VENUS: DETERMINATION OF ATMOSPHERIC PARAMETERS FROM THE MICROWAVE SPECTRUM

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Abstract. The microwave spectrum of Venus is compared with the structure and composition of the Venus atmosphere as determined by Veneras 4, 5, and 6 and Mariner V. The results are consistent with a radar radius of 6049.5 ± 3 km, surface pressures of 95 ± 20 atm, and a surface temperature of 770 ± 25 K, as well as a water vapor volume mixing ratio of 0.65 ± 0.35%.

The high atmospheric temperatures measured by the Mariner V and Venera 4, 5, and 6 space probes as well as many theoretical investigations (see e.g. Barrett and Staelin (1964)) have indicated that the microwave spectrum of Venus is produced by thermal emission from a hot surface overlaid by an atmosphere that is optically thick at millimeter wavelengths. In this paper we further investigate this suggestion, comparing theoretical spectra computed for a variety of models with a critically selected set of observations. When combined with recent data obtained by radar and by direct measurement by spacecraft, this analysis yields improved values for some parameters describing the troposphere and surface of Venus.

To define the microwave spectrum at wavelengths from 2 mm to 21 cm, we have selected 21 recent measurements of high quality. In addition, we have used the 43-meter telescope of the National Radio Astronomy Observatory to make two new determinations of the brightness temperatures: 700 ± 45 K at 6.0 cm wavelength and 495 ± 35 K at 1.9 cm wavelength. (These uncertainties are computed standard errors and include a 5% uncertainty in the assumed flux scale.) At wavelengths of 2 cm and larger, we have defined the spectrum using only measurements made with respect to standard celestial sources, and we have normalized all of these data to the flux scale of Kellermann *et al.* (1969). At shorter wavelengths, we have generally relied on the estimates of absolute antenna gain made by the observers. All of the data used in our spectrum have been published since 1963.

This observational spectrum, which is illustrated in Figure 1 below, has significantly smaller scatter than previous compilations, such as those of Dickel (1967). We estimate that these data define the spectrum with an absolute accuracy of ±50 K and a relative accuracy of ±30 K. The observations confirm the peak in the brightness temperature near 6 cm suggested by Dickel (1967) and show a rapid decline in temperature between 4 cm and 1.5 cm wavelengths.

For comparison with the observations, we have computed theoretical spectra using techniques similar to those described by Pollack and Wood (1969) and by Wood *et al.* (1969). We have explicitly accounted for variation of the microwave emissivity over the

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disk, and we have computed the opacity contribution of water vapor using corrections to the absorption coefficients (measured in air and nitrogen) to allow for the greater absorption that takes place in a predominantly CO_2 atmosphere. Our models of the temperature and pressure structure of the atmosphere are based on the measurements of Venera 4, 5, and 6 (Avduevsky *et al.*, 1969) and of Mariner V (Kliore *et al.*, 1969). At levels below those measured directly, we have extrapolated the temperature and pressure to the surface. The nature of this extrapolation and the composition of the atmosphere are constrained to match the observed radius of 6051 ± 5 km (Anderson *et al.*, 1968) and the radar measurements of a vertical optical depth of the atmosphere of 1.0 ± 0.1 at 3.8 cm wavelength (Muhleman, 1969). In our computations, we have considered variations in radius and surface dielectric constant, variations in the atmospheric content of CO_2, H_2O, and suspended dust, and departures from an adiabatic

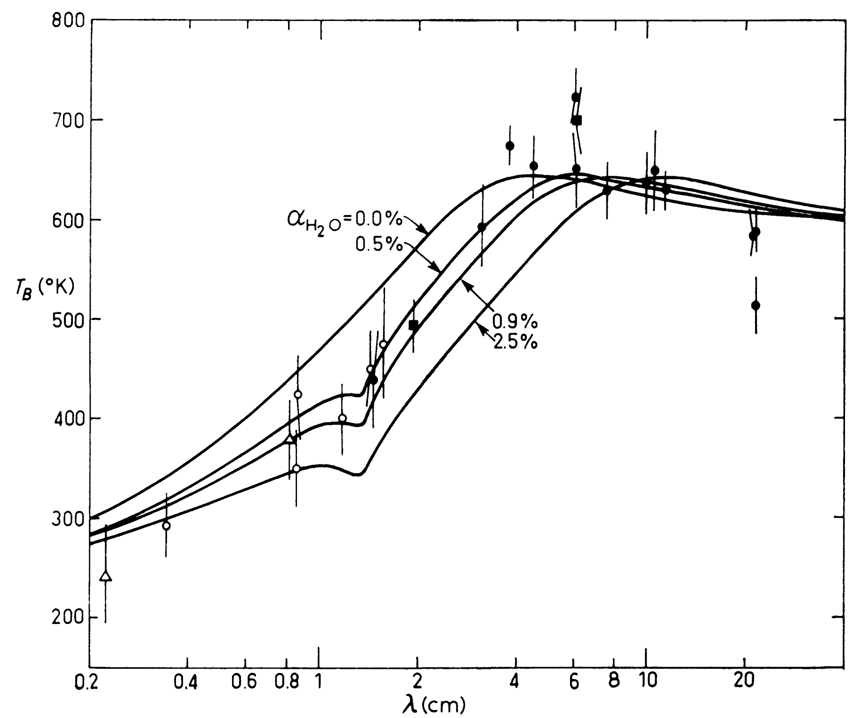

Fig. 1. A comparison of theoretical models containing various abundances of water vapor with observed microwave spectrum of Venus. The measured values of the brightness temperature are indicated by triangles, squares, or circles. The vertical lines associated with these points give the estimated errors.

structure in the lower few kilometers of the atmosphere. A good fit to the data is provided by the following 'standard' model: 90% CO_2 mixing ratio, 0.7% H_2O mixing ratio, no significant opacity contribution by dust, surface pressure 90 atm, surface temperature 760 K, dielectric constant 4.8, planetary radius 6051 km, and strictly adiabatic lower atmosphere. In view of the recent 11 cm interferometric study of Venus made by Sinclair *et al.* (1969), we do not expect any of these parameters to vary significantly with latitude and longitude on the planet.

In Figure 1 we compare the observed brightness temperatures with theoretical spectra in which the H_2O mixing ratio is varied. The other parameters of the model are the same as for the 'standard' model. It is apparent that CO_2 alone does not supply sufficient opacity to match the observed spectra, and this conclusion is not altered if we consider CO_2 mixing ratios up to 100%. Krupenio, in this symposium, has indicated that the radar data also require an additional opacity source. We note that the argument from the microwave spectrum is less ambiguous than that made from radar data alone, since the microwave emission between 1 and 3 cm arises primarily in parts of the troposphere where direct measurements of atmospheric structure are available. Alterations in the parameters of the model at the base of the troposphere, which can significantly change the computed radar cross section, do not influence the predicted spectra in this wavelength region; only by changing the composition can we produce agreement between the models and the microwave observations. We wish to stress, however, that in the absence of observational evidence for the 1.35 cm resonant absorption of H_2O, we cannot assert that the microwave spectrum demonstrates the presence of H_2O in the troposphere of Venus. However, the amount of H_2O required to fit the data – 0.4 to 1.2% volume mixing ratio – lies close to the lower limits of the *in situ* measurements of H_2O obtained from the Soviet Venera entry probes (Avduevsky *et al.*, 1969). In addition, for this range of mixing ratios, condensation of water will occur close to the top of the troposphere.

Our preliminary calculations indicate that the observed spectrum cannot be matched by models in which there is a substantial (>4 km) isothermal layer at the base of the troposphere or in which there is a major contribution to the microwave opacity by suspended dust particles. In addition we obtain values for the radar radius, surface pressure, and surface temperature of 6049.5 ± 3 km, 95 ± 20 atm, and 770 ± 25 K, respectively. Finally further analysis reduces the range of allowable water vapor volume mixing ratios to (0.65 ± 0.35)%.

Acknowledgment

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