emission, sometimes described as a cold ring, extending partly around a plateau of higher emission near the pole itself. This is the first observation of a low-emission region around a warmer plateau near the north pole, probably because of this year's favorable viewing geometry (*6*), although such features have previously been seen near the south pole (*2*, *4*).

The region of highest thermal emission on this day was on the nightside of the planet, at roughly 45°N. This sharply contrasts with the observations we made in April and May 1977 (*4*) at an identical solar phase angle, in which the region of intense emission was consistently on the sunlit side of the terminator. This striking change of appearance indicates that at least some of the major thermal features are not solar-fixed. In addition, since the features observed in 1977 did persist over the 26-day observation period, the time scale for the observed atmospheric thermal change must be on the order of several months, but less than the 19 months separating the observations. A solar component is observable, however, since postdawn infrared brightening begins at roughly 75° solar longitude in both data sets (although the warmest area shifted from north of the equator in May 1977 to somewhat south of the equator on 9 December 1978).

The north probe entered near the boundary of the subpolar cold ring and the warmer polar plateau, well within the region of the polar thermal feature characterized by rapid daily changes (*4*). The site of entry of the night probe was in one of the two well-developed warm regions near the antisolar meridian (the cooler of the two). The day probe entered near the boundary between the cold south polar region and the region of postdawn brightening, but definitely outside the cold polar zone. The large probe entered a stable area in the region of postdawn brightening, which extended roughly homogeneously from 30°N to 30°S latitude. The probes entered at least three distinct types of thermal provinces: the cold ring–warm plateau zone near the north pole, a region of nighttime thermal brightening, and the postdawn warming area. These areas were broadly representative of nearly all the types of thermal features observed on the hemisphere visible from Earth at the time of encounter, and should provide a good characterization of its major dynamical regions.

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5. The observations were centered at 1855 UT on 9 December 1978 (Julian date 2443852.29): the subearth Venus latitude was 0.6°S; subearth Venus longitude, 2.7°; subearth heliocentric longitude, 123.1°.
6. The subearth Venus latitude of 0.6°S was smaller than that during any previous observations and allowed nearly identical viewing geometries for both poles.
7. Supported by NASA contract NAS2-9127 from the Pioneer Project Office.

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Structure of the Atmosphere of Venus up to 110 Kilometers: Preliminary Results from the Four Pioneer Venus Entry Probes

Abstract. *The four Pioneer Venus entry probes transmitted data of good quality on the structure of the atmosphere below the clouds. Contrast of the structure below an altitude of 50 kilometers at four widely separated locations was found to be no more than a few degrees Kelvin, with slightly warmer temperatures at 30° south latitude than at 5° or 60° north. The atmosphere was stably stratified above 15 or 20 kilometers, indicating that the near-adiabatic state is maintained by the general circulation. The profiles move from near-adiabatic toward radiative equilibrium at altitudes above 40 kilometers. There appears to be a region of vertical convection above the dense cloud deck, which lies at 47.5 to 49 kilometers and at temperature levels near 360 K. The atmosphere is nearly isothermal around 100 kilometers (175 to 180 K) and appears to exhibit a sizable temperature wave between 60 and 70 kilometers. This is where the 4-day wind is believed to occur. The temperature wave may be related to some of the wavelike phenomena seen in Mariner 10 ultraviolet photographs.*

Each of the four Pioneer Venus probes carried instruments to measure the structure of the atmosphere, both below the cloud deck and above it to an altitude of at least 120 km (*1*). Below the clouds, the instruments were temperature and pressure sensors and accelerometers; above the clouds, accelerometers alone were used to define the structure from probe deceleration. A goal of the experiment was to measure the structure below the clouds with sufficient accuracy to define the thermal contrast available to drive the circulation.

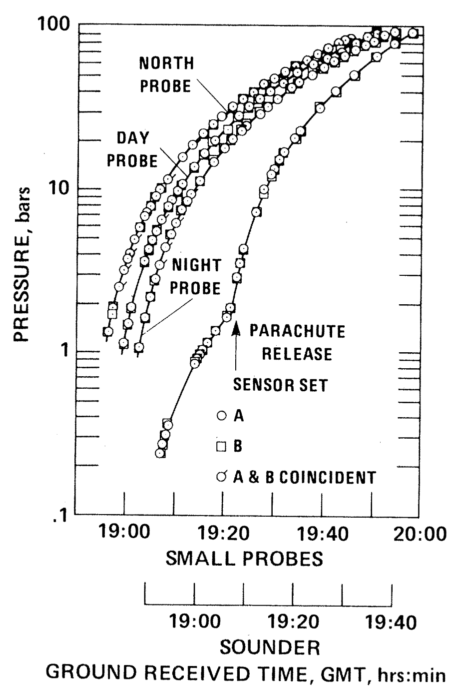
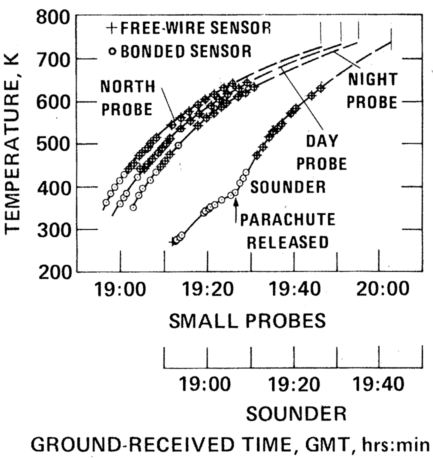


Fig. 1. Pressure data plotted as a function of ground received time. About one-tenth of the points are plotted. The slope discontinuity on the sounder marks the time of parachute release. The more rapid descent of the sounder after it began free fall caused it to land earlier than the three small probes. Its time axis has therefore been displaced. All landed between 19:43 and 19:56 GMT.

In this report we present preliminary results on lower-atmosphere structure, thermal contrasts, and atmospheric stability. We also give altitudes derived from the data and the temperature profile from 67 to 105 km derived from the first analysis of the entry data from the north probe.

In Fig. 1, pressure measurements made during the descent of the four probes are plotted against the time at which the data were received on Earth. Measurements have not yet been fully corrected. The circles and squares in Fig. 1 represent two independent sensor sets on each probe, which generally agree within about 1 percent. The data have been corrected for offset jumps that occurred at pressures above 20 bars, at which the lower range sensor diaphragms burst. Data corrected for the offsets agree well between the two sensor sets on each probe (the corrections for the two sets are independent and the jumps are not simultaneous), and we be-



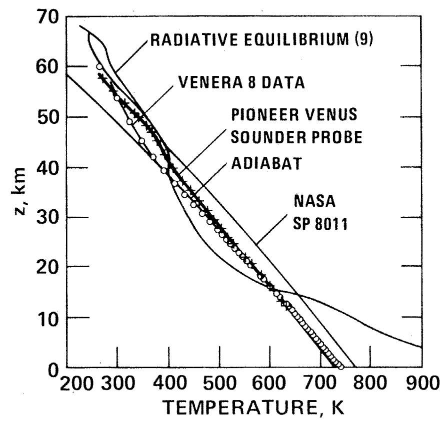


Fig. 2 (left). Temperature data plotted as a function of ground received time. The present sounder data extend to higher altitude, during parachute descent, than data from the small probes. Fig. 3 (right). Temperature profile with altitude, from the sounder probe, compared with Venera 8 data, an adiabat, a radiative equilibrium profile (9), and a preflight NASA model atmosphere. The Venera 8 entry site, like that of the sounder, was near-equatorial on the dayside of the morning terminator.

lieve they are valid within sensor accuracy below 40 bars and within about 1 percent of the reading above 40 bars.

The temperature data are similarly presented in Fig. 2. We expect temperatures to be defined up to the 240 K level when the data are complete. Dual sensors were again employed, one a free-wire resistance element exposed to atmospheric flow outside the probe boundary layer. While immersed in the clouds, this element was indicated to be partially shorted. We attributed this to collection of a conductive liquid film or droplets of an electrolyte such as sulfuric acid on the wire. Below the clouds, the droplets were gradually swept away or evaporated, and readings returned to close agreement (~ 1 K) with the second sensor, a wire raster (25 μm in diameter) mounted on the front surface of the sensor frame. This element was insulated by a thin glass coating and was not affected by the cloud droplets. The temperature profiles exhibit some waviness at cloud levels, which may be related to waviness reported around 55 km from Mariner 10 occultations (2).

Table 1. Probe altitudes as a function of time.

Time*	Altitude (km)			
	Sounder probe	Day probe	Night probe	North probe
18:53	57.9			
18:55	55.2			
18:58				43.1
19:00	50.0	48.8		38.7
19:04			47.2	
19:05	46.1	37.5	44.7	30.8
19:06	45.4			
19:10	35.3	30.2	35.3	24.7
19:15	26.1	24.6	28.7	19.8
19:20	19.6	19.8	23.3	15.7
19:25	14.3	15.5	18.7	12.0
19:30	9.5	11.4	14.8	8.8
19:35	5.4	8.3	11.2	5.8
19:40	1.8	5.4	8.0	3.0
19:42.9	0.0			
19:45		2.8	5.1	0.4
19:45.9				0.0
19:50		0.5	2.6	
19:51.2		0.0		
19:55.3			0.0	

*Greenwich mean time at which data were received on Earth. Altitudes listed are above the landing sites, which differ in elevation as indicated in Table 2.

All four probes lost temperature data at the 640 K level, which is at an altitude of about 12 to 14 km. On the basis of laboratory tests, it does not appear that this was due to the sensors. The cause has not been determined, but the data loss occurred simultaneously with anomalies in several of the other probe instruments and was accompanied by a buildup in ambient light emission seen in the nephelometers. Loss of temperature data below this level does not leave the surface temperatures in serious doubt (see below), but prevents us at present from making close comparisons to define the contrast at these lower levels.

To permit state properties to be expressed as a function of altitude (z), we have computed the probe altitudes above impact as a function of time by the assumption of hydrostatic equilibrium. Measured pressure (p) and temperature (T) were integrated in

$$z = \int_{p_0, T_0}^{p, T} \frac{RT}{g} \frac{dp}{p}$$

(g is the gravitational acceleration) with a gas constant (R) of 190.3 J/kg-K, corresponding to an atmospheric mean molecular weight of 43.7 (0.981 CO_2, 0.018 N_2, 0.0002 Ar, and 0.001 S) (3-5). Temperatures below the 640 K altitude level were extrapolated, first with time (Fig. 2) and then with altitude (Fig. 3) as independent variables. The uncertainty in surface temperature is probably no greater than about 5 K (6), and the resulting uncertainty in altitudes above 12 km is believed to be ~ 0.1 km. Overall altitude uncertainty is probably ~ 1 percent—for example, 0.5 km at 50 km—due primarily to the pressure uncertainty. Preliminary altitudes are given in Table 1.

Values of temperature and pressure at touchdown are given in Table 2. The pressure differences imply terrain elevation differences at the landing sites. These are given in Table 2, relative to the site of the sounder probe as the reference level. The three small probes landed at elevations within about ± 0.7 km of that of the sounder probe (7).

In Fig. 3 we compare the temperature profile of the sounder probe with Venera 8 data (8), with an adiabatic profile, and with a radiative equilibrium profile (9). Our measurements are very close to those of Venera 8 below an altitude of 25 km. Above that, they tend to diverge by a maximum of 30 K at the 45-km level.

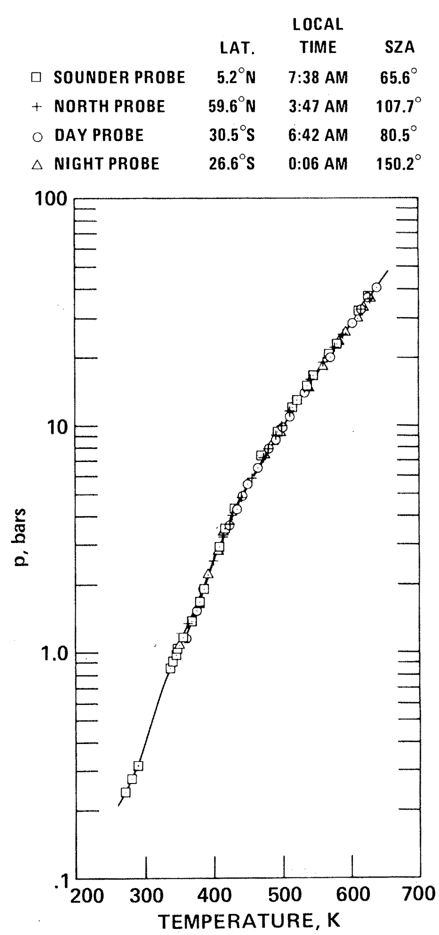


Fig. 4. Thermal structure comparison at the four probe entry sites.

This moderate divergence implies an important difference, however. The temperature lapse rate in our data above the 15-km level indicates that the atmosphere is stably stratified, whereas that in the Venera 8 data shows convective instability for altitudes below 35 km. This is highly significant in that a stable lapse rate requires that the near-adiabatic state of the atmosphere be maintained by the general circulation, rather than by local convective overturning. The general circulation would be expected to maintain a slightly subadiabatic lapse rate (*10*). Below about 20 km, our lapse rate is very close to adiabatic.

Above 40 km, the measured profile moves from near-adiabatic toward the theoretical profile for radiative equilibrium. The optically dense cloud (*11, 12*) is at an altitude (determined as above) between 47.5 and 49 km, at temperatures between 350 and 365 K (below the boiling point of water), and at pressures of 1.0 to 1.3 bars. Just above this cloud, at altitudes of 50 to 54 km, there is a region in which the temperature profile appears to be slightly unstable. This suggests that solar heat absorbed in the dense cloud generates convective motions just above this level.

The data comparison that bears on the central question of thermal contrasts at the four widely separated landing sites is given in Fig. 4, where measured temperatures are plotted against measured pressures. From remote sensing data (*13-15*) and from theoretical arguments (*16*), it had been expected that the contrasts would be small. They are, in fact, remarkably small. The small differences, however, have dynamical significance. It is too early to extract that significance as corrections still to be incorporated could move the curves by an amount on the order of 2 K. The temperatures appear to converge at pressures greater than 30 bars, as would be expected because of the large thermal inertia of the lower atmosphere, but they are never more than a few degrees apart, except at the highest altitudes for which we now have data from the small probe, between 1 and 2 bars. The temperatures measured by the two probes at ~ 30°S latitude are slightly higher than those of the sounder and north probes, as much as 6 K at the 1- and 15-bar levels, but appear to dip slightly lower (by ~ 1 K) above 30 bars (*17*). Above a pressure of 2 bars, the sounder temperatures are very close to those of the north probe; at lower pressures, the sounder is intermediate between the north and day probes.

From the preliminary data presented here, it appears that (i) large-scale planetary circulation is probably responsible for the subadiabatic lapse rate above 15 km to at least 30 km, and (ii) the transport of heat between equator and pole by the atmospheric circulation is efficient enough to reduce meridional temperature gradients to small values.

Table 2. Measured values at the planet surface.

Probe	Pressure (bars)	Temperature* (K)	Relative elevation† (km)	g (cm/sec^2)	Derived planet radius (km)
Sounder	90.3	731	0.0	886.1	6055‡
North	86.2	721	0.73	887.8	6049.2
Day	91.5	729	−0.21	889.2	6045‡
Night	94.5	732	−0.72	887.4	6050.6

*Extrapolated; use these values for magnitude only, not for contrast. †Relative to sounder landing elevation. ‡See text.

The data taken at higher altitudes, during entry, have been analyzed for only one probe, the north probe. Densities and the trajectory, defined by the measured decelerations and known initial conditions, are integrated over altitude with the assumption of hydrostatic equilibrium to define pressure. The equation of state then yields the temperature. From the initial entry conditions, which are not yet as well determined from tracking as they will be, we have obtained the preliminary temperature profile shown in Fig. 5, along with lower-atmospheric temperature profiles from two of the four probes. Figure 5 shows (i) a temperature level of 175 to 180 K from 95 to 105 km; (ii) structure suggestive of small-amplitude atmospheric waves, perhaps thermal tides; and (iii) a sudden downswing in temperature below 70 km, which, if supported by later analysis, indicates a large negative half-wave that must make its way back to about 260 K at 60 km. We are not yet confident of the reality of this wave, although it also occurs in the first analysis of the sounder entry data. It could be associated with the 4-day wind, which is believed to occur in this altitude region (*18*) or it could be evidence for the wave phenomenon alternatively used to explain patterns in the Mariner 10 ultraviolet photographs (*19*). The planetary wind can affect the derived temperature by adding to the velocity of the atmosphere relative to the probe, which in this altitude range is of the order of 1 to 3 km/sec. For wind velocities of 0.1 km/sec and the trajectory angle at 68.5°, as defined at present, the possible temperature effect appears to be only a few degrees Kelvin. Hence the indication is that a sizable temperature wave is present just above the clouds.

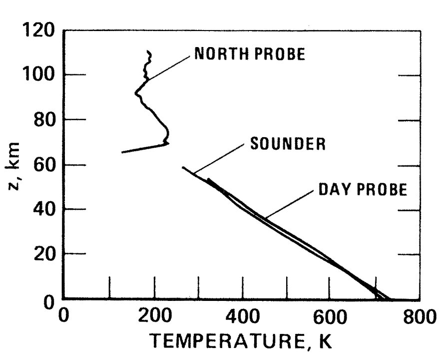


Fig. 5. Temperature variation with altitude in the atmosphere of Venus. The middle atmosphere shows a nearly isothermal region around 100 km, with small-amplitude waves. There is evidence of an apparent strong wave or an effect of the 4-day wind velocity in the profile between 60 and 70 km (see text). This feature appears near the altitude of the uppermost and strongest "inversion" in the Mariner 10 occultation temperature profile (*2*).

Accelerations measured during the descent period exhibited unsteadiness because of aerodynamic buffeting, which we anticipated and studied before the mission (*20*). The data indicate probe angles of attack randomly varying a few degrees around 5° for the sounder. For the small probes, angles near 1° were expected.

Mean values of axial acceleration measured just before touchdown are listed for the four probes in Table 2, and converted to planetary radii through the simple gravitation equation $R^2 = Gm_v/g$, where Gm_v, the product of the gravitational constant and the mass of Venus, is 324,883.8 km^3/sec^2. The radii defined by the north and night probes are plausible, 6049.9 ± 0.7 km, although the relative terrain elevation of the two probes is reversed, indicating that the radius measurement is uncertain by ~ 1.5 km. Angles of attack tend to increase the indicated radius, and we believe that this is the cause of the high radius obtained from the sounder. The small probe axial accelerations should be essentially unchanged from the values at zero angle of attack because of their small mean angle of attack. The low radius from the day probe probably indicates a sensor bias shift of $+0.0017g$. Sensor stability of the der was found to be excellent from a comparison of the z_1 and z_2 sensor data, which agreed to better than 0.1 cm/sec^2 (0.3 km radius) throughout the descent.

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6. Extrapolated surface temperatures are well supported by analysis of the near-surface pressure scale height.
7. The radius of Venus in the vicinity of the large probe landing site has been measured by ground-based radar and reported to be 6049.5 ± 0.5 km, near the mean planetary radius according to present data [D. B. Campbell, R. B. Dyce, R. P. Ingalls, G. H. Pettengill, I. I. Shapiro, *Science* **175**, 514 (1972)].
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17. At pressures above 10 bars, longitudinal temperature contrasts should be less than 1 K because of thermal inertia relative to solar heating rates (*9*). Hence the temperature contrasts in Fig. 4 above 10 bars are thought to be associated with the meridional direction. A balance in the meridional direction between the centrifugal force due to the mean zonal wind and the meridional pressure gradient, combined with the hydrostatic equation, gives
$$2\bar{u}\frac{d\bar{u}}{dz'}\text{ctn}\theta = \frac{R\,\partial\bar{T}}{H\,\partial\theta}$$
where $\bar{u}$ is the mean zonal wind, θ is colatitude, R is the gas constant for CO_2, H is a typical pressure scale height, $\bar{T}$ is the zonally averaged temperature, and $z' = -H \ln p$, where p is pressure A $d\bar{u}/dz'$ of 50 m/sec per 30 km would give meridional temperature gradients sufficient to create temperature differences of several degrees. Zonal wind profiles measured by Veneras 8, 9, and 10 are consistent with the boundaries of such regions being in the vicinity of 10 and 30 bars and possibly also near 1.5 bars [M. Ya. Marov, V. W. Avduevsky, V. V. Kerzhanovich, M. K. Rozhdestvensky, N. F. Borodin, O. L. Ryabov, *J. Atmos. Sci.* **30**, 1210 (1973); M. V. Keldysh, paper presented at the 19th COSPAR meeting, Philadelphia, 14 to 19 June 1976]. Figure 4 implies that temperature increases with latitude away from the equator up to some latitude, but then decreases toward the poles. Such temperature profiles have been seen in a numerical solution of the Venus circulation [R. E. Young and J. B. Pollack, *J. Atmos. Sci.* **34**, 1315 (1977)] when the mean zonal velocity has a latitudinal profile similar to that implied from the Mariner 10 ultraviolet observations, namely increasing away from the equator up to ≈ 45° latitude and then decreasing to zero at the poles [V. Suomi, *NASA Spec. Publ. SP-382* (1974)].
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16 January 1979

Preliminary Results of the Pioneer Venus Nephelometer Experiment

Abstract. *Preliminary results of the nephelometer experiments conducted aboard the large sounder, day, north, and night probes of the Pioneer Venus mission are presented. The vertical structures of the Venus clouds observed simultaneously at each of the four locations from altitudes of from 63 kilometers to the surface are compared, and similarities and differences are noted. Tentative results from attempting to use the data from the nephelometer and cloud particle size spectrometer on the sounder probe to identify the indices of refraction of cloud particles in various regions of the Venus clouds are reported. Finally the nephelometer readings for the day probe during impact on the surface of Venus are presented.*

A backscattering nephelometer instrument (*1*) was included in the experiments complement of each of the four Pioneer Venus probes (*2*). The objective of the nephelometer experiment (designated LN on the large sounder probe and SN on the other probes) was to investigate simultaneously the vertical structure of the clouds of Venus at four widely separated locations. A secondary objective was to attempt to vertically document the source of atmospheric ultraviolet absorption in the atmosphere. Each of the nephelometer instruments functioned, and data were recorded from the time the instrument was deployed (window cover opening) at altitudes of about 65 km until probe impact on the surface of the planet, or, in the case of the day probe, until 64 minutes after impact. Although data pertinent to both of these objectives were obtained during the mission, only the data applicable to the first have been analyzed and presented here.

A curve of the backscatter cross section recorded as a function of altitude above the surface of Venus during the descent of the sounder probe is shown in Fig. 1. The data reported for this probe (and also that for the high-altitude phases of early descent for the other probes) contain gaps as a result of a delay caused by the effort required for reprocessing and reconstituting data tapes from the receiver stations. These data will be available later. The altitude scales shown in each of the figures are only crudely known at the time of this report, but will be modified as improved trajectory data become available. Typical signals obtained were greater than 20 data elements (granular elements), whereas average noise was a fraction of one such unit. Thus, even many of the minor fluctuations shown in the data are believed to be real. Because below about 45 km the signals from each probe tended to be small, usually below the limit of instrument sensitivity [which confirmed the results of Marov *et al.* (*3*) that the clouds have a well-defined lower boundary overlying a relatively particulate-free atmosphere down to the surface], the data below about 45 km have not been plotted on this curve or on corresponding curves for the data from other probes. These will be discussed in subsequent reports. The magnitudes of the main cloud signals measured were also similar to those of Marov *et al.* (*3*).

The structure within the clouds is characterized by four distinct regions (Fig. 1). Region A, beginning at about 46.1 km, is made of narrow stratified layers (one 50 m, the other 200 m thick). Region B (maybe the only region that could really be called a "cloud") extends from about 47.4 to 49.4 km and is characterized by a strong maximum. Region C (about 49.4 to 56.0 km) is smooth over much of its extent. Region D (about 56.0 to above 62 km) is less smooth, and is considered different from region C by consideration of the large probe cloud particle size spectrometer (LCPS) data. The data from the highest altitude reported here are still far from the top of the cloud system.

The sparser data currently available from each of the other three probes are plotted in Fig. 2. The altitude intervals