10^4\ \mathrm{cm}^2$
Angle between spacecraft spin axis and velocity vector at periapsis	$\cong$ 24 degrees
Semimajor axis of orbit (a)	$\cong 3.96 \times 10^4$ km
Period of orbit (P)	$\cong$ 1 day 8.4 minutes
Eccentricity of orbit (e)	$\cong$ 0.843
Inclination of orbit with respect to equator of Venus	$\cong$ 105 degrees
Latitude of periapsis	$\cong$ 17 degrees
Longitude of periapsis	$\cong 167.2 + 1.5\,(N - N_0)$ degrees
Sun-Venus-periapsis angle	$\cong 66.3 + 1.6\,(N - N_0)$ degrees
Time of periapsis passage	$\cong$ 14 hours 31 minutes 44 seconds + (1 day 8.4 minutes) $(N - N_0)$

apsis to 1 hour before the next periapsis. Data obtained near periapsis are omitted because the theoretical model that is used, although taking into account solar gravitational and sunlight-pressure perturbations, ignores the acceleration due to air drag and omits all but the central force term in the gravitational potential of Venus. These omissions have no appreciable adverse effect on the accuracy with which ΔP is estimated. However, some orbit determinations involve only the tracking data obtained either in the interval from 1 hour after periapsis to just before the onset of thruster activity, or in the interval from just after the completion of thruster activity to 1 hour before the following passage of the spacecraft through periapsis. For such cases, the accuracy of the estimates of ΔP may be impaired more significantly (*6*). In all cases, the changes in orbital period are corrected for the effects of perturbations other than air drag before ΔP is estimated.

The magnitudes of the values obtained for ΔP range from about 0.6 to 8.3 seconds for the observations discussed here; the uncertainty in each value is estimated to be a few tenths of a second or less, except perhaps for those values obtained for periapsis passages that occurred near times of significant thruster activity (*6*).

For all of the data, the estimates of density were obtained with H set at a nominal value of 8 km. For the lower part of the altitude range of interest here [about 5 km above the nominal turbopause altitude of 144 km (*7*)], this value for H corresponds to an atmospheric temperature of about 350 K for the predominantly carbon dioxide composition there; for the upper part of the 50-km altitude range spanned by the satellite-drag measurements, the composition is predominantly atomic oxygen (*8*), and a temperature of about 130 K corresponds to H = 8 km. Although the inferred values of air density depend only on the square root of the scale height, use of a constant scale height for the entire altitude range covered here does introduce some error in these estimates of ρ. From Fig. 1a, for the data obtained early, when periapsis occurred on the dayside of the terminator, one can infer a value of between 15 and 20 km for the average scale height. But, since the different altitudes were sampled at different times and, consequently, at different values of solar phase, scale heights cannot be estimated reliably from the values of ΔP alone. Values for scale height as a function of altitude and time are, however, being obtained from other Pioneer experiments and can be used to reanalyze the values of ΔP to determine more accurate values of air density. For the present analysis, overall, a typical uncertainty of an estimated value of ρ is about 50 percent; however, the correlation of the errors in the estimates for neighboring points should be quite high, except possibly in the vicinity of epochs of significant thruster activity.

These difficulties notwithstanding, the main conclusion from inspection of all the data is clear: The data are incompatible with any model atmosphere that is time-invariant. For interpretation of this result, the estimates of density are displayed as a function of time in Fig. 1b. This representation exhibits the time variation, or, perhaps more relevantly, the variation with solar phase (*9*). The data obtained in the vicinity of a 150-km altitude with periapsis on the dayside of the terminator show an undulatory pattern which resembles a cycle of an oscillation with a 4- to 5-day period. The mean density for this undulation is about 1.4×10^{-13} g/cm^3 and its amplitude about 4×10^{-14} g/cm^3. On the nightside of the terminator, the density in this altitude range dips down nearly fourfold to a mean of about 4×10^{-14} g/cm^3 and shows somewhat larger fractional variations (*10*).

The density variations on the dayside are intriguing not only because of their possible oscillatory nature, but also because the apparent period is, perhaps coincidentally, near the 4-day value observed for the rotation period of the upper atmosphere of Venus (*11*). To understand better the possible nature and causes of this undulation, one needs more relevant data and a detailed study of the deposition and transport of energy within the atmosphere. One must also consider the possibility that we are observing a longitudinal wave pattern in the vicinity of the dayside of the terminator. However, there has not yet been time even to compare this pattern with the results obtained from other relevant Pioneer experiments or, for example, to seek correlations of it with variations in the ultraviolet and solar wind fluxes at Venus.

In summary, it is clear from the Pioneer data that for Venus, as for Earth, the upper atmosphere is a dynamic entity, rich with phenomena that await discovery and explanation.

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References and Notes

1. See, for example, L. G. Jacchia, J. W. Slowey, I. G. Campbell, *Planet. Space Sci.* **21**, 1835 (1973).
2. The reference radius for Venus is 6052 km, adopted by the Pioneer project for consistency in the computation of altitude.
3. See, for example, W. G. Melbourne, *Sci. Am.* **234** (No. 6), 59 (1976).
4. See, for example, T. E. Sterne, *An Introduction to Celestial Mechanics* (Interscience, New York, 1960), p. 157.
5. Laboratory work would be useful to evaluate C_D for both a carbon dioxide and an atomic oxygen atmosphere. G. Keating (personal communication) indicates that such laboratory experiments to measure C_D for CO_2 are planned at the NASA Langley Research Center.
6. The times of occurrence of periapsis passages are also estimated in the analysis, and the results can be compared with the corresponding estimates from the radar altimeter [G. H. Pettengill, P. G. Ford, W. E. Brown, W. M. Kaula, C. F. Keller, H. Masursky, G. E. McGill, *Science* **203**, 805 (1979)] for N = 4 through N = 13 (see Table 1 for definitions). The two sets are found to agree to within a few tenths of a second, except for N = 9 and N = 10 for which the altime-

ter yields values larger by 3 seconds for the former and smaller by 3 seconds for the latter. These differences, which have not yet been resolved, correspond to the interval during which the most significant thruster activity (the reduction of orbital period by 0.02 hour) took place.
7. H. B. Neimann, R. E. Hartle, W. T. Kasprzak, N. W. Spencer, D. M. Hunten, G. R. Carignan, *Science* **203**, 770 (1979).
8. The scale height, H, is related to the absolute temperature, T, by $H = RT/\mu g$, where R is the universal gas constant, μ is the mean molecular weight, and g is the local acceleration of gravity.
9. Conversion to solar phase (that is, Sun-Venus-periapsis angle) as the independent variable can be accomplished easily with the use of the data in Table 1.
10. The value of density for periapsis No. 31 (see Fig. 1b) may be significantly in error because of the effects of the thruster activity that just preceded this epoch.
11. C. Boyer and H. Camichel, *Ann. Astrophys.* **24**, 53 (1961); B. C. Murray *et al.*, *Science* **183**, 1307 (1974).
12. I. I. Shapiro, W. M. DeCampli, D. B. Campbell, *Astrophys. J.*, in press.
13. All determinations of ΔP were made from analysis of the radio tracking data by the Pioneer Venus orbiter navigation team at the Jet Propulsion Laboratory, headed by one of us (W.E.K.); no tracking data have yet been received for analysis by the Pioneer celestial mechanics experimenters. This report describes one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7- 100 sponsored by NASA. The experimenters at the Massachusetts Institute of Technology were supported in part by contract NAS2-9483 with the NASA Ames Research Center.

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Ultraviolet Spectroscopy of Venus: Initial Results from the Pioneer Venus Orbiter

Abstract. *Ultraviolet spectroscopy of the Venus cloud tops reveals absorption features attributed to sulfur dioxide in the atmosphere above the cloud tops. Measurements of scattered sunlight at 2663 angstroms show evidence for horizontal and vertical inhomogeneities in cloud structure. Images of the planet at SO_2 absorption wavelengths show albedo features similar to those seen at 3650 angstroms from Mariner 10. Airglow emissions are consistent with an exospheric temperature of ~ 275 K, and a night airglow emission has been detected, indicating the precipitation of energy into the dark thermosphere.*

The Pioneer Venus orbiter carries an ultraviolet spectrometer mounted with its line-of-sight offset 60° from the south-pointing spin axis. The instrument is a 125 mm, *f*/5 Ebert-Fastie design with a Cassegrain telescope and two detectors, sensitive from 1100 to 2000 Å and from 2000 to 3400 Å, respectively. The spectral resolution is 13 Å; further details have been described (*1*). The instrument operates both in a spectrometer mode, with its diffraction grating scanning, and in a photometer mode, with the grating fixed. We report here preliminary results concerning cloud spectroscopy, scattering, and imaging; day and night airglow emissions; and the atomic hydrogen corona.

Spectroscopy of the cloud layer is attempted only near periapsis, when changes in the illumination, emission, and phase angles during the motion of the diffraction grating are minimized. The ratio of two spectra obtained on different orbits, but with similar observing geometries, is shown in Fig. 1. Their ratio is dominated by two broad absorption features near 2100 and 2800 Å, attributable to the presence of SO_2 in the atmosphere above the cloud tops. If the control spectrum (from orbit 7) is assumed to contain no SO_2, then the depth of the absorption in the 2650 to 2800 Å region implies the presence of about 1×10^{17} cm^{-2} SO_2 in the spectrum from orbit 4. This column density is within the range reported by Barker (*2*). We observe both spatial and temporal variations in this phenomenon.

Fig. 1 The ratio of a cloud spectrum taken near the equator on orbit 4 to one taken near 60°N on orbit 7. The optical angles for the two spectra were very similar. The two broad absorption features centered near 2100 Å and 2800 Å are well matched by broad maxima in the absorption cross section of sulfur dioxide.

Figure 2 compares the reflectivity at 2663 Å, measured on a trace across the cloup tops near periapsis on orbit 3, with a scattering model. The model contains a homogeneous sulfuric acid cloud (*3*) overlain by 5 mbar of clear CO_2, and also takes account of the relevant geometric and instrument parameters and of the solar flux. Other traces are best fitted by variations of this model; for example, one including an absorbing layer (*4*) chosen to be consistent with measurements of the net solar flux within the clouds (*5*). We conclude that existing cloud structure models based on measurements at wavelengths > 3000 Å are generally compatible with our data, and that the evidence prior to the Pioneer Venus mission for vertical and horizontal structure inhomogeneities is similarly confirmed.

Images of the planet can be constructed by treating the instrument (in its fixed-grating mode) as a spin-scan camera, in the manner of the Pioneer 10 and 11 polarimeter experiments. Two such images of the southern part of Venus, viewed at half phase on orbit 8, are shown in Fig. 3. These images have been processed to show both the isophotes on the sunlit disk and the weak signal from the dark disk and limb (see below). Our simple rectification procedure presents the planet as it would be seen from 30°N ecliptic latitude. In Fig. 3, the equator crosses the central meridian about one-half radius up from the southern limb and intersects the eastern and western limbs near the top of the images.

Images from several orbits show variable bright and dark features that are generally reminiscent of the markings seen at 3650 Å from Mariner 10 (*6*). On orbit 8, images of the sourthern half of the planet were made at both 2068 Å, where SO_2 absorbs, and at 3297 Å, where it does not (Fig. 3). The isophotes at 3297 Å are smoother than those at 2068 Å. This suggests that the albedo markings seen at 2068 Å show the presence of varying amounts of SO_2 above the scattering cloud layer; this could be due either to true variations in the SO_2 abundance or to variations in the pressure at the cloud tops.

Prominent emissions in the vacuum ultraviolet airglow spectrum occur at wavelengths associated with atomic hydrogen (1216 Å) and atomic oxygen (1304 Å and 1356 Å). Figure 4 compares a disk trace taken at 1304 Å within 1 minute of periapsis (195 km) on orbit 4 with models assuming an exospheric temperature of 275 K and 4 percent T_∞ at 140 km. The lower curve shows that resonance scattering of solar photons and photoelectron impact on T_∞ are together

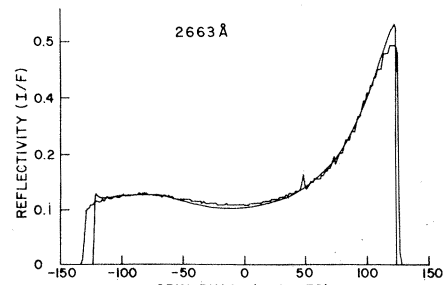

Fig. 2. A trace across the lighted disk taken at 2663 Å on orbit 3. The measurements (irregular line) are well matched by a model (smooth line), with the use of a homogeneous layer of sulfuric acid droplets underneath a 5-mbar layer of clear carbon dioxide.

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