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ABSTRACT

The near infrared reflectivity of ice clouds is computed and compared to observations of Venus. The difficulty in making an exact correction for CO_2 absorption precludes the possibility of either establishing or absolutely ruling out ice particles as the primary cloud constituent; however, it is possible to conclude that the clouds are not optically thick and composed of large ice crystals. There is still disagreement as to the quantitative significance of the infrared spectra, but, if it is assumed that a 20% depression may exist in the continuum near 2.0μ, then optically thin clouds ($\tau \lesssim$ 5-10) of ice particles with radii $\lesssim 4\mu$ are compatible with the observations. It is shown that there is a small amount of positive evidence for such clouds.

1. Introduction

Although the recent observational and theoretical investigations of Venus have greatly expanded our knowledge of that planet's atmosphere, the composition of the cloud particles is still unknown. Until a space probe samples the particles themselves, our primary sources of information on them will probably continue to be the solar light reflected by Venus and observed on Earth. The absolute value and the wavelength dependence of the absorbtivity of most materials is such that the near infrared is the most likely wavelength region for the reflectivity of the clouds to show measurable variations which can be correlated to particle composition. The interpretation, however, is complicated by the strong absorption shown by many gases in the same region. Even if the exact composition of the atmosphere of Venus were known it would be difficult to make a valid correction for gaseous absorption because, first, there is not a practical method for solving the transfer problem with highly anisotropic scattering and wavelength dependent absorption and, second, there is not sufficient evidence on the physical structure of the clouds. However, it is worthwhile to examine the spectra for the presence of gross features expected for ice clouds and to compare the magnitude of those features, or upper limits on them, to theoretical calculations for the reflectivity of ice clouds.

2. Observations

Bottema, Plummer, Strong, and Zander (1964,1965) obtained a reflection spectrum from 1.7μ to 3.4μ with a balloon-telescope at a resolving power of .08μ. They used the reflecting layer model to correct for assumed H_2O and CO_2 absorption above the clouds of Venus and they made laboratory observations of the reflectivities of many possible cloud particle constituents. On the basis of a remarkable agreement between the spectral reflectivity of Venus and the laboratory ice cloud (Fig.1), they concluded that the clouds of Venus were ice. Sagan and Pollack (1967) then made calculations with a two-stream approximation which confirmed the identification, and they derived a cloud thickness $18 \leq \tau \leq 43$ and a mean particle radius $7.5\mu \leq \bar{r} \leq 10.0\mu$.

However, higher resolution spectra obtained from the ground by Kuiper (1962) show no clear evidence of ice and Rea and O'Leary argue that the reflectivity minima at 1.5 and 2.0μ are due almost entirely to CO_2 absorption. Rea and O'Leary convolved Kuiper's spectrum to degrade the resolution to that of Bottema, et al. and the close fit that they obtained to the observed curve of Bottema, et al. supports their argument. Recent observations by Kuiper (1968) from a high altitude aircraft confirm his earlier results.

Thus, although the very low reflectivity observed by Bottema, et al. near 3μ is almost certainly due to absorption within the cloud particles themselves, the feature at 2μ is, at least in large part, the result of CO_2 absorption. It is, therefore, impossible to derive unique cloud parameters from the observations, yet it is of interest to examine the question of whether or not it is possible for ice clouds to be compatible with the observations of both Bottema, et al. and Kuiper, i.e.: Are there physically realistic ice clouds with a low reflectivity from 3.0 to 3.4μ and yet with no reflectivity minima at 1.5 and 2.0μ deep enough to be observed by Kuiper?

Rea and O'Leary (1968) examined the above question semiquantitatively and concluded that micron-sized particles were incompatible with the observations and that, if the particles were small enough to yield acceptably shallow minima at 1.5 and 2.0μ, the reflectivity at 3.2-3.4μ would be much too high. They argued that even if some additional material were present and absorbing at 3.2-3.4μ, the ice particle diameters would have to be much less than 1μ, and probably less than .1μ, in order to be consistent with the 1.5 and 2.0μ observations; therefore, since the existence of the required abundance of such particles on a planetwide basis is improbable, they concluded that the major scatterers of radiation are almost certainly not composed of H_2O ice.

In order to consider these questions in more quantitative detail the observations must be examined to, in effect, place error bars on the measured reflectivities. Bottema, et al. reported a nearly constant reflectivity of $\sim$ 5% from 3.0 to 3.4μ but clearly the significance of the reported curve decreases with wavelength in that region. The indium arsenide detectors of Bottema, et al. had a detectivity which increased with wavelength up to $\sim$ 3.25μ and then decreased precipitously to practically zero at 3.4μ (Strong and associates, 1966). Since the solar spectrum is decreasing in that region the net result was that their response to the solar spectrum was approximately constant from $\lambda \sim 1.8\mu$ to $\lambda \sim 3.25\mu$ and then decreased sharply. An additional possible source of error above 3μ, which also increased with wavelength, was the thermal emission from the blade of the beam chopper, although a correction was made for that. According to W. Plummer (1968) the observed reflectivity was getting down into the noise level at 3.3μ and at 3.4μ it was completely submerged, so that at the latter wavelength it is only possible to say that Venus is not highly reflective. Hence it appears that ice clouds will not be inconsistent with the observations of

Bottema, et al. if they yield a reflectivity at $3.3\mu \lesssim 10\%$ and a reflectivity at $3.4\mu \lesssim 20\%$.

The other observational question which must be examined is how deep the reflectivity minima at 1.5 and 2.0μ could be without being detected by Kuiper. Pollack and Sagan (1968) argue that depressions of 20% are possible because the ratios of the reflectivities at two wavelengths separated by $\sim .1 - .4\mu$ sometimes differ that much between different observers as well as for the same observer at different times. Kuiper (1968) however attributes at least part of the reflectivity variations to real changes in the atmospheric conditions on Venus and he states that the maximum depressions at 1.5 and 2.0μ compatible with his observations are $\sim$ 1%. Rather than attempting to place weights on the values suggested by the opposing camps, we will consider individually the limit favored by Pollack and Sagan and that favored by Kuiper.

3. Numerical Computations

Theoretical computations of the spectral reflectivity of ice clouds in the near infrared have been made to determine the magnitude of the expected ice absorption features and to determine their dependence on the particle size and on the cloud optical thickness. The single scattering phase functions and albedos were computed from Mie theory by H. Cheyney. The remaining computations and the application to Venus are the responsibility of J. Hansen.

It has been shown elsewhere (Hansen and Cheyney, 1968) that the major features in laboratory reflectivity spectra of clouds of highly nonspherical but randomly oriented ice crystals may be matched theoretically by treating the particles as spheres of equivalent volume. The assumption of random orientation for the cloud particles on Venus is probably valid unless the particles are large and the atmosphere has little motion, but such conditions appear to be improbable. Therefore computations were made for spherical ice particles with the "cloud" model size distribution used originally by Deirmendjian (1964). The upper limit of the size distribution was taken as diameter 30μ and the optical constants for ice were taken from the data compiled by Irvine and Pollack (1968). Some typical phase functions for one of the size distributions are shown in Figure 2. These illustrate the strong forward scattering and the damping of back scattering at wavelengths where the absorption is large. The multiple scattering computations were made with a "double only" method described by Hansen (1968) which is based on a doubling principle first stated by van de Hulst (1963). In the method employed here the scattering and transmission functions for a layer of optical thickness $\tau = 2^{-25}$ were obtained analytically from the phase function, since multiple scattering is negligible for a layer of that thickness. The corresponding functions for a plane parallel atmosphere of twice that thickness were then obtained from doubling equations and the doubling process was repeated until the results for thick atmospheres were obtained. The number of Gauss divisions in the integrations and the number of terms in the cosine expansions were varied to check the numerical accuracy; this procedure indicated that at all angles the results differed from the exact solution by less than 1%. The results were integrated over the illuminated part of Venus at the phase angle 59^{o} which corresponds to the phase angle at which the observations of Bottema, et al. were made and approximately to the phase angle (53^{o}) of Kuiper's (1962) observations. The "reflectivity" shown in Figs. 3-5 was obtained as the ratio of the calculated reflectivity to the reflectivity of a perfect Lambert sphere at the same phase angle. The fact that the optical thickness of a given cloud would vary with wavelengths was neglected; however, for the cloud models considered here the variation in opacity is significant only for wavelengths $\gtrsim 2.75\mu$ and in that region the reflectivity is nearly independent of the optical thickness (Figs. 3-5).

4. Discussion

Figs. 3-5 illustrate the dependence of the absorption features on particle size and on the cloud optical thickness. For particles still smaller than those shown the reflectivity in the 3.0-3.4μ region continues to increase rapidly. Thus if the upper limits on the reflectivity in that region suggested by the observations of Bottema, et al. (§2) are accepted, then, for the clouds of Venus to be ice, they must be composed primarily of particles $\gtrsim 1\mu$ in radius. (The cloud particles could of course be ice particles submicron in radius if we were willing to invoke an additional absorber for $\lambda \sim 3.0$-3.4μ.)

It is more difficult to establish an upper limit for the particle size since the 1.5 and 2.0μ features depend strongly on the cloud optical thickness. However, since the absorption features become still stronger for particles larger than those represented in Fig. 5, it is apparent that for the cloud thickness preferred by Sagan and Pollack ($\tau \sim 30$) the cloud particles could not be as large as they originally derived ($7.5\mu \le \bar{r} \le 10\mu$). In fact for ice clouds of that thickness it does not appear that particles of any size could be compatible with the observations of both Kuiper and

and Bottema, et al. Moreover, if the maximum depression in the continuum at 2.0μ allowed by Kuiper's observations is 1% then potential ice clouds would have to be so thin that they could not be regarded as the primary scatterers of visual and infrared radiation. However, if it is assumed that Kuiper's observations permit reflectivity absorption features of ∿ 20%, then clouds of optical thickness $\lesssim$ 10 and particle radii 1μ $\lesssim \bar{r} \lesssim$ 4μ are acceptable.

It is clear that ice clouds of thickness $\tau \sim 5 - 10$ would have to be regarded as the major scatterers of visual and near infrared radiation. The visual spherical albedo for clouds of optical thickness 5 and 10 would be ∿ 40% and 55%, respectively. The spherical albedo in the near infrared is shown in Fig. 6 for the particle size distribution peaking at $r = 2\mu$. It is interesting, although not too significant, that the spherical albedo for Venus at 2.3μ is ∿ 40% (Sinton, 1963) in agreement with an ice cloud of thickness $\tau \sim 5$, but the observed value is uncertain. The spherical albedo of Venus in the visual is ∿ 70-80% and hence for the clouds suggested above the reflectivity in that wavelength region would have to receive a significant contribution from ground reflection, dust particle scattering, or Raleigh scattering from below the ice clouds, but such possibilities are not unexpected for visual light.

It is important, however, to question the physical plausibility of having relatively thin planetwide ice clouds. Certainly such clouds could not be expected to be of uniform thickness even if the circulation pattern on Venus is unicellular. There would probably be some areas of the planet with no ice clouds at all, but with the resolution obtainable from Earth it is doubtful that these could be observed, especially since the atmosphere below the cloudtops almost certainly contains fine dust particles as a result of the dry surface conditions. In fact it would be difficult to fit any model with a single type of scattering particle, either ice or dust, to all of the observations. The reflectivity of the planet is relatively constant from 2000Å to 3000Å in the ultraviolet (Jenkins and Morton, 1968) with an albedo about half of that in the visual. Deep clouds of ice or water would have practically the same albedo in the ultraviolet as in the visual and according to Pollack (1968) the albedo of dust clouds, which is low at 3000Å, would continue to decrease toward 2000Å if the increased ultraviolet absorption is due to Fe_3^+ as it is for most dusts on Earth. The flat reflectivity from 2000Å to 3000Å would be understandable, however, if thin or broken ice clouds provide about half of the visual albedo as would be the case with clouds of average optical thickness $\tau \sim 5\text{-}10$.

A recent observation which is of special significance to this paper is that of the water vapor mixing ratio below the clouds which was measured by Venera IV (Arduevskiy, Marov and Rozhdestvenskiy, 1968) as > .1%. If that result is correct then it is probable that there are ice clouds covering at least part of the planet. Although the Venera IV result apparently contradicts several water vapor line measurements, it is just conceivable that the spectroscopic results are also compatible with ice clouds. The polarization measurements contain much information on the cloud particles but the results of those measurements are ambiguous; Lyot (1929) deduced a refractive index ~ 1.33 and a particle radius $\sim 1.25\mu$ but Coffeen (1968) infers a refractive index between 1.4 and 1.7. Moreover, since the polarization is primarily due to singly scattered photons it is possible that these measurements refer mainly to a thin haze layer above the clouds.

We have not mentioned many observations which bear on the cloud particle composition, but none of those observations unambiguously rules out the possible existence of ice clouds. We conclude from the near infrared reflectivity spectra that the clouds of Venus are not optically thick ice clouds; however, if depressions in the continuum $\sim$ 20% are accepted, then thin ice clouds ($\tau \sim$ 5-10) with particle radii $1\mu \lesssim \bar{r} \lesssim 4\mu$ are compatible with the infrared observations.

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REFERENCES

Avduerskiy, V.S., M. Ya. Marov and M. K. Rozhdestvenskiy, 1968: The Model of the Atmosphere of the Planet Venus on the Results of Measurements Made by the Soviet Automatic Interplanetory Station "Venera IV". This issue J. Atmos. Sci.

Bottema, M., W. Plummer, J. Strong and R. Zander, 1964: Composition of the Clouds of Venus. Astrophys. J., 140, 1640-1641.

____________, 1965: The Composition of the Venus Clouds and Implications for Model Atmospheres. J. Geophys. Res., 70, 4401-4402.

Coffeen, D. L., 1968: Polarization Measurements of Venus. The Second Arizona Conference on Planetary Atmospheres, Tucson, March 11-13.

Deirmendjian, D., 1964: Scattering and Polarization Properties of Water Clouds and Hazes in the Visible and Infrared. Appl. Optics, 3, 187-196.

Hansen, J. E., 1968: Radiative Transfer by Doubling very Thin Layers. (to be published).

Hansen, J. E. and H. Cheyney, 1968: Comparison of Theoretical near Infrared Reflectivities of Ice Clouds to Laboratory Observations. (to be published)

Hulst, H. C. van de, 1963: A New Look at Multiple Scattering. NASA Institute for Space Studies Report (New York), 81 pp.

Irvine, W. M., and J. B. Pollack, 1968: Infrared Optical Properties of Water and Ice Spheres. (to be published in Icarus)

Jenkins, E. B., and D. C. Morton, 1968: High Resolution UV Spectra of Venus. The second Arizona Conference on Planetary Atmospheres, Tucson, March 11-13.

Kuiper, G. P., 1962: Photometry of the Infrared Spectrum of Venus, 1-2.5 microns. Commun. Lunar Planetary Lab., 1, 83-117.

____________, 1968 : Presented at the second Arizona Conference on Planetary Atmospheres, Tucson, March 11-13.

REFERENCES (cont'd)

Lyot, B., 1929: Recherches sur la polarisation de la lumiere des planetes et de quelques substances terrestres. Annales de L'Observatoire de Paris (Meudon), 181 pp.

Plummer, W., 1968: Private communication.

Pollack, J. B., 1968: Private communication.

Pollack, J. B., and C. Sagan, 1968: The Case for Ice Clouds on Venus. (to be published, J. Geophys. Res.)

Rea, D. G. and B. T. O'Leary, 1968: On the Composition of the Venus Clouds. J. Geophys. Res., 73, 665-675.

Sagan, C., and J. B. Pollack, 1967: Anisotropic Nonconservative Scattering and the Clouds of Venus. J. Geophys. Res., 72, 469-477.

Sinton, W. M., 1963: Infrared Observations of Venus. Mem. Soc. Roy. Sci., Liege, 7, 300-310.

Strong, J. and associates, 1966: Infrared Balloon Astronomy. AFCRL, 115 pp. [DeF. Doc. Center, AD643-567, $3.00.]

FIGURES

Fig. 1. Infrared reflectivity of Venus measured by Bottema, et al. (1965) with a resolution .08μ. The corrected Venus reflectivity was assumed by Bottema, et al. to be the reflectivity of the cloud layer. This reflectivity was obtained by using a reflecting layer model and the transmissions shown in the lower part of the Figure to correct for gaseous absorption.

Fig. 2. Phase functions for three representative wavelengths in the near infrared. The phase functions are for spherical ice particles following the "cloud" model size distribution with the maximum of the distribution at radius 4μ.

Fig. 3. Reflectivity of ice clouds in the near infrared. This is the intrinsic reflectivity of the clouds with no account taken of gaseous absorption or scattering by other particles. The calculations apply to Venus at the phase angle 59° and are for the "cloud" model size distribution at radius 1μ.

Fig. 4. Reflectivity of ice clouds in the near infrared. The conditions are the same as in Fig. 3 except the size distribution has its maximum at 2μ.

Fig. 5. Reflectivity of ice clouds in the near infrared. The conditions are the same as in Fig. 3 except the size distribution has its maximum at 4μ.

Fig. 6. Spherical albedo of ice clouds in the near infrared. The calculations are for the "cloud" model size distribution of spherical ice particles with the maximum of the distribution at radius 2μ.

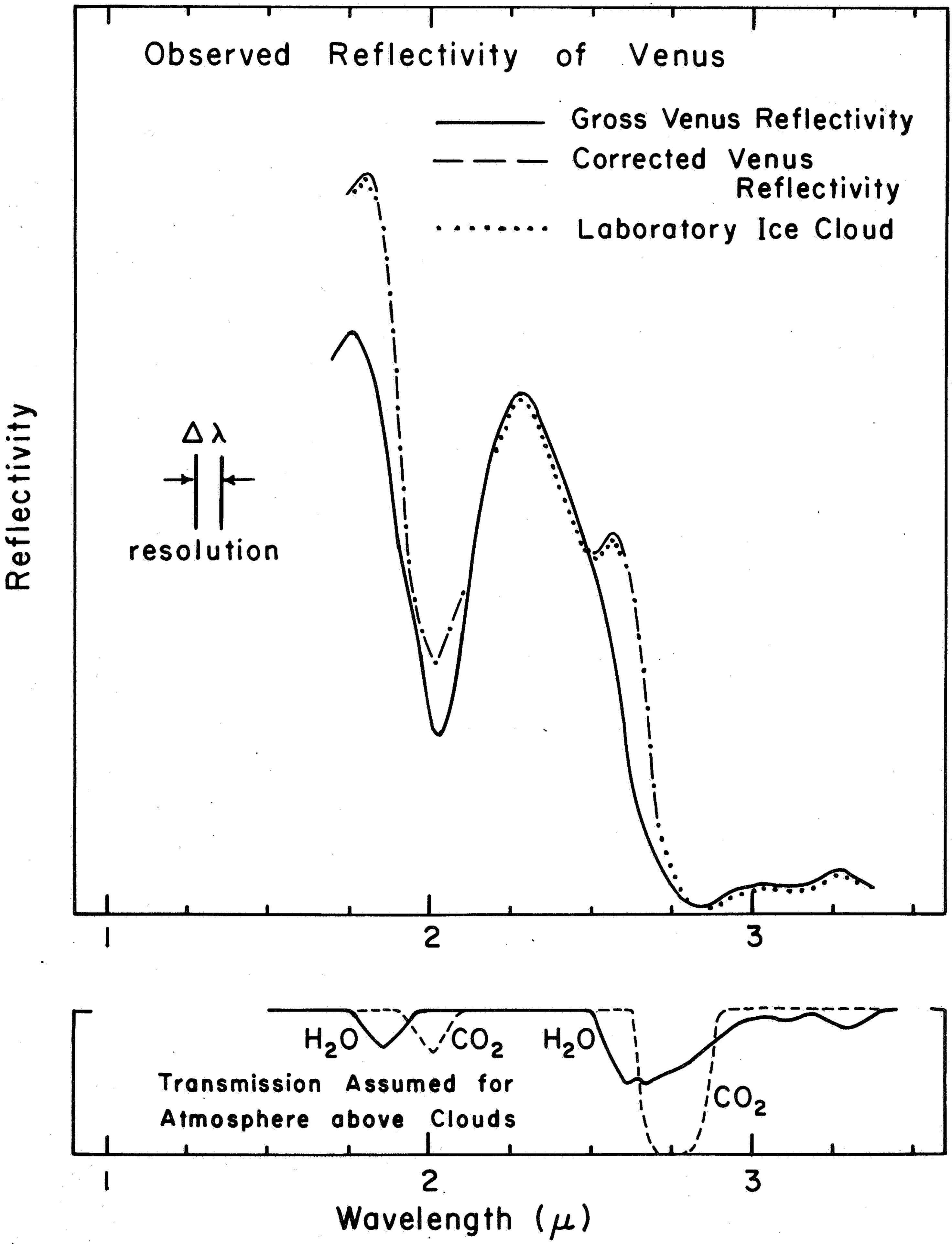
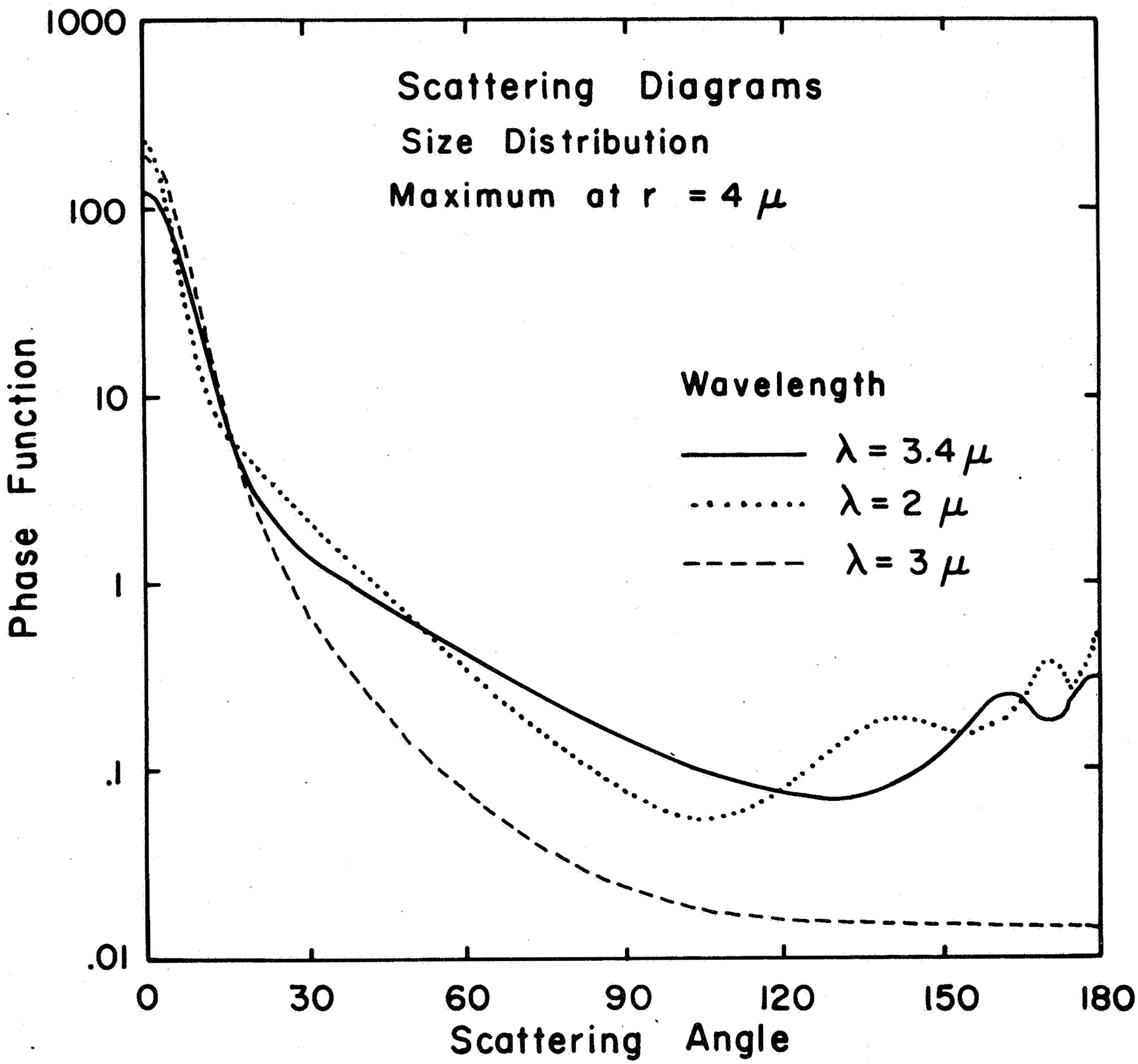

Observed Reflectivity of Venus
Gross Venus Reflectivity
Corrected Venus Reflectivity
Laboratory Ice Cloud
Δλ
resolution
Reflectivity
1
2
3
H2O
CO2
H2O
CO2
Transmission Assumed for Atmosphere above Clouds
1
2
3
Wavelength (μ)

Fig. 1



Scattering Diagrams
Size Distribution
Maximum at r = 4 μ
Wavelength
λ = 3.4 μ
λ = 2 μ
λ = 3 μ
Phase Function
1000
100
10
1
.1
.01
0
30
60
90
120
150
180
Scattering Angle

Fig. 2

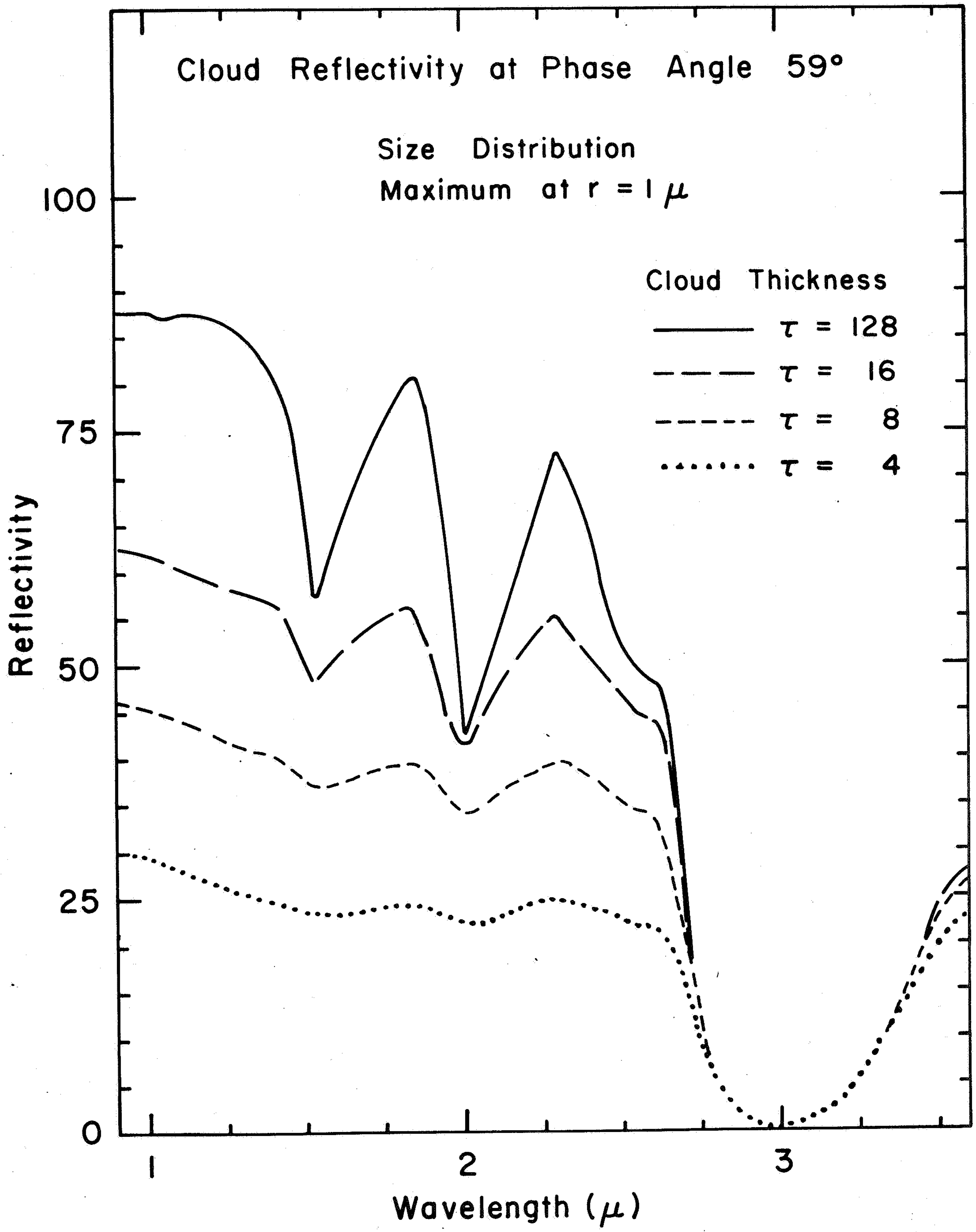

Cloud Reflectivity at Phase Angle 59°
Size Distribution
Maximum at r = 1 μ
Cloud Thickness
τ = 128
τ = 16
τ = 8
τ = 4
Reflectivity
100
75
50
25
0
1
2
3
Wavelength (μ)

Fig. 3

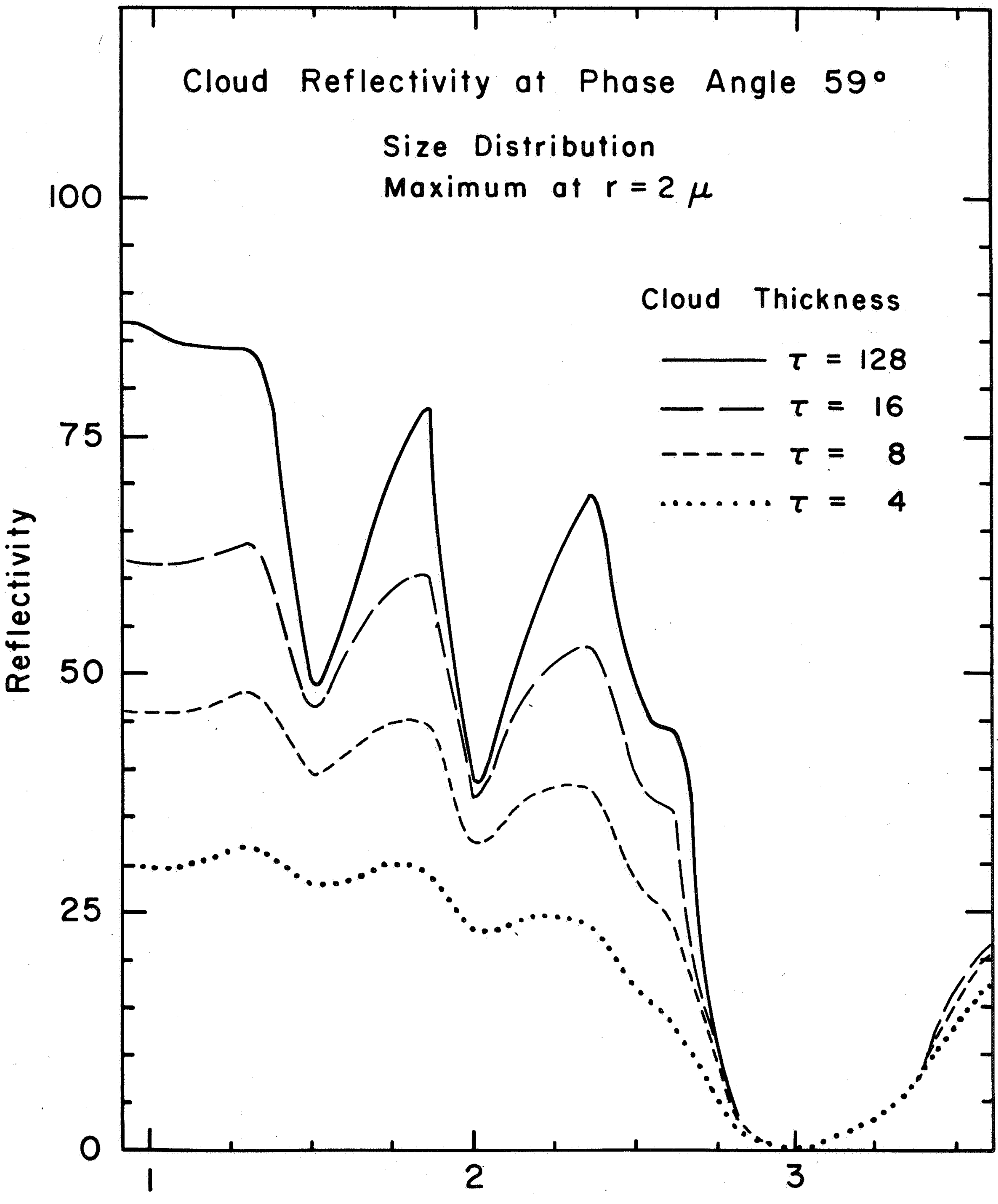

Cloud Reflectivity at Phase Angle 59°
Size Distribution
Maximum at r = 2 μ
Cloud Thickness
τ = 128
τ = 16
τ = 8
τ = 4
100
75
50
25
0
Reflectivity
1
2
3
Wavelength (μ)

Fig. 4

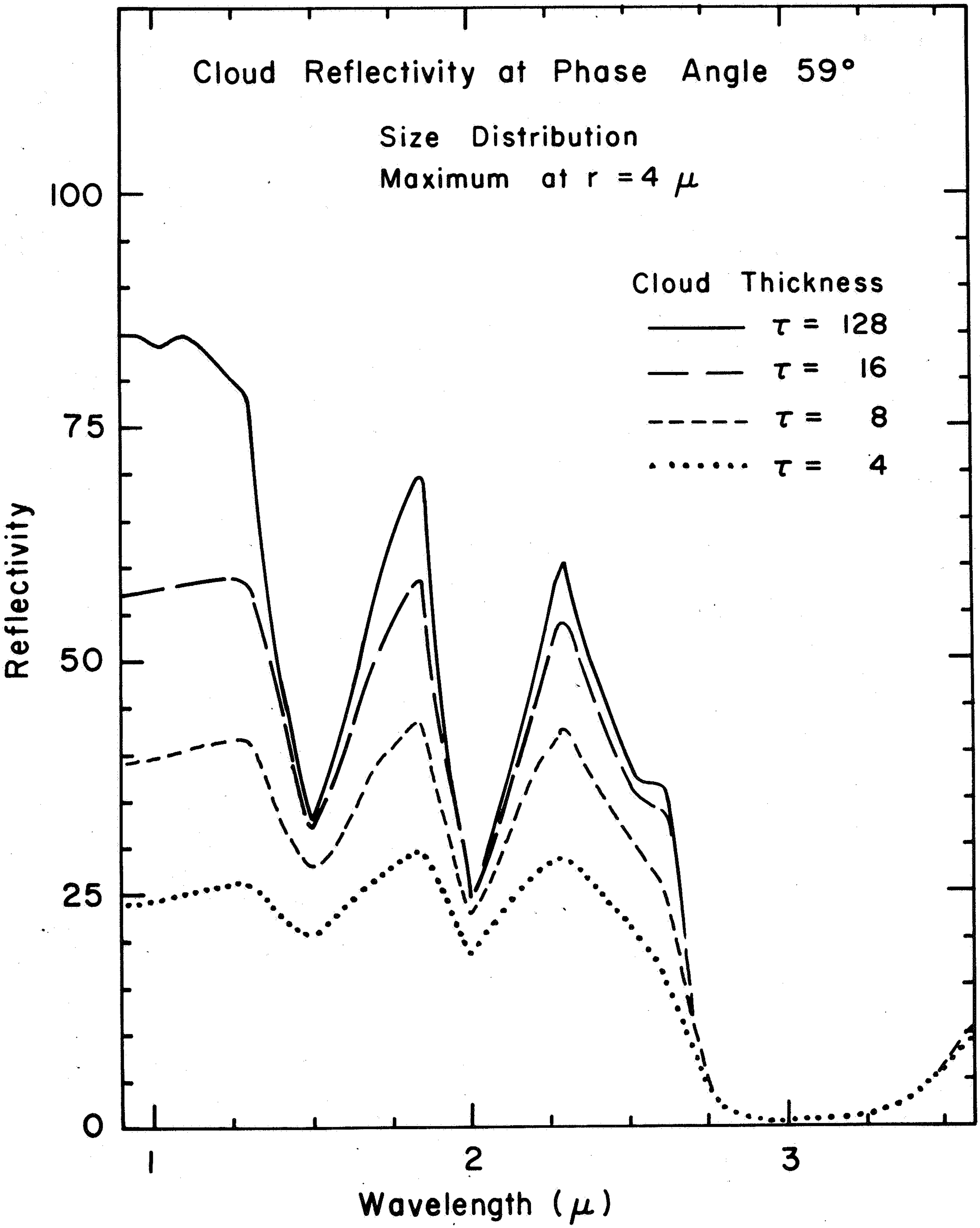

Cloud Reflectivity at Phase Angle 59°
Size Distribution
Maximum at r = 4 μ
Cloud Thickness
τ = 128
τ = 16
τ = 8
τ = 4
Reflectivity
100
75
50
25
0
1
2
3
Wavelength (μ)

Fig. 5

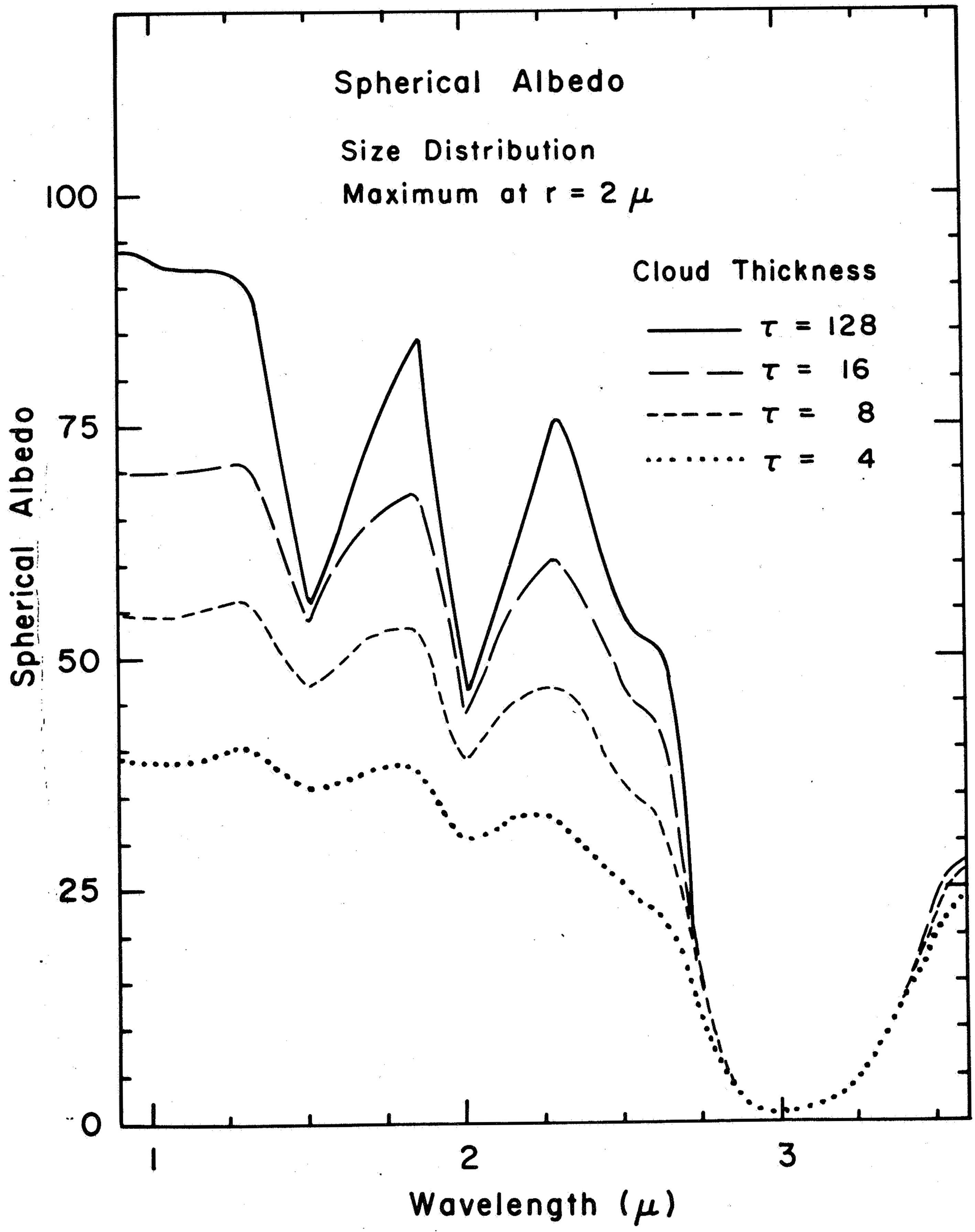

Spherical Albedo
Size Distribution
Maximum at r = 2 μ
Cloud Thickness
τ = 128
τ = 16
τ = 8
τ = 4
100
75
50
25
0
Spherical Albedo
1
2
3
Wavelength (μ)

Fig. 6