Reports

Venus: Implications from Microwave Spectroscopy of the Atmospheric Content of Water Vapor

Abstract. *From comparison of theoretical and observed microwave brightness temperatures of Venus at 1.35 centimeters, the center of a water-vapor line, we obtain an upper limit of 0.8 percent for the water-vapor mixing ratio in the lower atmosphere. This limit is consistent with the amount of water vapor detected by Venera 4, the existence of aqueous ice clouds, and a greenhouse effect caused by water vapor and carbon dioxide. The computed spectra suggest that a sensitive procedure for detection of water vapor is examination of the wavelength region between 1 and 1.4 centimeters.*

From data obtained by Venera 4 (*1, 2*) and Mariner 5 (*3*) the atmospheric structure of Venus is known sufficiently well for construction of rather unambiguous microwave spectra. We now compute brightness-temperature spectra so as to set limits on the amount of water vapor in the lower atmosphere, and these values are compared with the amount of water vapor detected by Venera 4.

In accord with the high temperatures found by Venera 4 and Mariner 5, we have assumed that the radio emission from Venus emanates from a hot surface and atmosphere, and that the decline in brightness temperature at wavelengths shorter than 3 cm is attributable to atmospheric opacity. We now describe our method of calculation.

To compute the brightness temperature, we integrated analytically Pollack and Sagan's Eq. 3 (*4*) over the disk and used a constant solid-angle average emissivity. The brightness temperature is a function of the microwave opacity at each atmospheric level, the atmospheric structure, and the surface emissivity.

We considered three sources of microwave opacity: pressure-induced transitions of carbon dioxide and of nitrogen, and permitted rotational transitions of water vapor. For the absorption coefficient of a mixture of carbon dioxide and nitrogen we used the empirical formula of Ho *et al.* (*5*). Barrett and Staelin (*6*) presented an equation for the absorption coefficient of water vapor, suggested by Chung (*7*). The absorption coefficient of water vapor (*6, 7*) consists of a resonant term, due to the 1.35-cm line, and a nonresonant component due to the overlapping wings of lines at shorter wavelengths. Chung derived his expression theoretically and adjusted one parameter to give a good fit with a laboratory spectrum near standard temperature and pressure.

To test the validity of Chung's formula at high pressures and elevated temperatures, we compared it with the laboratory results of Ho *et al.* (*5*). At the high pressures (45 to 125 atm), temperatures (393° to 473°K), and wavelength (3.2 cm) used (*5*), the nonresonant component is dominant; Ho *et al.* have no direct estimate of the resonant term. We find very good agreement between the two formulas near room temperature, but marked disagreement in the temperature-dependence of the absorption coefficient. Accordingly we have used Chung's formula (*7*) in our computations, with the temperature-dependence of the linewidth parameter ($\Delta\nu$) modified from $T^{-0.625}$ (*7*) to $T^{-2.5}$ (*5*).

The atmospheric structure was chosen to fit quite closely the measurements by Venera 4 (*1, 2*) and Mariner 5 (*3*). The temperatures and pressures at the position of measurement by Mariner 5 probably closely resemble the average properties of the atmosphere which exhibits no appreciable diurnal variations (*3*), as one would expect on the basis of heat capacity of the atmosphere; furthermore, the measurements were made at a midlatitude position of 37°.

Our model atmosphere consisted of three temperature domains: an adiabatic regime beginning at the pressure level of 4.05 atm and extending to the surface (*2*), a constant lapse rate of 7.9°K/km between the top of the adiabatic region and the tropopause temperature point of 230°K, and an isothermal profile above the tropopause (*3*). We assumed that the carbon dioxide mixing ratio was 85 percent, with the remainder of the atmosphere consisting of water vapor and nitrogen (*1–3*). The temperature at the 5.08-atm level was chosen as 437°K (*3*).

Wattson (*8*) estimated the surface temperature and pressure for us with a computer program for adiabatic profiles, which allowed for variation of the

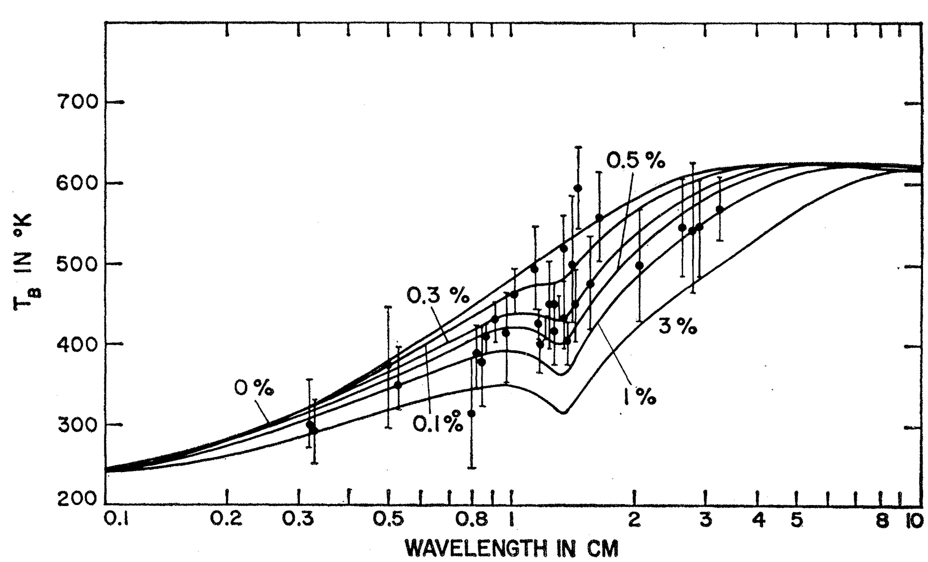

Fig. 1. Brightness temperature T_B as a function of wavelength for six values of the water-vapor mixing ratio in the lower atmosphere. The mixing ratio appropriate to each curve is indicated. Observed brightness temperatures are indicated by closed circles with appropriate error bars.

ratio of specific heats with temperature and pressure. Extrapolating from the 5.08-atm point to the radar radius of Venus (*9*), he obtained a surface temperature of 747°K and a surface pressure of 91.2 atm. We note that our computer program also allowed for a variable ratio of specific heats within the adiabatic portion of the atmosphere.

We selected a value of 0.82 for the surface emissivity. The fresnel reflectivity equations were used to average over solid angle a radar cross section of 0.14 at 70-cm wavelength (*10*).

A most important feature of our calculations was allowance for a rapid decrease in the water-vapor mixing ratio (ratio of moles of water vapor to moles of all gases in the atmosphere, including water vapor) above the level at which saturation is first reached. Since the resonant term of the water-vapor absorption coefficient varies inversely with pressure near the 1.35-cm line center, regions of low pressure can significantly influence the microwave spectrum near this wavelength. By allowing for saturation, we obtained only relatively shallow dips in the brightness temperature near 1.35 cm.

Once saturation is attained, condensation will occur and the water-vapor partial pressure will follow a saturation curve to the cloud tops. By analogy with Earth (*11*), the relative humidity in the stratosphere will probably be quite low. Finally, at sufficiently high altitudes, photodissociation of water vapor will occur. We have attempted to simulate this situation by having the water-vapor mixing ratio decrease exponentially above the saturation point with a 1-km scale height, a value appropriate for the water-vapor saturation curve. Changes in the value of the scale height by a factor of 4 do not significantly alter the computed spectra.

We performed spectral calculations of brightness temperature with a computer program written by Andrea Dupree and modified by one of us (A.T.W.). Integration step sizes of 1 km were used in performance of the vertical integration.

Figure 1 shows our calculated brightness-temperature spectra for six values of the water-vapor mixing ratio: 0, 0.1, 0.3, 0.5, 1, and 3 percent; also given are measurements of brightness temperature near inferior conjunction, with the estimated errors (*12*). The computed curves are rather insensitive to the exact choice of input parameters, especially at wavelengths between 0.8 and 1.4 cm. For the cases of larger water-vapor mixing ratios, a change of less than 15°K in brightness temperature resulted in this range when the following changes were made simultaneously: decrease in the surface temperature to 543°K (the value estimated by the Venera-4 experimenters); decrease in the surface pressure to 20 atm; increase in the emissivity to 0.9; ± 15-percent change in the carbon dioxide mixing ratio, a constant lapse rate used between tropopause and surface; and 15°K change in the tropopause temperature. Somewhat larger changes resulted for the cases of lower water-vapor mixing ratio, especially when the carbon dioxide mixing ratio or atmospheric structure was altered.

Table 1. Computed brightness temperatures at a wavelength of 1 cm [$T_B(1.0)$], and ratios of brightness temperatures at 1.4 and 1.0 cm [$T_B(1.4)/T_B(1.0)$]. αH_2O, water-vapor mixing ratio in the lower atmosphere.

αH_2O (%)	$T_B(1.0)$ (°K)	$T_B(1.4)/T_B(1.0)$
0	483	1.102
0.1	464	1.061
0.3	438	1.009
0.5	421	0.976
1.0	395	0.939
3.0	352	0.916

An interesting feature of Fig. 1 is the slight displacement toward wavelengths shorter than 1.35 cm of the center of the absorption feature for cases of low water-vapor mixing ratio; for example, the absorption minimum is located at 1.3 cm for the 0.3-percent case. This displacement is an effect of the steady increase in brightness temperature, toward longer wavelength, superimposed on the decrease caused by the resonance line.

We now set limits on the water-vapor mixing ratio in the lower atmosphere of Venus. Because of the shallowness of the absorption feature near 1.35 cm in the computed spectra, the depth of the feature is not a very useful discriminant with the present set of data. A more useful criterion is the absolute value of the brightness temperature at 1.35 cm; the curves of Fig. 1 are markedly different at this wavelength, and, as we have mentioned, the values of the brightness temperature here are relatively independent of the exact values of the input parameters. The following brightness temperatures have been measured near inferior conjunction at or quite close to 1.35 cm: 520° ± 40°K (*13*), 435° ± 40°K (*14*), 404° ± 28°K (*15*), 500° ± 70°K, (*16*), 560° ± 48°K (*16*), and 436° ± 39°K (*17*). Accordingly the brightness temperature at 1.35 cm probably exceeds 375°K, and water-vapor mixing ratios in the lower atmosphere greater than 0.8 percent can be excluded. Unfortunately the observations do not permit setting of a lower bound other than 0 percent.

This upper limit is compatible with a value of between 0.1 and 0.7 percent determined by the chemical-analysis experiment aboard Venera 4 (*1*, *2*). Moreover it does not exclude the presence of water-condensation clouds in the upper atmosphere of Venus; such clouds would have cloud-bottom temperatures below the equilibrium freezing point of water and so, except for possibly some supercooled droplets, would consist of ice particles. Finally, this limit does not exclude mixing ratios of water vapor, about 0.5 percent, required for a carbon dioxide and water-vapor greenhouse effect (*18*).

We have considered models having water-vapor mixing ratios of 0.1 percent or more, for which condensation can be expected to occur in the upper atmosphere. However, the occurrence of condensation for ratios between 0.001 and 0.1 percent is uncertain, depending on the exact choice of tropopause temperature. Were the tropopause temperature so high as to preclude condensation for some of these ratios, these cases could be immediately ruled out as being inconsistent with the small spectroscopically determined amounts of water vapor in the upper portion of the atmosphere (*19*). Finally, no condensation will occur with values less than 0.001 percent, and conceivably spectra produced for such models would contain very deep, narrow absorption features near 1.35 cm. However, their widths would be much smaller than typical instrumental bandwidths (*17*), and so a much shallower line would result. In addition, photodissociation may prevent formation of such an intrinsically deep line, by causing depletion of water vapor in the region of line formation.

The calculated spectra show very broad, shallow depressions near 1.35 cm. Previous searches for the presence of water vapor have been conducted at wavelengths centered around and quite close to 1.35 cm. Perhaps a more profitable procedure would be investigation of the region between 1 and 1.4 cm; for example, the brightness temperature declines by 50°K for the 0-percent case between 1.4 and 1 cm, but increases by 10°K for the 0.5-percent case. Table 1 shows ratios of the brightness temperature at 1.4 cm to that at 1 cm, as well as the absolute value of the brightness temperature at 1 cm.

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Earthquakes and the Earth's Wobble

Abstract. *Observational evidence is presented in support of the hypothesis that large earthquakes excite the earth's natural wobble and produce the observed secular polar shift. Previous theoretical calculations based on elasticity theory and earthquake statistics had predicted a significant effect. There appear to be some premonitory signs of large earthquakes in the pole path.*

It has been known for over 80 years that the earth's axis of rotation moves with respect to an observatory coordinate system. To earthbound observers this represents a variation of the astronomically determined latitude. Viewed from space, it represents a wobble of the earth about its rotation axis. The observed motion is most conveniently displayed as the path of the instantaneous north pole of rotation (Fig. 1).

In 1891, S. C. Chandler isolated a component of a 14-month period from the latitude observations (*1*). Rigid-body dynamics gives a 10-month period for the earth's natural wobble, but the longer observed period can be reconciled with theory if allowance is made for rotational deformation (*2*). The motion is now called the Chandler wobble. The accompanying rotational deformation implies that the Chandler wobble must be subject to damping, and therefore a more or less continuous excitation is required to maintain it. Identifying the source of the excitation has remained one of the principal problems in studies of the earth's rotation (*3*). We now report evidence in support of theoretical calculations (*4*) which led to the hypothesis that large earthquakes provide the hitherto unidentified excitation.

Latitude measurements are reduced independently by two organizations to produce pole paths. The International Latitude Service (ILS) collected and reduced latitude measurements from three to five observatories on a single latitude circle (39°8′N) from 1900 to 1962 (*5*). In 1962, the International Polar Motion Service (IPMS) took over this work (*6*). Using stations on a single latitude circle allows all stations to observe the same stars, avoiding dependence on the accuracy of star catalogs. Currently, mean pole positions for 0.05-year intervals are issued. The origin used is the mean pole position for the period 1900 to 1905, called the Conventional International Origin (CIO).

Since late 1955, the Bureau International de l'Heure (BIH) in Paris has also been reducing latitude measurements in order to correct star-transit times for polar motion (*7*). At the beginning of 1957 information from nine stations was being processed. By early 1967, 39 observatories were contributing. Ten-day means have been published (*8*). Pole positions were referred to a moving origin. Typical comparisons between the ILS-IPMS and BIH-CIO paths are shown at the top of Fig. 1.

The motion of the pole is complicated by the presence of an annual component which beats with the Chandler component to give a 6-year periodicity to the amplitude. The annual motion has been shown (*9*) to be produced by the seasonal rearrangement of atmospheric mass. Removal of the annual component from the paths shown at the top of Fig. 1 results in those shown directly below.

A connection between earthquakes and the motion of the pole had been suggested very early in the history of latitude observations (*10*). Until recently the displacement fields of even the greatest earthquakes were thought to extend to no more than a few hundred kilometers from the focus. Thus, estimates of the contribution of earthquakes to the Chandler wobble excitation fell several orders of magnitude short of the observed level (*11*).

The prevailing view on the extent of earthquake displacement fields was drastically altered by the work of Press (*12*). Both the theoretical predictions of elasticity theory and distant strain measurements were adduced to argue that a measurable displacement field may extend to epicentral distances of several thousand kilometers for a great earthquake.

When the effect of such large-scale deformation of the earth was calculated for a number of individual earthquakes, and when an estimate of the cumulative effect was made on the basis of earthquake statistics, it was found that earthquakes could account for both the excitation of the Chandler wobble and a slow secular shift of the mean pole of rotation (*4*).

The reality of a secular motion of the pole has been the subject of some debate among observers, but there seems now to be agreement that a drift of a fraction of 1 foot (0.3 m) per year does in fact occur (*13*).

If the displacement field of an earthquake is established in a short time as compared to the Chandler-wobble period (the best estimate of the period appears to be 1.2 year), the effect on the pole path is as illustrated in Fig. 2. Before and after the quake, the pole follows a circular path (with damping, the path is actually a gentle inward spiral) in an anticlockwise sense. At the time of the earthquake, the center of rotation (secular pole) is shifted, while there is a nearly equal and opposite vector contribution to the wobble (*4*). Hence, the position of the rotation pole is left nearly unaltered; only the path