Effect of Cloud Scattering on Line Formation in the Atmosphere of Venus

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ABSTRACT

Corrections for anisotropic scattering in a cloudy medium are added to a synthetic spectrum analysis by Belton, Hunten and Goody of CO_2 bands and a water vapor line in the spectrum of Venus. It is found that to a good approximation the introduction of anisotropic scattering merely renormalizes the theoretical curves so that the corrections can be applied without recalculating the synthetic spectra. Since the line shapes and relative intensities are unaltered, derived pressures and temperatures remain the same. The corrected results indicate that the scattering mean free path in the Cytherian clouds resembles that for terrestrial cirrus clouds and that there is at least 20 times too little water vapor present to be in equilibrium with a water or ice cloud.

1. Introduction

Two types of theory have been advanced to interpret observations of the spectra of light reflected from the clouds of Venus. The "reflecting layer" model assumes that the bands are formed above the cloud level, which behaves as a reflecting surface. This model has now been largely discarded because it does not correctly predict the observed variation with planetary phase of the equivalent width of CO_2 absorption lines. The "radiative transfer" model assumes that the absorption lines are formed within the clouds. Here photons may undergo many scatterings before re-emerging or being absorbed, the whole process being described by radiative transfer theory. The characteristics of a line can no longer be simply related to the amount of absorbing material in a straight path but become a function of the cloud parameters, including the phase function (or scattering diagram) $P(\cos\Theta)$, the single-particle albedo $\tilde{\omega}_\nu$, the total cloud optical depth B, the temperature and pressure at all levels in the cloud, and the degree of homogeneity of cloud particles and gases.

The radiative transfer model was first applied to Venus by Chamberlain and Kuiper (1956). More recently, an extensive discussion of the problem has been given by Chamberlain (1965) who assumed a well mixed atmosphere that scattered isotropically. This analysis, and previous ones, were mainly concerned with the equivalent widths of the absorption lines. Belton *et al.* (1968) went further and calculated detailed line shapes for whole spectral bands which they called "synthetic spectra." Comparing these calculations with new observations, they concluded that CO_2 was a major constituent of the Venus atmosphere before the recent space probes Mariner 5 and Venera 4 confirmed this result. This paper will be referred to as BHG.

In the models treated previously, including BHG, simple forms of radiative transfer theory were employed. First, an isotropic phase function was used, although the phase functions characteristic of clouds are highly anisotropic, and second, the so-called 2-stream approximation was used in solving the multiple scattering problem.

In the present work accurate numerical solutions of the multiple scattering problem are obtained for a realistic cloud scattering phase function and compared with the multiple scattering calculations of BHG. The results are significantly different but the difference is mainly in the normalization and its chief effect is a change in the volume scattering coefficient.

This allows us to correct the results of BHG without repeating the most difficult part of their analysis, the calculation of synthetic spectra and the comparison of these with the observed bands.

The purpose of the present work is not to determine the amount of CO_2 in the Venus atmosphere, which is fairly accurately known, but to use the fact that the bands depend on the scattering properties of the particles in the upper atmosphere to obtain information about the clouds.

It is found that the mean free path for scattering in the clouds is similar to that of terrestrial cirrus clouds.

The analysis of the water vapor line at 8189Å indicates there is at least 20 times too little water vapor to be in equilibrium with a cirrus cloud; due to the uncertainties involved, however, this is not taken as a definitive argument against them.

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2. The radiative transfer problem

We wish to investigate the formation of absorption lines in a gas that we assume is uniformly mixed with the particles of a cloud. Let κ_ν and κ_c be the volume absorption coefficients of the gas and the cloud particles, respectively, and σ the volume scattering coefficient of the cloud particles (scattering by the gas is neglected). The unit of these coefficients is cm^{-1}.

We shall use the same notation as BHG except that volume absorption coefficients will be indicated by κ instead of χ.

The subscript c can be thought of as indicating both "cloud" and "continuum" since it is assumed that κ_c is a constant and provides a continuum absorption upon which the line structure, due to the rapid variation of κ_ν, is superposed.

The single scattering albedo is given by

$$\tilde{\omega}_\nu=\frac{\sigma}{\kappa_\nu+\kappa_c+\sigma}=\frac{\sigma}{\kappa+\sigma}. \tag{1}$$

When $\kappa_\nu=0$, $\tilde{\omega}_\nu=\tilde{\omega}_c=\sigma/(\kappa_c+\sigma)$.

We shall assume that the lines have a profile of the Lorentz form. In the notation of BHG:

$$\kappa_\nu=\frac{N_0 n S_s(J,T)}{\pi}\frac{\alpha_0 p}{(\nu-\nu_0)^2+(\alpha_0 p)^2}, \tag{2}$$

where n is the number of molecules cm^{-3} divided by Loschmidt's number N_0, p the pressure in atmospheres, α_0 the line width at 1 atm, and $S_s(J,T)$ [cm] is the "strength" or integrated absorption cross section of the line with initial state J at temperature T. For a given frequency ν in the line the corresponding intensity I is obtained by solving the radiative transfer equation (Chandrasekhar, 1960):

$$\mu\frac{dI_\nu(\tau,\mu,\phi)}{d\tau}=I_\nu(\tau,\mu,\phi)-J_\nu(\tau,\mu,\phi),$$

$$J_\nu(\tau,\mu,\phi)=\frac{\tilde{\omega}_\nu}{4\pi}\int_{-1}^{1}\int_0^{2\pi}P(\mu,\phi;\mu'\phi')I_\nu(\tau,\mu',\phi')d\mu'd\phi'+\frac{F\tilde{\omega}_\nu}{4}P(\mu,\phi;-\mu_0\phi_0)e^{-\tau/\mu_0}, \tag{3}$$

with the boundary conditions

$$\left.\begin{aligned}I_\nu(0,-\mu,\phi)&=0\\ I_\nu(B,\mu,\phi)&=0\end{aligned}\right\}. \tag{4}$$

Here $P(\mu,\phi;\mu'\phi')$ is the phase function which describes the scattering by one particle (usually it is averaged over a distribution of particle sizes) and μ and μ_0 are cosines of the zenith angles of the emergent and incident directions. The corresponding azimuth angles are ϕ and ϕ_0. The optical depth in the cloud is τ and the total optical depth is B.

For an isotropic phase function there is a particularly simple solution for the semi-infinite case. The upward directed intensity in the nth approximation is given by Chandrasekhar (1960, p. 83) as

$$I_\nu(0,+\mu)=\frac{\tilde{\omega}_\nu}{4}F\left(\sum_{\alpha=1}^{n}\frac{L_\alpha}{1+\mu k_\alpha}+\frac{\gamma}{1+\mu/\mu_0}\right), \tag{5}$$

where L_α and γ are integration constants to be fixed by the boundary conditions and the k_α's are the roots of the characteristic equation.

In the first approximation,

$$\left.\begin{aligned}k_1&=[3(1-\tilde{\omega})]^{\frac{1}{2}}\\ L_1&=\frac{[1-(1-\tilde{\omega})^{\frac{1}{2}}]3^{\frac{1}{2}}\mu_0(1+3^{\frac{1}{2}}\mu_0)}{[1-3\mu_0^2(1-\tilde{\omega})]}\\ \gamma&=\frac{3\mu_0^2-1}{3\mu_0^2(1-\tilde{\omega})-1}\end{aligned}\right\}. \tag{6}$$

The quantity which is of interest in the line formation problem is I_ν/I_c which is the ratio of the intensity at a point within the line to the adjuacent continuum intensity [obtained by solving Eq. (3) for $\kappa_\nu=0$, $\tilde{\omega}=\tilde{\omega}_c$]. In the above approximation this quantity is

$$\frac{I_\nu}{I_c}=\frac{\tilde{\omega}_\nu[1+\mu\sqrt{3(1-\tilde{\omega}_c)}][1+\mu_0\sqrt{3(1-\tilde{\omega}_c)}]}{\tilde{\omega}_c[1+\mu\sqrt{3(1-\tilde{\omega}_\nu)}][1+\mu_0\sqrt{3(1-\tilde{\omega}_\nu)}]}, \tag{7}$$

which is the expression used by BHG for computing their synthetic spectra.

3. Scattering in clouds

We assume that the Venus cloud layer is homogeneous and very thick. In order to complete the specification of the radiative transfer problem outlined in Section 2 we need to determine a phase function for scattering in the cloud and a value of $\tilde{\omega}_c$. The nature of the clouds, and therefore the exact way in which they scatter light, is unknown. However, like terrestrial clouds, we do know that they have a very anisotropic phase function (Arking and Potter, 1968). The only phase functions available are those determined directly from photometric observations by inversion methods (Sobolev, 1964) and those calculated from Mie theory for distributions of spherical particles (see, for example, Deirmendjian, 1964).

Arking and Potter (1968) found that the phase function obtained by Sobolev from the inversion of the photometric data of Danjon did not give a good fit to the more recent photometric data of Knuckles *et al.* (1961). However, a phase function calculated from Mie theory for a model of a terrestrial water cloud did give rather good agreement. We shall use phase functions calculated for this model in the present work. This does not mean that the clouds are thought to be composed of water. These phase functions are chosen simply because they are typical of cloud scattering and the same model has given good results for other Venus data. Phase functions computed for spherical ice particles of the same size would give very similar results. It should be noted that if the Venus clouds are composed of some non-condensable material or of ice, then the cloud particles will probably not be spherical and the Mie theory will not apply. However, there is some evidence to show that scattering from randomly oriented nonspherical particles is similar to that of spherical particles of the same size (Hansen and Cheyney, 1969; see also Kratohuil, 1964). In any case, the fact that the phase function has a highly anisotropic character as shown by Arking and Potter (1968) means that the main conclusions of this paper are valid whatever the detailed shape of the phase function.

In the model considered here the size distribution for the cloud particles is the one given by Deirmendjian (1964), i.e.,

$$n(r)=\frac{6^6}{5!}\frac{1}{r_c}\left(\frac{r}{r_c}\right)^6 \exp\left(-\frac{6r}{r_c}\right), \qquad (8)$$

where $n(r)$ is the fraction of particles with radii between r and $r+dr$ and r_c is the radius at which n is maximum. Here r_c was taken to be $4\,\mu$.

The observations of BHG were taken at wavelengths of 10,500, 10,380 and 8189Å. The corresponding phase functions for 10,500 and 8189Å have been calculated by Cheyney (private communication) and are shown in Fig. 1. Differences between these functions are too small to significantly affect the results, and therefore the one for 10,500Å will be used for all cloud model calculations in this paper regardless of wavelength.

The Mie scattering calculations also determine the single scattering albedo $\tilde{\omega}_c$. In the case of the above-mentioned water cloud model there is negligible absorption at any of the three wavelengths considered and for each case $\tilde{\omega}_c$ is effectively equal to 1. This corresponds to one of the values considered by BHG. They also consider the value $\tilde{\omega}_c=0.995$. For the sake of consistency one could increase the imaginary part of the index of refraction so as to obtain this value from the Mie calculations. One would then obtain a different phase function as well. Fortunately, the phase function is not very sensitive to such changes in the index of refraction so we can use the one given above for both cases.

The numerical solution of the multiple scattering problem with the phase function shown in Fig. 1 is a difficult problem due to the sharp peak near 0°. However, it has been shown (Potter, 1969) that to a good approximation this peak can be truncated and a com-

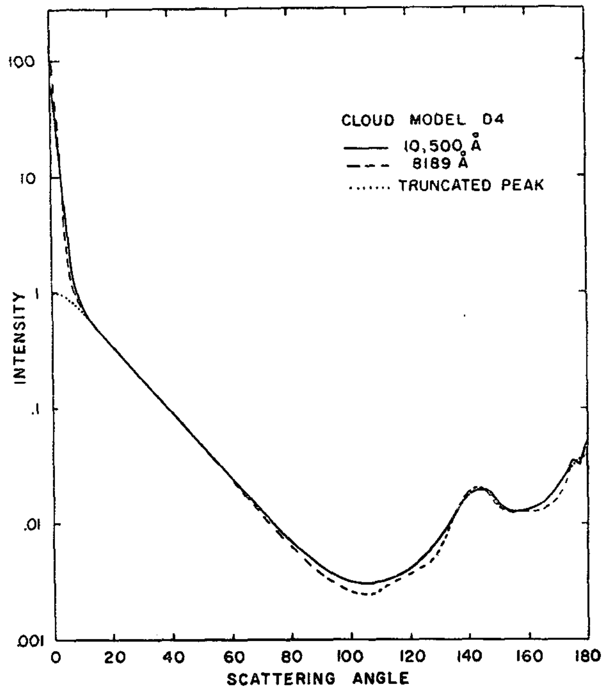

FIG. 1. Phase functions calculated from Mie theory for the particle size distribution of Eq. (8) and an index of refraction corresponding to water. The absicca is the scattering angle Θ. Results are given for two values of the wavelength. Truncation of the forward peak is also shown.

pensation made by altering the value of the volume scattering coefficient σ. We shall therefore solve the multiple scattering problem with the truncated phase function shown in Fig. 1 and later correct for the truncated peak by altering σ (see Section 4).

Multiple scattering calculations to solve the problem defined by (3) and (4) with the cloud phase function were carried out using a variant of the van de Hulst doubling method (van de Hulst, 1963; van de Hulst and Grossman, 1968). This method is further described by Hansen (1969) and by Potter and Grossman.[2] The calculations presented below are for an optical depth of 1024, which is effectively semi-infinite. They give the intensity I_ν as a function of the incident angle θ_0, the outgoing angle θ, the azimuth angle ϕ, and the ratio κ/σ. It is important to plot the intensities as a function of κ/σ since one then obtains a relation between our cloud model calculations and the calculations of BHG that considerably simplifies the problem [Eq. (9)]. Once I is known as a function of κ/σ one can calculate synthetic spectra and fit the data by adjusting the quantities p, T and n/σ that appear in κ/σ. BHG calls n/σ the specific amount and denotes it by M. The scattering mean free path in the cloud is $\lambda=1/\sigma$, so M is the number of atm-cm of gas in one scattering mean free path.

[2] To be published.

4. Results for the CO_2 bands

BHG made observations of two CO_2 bands with phase angles of 98° and 101°. The observations were of a field 9.4 sec square which was kept near the center of the illuminated part of the disc, and in the analysis it was assumed that the incident and outgoing angles were the same for light reflected from various parts of this field. The cosines of the incident and outgoing angles were taken to be $\mu_0=0.45$ and $\mu=0.80$ and were the same for the two bands.

The results of the radiative transfer calculations for the parameters relevant to the CO_2 bands are shown in Fig. 2 which is a log-log plot of the intensity as a function of κ/σ. The ordinate is the magnitude normalized to 0 at $\kappa/\sigma=0$, i.e., the quantity $-2.5\log_{10}[I_\nu(\kappa/\sigma)/I_\nu(0)]$ for $\mu_0=0.45$, $\mu=0.80$ and $\varphi=0$. The curve for the isotropic 2-stream approximation was obtained from Eq. (7) with $\hat{\omega}_c=1$ and that for the cloud model from the multiple scattering calculations described in Section 3.

The results obtained using the cloud model differ considerably from those obtained with the 2-stream isotropic theory of BHG. However, it is found that the cloud curve has a similar shape to the BHG curve and can be shifted into near coincidence with it for values of κ/σ <0.3, as shown in the figure. Thus, for this range of κ/σ the following relation holds approximately:

$$\frac{I_{\rm cl}(x)}{I_{\rm cl}(x_c)}=\frac{I_{\rm BHG}(\beta x)}{I_{\rm BHG}(\beta x_c)}, \tag{9}$$

where the subscripts cl and BHG indicate intensities calculated with the cloud model and the BHG approximation, respectively. The numbers x and x_c are any two values of κ/σ in the given range. We are interested in the case $x=\kappa_\nu+\kappa_c/\sigma$ and $x_c=\kappa_c/\sigma$. The values 1.0 and 0.995 for $\hat{\omega}_c$ used by BHG correspond to values for x_c of 0.0 and 0.005, respectively. By inspection of Fig. 2 one finds that the value of β for these curves is about 3.4. It will be seen that relation (9) holds very well for values of the magnitude <1.2, which corresponds to $I(x)/I(0)=0.3$. Values of $I(x)$ smaller than this would occur only very near the centers of the lines where one might have $I(x)/I(0)=0.1$. This corresponds to a magnitude of 2.5 and it will be seen from Fig. 2 that in this case the error is about 20%. Near the center of the line this is not significant.

Relation (9) means that if we repeat the analysis of BHG, using the more realistic cloud model phase function and without approximations in solving the multiple scattering problem, the only difference is that at the end of the analysis we will have determined a different value of the specific amount than the value $M_{\rm BHG}$ determined by BHG. This new value is equal to $M_{\rm BHG}/\beta$, the correction factor $1/\beta$ being independent of κ_c. Since the shapes of the theroretical line profiles are not altered, the temperatures and pressures determined by the original analyses will not be changed. The correction leads to a change in the value of σ (or λ) since this is what is ultimately determined by the analysis (see below).

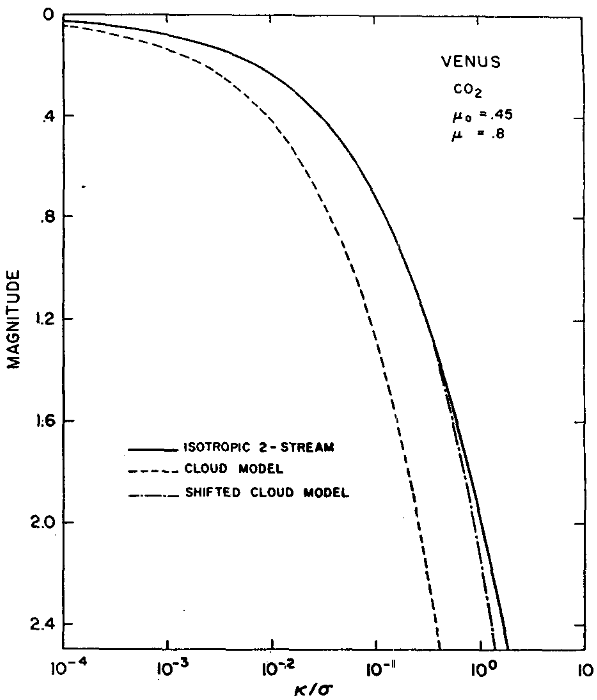

FIG. 2. Plot of the quantity, $-2.5\log[I(\kappa/\sigma)/I(0)]$, as a function of κ/σ, for angles relevant to the CO_2 band at 10,500 Å. Curves are given for the isotropic 2-stream approximation and a semi-infinite atmosphere, used by BHG, and for the cloud model calculations presented here. Also shown is the curve obtained when the cloud model curve is shifted to higher values of κ/σ for comparison with the BHG curve.

It now remains to correct for having truncated the forward peak of the phase function. It can be shown (Potter, 1969) that it is a good approximation to treat the photons scattered by this sharp peak as if they had not been scattered at all, since after scattering they are travelling in nearly the same direction as before. If σ is the total scattering coefficient when the particles scattered into the forward peak are considered to have been scattered, and σ' is the coefficient when they are considered not to have been scattered, then $\sigma=\sigma'/(1-A)$, where

$$A=\frac{1}{2}\int_{-1}^{1}(P-P')d\cos\Theta.$$

Here P and P' are the complete and truncated phase functions shown in Fig. 1, normalized such that $\int_{-1}^{1}P(\cos\Theta)d\cos\Theta=2$. The value of A in this case is 0.425. One gets nearly the same intensities by solving the multiple scattering problem with phase function P and scattering cross section σ or with phase function P' (properly normalized) and cross section σ'. Thus, this correction also results merely in a change in the value of σ.

Combining the two corrections we see that the results of an analysis using the complete cloud model can be related to those obtained with the BHG approximation by

$$M_{\mathrm{cl}}=\left(\frac{1-A}{\beta}\right)M_{\mathrm{BHG}}=0.17\ M_{\mathrm{BHG}},$$

or, equivalently, by

$$\sigma_{\mathrm{cl}}=\left(\frac{\beta}{1-A}\right)\sigma_{\mathrm{BHG}}=5.9\ \sigma_{\mathrm{BHG}}.$$

a. The 10,500 Å band

Analysis of this band by BHG indicated that the pressure was less than 0.2 atm.

They found that equally good agreement was obtained for $\tilde{\omega}_c=1$ or 0.995. A lower value of $\tilde{\omega}_c$ (higher value of κ_c/σ) decreases the intensity in the wings of the lines without changing the shape elsewhere. This can be understood by considering Fig. 2.

Taking $p=0.1$ atm, BHG found $T=270\pm25$K and $pM=3.5\times10^3$ and 4.5×10^3, for $\tilde{\omega}_c=1$ and 0.995, respectively. For other values of p, they found $pM=$ constant. Since $M=\lambda n$ and $n=273\ fp/T$, where f is the fraction by volume of CO_2, we have

$$\lambda=\frac{T}{273}\frac{(pM)}{fp^2}.$$

The recent Soviet and American Venus probes Venera 4 and Mariner 5 have shown that $f\sim0.9$. Taking this value for f, the above numbers lead to values for λ of 3.8 and 4.9 km for $\tilde{\omega}_c=1$ and 0.995, respectively. Applying the cloud scattering corrections discussed above leads to values of $\lambda=0.65$ and 0.84 km for $\tilde{\omega}_c=1$ and 0.995, respectively.

However, the temperatures and pressures obtained by BHG are consistent with the measurements of these quantities made by Mariner 5 only if one takes the lower limit on the temperature $T=245$K instead of the value 270K used above. Even this is slightly high since Mariner 5 indicated $T<240$K for a pressure between 0.1 and 0.2 atm (Kliore and Cain, 1968). Furthermore, it now appears that 0.2 atm is a better estimate for the pressure of line formation than 0.1 atm (Belton, 1968). Therefore, at the present time the best estimate for the pressure and temperature of line formation is 0.2 atm and 240K. If these values of p and T are taken, the values of λ obtained above are reduced to 0.14 and 0.19 km for $\tilde{\omega}_c=1$ and 0.995, respectively.

It is interesting to note that the temperature 270K determined above indicates a pressure of at least 0.4 atm according to the Mariner results. This would reduce the values of λ by a further factor of about 4.

b. The 10,380 Å band

Assuming a temperature of 270K, BHG found that the pressure was less than 0.25 atm. Taking $p=0.1$ atm they found values of pM of 2.5×10^3 and 4×10^3 for $\tilde{\omega}_c=1$ and 0.995, respectively. These numbers lead to corrected values for λ of 0.46 and 0.74 km for $\tilde{\omega}_c=1$ and 0.995, respectively. For 0.2 atm and 240K these are reduced to 0.10 and 0.17 km, respectively.

c. Comparison with terrestrial clouds

BHG took $pM=4\times10^3$ as a characteristic value for estimating the mean free path λ. For a temperature and pressure of line formation of 240K and 0.2 atm this corresponds to a corrected value for λ of 0.17 km.

This may be compared with the value obtained for the terrestrial cloud model used in these calculations. So far we have used only the phase function for this model and have thus had to specify only the particle size distribution and the index of refraction of the material. However, if one further specifies a liquid water content w for the cloud the Mie scattering calculations also give a value for the mean free path. If one follows Deirmendjian (1964) and takes 100 drops cm^{-3} in the present model (corresponding to $w=0.0627$ gm m^{-3}), one obtains $\lambda=0.0625$ km.

However as Deirmendjian (1964) points out the value 100 drops cm^{-3} is only a nominal one. The model is intended to represent a cumulus cloud and for these a typical figure which applies rather well to a variety of cumulus clouds having rather different particle size distributions is $w=0.5$ gm m^{-3} (Fletcher, 1962). In the present case this leads to $\lambda=0.008$ km.

We can also estimate the value of λ from the visibility V for various clouds given by aufm Kampe and Weickmann (1957) by using the Koschmieder formula, $V=\mathrm{constant}/\sigma$, where the value of the constant is between 3 and 4. We shall take the value 4 since it was the one used by BHG. A typical value for cumulus clouds obtained in this way is $\lambda=0.01$ km and there are very few cumulus clouds with $\lambda>0.05$ km. The corresponding numbers for stratus clouds are 0.03 and 0.14 km. Mountain fogs are similar to stratus clouds and coastal fogs have about the same maximum λ although they have a somewhat higher average value (about 0.07 km).

The mean free path for cirrus clouds can be estimated from data given by aufm Kampe and Weickmann. Typical densities are about 1 particle cm^{-3} with a cross-sectional area of about 4×10^{-5} cm^2, corresponding to $\lambda=0.13$ km. Here it has been assumed that diffraction scattering accounts for one-half the cross section. If this part is left out one obtains $\lambda=0.25$ km.

Thus, the present results indicate that the mean free path in the Venus clouds is similar to that of a very thin terrestrial fog or stratus cloud or of an ordinary cirrus cloud.

5. The H_2O line at 8189Å

BHG analyzed a single water vapor line at 8189Å. The line was observed at a phase angle of 66°, the cosines of the corresponding incident and emergent angles being taken as 0.67 and 0.95, respectively.

The corresponding absorption curves for the BHG isotropic theory and the cloud model calculations using the 10,500Å phase function as discussed in Section 3 are shown in Fig. 3. Again it is found that the cloud curve can be shifted into coincidence with the isotropic curve for a certain range of values of κ/σ. Here the coincidence is maintained only for values of the magnitude <0.8, but since the center of the water line at 8189Å is less than 10% below the continuum intensity, this is enough. In this case the value of β is 4.3. The difference is due entirely to the fact that the angles are different. The correction for truncating the forward peak is, of course, the same.

BHG found an upper limit of the pressure of 0.4 atm. It is reasonable that this should be higher than the corresponding limit for the CO_2 bands because the water line was weaker and therefore probably formed at a greater depth. For $p=0.1$ atm and $M(H_2O)=4.0$, a good fit was obtained to the observed line. Our corrections give a value of $M(H_2O)$ of 0.53.

a. *Water vapor mixing ratio*

BHG determined the mixing ratio of water vapor to CO_2 by taking the ratio of specific amounts measured for CO_2 and H_2O, assuming that the lines were formed at the same level (taken as 0.1 atm). This procedure assumes that the cloud scattering coefficient σ is the same at 10,500 and 8189Å. For our cloud model the Mie scattering calculations of Cheyney show that this is very nearly the case. Since the relatively weak water line was formed at a lower level, the mixing ratio obtained is an upper limit. The values BHG used were $M(H_2O)=4.0$ and $M(CO_2)=4\times10^4$, giving

$$\frac{n(H_2O)}{n(CO_2)}=1.0\times10^{-4}.$$

Our corrections lead to a value of 0.79×10^{-4} for this ratio. It is important to note that although these values were obtained using the results for $p=0.1$ atm, they are largely independent of p, since for both H_2O and CO_2 the quantity that is determined from the analysis is not M but pM.

Assuming $f=0.9$ we obtain 0.71×10^{-4} as the mixing ratio for water vapor in the atmosphere. This is about 21 times less water vapor than would be in equilibrium with an ice cloud at 0.2 atm and 240K, and 120 times less than would be in equilibrium with a water cloud at 0.4 atm and 270K.

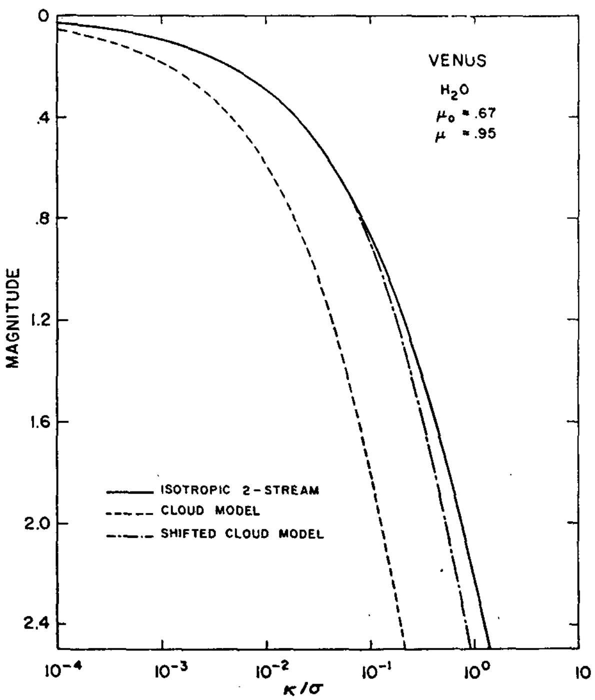

FIG. 3. Plot of $-2.5\log[I(\kappa/\sigma)/I(0)]$, as in Fig. 2, for angles relevant to the H_2O line at 8189Å.

6. Conclusion

Corrections for anisotropic scattering in a cloudy medium have been applied to the results obtained by Belton *et al.* (1968) in fitting synthetic spectra to observations of CO_2 bands and an H_2O line in the reflection spectrum of Venus. It was found that:

1) To a good approximation, the shapes and relative intensities of the lines were not changed so that the temperatures and pressures determined by the analysis were the same and the corrections could be applied without recalculating the synthetic spectra. The main effect can be expressed as a change in the scattering mean free path.
2) The scattering mean free path for the Cytherian clouds appears to be about the same as for terrestrial cirrus.
3) There is at least 20 times too little water vapor to be in equilibrium with a water or ice cloud.
4) Since the analysis involves certain approximations, the most serious of which is probably the assumption of a homogeneous atmosphere, the above conclusions may be altered when more sophisticated calculations are performed.

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