Thermal Structure of the Venus Atmosphere in the Middle Cloud Layer

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Thermal structure measurements obtained by the two VEGA balloons show the Venus middle cloud layer to be generally adiabatic. Temperatures measured by the two balloons at locations roughly symmetric about the equator differed by about 6.5 kelvins at a given pressure. The VEGA-2 temperatures were about 2.5 kelvins cooler and those of VEGA-1 about 4 kelvins warmer than temperatures measured by the Pioneer Venus Large Probe at these levels. Data taken by the VEGA-2 lander as it passed through the middle cloud agreed with those of the VEGA-2 balloon. Study of individual frames of the balloon data suggests the presence of multiple discrete air masses that are internally adiabatic but lie on slightly different adiabats. These adiabats, for a given balloon, can differ in temperature by as much as 1 kelvin at a given pressure.

As described by Sagdeev and co-workers (*1*), the two VEGA balloons did not float quietly at constant altitude but rather moved vertically over a range of a few kilometers as a result of the sizable vertical flow velocities that they encountered. These movements and the associated atmospheric vertical flow velocities made it possible to analyze the structure of the Venus atmosphere at pressures between 525 and 880 mbar. According to earlier probe data, this is within the middle cloud layer (*2–4*), identified from Pioneer Venus probe data to be a neutrally stable or slightly unstable and hence probably convective layer about 5 km deep (*4*). Data from the Venera 10, 11, and 12 landers (*5*), when analyzed to derive atmospheric stability (*6*), were found to be in essential agreement with stabilities derived from the Pioneer Venus probes at altitudes up to 53 km. Thus, before the mission, it was expected that the balloons would be floating in a convective region of the atmosphere. However, the degree of activity shown by the vigorous balloon vertical motions was not anticipated.

The balloon data (*1*) are plotted to show temperature as a function of pressure in Fig. 1. For each balloon, the data in the set correlate highly and show an essentially adiabatic variation, with deviations typically less than ±1 K. In arriving at this data set, the choice of the least count of the most significant bit (MSB) words of pressure and temperature was constrained to minimize the deviations. [These choices were sometimes ambiguous because the MSB words were read only at 10-minute intervals (*7*).] The dense clusters of data points between 530 and 600 mbar make up approximately 90 percent of the data, and only a comparatively few points were obtained at pressures above 670 mbar.

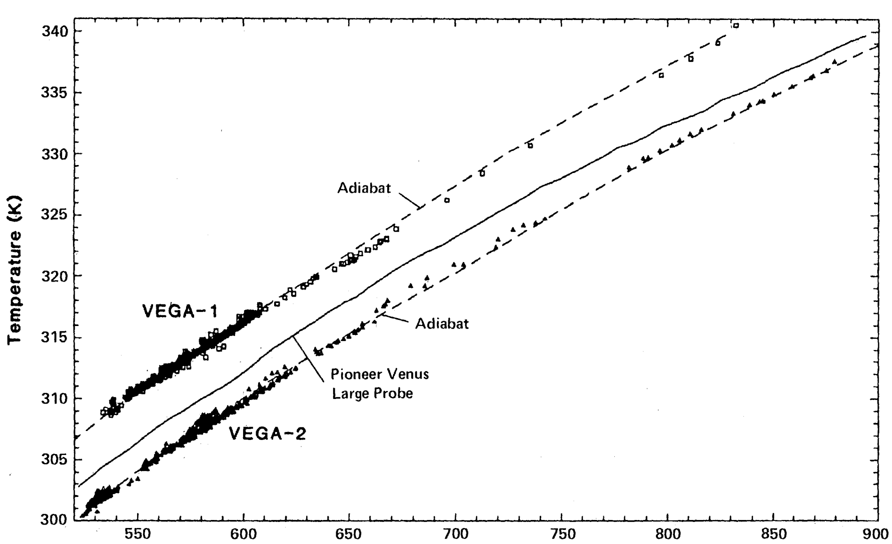

Fig. 1. Measurements of temperature as a function of pressure from the two VEGA balloons compared with data from the Pioneer Venus Large Probe. The data from each balloon define a single curve of variation with small scatter. However, data from the two balloons are offset by 6.5 K at a given pressure and lie on either side of the Large Probe data. The balloons and the probe were within 7° of the equator at injection.

The offset of the two data sets from one another is approximately 6.5 K, VEGA-1 being warmer than VEGA-2, and the balloon data fall on either side of the temperatures measured by the Pioneer Venus Large Probe, which entered the atmosphere at 4°N in December 1978 (*4*). Because of the symmetry in their placement about the equator (at 7.3°N and 6.6°S), it was surprising to find this offset in the temperatures. It is evident that the two balloons were in air masses differing in potential temperature. They remained in these different air masses for most of the mission, which carried them through a longitude range of more than 100°.

The cause of this temperature difference is of interest and potential significance for Venus atmospheric dynamics and is discussed in the companion report by Blamont and colleagues (*8*). It is characteristic of balloons that they move with the atmosphere, so that the observed temperature difference could be representative of air masses that are limited in spatial extent. This temperature difference need not be associated with latitude but could result from oscillatory variations in temperature with longitude (see below). Vertical movement of gas parcels into the convective layer from surrounding stable layers is one possible mechanism for introducing differences in potential temperature.

The possibility of error in the calibration has also been considered, and no error has been discovered. The VEGA-2 balloon data are confirmed within 1 K by data from the VEGA-2 lander, as may be seen in Fig. 2 where the lander data are compared with the same adiabat as that compared with the balloon data in Fig. 1. No corresponding data are available from the VEGA-1 lander. However, data from engineering temperature sensors in the nephelometers confirm the temperature difference between the two

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balloons. The VEGA-2 lander data were also used to establish the balloon altitudes by integration of measured pressures and temperatures upward from the surface in the equation of hydrostatic equilibrium.

The VEGA-2 lander temperature profile closely follows the adiabat at altitudes from 48 to 54.5 km. The initial equilibrium float altitudes of the balloons, near 53.6 km, were close to the top of this adiabatic layer. In general, the VEGA-2 data on atmospheric stability agree with those from the Pioneer Venus probes, but there are some differences, principally in the altitude of the convective layer. Thus the lower boundary of the middle cloud, identified by the 3 K temperature step at 355 K in Fig. 2, is at 48 km, somewhat lower than a similar step found at the cloud boundary by the Pioneer Venus Large Probe. The offset itself is remarkably repeatable between the two probes. A further difference between VEGA-2 and the Pioneer Venus probes, evident in both Figs. 1 and 2, is that above 750 mbar and 325 K the VEGA-2 data show the atmosphere to be adiabatic, where the Large Probe temperature slopes show the atmosphere to be stable (*4*).

Temperature differences at the balloon altitudes among the three low-latitude Pioneer Venus probes at 4°N (Large Probe), 29°S (Day Probe), and 31°S (Night Probe) ranged from 1 K at 550 mbar to 3.5 K at 900 mbar. Why are these differences smaller than the uniform 6.5 K difference between the two balloons? The probes entered Venus nearly simultaneously but at widely separated longitudes, such that the local Venus time varied from midnight to 7:40 a.m. (By chance, these local Venus times are comparable to those sampled by the VEGA balloons.) The two higher latitude Pioneer Venus probes, the Day and Night probes, were at the same latitude within 2.5° of each other. Although this minimized differences between them associated with latitude, they were separated in longitude by about 100°. Systematic temperature differences were seen between these two probes. The differences were oscillatory with altitude, with a 5 K amplitude and peaks near 50 and 60 km at the time of the probe entries (*9*). For the balloon and probe observations to be consistent, the phase of this oscillation with respect to altitude would have to be time-dependent; that is, the altitude of the peak temperature difference with longitude would have to vary with time. In the presence of such a time-dependent temperature oscillation with longitude, injecting two balloons into different phases of this oscillation could result in the observed steady temperature difference between the balloons, provided that a wave of horizontal

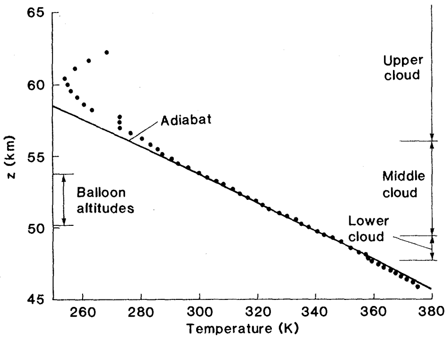

Fig. 2. VEGA-2 lander data compared with the reference adiabat. These data establish the VEGA-2 balloon altitudes. The temperatures follow the adiabat closely from altitudes of 48 to 54.5 km, indicating a convective layer that generally coincides with and extends somewhat below the middle cloud layer defined by Pioneer Venus data. Cloud boundaries indicated at the right are those defined by the Pioneer Venus Large Probe nephelometer.

temperature difference traveled with the balloons. Whether this explanation of the data is valid or not, it appears that there are complex variations of temperature with time and position in the clouds that were not suspected a decade ago.

From Fig. 1, mean temperature lapse rates, dT/dz, can be derived. They are close to adiabatic (10.17 K km^{-1} at 310 K). Some further insight into the fine structure of this convective layer can be obtained by studying the atmospheric stability in individual frames of the data, each of which was taken over a 30-minute period (Fig. 3). In Fig. 3A, data taken starting at 26.93 hours universal time (U.T.) by VEGA-2 are presented. This frame was taken in a period of rapid downflow (velocity of the atmosphere was -2.5 ± 1 m sec^{-1}), during which the balloon descended 0.57 km (velocity of the atmosphere relative to the balloon, w_r, was about -2.2 m sec^{-1}). The variation of measured temperatures with pressure is essentially linear over a pressure interval of 50 mbar. It is evident that the atmosphere is nearly adiabatic. The light line in Fig. 3A is, however, a better fit to the data in this frame and indicates a lapse rate stable by about 0.3 K km^{-1}. As will be seen, the temperature-pressure relation varies measurably among individual frames, so that this condition is not general.

Data taken in the half hour starting about 1 hour after terminator crossing (Fig. 3B) tend to follow the adiabatic slope, but the atmosphere is warmer than the reference adiabat by about 0.6 K. The data of this frame are, in fact, generally bounded by two adiabats about 0.25 K apart. The data intermittently move from one adiabat to the other. Points on the lower boundary could not be forced onto the higher adiabat by different choices of the MSB word. Convective downflow occurred during this frame, with an atmospheric vertical velocity relative to the balloon of about -2.5 m sec^{-1}. The air flowing downward over the balloon sensors from above appears to have consisted of a number of discrete air parcels that differed slightly in potential temperature. Because this downflow persisted for more than 30 minutes, the air parcels moving past the balloon could have come from distances of several kilometers.

In Fig. 3, C and D, data taken during periods of smaller vertical velocity by VEGA-2 are compared. Over most of frame B 3 (2.79 hours U.T.), the balloon was

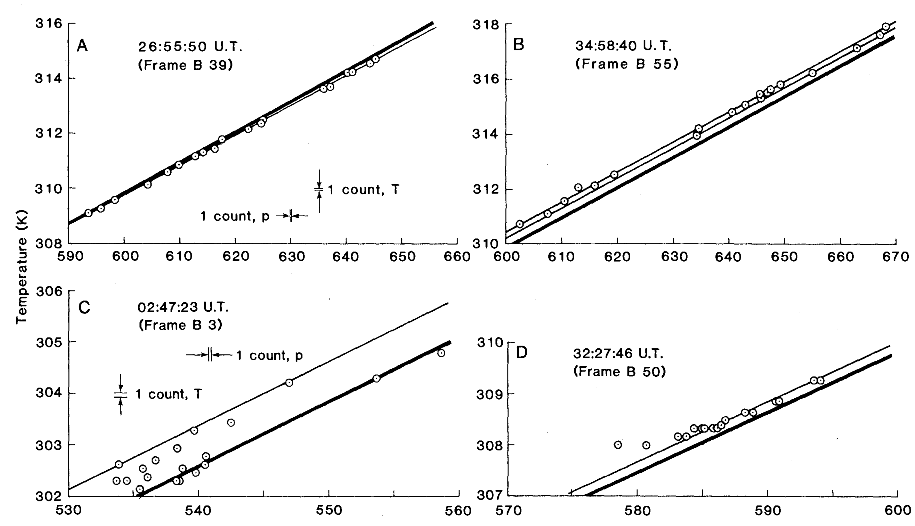

Fig. 3. Variation of temperature with pressure in individual frames of VEGA-2 balloon data. The heavy line is the reference adiabat, with entropy $S/R = 26.4500$ (R, gas constant), and is the same in each figure. Data in individual frames tend generally to follow an adiabat, but these adiabats differ slightly in temperature at a given pressure from frame to frame and sometimes within a single frame. Resolution of p and T in (B) corresponds to that shown in (A); resolution in (D) corresponds to that in (C).

floating at a constant altitude within 100 m (pressures between 534 and 542 mbar). Vertical velocities of the atmosphere were from +0.5 to −0.8 m sec^{-1} (*1*). Nevertheless, measured temperatures varied between two adiabats separated by 0.6 K (eight data counts) and moved between these limits four times in 20 minutes. This establishes a rough time scale of about 300 seconds for the variation. Since the vertical velocity of the atmosphere relative to the balloon in this frame was typically −0.5 m sec^{-1}, a time scale of 300 seconds corresponds to a scale size of approximately 150 m if the variations are a result of air parcels of differing temperature sweeping down past the balloon.

Because the amplitude of temperature variation seen in this frame with relatively small vertical motion of the atmosphere is higher than in some other frames with higher vertical velocities, we considered the possibility that the gondola wake was influencing the temperatures. Our analysis suggests that the gondola wake probably did not influence the temperature data. In frames with higher vertical velocities, such as B 39 and B 55 (Fig. 3, A and B), influence of the gondola wake is improbable because the wake is swept mainly upward or downward rather than to the side. In these cases, temperature influences of the balloon wake are possible.

In frame B 50 (Fig. 3D, 32.46 hours U.T.), except for the last two data points, the data lie close to an adiabat that is 0.2 K warmer than the reference adiabat. The maximum deviation from the reference adiabat is 0.7 K. The vertical wind velocities relative to the balloon were −0.4 to +1.25 m sec^{-1} (*1*), with the higher velocities occurring late in the frame when temperatures were drifting off the adiabat. These four frames illustrate the diversity of the temperature data and perhaps will give some clues as to the mechanisms of the convective heat transport processes in the clouds. Although not yet analyzed in as much detail, the VEGA-1 data appear to be similar in these respects.

Near the end of the VEGA-2 mission, when the balloon was advancing well into the dayside of Venus (solar zenith angle near 64°), measured temperatures were as high as 12 K above the reference adiabat. This was during a period of low vertical wind velocities (0.1 to 1 m sec^{-1}). Initially, the high temperatures seemed to indicate that the balloon had moved out of the air mass in which it rode 30 percent of the way around Venus and entered a new, warmer air mass. However, it now appears that these higher temperatures were a result of direct solar heating of the sensor on the dayside. The sensors were nickel-resistance elements within a thin (50-μm) sandwich of amber-colored polyamide plastic (*7*). Assuming that the sensor solar absorptivity is 0.5 and that the infrared emissivity is 0.8, it was estimated that solar heating would raise the sensor temperature at this solar zenith angle by 12 K at w_r = 0.1 m sec^{-1} to 5 K at w_r = 1 m sec^{-1}, with convective heat transfer to the atmosphere limiting the temperature error. Thus solar heating of the sensor can explain the observed higher temperatures, and data taken on the dayside will have to be interpreted with this effect taken into account.

In summary, the principal results of the early analysis of the VEGA balloon data pertaining to thermal structure of the middle cloud layer of Venus are as follows. (i) Temperatures correlated highly with pressures in the vertical excursions of the two balloons. (ii) The two balloons were immersed in air masses differing consistently in temperature at a given pressure by about 6.5 K over a range of longitudes from about 180°E to 70°E. (iii) The atmosphere was close to adiabatic in the middle cloud region, confirming earlier probe soundings. (iv) Small deviations from a single adiabat occurred, suggesting the presence of discrete, small-scale air masses of differing thermal history. (v) Comparisons of data from the two balloons with data from earlier probe soundings suggest variations in the thermal structure with time and position that were not suspected a decade ago.

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Implications of the VEGA Balloon Results for Venus Atmospheric Dynamics

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Both VEGA balloons encountered vertical winds with typical velocities of 1 to 2 meters per second. These values are consistent with those estimated from mixing length theory of thermal convection. However, small-scale temperature fluctuations for each balloon were sometimes larger than predicted. The approximate 6.5-kelvin difference in temperature consistently seen between VEGA-1 and VEGA-2 is probably due to synoptic or planetary-scale nonaxisymmetric disturbances that propagate westward with respect to the planet. There is also evidence from Doppler data for the existence of solar-fixed nonaxisymmetric motions that may be thermal tides. Surface topography may influence atmospheric motions experienced by the VEGA-2 balloon.

The VEGA Venus balloon mission was designed to determine atmospheric characteristics at the float altitude of the balloons in terms of horizontal and vertical winds, thermal structure, and cloud properties, with a goal of learning more about important dynamical processes. In this paper we discuss possible interpretations of certain aspects of the data, with the caveat that any conclusions are preliminary.

Vertical momentum and heat transport, which are derived from products of vertical velocity with horizontal wind and temperature, respectively, are among the principal quantities that determine the characteristics of the general circulation. Thus the VEGA balloon vertical wind data are of considerable interest. The initial balloon float altitudes near 53 km are in the region of the atmosphere identified by the VEGA-2 lander (*1*) and Pioneer Venus (*2*) as having

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