# Venus: Absence of a Phase Effect at a 2-Centimeter Wavelength

Abstract. *Observations of Venus made during 1967 and 1968 at a frequency of 15.4 gigahertz set an upper limit of 5 percent for the variation of brightness temperature with phase. This negative result appears to contradict earlier detections of a phase effect. By comparison with Virgo A (3C 274), which has an assumed flux density of 29 $\times$ $10^{-26}$ watt per square meter per hertz, the brightness temperature of Venus at this frequency is 485 + 60, $-40$°K (mean error).*

A slowly rotating planet that has a significant diurnal temperature variation at its surface exhibits a variation with phase in its microwave brightness temperature averaged over the disk, if radiation in the radio-wave region arises primarily in the subsurface material of the planet. Such a phase effect for Venus has been considered well established for wavelengths of observation between 0.8 and 10 cm (*1*) and has been suggested at wavelengths as short as 4 mm (*2*). These observations indicate that the brightness temperature varies by from 15 to 25 percent between inferior and superior conjunction. These variations could not be explained by systematic errors in the observations (*3*). The data on phase effect have thus been used with some confidence in theoretical analyses of the thermal properties of Venus (*3*). However, the observations reported here, representing more than 100 hours of observing time, show no phase effect even a third as large as those reported previously (*1*), thereby raising questions about the reality of the phenomenon.

The measurements were made between April 1967 and April 1968 with the 43-m equatorial radio telescope of the National Radio Astronomy Observatory and a standard 15.375-Ghz wideband radiometer (*4*). The aperture efficiency is a function of telescope orientation at this frequency and is known to decrease by more than a factor of two between 0° and 60° in zenith angle (*5*). The uncertainty in correcting for this variable gain, which is typical of large telescopes at high frequencies, usually limits the accuracy with which the phase effect can be measured, since in the course or a synodic period the declination (and hence the zenith angle near meridian transit) of Venus varies by nearly 50°. To circumvent this difficulty, I observed Venus on three occasions (in August 1967, November 1967, and April 1968), widely spaced in phase angle, when the planet was at the same declination (+ 1° to $-$ 2°). The phase angles for these observations were 144°, 270°, and 334°, respectively. I also observed in April and June 1967, when Venus was at a declination of about + 20°, but, because of the need to correct for the variation of gain with zenith angle, these observations have an added uncertainty of about 4 percent as compared with those made near the equator. For comparison sources I used 3C 274 (Virgo A) and 3C 123. Since these sources are in opposite parts of the sky, some check is provided on possible systematic errors that may be introduced by diurnal variations in telescope gain.

In order to eliminate the effects of pointing errors, the antenna temperatures for Venus and the comparison sources were obtained by making a grid of scans in right ascension, each scan offset from the next in declination by one-fourth of the half-power beam width. Before each set of scans a calibration noise source was measured; the calibration signals were repeatable with a root-mean-square scatter of less than 1 percent. The final antenna temperatures were obtained by first fitting a Gaussian function numerically to each right-ascension scan and then fitting a Gaussian function in declination through the derived peaks (*6*). Figure 1 illustrates some typical scans across Venus obtained in November 1967 when the planet was at about the same degree of brightness as the primary comparison source, 3C 274. Under good observing conditions, the root-mean-square error in the peak of the final fitted Gaussian function for each set of scans was only 2 percent (Fig. 2). Each temperature for Venus was corrected for the resolution of the antenna by assuming that the beam had a Gaussian shape with a half-power beam width of 2 minutes of arc and that Venus was a uniform disk. The largest such correction, made in August 1967, was 5 percent. From a single day's observations, the antenna temperature of Venus relative to the comparison sources could usually be determined with a computed mean error of from 1 to 3 percent (*7*).

In August and November 1967, I measured the absolute brightness temperature of Venus with respect to 3C 274 by mapping both sources (*8*). I adopted a flux density at 15.4 Ghz for the comparison source of (29 + 2, $-1$) $\times$ $10^{-26}$ watt $m^{-2}$ $hz^{-1}$ (*9, 10*). The derived brightness temperature of Venus is 485 + 60, $-$ 40°K (mean error). The corresponding correction factor for source size for 3C 274 with a half-power beam width of 2 minutes of arc is 13 $\pm$ 4 percent, larger by 6 percent than would be obtained by assuming a Gaussian shape for 3C 274 (*9*). This difference is consistent with a core-halo configuration for this source, such as Hogg (*11*) reports at a wavelength of

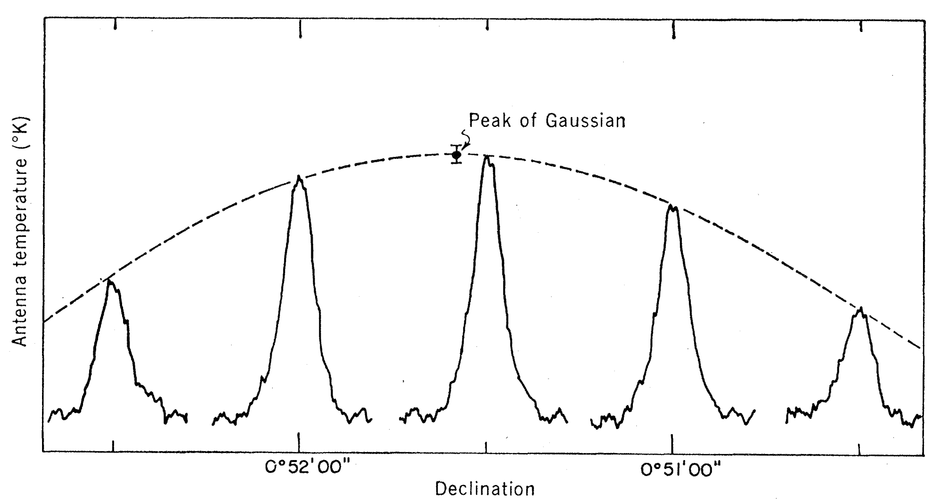


Fig. 1. Right-ascension scans of Venus made in November 1967. Each scan is displaced from the preceding by 1/4 half-power beam width in declination. The Gaussian curve fitted to the peak temperatures for each scan is illustrated by the dashed curve.

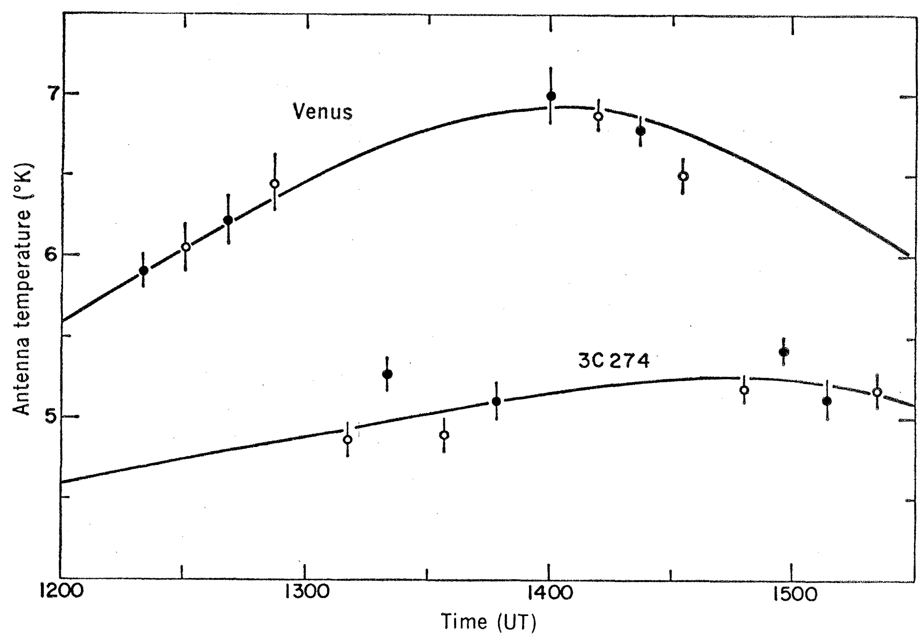


Fig. 2. Observations of the antenna temperatures of Venus and 3C 274 made on 10 November 1967. Each point is derived from a fitted Gaussian curve as illustrated in Fig. 1; the error bars are computed standard deviations in the peaks of the Gaussian curves. The open and solid circles represent two orthogonal linear polarizations. The curves show the nominal changes in gain of the telescope with hour angle (*5*).

10 cm. The flux density of 3C 123, derived with respect to 3C 274, is $(5.2 \pm 0.4) \times 10^{-26}$ watt $m^{-2}$ $hz^{-1}$.

The measured brightness temperature of Venus as a function of phase angle is shown in Fig. 3. No phase effect is indicated, and it appears possible to set an upper limit of about 5 percent for the variation with phase.

A brightness temperature of 485°K is in agreement with a value of 500 ± 70°K (probable error) at 2.07 cm (*12*), but it is significantly lower than the temperature at 1.9 cm derived from the Venus flyby made by Mariner II (*13*). When compared with the spectra computed by Pollack and Wood (*14*), a temperature of 485°K is more consistent with models incorporating 0.5 percent water vapor in the troposphere than with models of a dry atmosphere.

Recent measurements of high surface pressure (about 100 atm) on Venus indicate (*14, 15*) that the radiation at 1.95 cm must originate primarily in the lower atmosphere and not in the subsurface of the planet; in view of this, the absence of a phase effect is not surprising. However, it is difficult to reconcile this result with earlier observations (*1, 2*), particularly those at a wavelength of 3.15 cm. In observations made at a wavelength of 4.5 cm contemporary with those presented here, Dickel *et al.* (*16*) fail to find a phase effect. However, it is still possible to expect a phase effect at wavelengths longer than 5 cm, where, according to recent atmospheric models (*14, 15*), the radiation arises primarily in the subsurface of Venus rather than in the atmosphere.

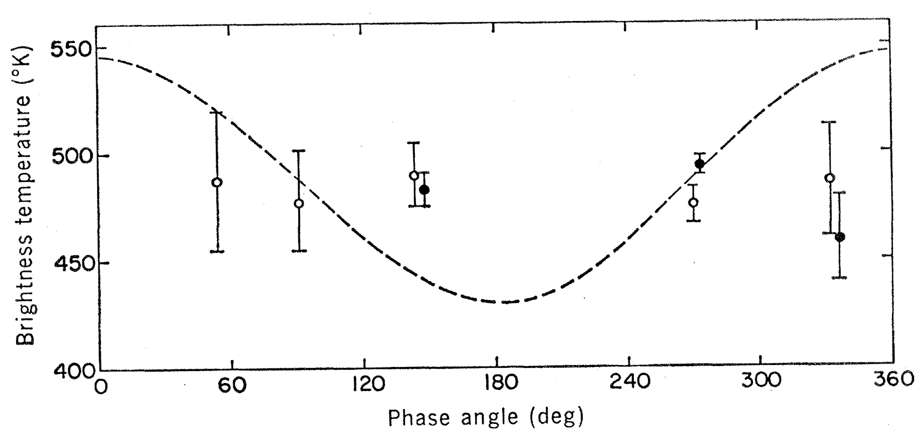


Fig. 3. Brightness temperature of Venus as a function of phase. Each point represents a weighted mean of the observations from 4 to 6 days. Open and solid circles represent temperatures derived by comparison with 3C 123 and 3C 274, respectively. Error bars are the computed mean error in each point, without inclusion of the 8-percent uncertainty in the absolute calibration. The dashed curve illustrates the 24-percent phase effect, such as has been suggested from observations at a wavelength of 3.15 cm (*1*).


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### References and Notes


1. Definite measurement of a phase effect is reported at 3.15 cm by C. H. Mayer, T. P. McCullough, R. M. Sloanaker, *Proceedings of the XIth International Astrophysics Symposium* [*Mem. Soc. Roy. Sci. Liege Ser. 5* **12**, 357 (1963)]; at 10 cm by F. D. Drake, *Astron. J.* **69**, 62 (1964); and at 8 mm by A. E. Basharinov, Y. N. Vetukhnovskaya, A. D. Kuz'min, B. G. Kutuza, A. E. Salomonovich, *Astron. Zh.* **41**, 707 (1964). Phase effects are also reported at 3.75 cm by J. R. Dickel [*Icarus* **5**, 305 (1966)] and at 6 cm by M. P. Hughes [*Planet. Space Sci.* **14**, 1017 (1966)]. However, A. D. Kuz'min [*Soviet Astron. AJ Engl. Transl.* **9**, 995 (1966)] finds no phase effect at a wavelength of 10.6 cm.
2. V. P. Bibinova, A. G. Kislyakov, A. D. Kuz'min, A. E. Salomonovich, I. V. Shavlovsky, *Proceedings of the XIth International Astrophysics Symposium* [*Mem. Soc. Roy. Sci. Liege Ser. 5* **12**, 331 (1963)]. However, this effect is contradicted by the observations of E. E. Epstein, J. P. Oliver, S. L. Soter, R. A. Schorn, W. J. Wilson [*Astron. J.* **73**, 271 (1968)] made at a wavelength of 3.4 mm.
3. D. O. Muhleman, *Space Programs Summary No. 37–26* (Jet Propulsion Laboratory, Pasadena, California, 1964), vol. 4, p. 276; J. B. Pollack and C. Sagan, *Icarus* **4**, 62 (1965).
4. The bandwidth of the radiometer is 2 Ghz, and the noise temperature of the system is about 2000°K. The telescope was used in the beam-switching mode. The half-power beam width is about 2 minutes of arc but this varies somewhat with telescope orientation. All observations were made at two orthogonal linear polarizations, within 2 hours of meridian transit, at times when there were no heavy clouds in the beam.
5. I have used the calibration of telescope gain as a function of zenith angle given by P. G. Mezger, H. Brown, I. Pauliny-Toth, J. Schraml, Z. Turlo, "Radio Tests of the NRAO 140-Foot Telescope in the Wavelength Range between 11 and 0.95 cm" [*Nat. Radio Astron. Observ. Intern. Rep.* (1966)].
6. The subroutine for Gaussian fitting was supplied by I. Pauliny-Toth and is similar to the one described by S. von Hoerner [*Astrophys. J.* **147**, 467 (1967)].
7. The exception was the observations of April 1968 at a phase angle of 334°, when Venus was less than 20° from the sun. In this observing period, there was evidence of short-term changes in gain of a few percent produced by rapid solar heating of the telescope and feed system.
8. The mapping procedure differed from that usually employed [R. N. Bracewell, *Australian J. Phys.* **9**, 287 (1956)] in that the maps were extended to only ± 1 half-power beam width

in declination and were extrapolated to an antenna temperature of 0°K by assuming a Gaussian shape for the convolution of the beam pattern with the source in this dimension.
9. R. J. Allen, A. H. Barrett, P. P. Crowther, *Astrophys. J.* **151**, 43 (1968).
10. P. A. G. Scheuer and P. J. S. Williams, *Annu. Rev. Astron. Astrophys.* **9**, 321 (1968); J. Schraml and P. Metzger, in preparation.
11. D. Hogg, paper presented at the 127th meeting of the American Astronomical Society, Victoria, British Columbia, 1968.
12. T. P. McCullough and J. W. Boland, *Astron. J.* **69**, 68 (1964).
13. F. T. Barath, A. H. Barrett, J. Copeland, D. E. Jones, A. E. Lilley, *ibid.*, p. 49.
14. J. B. Pollack and A. T. Wood, Jr., *Science* **161**, 1125 (1968).
15. D. O. Muhleman, in preparation.
16. J. R. Dickel, W. J. Medd, W. W. Warnock, *Nature* **220**, 1183 (1968).
17. I thank C. Sagan and J. B. Pollack for suggesting this investigation and for their encouragement and assistance. I am grateful to D. Heeschen and the staff of the National Radio Astronomy Observatory for the use of their facilities, and especially to K. I. Kellermann, I. Pauliny-Toth, and J. Schraml for assistance with observing and data reduction. I thank J. R. Dickel for communicating his results in advance of publication and A. E. Lilley and Y. Terzian for several useful discussions. Supported by NASA grants NGR 09-015-023 and NGR 33-010-082. The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.
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15 November 1968

## Critical Point Drying for Scanning Electron Microscopic Study of Ciliary Motion

*Abstract.* *Scanning electron microscopic study of the pattern of ciliary coordination and the form of ciliary beat is now possible. Rapid fixation stops the ciliary activity instantaneously, and critical point drying avoids distortion of the cilia by surface tension forces. Such studies have been made on the ciliate* Opalina *with this new technique.*

The scanning electron microscope provides a powerful new technique for studying the surface structure of biological material. However, the necessity of drying the specimen in air is a major problem in the preparation of material that is distorted by surface tension forces (*1*). In order to use the scanning electron microscope to study ciliary activity, we have devised a new combination of methods that overcomes this difficulty. In brief, the technique is to stop ciliary motion instantaneously by rapid fixation and then prepare the specimens for scanning electron microscopy by critical point drying.

The organism used in this study was the ciliated protozoan *Opalina ranarum*, from the rectum of the common frog *Rana temporaria*. Adjacent cilia beat with regular phase differences, so that waves of activity move over the organism in the same direction as the effective stroke of the ciliary beat (symplectic metachronal coordination). Successive stages in the cycle of one complete beat of a cilium are thus encountered sequentially in one metachronal wave. It is possible to preserve the movement of metachronal waves by instantaneous fixation, and thus analyze the form of the ciliary beat (*2, 3*). The following procedure was used.

Osmium tetroxide (2 percent solution in water) was pipetted rapidly on several hundred *Opalina* swimming in a few drops of suitable Ringer (*4*) in a watch glass, which was then maintained at 0°C for 10 to 15 minutes. The organisms were washed briefly and dehydrated in a graded ethanol series.

Organisms were dried by the critical point method of Anderson (*5*), thus avoiding distortion of the cilia by surface tension forces. The problem of handling during this step was overcome in the following way. *Opalina* in absolute ethanol were pipetted into a tiny bag of fine nylon bolting cloth (60 mesh per centimeter). The alcohol was replaced by clean amyl acetate, and the bag was quickly placed in the bomb of the critical point apparatus. The bomb was flushed out at room temperature with liquid carbon dioxide to replace the amyl acetate.

When it was completely filled with liquid carbon dioxide, the bomb was sealed off and the temperature raised to about 50°C. During this heating the liquid carbon dioxide was taken past its critical point and changed into a gas without the formation of a phase boundary. The valve was then opened slowly to allow the gaseous carbon dioxide to escape.

Dried *Opalina* were sprinkled on metal specimen stubs made sticky with a thin layer of a chloroform solution of Cellotape. The organisms were coated with approximately 30 nm of gold-palladium by rotating the stubs at an angle of 45° to the evaporation source. They were viewed in a "Stereoscan" (*6*) scanning electron microscope at a beam accelerating voltage of 20 kv with the stub tilted at an angle of 45° to the electron beam. Rotation of the

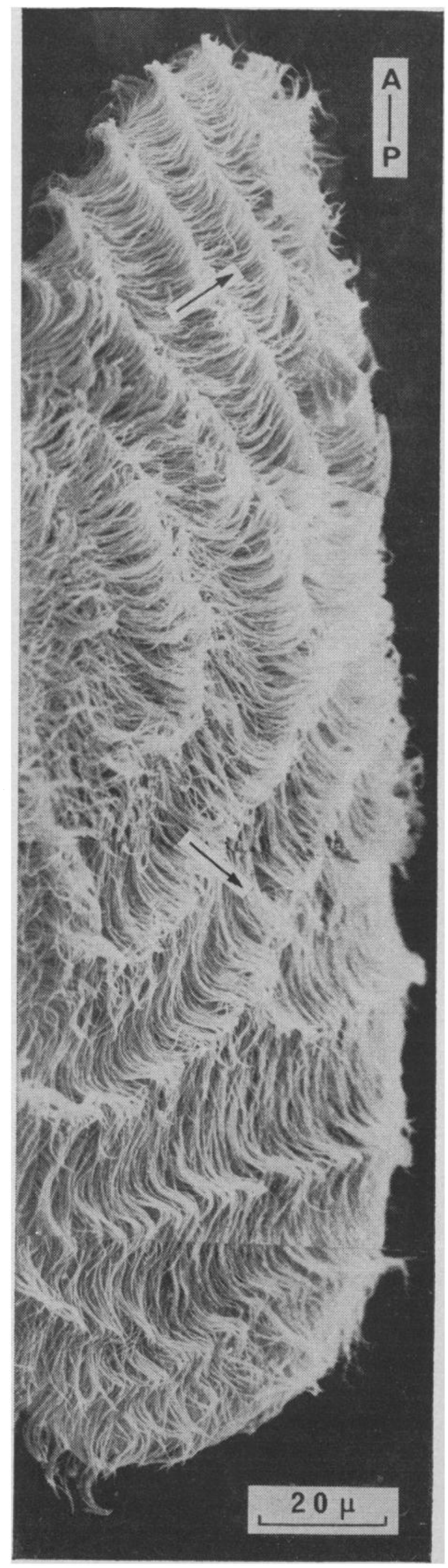


Fig. 1. Scanning electron micrograph of an *Opalina* fixed with metachronal waves traveling simultaneously in different directions. Arrows indicate direction of wave transmission and the effective stroke of cilairy beat in different regions. *A–P*, anterior-posterior axis.