Reports

Venus: New Microwave Measurements Show No Atmospheric Water Vapor

Abstract. *Two sets of passive radio observations of Venus—measurements of the spectrum of the disk temperature near the 1-centimeter wavelength, and interferometric measurements of the planetary limb darkening at the 1.35-centimeter water vapor resonance—show no evidence of water vapor in the lower atmosphere of Venus. The upper limit of 2×10^{-3} for the mixing ratio of water vapor is substantially less than the amounts derived from the Venera space probes (0.5×10^{-2} to 2.5×10^{-2}). This amount of water vapor cannot produce dense clouds, and it is doubtful that it may contribute significantly to a greenhouse effect.*

The physical structure and bulk composition of the atmosphere of Venus are now fairly well established. Nevertheless, our understanding of this remarkable atmosphere is limited by uncertainties about minor constituents beneath the visible cloud layer. From the radio occultation experiments of Mariner 5, the in situ measurements performed by the Venera 4, 5, 6, and 7 probes, and radar and passive radio astronomical studies, a consistent picture of the atmosphere has emerged (*1, 2*). The atmosphere is predominantly carbon dioxide, the surface lies some 60 km beneath the visible cloud tops, and the temperature lapse rate is approximately adiabatic from the clouds down to the surface, with a surface temperature and pressure near 750°K and 100 atm, respectively. Spectroscopic studies have determined the presence of the trace constituents H_2O, CO, HCl, and HF above the clouds, with mixing ratios of approximately 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-9}, respectively, and have established upper limits for a number of other candidates (*3*). Mixing ratios of possible minor constituents beneath the clouds are quite uncertain, however.

This uncertainty is paramount in current problems concerning the composition of the clouds, the source of infrared opacity that allows the observed high temperatures to be maintained, the dynamics of the atmosphere in general, and its evolution as an atmosphere so strikingly different from that of the earth. The question of the amount of water vapor, in particular, is a central issue in these problems.

We report the results of new passive microwave observations of Venus at wavelengths near 1 cm which bear on the question of water vapor abundance. Observations at these wavelengths are particularly sensitive to the presence of the H_2O molecule because of its rotational transition at 1.35 cm. Two techniques were used to search for the effect water vapor would have on the emission. First, the total emission from Venus was measured at several wavelengths in the range 0.8 to 1.5 cm with a well-calibrated radio telescope. Water vapor absorption in addition to the known absorption of CO_2 would tend generally to depress the observed flux spectrum, as well as produce a broadened absorption feature around 1.35 cm. Secondly, a two-element radio interferometer was used to observe Venus at 1.2 and 1.35 cm. The interferometer measures the overall planet limb darkening, which depends on the distribution of absorption with altitude. This distribution is markedly different for a resonant and a nonresonant absorber. Neither set of observations shows any evidence of atmospheric absorption other than that due to the bulk atmospheric constituent CO_2, and a low upper limit is confidently placed on the amount of water vapor which may be uniformly mixed beneath the cloud layer.

We used the 6-m telescope in Hat Creek, California, to measure the spectrum of the disk temperature in the range 0.8 to 1.5 cm at about the time of the inferior conjunction in April 1969. Wrixon *et al.* (*4*) have described in detail the calibration of this instrument and the techniques used for this

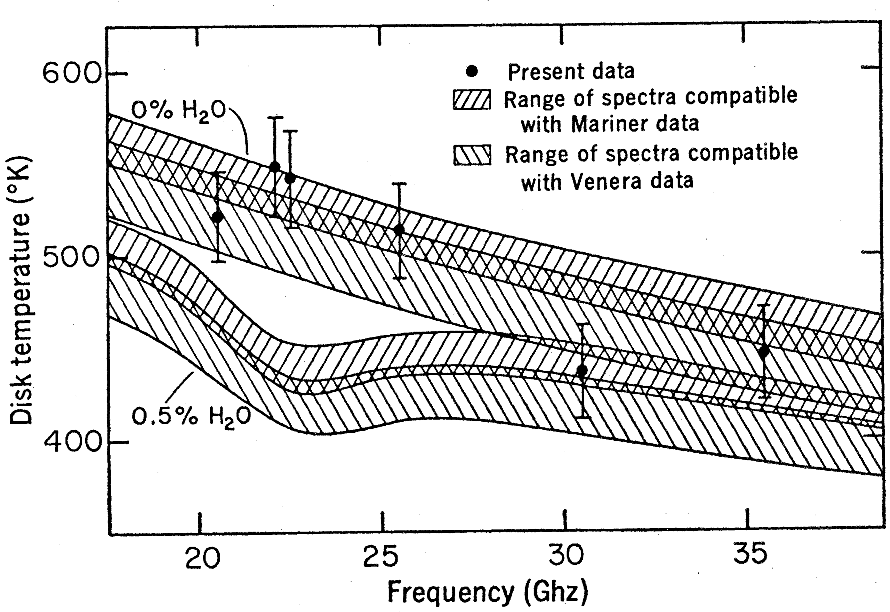

Fig. 1. Microwave spectrum of Venus at a wavelength around 1 cm. The data points represent absolutely calibrated measurements of the disk temperature of Venus. The error bars represent 1 S.D. The shaded bands show the range of disk temperatures consistent with the spacecraft data: the lines slanting right are from calculations for an atmospheric model based on the Mariner 5 occultation experiments, the lines slanting left from a model based on the direct measurements of the atmosphere by the Venera probes. In the upper pair of bands it is assumed that only the bulk atmospheric constituent CO_2 is responsible for the microwave emission, while the lower pair of bands include the effect of adding water vapor to the atmosphere at a mixing ratio of 5×10^{-3}.

type of observation. The disk temperatures obtained are shown in Fig. 1, along with the results of model calculations, which are described below. Each of the six points shown in the figure is the result of at least 2 full days of observation. The internal errors amount to no more than 2 percent at all wavelengths. We have also determined that systematic errors associated with antenna pointing, radiometer flux calibration, and correction for atmospheric extinction lie within the 2 percent level. Uncertainties in the absolute gain of the 6-m antenna provide the main source of error, and are limited to about 4 percent. The net errors in the Venus measurements are conservatively estimated as 5 percent [1 standard deviation (S.D.)] at each wavelength.

A computer program was written to provide the model spectra shown in Fig. 1. The program calculates an atmospheric structure from the basic spacecraft data, which are either refractivity as a function of altitude from the Mariner 5 occultation experiments, or pressure as a function of temperature from the Venera measurements. Hydrostatic equilibrium is assumed, and the atmospheric composition is input to the program. The atmospheric structure is taken to be independent of position on the planet. A thermal, nonscattering transfer of radiation is assumed, with the absorptive properties of CO_2 and H_2O taken from laboratory data (*5, 6*). The effects of the curvature and the finite thickness of the atmosphere, along with the refraction of rays emerging near the planet limb, are important in the interpretation of the interferometric data described below, and are included in the calculation. The emission at 1 cm comes almost entirely from the region above the level at 30 atm pressure in the atmosphere. In effect, the surface and lower half of the atmosphere are not seen. The emitting region coincides with that which has been most extensively examined by the spacecraft; further, the laboratory data for the absorption coefficients apply here with little extrapolation.

The model spectra of Fig. 1 were calculated for both a dry atmosphere of CO_2 and N_2, and the same atmosphere with water vapor uniformly mixed at a mixing ratio of 5×10^{-3} below an altitude of about 60 km. The shaded bands represent the range of spectra consistent with the spacecraft data, allowing for reasonable errors in these data and for uncertainties in the absorption coefficients. The largest source of spread in the model spectra is the uncertainty in the CO_2 content of the atmosphere, which we have permitted to vary between 90 and 100 percent. The most precise determination from the Venera probes gives the CO_2 content as 97^{+3}_{-4} percent (*7*). The emission models provided by the two sets of spacecraft data are kept distinct, since the refractivity data from Mariner 5 must be interpreted differently from the pressure-temperature data of the Venera probes as the composition is varied, and as (refractive) water vapor is added to the model atmosphere. The disk temperature is insensitive to the exact magnitude of the CO_2 absorption coefficient [Ho *et al.* (*5*) give the uncertainty in their measurements as a few percent]. Doubling this coefficient gives a decrease in the disk temperature of only 10 percent in the absence of water vapor. Water vapor becomes the dominant absorber near 1.35 cm, at concentrations in excess of 0.2 to 0.3 percent.

The data reported here are in clear disagreement with the spectra calculated for models with a water vapor mixing ratio of 5×10^{-3}. The measured disk temperatures are too high to permit the presence of any absorption beyond that of CO_2, and we determine an upper limit of 2×10^{-3} to the mixing ratio of water on this basis. We separately determine an upper limit of 4×10^{-3} from the lack of any apparent absorption feature in the data.

The second, independent, set of observations was made with a two-element radio interferometer. The interferometer began operation in January 1971, permitting observations of Venus after the inferior conjunction in November 1970. The interferometer consists of the 6-m antenna coupled to a second, 3-m antenna, with a fixed separation of 265 m (approximately 20,000 wavelengths) and a baseline azimuth of 130° east of north. The baseline vector has been determined by astronomical techniques to a precision of about 1 part in 10^5 (*8*).

The amplitude and phase of the interference pattern produced by a radio source, the "visibility function," is the two-dimensional Fourier transform of the source brightness distribution. The argument of the transform is the baseline, in wavelengths, as projected onto the sky in the direction of the source. This describes the spatial frequency of the finely spaced interferometer fringes, and for present purposes it is convenient to normalize this spatial frequency to the planet radius as:

$$\beta = \frac{\text{angular semidiameter}}{\text{angular fringe spacing}}$$

During a day's observation, the earth's rotation produced the range of projected baselines $0.3 \leq \beta \leq 1.5$. Eight days of observations were obtained at 22.11 Ghz, near the H_2O resonance, and 4 days were obtained at 25.4 Ghz. Figure 2 shows the data from the first 4 days, obtained at 22.11 Ghz. Limb

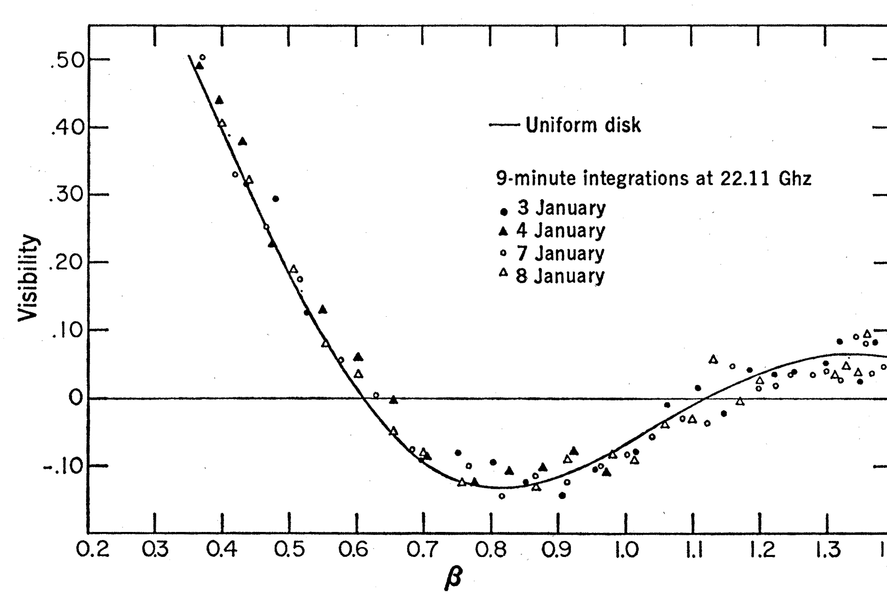

Fig. 2. Visibility function of Venus. The quantity β describes the interferometer fringe cycles per disk radius, and is proportional to the baseline projected in the direction of the source. The data points show 9-minute averages obtained during 4 days in January 1971. The visibility function which would be produced by a uniformly bright disk of the radius of Venus is drawn for reference.

darkening is evident from the comparison with the visibility function of a uniform disk.

The model calculation described above included a Fourier transformation of the model brightness distribution to obtain the visibility function. A series of calculations showed that the limb darkening for a range of model atmospheres, including the enhanced limb darkening produced by water vapor at its resonant frequency, has the greatest effect on the visibility function the range $0.3 \leqq \beta \leqq 0.9$. This range brackets the first zero of the visibility function near $\beta = 0.6$. The equivalent disk diameter, as determined by the measured position of the first zero crossing, gives a convenient description of the overall limb darkening and provides a scale for the measurement of water vapor.

An apparent disk diameter was determined from each day's data in the range $0.3 \leqq \beta \leqq 0.9$, along with an estimate of the variance of this determination from the scatter of the data. The results from all days at each frequency were then averaged to produce the two points shown in Fig. 3. The final error estimates are based on the daily variance estimates, and are consistent with the observed day-to-day scatter in the disk diameter determinations. The curves of Fig. 3 illustrate the dependence of the limb darkening on the water vapor content of the lower atmosphere. The calculations are largely insensitive to the details of the atmospheric structure which were considered above and in Fig. 1. The limb darkening at the wavelength of the H_2O resonance is again consistent with simply CO_2 absorption, and the presence of water is not evident. We find the corresponding upper limit to be 3.5×10^{-3}. No limb darkening resonance is apparent in the comparison of the two data points. This determination is limited by the greater uncertainty of the 25.4-Ghz point. Nevertheless, this comparison is of statistical significance, and yields an upper limit of 5×10^{-3} at the 80 percent confidence level.

We have obtained four independent determinations of the water vapor content of the lower atmosphere of Venus from the microwave data. All yield a probable mixing ratio of zero, and although the respective upper limits vary, a mixing ratio as high as 5×10^{-3} is strongly excluded. The most precise determination comes from the generally high disk temperatures which we measured. These leave little margin for the

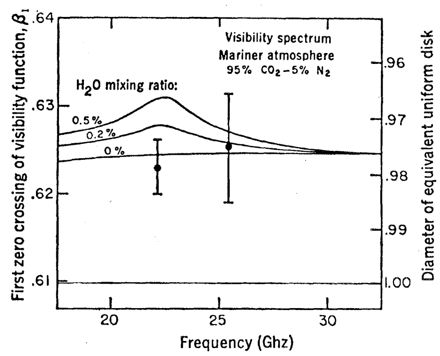

Fig. 3. Limb darkening resonance of Venus. The measured first zero crossing of the visibility function is a measure of the overall limb darkening of the apparent disk. The addition of water to the atmosphere would produce additional, frequency-dependent limb darkening due to the 1.35-cm rotational transition, as shown by the solid curves. The two data points represent 8 days of averaging at 22.11 Ghz and 4 days at 25.4 Ghz. (Error bars, 1 S.D.)

presence of any microwave absorption other than that due to CO_2, and yield the particular upper limit of 2×10^{-3} for water.

Evidence for a high water content comes from several sources. The Venera probes have repeatedly detected water at concentrations as high as 2.5 percent by direct measurement at the level of the atmosphere of 0.6 atm pressure, with a lower amount of about 5×10^{-3} seen at the 2-atm level (*7*). These constitute the only specific evidence for water vapor, and are supported indirectly by some earth-based measurements. Interferometric measurements at wavelengths of 3 and 10 cm (*9*) and radar measurements at 3.8 cm (*10*) appear to show the presence of a source of microwave opacity in addition to CO_2, and are consistent with a mixing ratio for water vapor of 5×10^{-3} (*2, 9, 10*). Also, a strong, effectively gray source of infrared opacity, with transparent windows in the visible, is required to support a greenhouse mechanism of heating the lower atmosphere. Although the opacity of CO_2 is strictly unknown under the relevant conditions, this source appears inadequate because of incomplete coverage of the infrared spectrum. Water vapor provides an attractive supplementary source; greenhouse models which have been considered require concentrations of about 0.5 percent (*11*).

The measurement techniques presented here are especially sensitive to water vapor at the level of the claimed Venera detections (0.6 and 2 atm), even though the mean brightness temperature corresponds to the atmospheric temperature just below the 10-atm level. Observe that the effect of water on the disk temperatures of Fig. 1 depends largely—and the limb darkening effect of Fig. 3 depends entirely—on the 1.35-cm resonance. From the half-widths of these features and the line broadening parameter for collisions between H_2O and CO_2, it is apparent that water at and above the 2-atm level plays by far the largest role in the present determinations. (The half-width parameter, that is, the half-width divided by the pressure, $\Delta f/P \approx 4$ Ghz/atm near 300°K.) Hence, the possibility suggested by the Venera analyses that there is a global water distribution which disappears beneath the 2-atm level is in conflict with our results. A layer of water vapor at the 0.6-atm level with a mixing ratio of 2.5 percent and a thickness of only 1.3 km is excluded by our data at a confidence level of 98 percent. Rather, it appears more likely that the Venera spacecraft may have measured a local concentration of water vapor, rather than sampling a global distribution.

The water vapor content of Venus' atmosphere is then unknown within the broad range between our upper limit of a mixing ratio of 2×10^{-3} and the spectroscopically determined value of the order of 10^{-5} above the clouds. At mixing ratios in this range saturation cannot occur at or below the level of the visible cloud tops, although a haze of water or hydrochloric acid droplets may form at higher levels according to the stratospheric structure determined by Mariner 5. We emphasize that our result is not inconsistent with the indications of an additional source of opacity at longer wavelengths, since the latter refer to a lower level of the atmosphere. Rather, the interesting implication is that the mixing ratio of the responsible trace components of the atmosphere varies toward the surface, a reasonable possibility in view of the high surface temperature. We point out that a natural consequence of such a compositional change would be a low-lying system of cloud layers. Finally, it remains to be shown that a "greenhouse" mechanism can be supported with the present constraints on the water vapor content.

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Polar Wandering on Mars?

Abstract. *Polar wandering during the past 10^8 years may be recorded by unique quasi-circular structures in the polar regions of Mars. Polar wandering on Mars is likely if deep convection is involved in the origin of the very large constructional volcanic features located near the equator. The magnitude of the nonhydrostatic low order components of the gravity field and their correlation with the equatorial volcanic features may be additional evidence of deep convection and associated polar wandering.*

Mariner 9 has revealed a variety of unexpected aspects of Mars. We speculate here that three of the most surprising may be related to the wandering of the spin axis of the planet.

To our knowledge, polar wandering has not been seriously anticipated on Mars, although the subject has been considered extensively for the earth (*1*). Goldreich and Toomre (*2*) have reinterpreted certain features of the earth's gravity field as indicative of internal conditions suitable for polar wandering. They argue that polar wandering may have come about as a result of the gradual redistribution of density inhomogeneities associated with the convective processes in the earth's mantle responsible for continental drift. In the case of Mars, internal heating just now may be reaching the point where convection processes are being initiated. Such a possibility was hinted at by Urey (*3*), and was suggested by the thermal models of Anderson and Phinney (*4*) and by more recent models of Anderson (*5*). Limited occurrences of "chaotic terrain" seen in the pictures returned by Mariner 6 and Mariner 7 were recognized as possible indications of recent internal activity (*6*).

Most conclusively, Mariner 9 has returned abundant and unambiguous evidence of extensive volcanic and tectonic activity over portions of the surface of Mars (*7, 8*). Thus, martian mantle convection now can be regarded as at least a reasonable possibility (*9*).

To us, the most suggestive evidence of polar wandering on Mars is found in the polar regions. There, peculiar quasi-circular topographic features are observed (Fig. 1). Such structures in the south polar area have been described by Murray *et al.* (*10*) and are believed to be roughly circular plates with outward sloping edges. The plates are composed of thin laminae of light and dark material (about 20 to 80 m thick) (*11*) and exhibit a profile at the edges which is convex outward, suggestive of ablation. The plates exhibit a surprising uniformity in width and the amount of progressive offset from one another. The laminated terrain and the associated quasi-circular topographic features are restricted to the area surrounding both poles, where carbon dioxide frost formation and disappearance take place on an annual basis. For this reason, the laminated terrain is believed to be genetically coupled to volatiles, perhaps still containing a high percentage of volatiles mixed with eolian dust.

The concentric pattern of the topographic steps suggests to us an origin and evolution symmetrical to the past location of the spin axis of the planet. If volatiles act only as a collecting agent for atmospheric dust and are later lost by sublimation, the symmetrical orientation relative to the spin axis may reflect the annual stability boundaries of the volatile carbon dioxide. On the other hand, if the laminated terrain still contains large amounts of permanent carbon dioxide, such an orientation would be expected on the basis of equal average solar insolation (*12*). Either way, the former position of Mars' spin axis may be recorded by the centers of curvature of the displaced circular topographic features of the laminated terrain. The positions of the circular arcs and of their apparent centers of curvature are shown in Fig. 1, c and d. A maximum polar wandering of about 15° would be indicated by the plates clearly discernible. In addition, it appears that a vertical sequence of concentric plates is discernible at some places. There, an apparent time progression of the pole seems to be recorded as well. Figure 1, c and d, suggests a correspondence between the apparent fossil locations of the north and south poles, although differences in visibility and perhaps tectonic response may complicate the correlation.

Is there any other evidence about Mars suggestive of polar wandering? One of the greatest surprises presented by the Mariner 9 pictures was the discovery of extremely large constructional volcanic features near the equator in the longitude region 90° to 150°W (Fig. 2). These are similar in general morphology to shield volcanoes on the earth except that they are of considerably larger extent. The largest is identified with the classic albedo feature Nix Olympica and has been designated by that name. The three next largest lie along a northeast-southwest line centered near the equator, and were first seen as dark spots on the dust-shrouded planet in Mariner 9 preorbital photographs. They acquired the temporary descriptive names North, Middle, and South Spots, due to their appearance at that time. They are about 400 to 550 km in diameter and have heights of the order of 10 km. In addition, there are other less dramatic evidences of vulcanism scattered over the planet, but not over the whole surface nor in a uniform way. The exis-