Reports

Venus: Lower Atmosphere Not Measured

Abstract. *The common ranges of pressure and temperature of the atmosphere of Venus measured last October establish the connection between the Soviet Venera 4 altitude scale and the United States Mariner V radial scale. But if the Venera 4 measurements extended to the surface, as claimed, this comparison implies a radius of the planet which is about 25 kilometers greater than the radius deduced from Earth-based radar data. This impasse has been resolved in favor of the smaller value by a new determination of the radius which is more direct than the method used in deriving the radar radius, and which involves concurrent ranging from Earth both to Mariner V near encounter and to the surface of Venus. It is concluded that neither spacecraft reported on atmospheric conditions near the level of the mean surface, but extrapolations of the measurements yield surface values for mid-latitudes of 100 atmospheres pressure (within a factor of 1.5) and 700°K temperature (within 100°), in distinction to the Soviet values of 19 ± 2 atmospheres and 544° ± 10°K. The higher values support radiometric and radar data on temperature and atmospheric absorption. It appears that the Soviet probe was not designed to work through such a thick atmosphere. A particularly simple (times two) ambiguity in the Venera 4 altimeter reading suggests itself, since this would bring all other data into excellent agreement and would explain the reason for the supposition that the probe reached the surface.*

Many aspects of the Soviet Venera 4 and the United States Mariner V missions were remarkably successful and complementary (*1, 2*). Nevertheless it was obvious soon after the data became available that atmospheric results from the two space probes and the planetary radar determination of the radius of Venus (*3*) could not be reconciled without a major change of results or interpretation for one or more of these experiments. Comparing the measured atmospheric parameters from the two spacecraft establishes a connection between the Mariner V radial scale and the Venera 4 altitude scale, and hence a value for the radius of the planet. But the radius determined in this way is about 25 km more than the radar-determined radius. While a large number of factors from these and other sources need to be considered, the central question has evolved around the radar radius and the altitude scale of the Soviet atmospheric probe relative to the mean surface. Although the evidence is impressive that the radar radius is accurate and the Venera 4 data are internally consistent, the incompatibility of the various results means that this evidence has to be questioned critically.

Workers at the Jet Propulsion Laboratory, the Arecibo Ionospheric Observatory of Cornell University, and Stanford University have now made new determinations of the radius of Venus based on concurrent radio transponder ranging to Mariner V and radar ranging to the planet's surface. Their results verify the radar radius in a way that is largely independent of the principal complexities of the experiments based on radar data alone. It also appears that Venera 4 was not designed to continue working all of the way through a very thick atmosphere, so that it could not have been expected to have reported on conditions at altitudes very much below the level of its final measurement, if indeed the Venus atmosphere extended further down.

It is concluded that the Venera 4 altitude scale must be incorrect, at least in terms of height above the mean surface level. Since the error approximately equals the value of the single altimeter reading, we wonder if the reading could be and was triggered at just twice the purported height of 26 km. Alternatively, the altimeter may have given a false timing pulse, or Venera 4 may have landed on a very high and undetected surface feature. In any event, the atmosphere near the mean surface of Venus is considerably denser and hotter than indicated by Venera 4 results.

Mariner V measured (by radio occultation) atmospheric parameters as a function of radius from the center of mass (*4*). Venera 4 directly probed temperature, pressure, and density as a function of time—after a single radio altimeter indication. Subsequent altitudes were deduced from considerations of the measured atmospheric parameters and the known fall characteristics of the parachute and descent probe (*1*). In Fig. 1 we show the approximate positions on Venus of the measurements made by occultation and by Venera 4. Figure 2 compares pressure profiles determined from measurements taken by the two probes. The Mariner V profile is a combination of the virtually identical (*5*) entry and exit (night and day) results deduced by integral inversion (*6*). The pressure profile from the Venera 4 measurements is fitted to the Mariner V profile over their common pressure range of about 0.7 to 7 atm. Thus a direct comparison is made of radial distance from the center of mass (the Mariner V ordinate) and the purported altitude above the surface (the Venera 4 ordinate) on the basis of the pressure profiles. It is clear that there was substantial (about 15 km) overlap of measurement, with Mariner V results extending to higher altitudes and those of Venera 4 to lower altitudes than the overlap region. The low-altitude cutoff of the Mariner V measurements is due to the superrefraction limitation of occultation measurements (*7*), while the upper limit for Venera 4 was apparently set by the planned conditions for parachute deployment and start of atmospheric measurements.

Mariner V temperature profiles, also deduced by integral inversion, are compared (Fig. 3) with the Venera 4 measurements, the same ordinate comparison being used as that found from the fit of the pressure profile of Fig. 2. It is apparent that fitting the pressure curves also produces very close agreement in temperature profiles over the common range of temperature, even though measurements were at different latitudes and local times of day. It is also apparent from the two Mariner V temperature profiles that day-night temperatures are approximately the same, and that the tropopause tempera-

Table 1. Computed radius of Venus. (Distance is measured in units of time; an adopted velocity of light, $c = 299792.5$ km/sec, is used.)

Time (U.T.)	Mariner V data Earth-center to Venus-center range (km)	AIO radar data Earth-center to Venus surface range (km)	Planetary radius (km)
$12^h\ 20^m\ 0.0^s$	79,517,193		
$12^h\ 34^m\ 34.763^s$	Interpolated value (79,528,216)	79,522,160	6056
$12^h\ 35^m\ 0.0^s$	79,528,534		

ture and height (about 270°K at 6110 km from the center of mass) do not differ appreciably on the day and night sides (*8*).

To us, the agreement between the two sets of atmospheric data is so striking that it leaves no question as to how the Venera 4 measurements are related to the radial scale from the center of Venus, which is provided by the Mariner V trajectory. From this comparison, a radius of 6078 km is inferred for the solid surface of Venus, if we assume that Venera 4 reached the surface. From the same type of considerations, Kliore and Cain (*5*) have independently derived a value of 6079 km. While the fit of the pressure curves is in itself better than 1 km, we use a $\pm$ 3 km error bar to account also for possible errors in the trajectory and in the Venera 4 height extrapolation, which are discussed below.

This derived radius of 6078 ± 3 km is not compatible with the radar radius (*3*). The value originally published by Ash, Shapiro, and Smith is 6055.8 $\pm$ 1.2 km, based on data from the Lincoln Laboratory, Arecibo, and Crimean radar stations taken from 1959 to mid-1966, and optical data obtained by the U.S. Naval Observatory from 1950 to 1965. More recent radar results have now been included by the Lincoln Laboratory group to yield a revised value of 6050 $\pm$ 0.5 km. Melbourne, Muhleman, and O'Handley recently have used radar data from the NASA–JPL tracking station at Goldstone, California, to determine independently a value of 6053.7 $\pm$ 2.2 km (*3*). In each case, formal errors are quoted, and it is recognized that small errors may be present which are greater than the quoted value. For further reference here, we use a radius of 6053 $\pm$ 4 km based both on the radar results and the combined radar and Mariner V tracking results discussed below. This value is used to show a second altitude scale in Figs. 2 and 3, for which it is seen that the lowest Venera 4 pressure and temperature determinations would be at an altitude above the mean surface of 25 $\pm$ 5 km.

From the radar and Mariner V radius, the comparison of atmospheric measurements of Venera 4 and Mariner V, and the Mariner V radial scale, it is concluded that the Venera 4 measurements extend over altitudes of about 25 to 50 km and that the Mariner V measurements go from approximately 35 to nearly 90 km altitude. For this situation, atmospheric conditions at the mean surface level can only be determined by extrapolation. Two possibilities are illustrated in Figs. 2 and 3. The "adiabatic" extrapolation is based on a continuation of the measured lapse rate (which is approximately adiabatic) over the lowest 25 km, while in the "isothermal" extrapolation we assume that the lapse rate goes to zero as the height decreases. These two extrapolations represent extreme limits, and when combined with the $\pm$ 5 km uncertainty, lead to pressures of 70 to 150 atm and a temperature range of about 600° to 800°K for mid-latitude atmospheric conditions at the level of the mean surface of Venus. We use nominal values of 100 atm pressure, accurate within a factor of 1.5, and 700°K temperature, accurate to 100°K.

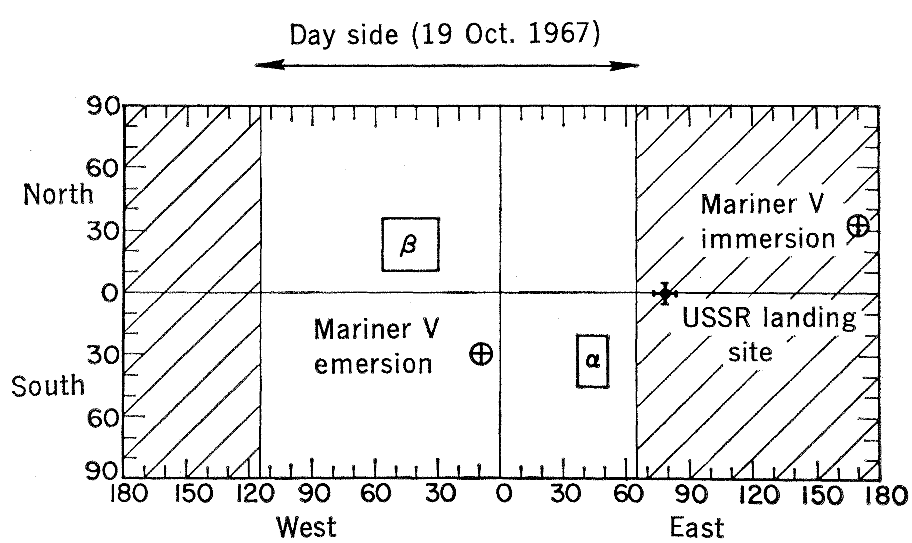

Fig. 1. Locations on Venus of the atmospheric measurements of Mariner V and of the Venera 4 probe. Zero longitude is toward Earth at inferior conjunction. Areas α and β are strong radar scatterers (*12*).

The planetary radius is not determined in a simple and direct way from Earth-based radar measurements; rather, it is a by-product of a broader study of celestial mechanics. Range (in light seconds) and range rate are determined with high precision (as good as one part in 10^8) between the radar site on Earth and the reflecting area on the target planet, which is a small region around the point on the surface nearest Earth. As Earth and the target planet orbit Sun, the reflecting point follows a path which is displaced from the orbit of the center of mass of the target planet by an amount equal to the mean planetary radius (measured along the locus on the planet of the surface reflecting point). Thus, in order to find the mean radius, it is also necessary to determine, to a very high precision, the astronomical unit, the radar site position relative to the Earth-Moon barycenter, the motion of this center around Sun, and the orbital elements of the target planet, including significant perturbations due to other planets. Observations over several years are important here. In the massive computational effort at the Lincoln Laboratory of M.I.T. and at the Jet Propulsion Laboratory (*3*), solutions for up to 23 parameters are obtained simultaneously by iterating corrections until convergence, in a weighted least-square sense, is achieved. The accuracy of the results is limited not only by measurement precision but also by the inherent assumptions and the choice of theoretical approaches that must be made.

We concluded that while we were very much impressed with the radar determinations of the radius of Venus, an independent measure of radius based on another approach was important in order to establish the result very convincingly for use in the problem of the Venus atmosphere. Such a measure has now been made, based on a combination of radio transponder ranging to Mariner V near Venus encounter, and concurrent radar ranging from Earth to the reflecting surface of Venus.

It is apparent conceptually that simultaneous transponder ranging to a spacecraft and planetary radar ranging can provide a relatively direct measure of the planetary radius. The acceleration of a spacecraft is toward the center of mass of a nearby planet, whereas a radar echo is from the surface. Transponder ranging can be used to establish the spacecraft orbit and hence the center of mass, and the difference between the distance to this center and to the small radar reflecting area on the surface is just the planetary radius.

We have used the orbit of Mariner V and radar results for 19 October 1967 from the Arecibo Ionospheric Observatory to compute (Table 1) the radius of Venus (*9*). From the spacecraft ephemeris (encounter orbit No. 1031) supplied by the JPL project office to the Mariner V experimenters, Earth-center to Venus-center distances are given for the two tabulated times which embrace the effective time of the radar measurement from the Arecibo radar site. Interpolation is used to deduce the Earth-center to Venus-center distance at the time of the radar observation, which has been used to determine the Earth-center to Venus-surface range. The difference of these two distances is 6056 km, a relatively direct measure of the radius of the solid reflecting surface at the subradar point on Venus (*10*). This point is near the Venera 4 entry location.

Since the Venus-centered trajectory is expected to be more precise than the formal errors of the radar radius and of the height spread at a given pressure or temperature for the Venera 4 results, we used the Mariner V radial scale as a reference in considering the apparent radar radius and Venera 4 altitude inconsistency. Of course, it is possible that the problem concerning the lower atmosphere of Venus is caused by very large but undetected Mariner V tracking or computational errors. However the agreement of entry and exit atmospheric results to within an accuracy of 1 km (*5*), the intrinsic measurement accuracy, the relative insensitivity of spacecraft positions for remaining Venus mass and other gravitational uncertainties, and the apparent precision in spacecraft position obtained by Anderson *et al.* (*10*) seem to preclude the possibility of an error in Mariner V results of anywhere near the amount needed to reconcile the problem. While there is admittedly some circularity in this argument, the close agreement obtained for the Venus radius as determined by the two methods nevertheless makes it less likely that either the radar radius or the Mariner V trajectory are appreciably in error. Experimental and theoretical studies of radio propagation in the atmospheres and ionospheres of Earth and Venus and in the interplanetary medium have revealed no effects which could explain the discrepancy discussed here.

The Venera 4 parachute was released by a pressure sensor, and the radio altimeter and radio system were first turned on at this same time. The single altimeter reading (26 ± 1.3 km) was also apparently made at this time. Pressure was measured for 50 minutes, and density was measured for 70 minutes, at which times the limits of the instruments were exceeded. Temperature was measured for 94 minutes, at which time the radio signal stopped abruptly. By considering both atmospheric parameters as measured and extrapolated, and the fall characteristics of the probe with parachute, it was determined that pressure was measured for 18 km, density for 23 km, and temperature for 28 ± 0.6 km below the starting point. (Other valuable measurements were made of atmospheric constituents, but the results are not discussed here.) The close check between the altimeter reading and the distance traversed before signal stoppage has been used to infer that the moment of signal interruption may have corresponded to landing on the surface, when the probe may have tilted, deflecting the telemetry antenna beam away from Earth (*1*).

However it should be noted that the energy storage capacity of the battery was designed to supply power for "no less than 100 minutes" from the time of separation of the landing probe from the main spacecraft (*1*). It is not clear whether the time from separation to parachute deployment is important in this regard, but it follows that the signals either stopped approximately at the

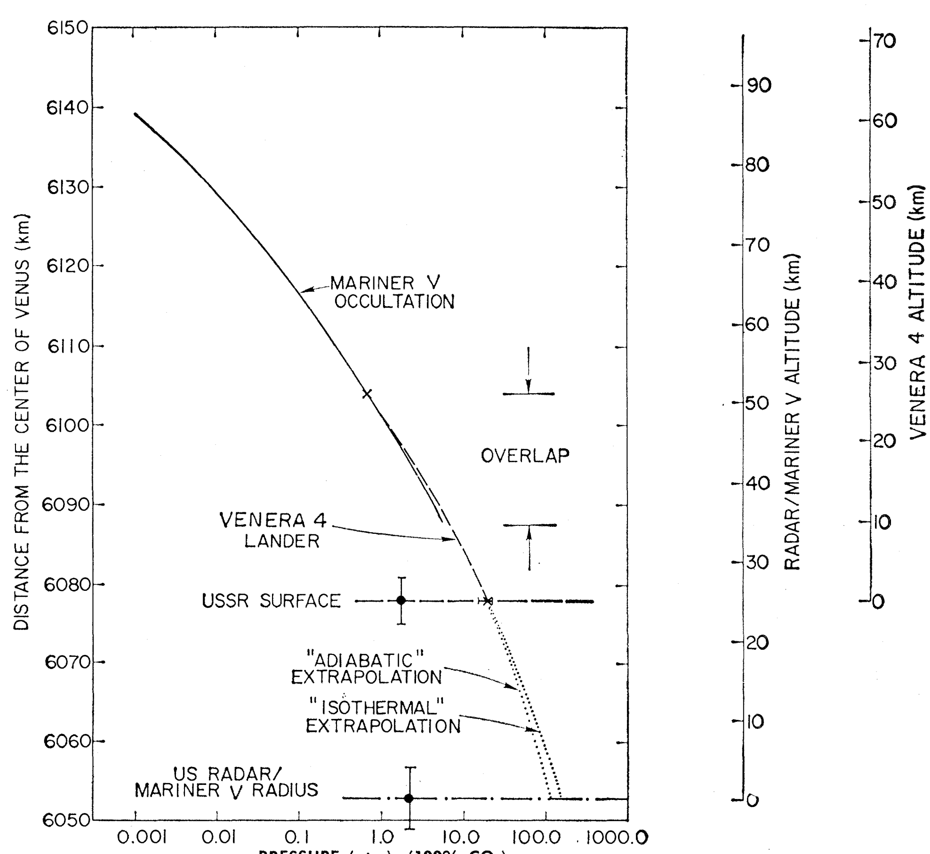

Fig. 2. Pressure profiles determined by Mariner V and Venera 4, and extrapolations to the level of the mean surface.

time corresponding to the expected minimum battery lifetime, or at a somewhat later time. At signal cessation, the probe was falling at about 2.5 m sec^{-1} (*1*). Thus a correspondence between the altimeter distance and the distance of fall would have been obtained within ± 10 percent if the power source had failed anytime during a 30-minute period which includes times exceeding the 100-minute minimum-design lifetime. For the proposed Venus atmosphere of about 100 atm and 700°K and no vertical winds, the battery capacity would have had to be at least several times the design value in order for Venera 4 to have reached the surface while still working.

Energy storage and power drain can easily be designed within small (say 10 percent) limits to fit requirements. Thus, it seems likely to us that Venera 4 could not have been expected to work all of the way through a very thick atmosphere. The suggestion that it did reach the surface while still operating depends only upon the radio altimeter indication. Without more details, one can only speculate on possible difficulties that might be encountered in this situation. Two factors are noteworthy. Only one measurement was reported to have been made, and it apparently was coincident with power first being supplied to the instrument when a malfunction, if it were to occur, might be most likely. Also, almost any radio ranging system has inherent range ambiguities, one example of many possibilities being that certain simple designs for measuring distance *D* would also respond to targets at distances of 2*D*, 3*D*, and so forth. If the parachute actually deployed at 52 instead of 26 km, all of the remaining data would be in excellent agreement, and it would seem that Venera 4 would then have been expected to cease transmissions because of the battery lifetime at about, or not far below, the 19 atm pressure level which we place at an altitude of 25 ± 5 km. The close correspondence between the values of the purported altimeter reading and the derived altitude discrepancy is very striking in regard to this last suggestion.

All of the reported results would also be in agreement if Venera 4 landed on a local surface which is 25 ± 5 km above the level of the mean surface (*11*). The period of rotation of Venus on its axis might be used to infer that there could be quite large topographic variations, to provide a large gravitational moment to establish and help maintain the strange synodic commensurability with Earth (*12*). As seen in Fig. 1, however the Venera 4 landing point is almost orthogonal to the direction to Earth at inferior conjunction (the zero reference of the longitude scale). Thus if Venus has unusually high or low elevations in localized regions for Earth-lock rotation, the Soviet probe entered at a longitude where the low regions would be expected, if they exist. A uniform equatorial bulge greater than an equipotential surface cannot be invoked to reconcile the problem since the radar radius and the Venera 4 measurement both apply to the equatorial region. In fact Venera 4 apparently entered very nearly at the subradar point for the time interval used in establishing the radius by the combination of radar and Mariner V ranging. It has also been reported that the radar results show no obvious changes of radius to an accuracy of a few kilometers (*13*). The very high temperature itself is argument against very large departures from hydrostatic equilibrium when one considers terrestrial types of materials. We conclude that the landing of Venera 4 on a very high terrain feature (which then must have been seen by the landing radar but not seen by Earth-based radars looking at approximately the same region of Venus at the same time) is a very unlikely interpretation of the various results. In any event, a very high landing site would not affect our conclusions about conditions at the level of the mean surface.

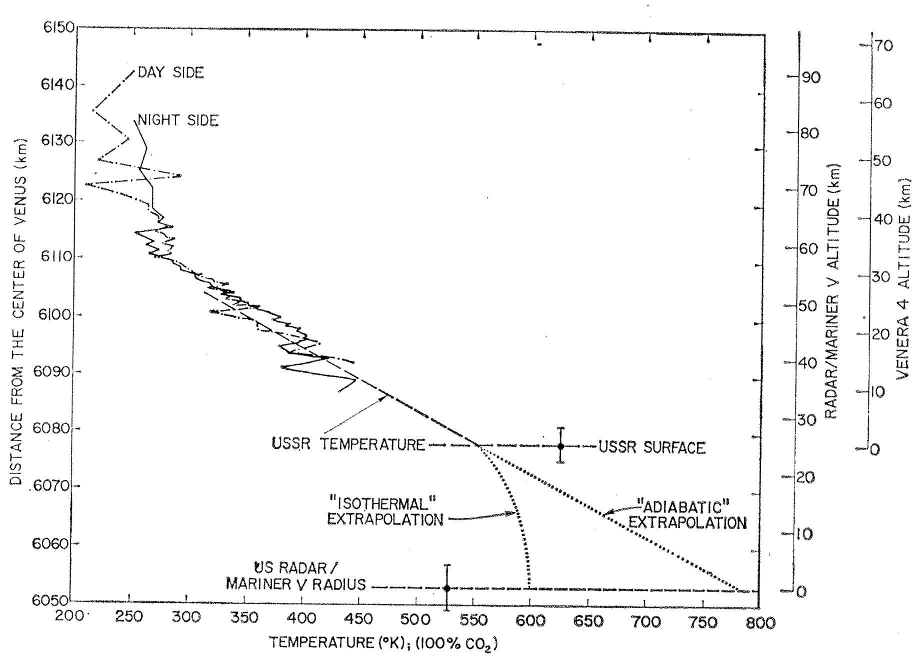

Fig. 3. Temperature profiles determined by Mariner V and Venera 4, and extrapolations to the level of the mean surface.

There are several additional areas of evidence and lines of argument that support the above conclusion concerning the high pressure and temperature of the atmosphere of Venus. We do not discuss these in detail but do outline the situation.

The radiometric, blackbody, disc temperature (radio brightness temperature) of Venus for wavelengths longer than a few centimeters is roughly 600°K, and it now appears well established that this is an emission measure of the physical temperature of the surface (*14*). Correcting for the emissivity on the basis of a 15 percent reflectivity, as measured by radar at decimeter wavelengths, yields an average disc temperature of about 700°K. The magnitude of changes of temperature with solar zenith angle and with latitude are not well established although values have been suggested (*14*). Evidence from the day-night measurements of Mariner V indicate little or no diurnal temperature difference above the 7 atm pressure level, and there is apparently little temperature difference at the same pressure level for latitudes of $\pm 30°$ as compared with the equator, from the Mariner V and Venera 4 measurements. Thus it appears that the magnitudes of the temperature changes are relatively small, and in any event the sense of the diurnal and latitude dependencies are such that they would be expected to tend to cancel in a comparison of mean disc temperature with the Venera 4 results. We conclude that a surface temperature of 544° ± 10°K at night and near the equator is incompatible with the average radiometric disc value (corrected for emissivity) of about 700°K, on the expectation that there is no appreciable temperature difference between the lower atmosphere and the surface.

The radar cross section of Venus, in percent of the area of the disc, is about 15 percent at decimeter wavelengths. At 3.8 cm wavelength, however, Evans concludes that the average value is only about 1.7 percent and that the most likely reason for the difference is atmospheric absorption of about 5 db for a one-way vertical path (*15*). While some minor constituent or the clouds may be responsible for this attenuation (*14*), it is interesting that atmospheric carbon dioxide itself could produce this absorption within the range of atmospheric parameters proposed here. On the other hand, the Venera 4 model for atmospheric conditions at the surface would be quite inadequate to explain the radar absorption, including effects of both carbon dioxide and water vapor.

There may be important additional information in the different transitional wavelengths for the radiometric and radar absorption results. The radar cross section drops nearly an order of magnitude at wavelengths between about 20 and 3.8 cm, while the radiometric temperature transition starts at wavelengths about 2 or 3 cm and reaches mid-transition only when wavelengths of about 1 cm are reached (*14*, *15*). As wavelength is shortened and appreciable absorption starts between 20 and 3.8 cm, the radiometric measurement must become more dependent on atmospheric temperature and less dependent on surface temperature. The fact that this effect is not apparent in the radiometric measurement until even shorter wavelengths are reached implies that the lower atmosphere cannot be appreciably cooler than the surface, a condition which would be needed to reconcile the Venera 4 atmospheric model with the measured brightness temperature.

Thus none of the arguments with respect to the radiometric temperature, the radar absorption, and their transition wavelengths appears compatible with having the Venera 4 measurements apply to mean surface conditions if carbon dioxide is the principal absorbing agent. The radiometric and radar results favor the high-pressure, high-temperature conditions proposed here. A strongly absorbing dust or cloud layer, or water vapor near the surface exceeding the amount measured by Venera 4, might be invoked to bring the absorption effects into agreement with the Venera 4 model, but the disagreement with regard to temperature would remain.

The combination of Earth-based and Mariner V radio and radar measurements has proved to be a remarkably effective method for deducing characteristics of the atmosphere of Venus. The measurement took on much more meaning than otherwise would have been possible because of the direct determinations by Venera 4 of constituents, temperatures, and pressures. All of the Earth-based and Mariner V radio and radar data combined lead to the conclusion that the lowest regions of the atmosphere of Venus have not yet been directly measured. However, extrapolation of Venera 4 and Mariner V results indicates that conditions at the mean surface for mid-latitudes are within a factor of 1.5 of 100 atmospheres pressure and within 100° of 700°K temperature.

VON R. ESHLEMAN
GUNNAR FJELDBO
Center for Radar Astronomy, Stanford University, Stanford, California 94305
JOHN D. ANDERSON
ARVYDAS KLIORE
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103
ROLF B. DYCE
Cornell–Sydney University Astronomy Center, Arecibo Ionospheric Observatory, Arecibo, Puerto Rico 00612, and *Stanford University*

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8. In order to deduce atmospheric temperatures and pressures from the Mariner V refractivity profiles, the Venera 4 measurement of the great preponderance of atmospheric carbon dioxide is of fundamental importance. The abscissas of Figs. 2 and 3 indicate an assumption of 100 percent carbon dioxide for the Mariner V curves. For 85 percent carbon dioxide and 15 percent nitrogen, for example, there would be virtually no difference in the pressure profiles, and the temperature curves would be in even better agreement with the Venera 4 results.
9. It may be of interest that discussions had been held between Arecibo and Stanford personnel concerning the advisability of obtaining radar measurements at the time of Venus encounter by Mariner V, even though no definite correlative experiments were envisioned. The Millstone Hill radar of the Lincoln Laboratory also ranged on Venus on this day.
10. A more complete study of the combined Mariner V and radar ranging data is under way at JPL by J. D. Anderson, L. Efron, R. Goldstein, W. G. Melbourne, D. A. O'Handley, G. Pease, and R. Tausworthe, who reported a value of 6052.5 km for the radius at the 20–23 August meeting of the American Astronomical Society in Victoria, B.C. Very little change in this value is expected in the continuing analysis. Range rate (Doppler) measurement accuracy to Mariner V was one part in 10^6 of the frequency change caused by encounter with Venus. From this high-precision tracking data, Kliore and Cain (*5*) conclude that occultation ray paths relative to the center of Venus should be accurate in position to better than 0.2 km. In fact, the position of the spacecraft with respect to Venus should be known to this order of accuracy in all three components. Range data accurate to about 0.015 km in one-way distance were also obtained around Venus encounter, but they add very little to the accuracy of the Venus-centered trajectory. However, they are necessary in the determination of the absolute distance to Mariner V. Because of the precision of the Venus-centered trajectory, as determined from the Doppler data, the distance from Earth to the center of mass of Venus should be known to about 0.3 km around encounter.
11. A. D. Kuzmin, in a short communication presented at the Kitt Peak Conference on Planetary Atmospheres, Tucson, Arizona, March 1968, suggested that Venera 4 may have landed on a 10-km mountain, on the basis of a comparison of the Venera 4 temperature measurement and the radiometric temperature of Venus.
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16. W. G. Melbourne of JPL, G. L. Tyler of Stanford, and one of the reviewers made useful comments on a draft of this paper. Research support at Stanford University was under NASA grants NGR-05-020-276 and NsG-377, and at the Jet Propulsion Laboratory of the California Institute of Technology under NASA contract NAS 7-100. The Arecibo Ionospheric Observatory is operated by Cornell University with the support from the Advanced Research Projects Agency.

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