Substituting in (10) the values of $\tau(\lambda)$ from figure 1 we evaluate the drop-water content as w grams per square cm = 0.2–0.3 g/cm^2; in the case of clouds with a water content of up to 1 g per m^3 this corresponds to a layer 3 km thick.

The expected correction to this water-content estimate due to cloud layers of crystalline structure is not higher than 20 to 30 percent.

Of course the data given here are not sufficient for a unique conclusion on the nature of the cloud layer of Venus. The features of the radiation spectrum must be investigated in greater detail; especially, the pattern of phase variation must be studied all over the superhigh frequency range.

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An Analysis of Microwave Observations of Venus

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The observed variation of the microwave brightness temperatures as a function of wavelength and of phase angle is in good agreement with the simultaneous solution of the one-dimensional heat conduction equation and the equation of radiative transfer. The constancy of the brightness temperature at a given wavelength for consecutive inferior conjunctions argues for an obliquity of the planetary axis of rotation $\leqslant 8°$. The phase effect and radar data is consistent with a wide variety of powdered oxides, carbonates, and silicates as predominant constituents of the surface of Venus, but is inconsistent with other materials—in particular, the hypothesized polycyclic aromatic hydrocarbons. The phase data points uniquely to retrograde rotation and to a small surface phase lag.

With the deduced subsurface temperature variations the predicted 8-mm phase effect can be estimated under a variety of assumptions and compared with observations. The observed phase effect is in disagreement with that expected from theory if atmospheric water vapor or carbon dioxide were the source of the millimeter-wave opacity; but is in agreement with theory if the opacity is due to dust distributed through the lower atmosphere and preferentially abundant in the illuminated hemisphere. The observations and theory are also in excellent agreement if the millimeter attenuation is due to clouds.

Determination of plausible surface materials properties permits the following estimates to be made of surface thermometric temperatures: mean disk, 700 °K; subsolar point, 1000 °K; antisolar point, 610 °K; pole, 470 °K. These temperatures are also in agreement with previous values obtained by Pollack and Sagan from their analysis of microwave interferometric observations of Venus. The corresponding surface pressures are ~ 50 atm.

The low radar reflectivity reported at 3.6 cm cannot be due to a general 3.6-cm absorption by the atmosphere or clouds. This result can be attributed to anomalously high absorption above a surface cold spot near the subterrestrial point at inferior conjunction, or to the variation of porosity, and therefore, of dielectric constant, with depth.

The output of the 19-mm channel of the Mariner II microwave radiometer can also be used to check various models of the atmosphere and clouds of Venus. The observed Venus limb darkening is due both to the variation of surface emissivity with angle, and to the slant path attenuation by microwave absorbers in the atmosphere and clouds. The observations cannot be consistently explained if the microwave attenuation is caused by CO_2, H_2O, or absorbing dust particles continuously distributed throughout the atmosphere of Venus. The limb-darkening observations

can be explained consistently either by an absorbing cloud or by scatterers arbitrarily distributed through the atmosphere. The limb darkening requires a variation of temperature from the dark to bright side consistent with that previously obtained from analysis of the phase effect and of interferometric observations.

We have developed a method for the solution, in the Schuster-Schwarzschild approximation, of the equation of radiative transfer for anisotropic scattering and arbitrary single scattering albedo. When compared with various exact limiting cases, the approximation appears accurate to within about 10 percent. Given the real and imaginary parts of the index of refraction, the particle dimensions, and the total optical thickness of the layer, the method permits a computation of the reflection, absorption, and transmission spectrum of any cloud layer. Using a computer solution of the Mie theory problem for ice crystals obtained by William Irvine, we have succeeded in reproducing the visible and near infrared albedo variation of Venus as observed by John Strong and others. Ice crystals with mean radii $\sim 7.5\mu$ match the observations satisfactorily; water droplets at temperatures $\geqslant 280$ °K do not. When allowance is made for the contribution of varying particle sizes on polarization and on single scattering albedo, and for the fact that single scattering at high altitudes dominates the polarization of reflected sunlight, the derived particle radii are consistent with those deduced from visual and near infrared polarization studies.

One promising attempt to explain the high surface temperature of Venus involves the greenhouse effect. With surface pressures of several tens of atmospheres, and the upper limits on the possible H_2O and CO_2 abundances of Venus (~ 100 g cm^{-2} and $\sim 10^6$ cm-atm, respectively), cloudless greenhouse models can account for almost all of the high surface temperature. With the same pressures, and the lower limits on the possible H_2O and CO_2 abundances on Venus, only a fraction of the observed temperatures can be accounted for by cloudless greenhouse models. Accordingly we have investigated the contribution to the greenhouse effect made by the same clouds required to explain the visible and near infrared reflection spectrum of Venus. It is found that such clouds, because they are poorly absorbing and strongly forward scattering in the visible, but strongly absorbing and nearly isotropically scattering in the infrared, can provide the additional opacity needed to construct consistent Venus greenhouse models. The clouds are effective by closing infrared radiation leaks in atmospheric windows, while permitting the bulk of the incident visible sunlight to reach the planetary surface.

The bolometric albedo of the planet and its distance from the sun specify its cloud temperature. The total water vapor abundance in the atmosphere, and the specifiable lapse rate, therefore determine the altitude of the clouds from the requirement that the saturation vapor pressure be reached at that altitude. The cloud temperature and altitude and the lapse rate in turn uniquely specify the surface temperature. In this way, the total water vapor abundance tends to control the surface temperature for cloud-covered planets.

We find that the same clouds—with ice crystals on top and water droplets towards their bottoms—and their underlying atmosphere explain, with no further assumptions, the general millimeter spectrum, the millimeter phase effect, the Mariner II microwave limb darkening, and the infrared limb darkening of Venus.

References

The detailed discussions of the foregoing brief summary can be found in the following:

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The microwave phase effect of Venus, Carl Sagan and James B. Pollack, Icarus **4**, 62 (1965).

Polarization of thermal emission from Venus, Carl Sagan and James B. Pollack, Astrophys. J. **141**, 1161 (1965), abstract in Astronom. J. **70**, 146 (1965).

An analysis of the Mariner II microwave observations of Venus, James B. Pollack and Carl Sagan, to be published.

On the Nature of the clouds and the origin of the surface temperature of Venus, Carl Sagan and James B. Pollack, to be published.

Discussion Following C. Sagan's Paper

A. H. Barrett: Do your models agree with the observations of Spinrad?

C. Sagan: Spinrad's unsuccessful search for water vapor on Venus is consistent with the values of water vapor abundance found by Strong and associates, provided the pressure at the cloud layer is ~ 1 atm. The water vapor observations are consistent with a brightness temperature at 8 to 13μ and at the center of the disk of 234 °K provided the atmosphere above the clouds is unsaturated, as is the case on Earth.

A. H. Barrett: Will your models agree with the observed variations of Venus spectrum with phase?

C. Sagan: The models required for the visible and infrared albedos also account for the small amplitude of the 8 mm phase variation. The magnitude of the 3 and 10 cm variation is due almost entirely to subsurface effects.

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