Interpretation of the Variation of Polarization over the Disk of Venus

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ABSTRACT

The polarization of reflected sunlight is computed for model atmospheres of Venus as a function of location on the apparent planetary disk. The calculations are for both homogeneous (uniformly mixed) and layered models, as required to investigate the vertical distribution of particles. The results are compared with available observations, which are few in number and of poor spatial resolution. The results for the homogeneous and layered models are also integrated over the planet and compared with whole-disk observations.

It is shown that the Rayleigh scattering observed in the polarization of Venus originates primarily from within the visible clouds, rather than from above the clouds. The photon mean free path is ~5 km at the 50 mb pressure level, which is well within the visible clouds. Thus the visible "clouds" are actually a very diffuse hazy region. This visible cloud layer extends at least up to the level where the pressure is ~10 mb.

The results indicate that the atmosphere behaves, for this type of observation, more nearly as the so-called "homogeneous model" than as the "reflecting layer model." However, there is some indication in the data that the turbidity (ratio of cloud particle opacity to Rayleigh opacity) increases with depth into the atmosphere. This conclusion receives stronger support from a comparison of particle number densities obtained from the polarization data (~30 particles cm^{-3} at the 50 mb level) with the number densities obtained from other observations which refer on the average to higher and lower levels in the atmosphere.

1. Introduction

The polarization of sunlight reflected by Venus has been analyzed by Hansen and Hovenier (1974) for observations of the unresolved planet. Detailed properties of the cloud particles could be obtained using homogeneous model atmosphere because it could be demonstrated that the polarization from the whole disk is predominantly due to light scattered by a single type of particle; in particular, particles of one shape and refractive index. The particle shape (spherical) and refractive index ($n_r \approx 1.44$) thus refer to the main constituent of the visible clouds. The effective particle radius ($r_{eff} = 1.05\ \mu m$) and effective variance ($v_{eff} = 0.07$) of the size distribution refer to a certain average over the planetary disk, but the possible range of values for these quantities is severely limited by the remarkably small value of v_{eff} for the whole planet. The remaining quantity deduced by Hansen and Hovenier, the pressure (~50 mb) at cloud optical depth unity, is significantly model-dependent, i.e., it depends on the actual vertical distribution of cloud particles and gas; hence it is useful to check that result by means of computations for an inhomogeneous atmosphere.

Much more information than that obtained from the whole-disk observations could be obtained from measurements of the polarization with high spatial resolution. Such observations could yield the cloud particle properties for local areas and the distribution of particles with altitude. The local cloud particle properties could be obtained with an analysis similar to that of Hansen and Hovenier, based on the variation of the polarization with phase angle and wavelength. The vertical distribution of particles (above optical depth ~1) could be obtained with observations of a given area from several different zenith directions, based on the relative contributions of Rayleigh and cloud particle scattering. The required observational conditions can not be fully achieved for either of the above experiments with earth-based measurements, because the time required for the variations in phase angle and zenith angle is at least on the same order as the time scale for significant changes in the atmosphere (and also because the zenith angle is restricted in range away from the equator). Nevertheless, it should be possible to extract some new information from ground-based regional polarization observations.

2. Model atmosphere

The available observations of regional polarization on Venus, illustrated in the next section, are few in number and of low spatial resolution. Thus the amount of detail on the vertical structure of the atmosphere that we are likely to be able to extract from them can be specified in terms of a two-layer model of the atmosphere.

Fig. 1 is a sketch of our two-layer model, which consists of a finite Rayleigh scattering layer above a semi-infinite homogeneous layer. It is described by two parameters: τ_R, the optical thickness of the upper (Rayleigh) layer, and f_R, the ratio of the Rayleigh scattering coefficient within the cloud to the cloud particle scattering coefficient. This two-layer model

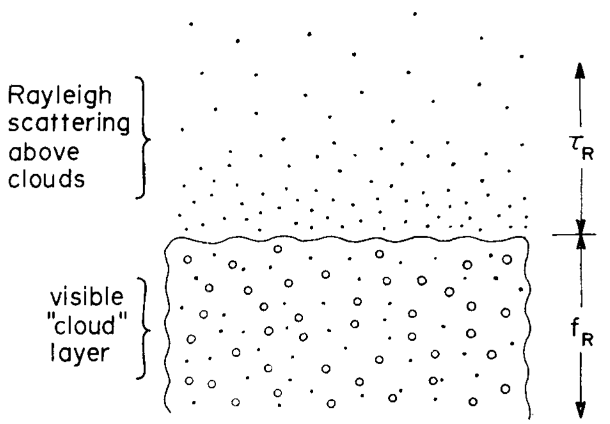

FIG. 1. Diagram of the two-layer model. τ_R is the optical thickness of the Rayleigh layer above the visible clouds, and f_R is the ratio of the Rayleigh scattering coefficient within the homogeneous cloud layer to the cloud particle scattering coefficient.

contains as special cases the two most common models for planetary atmospheres: the homogeneous atmosphere[1] model (for $\tau_R=0$) and the reflecting layer model (for $f_R=0$).

In our illustrations of the computed distribution of polarization over the planetary disk, f_R and τ_R are constant over the planet. However, this does not restrict the applicability of the computations to horizontally homogeneous atmospheres. If the spatial scale for significant horizontal variations in the atmosphere is several times larger than the photon mean free path, our computations are strictly applicable with the appropriate local values of f_R and τ_R.

We make contours of the percent polarization on the apparent planetary disk, assuming a spherical but locally-plane-parallel atmosphere. The reflection matrix for the plane-parallel atmosphere is found by using the adding method in the manner described by Hansen and Travis (1974). This yields the Fourier coefficients of the Stokes parameters at discrete values of the zenith angle of reflected radiation ($\theta=\cos^{-1}\mu$) and the zenith angle of the sun ($\theta_0=\cos^{-1}\mu_0$). For a given phase angle ($\rho=\pi-\alpha$, where α is the scattering angle) the Stokes parameters are found on a dense Cartesian grid by interpolating the Fourier coefficients to the appropriate values of μ and μ_0. The geometry relating the different angles is illustrated by Sekera and Viezee (1961).

[1] By a "homogeneous" atmosphere we mean that the single scattering albedo and phase function are constant throughout the atmosphere. We could also call this a "uniformly mixed" atmosphere. This use of the word homogeneous corresponds to the classical usage in radiative transfer; the homogeneous model holds a special place because it simplifies the multiple scattering solution in many methods of computation.

But note that Devaux *et al.* (1975) use the term "homogeneous cloud layer" to mean a layer in which the number of cloud particles per unit volume is constant with height. So in their cloud layer the phase function and single scattering albedo vary with height.

And note that, even if we find evidence that the homogeneous model fits the polarization data, this does not prove that a homogeneous model is sufficient to interpret absorption line observations. The "homogeneous" atmosphere model often used to interpret absorption line data refers to the same definition for homogeneous that we use: the single scattering albedo and phase function are constant throughout the atmosphere. But for the absorption line problem this requires not only uniform mixing, but also that a single temperature and single pressure can be used in the interpretation. With the polarization we test only the uniform mixing assumption.

3. Polarization over the disk

Observations of regional polarization on Venus have been reported by Lyot (1929), Dollfus (1955) and Coffeen and Gehrels (1969). Coffeen and Gehrels had the broadest spectral coverage and published their results in detailed tabular form. Hence the comparisons we illustrate are made with their data.

Regional observations of Coffeen and Gehrels are shown in Figs. 2–4. The circles represent the diaphragm size (~2 arcsec) for the phase angle of the observations ($\rho\approx77°$). The numbers within the circles are the observed percent linear polarization and the straight lines attached to the circles indicate the direction of vibration of the electric vector. The positions of the observed areas on the disk are those observed on the visual image. Refraction in the earth's atmosphere displaced the images for other wavelength regions, by as

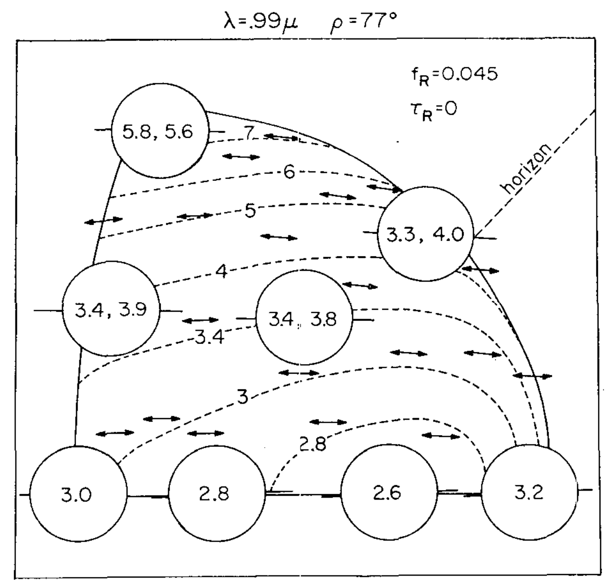

FIG. 2. Distribution of percent linear polarization over the disk of Venus for phase angle 77° and wavelength 0.99 μm. The calculations, for a homogeneous atmosphere of spherical particles with $n_r=1.43$, $r_{\rm eff}=1.05$ μm and $v_{\rm eff}=0.07$, are given by the contours which are symmetrical about the intensity equator. The percent polarization observed by Coffeen and Gehrels (1969) is indicated within the circles which represent the nominal size and location of the diaphragm, with the left (right)number being the result for the Northern (Southern) Hemisphere.

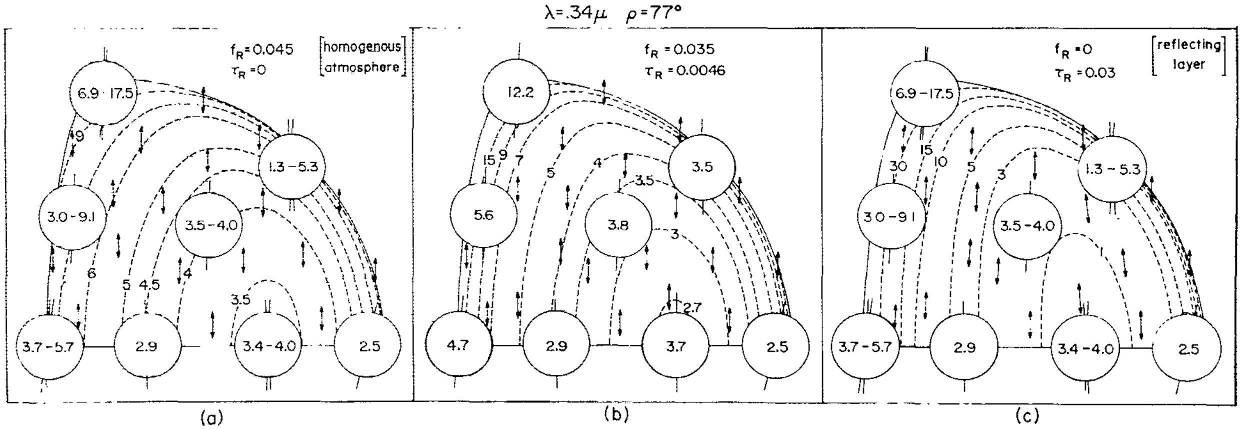

FIG. 3. Distribution of percent linear polarization over the disk of Venus for phase angle 77° and wavelength 0.34 μm. The calculations, indicated by the contour lines, are for spherical particles with $n_r=1.46$, $r_{eff}=1.05$ μm and $v_{eff}=0.07$: the three cases are for different vertical distributions of the Rayleigh scattering, ranging from a homogeneous mixture of gas and cloud particles (a) to pure gas above a dense cloud layer (c). The range of polarization values observed by Coffeen and Gehrels (1969) is indicated in parts (a) and (c), and the mean of the observed values is given in part (b).

much as 2 arcsec in the ultraviolet (Coffeen and Gehrels, 1969). The UV image was displaced perpendicularly upward from the horizon (which is parallel to the straight dashed line in Fig. 2), so that, e.g., the north cusp UV observation actually refers to a point somewhat closer to the center of the disk, and the south cusp observation remains on the limb.

a. $\lambda=0.99$ *μm*

We first compare observations and theory in the infrared where the effect of molecular scattering is negligible. The observations of Coffeen and Gehrels (1969) are shown in Fig. 2. These were taken on 28 May 1967 when the phase angle was $\sim 77°$. Where there are two numbers within a circle, the left number refers to the Northern Hemisphere and the right number to the Southern Hemisphere.

The theoretical results for $\lambda=0.99$ μm are given by the contour lines in Fig. 2. The calculations were made using the cloud particle parameters determined by Hansen and Hovenier (1974), $n_r=1.43$, $r_{eff}=1.05$ μm, and $v_{eff}=0.07$. The spherical albedo of Venus was assumed to be 89.5% which required a single scattering albedo for the cloud particles $\tilde{\omega}_0^c=0.999334$. The particle size distribution was that given by Eq. (8) of Hansen and Hovenier. A homogeneous mixture of cloud particle and Rayleigh scattering was employed ($\tau_R=0$ and $f_R=0.045$ at $\lambda=0.365$ μm), but only the cloud particles contribute significantly to the polarization at $\lambda=0.99$ μm.

In view of the fact that there were no adjustable parameters in the computations, the theoretical results are in very close agreement with the observations, as noted previously by Whitehill (1972). Qualitatively the observed variation in the polarization over the disk is predicted by the theory. The only significant quantitative discrepancy is at the poles. But, because of the strong gradient in the theoretical polarization there and the difficulty in maintaining precise pointing in the observations, this does not provide strong evidence for horizontal inhomogeneities in the atmosphere.

b. $\lambda=0.34$ *μm*

In the ultraviolet a more complex distribution of polarization over the planet can be anticipated. Both gas molecules and cloud particles contribute significantly to the scattering, so the polarization depends on the relative vertical distribution of cloud particles and gas, and on the variation of that distribution over the planet. In addition, we know that the global polarization in the UV is highly variable (cf. Coffeen and Gehrels, 1969; Dollfus and Coffeen, 1970; Coffeen and Hansen, 1974; Bowell, 1975), and that there are strong regional contrasts in UV images.

Fig. 3 shows the observations of Coffeen and Gehrels (1969) for a filter centered at $\lambda=0.34$ μm. The observations were taken on 26–29 May 1967. Parts (a) and (c) of the figure show the ranges in values measured for the four days of observations and two hemispheres; part (b) gives the average value for each region.

The theoretical computations were made using the cloud particle properties determined by Hansen and Hovenier (1974): $n_r=1.46$, $r_{eff}=1.05$ μm and $v_{eff}=0.07$. Once a value was chosen for one of the two parameters describing the vertical distribution of Rayleigh scattering (f_R and τ_R), the other was determined by the requirement that the amount of Rayleigh scattering be appropriate to match the global polarization near phase angle 90°, as illustrated in the following section. Thus the range of models is from $\tau_R=0$ (homogeneous atmosphere) to $f_R=0$ (reflecting layer). The intermediate case in Fig. 3 ($f_R=0.035$) corresponds to a pure gaseous

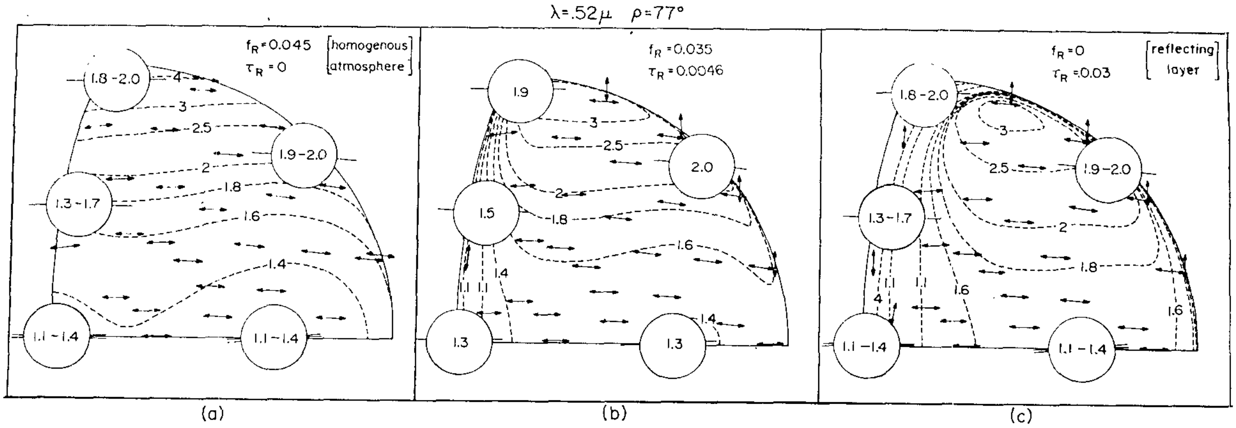

FIG. 4. As in Fig. 3 except for $\lambda=0.53\ \mu$m and cloud particle refractive index 1.44.

atmosphere above ~5.3 mb and a homogeneous atmosphere below that level. Following the convention of Hansen and Hovenier, the values given for f_R and τ_R always refer to $\lambda=0.365\ \mu$m, and following Hansen and Travis (1974), we assume that f_R and τ_R are proportional to $\lambda^{-4}(1+0.013\lambda^{-2})$. The spherical albedo of the planet was assumed to be 53%, requiring the cloud particle single scattering albedo to be, e.g., 0.9776 for the case $\tau_R=0$ and 0.98064 for the case $f_R=0$.

The observed variation of the polarization along the equator does not agree even qualitatively with any of the models. This is probably due to horizontal variations in the atmosphere, which could perhaps be related to the markings in UV images of Venus. Dollfus (1966) has obtained polarization maps in the green and red regions which do not seem to have a strong correlation with simultaneous visual images. However, it would be very useful to quantitatively analyze simultaneous polarization and intensity maps with both observations extended into the ultraviolet.

The two small values of polarization indicated on the equator were single measurements made on the same day. Thus the other equatorial measurements probably deserve a greater weight, suggesting that the limit $\tau_R\rightarrow 0$ is in better agreement with the equatorial measurements than is the limit $f_R\rightarrow 0$. The mid-latitude and polar observations tend to support the same conclusion, as do the only observations of Coffeen and Gehrels (1969) at a different phase angle (91°). Thus the presently available measurements of the UV polarization over the disk suggest that the homogeneous model atmosphere is closer to representing the Venus atmosphere than is the reflecting layer model.

c. $\lambda=0.52\ \mu m$

Fig. 4 shows the observations of Coffeen and Gehrels (1969) for the regional polarization at $\lambda=0.52\ \mu$m and $\rho=77°$, obtained on 27–29 May 1967. Parts (a) and (c) of the figure show the ranges in the measured values and part (b) gives the average values.

The theoretical computations were made using the cloud particle properties determined by Hansen and Hovenier, with $n_r=1.44$ at this wavelength. The three theoretical models correspond to those in Fig. 3 for $\lambda=0.34\ \mu$m; as in that case the values of τ_R and f_R refer to $\lambda=0.365\ \mu$m.

As expected, the theoretical polarization is not as sensitive to whether the Rayleigh scattering is above or within the clouds as it is in the ultraviolet. However, the observations appear to again be in better agreement with the homogeneous atmosphere model than with the reflecting layer model. Note that this is suggested by the direction of polarization as well as its magnitude. The other visual observations of Coffeen and Gehrels (1969), for a phase angle of 91°, do not alter these qualitative conclusions.

4. Disk-integrated polarization

It is also useful to compare the calculations for the two-layer model to polarization observations of the unresolved planetary disk. Such observations are available for a wide range of phase angles, and the measurements are more accurate than the measurements of polarization for local areas because the global observations are not as sensitive to errors in the pointing (e.g., due to atmospheric seeing). Also it can be anticipated that they retain some information on the vertical atmospheric structure. As the phase angle increases, the observations tend to refer to a higher and higher altitude in the atmosphere.

a. $\lambda=0.34\ \mu m$

Figs. 5 and 6 show observations of the global polarization of Venus for an effective wavelength $\lambda\approx 0.34\ \mu$m. The observations were taken during several different apparitions by Coffeen and Gehrels in 1961–69 (Coffeen and Gehrels, 1969; Dollfus and Coffeen, 1970) and by Dollfus in 1966–69 (Dollfus and Coffeen, 1970).

The theoretical curves in Fig. 5 are for different amounts of Rayleigh scattering above a cloud layer of spherical particles with refractive index $n_r=1.46$. The Rayleigh optical thickness required to raise the theoretical results to the value observed at phase angles of $\sim 90°$ is $\tau_R \approx 0.03$. The relation between pressure and Rayleigh optical thickness for a CO_2 atmosphere is (Hansen and Hovenier, 1974; Hansen and Travis, 1974)

$$p[\text{bars}] \approx 1.16\tau_R. \quad (1)$$

Thus $\tau_R=0.03$ corresponds to a pressure of ~ 35 mb at the cloud top.

But note that there is no value of τ_R which produces good agreement with the global polarization, at all phase angles, for the case $f_R=0$. Basically the difficulty is that if enough Rayleigh scattering is added to match the observations at $\rho \approx 90°$, there is too much Rayleigh scattering for $\rho \approx 120°$–$140°$ where the longer slant paths of the incident and reflected light enhance the effect on the polarization of an optically thin layer at the top of the atmosphere.

Fig. 6 explicitly compares the homogeneous atmosphere model ($\tau_R=0$) and the reflecting layer model ($f_R=0$). The intermediate case ($\tau_R=0.0088$) corresponds to a pressure of ~ 10 mb for the cloud-top level.

Although it is somewhat arbitrary to choose a particular value of τ_R at which the results can be said to become inconsistent with the observations, the results for global polarization suggest that cloud particles reach at least as high as the altitude where the pressure is 10 mb. This conclusion is reinforced by the distribution of polarization over the disk for the same class of models, as discussed in the preceding section.

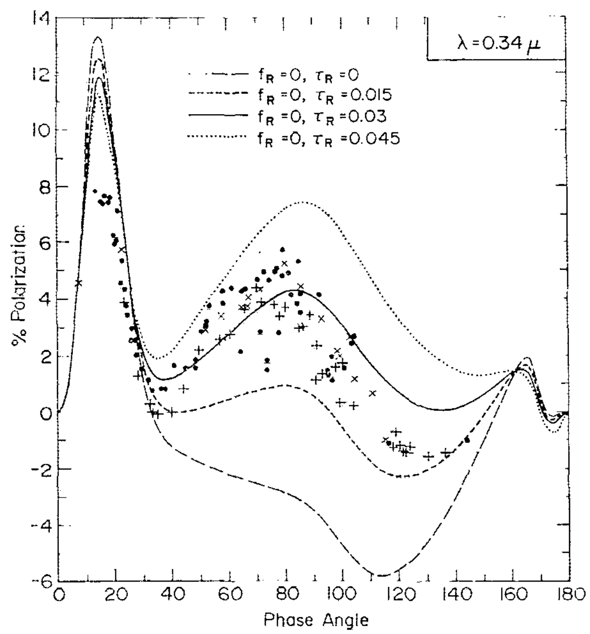

FIG. 5. Observations of the global (whole disk) linear polarization of Venus for filters with effective wavelength 0.34 μm. The ●'s were obtained by Coffeen and Gehrels (1969) in 1961–67, the ×'s by Coffeen in 1968–69 (Dollfus and Coffeen, 1970) and the +'s by Dollfus in 1966–69 (Dollfus and Coffeen, 1970). The calculations are for a cloud of spherical particles with $n_r=1.46$, $r_{eff}=1.05$ μm and $v_{eff}=0.07$; the different curves are for different values of the Rayleigh optical thickness above the clouds.

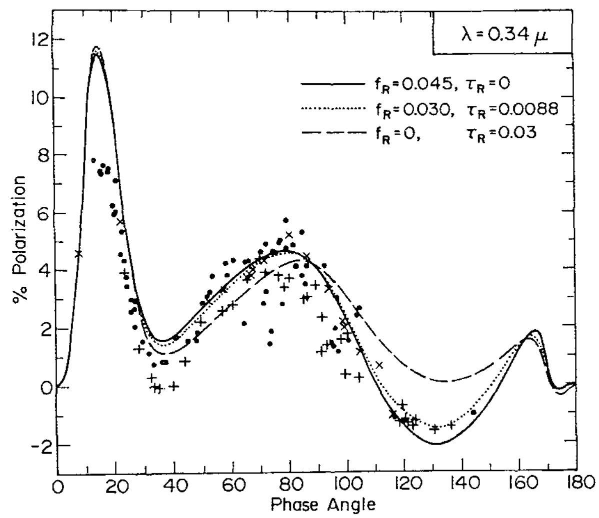

FIG. 6. The observations are the same as in Fig. 5. The calculations are for spherical particles with $n_r=1.46$, $r_{eff}=1.05$ μm and $v_{eff}=0.07$; the three cases are for different vertical distributions of the Rayleigh scattering, ranging from a homogeneous mixture of gas and cloud particles ($\tau_R=0$) to pure gas above a dense cloud layer ($f_R=0$).

b. $\lambda=0.52$ μm

Two-layer models, including the extremes $\tau_R=0$ and $f_R=0$, are compared with observations of the global polarization at $\lambda=0.52$ μm in Fig. 7. Also included in the figure are observations of the central portion of the crescent for large phase angles where the theory gives nearly the same value for the polarization of the whole disk and the central portion (cf. Hansen and Hovenier, 1974). Theory and observations are in good agreement, but it is clear that the effect of Rayleigh scattering is too small to allow model discrimination of the relative vertical distributions of cloud particles and gas. The same is true *a fortiori* at the longer wavelengths.

5. Conclusions

The calculations we have made show that the visible clouds of Venus are a diffuse haze rather than a dense cloud. The relative vertical distribution of gas and cloud particles is more like a homogeneous mixture than like gas above a cloud deck. Previous indications of the diffuse nature of the clouds were obtained by Dollfus and Maurice (1965) from analysis of the extension of the cusps of Venus, by Link (1969) and Goody (1967) from analysis of Venus transits across the sun, and by Young (1974) from analysis of thermal infrared spectra of Venus.

One consequence of our conclusion about the vertical mixing is that the one model-dependent number given

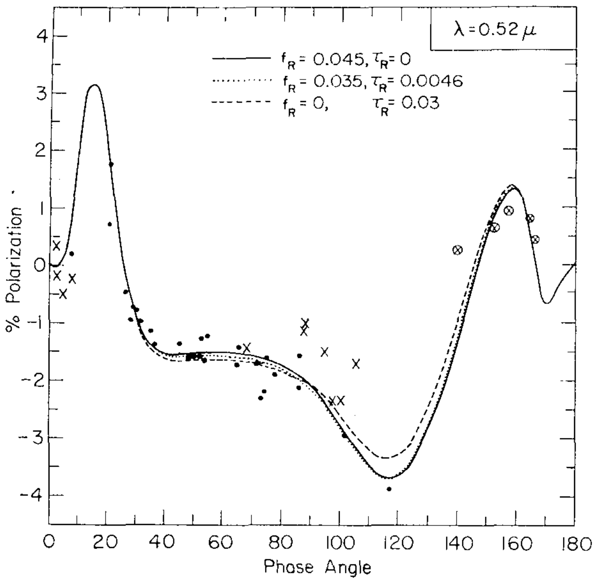

FIG. 7. Observations of linear polarization of Venus for a filter centered at $\lambda \approx 0.52$ μm. The ●'s were obtained by Coffeen and Gehrels (1969) in 1961–67, and the ×'s and ⊗'s by Coffeen in 1968–69 (Dollfus and Coffeen, 1970). The ⊗'s are observations of the central portion of the crescent and the other observations are global. The calculations are for the global polarization for spherical particles with $n_r=1.44$, $r_{eff}=1.05$ μm and $v_{eff}=0.07$; the three cases are for different values of the Rayleigh optical thickness above the clouds.

by Hansen and Hovenier (1974), the pressure at cloud optical depth unity (~50 mb), can be accepted as a reliable value. Another consequence is that the homogeneous atmosphere model can be used to compute a fairly accurate number for the photon mean free path $\langle l\rangle$ at the 50 mb level:

$$\langle l\rangle = \frac{1}{k_{sca,c}} = \frac{f_R}{k_{sca,R}}, \quad (2)$$

where $k_{sca,c}$ is the scattering coefficient (cross section per unit volume) of the cloud particles, and the Rayleigh scattering coefficient[2] is (cf. Hansen and Hovenier, 1974; Hansen and Travis, 1974)

$$k_{sca,R} = \frac{8\pi^3}{3}\frac{N}{\lambda^4}\left[\frac{(n_g{}^2-1)^2}{N^2}\right]_{STP} \quad (3)$$

where N is the number density of gas molecules. Assuming that the refractive index (for CO_2 at STP) is (Allen, 1963)

$$n_g = 1+0.000439(1+0.0064/\lambda^2)\ [\lambda \text{ in } \mu\text{m}] \quad (4)$$

and the temperature is ~240 K at the 50 mb level, we find

$$\langle l\rangle \sim 5 \text{ km} \quad (5)$$

[2] We neglect molecular anisotropy in computing $k_{sca,R}$ because f_R was derived for isotropic Rayleigh scattering. Accounting for anisotropy would increase f_R and $k_{sca,R}$ by similar amounts (~15%) and leave $\langle l\rangle$ and $k_{sca,c}$ essentially unchanged.

for the visible part of the spectrum. The same result could be obtained by computing the gas scale height, since for an exponential distribution of scatterers $\langle l\rangle$ at $\tau=1$ is equal to the scale height.

The mean free path $\langle l\rangle$ for terrestrial clouds is usually on the order of 0.1 km or smaller. The value $\langle l\rangle \approx 5$ km corresponds to a horizontal visibility of ~20 km. Thus the visible clouds of Venus are indeed a very diffuse haze.

The number density of cloud particles at the 50 mb level is approximately

$$n_p \approx \frac{k_{sca,c}}{2\pi r_{eff}{}^2} \approx 30 \text{ particles cm}^{-3}. \quad (6)$$

The mass of the cloud particles per unit volume of atmosphere at the 50 mb level is

$$M_p \approx 0.00015\rho_p\ [\text{g m}^{-3}], \quad (7)$$

where ρ_p is the density of the cloud particle material [g cm^{-3}].

The polarization data do contain a weak indication of deviations from a homogeneous mixture of cloud particles and gas. Both the local and global polarization observations differ to some extent from the theoretical results for a homogeneous atmosphere, and there are slightly better fits to the data with a small amount of Rayleigh scattering above the clouds; a similar improvement could no doubt be obtained with the particles and gas both distributed approximately exponentially, but with the cloud particles having the smaller scale height. But these effects are comparable to the uncertainties in the presently available observations. Furthermore the data do not allow a determination of the effects of horizontal inhomogeneities in the atmosphere. We conclude that the available polarization observations do not by themselves provide a basis for a *quantitative* deduction of deviations from a homogeneous atmosphere.

However, it is useful to compare the particle number density derived from the polarization ($n_p \approx 30$ cm^{-3} at 50 mb) with values derived from other types of observations which refer, more or less, to different levels in the atmosphere.[3]

Transit observations (cf. Goody, 1967) yield $n_p \approx 0.33$ cm^{-3} ($\langle l\rangle \approx 440$ km) at $p=7$ mb, if we approximate that region as homogeneous, the composition as CO_2, and the temperature as 230 K. For a homogeneous atmosphere model near-infrared absorption line profiles (Belton *et al.*, 1968) yield $n_p \approx 120$ cm^{-3} ($\langle l\rangle \approx 1.2$ km), where we have assumed that the atmosphere is CO_2 and that the effective pressure level is 100 mb; anisotropic scattering is accounted for with similarity relations (Hansen, 1969) assuming that the asymmetry parameter is $\langle\cos\alpha\rangle \approx 0.7$. The cloud particle extinction coeffi-

[3] A more complete examination of Venus cloud structure is made by Lacis (1975).

cient derived by Samuelson *et al.* (1975) from thermal infrared observations ($k_{ext} \approx 10^{-5}$ cm^{-1} at $\lambda = 10\,\mu$m) yields $n_p \approx 500$ ($\langle l \rangle \approx 0.3$ km) at $p \approx 300$ mb, if we assume that the cloud composition is a 75% sulfuric acid solution in water (cf. Lacis, 1975). Each of these numbers for n_p was obtained under the assumption that the particle radius is $\sim 1.05\,\mu$m at the level being considered; the value for $\langle l \rangle = 1/k_{sca,c}$, which refers to optical wavelengths, is a more direct result and only in the case of the thermal IR data does it require an assumption about the particle size.

If the atmosphere were homogeneous n_p would be proportional to p. The above numbers yield values for n_p/p (in cm^{-3} mb^{-1}) of ~ 0.05 at 7 mb, 0.6 at 50 mb, 1.2 at 100 mb, and 1.7 at 300 mb. This indicates that the average scale height of the particles is less than that of the gas. For CO_2 with $T = 240$ K and $g = 870$ cm s^{-2}, the gas scale height is ~ 5.2 km. The above number densities imply an average particle scale height of about half that value, i.e., 2–3 km, over the pressure range 7–300 mb; cf. Lacis (1975) for a more complete discussion. Since each of the number densities represents an average over a considerable altitude range, we cannot be certain whether there is a continuous increase in turbidity with depth (over the range 7–300 mb) or whether there is layering within that region.

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