Atmospheres of Earth, Mars, and Venus, as Defined by Entry Probe Experiments

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In 1963, it was proposed that small spacecraft be sent to Mars and Venus to define the structure of their atmospheres. The capabilities of such atmospheric probes were demonstrated by the Planetary Atmosphere Experiments Test in the Earth's atmosphere in 1971. The techniques developed were subsequently applied in experiments on the Viking Landers at Mars in 1976 and at Venus on the four Pioneer Venus Probes in 1978. The Mars and Venus results made major contributions to the current working definition of these atmospheres. They yielded not only the first-order parameters of atmospheric structure, i.e., the profiles of temperature, pressure, and density with altitude, but also insights into some basic meteorological conditions in those atmospheres, such as atmospheric stability, the presence of waves and turbulence, and the evaluation of thermal contrasts on a global scale. This paper reviews the results obtained from these experiments and outlines the concepts and approaches employed.

Introduction

THIRTY years ago, knowledge of the atmospheres of Mars and Venus was comparable to our knowledge of the atmospheres of the remote outer planets today. Basic properties such as the pressure-temperature relationship, density scale height, and proportions of major constituents were poorly known. Around 1960, the surface pressure of Mars' atmosphere was believed to be ~80 mb, and that of Venus' was ~4 bar; this is in disagreement with present knowledge by factors of 12 and 1/25. The variation of atmospheric temperature with altitude, which is important to aerospace design because it determines density variation with altitude, was comparably uncertain. Mission studies for in situ exploration of these planets in the early 1960s included both unmanned and manned missions. They faced the problem that it was difficult to design entry vehicles and landers for use in poorly characterized atmospheres; yet, it seemed necessary to send vehicles into the atmospheres to determine their characteristics adequately.

Prior to 1960, information on planetary atmospheres was limited to what could be derived from Earth-based astronomy. Starting in 1964, spacecraft that flew by the planets conducted remote sensing experiments to answer basic questions about their atmospheres. Radio occultation[1] and microwave and infrared radiometry[2] techniques were employed to assess temperature and pressure magnitudes over limited ranges. These techiniques significantly advanced the definition of the atmospheres of Mars and Venus. (The radio occultation experiment on Mariner 4 determined correctly that Mars' surface pressure was about 6 mb. Earth-based spectrometry of the atmosphere had indicated that its CO_2 abundance was equivalent to about 5 mb surface pressure. It was thus indicated that the atmosphere was predominantly CO_2.) However, the remote sensing data required theoretical interpretation and were limited in vertical range and resolution. Verification was needed, with improved resolution and over wider ranges of altitude, both to satisfy basic scientific interest in the physics and chemistry of the atmospheres of these planets and for aerospace design purposes.

In 1963, it was proposed[3] that atmospheric probes be sent into the atmospheres of Mars and Venus to determine atmospheric structure and composition by in situ measurements. These probes were visualized as precursors to larger, more ambitious missions to follow. A key suggestion was that the structure of the upper atmosphere be determined from aerodynamic responses of the probe during hypersonic entry and that of the lower atmosphere from direct sensing during low-speed descent. Analysis indicated that the structure of both upper and lower atmospheres could be determined to a vastly improved level of accuracy.

A program of flight tests and analyses was initiated at NASA Ames Research Center to learn how best to achieve accurate atmospheric definition by use of such probes. (A review of this development activity and the concurrent debate over planetary mission selection is to be submitted for separate publication.[4]) The development period culminated in the test of a complete Earth's atmosphere probe, the Planetary Atmosphere Experiments Test (PAET) vehicle,[5] that was launched over the Atlantic from Wallops Island in 1971. It reached apogee at 400 km and was driven downward by a forth-stage rocket to enter the atmosphere near Bermuda at 6.6 km/s. The Earth's atmosphere from 85 km altitude to the surface was reconstructed accurately from the data transmitted. This demonstration of the capability of atmospheric probes helped gain acceptance for exploring the atmospheres of Mars and Venus with such techniques.

The first U.S. spacecraft to carry an atmosphere structure experiment to another planet were the Viking Landers in 1976.[6] The experiment defined the atmosphere of Mars far more accurately than it had previously been known, indicating, e.g., the stability of the atmosphere against overturning and the convective boundary-layer thickness. It also showed the presence of thermal tidal oscillations in the temperature structure, which was of interest for both meteorology and the design of entering spacecraft.

In 1978, the U.S. Pioneer Venus Mission sent four dedicated atmospheric probes and an orbiter to the planet Venus. The probes were directed to widely separated locations over the Earthward face of the planet in order to define the global and diurnal contrasts in the structure. The objective was to try

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to identify the processes responsible for Venus' high velocity, cloud level winds. The data also defined the atmospheric stability, showed the presence of gravity waves, located cloud boundaries, etc.[7]

In the 1980s, atmosphere structure experiments using accelerometers also were flown on a series of Space Shuttle missions. Although the Shuttle is clearly not an atmospheric probe, these measurements used the probe experiment approach to improve the definition of Earth's upper atmosphere and to demonstrate its variability.[8] Gravity waves (similar to those seen on Mars and Venus) were found to cause wavelike perturbations in the density profiles.

The Soviet Union was very active in sending probes to the terrestrial planets throughout the 1970s and 1980s, with noteworthy success at Venus. Results from the early missions have been described by Marov,[9] and the atmospheric structure results have been well summarized by Avduevskiy et al.[10] In this paper, we will concentrate on summarizing key results obtained from atmospheric probe experiments on the PAET, Viking, and Pioneer Venus missions and the measurement techniques employed.

Atmospheric Measurement Concepts

In order to effectively support the objective of defining the atmosphere for later spacecraft, atmosphere probes must sound the region of the upper atmosphere where spacecraft decelerate and not merely the parachute-descent region of the lower atmosphere. This is achieved by inverting the usual problem of entry vehicle analysis: Given the atmosphere and entry vehicle design, predict the performance variables such as the trajectory, heating, stability, etc. The inverted problem is: Given the vehicle and the entry performance, determine the atmosphere.[3,11]

With this approach, the measurement regime may be extended to as high an altitude as the atmosphere measurably affects the probe, typically into the upper atmosphere. Most important, this extends the measurement regime to include hypervelocity and low density flight conditions where direct sensing of pressure and temperature is infeasible.

The basic problem for the definition of atmosphere structure is the following: From the deceleration history of the probe, measured by on-board accelerometers from the sensor threshold down to parachute deployment, determine the structure of the atmosphere. The deceleration profile must define the atmospheric density variation not only with time, but also with altitude.

In principle, atmospheric characteristics other than the atmospheric structure can be obtained through the inverted problem approach. Examples are identification of the presence and magnitude of horizontal and vertical winds from measurement of the probe response to the winds, and identification and characterization of wave phenomena and atmospheric convection from probe responses. Such analyses have been performed to obtain insights into these phenomena in the atmospheres of Mars, from Viking data, and Venus, from Pioneer Venus data.

The analysis of the accelerometer record to define both the entry trajectory and the atmosphere has been described previously.[3,11,12] It will be outlined briefly, as will the treatment of descent phase data to define altitude and vertical velocity.

Analysis of Entry Phase Measurements

The key sensors of the entry phase are a set of three-axis accelerometers, aligned parallel and perpendicular to the probe axis of symmetry. In addition to their other functions, these sensors permit the probe angle of attack to be defined through the relation,

$$a_n / a_z = f(\alpha) \tag{1}$$

where a_n is the resultant lateral acceleration, a_z the axial deceleration, and $f(\alpha)$ is established from tests in ground facilities. The probe deployment design typically seeks to keep the angle of attack at entry small, e.g., <5 deg, by use of spin stabilization and control of tipoff disturbances. The Pioneer Venus Large Probe resultant angle of attack at entry into the atmosphere was measured by the lateral accelerometers to be <1.2 deg, damped to 0.1 deg at 80-km altitude, and remained below 0.2 deg to the end of the entry period. Thus, the probe axial deceleration was aligned with the drag force within close limits.

The ambient density of the atmosphere during entry is derived from the measured axial deceleration,

$$\rho = \left[-2(m/C_D A)(a/V^2)\right] \tag{2}$$

where m is the probe mass, C_D its drag coefficient, A the frontal or reference area, a the acceleration along the flight path (which is negative), and V the instantaneous flight velocity. Other than the acceleration and velocity, all parameters are known from preflight measurements, which include ground facility measurements to define C_D as a function of Mach number, Reynolds number, and angle of attack.[13,14] The ground facility calibration of the probe aerodynamics is an essential feature of the technique. Velocity is tracked during entry from its initial value, known at entry by deep space tracking, by integration of measured accelerations in the equations of motion (see, e.g., Refs. 3 and 12).

Equation (2) defines density as a function of time. To define its variation with altitude, altitude is determined by time integration of the vertical component of velocity,

$$z_i - z = \int_0^t V(\sin\gamma)\,dt \tag{3}$$

where z_i is the initial or threshold altitude and γ is the flight-path angle below horizontal. Since the planet surface is usually the desired altitude reference, it is necessary to join the entry phase to the descent phase data, in which altitudes are determined by a related technique from measured ambient pressures and temperatures.

This procedure defines density as a function of altitude in the upper atmosphere. Pressure at a given altitude may then be calculated by integrating measured densities in the equation of hydrostatic equilibrium,

$$p - p_i = \int_z^{z_i} \rho g\,dz \tag{4}$$

which equates pressure to the weight per unit area of the overlying atmosphere. Hydrostatic equilibrium holds quite generally in atmospheres. Only extreme dynamic activity in-

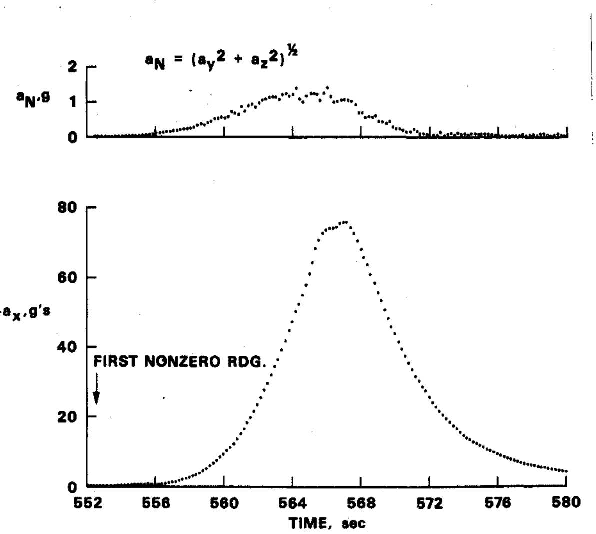
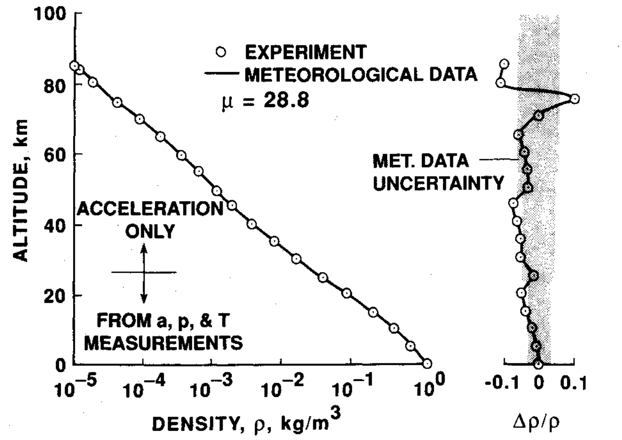
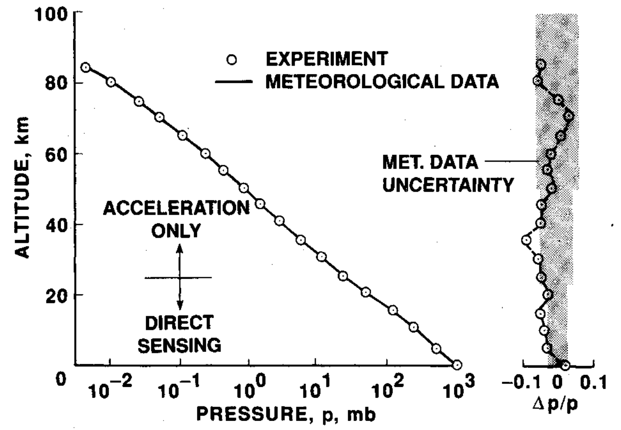


Fig. 1 Accelerations measured by the PAET probe during entry.



a) Density



b) Pressure

Fig. 2 Density and pressure profiles in Earth's atmosphere, derived from sensors on the PAET probe.

volving large atmospheric vertical accelerations can affect its applicability. Then, from p and ρ, the equation of state is used to determine the temperature profile of the atmosphere,

$$T = p\mu/\rho R_u \tag{5}$$

where R_u is the universal gas constant, and μ is the atmospheric mean molecular weight. Thus, the mean molecular weight is a required input to the determination of temperature. At Mars, it was provided by the data of the Upper Atmosphere Mass Spectrometer[15]; at Venus, it was provided by the data of the Orbiter Mass Spectrometer.[16]

Analysis of Descent Phase Measurements

The period of low-speed descent may be on a parachute or may be in free-fall, as it was for the Pioneer Venus Small Probes, the Large Probe in the deep atmosphere, and the PAET probe, all of which are discussed later. Descent velocities are in the low subsonic range, and the measurement set becomes primarily pressure and temperature as functions of time, supplemented by acceleration data. The pressures and temperatures, corrected for dynamic effects (typically quite small), are now used as inputs to the equation of hydrostatic equilibrium, Eq. (4), in the form,

$$z = \int_0^z dz = -\int_{p_0}^{p} (R_u T/\mu g)(dp/p) \tag{6}$$

to define altitude as a function of pressure. If the probe is still operating at impact on the planet surface, this level may be used as altitude reference for both the lower and upper atmospheres. (The 1-bar level is generally used for the giant gaseous planets, such as Jupiter.)

One more note is essential to establish the basis for the principal measurements that we have made in planetary atmospheres. That is to point out that, by expressing Eq. (6) in derivative form, with t as an independent variable, an equation for absolute velocity of probe descent is obtained,

$$w_p = dz/dt = -(R_u T/\mu g p)\, dp/dt \tag{7}$$

This provides the vertical velocity needed to make dynamic corrections to measured p and T in low-speed descent (iteration is required). It is also an essential input to the derivation of atmospheric vertical wind velocities.

In the following sections, we will present the results of the application of these techniques to the atmospheres of Earth, Mars, and Venus.

Measurements of the Atmospheres of Earth, Mars, and Venus

Earth's Atmosphere from the Planetary Atmosphere Experiments Test

PAET was conducted to simulate the entry of an atmospheric probe into the unknown atmosphere of another planet and test its capability for determining the atmosphere.[5] An instrumented probe was built as an in-house project of the Vehicle Environment Division at NASA Ames Research Center. It was launched by a Scout booster out of Wallops Island, Virginia; it passed over apogee at 400-km altitude; and it was driven downward by the fourth-stage booster into the atmosphere over the ocean near Bermuda at hypersonic speed (6.6 km/s or 21,600 ft/s). The probe was 1 m in diameter, had an ablating heat shield, and a spherical, ablating afterbody. The probe mass was 62 kg; the total instrument mass was 14 kg. The instruments carried were three-axis accelerometers, a spin gyro, pressure and temperature sensors, a mass spectrometer, and a shock-layer radiometer. The mass spectrometer and inlet system were provided by a team from Goddard Space Flight Center, led by Hasso B. Niemann, who also interpreted data from it.

To test the capability of the system to define the atmosphere under unfavorable circumstances, the spinning probe was programmed to enter the atmosphere with an angle of attack of 30 deg. The trajectory was tracked by radars to establish the trajectory state at entry and, within the atmosphere, to provide comparison data for the on-board trajectory reconstruction. Meteorological soundings were also taken for comparison purposes by use of sounding rockets, balloons, and falling spheres.

The principal deceleration pulses measured by the sensors in the PAET probe axis of symmetry a_x and normal to the axis of symmetry, a_N are shown in Fig. 1 (every second data point). Peak deceleration was 75.8 g in the x axis and ≈ 1 g resultant acceleration normal to the x axis. The latter peak occurred slightly earlier because amplitude of angle of attack was decreasing with time. The complete entry and descent period was about 5 min, of which only 28 s are shown here. In the remainder of the descent, a_x approached 1 g, and a_N approached zero.

The densities derived from these data are plotted against the derived altitudes in Fig. 2a and the pressures in Fig. 2b. The curves through the points are the independent meteorological data. Fractional differences are indicated at the right of each figure. For the most part, the deviations were within the uncertainty in the meteorological data, which also were not perfectly simultaneous with probe entry. (The sounding rockets went up 5 h before and 2 h after probe entry and showed atmospheric time dependence.) It was concluded in 1972 that the probe had measured the atmosphere within the accuracy with which it could be otherwise determined.

An important result of the experiment was the evaluation of its accuracy in defining the temperature profile. The results are shown in Fig. 3. Below 40 km, there were no significant differences from the meteorological data. Above that, the probe data agreed with the data from the two sounding rockets as well as the latter agreed with one another. It was clear that temporal variations were occurring. The probe data indicated a local inversion at 65 km, which had apparently moved downward a few km in 5 h, and had either disappeared or moved downward substantially 2 h later. These data demonstrated that upper atmospheric temperatures could be measured accurately from the deceleration of an entry probe.

To sum up other PAET results briefly, the shock layer radiometer[5,17] measured the bulk composition (0.8 N_2 and 0.2 O_2) within a few percent and fixed the CO_2 fraction of the atmosphere at 0.0003, in agreement with the known value. The mass spectrometer, however, found less than the known concentration of atmospheric oxygen. This was believed to be associated with the reaction of atomic oxygen with the stainless steel particles in the sintered inlet leak, used to reduce pressure from that in the shock layer. This negative result was valuable. It showed the criticality of inlet system design for mass spectrometers on entry probes.

The probe angle of attack at entry, measured by use of ratios of lateral to axial acceleration [Eq. (1)], was found to be 30 deg, as planned. Amplitude decreased during entry to about 1 deg at the time of peak deceleration, primarily as a result of increasing dynamic pressure. The angular motion was approximately a pure coning motion, as anticipated for the case of a spinning body with no angular disturbance at entry. This was an important verification of the expected, nearly constant resultant angle of attack during one or a few cycles of motion, which reduces the need for frequent sampling of accelerations.[5]

Mars Atmosphere from Viking

The two Viking Landers were the first U.S. spacecraft to enter the atmosphere of another planet. They represented a

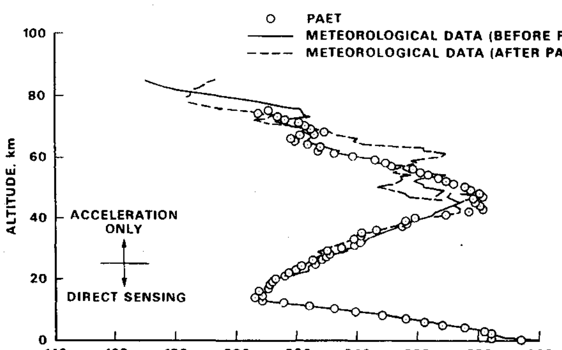


Fig. 3 Earth's atmospheric temperature profiles derived from PAET measurements: deceleration above 25 km and sensing by thermocouples below that.

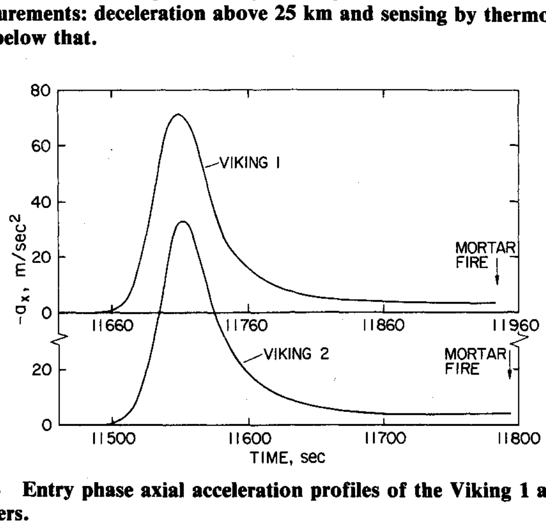


Fig. 4 Entry phase axial acceleration profiles of the Viking 1 and 2 Landers.

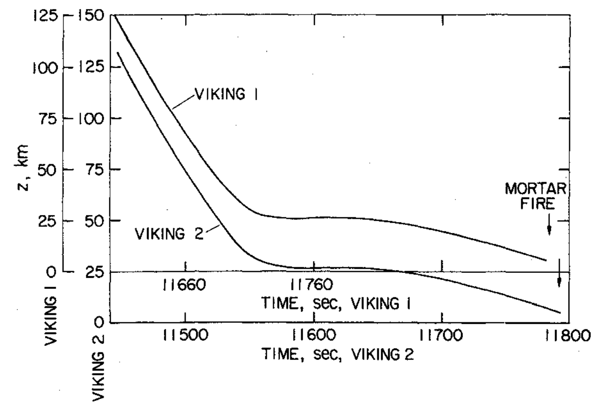


Fig. 5 Trajectories of the Viking Landers during high-speed entry. (Mortar fire indicates initiation of parachute deployment.)

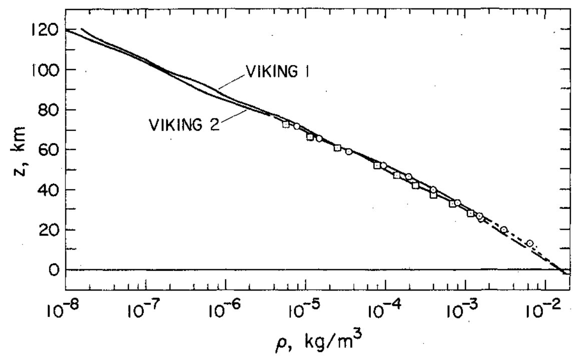


Fig. 6 Density structure of Mars' atmosphere, as defined by data from the two Viking Landers.

bold step in that, on this first entry mission, the Landers were large and complex and had an ambitious central goal, the search for life. Although the Viking Mission was not a dedicated atmospheric mission, the Atmosphere Structure Experiment was proposed and accepted as a key part of "Entry Science," which also included a mass spectrometer to determine composition of the upper atmosphere[15] and a retarding potential analyzer to make in situ measurements of the ionosphere.[18]

There were at that time outstanding questions to be answered concerning the atmosphere of Mars. Surface pressures were uncertain within the range of 4–10 mb (the range used in the engineering model atmospheres for Lander design), and a range of models was used for density and temperature profiles as well. (It is now clear that part of the range shown in earlier radio occultation and infrared temperature data was a result of variability in the atmosphere with season, latitude, dust in the atmosphere, and time of day.) The argon fraction was placed between 0 and 18%. In spite of these uncertainties, both Landers soft landed without incident, met all primary science objectives, and survived and transmitted data back to Earth from the surface for periods of years—a tribute to the the NASA Langley Research Center Viking Project Office, the Lander contractor (Martin Marietta Aerospace), and the Orbiter design and operations teams at the Jet Propulsion Laboratory.

The measured acceleration profiles and the descent histories of the two Landers given by radar altimeters are shown in Figs. 4 and 5.[6] Three features stand out. The peak accelerations were modest, near $7g_E$; the entry duration was short, about 8 min from threshold to touchdown; and the Landers pulled up into nearly horizontal flight at about 25 km altitude, because of the shallow entry path angles ($\gamma_E = -12$ deg), and the use of lift (nominal $L/D = 0.18$). The parachute descent began only 6 km off the surface.

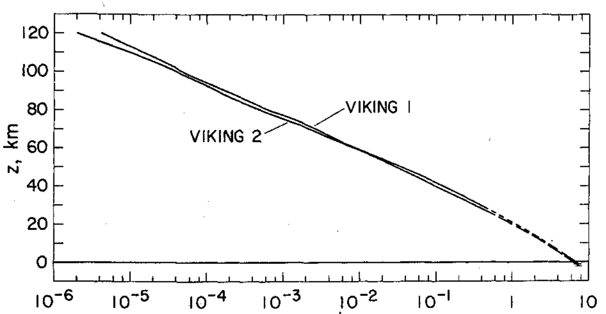


Fig. 7 Pressures in Mars' atmosphere, from integration of the density data in the equation of hydrostatic equilibrium.

The atmospheric composition, directly measured by a mass spectrometer after landing, showed a nitrogen fraction of 2.7% by volume and an argon fraction of 1.6%, the bulk of the atmosphere being CO_2,[19] thus quickly resolving questions that had been pending for years.

The density structure of the atmosphere derived from data taken during entry and descent is shown in Fig. 6, which combines data from three measurement modes[6]: 1) accelerometer data, shown by the solid curves from sensor threshold at ≈ 120 km to the level of horizontal flight at 25 km. (In horizontal flight, accuracy in $\rho(z)$ from deceleration measurements was degraded by small uncertainties in path angle and, hence, in altitude and the possible existence of horizontal winds); 2) ambient pressures and temperatures, shown by the solid curves at altitudes below 6 km and above 1.5 km, where retrorockets were fired; 3) pressures at the aeroshell stagnation point, measured between 60 and 6 km, and interpreted to define density through the theoretical stagnation pressure coefficient and the measured velocity. In addition, data on pressure and temperature taken on the surface immediately after landing gave the surface density. It can be seen that data from the independent sensors and sensing regimes were in good agreement and that the Viking 1 and 2 soundings differed only in detail. The density structure of the atmosphere from the surface to an altitude of 120 km had never been seen in this detail before.

Pressures derived from the density profiles by use of Eq. (4), and from parachute phase direct sensing, are given in Fig. 7; temperatures are given in Fig. 8. The pressure variation with altitude, similar in appearance to that of the density, extends from about 7.5 mb at the surface to the order of 10^{-6} mb at 120 km. The temperatures decrease from the surface values (near 230 K) toward a nearly isothermal mean state at 140–145 K above 40 km, with an irregular oscillation superimposed. The oscillation in temperature with altitude had been anticipated theoretically.[20] It is attributed to the thermal tide, a solar-fixed stationary wave driven by heating of the atmosphere near the surface as it rotates out of the nightside into the day. (This phenomenon also occurs on Earth, but is more prominent on Mars because of the large diurnal variation in surface temperature and the low atmospheric density.) Wavelengths and amplitudes observed were in reasonable correspondence with those predicted theoretically.

The mean temperature profiles, represented by the curves labeled $\bar{T}$, are not far removed from radiative equilibrium profiles for a surface temperature of 245 K. The theoretical results were derived from work of Gierasch and Goody,[21] published in 1968, and are surface temperature dependent. Except near the surface, the two temperature profiles were similar, even though they were made 45 days apart, at different latitudes (22.3° N and 47.7° N), and at different times of day (4:13 p.m. and 9:49 a.m.). Nevertheless, the temperature profiles on Mars do vary with season, at extremes of latitude, and with dust loading of the atmosphere. The Viking entries were made in late spring and summer seasons of the Northern hemisphere under relatively clear atmosphere conditions (small dust content).

The temperature lapse rates dT/dz are smaller than the adiabatic lapse rate and, thus, indicate a statically stable atmosphere. Therefore, except in the boundary layer, thermal convection should not occur. Stable atmospheres are required to support gravity waves and the observed semidiurnal tides. Temperatures at these times and locations were appreciably above the condensation boundary for CO_2 (labeled COND in Fig. 8). It is known from other observations, however, that condensation does occur in winter, overnight, to form tenuous CO_2 morning clouds.

An expanded view of temperatures near the surface, shown in Fig. 9, illustrates the limited altitude range of the descent mode measurements. These were sandwiched between parachute deployment, aeroshell jettison, Lander leg deployment (the descent phase temperature sensor was deployed on one of the landing footpads), and the firing of retrorockets at 1.5 km, below which the sensors were heated by rocket exhaust. The figure also shows the dynamic correction to measured temperatures in parachute descent, $rV^2/2c_p$, which was ≈ 1 K. The corrected temperature variation with altitude is the lower line, which, extended to the surface, is within 2 K of temperatures measured by the independent Meteorology Experiment sensor a short time after landing (circular symbols at $z = 0$).

The substantial difference in lapse rates seen by the two Landers between 1.5 and 4 km was attributed to diurnal changes in the boundary layer. In the afternoon (Viking 1), the

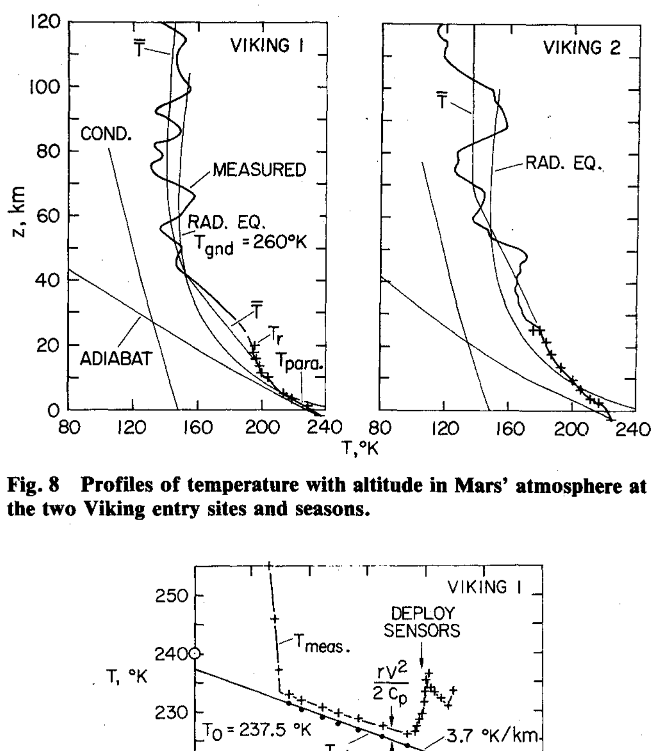


Fig. 8 Profiles of temperature with altitude in Mars' atmosphere at the two Viking entry sites and seasons.

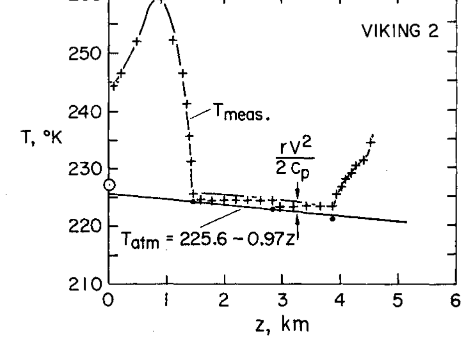


Fig. 9 Viking Lander descent mode temperature measurements.

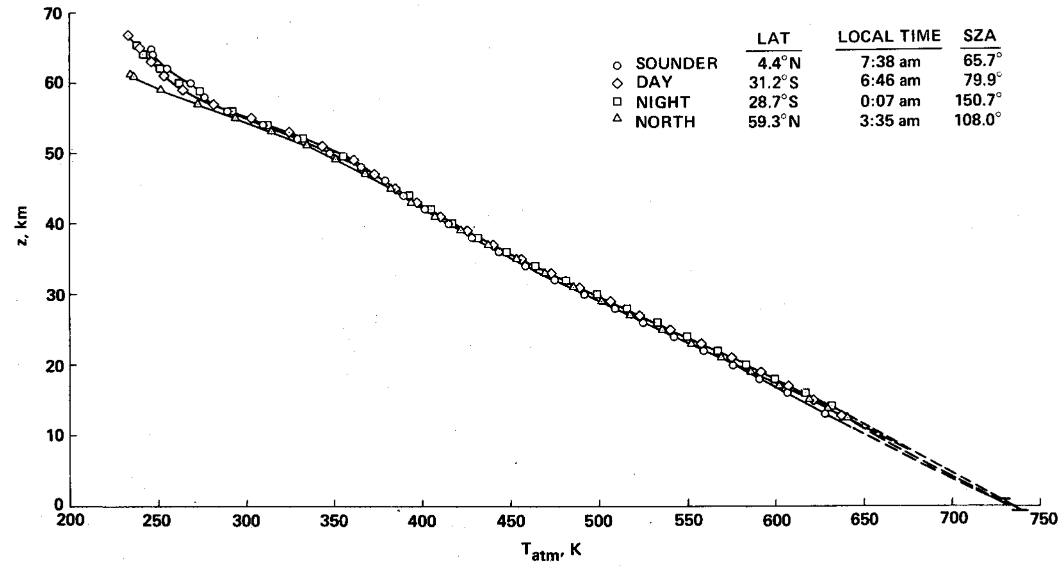


Fig. 10 Temperatures reported by the Pioneer Venus probes in descent at four widely separated locations on the planet.

lapse rate was near adiabatic and the convective boundary layer was 6.5 km thick, as revealed by the constancy of potential temperature below this level.[22] In the morning hours (Viking 2), the lapse rate was subadiabatic; the thick boundary layer was not developed. (Boundary-layer thickness appeared, from comparison of the temperature profile with near surface temperature after landing, to be <1 km.) Thus, the Viking 2 temperature data were taken above the boundary layer, and the temperatures were radiatively controlled by the ground temperature.

As a point of interest, on Viking 2, the descent mode temperatures were so close to isothermal that a one-count step, 1.2 K, occurred only after seven sample intervals. The line representing $T(z)$ was drawn through the first points after surmounting the one-count step, when temperature was very close to this discrete level. This improved the effective measurement resolution from 1.2 to 0.17 K.

Surface pressures measured at the two landing sites at the times of landing were 7.62 and 7.82 mb, respectively, at sites determined by radio tracking to be below the mean figure of Mars by 1.49 and 2.45 km, respectively. Pressures measured in descent through mean Mars level were 6.70 and 6.34 mb. It has been established that Mars surface pressure varies seasonally over a range >2 mb, as the polar caps vaporize and condense,[23,24] so that surface pressure cannot be characterized by a single value.

The Upper Atmospheric Mass Spectrometer[15] measured atmospheric species number densities extending to altitudes above 120-200 km. These densities were quite consistent with those obtained by the accelerometers and, in fact, were used to continue the atmospheric profiles of all state properties upward to 200 km.[6]

Structure and Contrasts in the Atmosphere of Venus—the Pioneer Venus Probes

The Pioneer Venus mission sent four probes into the atmosphere of Venus, widely separated over the Earthward face of the planet.[25] One major purpose was to define *contrasts* in the atmosphere, differences in temperature and other atmospheric properties at a given pressure level, with location and time. This was emphasized in the hope of gaining insight into the great dynamics mystery of Venus: what drives and sustains the high velocity winds at the cloud tops? This objective posed a difficult challenge for the atmosphere structure instruments on the four probes because it required very high relative accuracy in temperature and pressure measurements among the four probes.

These were the first dedicated atmospheric probes launched to another planet by the United States. One, designated simply the Large Probe, was 1.4 meters in diameter and carried seven experiments, including two atmospheric composition instruments, the atmosphere structure instrument, two cloud characterizing instruments, and two radiometers to measure radiative energy transfer from the sun, the planet, and the surrounding atmosphere. The three Small Probes were 0.76 meters in diameter and carried only three experiments: an atmosphere structure instrument; a net flux radiometer (to measure radiative heat deposition in the atmosphere); and a nephelometer (for cloud detection and characterization). The Large Probe descended on a parachute from 64 to 44 km, then jettisoned the chute and dropped to the surface in free fall. The Small Probes used no parachutes; they were in free fall throughout the descent. With the exception of the entry phase measurements of the atmosphere structure experiment, all measurements were taken in descent, beginning near the cloud tops at about 64-km altitude. All of the probes were, in addition, tracked with astonishing accuracy from Earth by very long baseline interferometry (VLBI) to measure wind velocities.

The four probes entered the atmosphere essentially simultaneously at widely dispersed locations on Venus, latitudes from 30°S to 60°N, and longitudes from the midnight meridian to 7:40 a.m. on the dayside, as will be shown later. Comparable landing sites on Earth would extend from Oslo, Norway to the Amazon Basin in South America to Madagascar, off the southeast coast of Africa.

Information on the atmosphere of Venus from this mission has provided the basis for a book entitled Venus,[26] and numerous other publications. Here, we can only highlight a few of the key results in the areas of atmospheric composition, winds, and clouds and describe some results of the structure experiment. There are articles describing all of these results in detail in Ref. 26.

Composition measured was 96.5% CO_2, 3.5% N_2, with trace amounts of SO_2 (the cloud forming species), argon, CO, and O_2, startlingly similar in bulk composition to Mars atmosphere. Water, on the other hand, was found to be far less abundant than on Earth. This is currently attributed to the escape of water from the planet over the age of the solar system. Winds were almost purely zonal (from east to west), decreasing from a peak magnitude of 110 m/s at the cloud tops to 1 m/s at the surface. Cloud top winds spiral very gradually toward the poles, where they form a polar vortex. The winds are in cyclostrophic balance with the meridional

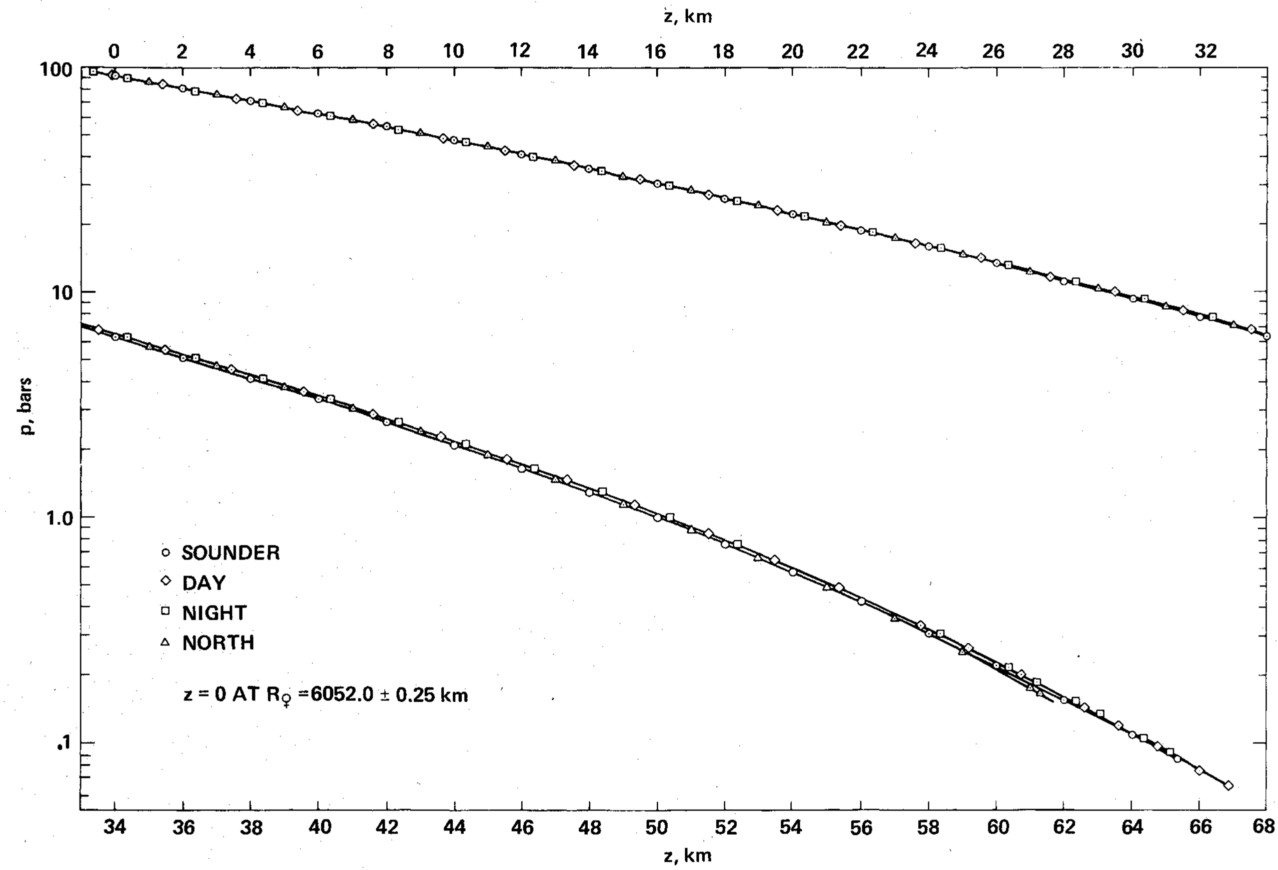


Fig. 11 Pressure as a function of altitude at the four probe entry sites.

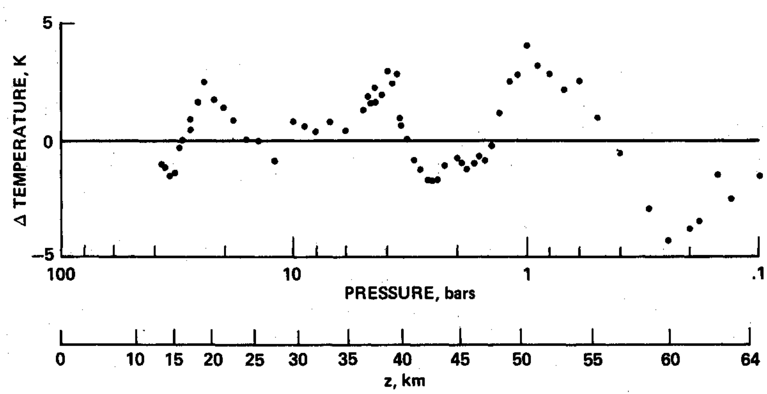


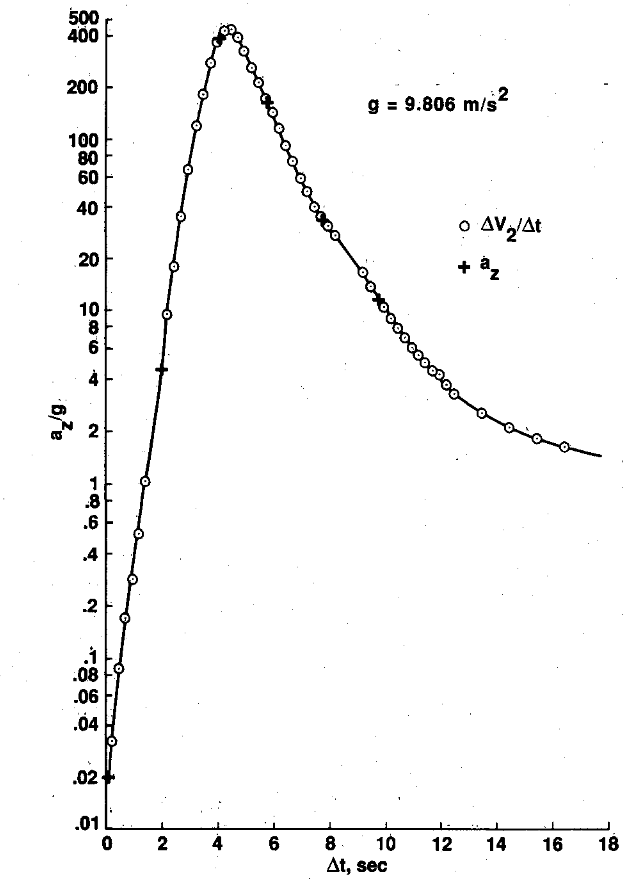
Fig. 12 Altitude profile of temperature differences between the two Small Probes near 30°S latitude. (The oscillatory pattern suggests the presence of atmospheric waves of global extent.)

(i.e., north-south) pressure gradient. (The pressure gradient provides the horizontal component of the centripetal force needed to balance the zonal winds.) Clouds opaque to visible light are always present at altitudes from 48 to 66 km, so that the surface is never seen in visible light. However, about 3% of the solar photons do reach the surface near the subsolar point after multiple scattering (diminishing to fewer than 0.1% near the terminators). Optical depth of the clouds is 25-35. The clouds were in three layers at the Large Probe location, but at some locations and times, they appear to merge into two layers, or to overlap. The cloud particles are composed of concentrated sulfuric acid aerosol with diameters from a few microns to $<1\ \mu$.

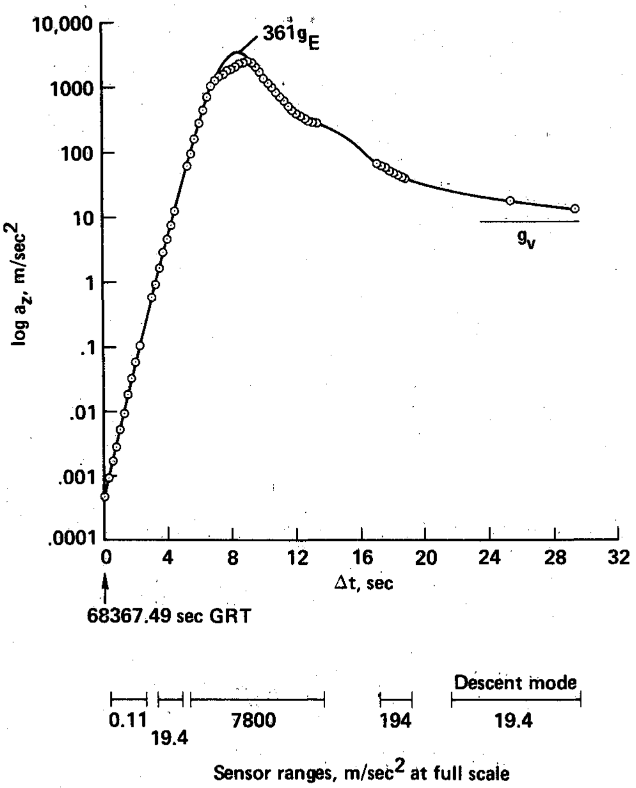
The atmosphere structure experiment[7] was very much like the model experiment described earlier. The entry phase began on two of the probes just below 140-km altitude, at sensor thresholds of 0.1 and 0.7 mg. The other two probes had thresholds near 8 and 16 mg. The Large Probe entry mode continued to parachute deployment at $M = 1$ (67-km altitude), and descent mode was commanded at comparable altitudes for the three Small Probes. Time to descend from there to the surface was about 1 h.

In descent, temperature sensors were deployed and stagnation pressure was sampled, along with acceleration readings every 16 s. From these data, the descent trajectory and lower atmosphere structure were reconstructed. Temperature and pressure data for the four probes in descent are shown as functions of altitude in Figs. 10 and 11, with latitudes and local Venus times of descent indicated in Fig. 10. The surface temperature and pressure indicated by the data were 735 K and 95-bars pressure at the 6051.5-km mean radius level.

The initial reaction to the temperature data was that, below 56 km, the profiles from the four probes were like repeated measurements of a single structure. However, close examination showed a dispersion of a few K, which is larger than both the expected measurement accuracy (~0.5 K) and the accu-



a) North Probe; $V_E = 11{,}595$ m/s, $\gamma_E = -68.57$ deg



b) Night Probe; $V_E = 11{,}538$ m/s, $\gamma_E = -41.50$ deg

Fig. 13 Entry deceleration profiles of two of the Small Probes.

racy suggested by postflight analysis (1-2 K). The pressure data from the four probes were even less dispersed than the temperature data, defining essentially a single curve up to 30 km. These small contrasts were not unexpected. Theorists had predicted extremely small contrasts in the atmosphere of Venus, in fact, much smaller than those measured (for example, 10^{-2} K in the deep atmosphere). This is because Venus' deep atmosphere has tremendous thermal inertia, relative to the dynamical time constant. That is to say, the general circulation moves the atmosphere around the planet in a time short compared to its radiative relaxation time.

The observed contrasts were systematic, however. Temperature at a given pressure decreases with increasing latitude. This variation was found to be consistent with cyclostrophic balance of the measured winds within measurement accuracy. (Initially, the winds were predicted from the pressure data under the assumption of cyclostrophic balance and found to agree with winds from radio tracking.[27]) There were also indications of waves in the temperature data, e.g., Fig. 12, which shows the altitude variation of temperature difference between the two probes at $-30°$ latitude. These wave observations are consistent with observations by other techniques, such as the patterns seen in ultraviolet images.[26] The later Vega balloon measurements in Venus' cloud layers also found temperature differences consistent with the temperature differences between the Day and Night Probes.[28] Present indications are that waves of many scales and types are present in the atmosphere of Venus, and it is believed that they play a major role in determining its dynamics.

The entry mode data were equally informative. The acceleration records transmitted to Earth from the North Probe, the Small Probe, which landed at 60°N latitude at 3:35 a.m. local Venus time, and the Night Probe, which landed at 30°S latitude at midnight, are reproduced in Figs. 13a and 13b. The North Probe entered the atmosphere on a steep path, 68.57 deg below horizontal, whereas the other three entered at smaller path angles, down to 25.4 deg for the Day Probe at 30°S latitude. As a result, the North Probe experienced the highest peak deceleration and the shortest entry period of the four probes. Its deceleration increased by over four decades in 4 s after threshold to a peak near $450g_E$. The accelerometers made several automatic range changes in this interval (with some data loss due to transients following range change). The entry data were stored in probe memory during communications blackout and read out during descent.

When one lays a straightedge on the rising branch of the entry deceleration data, it is immediately evident that $a_z(t)$ was, in all cases, a somewhat wavy variation, and this waviness feeds through directly into the density variations with altitude, shown for three probes in Fig. 14. Pressures obtained by integrating the densities are given in Fig. 15. A striking feature of these data is the divergence of the densities and pressures on the day and night sides of Venus, which begins at about 110 km and becomes dramatic at the altitudes of the Orbiter data. Two Orbiter in situ experiments define profiles which extend those of the Probes above 150 km, the Orbiter Atmospheric Drag (OAD) experiment, and the Orbiter Neutral Mass Spectrometer (ONMS) experiment. Data taken above 130 km by the Bus Neutral Mass Spectrometer (BNMS), also shown, overlap Probe data altitudes and define densities for an entry site near that of the Day Probe. The data in Fig. 14 are the raw evidence for major diurnal variations in temperature in Venus' upper atmosphere.

This is clear from the following: For an isothermal atmosphere, $\log\rho(z)$ is a straight line plotted against z, and the slope of the line defines T. Thus, divergence and the waviness reflect variations in temperature with altitude. The upper atmospheric temperature structure derived from these data is shown in Fig. 16 for the three Small Probes, two on the nightside, and one on the dayside of Venus.[29] The waves in the density structure lead to waves in $T(z)$. Note that the temperatures are continuous with those directly sensed in the lower atmosphere, shown below 66 km by flagged symbols. Within the amplitude of the wave-induced oscillations, i.e., within 10 or 15 K, the three widely separated soundings show the same structure below 100 km. The upper atmospheric temperature divergence begins just above 100 km, the two nightside probes moving toward temperatures as low as 120 K, whereas the mean curve through the dayside data moves upward to 220 K.

In situ data taken by three Pioneer Venus Orbiter and Bus experiments[16,30,31] show this day/night contrast at altitudes above 150 km to be large, 300 K by day and 150 K by night. Figure 17, which summarizes the present state of knowledge of the temperature structure of Venus' atmosphere from the surface to 200 km, shows this diurnal temperature contrast, as well as the correspondence between Probe entry, and Orbiter and Bus experiments. The diurnal contrast in the upper atmosphere is understood to result from solar heating on the dayside, and rapid radiative cooling by CO_2 in the atmosphere by night.

The Pioneer Venus entry experiments were limited to a very small data quantity by the probe electronic design. The Small

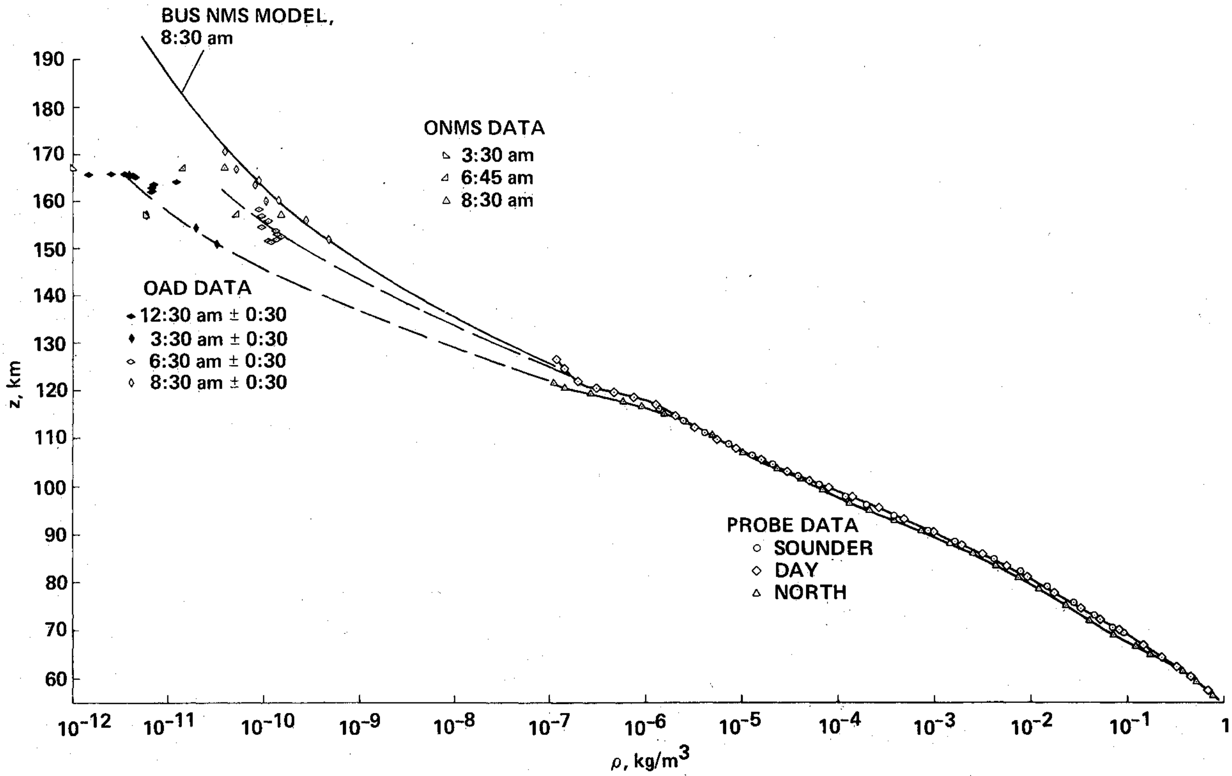


Fig. 14 Entry mode density data from deceleration measurements extended to pass through densities measured by Orbiter and Bus experiments at corresponding local Venus times.

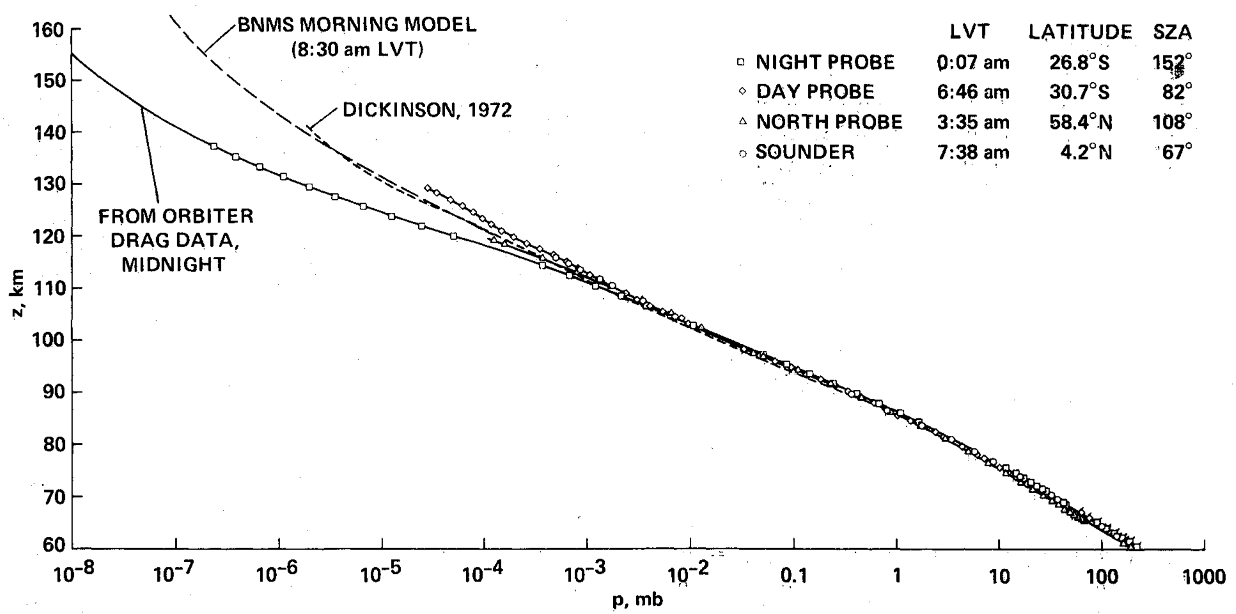


Fig. 15 Pressure profiles in the upper atmosphere, from densities of Fig. 14. (Flagged symbols below 70 km are from descent mode direct sensing.)

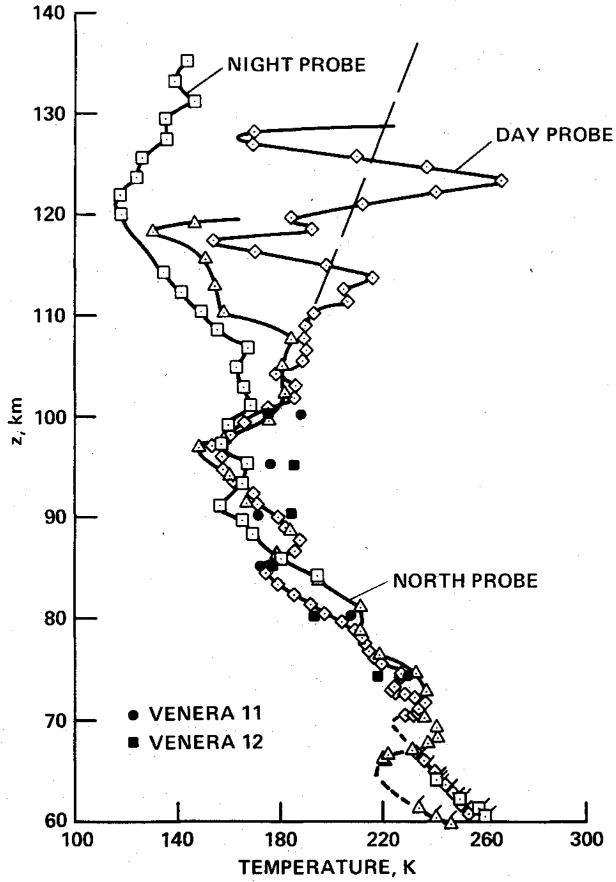


Fig. 16 Temperatures in Venus' middle and upper atmosphere, determined from entry deceleration measurements. Filled symbols are Soviet data, also obtained from deceleration measurements.

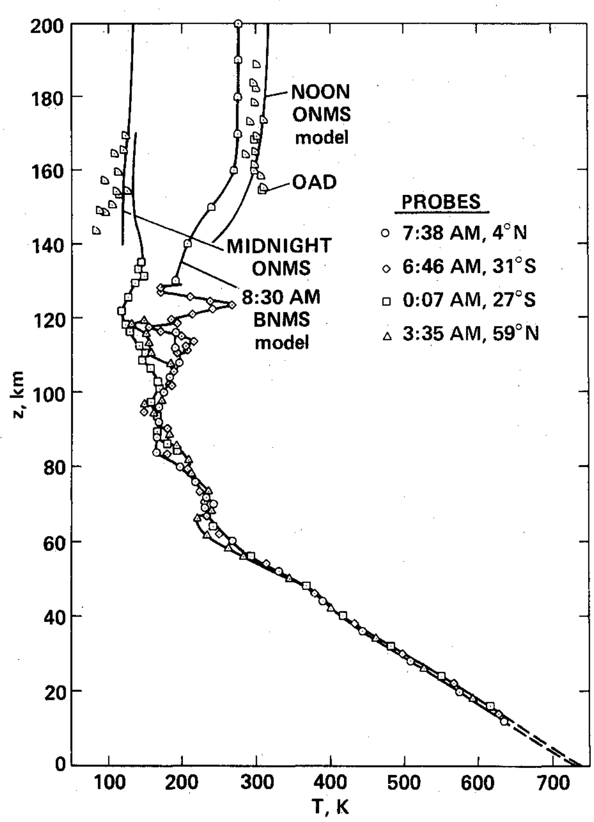


Fig. 17 The temperature structure of Venus' atmosphere from the surface to 200 km, given by Pioneer Venus experiments on the Probes (below 140 km), on the Orbiter (above 145 km), and on the Bus (above 130 km).

Probe memories held only 3072 bits, of which the experiment was allocated 2560 bits (320 eight-bit words). The eight-bit words gave measurement resolution of 0.4% at full scale, but a relatively crude 4% of measurement at 0.1 of full scale. Thresholds were defined by four or five counts, with 20% resolution uncertainty. Altitude resolution also was impacted by the limited data quantity. For example, the altitude resolution was 3 km for the North Probe at entry. An earlier threshold and finer altitude resolution, could have been achieved with more probe memory. Thus, although the entry data were informative, they could on future missions be extended to higher altitude thresholds and made to yield much more detail on the wave structure by use of new technology that permits very large memories on a single chip.

Concluding Remarks

The use of entry probes as devices for exploring the atmospheres of the planets has proven to be rewarding. Results achieved have gone beyond the original goals, which were merely to define basic parameters such as surface pressure and scale height. They have led to new, albeit limited, understanding of some of the dynamic characteristics of the atmospheres of Mars and Venus.

It is recognized that these experiments, especially in the upper atmosphere, could now be done with better accuracy and resolution. The importance of this is that it could lead to better definition and, hopefully, better understanding of variability and such dynamical features as the wave induced oscillations in the atmosphere structure. Waves of this kind are now recognized to be a prevalent feature of planetary atmospheres, and they have important consequences for vertical momentum transfer, that is to say, the general circulation.

Although the pace of starting new missions of planetary exploration slowed in the 1980s, there is one atmospheric probe/orbiter mission now in flight (Galileo, to Jupiter) and one in preliminary design (Huygens, to Saturn's major satellite, Titan), to which we can look forward with high anticipation. Possible future missions include missions to other outer planets. Missions to return to Mars and Venus also offer promise of further gains in our understanding of those atmospheres. Mars is currently under intensive study because of interest in further efforts at life detection, as well as manned exploration (under the Space Exploration Initiative). From the standpoint of manned missions, there is great interest and possibly a need to better understand the variability in Mars atmosphere, associated with latitude, season, and dust loading because these factors can affect retrobraking, entry, and manned operations on the surface. Manned missions would also benefit from improved knowledge of Mars meteorology and geology. To respond to these interests and needs, multiple probe missions have been advocated. Thus, it seems probable that atmospheric probes will make still further contributions to our knowledge of atmospheres in the solar system.

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