Reports

Venus: Estimates of the Surface Temperature and Pressure from Radio and Radar Measurements

Abstract. *The radio brightness temperature and radar cross section spectra of Venus are in much better accord with surface boundary conditions deduced from a combination of the Mariner V results and the radar radius than those obtained by the Venera 4 space probe. The average surface temperature and pressure are approximately 750°K and 90 atmospheres.*

The Soviet space probe Venera 4 (*1*) secured temperature and pressure measurements of the lower atmosphere of Venus as a function of altitude, whereas Mariner V (*2*) obtained similar data as a function of the distance to the center of the planet. The two sets of temperature and pressure points, as well as the temperature gradients, agree quite well. However, Ash *et al.* (*3*) and Melbourne *et al.* (*4*) have questioned the validity of the zero points of the distance scales. Even with the recent revision of Mariner V's orbit (*2*), there exists a serious discrepancy of about 25 km between ground-based radar estimates of the radius of Venus and that found from a combination of the Mariner V and Venera 4 distance determinations. Below we consider a different pairing of distance scales in an attempt to discover which ones are correct. We contrast the Venera 4 altitude measurement with an altitude estimate obtained from a combination of the radar radius and the distance of the Mariner V points from the center of Venus. The two altitude estimates imply significantly different surface temperatures and pressures and can be tested by a comparison of predicted and observed brightness temperature and radar cross section spectra.

Venera 4 obtained a surface temperature of 544° ± 10°K and a surface pressure of $18.5^{+2.5}_{-1.5}$ atm for a region quite close to the equator. To obtain the corresponding boundary conditions implied by the Mariner V data and the radar radius, we performed an adiabatic extrapolation from the 5-atm pressure level situated 6088.5 ± 0.5 km from the center of the planet (*2*) to the radar radius of 6050 ± 5 km (*3*). The Soviet measurements indicate that the temperature gradient below the 5-atm level has a value quite close to the adiabatic value. An alternative extrapolation procedure involves the application of the lapse rate measured at the terminal point of observation to the hotter, unobserved portion of the atmosphere. However, at such deep locales, this lapse rate would be superadiabatic, an unlikely situation in view of the great efficiency of convective heat transport (*5*). One of us (R.B.W.) wrote a computer program to perform an adiabatic extrapolation with allowance made for the dependence of the specific heats on temperature and pressure. In addition, we used the van der Waals equation of state, because of significant deviations from the perfect gas law near the surface, and appropriately modified the usual adiabatic relation between temperature and pressure (*6*). Table 1 summarizes the temperatures and pressures so derived for carbon dioxide mixing ratios which span the range indicated by Mariner V and Venera 4 (*1, 2, 7*). The remainder of the atmosphere was assumed to consist of nitrogen. The error estimates reflect the uncertainty in altitude. These surface conditions should be quite close to average values. The Mariner V measurements were performed at a midlatitude position of 37° and there is little difference between the day and night data (*2*).

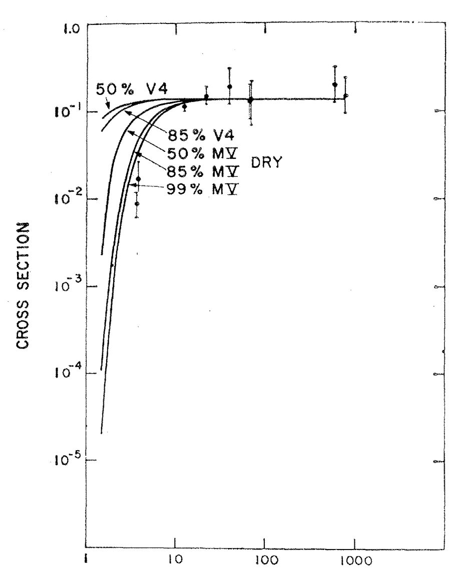

Fig. 1. Radar cross section, in units of the geometrical cross section of Venus, as a function of wavelength for five values of the surface boundary conditions. The percentages directed to the curves indicate the carbon dioxide mixing ratio used; MV refers to the use of the radar radius–Mariner V altitude, while V4 refers to the use of the Venera 4 altitude. Observed values are indicated by closed circles with appropriate error bars. All models contain 0 percent water vapor.

The same extrapolation procedure was used to find the average surface conditions for the Venera 4 altitude scale. Because the Venera 4 data were obtained close to the equator, the average surface temperature may be somewhat lower than the figure quoted above, though by terrestrial analogy little pressure variation would be expected. Halting the Mariner V extrapolation at a pressure level of $18.5^{+2.5}_{-1.5}$ atm, we obtained the average surface temperatures shown in Table 1. The error estimates for the Venera 4 surface conditions are those given by the experimenters. No result is given for the case of a 99 percent carbon dioxide mixing ratio, since an average temperature in excess of the equatorial temperature was obtained.

We calculated radio brightness temperature and optical depth spectra in a manner quite similar to that used in a previous paper (*8*). We assumed that the radio flux was solely of thermal origin and that carbon dioxide, water vapor, and nitrogen were the only sources of microwave atmospheric opacity.

We computed the brightness temperature by analytically integrating equation 3 of Pollack and Sagan (*9*) over the disk and used a constant solid-angle average emissivity. The equation for the microwave absorption coefficient of carbon dioxide and nitrogen was adopted from the experimental work of Ho *et al.* (*10*).

The formula given by Barrett and Staelin (*11*) for the microwave absorption coefficient of water vapor apparently has an incorrect temperature dependence (*8*) and its use would have led to an overestimate of nearly an order of magnitude of the water vapor opacity, evaluated at the surface. We used the temperature variation experimentally determined by Ho *et al.* (*10*) and appropriately modified Barrett and Staelin's formula (*8*). We allowed for the condensation of water vapor in the upper atmosphere by letting the water vapor mixing ratio decrease exponentially with a scale height of 1 km, a value appropriate for a condensation adiabat, above the position at which saturation is first achieved (*8*).

We used a mathematical model to stimulate quite exactly the atmospheric profile observed by Mariner V (*2*) and Venera 4 (*1*). In accord with the observations, the model atmospheres consisted of three main regions: an adiabatic region from the surface to 400°K level for carbon dioxide mixing ratios of 85 and 99 percent, and 378°K for the ratios of 50 percent; a portion of the atmosphere divided into five layers, each characterized by a constant lapse rate; and an isothermal region above the second region. A computer program, similar to the one used for extrapolating to the surface, furnished the main program with punched cards describing the atmospheric structure. The latter program was written initially by Dr. A. Dupree and substantially modified by one of us (A.T.W.).

We first apply these calculations to predict radar spectra. The radar cross section measured near a wavelength of 3 cm is about an order of magnitude lower than values obtained at decimeter wavelengths (*12, 13*). The reality of this precipitous decline seems quite well established; measurements have been performed by two separate radar units (*12, 13*). In addition, the value for the cross section of Mercury obtained by one of these instruments, the Haystack radar unit, is quite similar to values found at longer wavelengths (*12*). Since the brightness temperature noticeably declines below 3 cm because of atmospheric opacity, it is natural to explain the decline in cross section in the same manner. Also consistent with this interpretation is the flatness of the radar cross section at decimeter wavelengths, where little atmospheric opacity is expected.

As the returned radar signal originates chiefly from regions near the subearth point, the observed cross section will be diminished by a factor of $e^{-2\tau}$ from its value in the absence of attenuation (τ being the optical depth of the atmosphere at the wavelength of interest). The atmospheric regions principally responsible for the attenuation will be characterized by equatorial temperatures. We have compared the average temperature profiles with the Venera 4 data at the 18.5-atm level to correct the average temperatures to equatorial ones.

Table 1. Extrapolated average surface temperature T_s and average surface pressure P_s as a function of the carbon dioxide mixing ratio, α_{CO_2}.

α_{CO_2} (%)	Radar radius–Mariner V altitude		Venera 4 altitude	
	T_s (°K)	P_s (atm)	T_s (°K)	P_s (atm)
50	707 ± 45	82.8 ± 22	511 ± 10	18.7 ± 1.5
85	762 ± 45	92.7 ± 26	555 ± 10	16.9 ± 1.5
99	783 ± 45	97.2 ± 28		

Figures 1 and 2 compare predicted radar cross section spectra with observed values. We normalized the cross sections to yield a value of 0.14 at the longer wavelengths (*12*). The measured values of the cross section were obtained from a compilation by Evans (*12*). In addition the measurement by Karp *et al.* (*13*) at 3.6 cm is also indicated. The model atmospheres used to construct Fig. 1 have no water vapor present, while the model atmospheres represented in Fig. 2 contain a water vapor mixing ratio of 0.5 percent in the lower atmosphere; this latter figure is consistent with a value of between 0.1 percent and 0.7 percent found by Venera 4 (*14*) and with an upper limit of 0.8 percent inferred from the observed brightness temperatures at 1.35 cm (*8*). We see that those models having the Venera 4 surface conditions are grossly inconsistent with the observations. They contain an optical depth about an order of magnitude below the indicated value. Because of the above cited upper limit on the water vapor mixing ratio, we cannot secure agreement by significantly increasing the water vapor mixing ratio above the 0.5 percent level. On the other hand the models that incorporate the combined radar–Mariner V conditions are in reasonable agreement with the observations. The best fit to the radar data would appear to come from models containing several tenths of a percent of water vapor. Future radar cross section measurements at wavelengths shorter than 3.8 cm should help check this point.

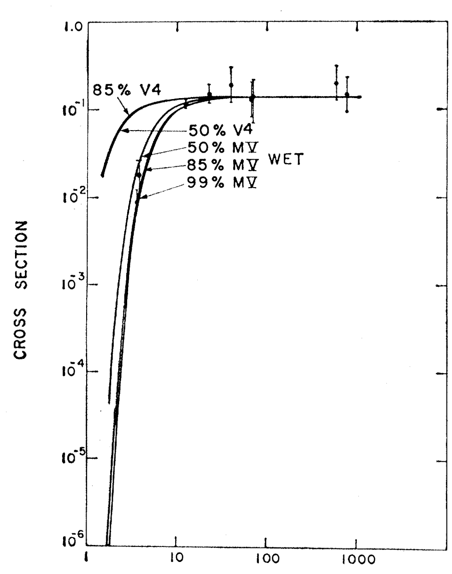

Fig. 2. Radar cross section, in units of the geometrical cross section of Venus, as a function of wavelength for five values of the surface boundary conditions. The labels for the curves and the closed circles with error bars have the same meaning as their counterparts in Fig. 1. All models contain 0.5 percent water vapor in the lower atmosphere.

In computing brightness temperature spectra, we used a surface emissivity of 0.82 for wavelengths longer than 6 cm, as in our previous calculation (*8*): thermal emission at 6 cm arises from depths comparable to the ones probed by a radar signal of 12 cm. The radar cross section at 12 cm is similar to the longer wavelength values. The value of 0.82 for the emissivity is derived by using the Fresnel reflectivity equations to average over solid angle a radar cross section of 0.14 (of the data points of Fig. 1). For those atmospheric models with insufficient atmospheric opacity to account for the 3.8-cm radar cross section, we assumed that the difference was due to a change of dielectric constant and used appropriate emissivities at wavelengths less than 2 cm. Intermediate values of emissivity were employed between 2 and 6 cm.

The computed brightness temperature spectra for models with 0 percent water vapor are shown in Fig. 3, and those with 0.5 percent water vapor are shown in Fig. 4. The values of the brightness temperatures at wavelengths longer than 3.5 cm provide a discriminant between the two main sets of boundary conditions. Many of the observed points are compatible only with the radar–Mariner V surface temperatures, while only one point shows

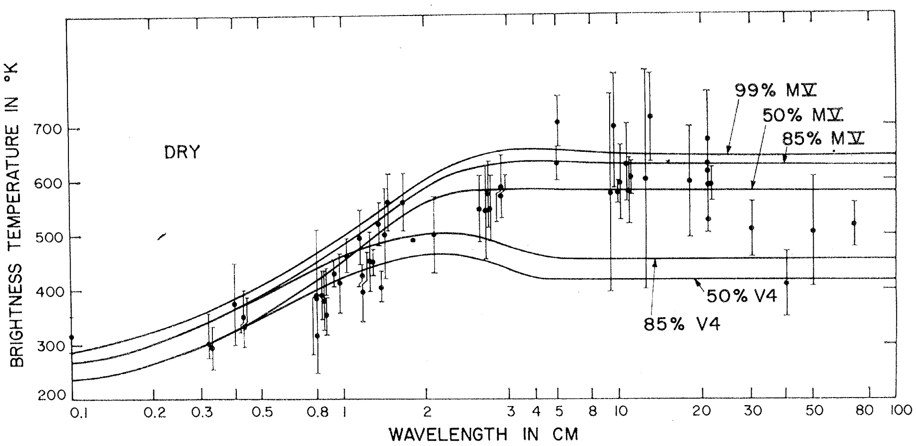

Fig. 3. Brightness temperature as a function of wavelength for five values of the surface boundary conditions. The labels for the curves and the closed circles with error bars have the same meaning as their counterparts in Fig. 1. All models contain 0 percent water vapor.

a decided preference for the Venera 4 temperatures. We might add that the measurements beyond 21 cm are more difficult to perform because of the low flux density of Venus at these wavelengths and potential interference from solar radiation (*15*). A check on our basic assumptions is provided by the good fit of the predicted spectra to the observations at wavelengths shorter than 3.5 cm.

By comparing Figs. 3 and 4 we see that the best fit to the observed spectra below 3 cm in wavelength would be given by a model characterized by a water vapor mixing ratio somewhat less than 0.5 percent. However, as with the radar observations, more observations are needed before definite conclusions can be reached on this matter.

In summary, surface conditions inferred from the Mariner V–radar distance scales are consistent with passive and active radio observations of Venus. Within the context of our assumptions, the Venera 4 altitude scale leads to inconsistencies. Reasonable variations in the values of parameters used in the above calculations, such as surface emissivity, will not change this conclusion. For example, were we to assume that the emissivity is 0.82 at all wavelengths for the Venera 4 surface conditions, the brightness temperature between 1.5 and 6 cm would be lowered and the disagreement exhibited in Figs. 3 and 4 would be enhanced. To overcome the difficulties faced by the Venera 4 surface conditions, one could invoke an additional nonthermal component to the radio emission to explain the radio results and an extra source of microwave opacity or a change in the surface dielectric constant with depth to match the radar cross sections; however this would be a rather *ad hoc* approach. Ash *et al.* (*3*) have pointed out that their radar measurements imply only very small topographical relief; so it seems unlikely that elevation differences on Venus are the cause for the above discrepancies. Furthermore, it is significant that the other boundary conditions can match the data. We conclude that the Venera 4 altitude measurement is in error or at the very least the surface conditions indicated by Venera 4 are far from representative. It is interesting that our predicted altitude of the Venera 4 craft above the mean surface of Venus at the moment of the altimeter reading is almost exactly twice the reported value.

The average surface temperatures and pressure of Venus are approximately 750°K and 90 atm. These values are within 50°K and a factor of 2, respectively, of estimates of these quantities given by Sagan (*16*) in 1962.

A. T. Wood, Jr.
Harvard College Observatory, Cambridge, Massachusetts

R. B. Wattson
Smithsonian Astrophysical Observatory, Cambridge, Massachusetts

J. B. Pollack*
Smithsonian Astrophysical Observatory and *Harvard College Observatory, Cambridge, Massachusetts*

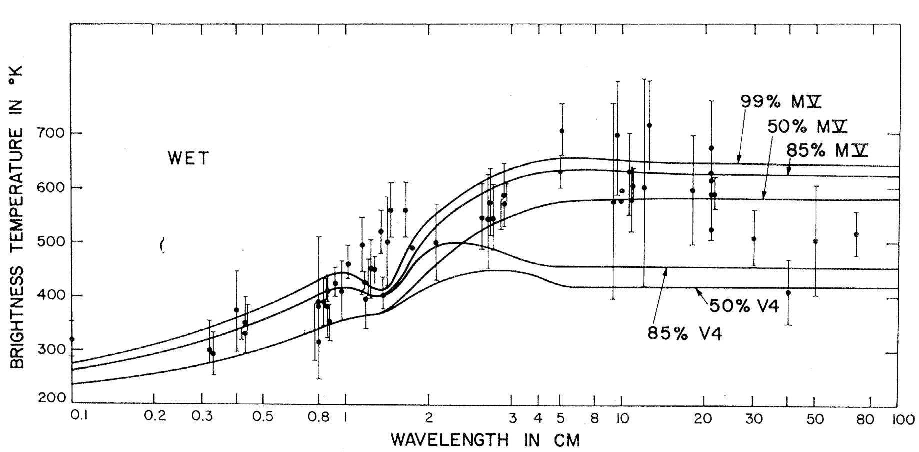

Fig. 4. Brightness temperature as a function of wavelength for five values of the surface boundary conditions. The labels for the curves and the closed circles with error bars have the same meaning as their counterparts in Fig. 1. All models contain 0.5 percent water vapor in the lower atmosphere.

References and Notes

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* Present address: Center for Radiophysics and Space Research, Cornell University, Ithaca, N.Y.

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