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AN ANALYSIS OF THE VENUS MEASUREMENTS

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Abstract

Plots of the Mariner 5 and Venera 4, 5, and 6 pressure vs. temperature, P(T), show that the Venera profiles are essentially congruent with the Mariner 5 day and night profiles, but are displaced 28% higher in pressure. There is evidence that this displacement is a characteristic of the Venus atmosphere that arises from a latitude dependence of the height of the isotherms caused primarily by dynamic processes. Use of the Venera water vapor measurements with the Venera and Mariner 5 P(T) profiles leads to the suggestion of a variability in the atmospheric water vapor content in the region from 30 to 50km. This result is consistent with the measurements of Venus radiation at 18.5 to 24.0 GHz by Jones, Wrathall, and Meredith (1972). The Venera 7 measurements are interpreted as presenting evidence for updrafts, down-drafts, horizontal wind layers, and non-aqueous precipitation. The previously observed band of retrograde winds which circle the equator with an average speed of 110m/s is found to extend downward to the one atmosphere level at the equatorial morning terminator. The possibility of a low altitude equator-to-pole circulation with warm gas rising at the poles is inferred from the Venera probe and Earth-based microwave interferometer measurements. Venera 7 temperature data used in conjunction with a comparison of radar topography and microwave interferometer measurements suggests that the variation of surface temperature with altitude in a band about the equator is less than 5K/km and may approach zero. The possible existence of clouds at 6 or more altitude regions above the Venus surface is discussed. Venera data are interpreted as yielding mean surface pressure and temperature values of 71 atmospheres and 748K. Mariner and Venera data are interpreted as requiring a mean planet radius of 6055 $\pm$2km. The available data is used to calculate a model of the structure of the Venus atmosphere for the first 75km above the equatorial region.

Introduction

Our understanding of the Venus atmosphere has been greatly increased by the data obtained from the Mariner 5 and the Venera 4, 5, 6, and 7 missions. From this data and from ground-based measurements it is possible to devise a model of atmospheric composition, temperature, and dynamic processes which exploits the consistencies in all the measurements and attempts to explain the apparent discrepancies. The purpose of this paper is to devise such a model and to examine critically the arguments of selection and rejection which lead to the choice of the key parameters. *

The analysis comprises twelve sections based on major features in the data which delineate the scope of the work. The sections are:

*Articles by Gierasch and Goody (1970), Hunten (1971), and Marov (1972) furnish an excellent background for the developments presented in this paper.

** All altitudes are referred to a nominal planet radius of 6055km obtained in Section 11. The atmospheric structure is given in Table 2.

Our starting point for the analysis is the Mariner 5 measurements obtained from Fjeldbo et al. (1971) and shown in Figures 1, 2, 3, and 13. A conspicuous feature of these measurements is that from the 7 atmosphere level at 30km to the 0.007 atmosphere level at 73km the altitude profiles of pressure and temperature obtained on the day-side are essentially identical to those obtained on the night-side, despite the fact that the measurement region on the sunlit side had experienced 24 Earth days of continuous solar heating while the measurement region on the night-side had continuously radiated energy to space for 24 days. Since the radiative heating and cooling time constants of the atmosphere at 73km are of the order of 1 Earth day, the fact of identical temperature profiles suggests atmospheric mixing on a global scale and is consistent with the existence of the equatorial band of high speed horizontal winds described by Boyer and Guerin (1969) and discussed in Section 6. In the following sections repeated use will be made of the near identity of day and night-side data to deduce additional information about the Venus atmosphere.

An important additional feature of the Mariner 5 measurements is the existence of roughly identical S-band microwave attenuation profiles in the region between 30km and 55km on both the day and night sides of Venus.

According to Fjeldbo et al. this feature, in association with sub-adiabatic regions in the temperature profile, suggests the presence of two different cloud systems separated in altitude by about 10km. Our work will lend support to this interpretation.

1. The sub-adiabatic region at 40km

In order to work with data which had received a minimum of processing, values of P(t) and T(t) were used to obtain the plots of P(T) shown in Figure 4. Venera 4 data was obtained from two sources, T(t) from the telemetry data presented by Mickhnevich and Sokolov (1969), and P(t) from Avduevsky et al. (1968). Venera 5 and 6 data were obtained from Avduevsky et al. (1970a). Tabulated Mariner 5 pressure and temperature data was obtained from Fjeldbo and was plotted using an average atmospheric mean-molecular-mass of 43.3g/mole corresponding to an atmosphere of 97% CO_2 and 3% Ne. This atmosphere is consistent with the Venera composition measurements described by Vinogradov et al. (1970) who obtained 97 ±4% CO_2, less than 2% N_2, and up to 1.5% H_2O vapor in certain regions.

It is apparent from Figures 4 and 5(a) that the Venera 4 and Mariner 5 P(T) profiles show similar sub-adiabatic temperature regions at 370K (40km) and are almost identical except for a uniform displacement of the Venera profiles by 28% in pressure. The Venera 5 and 6 profiles are also separated from Mariner 5 by a 28% pressure difference over much of the measurement region but they do not show the sub-adiabatic region at 370K. This absence of a sub-adiabatic region could be due to the following reasons: (a) the higher descent speed of the Venera 5 and 6 vehicles, roughly 2.5 times larger than the descent speed for Venera 4, may have resulted in omission of detail in the data needed to determine the precise shapes of the temperature and pressure profiles in the sub-adiabatic region, (b) the sub-adiabatic region tends to disappear from plots of T(h) when h is obtained from parachute descent computations that ignore the effect of the large vertical wind gradient resulting from our analysis and shown in Figure 11 at 42km, or (c) the sub-adiabatic region is transient.

The almost identical shapes of the Venera 4 and Mariner 5 P(T) profiles at three widely separated locations suggests that at the time of these measurements the sub-adiabatic region at 40km existed in a band about the Venus equator extending from 30° S to 30° N. The fact that both above and below 40km the Venera P(T) profiles remained unchanged with time suggests that the Venera 5 and 6 telemetry data should be re-examined to determine whether it is possible that the sub-adiabatic region existed 18 months after the Venera 4 and Mariner 5 measurements and may thus be either a recurring or permanent temperature feature at the equatorial morning terminator and possibly in a band surrounding the Venus equator.

2. The uniform 28% separation of the P(T) profiles

The good agreement among the Venera P(T) profiles and among the Mariner P(T) profiles, as is evident in Figure 4, is a measure of the permanency of the uniform 28% separation and of the precision of both sets of measurements. It is apparent from Figure 4 that at any temperature the sum of the deviations of the Venera and Mariner profiles from their respective mean profiles, even in the sub-adiabatic region, is a small fraction of the 28% separation.

We are unable to obtain an explanation of the uniform 28% separation based upon systematic error in the Venera and Mariner measurements. It is apparent from the description of the Venera 4 pressure and temperature instruments given by Avduevsky et al. (1969) that the separate or combined systematic error for these instruments is not sufficiently large or properly distributed to account for the 28% separation. In the case of Mariner 5, the Doppler frequency in this region of high atmospheric density is measured to better than one part in 10^4. The relations between Doppler frequency and ray-bending, and between ray-bending and refractivity, have been carefully evaluated by Fjeldbo et al. (1971), by Phinney and Anderson (1968), and by Fjeldbo and Eshleman (1968) to the extent that a constant error of 28% over the range 0.7 to 7 atmospheres does not seem possible. The polarizability coefficients of CO_2, N_2, and H_2O used for the conversion of refractivity to temperature and pressure* have been determined

*To convert from measured refractivity N(h) to pressure we use the relations $N(h) = n(h) \sum_i f_i(h)\, \alpha_i$, $P(h) = n(h)\, k\, T(h)$, and $T(h) = T_0 N_0 / N(h) + m/[kN(h)] \int_h^{h_0} N(h)\, g(h)\, dh$ where $f_i = n_i/n$ is the fraction of constituent with polarizability α_i. Discussion of the effect of water vapor on the temperature and pressure measurements is deferred until Section 3.

in the range of the Mariner 5 temperature and pressure measurements by Essen and Froome (1951), and more recently Tyler and Howard (1969) have verified the CO_2 coefficients. From the measurements made by Essen and Froome of the refractivity of a mixture of CO_2 and H_2O vapor there is no evidence that it differs from the refractivity computed using the polarizability coefficients of the separate constituents.

We shall see in Section 3 that correction of the Mariner 5 P(T) profile to account for effect of the Venus H_2O vapor content given by Vinogradov et al. (1970) removes the apparent converging of the P(T) profiles at 300K and thus reinforces the assumption of the existence of a uniform 28% separation. The possibility that one or more unknown polar substances could cause the uniform 28% separation was examined. It was found that not only would large amounts be required, but the sensitivity of the polarizability of these substances to temperature would require mixing-ratios which vary roughly as the inverse of temperature. No reason has been found which suggests a highly specialized mixing-ratio profile of large size and unusual shape.

The remaining parameter used in determining the Mariner 5 P(T) profile is $\overline{m}$, the mean-molecular-mass of the atmosphere. Reduction of the value of the average separation between the Mariner 5 and Venera 4 P(T) profiles to zero requires that $\overline{m} \simeq 41.2$g/mole, but this expedient encounters difficulties. For a carbon dioxide and nitrogen atmosphere the required 82.5% CO_2/17.5% N_2 is in disagreement with both the CO_2 and the N_2 measurements of Vinogradov et al.

(1970). If we suppose a primitive atmosphere as suggested by Suess (1964), we can obtain an atmosphere of 88% CO_2/12% Ne, but 88% CO_2 is still considerably less than the 93% minimum amount determined by Vingoradov. An atmosphere of 93% CO_2/7% He satisfies the minimum CO_2 requirement but because of the greater escape rate of He both during and after the formation of Venus, the amount of He remaining is considered to be much less than that of Ne. Furthermore, the measurement method used by Vinogradov requires that the total quantity of gases such as He, Ne, and Ar which would remain in the gas analyzer chamber after the analysis was completed cannot exceed the 4% uncertainty in the CO_2 measurements or the 2% uncertainty in the N_2 measurement. The 3% Ne we have assumed to exist in the atmosphere appears possible, but neither the suggested 12% Ne or 7% He which are required for $\overline{m}$ = 41.2 g/mole are consistent with Vinogradov's measurement errors. * Finally, we can see in Figure 5(b) that the use of $\overline{m}$ = 41.2g/mole to eliminate the average separation results in a poorer fit of the Venera 4 and Mariner 5 P(T) profiles than does a 28% translation in pressure with $\overline{m}$ = 43.3g/mole. **

If a permanent constant-percentage pressure-separation or the equivalent implied temperature-separation of the P(T) profiles is a characteristic of the Venus atmosphere and not due to measurement difficulties, matching the shapes

* We have studied the descriptions of the equipment and techniques used by Vinogradov and conclude that the error limits of his measurements are reasonable. See also Surkov et al. (1970).

** The water vapor correction described in Section 3 has not been applied to the Mariner 5 curves in Figure 5.

of the Mariner and the Venera P(T) profiles as in Figure 5(a) would enable one to determine the mean-molecular-mass of the Venus atmosphere. From this procedure a mean-molecular-mass is obtained which lies in the interval 43.1 to 44.0 g/mole.

Because of the apparent lack of any satisfactory measurement-difficulty explanation for the uniform 28% separation we are led to assume that the separation is a characteristic of the Venus atmosphere and to search for some physical basis for this characteristic. We are unable to relate the 28% separation to the longitudes of the measurement positions. In the body-fixed coordinates of Figure 6 there is shown a Westward longitude progression of 0°, 28°, and 90° for Veneras 4 and 5, and the Mariner 5 exit, but there is no apparent related progression in the separation of the P(T) profiles in Figure 4. If, as suggested in Section 6 the true Venera 4 entry was 20° W of the position given by Avduevsky, the Venera entry positions in Figure 6 are now more closely bunched. The resulting increased asymmetry of the Venera positions with respect to the Mariner 5 exit and entry positions then suggests that the Mariner 5 day and night P(T) profiles should show a longitude dependence, but it is seen that they are identical.

The fact that in the solar coordinate system of Figure 1 the Venera measurements all have about the same separation in longitude from the Mariner measurements suggests that the cause of the 28% separation is more simply related to the solar coordinate system than to the body coordinate system. However, the location of the sun near the position of the Mariner 5 signal exit introduces an asymmetry that hinders relating the 28% separation to longitude for both the solar and body-fixed coordinate systems. In Figure 17 it can be seen that the positions of the Venera and Mariner measurements in relation to the geometric shape of the equatorial plane and to the planet center-of-mass also fail to provide an explanation for the separation of the P(T) profiles.

Both the solar coordinate system of Figure 1 and the body-fixed coordinate system of Figure 6 have the latitude progression of 3, 6. 15, and 30° for Veneras 6, 5, 4, and Mariner 5 respectively but in Figure 4 we see no apparent related displacement of the P(T) profiles. It is possible, of course, that a non-linear relation exists. Boyer and Guerin (1969), for example, show a non-linear variation of the speed of the equatorial wind with latitude.

Ingersoll (1970) shows that the effect of an equatorial band of high speed horizontal winds is to create a decrease in the height of the isobars as latitude increases. His explanation can account for the uniformity of the pressure separation of the Mariner and Venera P(T) profiles and furnishes a non-linear decrease of isobar height with latitude. However, the decrease of isobar height which he obtains in going from the Venera positions near the equator to the Mariner 5 positions at ~30° from the equator is an order of magnitude smaller than the 2.5km decrease indicated by the 28% separation.

The modification of Ingersoll's work or the use of any other theory to obtain the desired decrease of 2.5km in isobar height encounters two difficulties. Because the Mariner 5 pressure profile at 30° latitude is the radius reference used for the Venera data at the equator, the required 2.5km decrease in isobar height with latitude is reflected as a 2.5km increase in the Venera determined value for the semi-minor axis of Venus. The resulting Venera semi-minor axis value of 6057km* is in reasonable agreement with the value of 6055.8 ± 1.4km obtained by Ash et al. (1967), but in poor agreement with the value of 6053.7 ±2.2km given by Melbourne et al. (1968).** The suggestion that Veneras 5, 6, and 7 may have descended in regions where the surface was 2-3km higher than Melbourne's radius value is only weakly tenable since a radius of 6053.7km leads to an average surface pressure of 77 atmospheres. Muhleman (1970) concluded that CO_2 alone could account for the opacity of the atmosphere for microwaves if the surface pressure was as high as 78.5 atmospheres. Thus a surface pressure of 77 atmospheres accounts for almost all of the measured microwave opacity and essentially excludes the additional atmospheric attenuation measured by Fjeldbo et al. (1971) in the vicinity of 40km and also excludes the finding of Pollack and Morrison (1970) that a source of microwave opacity in addition to carbon dioxide is required to match the microwave emission spectrum measurements.

The second difficulty encountered if we attempt to obtain a 2.5km decrease in surface radius at 30° latitude is related to the fact that, except for a minor temperature dependence, Venus isobars must follow the gravitational shape of

* See Section 11.

** Since the majority of the Earth based radar measurements were made near the time of inferior conjunction, see Figure 17, the results are believed to be biased toward a semi-minor axis value.

the planet. The value of $(-5 \pm 10)\ (10)^{-6}$ for the J_2 gravitational coefficient obtained by Anderson and Efron (1969) from their analysis of the Mariner 5 encounter with Venus indicates that the difference between the polar and equatorial radius of the average gravitational figure of Venus is of the order of 100 meters rather than the required 2.5km or more.* However, the equatorial topography shown in Figure 16, the equatorial equipotential profile of Shapiro et al. (1972), and the radar maps of Goldstein and Rumsey (1970) and Campbell et al. (1970) suggest that there is a probability, although somewhat small, that the 28% separation was caused by the existance of similar local depressions of roughly 2.5km in the equipotential surfaces at the Mariner 5 entry and exit positions. The possibility that these depressions are zonal rather than local seems to be ruled out by the fact that they were not observed as hot bands by the microwave interferometer measurements of Sinclair et al. (1972) discussed below. But local depressions, while explaining the 28% separation, lead again to a semi-major axis value of 6057km.

Finally we shall examine the possibility of a latitude dependence of the height of Venus isotherms as an explanation for the separation of the P(T)

*Primordial Venus according to Singer (1970) might be expected to have had a prograde spin with a period 10 to 20 hours. For a fluid body this would correspond to polar radius depressions of roughly 100km and 30km respectively. For the present rotation period of 243 days we obtain a polar radius depression of the order of 100 meters for a fluid body.

profiles. We assume constant isobar height and using Figure 4 it is seen that for a given isobar there is an increase in temperature with latitude or, in equivalent terms, an increase in the height of the isotherms with latitude.* This increase of temperature with latitude is consistent with the enhanced polar brightness observed by means of the microwave interferometer measurements of Sinclair et al. (1972). They find that the enhanced brightness is equivalent to that obtained for a spherical planet with both poles 16 ± 2.5K hotter than the equator and that the temperature difference between the poles is less than 3K.** Thus we must search for those causes for Sinclair's "hot poles" which may at the same time contribute to an explanation of the separation of the P(T) profiles.

Possible causes for "hot poles" are:

a) A concentration of internal planet-heating-sources at the poles leading to a higher temperature than at the equator.

*In the Venera measurement region the pressure separation of the P(T) profiles is a constant 28% of the pressure, independent of altitude. But the temperature separation is somewhat variable with altitude and thus a simple temperature transformation between the Mariner and Venera P(T) profiles will not be sufficient. It is possible, however, that a simple temperature transformation is the proper first order solution and that the unresolved temperature differences represent second order effects in the Venus atmosphere. The identification and explanation of second order effects will require extensive *in situ* Venus measurements such as those planned in the Venus Pioneer program.

**The magnitude of the inferred pole temperature is based on the assumption of a spherical Venus model with 99.35% CO_2, and with surface pressure, temperature, and radius values of 106 atmospheres, 751K, and 6050km. Although the substitution of a new model cannot change the fact of the measurement of enhanced brightness at the poles it would be worthwhile to obtain an improved value for the inferred pole temperature. Our suggested model is developed in this paper and comprises a spherical planet with the atmospheric structure given in Table 2 and the water vapor profiles discussed in Section 3. The model should also attempt to assess any possible effects due to the precipitation and clouds discussed in Sections 9 and 10.

b) Atmospheric conditions leading to greater direct or indirect solar energy deposition in the polar region than in the equatorial region.

c) An oblate geometric planet figure and a spherical gravitational planet figure which result in greater atmospheric density at the poles than at the equator.

d) Greater planet surface-emissivity in the polar regions than at the equator.

e) Atmospheric conditions which encourage a larger rate of energy loss from the planet surface at the equator than at the poles leading to a cool equator.

No support has been found for a symmetrical distribution of internal planet heating sources which would lead to "hot poles"; nor have we been able to discern atmospheric conditions which would lead to greater solar energy deposition at the poles than at the equator. The analysis by Anderson and Efron (1969) of the Mariner 5 encounter with Venus indicates that the difference between the polar and equatorial radius of the Veneroid, the gravitational figure of Venus, is of the order of 100 meters. A crude estimate indicates that it is necessary for the polar radius of the geometric figure to be 2km less than the polar radius of the Veneroid in order to obtain the atmospheric denity increase required for the measured polar brightness enhancement. A consideration of Earth topography and of the Venus topography measurements of Campbell et al. (1972) discussed in Section 11 suggests that a 2km depression of both poles below the Veneroid is a plausible explanation for hot poles. But this explanation does not at the same time contribute in any way to an explanation of the separation of the P(T) profiles and thus we are reluctant to accept it. It is possible, of course, that the two effects are not directly related and require separate explanations.

According to Sinclair et al. (1972) "substantial surface differentiation, with rock at the equator grading to sand at the poles, could produce... " the same effect as enhanced polar surface emissivity. The possibility must be considered that the poles are cooler than the equator and are covered with a condensate which is fine grained and/or has a higher emissivity than the nominal planet surface material with the result of a net brightening of the poles. This explanation is consistent with both our normal expectation of cold poles and with the possibility of a cloud of condensed material near the equatorial surface.* But in order to explain the separation of the P(T) profiles it is now required that the mid-latitude region be warmer than either the equator or the poles.

There remains the possibility of a cold equator explanation for "hot poles". The visible evidence for a thick cloud C2** which is featureless in the red and infra-red and covers the entire light side of Venus, the S-band attenuation

*Sections 9 and 10

**Section 10.

evidence of Fjeldbo et al. (1971) for thick lower clouds C3 and C4 forming a wide band about the equator, along with possible Venera 7 evidence for clouds C5 and C6 suggests that the boundary of the Venus Heliosphere is well above the planet surface. Below this boundary the principal source of energy is the planet interior.* If the planet internal-energy-sources are uniformly distributed, any variation in surface temperature such as a cool equator, or any wind system which lies beneath the boundary of the Heliosphere must have associated with it some variation in the structure and/or motion of the atmosphere which affects the rate of loss of energy from the planet surface, and the origin of this variation in the structure and motion of the atmosphere must lie above the boundary of the Heliosphere. It is clear that a major part of the equatorial band of high speed retrograde horizontal winds discussed in Section 6 lies within the Heliosphere and must be examined both as to its ability to effect a cool equator** and its suitability in explaining the temperature separation of the P(T) profiles.

Both polar heating and equatorial cooling explanations of Sinclair's results suggest the existence of a circulation cell with cool air descending at the equator and warming and rising as it travels toward the pole. It is clear that such a cell would effect an increase in isotherm height with latitude as is required in explanation of the separation of the P(T) profiles. The substantial equatorial

* Hansen and Matsushima (1967) discuss this possibility for the case of a dust cloud. We find no evidence at the surface for winds of sufficient strength to raise dust and as discussed in Section 10 would substitute condensates for dust. It is possible, however, that there exists dust of volcanic or cosmic origin.

** The cooling rate at the equator is required to be roughly 8 greater than that at the poles.

down-draft obtained below 18km from our analysis of the Venera 7 data, and shown in Figure 11, suggests that such a circulation may take place in the lower regions of the atmosphere. The Venera 4, 5, 6, and 7 data indicate that this down-draft may be a permanent feature* in the vicinity of the equatorial morning terminator, but as yet no evidence has been found which indicates that the down-draft occupies a band about the equator as might be expected for a general equator-to-pole circulation.

If it is assumed that escape of energy from the planet surface takes place at the equator in relation to the equatorial band of high speed winds, and at the poles due to rising currents, a search must be made for evidence for these conditions in the 8-14 micron** I.R. maps of atmospheric temperature by Murray et al. (1963) and Westphal et al. (1965). In a number of instances, particularly when the sub-earth point is near the dark side of the morning terminator, these maps yield temperature contours which are elongated in the direction of the equatorial wind belt and show an abrupt increase in temperature gradient above 15 - 20° latitude in a region where we suppose the wind speed decreased rapidly.*** And in one instance near the South pole there is a 2500km diameter hot region which suggests rising air currents. In general, however, the maps and their descriptions indicate that if coupling exists between

* See Section 5.

** According to Chamberlain (1965) this emission originates from a region where the atmospheric temperature is 255K. Corresponding pressure and altitude from Table 2 are 0.25 atmos. and 55km. The source of this emission is believed to be the top portion of the dense visible global cloud C2 discussed in Section 10.

*** See Section 6.

the temperature contours and the equatorial and equator-pole circulations it is variable and may be influenced by position of the sun and/or by temporal variations in atmospheric motions. Goody (1965) suggests that in this region "dynamical activity.... must be comparable to that on Earth and perhaps stronger."

3. Water vapor content

In Figure 4 in the vicinity of 300K the Venera 4 and 5, and the Mariner 5 P(T) profiles converge. A careful study of this apparent boundary to the separation of the P(T) profiles is important to our further understanding of the cause of the separation. We shall first consider whether error in the initial pressure and temperature measurements of the Venera 4 and 5 probes can be the cause of the convergence. Then we shall examine the effect on the convergence of error in the Mariner 5 measurements.

Five sources from which initial Venera measurement error might arise have been identified: digital system "initial error", initial gauge-response-error, systematic gauge measurement-error, frosting of the temperature sensor, and other-gauge interposition. In a digital data system we have no means for determining whether the first measurement number returned represents the beginning, center, or end of the measurement encoding interval.* Thus, for Veneras 4 and 5, the first pressure and temperature measurement numbers must in each instance be less than or equal to the true values of pressure and temperature which, if known, could increase the rate of convergence, maintain the profiles as they are, or sustain the uniform 28% separation. Initial gauge-response-error is related to the ability of the gauge sensor to adjust itself to ambient conditions in the interval between deployment and the first measurement. For the Venera 4 pressure gauge described by Avduevsky et al. (1969)

* In the example of digital measurement shown in Figure 12 consider the problem of constructing the true temperature profile if the first measurement return had occurred at 34.5^m.

and an appropriate gas inlet-system we estimate a total time-constant of roughly 0.2 sec and thus the error in the initial pressure-gauge-response is assumed to be negligible. For the Venera 4 and 5 initial descent speeds of 10 and 30 m/s we estimate a temperature sensor time-constant of less than 2 seconds. * Since the temperature of the stowed sensors did not differ greatly from the ambient temperature at the time of deployment, we expect that negligible initial temperature measurement error was obtained. Our estimates of possible systematic gauge error indicate that systematic error in either the pressure or the temperature, singly, is probably not sufficient, but that the combination of a deficiency in pressure with an excess in temperature is sufficient to achieve the observed convergence. Frosting of the temperature sensor would reduce the measured temperatures and thus tend to restore the uniform 28% separation. Error due to other-gauge interposition occurs when a pressure or temperature measurement switch-point is not recorded because information from another gauge is being transmitted at the time. This kind of error can be significant and is seen in the Venera 4 temperature data given by Mickhnevich and Sokolov (1969).

It is apparent at this point that there are enough sources of sufficiently large error to imply that both the agreement of the initial Venera 4 and 5 P(T) values and the convergence of the Mariner and Venera profiles are fortuitous. The fact that the extrapolated Venera 4 point of Vinogradov et al. (1970) shown

* An examination of the response of temperature measuring instruments which are believed to be similar to the IS-164A$_1$ Venera 4 thermometer described by Avduevsky et al. (1969) showed that for the slowest instruments the maximum time-constant was less than 6 seconds. After correction, or for an instrument specifically designed for descent probe use, likely values for the temperature measurement time-constant are less than 2 seconds.

in Figure 7 supports the convergence can be attributed to its having been obtained, in part, by means of an extrapolation of the initial Venera 4 and 5 pressure measurements.* But it is also possible that these errors were not realized, or that they cancelled, with the result that the initial Venera P(T) values are correct. We are unable to determine the validity of the initial Venera P(T) values, but because of the importance of the question of convergence we shall further examine the possibility of error in the Mariner 5 P(T) profiles.

In the discussion of the uniform 28% separation in Section 2 it is shown that the only recognizable source for substantial local error in the Mariner 5 P(T) profiles is local distributions of polar substances. This fact suggests an examination of the effect of the H_2O content of the atmosphere. Shown in Figure 7 is an estimate of the combined water and ice content of the atmosphere by Vinogradov et al. (1970); the water vapor saturation curve; an extrapolated Venera 4 P(T) point by Vinogradov; and the Venera 4, 5, and 6 water vapor measurements described by Vinogradov et al. (1968, 1970). Following the method of Corkum (1952), the estimated water and ice content were considered to behave like dielectric spheres imbedded in a homogeneous dielectric of CO_2, Ne, and water vapor, and an upper limit of one part in 10^4 was obtained for the correction required for the Mariner 5 refractivity measurements. It is clear that increasing Vinogradov's estimated water and ice content by as much a

* The temperature value for Vinogradov's point is obtained by the extrapolation of his water vapor measurement to intersect the saturation line.

factor of 10^2 would have a negligible effect on the pressure and temperature calculated from the refractivity.

The Venera water vapor measurements shown in Figure 7 were obtained by means of electrolytic (e) and manometer (m) instruments. At 298K Venera 5 measurement V5m is likely to be accurate since the manometer instrument is believed to have had a small range and a linear output. For measurements V5e at 298K and at 423K both electrolytic instruments were saturated and the measurements thus set a lower-bound on the water vapor content at these temperatures at the time and place of the Venera 5 measurements. Saturation is expected within a cloud and thus the fact that V5m lies close to the saturation value in a region where a dense and continuous cloud C2* is believed to exist at all times can be interpreted as an indication of both the accuracy of V5m and the continuity in time and space of C2. For this reason we shall select the saturation curve to represent permanent planet wide conditions for the region 249.5K (56km) to 285K (52km). Venera 6 measurement V6m is also believed to be accurate and is used with V6e and V5m to obtain the crude Venera 6 profile shown in Figure 7. For Venera 4, V4e represents saturation of the electrolytic instrument and V4m represents a water vapor content less than the minimum value measurable by the manometer instrument. Thus for an initial trial correction of the Mariner 5 P(T) profiles we use the Venera 6 water vapor profile.

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* See Section 10.

The increase in refractivity due to the Venera 6 water vapor profile was computed using the work of Essen and Froome (1951) and was subtracted from the measured Mariner 5 refractivity. The resulting refractivity profile was used to compute the corrected Mariner 5 P(T) profile given by the dashed line in Figure 7. We find that the water vapor correction has restored the 28% separation both at the Vinogradov point and at the initial Venera 4 and 5 measurement points. As a result of this additional consistency it shall be assumed that, despite our earlier finding of the possibility for significant error, the actual error in the initial Venera 4 and 5 pressure and temperature measurements is small and that there is an initial 28% separation of the Mariner and Venera P(T) profiles.

At 315K the Venera 6 water vapor correction has resulted in a 45% separation of the P(T) profiles. As an exercise we construct in Figure 7 a Mariner 5 water vapor profile which will everywhere result in a 28% separation of the Mariner 5 and Venera 4 P(T) profiles. We then search for a possible justification for this procedure by examining the implications of the difference between the assumed Mariner 5 water vapor profile and the measured Venera 6 water vapor profile. If the proposed Mariner 5 water vapor profile is correct, the Venera 4 and Mariner 5 data present a sub-adiabatic region at 302K (49.5km) which, like the sub-adiabatic region at 370K, apparently extends from 30°S to 30°N in a band about the equator. Furthermore, the Venera 5 P(T) data obtained 18 months later suggests that in the vicinity of the equatorial morning terminator the sub-adiabatic region at 302K is either recurrent or permanent.

We now examine a number of possible implications of the difference between the Venera 6 water vapor profile and the water vapor profile proposed for the Mariner 5 entry and exit positions:

a) The difference is due to small-scale and possibly variable conditions at the Venera 6 descent region.

b) The difference is longitude dependent. At the equatorial morning terminator the Venera 4, 5, and 6 water vapor profiles are identical and unchanging, and in the vicinity of the sub-solar and anti-solar points the Mariner 5 day and night water vapor profiles are identical and unchanging, but different from the Venera profile.

c) The difference is latitude dependent and unchanging.

d) The difference is time dependent and independent of latitude and longitude.

The band of high speed retrograde horizontal winds surrounding the equator seems to have succeeded in establishing identical day and night-side Mariner 5 P(T) and water vapor profiles, despite the great separation of the measurement regions and the great difference in incident energy. This fact suggests that a difference between Venera 6 and Mariner 5 entry water vapor profiles, both of which are on the night-side, is not likely to be due to local and possibly variable small-scale conditions or to be related to longitude.

If it is assumed that, despite the band of high speed retrograde horizontal winds, the Venera 4 water vapor profile differs from the Mariner 5 profile and is identical with the Venera 6 profile, the change in the water vapor profile with latitude must occur between the Venera 4 position at 15°N and the Mariner 5 position at 30°N. It is in this region that the increase in isotherm height with latitude indicated by the separation of the P(T) profiles is obtained, but as yet we are unable to explain how a sharp decrease in water vapor content at 310K might be related to an upward displacement of the isotherms.

If it is assumed that the Venera 4 and Mariner 5 water vapor profiles are identical, then any change in the water vapor profiles with latitude must have taken place between the Venera 6 location at 6° latitude and the Venera 4 location at 15° latitude. It is in this region that Boyer and Guerin (1969) find a rapid decrease in the speed of the retrograde horizontal winds with increasing latitude. We are left with the suggestion that the slow decrease of water vapor content with decreasing altitude shown by the Venera 6 water vapor profile may be due to the existance of higher wind speeds at low latitudes. *

Lastly we consider the possibility that at any time the vertical distribution of water vapor is roughly the same within a 60° band surrounding the equator and that the difference between the Venera 6 and Mariner 5 water vapor profiles represents a change in the vertical distribution of water vapor with time.

* The sharp decrease in Mariner 5 water vapor content at 315K (47.3km) in Figure 7 corresponds to an apparent minimum in the Venera 4 horizontal wind speed at 47.3km in Figure 10. We do not attempt to relate the two effects at this time because of uncertainty as to the proper procedure for analysis of the Venera 4 winds data.

Variations with time of the water vapor content in the vicinity of 20 to 30km altitude may have been observed by Jones et al. (1972) in their measurements of 18.5 to 24.0 GHz Venus radiation (a) near inferior conjunction in 1964, (b) during a period including the Venera 4 and Mariner 5 encounters with Venus in October of 1967, and (c) for a four month period starting in January of 1968. They suggest that during the Venera 4 and Mariner 5 encounters in 1967, the water vapor content in the measurement region was 0.1% or less by volume and was essentially unobservable, but that near the 19[illegible] inferior conjunction and also during the period from 3 months to 7 months following the Mariner 5 encounter with Venus the observations were compatible with the presence of possibly 3 times the minimum observable amount of water vapor. The absence of water vapor in October of 1967 is, of course, consistent with the reduced water vapor content assumed for Mariner 5 in order to maintain the 28% separation of the Mariner and Venera P(T) profiles.* The subsequent measurements made by Jones et al. in 1968 indicate that a time interval of from 3 to 7 months may characterize the variability of the large-scale vertical distribution of water vapor.** The water vapor measurements raise the interesting question of where did the water go during the 1967 encounter and why.

*The Mariner 5 and Venera 6 water vapor profiles yield average water vapor mixing ratios of $1.1\ (10)^{-4}$ and $2.5\ (10)^{-4}$ for the region from 0 to 60km. Total water vapor content is 9 g/cm^2 and 20 g/cm^2 respectively.

**It should be noted that there is a large change in the solar coordinate longitude of the sub-Earth point on Venus between the time of the October 1967 encounter and the end of the measurement period 3-7 months following this encounter. Thus the increased water vapor content which was observed could be described as either a transient or longitude effect. Earlier in this section we dismiss the possibility of a longitude effect.

4. Winds data

Venus winds are obtained by means of the Venera 7 temperature and Doppler measurements published by Avduevsky et al. (1971a) and shown in Figure 8. Because of difficulties inherent in one-way Doppler systems and arising also from deterioration of the Venera 7 parachute, the Doppler data must be examined in detail.

The Doppler frequency depends mainly upon the rate-of-separation of the Venus probe transmitter and the Earth receiver caused by (1) the rate of separation of the centers-of-mass of Earth and Venus, (2) the rotations of Earth and Venus, and (3) the vertical and horizontal motions of the Venus probe as it descends to the surface.* That portion of the total separation-rate caused by Earth and Venus motions can be predicted accurately and has been subtracted by Avduevsky from the total separation-rate to obtain f_D which is thus related only to motion of the Venus probe relative to the Venus surface.

From 2.8^m to 13^m the Venera 7 probe descended with a reefed parachute. The abrupt change in the slope of f_D at 3.8^m in Figure 8 is found to be due primarily to the peak in the vertical wind profile shown in 44km in Figure 11. At 13^m the parachute reef was removed and the descent speed slowed abruptly. At 19^m there is an abrupt increase in f_D which, based on an exhaustive examination of conceivable causes, is believed to be due to the parting of a shroud line or to tearing of the canopy. From 19^m to 21^m there is a further increase in f_D which

* There are in addition transmission media and equipment contributions to the Doppler frequency. These effects are small and the error remaining after their correction is negligible.

suggests slowly occurring additional parachute deterioration, but it is interpreted later as due primarily to a sharp rise in the horizontal wind profile shown at 19km in Figure 11. Starting in the vicinity of 23.5^m there is an oscillation in f_D that continues with increasing period to 33.3^m. Based on Earth experience the regularity of the oscillation precludes the possibility that it was caused by atmospheric motions. Pendulum motion alone cannot be the cause of the oscillation because the length of the parachute lines suggested by the oscillation-periods would be far too large, and because the oscillation-periods continually increase. Further examination of the shapes of the individual oscillations suggests that the motion of the probe resembled to some extent the periodic swoop and glide obtained by an unbalanced glider. We propose that assymmetric parachute deterioration resulted in a combination of pendulum motion, and a swoop and glide motion during which considerable lift forces were obtained. Minima in the true descent speed occur at times of maximum lift and thus correspond to times of maximum horizontal speed. Figure 10 shows that the near zenith position of Earth results, at most, in a small Earth-component of horizontal speed and that, depending upon its direction, the component can either add to or subtract from the Earth-component of the descent speed.

At 33.3^m in Figure 8 oscillation due to swooping has diminished and there is a steady glide which developes almost constant lift. At 34^m there is an abrupt change in speed suggesting a second major deterioration of the parachute. However, an extrapolation of the new values of f_D backward in time forms an envelope for the maxima of the preceeding oscillations. The fact that the maxima of f_D represent the time at which minimum lift occurred suggests that because of increasing turbulence in the flow past the parachute, or because of minor additional parachute deterioration at 34^m, the gliding was greatly reduced and the probe returned essentially to a standard "no-lift" descent. *

In Section 7 it is shown that there is a possibility of an eastward drift of the probe at 3.5km (34^m) above the mean surface. If this point is used as a reference, the wind profiles of Figure 11 and the shapes of the Doppler oscillations suggest the descent motions shown in Figure 9. ** From Figures 9 and 10 it can be seen that under these circumstances the Earth-directed components of the swoop-and-glide motion cause a reduction in the Doppler speed.

After the Venera 7 data processing described later in this section was completed and the wind profiles shown in Figure 11 were obtained, re-examination of the Doppler data led to several additional observations.

1. The uniformity in shape and amplitude of the oscillations between 24.1^m and 33.3^m suggests that throughout this period the plane of the swoop and glide motion remained fixed. The gradient in the estimated prograde or South-directed wind from 13km to 4km may have been the agent for maintaining this fixed direction.

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*During descent the Reynolds numbers associated with the probe and its parachute are roughly two orders of magnitude greater than the critical value of $3.5\ [10]^5$. Thus we are unable to associate anomalous descent speed changes with a Reynolds number transition.

**Note from Figures 9 and 14 and from Table 1 that Venera 7 landed at a position 0.5km higher than the mean surface.

2. In the region between 21.3^m and 23.5^m there are additional oscillations. The uniformity in amplitude of these oscillations suggests that the plane of oscillation remained fixed and that the oscillations were driven by the strong gradient in the retrograde wind between 17 and 14km. The periods of the oscillations seem to be identical and approximately 5.4 sec, corresponding to an effective pendulum length of 6.5 meters for the Venera 7 parachute system. The amplitude of the oscillations coupled with the motions shown in Figure 9 indicates pendulum excursions of as much as 40° from the vertical.

There are suggestions of oscillations in the Doppler data prior to 21.3^m but we are not able to determine the shapes or frequencies or to relate them to the wind profile. The amplitude of pendulum oscillation should increas following the release of the parachute reef at 13^m and it is expected that the plane of the oscillations remains fixed in direction in the vicinity of strong gradients in the horizontal wind such as the gradient at 19km. The detection of fixed plane oscillations in the Doppler data in the vicinity of 19.9^m to 20.6^m (19.5km to 18.5km) and their association with similar oscillations at 21.3^m to 23.5^m (17 to 14km) would present additional evidence for the existence of the horizontal wind at 18km.

An additional Doppler data consideration for a one-way measurement system is the change in the frequency of the probe transmitter resulting from the temperature and shock environment obtained during descent, at impact, and after landing. Temperature induced frequency change is believed to be negligible during descent since the first evidence for drift in the Doppler frequency appears at about 5 minutes after landing. During descent the maximum shock occurred at the time when the parachute reef was removed and is believed not to have exceeded 4 g. Impact on the surface was at an estimated 13.5 m/s with an estimated peak deceleration of as much as 1000g if the landing was on a hard smooth surface, or 50g if there was a 0.5 meter penetration of a granular surface. The measured reduction of signal strength of a factor of 30 after landing is believed by Avduevsky et al. (1971b) to have been caused by a displacement of the antenna beam direction by 50° or more immediately after impact. This rolling displacement of the spherical descent probe suggests a hard impact with a minimum impact deceleration of 200g or larger.

From these considerations it seems reasonable to assume that the probe transmitter frequency remained essentially constant during the entire descent but changed by a discrete amount as a result of high shock during impact. A single correction to the transmitter frequency measured following landing should be sufficient to obtain the true Doppler frequency during descent from the measured Doppler frequency f_D.* It will be implicit as we proceed that this correction, selected by trial and error, is a crucial parameter which at this stage in our knowledge of Venus influences, or is influenced by, almost every facet of our final Venus model - winds, temperature lapse-rate, clouds, and planet radius.

* The required frequency correction Δf_D -16 Hz corresponds to an impact speed correction of -5.2m/s.

Our first use of the Venera 7 Doppler and temperature data was an attempt to obtain further evidence that P(T) profiles remain unchanged with time at the equatorial morning-terminator region of the Venera measurements and that the sub-adiabatic regions at 16 and 40km were permanent features of the atmosphere.* We computed a family of Venera 7 P(T) profiles by using the ideal gas law and the hydrostatic equation with (1) the temperature data, (2) a family of Doppler descent speed profiles displaced by the assumption of different initial values, (3) a mean-molecular-mass of 44.3, and (4) a series of initial pressure values P_o - and with the assumption of no winds. In each instance these computed profiles showed substantial differences from the Venera 4, 5, and 6 P(T) profiles. The amplitudes and distribution of these differences were such that the only satisfactory explanation was found to be the existence of winds. In Figure 4 the agreement between the Venera 4, 5, and 6 P(T) profiles is good except in the region between 320 and 390K where we believe there was difficulty in determining the proper Venera 5 and 6 profiles. Thus in order to further evaluate the Venera 7 measurements it is reasonable to start with the assumption of an unchanging structure for the lower atmosphere of Venus. As a result the original objective was abandoned. It is now assumed that the structure of the lower atmosphere in the vicinity of the Venera entries is unchanging, and an attempt is made to extract wind information from the Venera 7 data.

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* The sub-adiabatic region at 16km is seen in the Venera 5 and 6 P(T) profiles in the vicinity of 590K in Figure 4. See also Figure 13.

The procedure for obtaining winds requires that we determine (1) the true probe descent speed, (2) the unperturbed* probe descent speed, and (3) the adjusted Doppler speed.** As can be seen from the Doppler geometry shown in Figure 10 subtracting the true descent speed from the unperturbed descent speed yields the vertical wind speed; and subtracting the true descent speed from the adjusted Doppler speed yields a horizontal-wind component. In this instance the Venera 7 Earth-Venus geometry limits the horizontal wind determination to East directed (prograde) or West directed (retrograde) components.***

* The unperturbed probe descent speed is obtained by removing the effects of lift, glide, and vertical winds from the true probe descent speed.

** The measured Doppler frequency is corrected for the frequency change obtained at impact, multiplied by the secant of the angle of Earth from the zenith, and then converted to speed.

*** Our analysis indicates that the 11.3° displacement of Earth from the zenith cited by Avduevsky is toward the East, and that the North-South displacement is negligible.

5. Vertical winds

First the true descent speed is determined. The Venera 4 pressure and temperature values, shown in Figure 4 from 300 to 460K, and the Venera 5 and 6 values from 460 to 600K, are used with the hypsometric formula* to obtain an average Venus temperature vs altitude profile T(h). T(h) is then used with the Venera 7 T(t) profile to yield the true descent speed of the probe shown in Figure 10 by the heavy line from 3^m to 23^m.

From 23^m to the surface the true descent speed must be estimated. Accounted for in the estimation are (1) the change in the sign of the gradient in the horizontal wind as deduced from the shapes of the Doppler oscillations shown in Figure 9, (2) the wind-speed and the speed changes near the surface discussed in Section 7, and (3) the limits placed on vertical wind speeds at the beginning of probe descent. We assume that the large retrograde horizontal wind at 21^m (18km) is replaced at 23.5^m (14km) by the small prograde or South-directed wind discussed in Sections 6 and 7, and as a result the adjusted Doppler speed from 23.5^m to the surface must be essentially the same as the true descent speed. However, it is necessary to consider the small corrections to the adjusted Doppler speed needed to remove the Earth components of (1) pendulum motion, (2) horizontal glide speed, and (3) estimated horizontal wind speed. In the earlier region from 17 to 14km (21.3^m to 23.5^m) where a high gradient in the horizontal wind seems to have caused large amplitude pendulum motion,

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*$h_2 - h_1 = (R\bar{T}/mg)\ln(P_1/P_2)$.

the Earth component of the pendulum motion was $\sim\pm 1$m/s. In the lift region from 23.5^m to 34^m (14 to 3.5km) the gradient of the horizontal wind is estimated to be smaller by possibly a factor of 100 and thus the pendulum motion component is expected to be negligible and is ignored. The horizontal glide speed cannot be accurately determined from the available data. We estimate, however, that its average Earth component was about 20% of the peak-to-peak amplitude of the oscillation of the adjusted Doppler speed. The low-speed-boundary of the oscillations of the adjusted Doppler speed was raised* by the estimated amount.** The estimated horizontal wind in the lift region is shown in Figure 10 and is developed in Sections 6 and 7. For either a prograde or a South-directed horizontal wind the maximum correction to the true descent speed is less than 0.4m/s and the total correction to the distance descended is less than 0.1km. These corrections are ignored. The preceeding corrections are small and result in a difference between the adjusted Doppler speed and the estimated true descent speed that is everywhere less than 1m/s.*** The resulting estimated true descent speed is shown in the lift region of Figure 10 by the heavy line.**** In Section 11 there is a discussion of several of the consequences caused by a major deviation from this estimated true descent speed.

* In accordance with the geometry shown in Figure 9.

** Estimated maximum values for the Earth-directed components of the horizon-glide-speed varied from 0 m/s at 23^m to 2 m/s at 34^m.

*** Except in the interval 33^m to 34^m where the correction went from 0.9 to 2.0m/s.

**** For ease in presentation we show a smoothed curve.

Next we determine the unperturbed descent speed. During unperturbed descent by parachute, the descent speed is inversely proportional to the square root of the atmospheric density. Atmospheric density* is obtained through use of the ideal gas law and the hydrostatic equation with the Venera 7 T(t) data, the computed and estimated true descent speed, the measured mean-molecular-mass, and a Venera reference pressure-point of 6.85 atmospheres at 456.3K. We assume that there is no wind and negligible lift at the Venus surface, use the true descent speed obtained at the surface as our reference speed, and from the atmospheric density compute the unperturbed descent speed for the entire descent. In performing this calculation it is necessary to introduce the indicated step changes in the descent speed at 13^m where the parachute reef was removed and at 19^m where major parachute damage occurred. The true descent speed is subtracted from the unperturbed descent speed to obtain the vertical wind profile shown in Figure 11.

In the lift region, however, the difference between the true descent speed and the unperturbed descent speed also contains an apparent vertical wind due to lift. This "lift-wind" must be removed either from the difference or from the true descent speed. The dashed line of Figure 10 shows the true descent speed with the "lift-wind" removed. This no-lift curve corresponds roughly to the upper envelope of the oscillations of the adjusted Doppler speed, but with the effect of the small prograde or South-directed wind removed. The small

* See Table 2.

difference between the dashed curve and the dotted curve at 31^m is believed to represent the effect of unanticipated additional lift that developed during this portion of the flight contrary to our assumption that lift disappeared completely during a portion of each swoop-glide cycle. In regions where there are high gradients in the vertical wind, inertia delayed the probe's response to changes in the wind. The maximum inertia-correction applied to the computed vertical wind profile was -0.5m/s at 46km.

Variations in the Venus atmosphere with time and position, error in the Venera 7 temperature data, error in the estimation of the true descent speed, and error in the measured mean-molecular-mass could lead to uncertainties of the magnitude of the up-draft at 22km. With the given data, however, we cannot determine any means for removing the large gradient in the vertical wind at 15 to 20km. The prominence of this gradient and the gradient at 41 to 44km argues strongly that there must be some evidence for them in the Venera 4, 5, and 6 measurements. Our examination of these measurements confirms the presence of the gradients although we find only their average effects, i.e., a small net down-draft in the vicinity of 19km and a small net up-draft in the vicinity of 44km. The net down-draft at 19km is in agreement with our wind profile but the net up-draft at 44km indicates that our down-draft should be decreased by about 1m/s in the region 30 to 42km.* The Venera 7 up-drafts at 22km and

* An upper limit to an updraft at 45km at 15°N is set by the 10m/s parachute descent speed that would be obtained by Venera 4 in this region in an unperturbed atmosphere. Venera 4 must be allowed to descend. If vertical and horizontal wind speeds are assumed to have the same latitude dependence determined by Boyer and Guerin (1969) and discussed later in this section we obtain an upper limit of 17m/s to the Venera 7 vertical wind speed at 45km.

45km are consistent with the evidence discussed in Sections 9 and 10 for precipiuation at 19km and for clouds C5 and C3 in the vicinity of 22km and 45km.

The association of the up and down-drafts at 42km with the equatorial sub-adiabatic temperature lapse-rate region at 40km discussed in Section 1, and with the equatorial high speed retrograde horizontal wind layer shown in Figure 11, suggests that the up and down-drafts also occupy an equatorial band. The Venera 5 and 6 pressure and temperature measurements and the Venera 7 data suggest that the up and down-drafts at 20km are a recurrent or permanent feature in the vicinity of the equatorial morning-terminator but as yet no evidence has been found which suggests that they occupy a band about the equator.

6. Horizontal winds

The horizontal-wind-component shown in Figure 11 is obtained by subtracting the true descent speed from the adjusted Doppler speed and multiplying the difference by the cotangent of the angle of Earth from the zenith as shown in Figure 10. It is assumed, as in computing the vertical wind, that there are no winds at the surface and thus the true descent speed at the surface is used as the reference value for obtaining the adjusted Doppler speed. In the lift region, we must estimate the horizontal speed. Our estimation, shown in Figure 11, considers (1) the change in the sign of the gradient in the horizontal wind as deduced from the shape of the Doppler oscillations in Figure 9, (2) the wind speeds at the surface discussed in Section 7, and (3) the dissipation near the surface of the down-draft at 15km discussed in Section 7. The change in shape of the Doppler oscillations suggests that the down-draft should be channeled into either a prograde or pole-directed wind. The hot pole considerations in Section 2 along with the South-of-the-equator location of Venera 7 descent suggest that the down-draft should be channeled toward the South-pole. Since the estimated prograde or South-directed wind is small, the difference between the true descent speed and the adjusted Doppler speed is not distinguishable in Figure 10 in the region from 23.5^{m} to impact.

In regions where there are high gradients in the horizontal wind, inertia delayed the probe's response to changes in the wind velocity. The maximum inertia correction applied to the computed horizontal wind profile was -10m/s at 45.5km. Possible errors in the Doppler frequency-correction and in the geometry of the sub-Earth and impact points, * along with the possible errors presented in the preceeding discussion of vertical winds, could lead to horizontal wind uncertainties of 5-20m/s over much of the measurement region, but use of the maximum permissible error still leaves the large retrograde winds at 18km and 44km. The possibility that a portion of the high retrograde wind at 47km was due to horizontal motion remaining from the high speed entry was studied, but it was found that the terminal speed for the probe with parachute undeployed would have been reached prior to first Doppler measurements taken at 2.8^{m} with the parachute deployed.

The dot-dash line at the bottom of Figure 11 is the Venera 4 wind data given by Kerzhanovich et al. (1969), ** and is equal to the difference between the adjusted Doppler speed*** and the unperturbed descent speed. As shown in Figure 10 this difference is the vector sum of the vertical wind speed and the vertical projection of the Earth-directed component of the horizontal wind-component. **** If, as suggested by the Venera 4, 5, and 6 temperature and pressure measurements, the vertical winds in the vicinity of the equatorial morning terminator from 15km to 49km altitude are a permanent feature of

* Error in our knowledge of the coordinates of the impact position may be the greatest contribution to error in the horizontal wind-component. It affects both the magnitude and direction of the horizontal wind but not its shape.

** We have changed the sign of Kerzhanovich's data for reasons discussed later.

*** In this instance the adjusted Doppler speed is uncorrected for frequency drift obtained during the flight to Venus and during entry into the Venus atmosphere.

**** The Venera 4 Doppler geometry is, however, different from Venera 7.

this region; if the vertical and horizontal winds in this region are only mildly latitude dependent; and if the horizontal wind in the region is predominently zonal and retrograde, the Venera 7 vertical wind W_7 should be able to be added to the Venera 4 difference data V_K to reconstruct a Venera 4 horizontal wind-component $U_4 = (W_7 + V_K + W_o)\, C$ which is roughly identical to the Venera 7 horizontal wind-component shown in Figure 11. W_o is the speed correction associated with the Venera 4 transmitter frequency change which occurred prior to parachute descent, and C is the Venera 4 Doppler geometry constant. For the best fit, which is shown by the upper dot-dash line in Figure 11, our value of $W_o = 9.5$m/s is close to Kerzhanovich's suggested limit values of $\pm$6m/s, and our value of $C = 4.5$ lies within the range 2.8 to 5.2 suggested by Kerzhanovich.

Although we obtain a satisfactory matching of the Venera 4 and 7 horizontal wind profiles, two expedients are required. New coordinates are necessary for the Venera 4 entry location, and the sign of the Venera 4 difference data given by Kerzhanovich must be changed. The Venera 4 entry is generally believed to have occurred 15° N and 5° E of the sub-Earth point. The new location at 15° N and 15° W of the sub-Earth point lies, however, within the region allowed by the ambiguity and error in the method used for determining the entry location. We have been unable to find any combination of Venera 4 entry geometry and E-W or N-S winds which can eliminate the requirement for these changes. It can be seen from Figure 11 that if the Venera 7 vertical wind is added to the Venera 4 difference data without the suggested change in sign, the high speed horizontal wind at 45km at the Venera 4 location at 15°N would be essentially eliminated.

Because of the relatively large error in determining the true descent speed of Venera 7 in the region from 45 to 47km, the calculated Venera 7 horizontal wind-component of 125m/s could be in error by as much as 50m/s. A wind speed of 125m/s is consistent, however, with the speed of 110m/s obtained by Boyer and Guerin (1969) from their analysis of the average period of the retrograde rotation of the permanent Y cloud features seen in ultra-violet light in the vicinity of 70km (0.01 atmos.)* Boyer and Guerin's measurements are in agreement with the Doppler measurements of cloud motion in this region by Guinot (1965) and Guinot and Feissel (1968) at 5500-5700Å. Recently N. P. Carleton (1972) has measured the Doppler component of the 8710Å CO_2 line originating in the vicinity of 60km (0.1 atmos.) in the equatorial region and finds retrograde winds of roughly 100m/s at 20° to 30° East and West of the sub-solar point. The spacial distribution of the in situ Venera 4 and Venera 7 winds data, Boyer's photographic wind-measurements, Guinot and Feissel's, and Carleton's Doppler wind measurements, the congruent Mariner and Venera P(T) profiles, and the identical Mariner temperature profiles combine to present evidence for a wide band of high speed retrograde winds surrounding the

* Boyer and Guerin (1969) find a spectrum of cloud speeds ranging from 68 to 229m/s. Nikander and Boyer (1970) find lower and upper limits for the velocity of individual clouds of 89m/s and 205m/s respectively.

equator and extending from the one atmosphere level at 46km to above the 0.004 atmosphere level at 75km.*

Boyer and Guerin (1969) find a distinct change in the speed of the visible clouds with latitude. The average rotation period is 4 days from 0 to 5° latitude, and at 5° they obtain an almost linear increase to a period of 6.5 days at 15°. If it is assumed that this latitude effect extends from 70km downward to 35km and affects both the horizontal and vertical Venera 4 winds, the profile shown by the dotted line in Figure 11 is obtained. The improved agreement in shape between the Venera 4 and Venera 7 horizontal wind profiles in the region between 20 and 40km suggests that the latitude dependence of the wind speed may extend downward to 35km at 15°N.

*In an interview with the Novasti press agency, A. P. Vinogradov has reported on the analysis of the new data on Venus from the Venera 8 probe. There is practically no movement of the atmosphere at the surface, and weak winds begin to occur only at altitudes of several kilometers. However, at 15-20km above the surface, wind velocity exceeds 50m/s, and above 45km it reaches a velocity of 100m/s. (EOS, 15, 1151-1152). The altitude reference is not specified.

7. Winds near the surface

The Venera 7 unperturbed descent speed and adjusted Doppler speed profiles are found to differ slightly in the region from the surface* to 3.5km. When the profiles are constructed to have the same speed at the surface, it is found that at 3.5km the adjusted Doppler speed is lower than the unperturbed descent speed by 0.4 ±0.2m/s. This speed difference could be due to: (1) a prograde wind component that increases by 2 ±1m/s from the surface to 3.5km, (2) a South-directed wind which increases by greater than 2 ±1m/s from the surface to 3.5km, (3) additional parachute deterioration which increases the descent speed by 0.4 ±0.2m/s as we approach the surface, (4) a smooth glide with a horizontal speed of 1 ±0.5m/s directed to the East at 3.5km (34^m) and rotating to the West at 0.5km (37.5^m), (5) vertical convection which increases in speed by 0.4 ±0.2m/s from the surface to 3.5km, or (6) some combination of smaller individual values of the above. Since no wind gradient is evident from the Doppler data in the first 0.1km above the surface it is assumed that the down-draft shown at 14km in Figure 11 is the only source for either a prograde or a South-directed horizontal wind. A two dimensional analysis of the down-draft suggests an upper limit to the horizontal wind speed of from 1.5 to 2m/s in the vicinity of 12km and a decrease in speed to 0.1m/s or less at 3.5km. We do not obtain the required minimum values of 1 to 3m/s at 3.5km. Additional parachute deterioration as a solution requires a small but fairly uniform rate of

* The Venera 7 surface is at 0.5km above the mean planet radius.

deterioration over a period of 3.5 minutes. No basis can be found for either accepting or rejecting this solution. A crude estimate for the lift coefficient of the parachute indicates that horizontal speeds of as much as 10m/s were caused by the gliding which occurred directly above 3.5km and thus it is reasonable that some horizontal glide speed remained despite the transition at 3.5km. At the required horizontal glide speed of 1 ± 0.5m/s negligible lift would be developed and, since the prograde or South-directed wind derived from the downdraft is greatly diminished below 3km there is a negligible wind gradient and the glide path would be free to rotate.

There remains the possibility that there is vertical convection which increases in speed by 0.4 ± 0.2m/s from the surface to 3.5km. Avduevsky et al. (1970b) have studied Venus vertical convection in two dimensions for a double vortex cell* in a dry viscous atmosphere with a 30K/km lapse rate at the surface and obtain vertical convection speeds of the order of 35m/s. Based on this study and the measured Venera 7 lapse-rate of 17.5K/km at 3km.** the speed difference of 0.4m/s obtained at 3.5km is too low by almost two orders of magnitude. Because there is considerable noise in the Doppler signal and the difference between the unperturbed descent speed and the adjusted Doppler speed is small we are unable to obtain a speed difference profile which can be compared with the lapse-rate profile of Figure 13 to determine if they are related in any way.

* The vertical current rises at the center of the cell and separates at the top. Vertical and horizontal dimensions of the cell are approximately a scale height, i.e., 16km.

** See Section 8.

The following possibilities must be considered: (a) the lapse-rate of 17.5 K/km at 3km is much too high; (b) the vertical convection speed change is too low; (c) Avduevsky's theoretical convection speeds are too large, or (d) some combination of the above. In Section 11, we will show that attempts to significantly lower the lapse-rate by assuming larger descent speeds below 15km fail because, as shown in Figure 15, they result in obtaining an updraft at 45km which is too large to allow the Venera probes to descend and they result in atmospheric pressures at the surface which are too high to allow the explanations of Muhleman (1968), of Fjeldbo et al. (1971), and of Pollack and Morrison (1970) for the measured microwave attenuation. Any attempt to increase our convection speed change in the region from 0.5 to 3.5km is restricted by an upper limit to the speed difference of 1.1m/s obtained by comparing the Doppler "descent" speed with the unperturbed descent speed obtained for the extreme case of an isothermal atmosphere. This upper limit to the speed difference is still less than Avduevsky's convection speeds by more than an order of magnitude. We have not attempted to extend the theoretical estimates of the vertical convection speed obtained by Avduevsky. It would be worthwhile, for example, to determine whether a major decrease in convection speed is achieved by extending his work to a three dimensional case where the planet surface is covered by closely spaced double vortex cells associated with precipitation and a low lying cloud as suggested in Sections 9 and 10.

For our Venus model we shall assume that the horizontal winds between 0.5 and 3.5km altitude have a negligible gradient and are of the order of 0.1m/s as suggested by the analysis of the down-draft at 14km; and that the measured 0.4 ±0.2m/s speed difference at 3.5km is due to the combined effect of a small increase in vertical convection speed and a slow side-wise probe glide covering 90 to 180° along a circular path.

According to Ronca and Green (1970) surface winds of 0.5m/s or greater at 100 meters altitude are required if dry particles are to be lifted from the Venus surface. We find no basis for predicting equatorial, mid-latitude, or polar region surface winds which are larger than the estimated 0.1m/s surface winds at the Venera 7 landing position. Thus, any dust in the atmosphere is expected to result from other sources such as the collecting of cosmic dust or the injection of dust by volcanic activity.

8. Temperature lapse-rate near the surface

We now examine the Venera 7 temperature profile in Figure 8 in the region from 26^m to the surface. From 26^m to 34^m the change in the slope of the temperature profile is almost directly proportional to the change in the descent speed shown in Figure 10 and thus the profile holds no surprises. At 34^m lift ceases and the average descent speed shows an abrupt increase of roughly 10%. The apparent attendant increase in the slope of the temperature profile should also amount to 10%, but is found to be 65% and thus indicative of a high super-adiabatic lapse-rate. By 37^m the temperature profile has changed from highly super-adiabatic to become almost isothermal. Following impact the temperature decreases. In order to better understand the behavior of the temperature profile after 34^m we attempted a reconstruction of the data, but the reconstruction yielded only the minor revisions suggested in Figure 12. In Figure 13 we show the resulting temperature lapse-rate profile for the region near the surface.

It is assumed that the behavior of the temperature profile near the surface was not caused by erratic operation of the temperature measuring instrument. Typically, these instruments are simple and extremely rugged and there has been no evidence for temperature gauge malfunction on the Venera 4, 5, 6, and 7 probes. Neither the high super-adiabatic lapse-rate at 3km nor the near isothermal lapse-rate at the surface could have resulted from unaccounted-for increases and decreases in descent speed obtained from changes in the parachute and/or from vertical winds since the Doppler data of Figure 8 limits possible speed changes to an order-of-magnitude less than the required minimum speed-change of 65%. Attempts to reduce the 17.5 K/km maximum value of the lapse-rate at 3km by means of varying the curve connecting the reconstructed data points, along with estimates as to possible data reconstruction error suggests that the lapse-rate maximum cannot be less than 15 K/km, or approximately twice the adiabatic value.

The lapse-rate obtained for the surface is influenced by the region of uncertainty in the reconstructed temperature data in Figure 12 and by the assumption that the lapse-rate is monotonically decreasing and positive in the region from 2km to the surface. For these conditions we find that the lapse-rate at the surface can lie within the interval 3.5 ± 3.5 K/km. However, in view of the requirement for a small lapse-rate obtained from the combined microwave interferometer data of Sinclair et al. (1972) and the equatorial topography data of Campbell et al. (1972)* we further restrict the possible range of the surface lapse-rate and assign a value of 2.5 ± 2.5 K/km to the Venera 7 landing position and to a band surrounding the Venus equator.

* See Section 11. Preliminary processing of the data of Campbell et al. indicates that the Venus surface may be essentially isothermal.

9. Precipitation

There appears to be a discrepancy between the Doppler and temperature profiles shown in Figure 8. At 19^m the change in the Doppler frequency corresponds to a factor of two increase in the descent speed but the expected attendant increase in the slope of the temperature profile does not occur until 21^m, 120 seconds later, and at that time the slope of the temperature profile increases by slightly more than the expected factor of two. Since curve-drawing through digital data usually results in some smoothing it is expected that the true change in the slope of the temperature profile is greater than is indicated. It is expected that the true temperature profile is more nearly isothermal as we approach 21^m and/or steeper following 21^m than is indicated in Figure 8. An explanation of the temperature discrepancy should satisfy this requirement.

An examination of the response of temperature measuring instruments which are believed to be similar to the IS-164A, Venera 4 thermometer described by Avduevsky et al. (1969) showed that the 10K and 120 second lag indicated by the temperature profile cannot be attributed to slow instrument response. Even for the slowest instruments the maximum uncorrected lag was less than 1.5K and 6 seconds. After correction, or for an instrument specifically designed for descent probe use, likely values for temperature measurement lag are less than 0.5K and 2 seconds. Nor can speed changes resulting from parachute changes and from winds serve as an explanation since from 21^m to 24^m there is no evidence in the Doppler data of even a small fraction of the required factor of 2 increase in speed. The possibility that a sharp decrease in the temperature-lapse-rate of the ambient atmosphere suppressed the effect on the temperature profile of the abrupt descent speed increase at 19^m (20.7km) and was followed by a sharp increase in lapse-rate starting at 21^m (17.8km) was considered and discarded. We are unable to explain the resulting lapse-rate profile shown by the dot-dash line of Figure 13. A temperature change suppression due to lateral transport of the descent probe system by the horizontal wind at 18km is found to require a gradient of -3K/km* in the horizontal temperature profile. A gradient of this magnitude could be obtained by a downdraft of cool air which spreads laterally.** However, the temperature suppression begins at 20.7km (19^m) in the presence of the up-draft shown in Figure 11 and ends at 17.8km (21^m) well before the down-draft is fully developed. A down-draft explanation of temperature quirk would be more plausible if the quirk occupied the region between 14km to 17km where the down-draft is fully developed.

Finally, because of the presence of an up-draft in this region, it is necessary to consider the possibility that the temperature quirk was caused by condensation or precipitation acting upon the temperature measurement system.*** It is not likely that condensation or precipitation on the body of the descent

* The measured temperature at 21^m is 10^o lower than that given by a descent-speed-determined extrapolation from 19^m; and based on the horizontal wind speed profile of Figure 11 the change is obtained over a horizontal distance of approximately 3km.

** On Earth the lateral spreading of a down-draft from a mature thunderstorm can cause horizontal temperature gradients of greater than 11K/km.

*** Up-drafts are regarded as a necessary, but not sufficient condition for precipitation.

vehicle caused the temperature quirk since for a system designed to thermally decouple the descent vehicle from the temperature sensor a 10K discrepancy seems large. The temperature-sensing element itself may have become "frosted" or moist from its contact with the atmosphere. "Frost" would present the greater problem. Gravity and blowing would tend to prevent accumulation on the sensor of a layer of liquid which was thick enough to result in a 10K error in following the ambient air temperature, but the latent heat of melting would allow frost to establish the 10K discrepancy for short periods. Solid or liquid precipitation are both assumed to be relatively ineffective; both would blow away and the latter would also drain. A non-aqueous "wet snow," it would seem, might present a substantial measurement problem since it resists both blowing and flowing and would attempt to pack the sensor and/or the sensor protector, or portions of them, with a thick relatively long lasting blanket. Furthermore a long constant-temperature melting period followed by a rapid rise in temperature fulfills the requirement stated earlier for a temperature profile which is near isothermal prior to 21^m and/or steeper following 21^m. The data suggests that in the region of high horizontal wind shear at 19km the parachute-suspended descent probe system experienced the same large-excursion oscillations that are indicated in the similar wind shear region at 16km on the low edge of the wind layer*, and that at a time of maximum excursion when the

* See Section 4 and Figure 9.

temperature measuring instrument was displaced to point in a sidewise direction, it accumulated "wet snow".

A study of the various ways in which "frost" or "wet snow" might explain the quirk in the temperature profile suggests that the fusion temperature of the "frost" or "wet snow" material was 556 ±6K at a pressure of 17 atmospheres. Typical candidate materials are $FeCl_3$ and $HgCl_2$.

The quirk in the Venera 7 temperature data is highly visible. If "wet snow" is a continuous event in this altitude region in the vicinity of the morning terminator we would expect to find the same effect in the Venera 5 and 6 temperature data. In the reports on Venera 5 and 6 we cannot find a similar temperature perturbation, but in the Venera 7 report by Avduevsky et al. (1971a) individual Venera 5 and 6 points are plotted and there is a faint suggestion of the effect. Although, according to the Venera 7 data, the effect should amount to possibly 10K, the large encoding interval of 17K, the requirement for sharing the telemetry with a number of other instruments, or the possibility of the use of different temperature sensor configurations may have partially or completely prevented the effect from appearing in the Venera 5 and 6 measurements. It is possible, of course, that "wet snow" at the morning terminator is intermittent. At this time it cannot be determined from the data whether "wet snow" at 19km would be a local Venera 7 effect or whether it would be continually associated with the down-draft at 19km and thus possibly an equatorial morning terminator effect.

It is of interest to speculate in regard to the reason for the behavior of the Venera 7 temperature measurements following landing on the Venus surface. In Figures 8 and 12 it is seen that the output of the temperature measurement instrument either drifted slowly downward after landing or was reduced abruptly at about 38^m. The reduction of the strength of the radio signal from Venera 7 by a factor of 30 immediately following landing suggests a rolling displacement of the spherical descent probe of $50°$ or more and a landing shock of the order of 200g. Thus, it is likely that after the landing motion had ceased the temperature sensor pointed in a near horizontal direction; and in this attitude it may have been exposed to direct access by "rain" or "wet snow"*. It is possible, of course, that landing shock and/or the gradual rise in the internal temperature of the probe which led finally to the probe's destruction could have been the cause of the decrease in temperature gauge output following impact.

As discussed in Section 7, Ronca and Green (1970) require a wind speed of 0.5m/s or greater at 100 meters altitude in order to lift particles from a dry Venus surface. If the surface is dampened by precipitation, additional cohesion of the surface material would be expected and a higher minimum wind speed would be required for lifting particles from the surface.

Recent radar measurements, described in Section 10, suggest that if precipitation existed at the surface and/or at 19km, it was of low density, or intermittent, or local with a scale of 200km or less.

* A material with a fusion temperature in the vicinity of 740K. The distribution of precipitation on the Venus surface, the rate of precipitation, the electrical conductivity and viscosity of the precipitating liquid, and the porosity of the Venus surface must be consistent with the average dielectric constant of 4.4 ± .4 measured by Sinclair et al. (1972) and with the features of the Venus radar maps of Goldstein and Rumsey (1970), and Campbell et al. (1970).

10. Clouds

There are indications of clouds at 6 or more altitude regions above the Venus surface. Rea (1972) and Chamberlain and Smith (1972) discuss two-layer cloud models for the visible global clouds with an optically thin upper cloud or haze and a dense lower cloud. Rea places the top of the thin upper cloud C1 at 78km*. An analysis of the 1.05μ CO_2 band and the 0.8189μ H_2O line by Regas et al. (1972) indicates that C1 is not uniform and confirms Potter's (1969) conclusion that it has scattering properties resembling terrestrial cirrus clouds. Boyer and Guerin (1969) have analyzed the ultraviolet observations of C1. They conclude that it has two permanent features each having the shape of a horizontal Y lying on the equator** and that the Y features, which are recorded on sketches made as early as 1903, have an average retrograde rotation period of 3.995 Earth days (111.4m/s). At times the Y features are covered by higher clouds and thus C1 is not a single cloud but comprises two or more layers moving at different speeds. They find other features of duration as small as one day and obtain a spectrum of instantaneous cloud speeds ranging from 68 to 229m/s. Spectral and polarization studies of C1 suggest that it meets the requirements of Hapke's (1972) dirty hydrochloric acid cloud. In order to reconcile the high water vapor content measured in the vicinity of 50km by the Veneras 4, 5, and 6 with the low water vapor content obtained by spectroscopic

* At approximately 175K and 0.002 atmos., see Table 2.

** Each Y has a total length of roughly 2000km.

means Chamberlain and Smith (1972) have investigated the hypothesis that a clear region may separate C1 and C2. This possibility is illustrated in Figure 13.

Rea places the top of the dense lower cloud C2 at 55km.* When the sunlit side of Venus is viewed from Earth with a resolution of roughly 100km C2 appears featureless in near-infrared and in red light, but in pale yellow light quasi-permanent low contrast features are seen. These features have dimensions ranging from several hundred kilometers to 4000km or more and have been thought by Mintz (1961) to be related to a circulation pattern centered about the sub-solar point. Because of the near identity of the day and night-side Mariner 5 temperature profiles and the existence of the broad band of high speed equatorial winds in this region it is assumed that the day and night-side structure of C2 are similar. When viewed from Earth in the 8 to 14μ thermal infrared with a resolution of roughly 400km C2 is found to be continuous over the entire planet but with a large-scale day-to-day variability in its temperature contours which according to Goody (1965) indicates the presence of strong dynamical activity in this region. Limb darkening at 8 to 14μ suggests that the region near the top of C2 is bumpy and irregular or according to Samuelson (1968) that visibility within the cloud is large. For the purpose of our model we suppose that the base of C2 is in the region shown in Figure 13 where the Venera water vapor measurement profile intersects the water vapor saturation curve.

* At approximately 260K and 0.27 atmos., see Table 2.

The existence of cloud C3 at 45km is indicated by the Mariner 5 S-band ray-path attenuation measurements of Fjeldbo et al. (1971). The fact that the attenuation is roughly identical on the day and night-sides, and the spacial relation of the attenuation profiles to the large retrograde horizontal winds measured by Veneras 4 and 7, and to the up-drafts measured by Veneras 5, 6, and 7 suggests that C3, the retrograde horizontal wind at 46km, and the up-draft* may be associated recurrent or permanent features in this region and occupy a band about the equator from 30°S to 30°N. **

The maximum in the night-side S-band attenuation-coefficient curve at 38km in Figure 13 along with the results of an analysis of the night-side attenuation by Rasool (1970) shown in Figure 14 suggest the existence of a night-side cloud of HgI_2 at 38km at the time of the Mariner 5 measurements. Since a similar maximum is not seen in the day-side attenuation coefficient profile, this cloud may be either local, or enhanced or less diffuse on the night-side. Or the maximum could be the result of unexplained flucutations in the Mariner 5 signal. The continued increase with decreasing height of both the day and night-side attenuation-coefficient curves suggests the existence of an additional but more poorly defined cloud C4 at 35km and suggests that C4 occupied a band around the equator from 30° S to 30°N at the time of measurement but no evidence has been found which either supports or precludes its recurrence or permanence.

*Up-drafts are often associated with clouds and are regarded as a necessary, but not sufficient, condition for precipitation.

**The increase in the measured Mariner 5 attenuation coefficient shown in Figure 13 is concurrent with a decrease in the proposed Mariner 5 water vapor distribution and suggests that the material causing the S-band attenuation may absorb water vapor.

At 22km, the up-draft and the indication for precipitation obtained from the Venera 7 measurements suggest cloud layer C5. It must be noted that C2, C3, C4, and C5 each occur at positions where there is a maximum in the lapse-rate profile shown in Figure 13. If the presence of a maximum can be regarded as a condition indicating the presence of a cloud in the Venus atmosphere, the Venera 5, 6, and 7 data suggests that C5 existed in the vicinity of the morning terminator over a period of 18 months and is a recurrent or permanent feature at the equatorial morning terminator. However, the data does not preclude the possibility that C5 also occupies a band about the equator. The shape of the Venera 7 lapse-rate curve, and the possibility of precipitation and mild vertical convection indicated by the Venera 7 measurements suggest the existence of C6 at 3km, but the horizontal extent of C6 is unknown.

The distribution of clouds of condensed materials above the surface of Venus is determined by the spacial and temporal patterns of large. intermediate, and small scale atmospheric temperature, circulation, precipitation, and evaporation conditions. Thus the fact that the equatorial band of high speed horizontal winds may extend downward to the region of C3 and that an equatorial band of vertical winds may exist in this same region suggests that the condensed material which comprises C3 may be more concentrated and/or more continuously distributed in an equatorial band at 45km than elsewhere, but there is no information which precludes the presence of this material in varying amounts and <u>at different altitudes</u> over the remainder of the planet including the poles.

The vertical extent of C3, shown as 4km in Figure 13, is determined by the same conditions that determine the horizontal distribution and in addition by the spacial and temporal pattern and magnitude of large, intermediate, and small scale vertical winds. On Earth the vertical extent of a single condensate, water and ice clouds, ranges from 0.1km to 17km or more; the height of the cloud bases ranges from 0 to 12km or more; and there may be 2 or more cloud layers with separation of 0.5 to 12km or more between the layers.

There are indications that there may be additional clouds of condensates. In the region from 35 to 50km where the Venera temperature and wind data suggests two cloud layers, Rasool (1970) has examined the Mariner 5 signal attenuation and with the assistance of the work of Lewis (1969) has suggested the possible existence of the five layers shown in Figure 14.* In our processing of the Venera data a number of small features encountered in the wind and temperature-profiles suggested additional layer structure in the atmosphere. It is clear, however, that for layers C3 to C6 and for the possible additional layers positive identification will require more definitive measurements.

In view of the ability of high frequency radar to detect precipitation in the presence of ground and sea returns, the equatorial topography measurements of Campbell et al. (1972) were examined to determine whether precipitation from C6 may have been detected in the region from 0.5km to 4km with the result that the measurements at 7840 MHz obtained a higher apparent surface than was observed at 430 MHz. The search indicated that if P6 does exist and is of

Rasool's model assumes particle diameters of 20 microns and peak concentrations varying from 330 to 400cm^{-3}. These particle sizes and concentrations are similar to those for Earth cumulus congestus clouds in which visibility is reduced to roughly 10 meters sufficient density for detection, it is intermittent, and/or its vertical and horizontal scales are less than 0.8km and 3000km respectively. According to Ingalls and Shapiro (1972) a preliminary search of the Venus radar reflection measurements at 7840 MHz obtained during July of 1972 and of the measurements made near the times of previous inferior conjunctions indicates that any returns from clouds or precipitations must be 10^{-3} or less of the surface echo. This result suggests that P5 and any precipitation resulting from global cloud C2 or from equatorial bands C3 or C4 must be of low density, intermittent, and/or local with a scale of 200km or less.

Further study must be made to determine the extent to which the cloud structure shown in Figure 13 would lend itself to the theories of Schubert and Whitehead (1969) and of Malkus (1970) in establishing the retrograde winds shown in Figure 11 at 18km and 45km.

* The repeatability of vertical measurements was 0.2 to 0.5 km.

11. Planet radius and topography

The Venera 7 temperature measurements and true descent speed are used to obtain an altitude profile of temperature. This temperature profile is used with a reference pressure of 6.85 atmospheres obtained from the Venera 4, 5, and 6 measurements at 456.3K; with a reference planet radius of 6085.0km obtained from the average Mariner 5 pressure data for $\overline{m}$ = 43.3;* and with the assumption of spherical isobars to obtain the pressure vs radius values given in Table 2 from 6105km to Venera 7 impact at 6055.5km. The Venera 5 and 6 measurements of pressure given in Table 1 are referred to the Table 2 pressure profile to obtain the radius values at which altitude measurements were made** and the altitude measurements are used with these radius values to yield the radius at the surface. It is assumed that the smallest altitude measurements give the smallest absolute error. The Venera 6 and 7 surface radius values of 6055 and 6055.5 are in good agreement with the values of 6053.7 and 6055.8 obtained by Melbourne et al. (1968) and by Ash et al. (1967).

* The reference radius is relatively insensitive to the value of $\overline{m}$. For $\overline{m}$ = 41.2 we obtain 6.85 atmospheres at 6085.3km.

** The Venera 5 and 6 pressure values all fall above the region in which estimation of the true descent speed was necessary to complete the computation of the Venera 7 atmospheric structure, and thus their surface radius values are unaffected by the estimation.

Table 1. Venus Radius Measurements

Method	Altitude Marker	Pressure Atmos.	Radius km	Altitude km	Surface Radius km
Venera 5	1	6.5	6085.5	43.8 (34.9)	6041.7 (6050.6)
	2	14.8	6076.6	34.9 (25.2)	6041.7 (6051.4)
	3	27.5	6068.8	25.2 (15.9)	6043.6 (6052.9)
Venera 6	1	6.8	6085.1	27.8	6057.3
	2	19.8	6073.1	18.1	6055.0
Venera 7	Estimate the true descent speed from 15km to the surface to obtain				6055.5
Earth-based	Ash et al. (1967)				6055.8 ±1.4
	Melbourne et al. (1968)				6053.7 ±2.2
	Campbell et al. (1972)				6050.0 ±0.5

The 11.4km difference in the Venera 5 and 6 surface height measurements in Table 1 is puzzling. Lyttleton (1969) states that due to a contraction of about 250km in radius during its formation "Venus can be expected to have formed folded and thrusted mountain systems at its surface" and with its reduced gravity "it is possible that the corresponding features might be even more impressive than their terrestrial counterparts. The. . . higher temperature and pressure on Venus seems unlikely to affect the conclusion, for the strengths of most rocks change only slightly with temperature so long as this is not near their melting point, and any slight reduction of strength for this reason would probably be

more than offset by the large ambient pressure. . . ."* The highest local feature that has been seen on the Venus surface by Earth-based radar has been described by Smith et al. (1970) as about 2km high and extending about 150km in longitude, and was obtained with a resolution of 25km in longitude and 200km in latitude. The 11.4km difference in the surface height measurements of Venera 5 and 6 was obtained with only slightly greater resolution in longitude than Smith's measurement, but with considerably greater resolution in latitude.** Since the Venera 5 and 6 surface height difference is 6 times the height of Smith's peak and in a region near the equator*** which has apparently been carefully observed by Earth radar we must assume that the difference escaped radar observation because it is in the North-South direction where reduced radar resolution is obtained. In Figure 6 we see that the Venera 5 and 6 entry positions are indeed separated in a North-South direction and by about 300km. Despite this seemingly reasonable solution to the problem there are a number of misgivings that remain: (a) because of the uncertainty in determining the entry position of Venus probes it would not be surprising if the true separation of the Venera 5 and 6 entry positions was East-West rather than North-South; (b) the supposed 300km separation is greater than the 200km latitude resolution of the radar observations; (c) the large elevation difference is unique; and (d) it is not directly associated with substantial adjacent East-West differences.

* "Once contraction has commenced, it may contribute importantly to the continued production of heat within Venus."

** Horizontal resolution of the Venera 5 and 6 altimeters is of the order of 15km.

*** Within 15° of Smith's peak.

Further consideration suggests that the 11.4km difference in the Venera 5 and 6 surface height measurements could be due to (a) surface range confusion caused by large excursion pendulum-motion of the descent probe, (b) Venera 5 altimeter malfunctioning, or (c) Venera 5 altimeter confusion by means of simultaneous returns from the surface and from precipitation in the vicinity of 10km and/or 20km above the mean surface. There is evidence for large-excursion pendulum-motion of the Venera 7 descent probe, and also evidence for the possibility that the winds causing this motion represent frequent or permanent equatorial morning-terminator conditions* affecting Veneras 5, 6, and 7. But altimeter confusion due to this cause is rejected for the reason that the large decrease in signal amplitude obtained at the required excursion angles should have readily identified this difficulty. It is clear from the data of Table 1 that in several respects the Venera 5 altimeter performed well. The fact that the proper distance between altitude measurements was obtained suggests that the $\Delta f/T$ characteristic for the frequency modulated altimeter was stable. The fact of three altitude measurements, rather than two, as in the case of Venera 6, indicates that the altimeter power output, receiver sensitivity, and antenna system were unimpaired. The only altimeter malfunction which we can suggest at this time must lie in the circuitry used for the identification of the return-signal frequency-filter assigned to each of the pre-selected altitudes. Since the proper sequence of the pre-selected altitude returns was apparently

*Sections 5 and 6.

observed, a malfunction must consist of a filter identification-number shift which caused each filter to become identified as the next higher altitude filter. In parentheses in Table 1 we present the radius values which are obtained for Venera 5 when we reduce those altitudes given by Avduevsky to the next lower value with a final altitude estimate of 15.9km based on the average interval between the preceeding ranges. The resulting radius measurement of 6052.9km is close to the Venera 6 and 7 measurements and the Earth-based radar measurements of Melbourne et al. (1968) and Ash et al. (1967). Precipitation in the vicinity of 10 and 20km above the mean surface would be properly placed for confusing the Venera 5 altimeter. But if the signal returned by precipitation at the estimated altimeter frequency of 770 MHz was of sufficient strength to have confused the altimeter, the λ^{-4} increase in signal return at 7840 MHz would have been sufficient to present a major obstacle to the Venus topography measurements of Campbell et al. (1972) unless the precipitation was local with a scale of 200km or less. The existence of high density local precipitation at 20km is consistent with the Venera 7 evidence for precipitation at 19km and high density local precipitation at 10km and/or 20km is also consistant with radar measurements which indicated that any cloud or precipitation returns are 10^{-3} or less than the surface echo.* The greater range of the Venera 5 altimeter suggests that either its sensitivity and/or power output were greater than that of the Venera 6 altimeter and thus it was more capable of detecting precipitation,

* See Section 10.

or that the surface beneath Venera 5 was of higher reflectivity than the surface beneath Venera 6.

At this time we are unable to determine whether or not an 11.4km difference in planet radius values is a valid interpretation of the Venera 5 and 6 altimeter measurements. For the purpose of our model we shall assume that the interpretation is not valid and that the true values for the altitude of Venera 5 are given in parentheses in Table 1.

For our estimate of the Venus radius we assume that the smallest altitude measurements are the most accurate.* We take the average of the Venera 5, 6, and 7 radius measurements to diminish the effect of possible small-scale surface-height variations and we obtain a value of 6054.5km in the vicinity of the Venera measurement region near the semi-minor axis of the equatorial plane, see Figure 17. This result is almost centered between the values of 6053.7 ±2.2km and 6055.8 ±1.4km measured by Melbourne et al. (1968) and Ash et al. (1967). We assume according to Smith et al. (1970) that a -b = 1.1 ±0.4km** and obtain a semi-major axis radius of 6055.6 and a mean-equatorial-radius of 6055km. Muhleman (1970) concluded that CO_2 alone could account for the total opacity of the atmosphere for microwaves if the surface pressure was as high as 7_ 5 atmospheres. Thus our finding of an average surface radius of 6055km which corresponds to a surface pressure of 71

* It should be noted that the Venera 5 and 6 radius values shown in Table 1 converge as the probes approach the surface.

** The results of Campbell et al. (1972) shown in Figure 16 confirm Smith's value for a -b.

atmospheres suggests the existence of the microwave loss at 6100km* discovered by Fjeldbo et al. (1971) in their analysis of the Mariner 5 data and/or the source of microwave opacity suggested by Pollack and Morrison (1970) in explanation of the microwave emission spectrum measurements.**

In a more recept paper Campbell et al. (1972) obtained a smaller value, 6050 ±0.5km, for the Venus radius. Our sole means for reducing the Venera 6 and the assumed Venera 5 radius values from 6055km and 6052.9km, respectively, to 6050km lies in the assumption of a 3 to 5km decrease in the radius of the reference isobar as we go from the Mariner reference positions at ~30° latitude to the Venera positions nearer the equator. This solution is the opposite of our earlier requirement for an increase in isobar height as the equator is approached in order to explain the uniform 28% separation of the P(T) profiles and it further complicates the variable isotherm height explanation of the separation of the P(T) profiles given in Section 2.

For Venera 7 there is an additional expedient. We can also obtain a surface radius of 6050km by means of an average increase of 6 m/s in the estimated true descent speed in the region from 23^m to impact. This increase results in the large up-draft shown at 47km in Figure 15. In the presence of this up-draft the Venera 4, 5, and 6 probes would not have descended. They would have ascended, starting at the moment of parachute opening. The Venera 7 probe would have descended to 25km where the parachute reef was removed and

*See Figure 13.

**The preliminary Venera 8 surface pressure of 87.1 ±1.5 atmos. implies a radius of 6051.7km, and with the Venera 5, 6, and 7 results yields a mean-equatorial-radius of 6054.3km [74 atmos.].

would have then ascended to 35km and hovered. A comparison of the Venera 4, 5, and 6 probe descent-distances obtained from the hypsometric formula with those descent distances obtained using the ballistic coefficients for the respective probe descent systems shows that the average up-draft in the region 20 to 47km is likely to be less than 1m/s instead of the 30m/s shown in Figure 15. On the basis of the maximum permissible average-vertical-wind, together with the assumptions of an unchanging Venus lower atmosphere and spherical isobars, we find that the Venera 7 surface radius cannot be reduced to less than 6055km.

A further difficulty associated with the use of increased descent speed to reduce the Venera 7 surface radius value is that we obtain a pressure of 100 atmospheres* at 6050km and this high pressure presents difficulty in explaining both Muhleman's (1970) microwave loss requirement for 78.5 atmospheres of CO_2, and the resulting requirement of Fjeldbo et al. (1971), and of Pollack and Morrison (1970) for less than 78.5 atmospheres. We encounter this same difficulty if we assume that Veneras 5, 6, and 7 all landed in locally-elevated-regions for which the atmospheric pressure is in the vicinity of the Venera 7 value of 71 atmospheres, or, if we assume that the final Venera 6 radar altimeter measurements and corrected Venera 5 altimeter measurements were both too small by 25 to 30%.

A similar disparity between space-craft and Earth-based methods for radius measurements exists for Mars where recent measurements have

* If for $\bar{m}$ 43.3 we substitute m 41.2 we obtain 93 atmos.

yielded a mean-equatorial-radius of 3398.7km by occultation (Kliore, 1972) and 3394 ±2km by Earth-based radar (Shapiro, 1972). No relation has as yet been established between this +4.7km difference and the corresponding +5.0km difference for Venus.

In summary, we obtain a mean radius of 6055km for the geometric equatorial figure and, based on the J_2 measurements of Anderson and Efron (1969) discussed in Section 2, we obtain this same mean radius for the polar gravitational figure.

We shall now attempt to relate the topographical measurements of Campbell et al. (1972), shown in Figure 16, to the microwave interferometer measurements of Sinclair et al. (1972). In addition to the enhanced polar brightness at 11.1 cm wavelength discussed in Section 2, Sinclair et al. obtained measurements indicating an East-West brightness asymmetry. From their measurements we obtain a longitude profile of the equivalent temperature difference between the East and West equatorial limbs of a spherical surface having the maximum difference of 18 ±8K shown in Figures 1, 6, and 17.*

No support has been found for explanations of the East-West temperature difference based upon appropriate distributions of surface material emissivity, surface material particle size, or internal planet energy sources. Despite the fact that the position of the maximum East-West temperature difference as shown in Figure 1 strongly suggests a diurnal effect, this explanation is not satisfactory. From the work of Golitsyn (1970) and Gierasch et al. (1970) it is clear that the high heat capacity of a massive atmosphere reduces the diurnal

* Sinclair obtained a maximum difference of 14 ±8K. Our curve fitting of the data yields a slightly higher value.

temperature variation at the surface to several degrees at the most. Lewis (1971) suggests that there may be chemical reactions which would further reduce diurnal effects at the surface of Venus. Above an altitude of 30km, clouds, the equatorial band of high speed winds, and the reduced density of the atmosphere would combine to prevent a substantial contribution by this region to a diurnal brightness-temperature variation at 11.1 cm.* It is also unlikely that the East-West temperature difference is caused by an atmospheric density distribution at the surface which varies in relation to the displacement of the center of mass from the geometric center of the planet, since Figure 17 shows that the measured displacement is roughly symmetric with respect to the hot and cold regions.**

We are left with the possibility that Sinclair's East-West temperature difference profile results from the combined effect of changes in surface temperature and atmospheric density associated with the surface-height profile of Campbell et al. As an exercise, we assume that the Venus surface is isothermal, perform a crude conversion of Sinclair's measured East-West limb temperature-differences to obtain equivalent atmospheric denisty-differences, and then convert the density-differences to obtain the equivalent surface-height-differences between the East and West limbs. The surface-height-differences are divided

*The winds are apparently so efficient in their distribution of solar energy that the first evidence of a possible diurnal temperature difference in the Mariner 5 data occurs at 73km where according to Table 2 the atmospheric density is $2(10)^{-4}$ times that at the surface.

** Shapiro et al. (1972) have obtained the height relative to the mean planet radius, of the gravitational equipotential surface around the equator. A comparison of this height profile with the equatorial topography profile of Campbell et al. (1972) suggests the magnitude and direction of the displacement of the Venus center-of-mass obtained by Smith et al. (1970) and shown in Figure 17.

by two and plotted with alternating signs at 180° intervals and are shown as circles and crosses along the height reference line at the bottom of Figure 16. The longitude of each circle is that of the West limb at the time of measurement. The longitude of each cross is that of the East limb. The solid curve at the bottom of Figure 16 is the profile of the surface-height-difference between the East and West limb as obtained from Campbell's height profile and is plotted with respect to the longitude of the West limb. A proper comparison of Campbell's surface-height-difference profile and the converted temperature-difference measurements of Sinclair must take into account that the resolution of Sinclair's measurements is considerably less than that of Campbell's. We compensate for this difference in resolution by degrading the resolution of Campbell's surface-height-difference profile in a manner crudely consistent with the resolution of Sinclair's measurements and obtain the dot-dash line in Figure 16. The good agreement between the dot-dash curve and Sinclair's converted temperature-difference data suggests that Sinclair's East-West temperature assymetry results primarily from atmospheric density variations determined by the Venus topography and that in a band about the equator the variation of planet surface temperature with height is small. Estimates which take into account the crudeness of our methods suggest an upper limit to the surface lapse rate of 5K/km with more reasonable values ranging from 2.5K/km to isothermal.

12. Atmospheric structure

The atmospheric structure given in Table 2 is derived from the Mariner 5 and the Venera 4, 5, 6, and 7 measurements and is intended to represent conditions in the equatorial region. Below 6056km we use the lapse-rate of 2.5K/km obtained from the comparison of the inferometer measurements of Sinclair et al. with the topography measurements of Campbell et al. From 6056 to 6104km the Venera data is used with radius values based on the Mariner 5 pressure vs radius measurements and the assumption of spherical isobars. *

From 6104 to 6130km the average Mariner 5 temperature profile is transformed to obtain a temperature profile which is representative of the equatorial location of the Venera probes. First we correct the Mariner 5 data to account for the water vapor content given by the dashed saturation-line and the dotted Mariner 5 profile shown in Figure 7. Then an altitude profile of the temperature-difference of the P(T) profiles shown in Figure 4 is constructed and this temperature-difference profile is extrapolated to 6130km where it vanishes. The extrapolated temperature-difference profile is then used to transform the Mariner 5 temperature profile.

At 6140km we select a Mariner temperature data integration constant T_0 = 159K which results in a temperature minimum of 153K at 6137km. The 153K minimum temperature is derived from the H_2O mixing ratio of 10^{-6}

*In Sections 3 and 11 we have seen that the deviation of the planet from a sphere is less than 0.1km for the average polar gravitational figure and ±0.6km for the average geometric equatorial figure.

Table 2. Atmospheric structure derived from the Mariner 5 and Venera 4, 5, 6, and 7 measurements with $\overline{m} = 43.3$ g/mole

Height km	Radius km	Temp. °K	Pressure Atmos.	Density g/cm³	Density n/cm³	Gravity cm/s²
-12.0	6043.0	778.0	1.45E 02	9.83E-02	1.37E 21	888.5
-11.0	6044.0	775.5	1.39E 02	9.43E-02	1.31E 21	888.2
-10.0	6045.0	773.0	1.31E 02	8.91E-02	1.24E 21	887.9
-9.0	6046.0	770.5	1.23E 02	8.42E-02	1.17E 21	887.6
-8.0	6047.0	768.0	1.16E 02	7.96E-02	1.11E 21	887.3
-7.0	6048.0	765.5	1.09E 02	7.52E-02	1.04E 21	887.0
-6.0	6049.0	763.0	1.03E 02	7.10E-02	9.87E 20	886.8
-5.0	6050.0	760.5	9.66E 01	6.70E-02	9.32E 20	886.5
-4.0	6051.0	758.0	9.09E 01	6.33E-02	8.80E 20	886.2
-3.0	6052.0	755.5	8.55E 01	5.97E-02	8.30E 20	885.9
-2.0	6053.0	753.0	8.04E 01	5.64E-02	7.84E 20	885.6
-1.0	6054.0	750.5	7.56E 01	5.32E-02	7.39E 20	885.3
0.0	6055.0	748.0	7.11E 01	5.02E-02	6.97E 20	885.0
1.0	6056.0	745.5	6.68E 01	4.73E-02	6.58E 20	884.7
2.0	6057.0	736.5	6.28E 01	4.50E-02	6.26E 20	884.4
3.0	6058.0	720.0	5.90E 01	4.32E-02	6.01E 20	884.1
4.0	6059.0	705.0	5.53E 01	4.14E-02	5.75E 20	883.8
5.0	6060.0	694.6	5.17E 01	3.93E-02	5.47E 20	883.5
6.0	6061.0	685.0	4.84E 01	3.73E-02	5.19E 20	883.2
7.0	6062.0	675.0	4.52E 01	3.54E-02	4.92E 20	883.0
8.0	6063.0	664.2	4.22E 01	3.36E-02	4.67E 20	882.7
9.0	6064.0	653.8	3.94E 01	3.18E-02	4.42E 20	882.4
10.0	6065.0	643.3	3.67E 01	3.01E-02	4.19E 20	882.1
11.0	6066.0	632.7	3.41E 01	2.85E-02	3.96E 20	881.8
12.0	6067.0	622.4	3.17E 01	2.69E-02	3.74E 20	881.5
13.0	6068.0	612.4	2.95E 01	2.54E-02	3.53E 20	881.2
14.0	6069.0	603.0	2.73E 01	2.39E-02	3.32E 20	880.9
15.0	6070.0	593.7	2.53E 01	2.25E-02	3.13E 20	880.6
16.0	6071.0	586.5	2.34E 01	2.11E-02	2.93E 20	880.3
17.0	6072.0	579.0	2.16E 01	1.97E-02	2.74E 20	880.1
18.0	6073.0	571.0	2.00E 01	1.85E-02	2.57E 20	879.8
19.0	6074.0	563.2	1.84E 01	1.73E-02	2.40E 20	879.5
20.0	6075.0	554.5	1.70E 01	1.62E-02	2.25E 20	879.2
21.0	6076.0	545.8	1.56E 01	1.51E-02	2.10E 20	878.9
22.0	6077.0	536.3	1.43E 01	1.41E-02	1.96E 20	878.6
23.0	6078.0	526.3	1.32E 01	1.32E-02	1.84E 20	878.3
24.0	6079.0	515.7	1.21E 01	1.23E-02	1.72E 20	878.0
25.0	6080.0	505.7	1.10E 01	1.15E-02	1.60E 20	877.7
26.0	6081.0	495.3	1.01E 01	1.07E-02	1.49E 20	877.4
27.0	6082.0	485.7	9.16E 00	9.96E-03	1.38E 20	877.2
28.0	6083.0	476.0	8.33E 00	9.24E-03	1.28E 20	876.9
29.0	6084.0	466.0	7.56E 00	8.57E-03	1.19E 20	876.6
30.0	6085.0	456.3	6.85E 00	7.93E-03	1.10E 20	876.3
31.0	6086.0	447.2	6.19E 00	7.31E-03	1.02E 20	876.0
32.0	6087.0	438.0	5.58E 00	6.73E-03	9.36E 19	875.7
33.0	6088.0	429.3	5.03E 00	6.18E-03	8.59E 19	875.4
34.0	6089.0	420.5	4.52E 00	5.67E-03	7.88E 19	875.1
35.0	6090.0	410.3	4.05E 00	5.21E-03	7.24E 19	874.8

*g_0 = 885.0 cm sec^{-2} at R_0 = 6055 km according to Lyttleton (1969)

Table 2 (continued)

Height km	Radius km	Temp. °K	Pressure Atmos.	Density g/cm^3	Density n/cm^3	Gravity cm/s^2
36.0	6091.0	401.3	3.62E 00	4.76E-03	6.61E 19	874.6
37.0	6092.0	392.5	3.22E 00	4.34E-03	6.03E 19	874.3
38.0	6093.0	384.5	2.87E 00	3.94E-03	5.47E 19	874.0
39.0	6094.0	377.5	2.54E 00	3.56E-03	4.94E 19	873.7
40.0	6095.0	371.0	2.25E 00	3.21E-03	4.45E 19	873.4
41.0	6096.0	365.3	1.99E 00	2.88E-03	4.00E 19	873.1
42.0	6097.0	358.3	1.76E 00	2.59E-03	3.59E 19	872.8
43.0	6098.0	350.0	1.54E 00	2.33E-03	3.24E 19	872.6
44.0	6099.0	342.5	1.35E 00	2.09E-03	2.90E 19	872.3
45.0	6100.0	334.1	1.18E 00	1.87E-03	2.60E 19	872.0
46.0	6101.0	326.0	1.03E 00	1.67E-03	2.32E 19	871.7
47.0	6102.0	318.0	8.96E-01	1.49E-03	2.07E 19	871.4
48.0	6103.0	310.7	7.75E-01	1.32E-03	1.83E 19	871.1
49.0	6104.0	304.5	6.69E-01	1.16E-03	1.61E 19	870.8
50.0	6105.0	299.0	5.75E-01	1.02E-03	1.41E 19	870.6
51.0	6106.0	293.0	4.94E-01	8.89E-04	1.24E 19	870.3
52.0	6107.0	285.0	4.22E-01	7.82E-04	1.09E 19	870.0
53.0	6108.0	275.0	3.59E-01	6.89E-04	9.58E 18	869.7
54.0	6109.0	266.5	3.04E-01	6.01E-04	8.36E 18	869.4
55.0	6110.0	257.0	2.55E-01	5.24E-04	7.29E 18	869.1
56.0	6111.0	249.5	2.13E-01	4.52E-04	6.28E 18	868.9
57.0	6112.0	247.0	1.78E-01	3.80E-04	5.28E 18	868.6
58.0	6113.0	243.0	1.48E-01	3.21E-04	4.47E 18	868.3
59.0	6114.0	241.5	1.23E-01	2.68E-04	3.73E 18	868.0
60.0	6115.0	237.5	1.02E-01	2.26E-04	3.14E 18	867.7
61.0	6116.0	235.0	8.39E-02	1.88E-04	2.62E 18	867.4
62.0	6117.0	232.5	6.91E-02	1.57E-04	2.18E 18	867.2
63.0	6118.0	229.7	5.69E-02	1.31E-04	1.82E 18	866.9
64.0	6119.0	224.5	4.66E-02	1.10E-04	1.52E 18	866.6
65.0	6120.0	220.0	3.80E-02	9.13E-05	1.27E 18	866.3
66.0	6121.0	216.5	3.09E-02	7.54E-05	1.05E 18	866.0
67.0	6122.0	212.5	2.51E-02	6.23E-05	8.65E 17	865.7
68.0	6123.0	208.5	2.02E-02	5.12E-05	7.12E 17	865.5
69.0	6124.0	205.0	1.63E-02	4.19E-05	5.82E 17	865.2
70.0	6125.0	200.5	1.30E-02	3.43E-05	4.76E 17	864.9
71.0	6126.0	196.0	1.04E-02	2.79E-05	3.88E 17	864.6
72.0	6127.0	191.0	8.22E-03	2.27E-05	3.16E 17	864.3
73.0	6128.0	187.0	6.47E-03	1.83E-05	2.54E 17	864.0
74.0	6129.0	183.0	5.08E-03	1.46E-05	2.04E 17	863.8
75.0	6130.0	180.5	3.96E-03	1.16E-05	1.61E 17	863.5
76.0	6131.0	179.0	3.08E-03	9.10E-06	1.26E 17	863.2
77.0	6132.0	177.0	2.40E-03	7.15E-06	9.93E 16	862.9
78.0	6133.0	175.0	1.86E-03	5.60E-06	7.78E 16	862.6
79.0	6134.0	172.0	1.43E-03	4.40E-06	6.11E 16	862.4
80.0	6135.0	162.0	1.09E-03	3.57E-06	4.96E 16	862.1
81.0	6136.0	155.5	8.24E-04	2.80E-06	3.89E 16	861.8
82.0	6137.0	153.0	6.16E-04	2.13E-06	2.96E 16	861.5
83.0	6138.0	154.0	4.60E-04	1.58E-06	2.19E 16	861.2
84.0	6139.0	156.5	3.45E-04	1.16E-06	1.62E 16	860.9
85.0	6140.0	158.5	2.59E-04	8.63E-07	1.20E 16	860.7

obtained for this region by Kuiper et al. (1969) along with the HCl content determined by Connes et al. (1967).

Use of Table 2 should be limited to a band about the equator extending from 20°S to 20°N and to an altitude of 75km. At high latitudes the temperature profile is not sufficiently known, and above 75km we find evidence in the Mariner 5 measurements for a possible day-night variability in the temperature profile.

13. Summary

(a) There is evidence that at the time of the Mariner 5 and Venera 4 measurements a prominent sub-adiabatic region existed at 370K (40km) and extended around the equator from 30°S to 30°N. Water vapor considerations suggest that there may have been a similar sub-adiabatic band at 302K (49.5km) during this same period.

(b) We conclude that the uniform 28% separation of the P(T) profiles is a characteristic of the Venus atmosphere. It was anticipated that this effect could be explained by a variation in isobar height but we have been led by Sinclair's "hot poles", by the radar measurements of the equatorial radius, and by the Mariner 5 measurements of the average polar gravitational shape to interpret the effect as a latitude dependence of the height of the isotherms in the region below 6130km.

(c) The data suggests that little of the incident solar energy reaches the Venus surface directly or by scattering and that Sinclair's "hot poles" may be due to a cooling of the planet surface in the equatorial region resulting from the presence of the band of high-speed retrograde equatorial wind.

(d) If the profile of the temperature-differences between the P(T) curves is indeed the equivalent of a constant percentage pressure separation we conclude that the mean-molecular-mass of the atmosphere lies between 43.1 to 44.0g/mole.

(e) The assumption of a constant percentage pressure separation of the P(T) profiles or an equivalent temperature-separation leads to the conclusion that if water vapor is the principle polar compound in the vicinity of 50km, the Venera 5 measurements of the maximum water-vapor content are correct, and that the water-vapor content below 50km (300K) may decrease with increasing latitude and/or may be variable with time. The latter suggestion is consistent with the results of the microwave measurements of Jones et al. (1972).

(f) The combined winds measurements of Boyer and Guerin, Carleton, and Veneras 4 and 7 indicate that the 4-day (110m/s) retrograde wind occupies a band about the equator which extends from above the top of cloud C1 at 78km downward to the one atmosphere level at 46km. The speed of the wind appears to be latitude dependent, decreasing at 15° latitude to possibly 0.60 of the equatorial value.

(g) At the equatorial morning-terminator at the time of the Venera 7 entry the high speed retrograde wind at 46km decreased to roughly 15m/s at 40km and remained at this value down to 19km. At 18km altitude (20 atmospheres) there was a retrograde wind layer of roughly 3km thickness, and with a peak speed of 35m/s. Below 14km we assume a prograde or south-directed wind decreasing from 1.5 to 2m/s at 13km to roughly 0.1m/s at 3km.

(h) The data suggests that horizontal winds at the surface are of the order of 0.1m/s and thus incapable of lifting dust from the surface. Any dust in the atmosphere is expected to result from other sources such as the collecting of cosmic dust or the injection of dust by volcanic activity.

(i) The latitude dependence of temperature indicated by the separation of the P(T) profiles and by Sinclair's hot poles, and the Venera 7 low altitude vertical wind profile, suggest the possibility of a low altitude equator-to-pole circulation with hot air rising at the poles.

(j) The association of the up and down-drafts at 42km with the equatorial sub-adiabatic lapse-rate region at 40km, with the equatorial high speed retrograde horizontal wind, and with the Mariner 5 attenuation-coefficient profile suggests that the up and down-drafts occupy an equatorial band.

(k) The Venera 4, 5, 6, and 7 data suggests that the up and down-drafts at 20km are a permanent feature in the vicinity of the equatorial morning-terminator but as yet no evidence has been found which suggests that they occupy a band about the equator.

(l) In our model the visible thin global cloud or haze C1 extends downward from 78km to a clear region which is assumed to start at 63km and ends at the top of the visible dense global cloud C2 at 55km. At times C1 consists of several layers moving with different speeds. It is assumed that the base of C2 is at 52km and is determined by the Venera water vapor profile.

(m) The existence of Cloud C3 in the region from 47 to 43km is indicated by the Mariner 5 attenuation-coefficient measurements. These measurements and their spacial relation to the Venera 7 up-draft measurements and to the high speed retrograde wind band suggest that C3 may be a recurrent or permanent feature in a band about the equator from 30° S to 30° N.

(n) The Mariner 5 attenuation-coefficient measurements also suggest a night-side cloud of HgI_2 at 38km at the time of measurement and a cloud C4 at 37 to 33km occupying a band about the equator at the time of measurement.

(o) Cloud C5 at 25 to 20km is based upon the Venera up-draft and lapse-rate measurements and upon possible Venera 7 evidence for precipitation at 19km. There are indications that C5 and its associated up-draft are recurrent or permanent equatorial morning-terminator features but the data does not preclude a greater extent to C5. The possible evidence for precipitation seen at 19km suggests a material with a fusion temperature of 556 ±6K.

(p) The shape of the Venera 7 lapse-rate curve, and speculation concerning Venera 7 evidence for precipitation and mild vertical convection suggest the existence of C6 at 3km, but the horizontal extent of C6 is unknown. Precipitation associated with C6 would be expected to have a fusion temperature in the vicinity of 740K.

(q) The Venera 7 data indicates that the temperature lapse-rate at the surface lies between 0 and 7K/km. The microwave interferometer measurements of Sinclair et al. (1972) combined with the radar topographical measurements of Campbell et al. (1972) indicate that below 6056km in a band about the equator an upper limit to the lapse-rate is 5K/km with more reasonable values ranging from 2.5K/km to isothermal.

(r) The mean radius of the planet is found to be 6055 ±2km and in conjunction with a mean surface temperature of 748K yields a mean surface pressure of 71 atmospheres. This pressure value is consistent with the microwave attenuation studies of Muhleman, of Fjeldbo et al., and of Pollack and Morrison.

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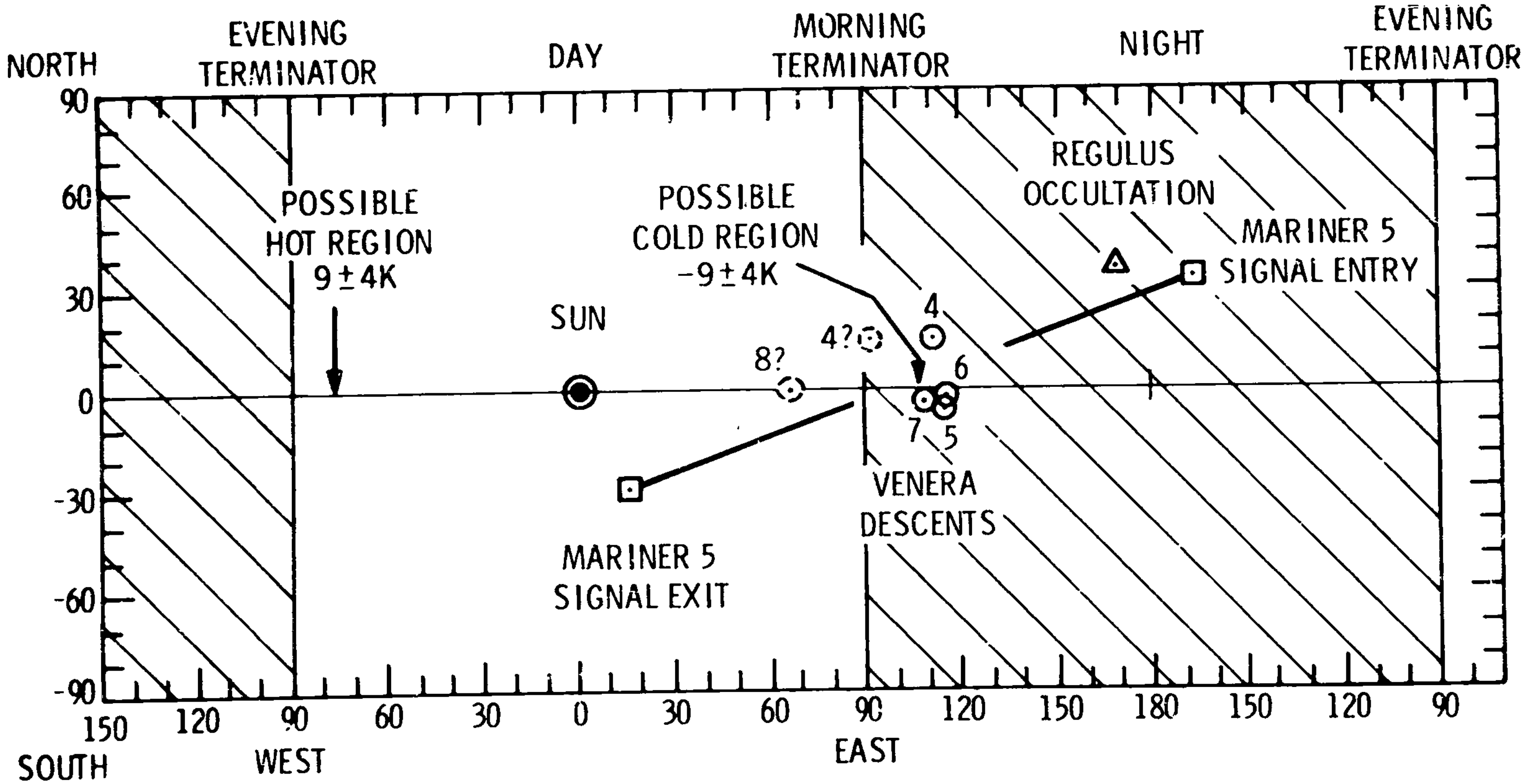

Figure 1. The positions of the Venera probe descents (Avduevsky et al., 1971b) and the two regions in which the Mariner 5 radio signals passed through the Venus atmosphere are shown in their solar coordinates. Out work suggests that Venera 4 may have entered ~20° West of the position given by Avduevsky. An estimated position is given for Venera 8. The hot and cold regions were derived from the 11.1cm radiation interferometer-measurements of Sinclair et al. (1972).

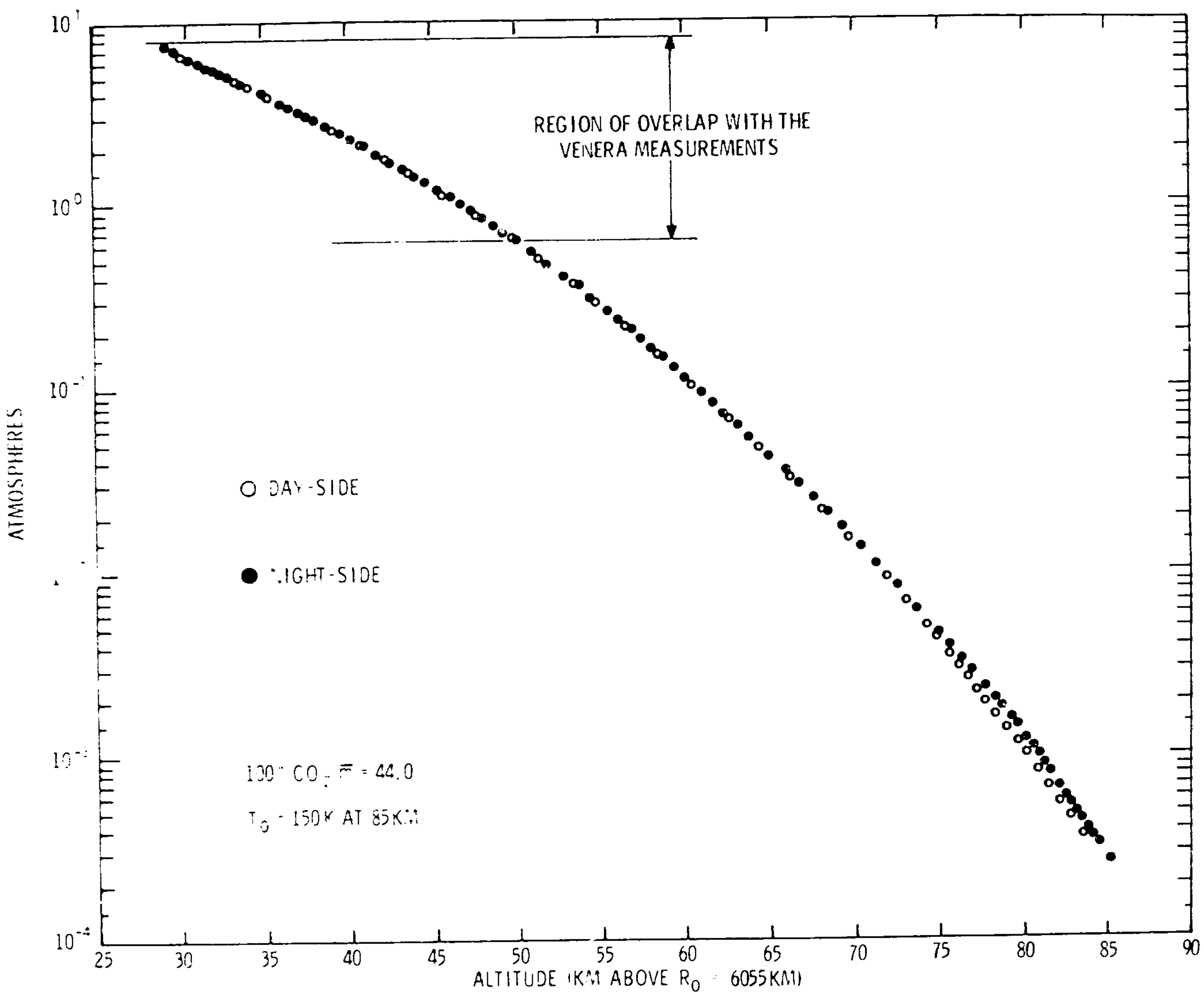

Figure 2. Mariner 5 day-side and night-side pressure profiles based on 100% CO_2 and a temperature integration constant of 150K at 85km. Increasing the integration constant to 250K changes the pressure below 65km by less than 0.3% (Fjeldbo et al., 1971).

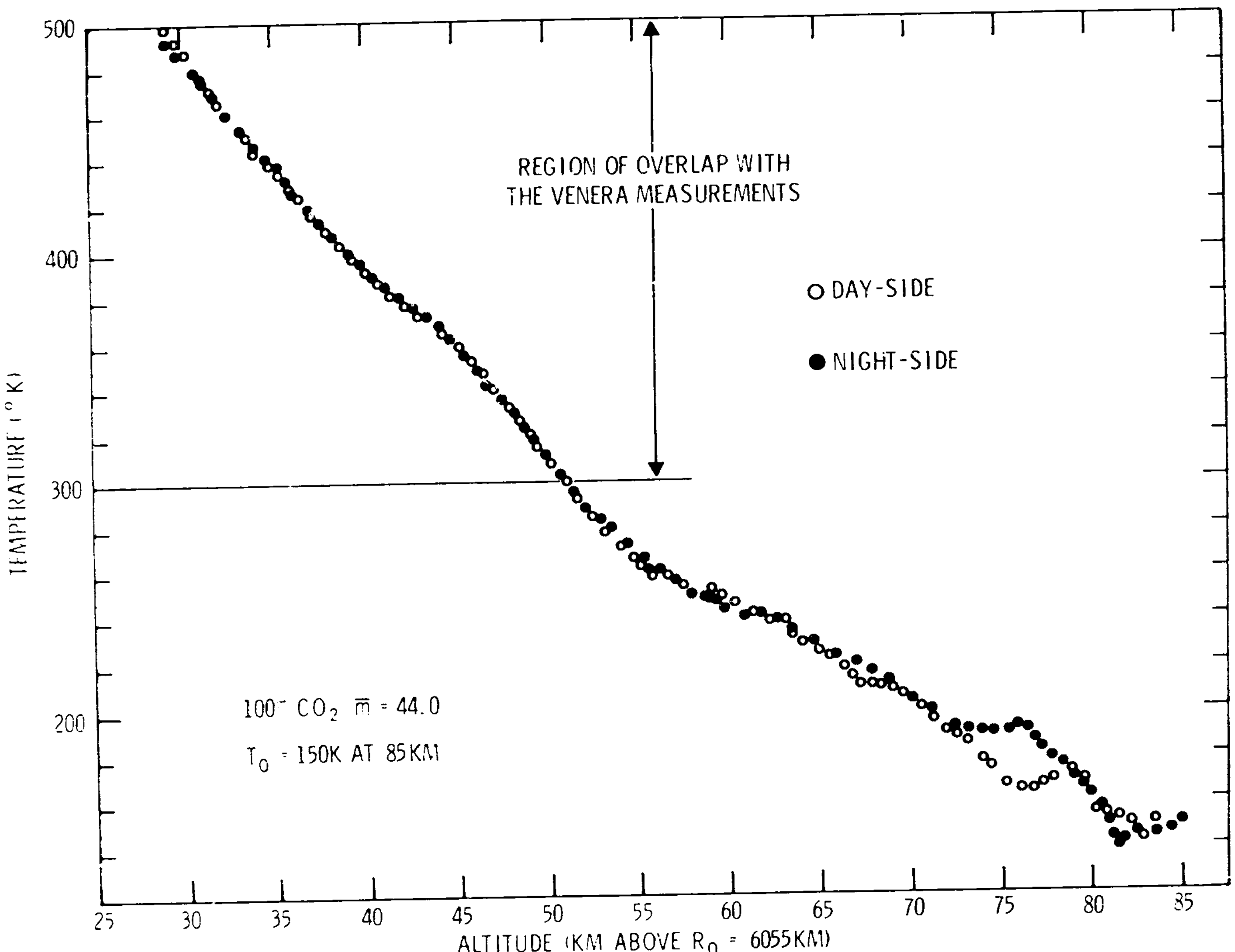

Figure 3. Mariner 5 day-side and night-side temperature profiles based on 100% CO_2 and an integration constant of 150K at 85km. Increasing the integration constant to 250K changes the temperature below 65km by less than 1K (Fjeldbo et al., 1971).

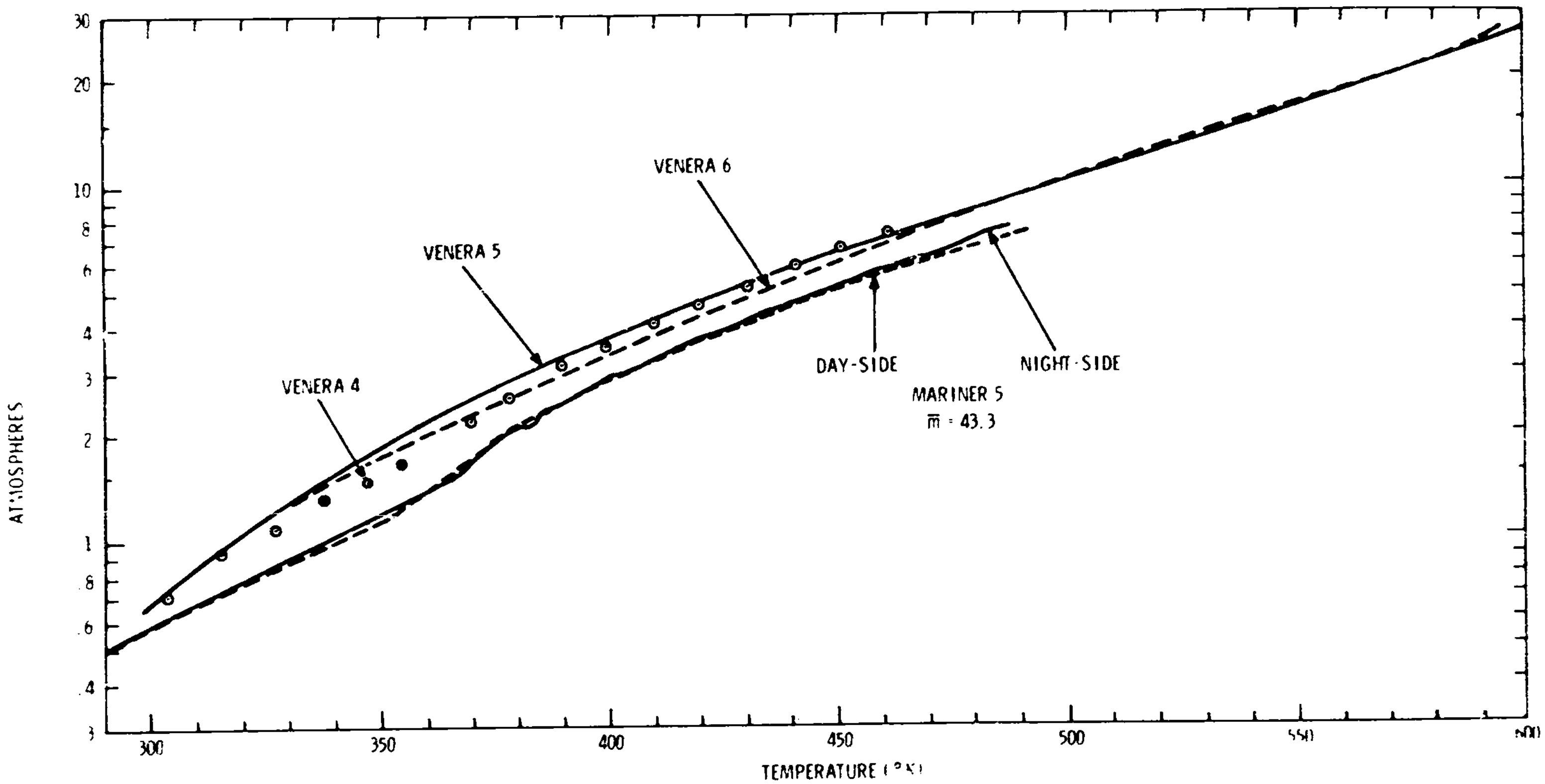

Figure 4. A comparison of Venera 4, 5, and 6, and Mariner 5 P(T) profiles.

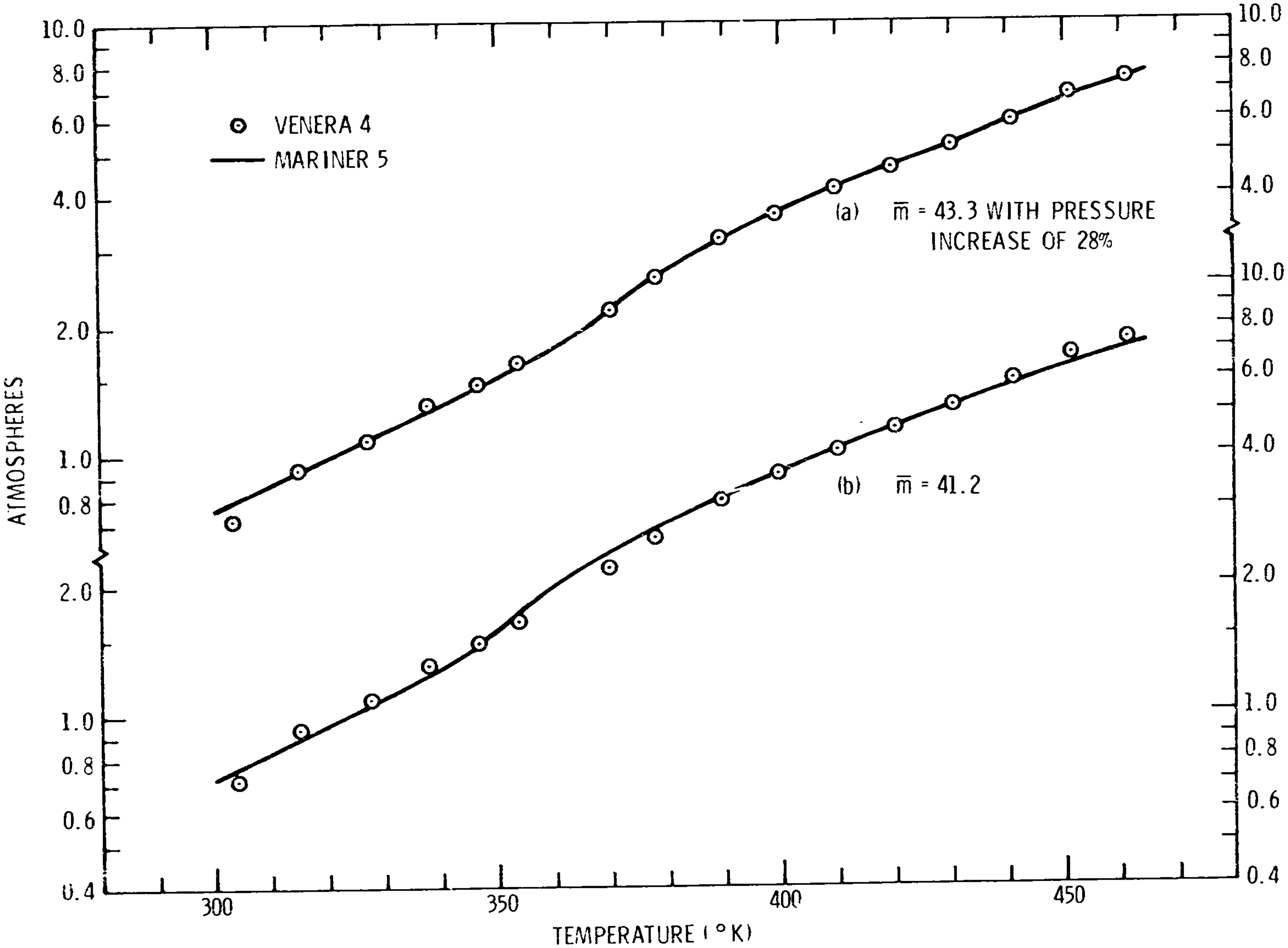

Figure 5. The average Mariner 5 P(T) profile is transformed to fit the Venera 4 P(T) data points (a) by a 20% increase in pressure and (b) by changing $\overline{m}$ from 43.3 to 41.2g/mole.

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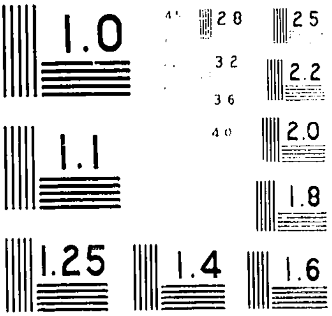

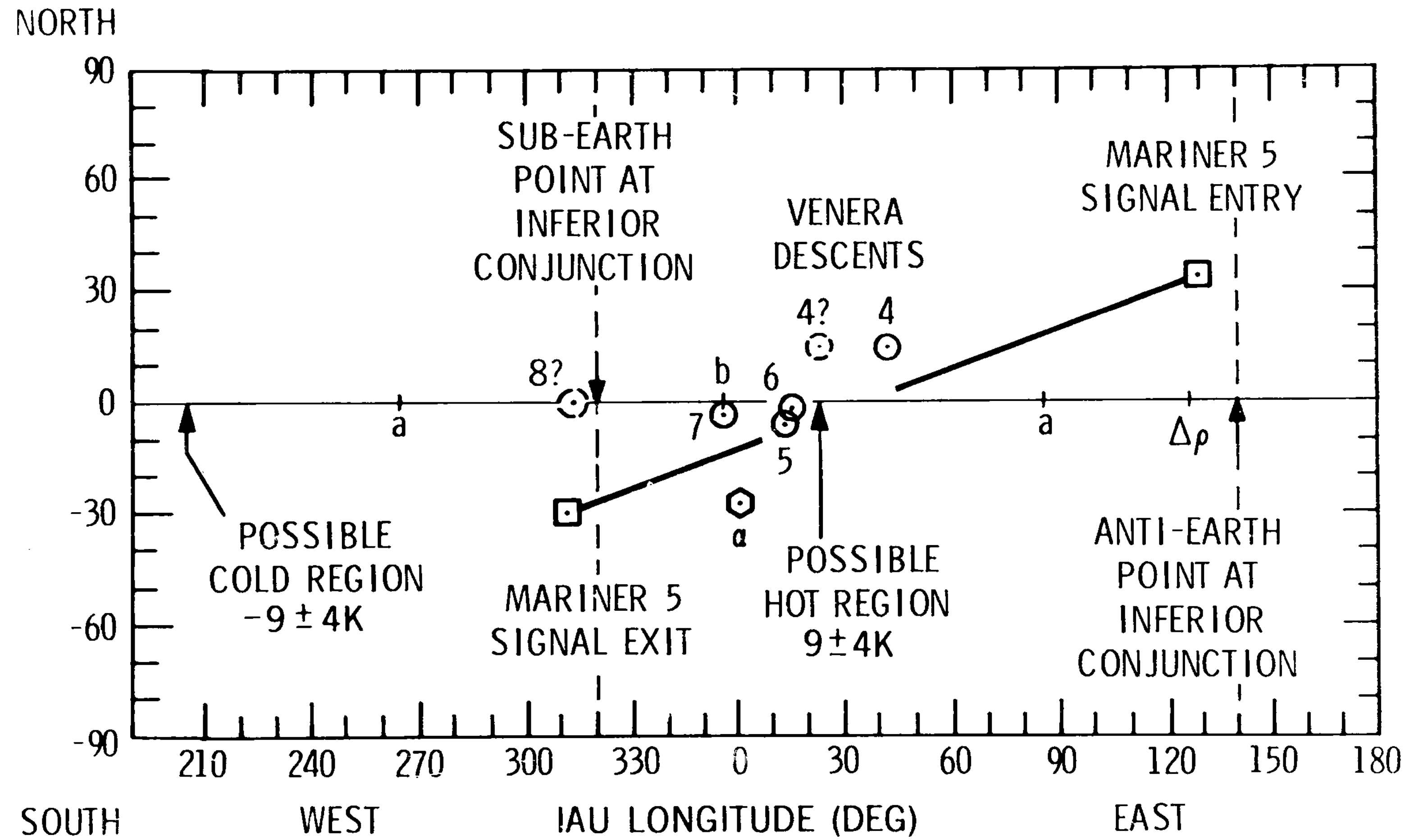

Figure 6. The positions of the Venera probe descents (Avduevsky et al., 1971b) and the two regions in which the Mariner 5 radio signals passed through the Venus atmosphere are shown in their relation to the Venus surface. Our work suggests that Venera 4 may have entered ~20° West of the position given by Avduevsky. An estimated position is given for Venera 8. The positions of the semi-major and semi-minor axes of the equatorial ellipse were determined by Smith et al. (1970). The recent equatorial topography measurements of Campbell et al. (1972) suggest that a and b should be moved ~20° to the west. The zero meridian, as adopted by the IAU (1970), passes through surface feature α and was selected so that the sub-Earth point was at 320° longitude at 0^h June 20, 1964. Due to the synchronous or near synchronous rotation of Venus the sub-Earth point is at approximately 320° longitude at each successive inferior conjunction. The hot and cold regions were derived from the 11.1cm radiation interferometer-measurements of Sinclair et al. (1972).

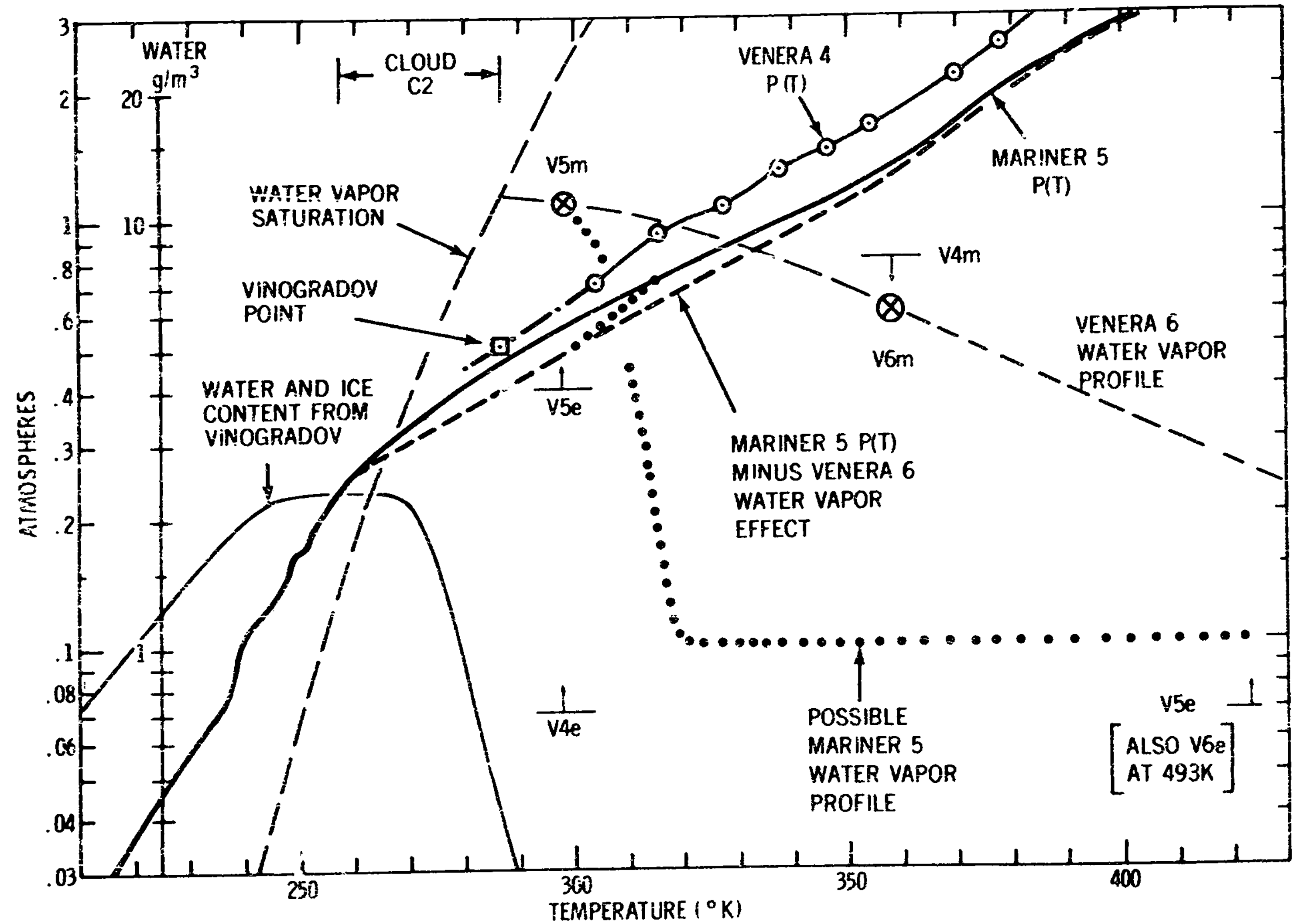

Figure 7. The effect of water vapor on the Mariner 5 P(T) profile is shown. To preserve the uniform 28% separation of the P(T) profiles we require the water vapor profile shown by the dotted curve. The estimated water and ice content shows no effect on the Mariner P(T) profile. Venera water vapor measurements were made using electrolytic (e) and manometer (m) instruments and in a number of instances represent upper or lower bounds to the water vapor content.

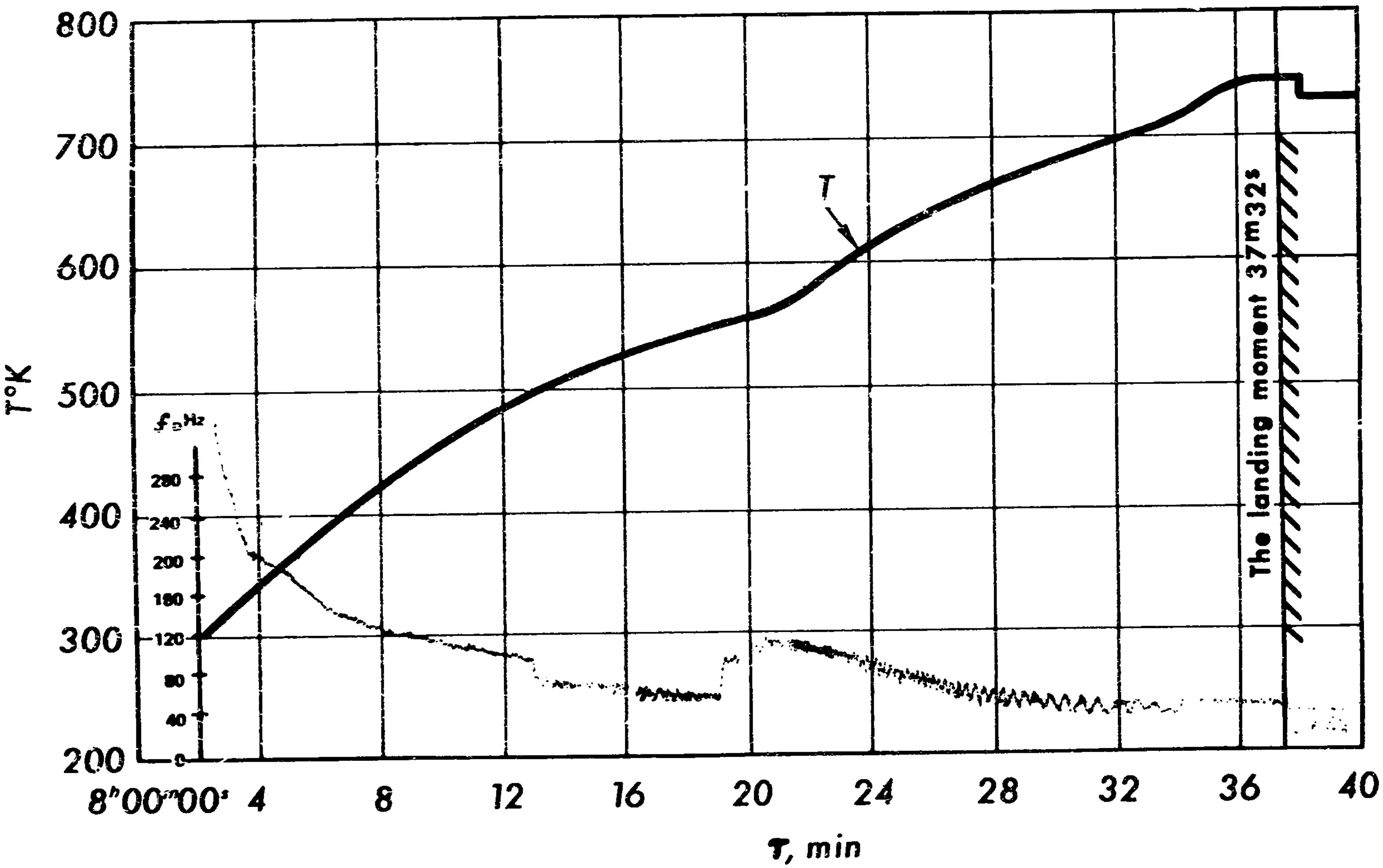

Figure 8. The Venera 7 data. The Doppler data shown is representative; part of the Doppler data has been omitted in order to simplify the discussion.

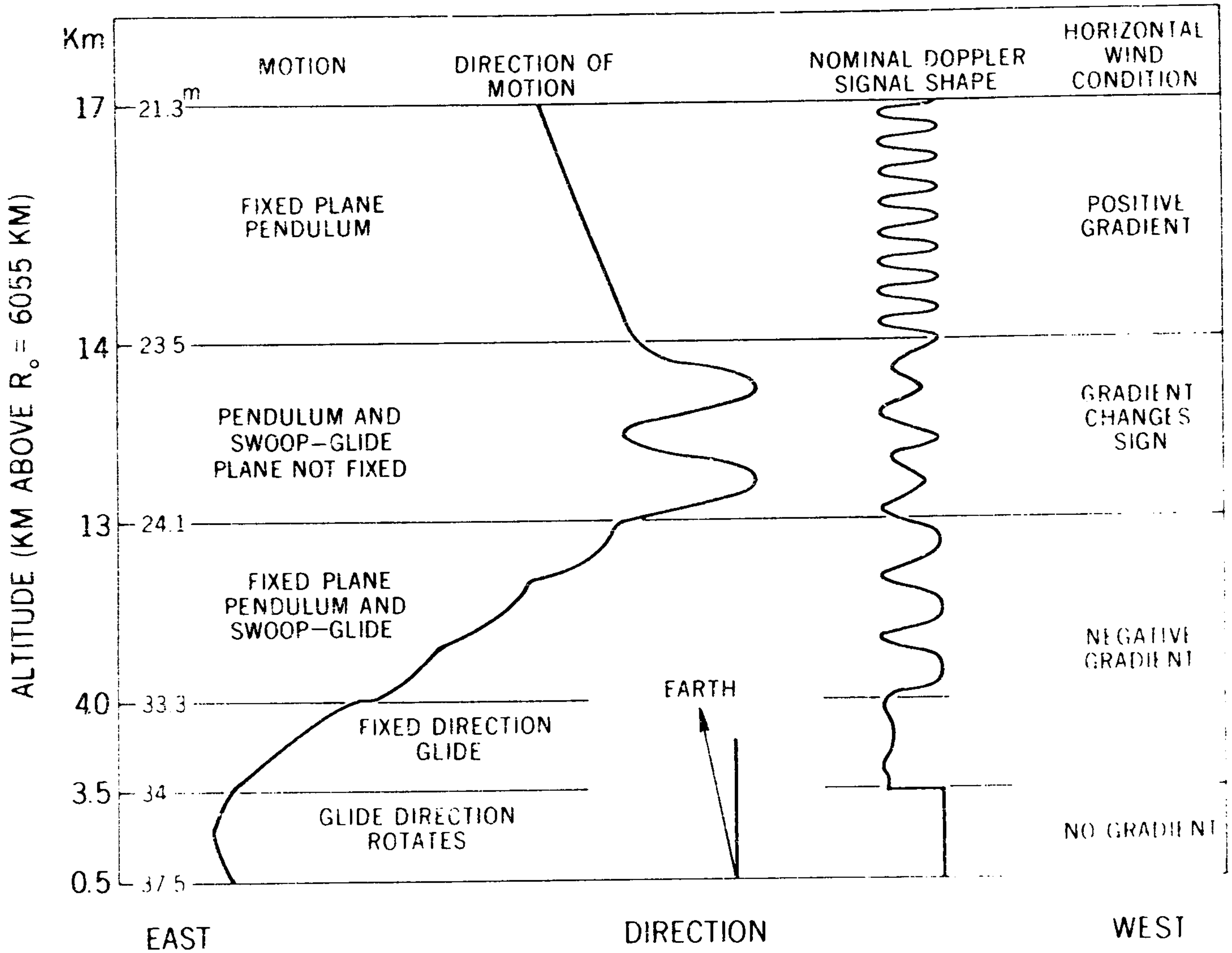

Figure 9. A schematic of the direction and kinds of probe descent motion suggested by the Venera 7 Doppler frequency and wind profiles. The vertical and horizontal scales have been distorted in order to simplify the discussion. The view is from the north pole looking at the equatorial plane.

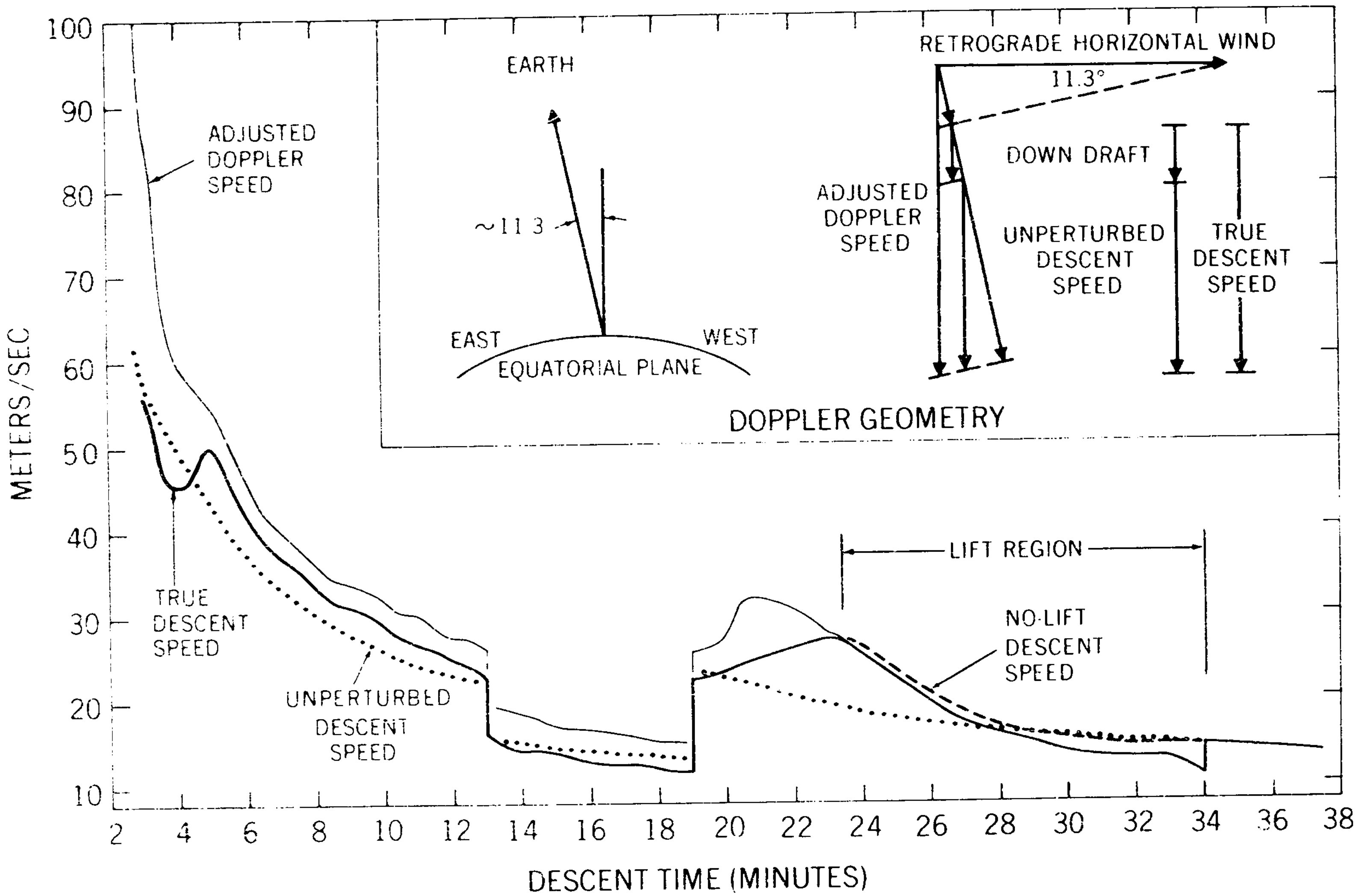

Figure 10. The Venera 7 Doppler geometry and descent speeds. The Doppler geometry lies on the equatorial plane and is viewed from the north pole.

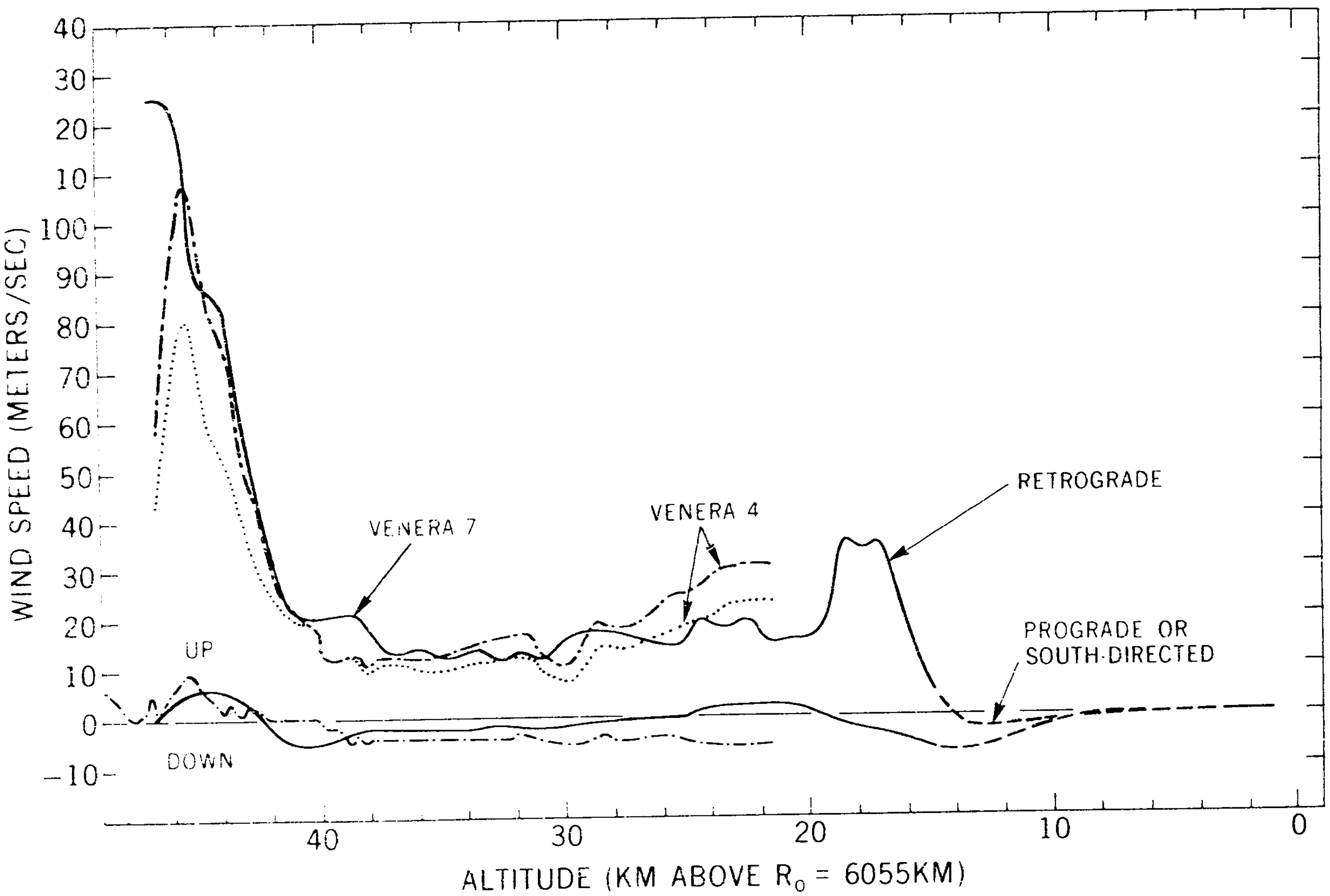

Figure 11. The solid lines are the vertical wind and a component of the horizontal wind obtained from the Venera 7 data. The dashed lines are estimated values. Kerzhanovich's Venera 4 wind data is shown by the lower dot-dash curve. The upper dot-dash curve represents our reconstruction and fitting of the Venera 4 wind data to the measured Venera 7 horizontal wind-component. The dotted line shows the possible effect on the Venera 4 data of a latitude dependence.

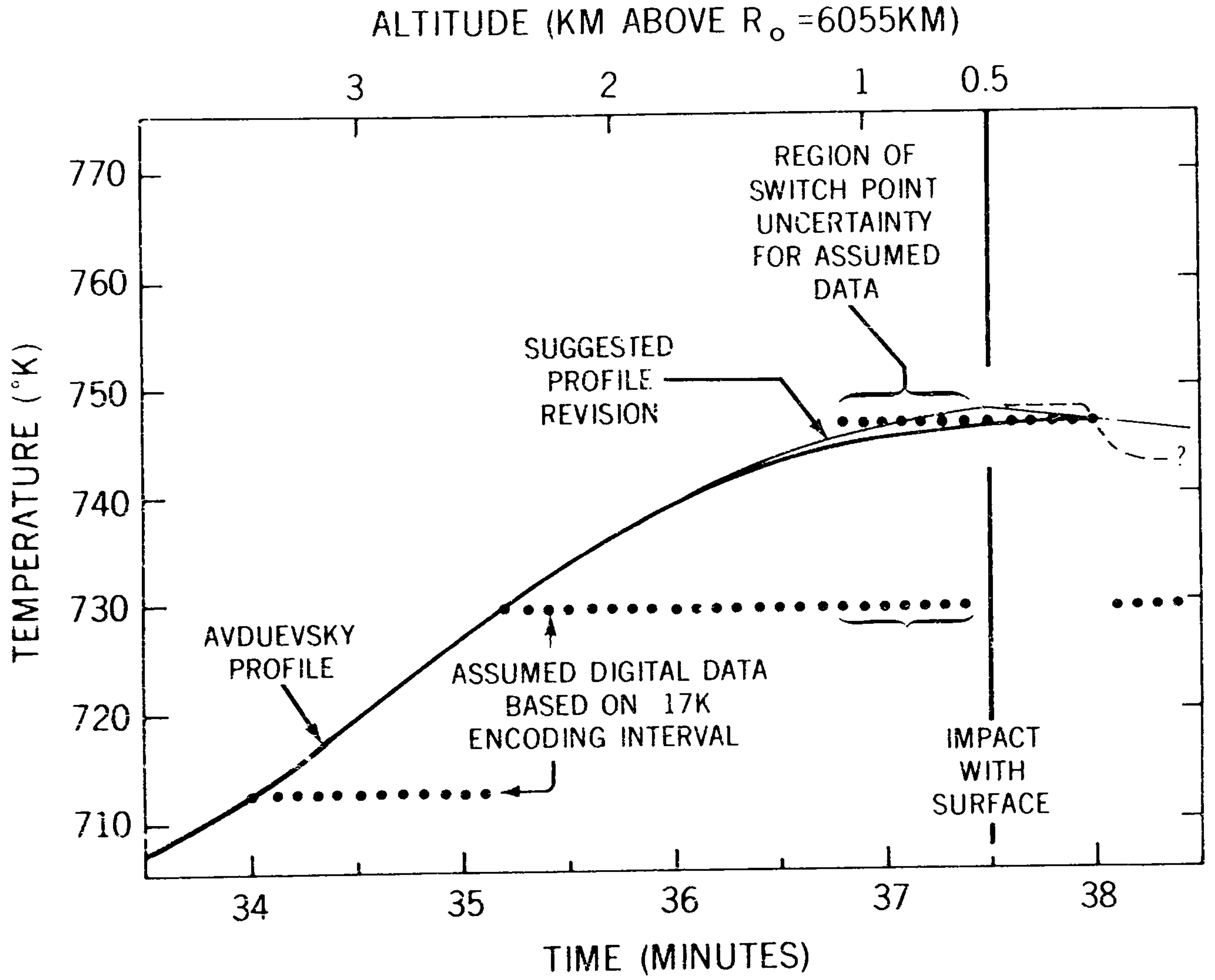

Figure 12. A proposed revision of the Venera 7 temperature profile immediately before and after impact. The dashed line represents the possible response from an accumulation of "wet snow" by the temperature sensor.

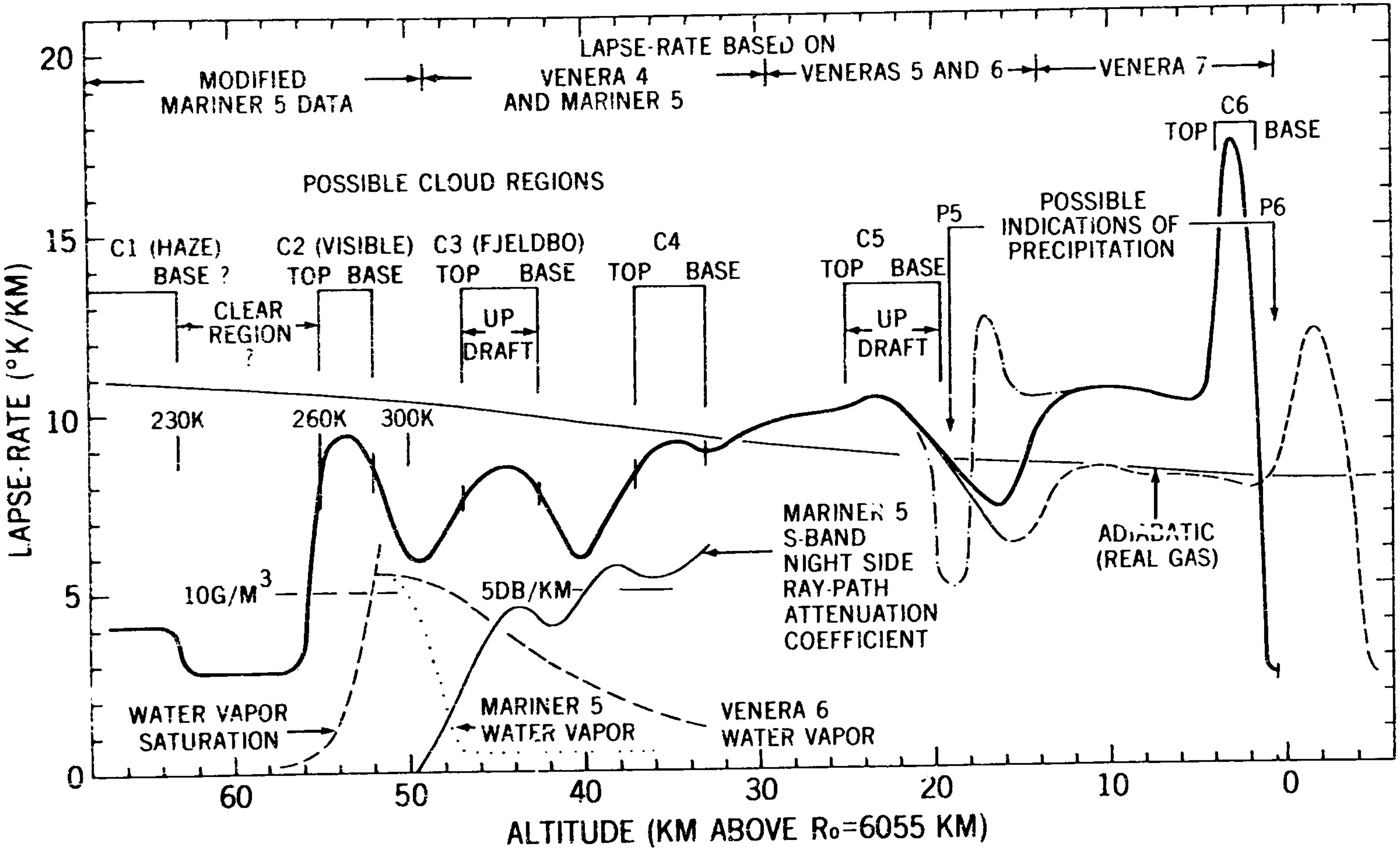

Figure 13. The atmospheric lapse-rate profile obtained from the Mariner and Venera data. The dot-dash curve at 2υ .m is a literal interpretation of the temperature anomaly shown at 21^m in Figure 8. The dashed curve from 16km to the surface shows the lapse-rate obtained for a Venus surface radius of 6050km. Shown also are the adiabatic lapse rate for the Venus atmosphere, the Venera water vapor measurements, the night-side Mariner 5 S-band ray-path attenuation coefficient profile, and the positions at which cloud layers and precipitation may exist.

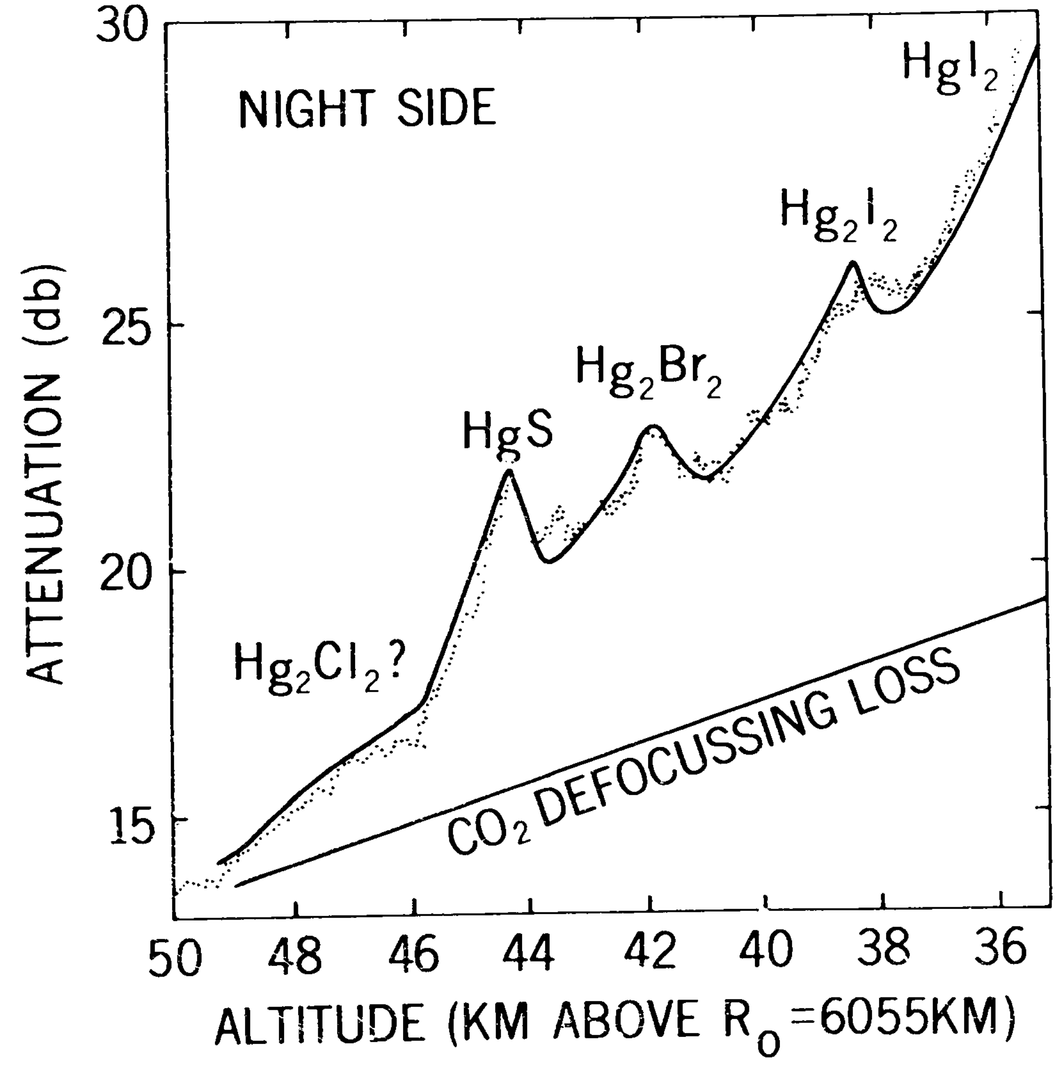

Figure 14. The 5 layer mercury-compound attenuation profile shown by the solid line was computed and fitted to the Mariner 5 attenuation data by Rasool (1970). We have changed the altitude scale to refer to a planet radius of 6055km.

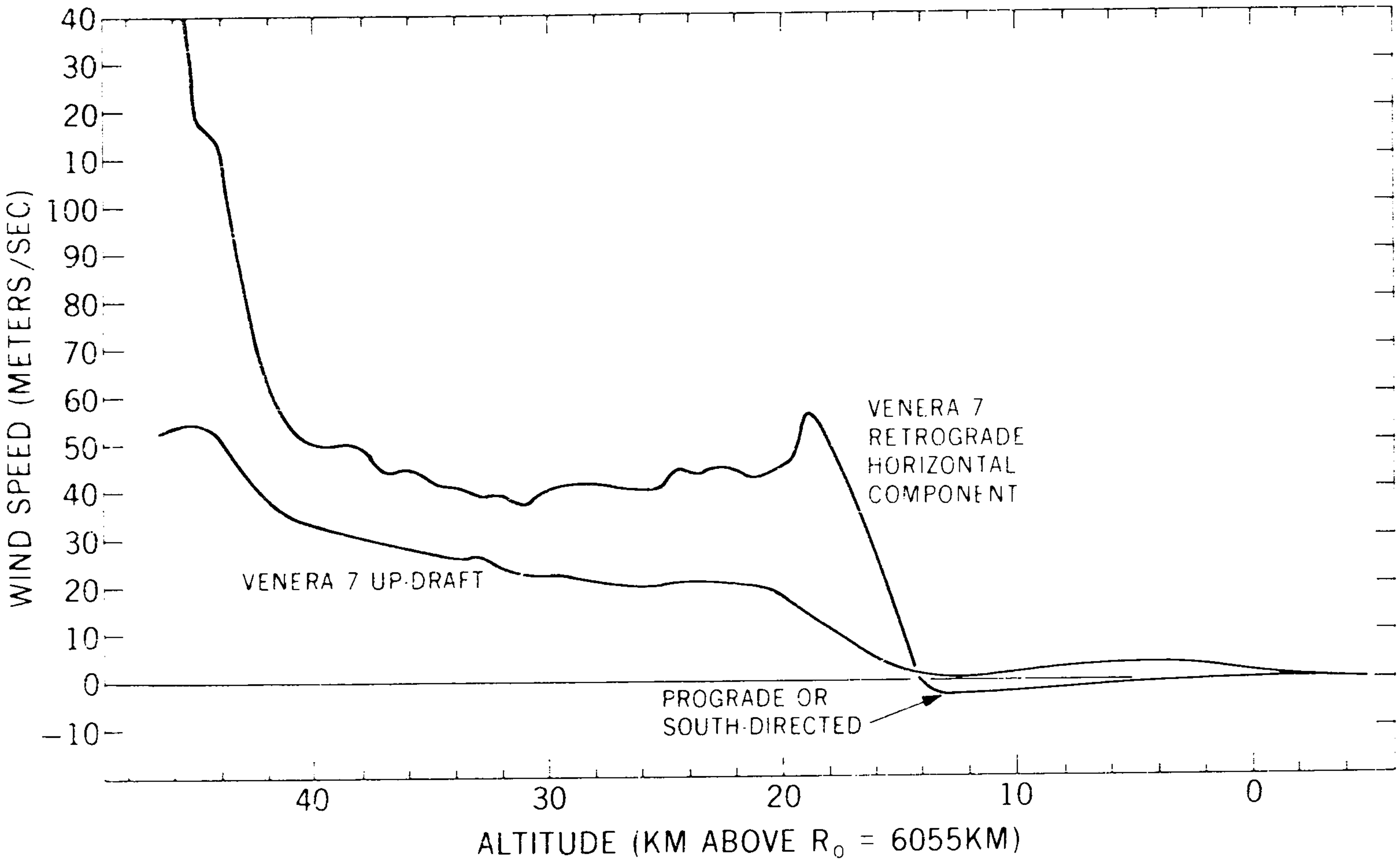

Figure 15. Venera 7 winds computed by means of a "true" descent speed which results in a surface radius of 6050km.

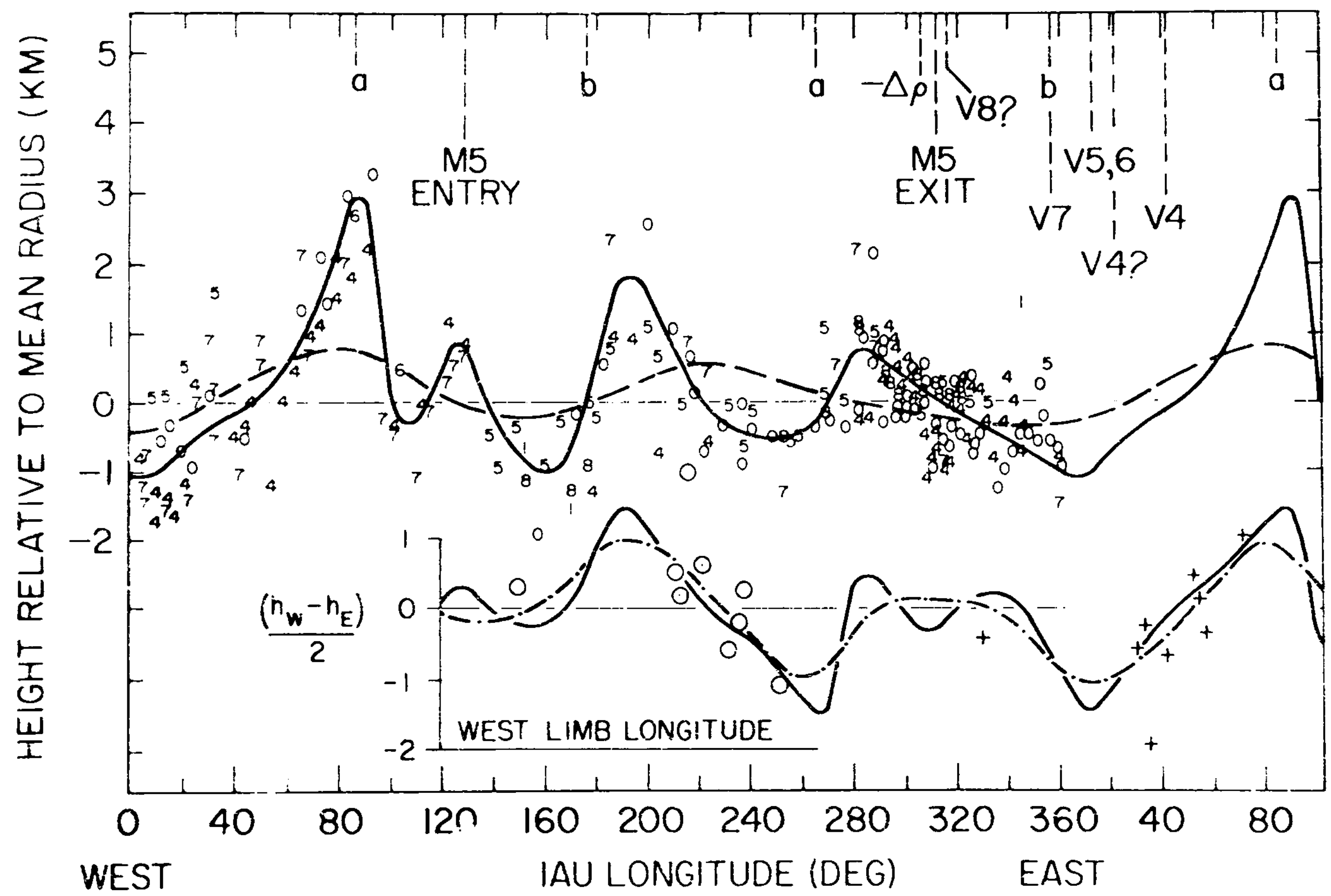

Figure 16. The upper solid line drawn through the topography data of Campbell et at. (1972) is eye estimated. The dashed line is an area averaging curve for the solid line and is intended to show the elliptical equatorial figure. It shows that the ellipse axes a and b given by Smith et al. (1970) have the required difference of 1.1 ±0.4km but should be shifted 20° to the West for better agreement. The circles and crosses represent the East-West temperature difference measurements of Sinclair et al. (1972) converted to height-differences based on the height variation of atmospheric density for a constant Venus surface temperature. The lower solid curve is the difference between Campbell's East and West limb surface heights plotted with respect to the longitude of the West limb. This curve is smoothed in a manner consistant with the resolution of Sinclair's measurements to obtain the dot-dash curve. (See text.) Shown also are the approximate Mariner 5 occultation positions, the Venera 4, 5, 6, and 7 entry positions, and the direction of the displacement -Δ, of the center-of-mass from the geometric center, as obtained by Smith et al. (1970). Our work suggests that Venera 4 may have entered ~20° West of the position given by Avduevsky et al. (1971b). An estimated position is given for Venera 8.

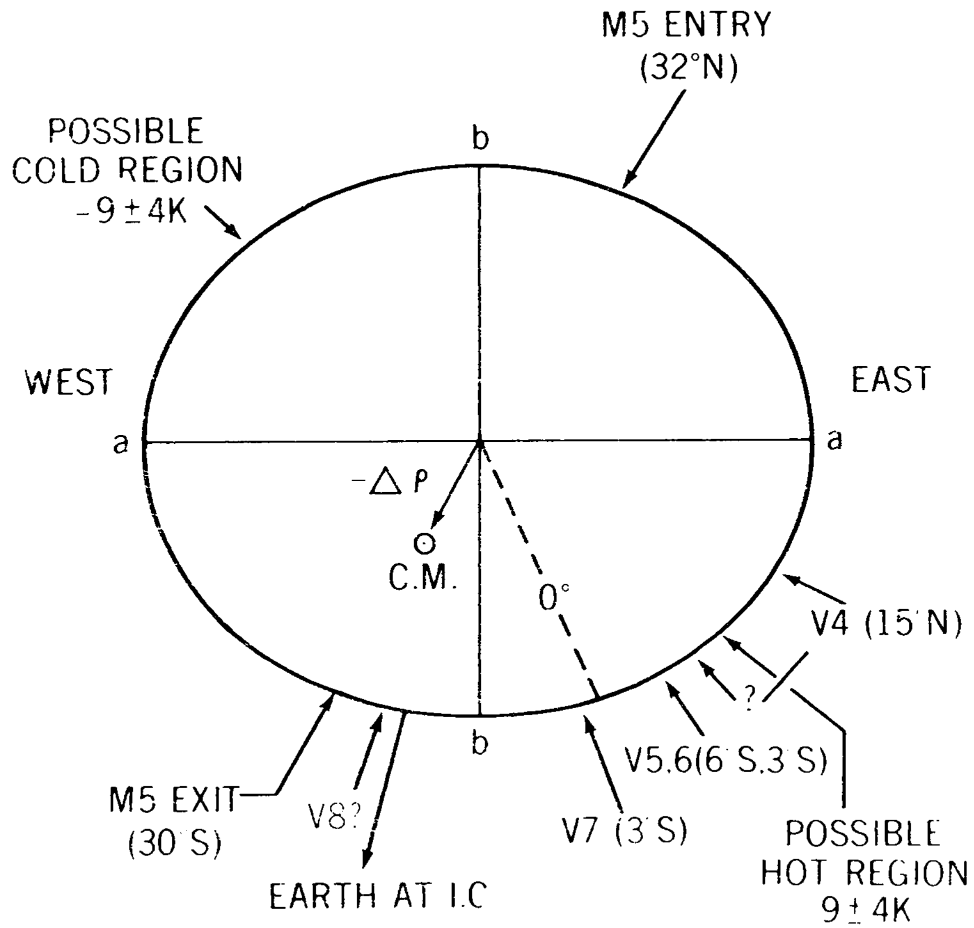

Figure 17. The average equatorial figure and the Venera descent and Mariner 5 signal occultation positions are shown as seen from the north pole. Our work suggests that Venera 4 may have entered -20° West of the position given by Avduevsky et al. (1971b). In parentheses we show the actual latitudes for each probe. An estimated position is given for Venera 8. Shown also are the direction of Earth at inferior conjunction and the 1.5 ±0.3km displacement of the center-of-mass of Venus from its geometric center obtained by Smith et al. (1970). The longitudes of the semi-major and semi-minor axes a and b have been displaced 20° to the West of the original direction given by Smith et al. (1970) and shown in Figures 6 and 16 in order to more closely agree with the average planet equatorial figure we obtain from the data of Campbell et at. (1972) shown in Figure 16.