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WAVELENGTH DEPENDENCE OF POLARIZATION. XXXV. VERTICAL STRUCTURE OF SCATTERING LAYERS ABOVE THE VISIBLE VENUS CLOUDS

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ABSTRACT

New high-resolution and whole-disk observations of the polarization of Venus are analyzed with one- and two-layer models. The high-resolution polarization data studied are limited to observations of a single phase angle and wavelength. Although this precludes a unique interpretation, it is possible to make plausible interpretations of the observed spatial variation in the polarization. The variation of polarization with latitude suggests a decreasing cloud top height with increasing latitude, the decrease amounting to the order of 15 mbar of pressure (1.4 km) between low latitudes and mid- to high latitudes ($\sim 60°$). The variation of polarization with longitude is less systematic and probably is caused by variations in the aerosol characteristics with height in the atmosphere. A thin haze of small (< 1 μm radius) particles above a base cloud of 1.05-μm-radius H_2SO_4 particles can explain the longitude variation of the polarization, but again the limitation of the observations used to a single wavelength and phase angle prevents a unique interpretation. A change in the global cloud top heights between June and November 1975 is indicated by the whole-disk polarization observations. Results are also presented for two-layer models that can explain the observed 3.4-μm-wavelength phase curve (reflectivity) while retaining compatibility with visual polarization measurements. Such models require very large absorption in either the base cloud or the upper haze layer and are probably unacceptable.

I. INTRODUCTION

An analysis by Kawabata and Hansen (1975) of ground-based, regional polarization measurements of Venus indicated that the clouds of that planet are a diffuse haze more like a uniform mixture of cloud particles and gas than like a cloud deck with a sharp top. However, the low resolution of the observations did not allow a quantitative analysis of vertical layering of the haze or any deductions concerning possible horizontal inhomogeneities.

Gehrels *et al.* (1979) have recently employed their Digicon instrumentation to obtain polarimetric observations of Venus with an improved spatial resolution. Although these observations are limited to phase angles of 67° and 71° and two wavelengths, they provide continuous and complete coverage of the illuminated portion of the Venus disk from which inferences on the vertical structure of the upper atmosphere can be made. We have particularly considered (1) whether there is evidence for a high, thin haze layer, in the whole-disk and high-resolution observations, (2) the possibility of differences in vertical structure as a function of latitude, and (3) the correlation of polarization with the ultraviolet contrast features. Conclusions based on these analyses have been applied to model calculations for the wavelength region near 3.4 μm in an attempt to explain the reflectivities of Venus observed by Martonchik and Beer (1975).

II. MODEL ATMOSPHERE

Any radiative transfer modeling of the Venus upper atmosphere must rely heavily on the analysis by Hansen and Hovenier (1974) of the observed whole-disk polarization. They were able to demonstrate that the polarization is due to scattering from spherical particles of refractive index $n_r = 1.44$ (at $\lambda = 0.55$ μm) with a size distribution parameterized by an effective radius $r_{\rm eff} = 1.05$ μm and effective variance $v_{\rm eff} = 0.07$. Furthermore, the cloud particles must be very nearly identical over the entire visible disk because of the small value of the effective variance of the derived size distribution. We have thus assumed for all the model calculations presented here that the main cloud layer over the entire visible disk is made up of these particles; i.e., the models have been required to give a disk-integrated polarization as a function of phase angle that agrees with earlier whole-disk observations. But the new measurements of regional polarization on Venus have made it desirable to consider models somewhat more complex than those previously employed, including the homogeneous model of Hansen and Hovenier (1974) and the two-layer model of Kawabata and Hansen (1975). We employ a two-layer model which, unlike the latter work, includes an upper layer that may contain cloud particles as well as gas. The cloud particles in this layer may have properties different from those of the main cloud deck particles.

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The model is described by two parameters for the semi-infinite lower H_2SO_4 cloud layer, the Rayleigh fraction f_R, which is the ratio of the Rayleigh scattering coefficient to the cloud particle scattering coefficient, and the cloud single scattering albedo $\tilde{\omega}_0$. [An optical thickness of 128 is used to approximate the semi-infinite homogeneous layer. There is some uncertainty as to the optical thickness of the Venus clouds. Moroz *et al.* (1976) obtain a cloud optical thickness of ~25 based on narrow-band photometric measurements from Veneras 9 and 10, and Sato, Kawabata, and Hansen (1977) find a slightly larger thickness to be consistent with CO_2 line profile analysis. However, Travis (1975) and Lacis (1975) find that a much thicker cloud is necessary. At any rate, the degree of polarization at the top of the atmosphere should be insensitive to the total optical thickness, but is rather a function of the total intensity, and the scattering properties (phase matrix) above optical depth 1 or 2.] The upper layer is described by its optical thickness τ^u, Rayleigh fraction f_R, and cloud particle parameters n_r^u, $\tilde{\omega}_0^u$, and radius r^u.

We compute the reflectivity and degree of linear polarization for a spherical but locally plane parallel atmosphere using the adding method described by Hansen and Travis (1974). This method gives the Fourier coefficients of the Stokes parameters at discrete values of the solar zenith angle and zenith angle of the reflected radiation. The Fourier coefficients are then interpolated to the desired values of these angles to give the Stokes parameters for a given phase angle and location on the disk. For comparison to the Digicon observations, results were computed at a single point at the center of each observed region except near the limb and terminator where an average was taken over a sufficient number of points within the observed region to account for the rapidly varying intensity and polarization there. For comparison with the whole-disk observations, the results were integrated over the planetary disk.

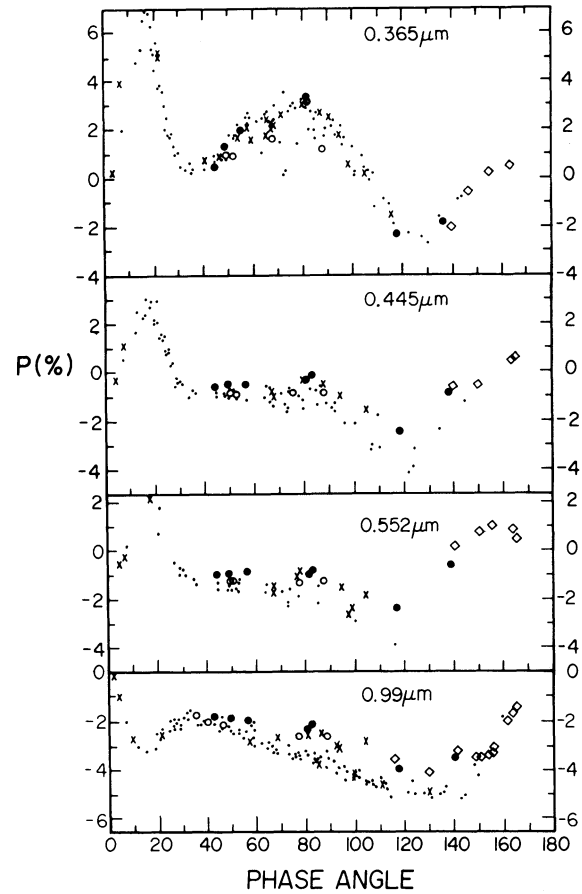

FIG. 1 Whole-disk polarization measurements of Venus at wavelengths of 0.365, 0.445, 0.522, and 0.99 μm. Open circles denote observations made between March and June 1975 and filled circles those made between September 1975 and February 1976 by Gehrels *et al.* (1979). Dots refer to observations reported by Coffeen and Gehrels (1969), and the observations of Coffeen (Dollfus and Coffeen 1970) are denoted by crosses for the complete disk and by diamonds for the equatorial region only.

III. DISK-INTEGRATED POLARIZATION

The whole-disk polarization measurements by Gehrels *et al.* (1979) are shown in Fig. 1 together with previously published observations by Coffeen and Gehrels (1969) and Dollfus and Coffeen (1970) at wavelengths of 0.365, 0.439, 0.522, and 0.99 μm. At the shortest wavelength, the polarization at phase angles near 80° shows a significant change between observations made in June 1975, when the polarization was ~1.3%, and those made in November 1975, when the value had increased to over 3%. Since the polarization at these midphase angles is strongly dependent on the amount of gas contributing to the scattering, changes in the average cloud top height on a global scale are the most likely explanation. Such an interpretation is supported by the decrease of this polarization difference at 0.439- and 0.522-μm wavelengths. Using a homogeneous, semi-infinite model atmosphere and a constant value of $\omega_0 = 0.98237$ to give a spherical albedo of 56%, the 0.365-μm observations are best fit with Rayleigh fractions of 0.037 and 0.046, respectively, for the June and November points. This implies a lowering of the average cloud top height, or more precisely for the one-layer model, the height of optical depth unity, at some time between June and November 1975. The difference in height of optical depth unity may be derived from the relation between pressure and Rayleigh optical thickness for a CO_2 atmosphere (Hansen and Hovenier 1974, Hansen and Travis 1974),

$$p \text{ (in bars)} \approx 1.16\tau_R,$$

where p is the pressure measured in bars and τ_R is the Rayleigh optical thickness at 0.365 μm. The June and November Rayleigh fractions then correspond to 43- and 53-mbar pressure at cloud optical depth unity. Cochran, Trafton, and Macy (1977) have observed a similar change in cloud top height by measuring changes in CO_2

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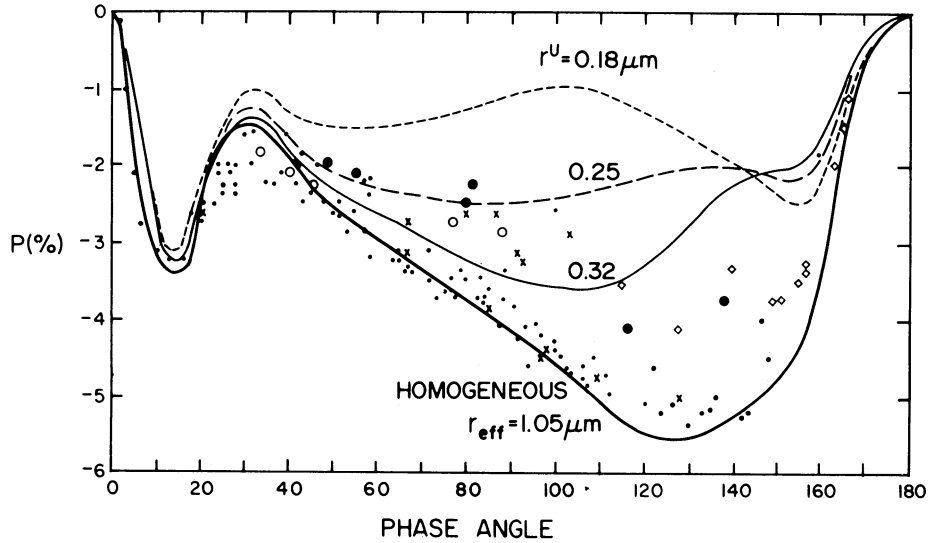

FIG. 2 Computed whole-disk polarization at $\lambda = 0.99$ μm for homogeneous and two-layer models. The heavy solid line is the computed polarization for a homogeneous cloud layer with particles of radius $r_{eff} = 1.05$ μm and $n_r = 1.43$. The other curves are for two-layer models that include an upper layer of thickness $\tau^u = 0.031$ and particle radii of 0.18, 0.25, and 0.32 μm, as noted. Whole-disk observations are also shown, with symbols as in Fig. 1.

line profiles. Their model II covers observations made in the period December 1974–October 1975 following an abrupt change in November, 1974. This period includes the two measurements by Gehrels *et al.* of ~1.3% polarization near 80° phase angle. Model II of Cochran, Trafton, and Macy gives $\tau = 1$ ($\lambda = 0.7834$ μm) at a pressure level of 36 mbar compared, with $\tau = 1$ at 42 mbar for their model I, which was fit to observations made between May 1973 and October 1974, prior to the polarization measurements analyzed here.

At longer wavelengths, the new measurements of polarization tend to be less negative than most of the previous observations. At 0.99 μm, the polarization is approximately −2.5% at phase angles near 80°. This is very close to values reported by Coffeen (Dollfus and Coffeen 1970), which happen to be the most recent published observations made before those of Gehrels *et al.* in 1975–1976. Since molecular scattering is unimportant at this wavelength, cloud particles with properties different than the 1.05-μm-radius H_2SO_4 particles must be responsible for the less negative polarization. Any analysis of the properties of these particles is hindered by the limited phase angle range of the observations, but a simple two-layer model may be used to find possible properties that will produce agreement with the available observations without seriously contradicting other observations. The model consists of a base cloud deck of 1.05-μm H_2SO_4 particles with single scattering albedo to produce the observed spherical albedo and a thin upper layer of conservatively scattering particles. As a starting point, we take the refractive index for the upper-layer particles to be that of 75% H_2SO_4 and consider various combinations of upper-layer thickness and particle size. A number of resulting polarization versus phase angle curves at 0.99 μm are shown in Figs. 2 and 3. Figure 2 displays results for models with top

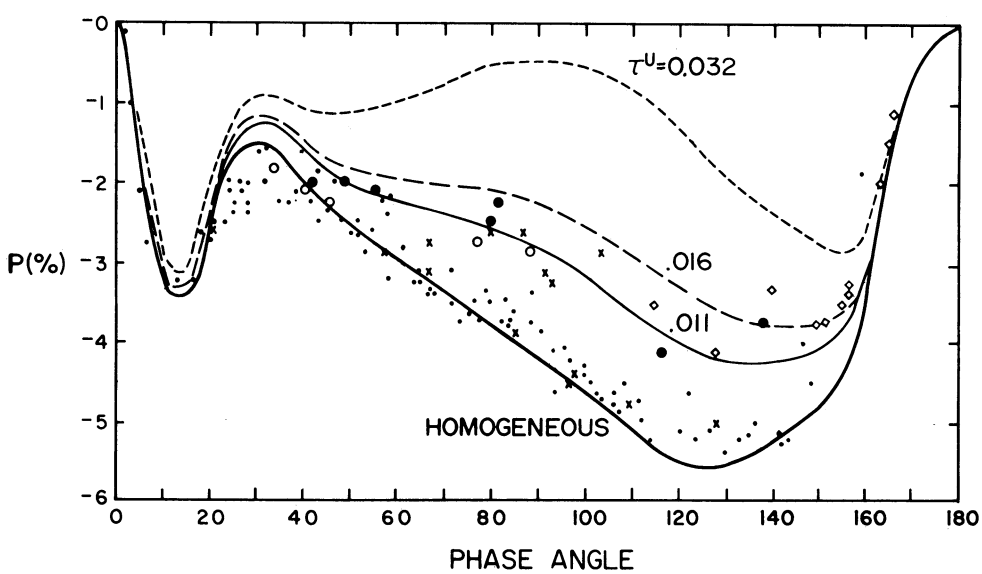

FIG. 3 Same as Fig. 2 but upper curves now display results of two-layer models, including upper-layer particles with $r_u = 0.1$ μm and optical thickness as noted.

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haze layers having optical thickness $\tau^u = 0.031$ for various particle sizes. Figure 3 shows models including a haze layer made up of 0.1-μm-radius particles with three different optical thicknesses. The best fit obtained was for a haze layer of optical thickness $\tau^u = 0.011$ made up of particles with $r^u = 0.18$ μm. The assumption of the H_2SO_4 refractive index for the upper-layer particles has little significance, since to fit the limited phase angle range of the observations, small changes in the refractive index could be offset by adjustments in particle size and/or layer thickness and still retain compatibility with observations at other wavelengths. A refractive index radically different from that of H_2SO_4, on the other hand, could result in small phase angle polarization that would markedly disagree with other observations. The observations at shorter wavelengths offer little help in confirming the possibility of an upper haze layer. At 0.514 μm, the upper layer of small particles would raise the predicted polarization to that observed at a phase angle of 118°, but the observed polarization is still higher (less negative) than that computed for phase angles in the range 40°–80°. Base cloud particles of radius 1.20 μm would account for this observed polarization without significantly altering the computed polarizations presented for the two-layer models. However, an increased base cloud particle size is probably not justified considering the 1% or so scatter in previously published observations and the lack of new measurements in the rainbow (phase angle ~20°) or anomalous diffraction (phase angle ~155°) features, which are particularly sensitive to particle size near a wavelength of 0.55 μm.

IV. HIGH-RESOLUTION OBSERVATIONS

Regional polarization measurements of Venus have the potential of providing much more information concerning cloud particle characteristics and vertical distribution. Analysis of regional cloud particle properties would require observations at several wavelengths over a wide range of phase angles. However, the Digicon observations, even at effectively a single phase angle, provide polarization data at a range of observed zenith angles for regions over the disk. Some vertical structure information may be inferred from this type of data, but no unique interpretation is possible.

Gas molecules and cloud particles both contribute significantly to the scattering at $\lambda = 0.365$ μm, so the polarization depends on the relative vertical distribution of gas and cloud particles as well as the nature of the cloud particles themselves. In addition, strong regional contrasts have been observed in the UV brightness and polarization (Coffeen and Gehrels 1969, Dollfus and Coffeen 1970, Coffeen and Hansen 1974). After comparing the observed regional polarization of Gehrels *et al.* (1979) with a one-layer, homogeneous atmosphere model, the (a) latitude and (b) longitude dependence of the polarization will be discussed followed by (c) a presentation of the regional UV contrast features.

The observations are first compared with homogeneous model calculations with constant parameters at every point on the visible disk. Kawabata and Hansen (1975) found good agreement for such a model with lower-resolution measurements made by Coffeen and Gehrels (1969). The cloud particle properties are those determined by Hansen and Hovenier (1974), $n_r = 1.46$, $r_{\rm eff} = 1.05$ μm, and $v_{\rm eff} = 0.07$. The free parameters are the cloud particle single scattering albedo $\tilde{\omega}_0$, and the Rayleigh fraction f_R, both assumed constant with depth in the homogeneous-type model. At the 67° phase angle the Rayleigh fraction is specified as that value required to yield the observed disk-integrated polarization, whereas the spherical albedo is determined primarily by $\tilde{\omega}_0$. To obtain a spherical albedo of 56% [cf. the analysis of Travis (1975) based on observations by Irvine (1968)] and the observed disk-integrated polarization requires a single scattering albedo $\tilde{\omega}_0 = 0.9928$ and Rayleigh fractions $f_R = 0.042$ and $f_R = 0.044$ for the 7 May and 14 May observations, respectively.

Contour maps are presented in Fig. 4 for the polarization difference (in percent polarization) between the homogeneous model calculation and the observations, $P_{\rm obs} - P_{\rm model}$, for the 7 May and 14 May Digicon maps at 0.365 μm. Any small variations of the direction of vibration of the electric vector from the perpendicular to the scattering plane have been ignored. Thus, positive contours denote regions where the observed polarization is greater than predicted by the homogeneous model. Aside from the small-scale variations in the contours resulting from UV contrasts and noise, the most noticeable features in both maps are increased observed polarization at the north and south polar regions and decreased observed polarization at the limb and terminator. These variations are remarkably similar for the two maps taken seven days apart, which reduces the likelihood that local cloud inhomogeneities are responsible for the polarization differences.

a) Latitude Dependence of Polarization

In order to explain the large observed polarization at the poles relative to the homogeneous model, variations in the cloud particle parameters or the vertical structure of the cloud may be invoked. Due to the large contribution of Rayleigh scattering at this wavelength and phase angle, substantial changes in the cloud particle parameters would be necessary to account for the increased polarization at the poles. Thus, without considering a wide phase angle range for the regional observations, only a variation in the amount of Rayleigh scattering is considered responsible. A horizontally inhomogeneous model was constructed, employing separate one-layer atmospheres for the "equatorial" zone (latitudes between 45° N and 45° S), and the "polar" zone (latitudes greater than 45°). For each zone, f_R was varied until the average polarization in the zone agreed with that observed. Best agreement was obtained with Rayleigh

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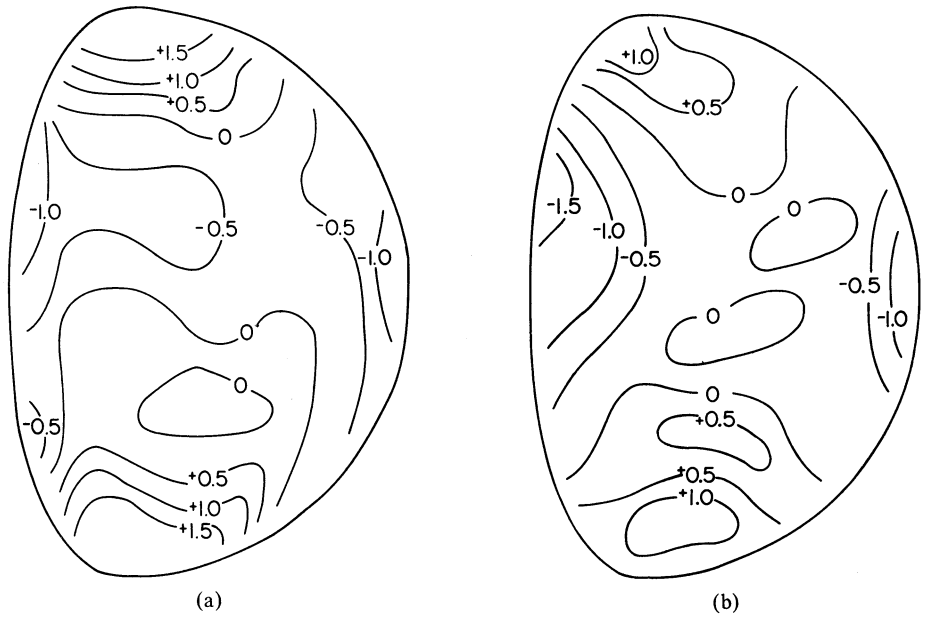

FIG. 4 Polarization difference contour maps for Digicon observations by Gehrels *et al.* (1979) of (a) 7 May and (b) 14 May 1975 at $\lambda = 0.365\ \mu$m. Contours are of $P_{obs} - P_{model}$ where P_{obs} is the observed regional polarization in percent and P_{model} is the degree of polarization computed for a homogeneous H_2SO_4 cloud layer (see text). North is up.

fractions of 0.039 (0.042) and 0.052 (0.053) for the equatorial and polar zones, respectively, on 7 May (14 May). This result implies a lowering of the average cloud top height for the polar zone. Applying the pressure–Rayleigh thickness relation as in the previous section, the pressure at cloud optical depth unity is 45 and 60 mbar for the equatorial and polar zones, respectively, of the 7 May observation. Using a gas scale height of 5 km, this corresponds to a physical height difference of 1.4 km. This height difference is quite model dependent, however. The homogeneous model used in the calculation allows only a thinning of the cloud, or reduction in the cloud particle number density, giving unity optical thickness at an increased gas pressure. If the increased polar zone polarization is due solely to a change in the amount of pure gas above a cloud deck, the derived height difference would be significantly less. This model is of course an idealization, oversimplifying what is more likely a smoother variation with latitude. Also, because of the limited resolution, the polar zone fit probably has little significance for latitudes greater than about 70°.

Young, Woszczyk, and Young (1974) have reported an increase in the CO_2 absorption at high latitudes. Such a result is consistent with the interpretation of the large polar zone polarization resulting from increased molecular scattering, but cannot aid in further defining the vertical structure.

b) Limb and Terminator Polarization

Although the horizontally inhomogeneous model discussed above shows better agreement with the equatorial zone polarization, the observed equatorial limb and terminator values are still significantly less than those calculated. Again, the decreased limb polarization seems to agree with a decrease in the CO_2 absorption at the limb found by Young, Woszczyk, and Young (1974) for a similar phase angle. As they speculate, a cloud height variation could account for these observations, with a higher or denser cloud top near the subsolar region. However, there are a couple of problems with this interpretation. First, the terminator polarization is also reduced, leading by this argument to increased cloud top heights at the terminator as well. [Young, Woszczyk, and Young (1974) have no CO_2 observations as close to the terminator as the polarimetry.] By an analysis similar to that of the previous section, the cloud tops would have to be ~1.5 km higher at the limb and ~0.8 km higher at the terminator relative to the central region of the disk. Thus, if convective processes are responsible, they would be required at both the subsolar point and the evening terminator. Second, the CO_2 absorption measurements as function of longitude may be biased by the apparent decrease in cloud height at high latitudes, with more high-latitude contribution to the slit positions at the central portion of the disk.

The small limb and terminator polarizations may alternately be explained by a single equatorial zone model with suitable cloud particle parameters that produce polarization compatible with previous measurements. A simple two-layer model like the one used in the analysis of the whole-disk polarization is employed. The base semi-infinite layer consists of 1.05-μm-radius particles with $n_r = 1.46$, and the thin upper layer may contain cloud particles and gas. This upper layer, if suitably thin, would have negligible effect in the central portion of the disk but could alter the polarization at the limb and terminator where the path lengths of scattered and incident photons, respectively, are the greatest. Since the model polarization needs to be decreased at the limb, a

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first guess for the haze layer might be one with identical 1.05-μm H_2SO_4 particles but a decreased Rayleigh fraction. However, just as the cloud top height variation model requires cloud heights different for the limb and terminator regions, so does this model require different haze thicknesses to reduce the polarization to observed levels at limb and terminator. The characteristics of the cloud particles themselves must therefore be altered in the upper layer to achieve a single two-layer model to account for the observed polarization. The single scattering polarization as a function of particle size at this phase angle and wavelength (Hansen and Hovenier 1974, Figs. 2 and 3) indicates a limited range of particle sizes so as to produce the desired result for the two-layer model. The single scattering polarization is very large for large particles but decreases through zero to negative values (electric vector vibrating parallel to scattering plane), reaching a minimum for sizes less than 1 μm and then increasing again to positive polarization as the particles become like Rayleigh scatterers at very small sizes. For particles with $n_r = 1.40$, singly scattered light is negatively polarized for the size range 0.3 μm $\lesssim r \lesssim$ 0.9 μm with a minimum at $r \approx 0.55$ μm. Thus, for example, with an upper layer made up of particles with $n_r^u = 1.40$, $r^u = 0.55$ μm, and $\tilde{\omega}_0 = 1$, good agreement with the observed polarization is obtained for an upper layer thickness $\tau^u = 0.06$ and Rayleigh fraction $f_R^u = 0.040$.

The range of upper-layer particle sizes that will produce the desired reduction of limb and terminator polarization does not vary much with refractive index; however, there are limits to the range of possible refractive index. Particles with n_r^u values of 1.3 or less would not produce sufficient reduction in the limb polarization without a prohibitively large upper-layer optical thickness. For n_r^u values greater than 1.5 a much thinner layer would suffice, but the rapid rise of the polarization in the anomalous diffraction feature (phase angle ~160°) would produce disagreement with whole-disk measurements. Thus, given the constraints of the single phase angle and wavelength of the Digicon observations used, no better accuracy can be ascribed to these haze particles than 0.3 μm $< r^u <$ 0.9 μm, 1.3 $< n_r^u <$ 1.5, and $\tau^u < 0.1$.

c) *Polarization–UV Contrast Correlation*

The variation of polarization with intensity across the disk at 0.365 μm may be useful in an interpretation of the cause of the contrast features observed in the ultraviolet. In order to quantize this variation we have compared observed regions which present the same geometry, i.e., which have the same incident and emergent angles with respect to the local normal. Such regions occur in pairs, one in each hemisphere, equidistant from the intensity equator. The difference in intensity for all such pairs of regions varies between 0% and 24% for the 7 May 1975 map and between 0% and 29% for the 14 May 1975 map. This is consistent with the contrast measurements made by Coffeen (1971), although he observed a large, central dark region that does not occur in the Digicon maps.

In order to compare polarization changes with intensity features, we define a parameter δ such that

$$\delta = \Delta P / \Delta I,$$

where

$$\Delta P = \frac{2(P_N - P_S)}{P_N + P_S}, \quad \Delta I = \frac{2(I_N - I_S)}{I_N + I_S},$$

where P and I stand for percent polarization and intensity, respectively, and subscripts N and S refer to the respective region of the pair in the northern and southern hemisphere. Values of δ are shown against the northern hemisphere in Fig. 5. The δ values for pairs in which ΔI is less than 0.025 have been omitted due to the large δ value that results if ΔP is as large as the random error in a polarization measurement. In the 7 May map, most of the δ values are negative, indicating a decrease in degree of polarization with increased intensity. The 14 May map, on the other hand, shows about an equal number of positive and negative δ values, although there are twice as many negative as positive values between latitudes 35° S and 35° N.

Correlation between intensity and polarization at 0.365 μm was also sought in the Minipol observations of Gehrels *et al.* (1979). Table I lists δ values for all pairs of observed zones symmetric about the intensity equator. As the phase angle changes, these zones do not corre-

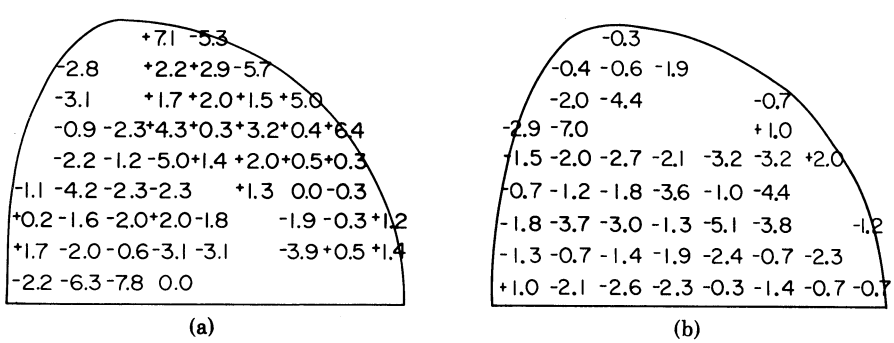

FIG. 5 Values of $\delta = \Delta P / \Delta I$ (see text) for pairs of Digicon regions with the same geometry, one region in the northern hemisphere and the other in the southern hemisphere, displayed against the northern hemisphere for the (a) 14 May and (b) 7 May 1975 Digicon maps.

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TABLE I. Minipol δ values for zones having the same scattering geometry.

Date (1975)	Phase angle (deg)	Zones 1–3	5–4	6–7
2 May	65.0	−0.2	−0.3	−0.8
3 May	65.5	−0.5	−3.5	+0.3
4 May	66.0	−0.6		
7 May	67.5	−1.3		
11 May	69.4	+2.7	+1.6	−4.7
12 May	69.9	+2.2	+6.8	
13 May	70.4	−4.2	−2.1	−0.9
27 May	77.7	+1.5	−3.9	−0.2
14 June	88.2	−2.8	−3.1	−1.4
23 June	94.1	+32.0	+3.0	+2.6
2 October	117.9	−2.4	−1.0	−0.1

spond to the same location on the disk. Again, δ values are omitted when ΔI is less than 0.025. Here, as in the equatorial region of the 14 May Digicon map, negative δ values outnumber the positive by approximately 2 to 1.

These data suggest that there is a negative correlation of intensity and polarization, with brighter UV regions having decreased polarization. Such a correlation supports Coffeen's measurement (Coffeen and Hansen 1974) using a scanning photometer/polarimeter. One of the simplest model types that would exhibit such a correlation involves an absorbing layer below the cloud particles producing the polarization. When the absorbing material is present, the intensity is decreased and the degree of polarization increases. A notable proposal of a model of this type has been made by Young (Young 1977, Crisp and Young 1978). However, there is no apparent large-scale variation of the δ values with changing geometry, and consequently these new data cannot further support or refute any of the various physical model types (see Travis 1975) that produce such a correlation of polarization and intensity.

V. 3.4-μM VENUS PHASE CURVE

Observations of the Venus phase (reflectivity) curve at $\lambda = 3.4$ μm have been reported by Martonchik and Beer (1975). In Fig. 6 we reproduce Fig. 1 of their paper, showing the 3.4-μm flux measurements along with calculated phase curves for homogeneous model atmospheres with cloud particles of 75% H_2SO_4, size distribution given by Hansen and Hovenier (1974), and effective radii as noted. All data and computed fluxes are normalized to a Venus–Earth distance of 1 AU. The computed fluxes presented are for scattered sunlight only, ignoring the thermal contribution, which is probably less than 10% for the phase angles of the observations. The solar flux was taken to be 1.92×10^{-6} W cm^{-2} cm^{-1} (Thekaekara 1972). Obviously there is no homogeneous model that will fit both the infrared phase curve and visual polarization data, thus requiring some vertical inhomogeneity in the model. Martonchik and Beer used a two-layer model and found agreement with the observed fluxes with a top layer of 0.4-μm-radius H_2SO_4 particles with an optical thickness of 0.2–0.3. As they point out, however, such a model would produce visual polarization incompatible with whole-disk observations.

In light of the Mariner 10 observations of high-haze layers (O'Leary 1975) and the evidence for a high haze in the measurements analyzed in the preceding sections, we have attempted to explain the infrared phase curve with a two-layer model including a base cloud consistent with visual observations plus a thin haze layer that would have little or no effect at visual wavelengths. The most straightforward approach is to increase the infrared absorption, but not the visual absorption, of the base cloud and to add a thin, conservatively scattering haze of small particles. Increasing the absorption in the base cloud essentially preserves the shape of the phase curve while reducing the reflectivity, allowing a reduction of the flux at large phase angles (~140°) to the observed level. The thin layer of small particles is added to the top of the base cloud to obtain the increased backscattering required by the large fluxes at small phase angles. We have assumed a particle refractive index $n_r = 1.34$ for both layers. This is the value used by Martonchik and Beer (1975) for 75% H_2SO_4 at $\lambda = 3.4$ μm and is close to the value of 1.354 reported by Palmer and Williams (1975). Agreement of calculated reflectivities with the observed fluxes may be obtained with such a model, but only with a large amount of absorption in the base layer. Computed results are shown in Fig. 7 for haze layers with particle radii of 0.4 μm and optical thickness $\tau^u \approx 0.025$

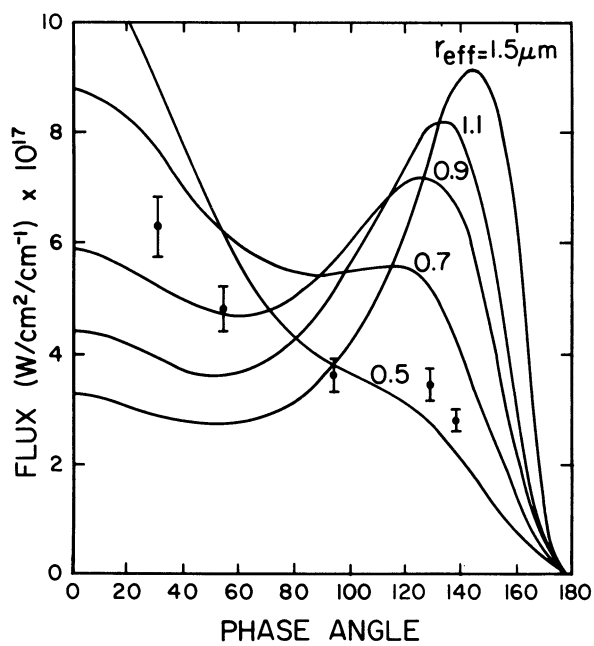

FIG. 6 Venus reflectivity measurements of Martonchik and Beer (1975) at $\lambda = 3.4$ μm and $n_r = 1.35$ normalized to a Venus–Earth distance of 1 AU. Also shown are reflectivity phase curves computed for homogeneous model atmospheres with 75% H_2SO_4 cloud particles and radii as noted.

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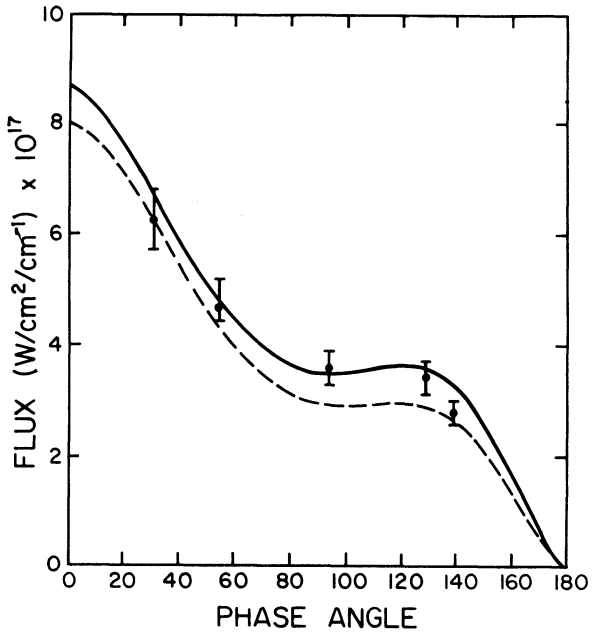

FIG. 7 Computed reflectivity phase curve for Venus at $\lambda = 3.4\ \mu m$ and $n_r = 1.35$ consisting of an absorbing cloud with 1.05-μm-radius H_2SO_4 particles with $\tilde{\omega}_0 = 0.05$ plus a thin haze layer with thickness and particle size as noted. Dashed line: $\tau^u = 0.025$, $r_{eff} = 0.34\ \mu m$. Solid line: $\tau^u = 0.031$, $r_{eff} = 0.40\ \mu m$.

above a base layer having a single scattering albedo $\omega_0 = 0.05$. Such a haze layer would not appreciably affect the visual polarization, but the amount of absorption required to give this low ω_0 value is very large. One possible source of absorption would be impurities in the cloud particles themselves. However, for a given particle size and refractive index, there is a minimum value of the single scattering albedo as the absorption is increased (cf. Fig. 10, Hansen and Travis 1974). For 0.05-μm-radius particles, the minimum obtainable ω_0 value is 0.33. Thus, any absorption producing a lower ω_0 value must come from other particles or the gas. But this is far too much absorption to be explained by a gas alone, and if other particles were causing the absorption their presence would certainly significantly influence the visual polarization. Thus, absorption in the base cloud layer is unacceptable.

A model may be constructed, however, employing the standard H_2SO_4 base cloud layer with no additional absorption that will produce agreement with the observed phase curve. The solid curves in Fig. 8 are results for a homogeneous H_2SO_4 cloud layer with the minimum value $\omega_0 = 0.33$ [compared with ω_0 values of 0.38 and 0.43 for 75% H_2SO_4 absorption values by Martonchik and Beer (1975) and Palmer and Williams (1975), respectively], and this layer plus a thin upper layer of conservatively scattering, 0.1-μm-radius particles with $\tau^u = 0.031$. The shape of the phase curve is quite close to that observed for the two-layer model, but the fluxes are too large by about a factor of 2. Better agreement may be obtained if the upper layer consists of strongly absorbing particles in order to have the dominant influence on the reflectivity at all phase angles. Results are shown in the lower curves of Fig. 8 for two-layer models with the same base layer and a haze layer consisting of 0.1-μm particles with absorption values of n_i^u (refractive index $n = n_r + in_i$) of 6.3 and 5.5 and $\tau^u = 0.125$. Although good agreement with the observed phase curve is seen, the upper-haze-layer particles must be very strongly absorbing, almost metallic in character, in the infrared, but have low absorption in the visual.

Thus, the two possible model types appear to be unacceptable in explaining the infrared phase curve while retaining compatibility with the visual polarization observations. Although additional measurements (Martonchik 1977) have supported these observed fluxes, an independent verification of the absolute value of the reflectivity needs to be obtained to determine just how much absorption is required in the upper atmosphere at this wavelength.

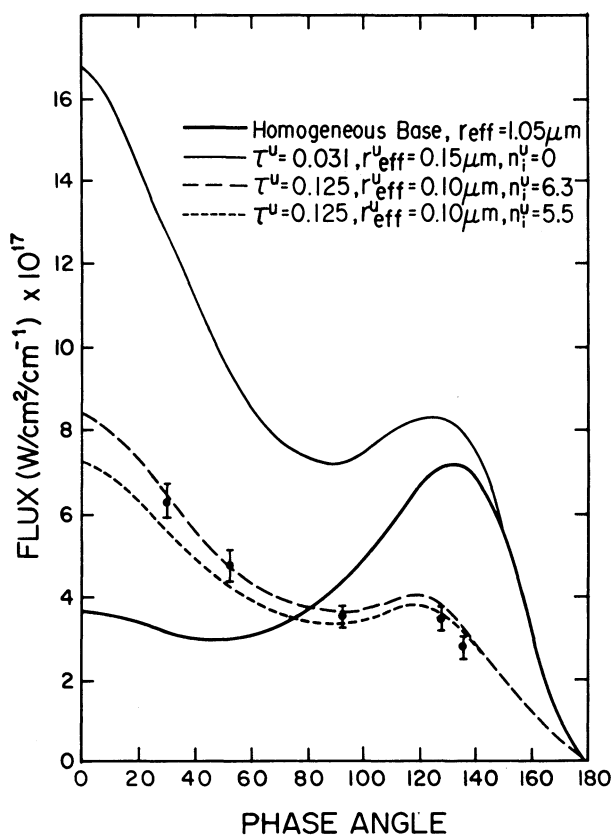

FIG. 8 Computed reflectivity phase curve for Venus at $\lambda = 3.4\ \mu m$ and $n_r = 1.35$ for one- and two-layer models. The one-layer model (heavy solid line) is made up of 1.05-μm H_2SO_4 particles with $\tilde{\omega}_0 = 0.33$. This layer is the base cloud of the two-layer models displayed, which include conservative scattering (light solid curve) and absorbing (dashed curves) upper layers, with layer thickness, particle size, and particle absorption as noted.

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VI. SUMMARY

The multiple scattering computation results presented, based on both the whole-disk and Digicon polarization observations, indicate vertical inhomogeneity in the upper atmosphere of Venus. The whole-disk observations support a thin, upper haze layer of 0.18-μm particles. This feature may be relatively new, since the increased midphase angle polarizations were not observed before 1969. The low polarization near the limb and terminator of the Digicon observations require a haze of slightly larger particles. The models based on the two types of models are not contradictory; i.e., a three-layer model which includes both of these haze layers with the smallest particles on top can show negligible differences with the two-layer model results discussed. At present, however, the detailed consideration of more complex models would simply be an exercise in speculation. The infrared reflectivity measurements of Martonchik and Beer also support a model that includes a haze layer of small particles, but very strong absorption is required in the particles of the top layer to obtain the low absolute value of the reflectivity reported. However, since the shape of the phase curve is explained by a thin haze of small conservatively scattering particles above the base H_2SO_4 cloud layer, it may perhaps be wise to wait for additional infrared reflectivity measurements before attempting to explain the source of the absorption needed by this model.

The Digicon polar regions show increased polarization which are explained by increased molecular scattering above the cloud, compatible with CO_2 absorption measurements. The decrease in the cloud top height for latitudes greater than 45° amounts to approximately 1.4 km.

The whole-disk polarization at 0.365 μm indicates a variation in cloud top height on a global scale at some time between June and November 1975. The data indicate a higher than average cloud top height in June 1975, consistent with the CO_2 line profile analysis of Cochran, Trafton, and Macy (1977).

Concerning the cause of the ultraviolet contrast features, the new observations do not provide sufficient information for supporting a model. The observed degree of contrast at a wavelength of 0.365 μm and the predominance of increasing polarization with decreasing intensity agree with the earlier polarimetric measurements of Coffeen (1971), but the limitations of short observing time and a single phase angle preclude any serious consideration from the Digicon maps of model types beyond the discussion of Travis (1975).

In spite of the increasing level of sophistication and effort, the quality of these and any other ground-based observations is of course limited. However, the continuous coverage of the Digicon maps is extremely useful for studies of the vertical structure and regional variations of the upper atmosphere of Venus. Lower-resolution Minipol-type observations can also be valuable especially if they cover the extreme limb and terminator regions of the disk. Whole-disk observations continue to be important as well for monitoring short and long term variations in the vertical structure. Continued polarization observations of Venus can still provide useful information for modeling the vertical structure of the upper atmosphere more accurately.

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