UPPER LIMITS ON LIQUID WATER IN THE VENUS ATMOSPHERE

W. J. Welch and D. G. Rea
Space Sciences Laboratory, Radio Astronomy Laboratory,
and Department of Electrical Engineering
University of California, Berkeley, California 94720

The exciting recent discovery of HCl and HF in the atmosphere of Venus (Connes et al., 1967) will undoubtedly have an important influence on future models of the planet's atmosphere. The purpose of this note is to point out one consequence of the discovery, namely, that on account of the presence of HCl there cannot be much liquid water in the Venus atmosphere. HCl is highly soluble in water, and the resulting acid has a high DC conductivity. If there were much of this acid in the Venus atmosphere, the long wavelength radar signals would be strongly attenuated, whereas the radar signals appear to reach the planet's surface with little attenuation (Evans, Ingalls, Rainville, and Silva, 1966).

A quantitative estimate of the centimeter wavelength attenuation of the acid clouds follows from the observed abundance of the HCl (Connes et al., 1967) and some assumptions about the atmospheric temperature and pressure at the level of the clouds. The HCl/CO_2 abundance ratio was found to be about 6×10^{-7} and the total effective pressure 80^{+100}_{-40} millibars (Connes et al., 1967) Moreover, from the strength of the CO_2 lines, they concluded that CO_2 "is probably the major constituent in the Venus atmosphere". We have carried out calculations for three temperatures: 240° K, 273° K and 283° K, and for partial pressures of HCl of 10^{-4} and 10^{-3} mb. These pressures correspond to total pressures at the supposed liquid H_2O clouds of about 200 and 2000 mb respectively. For these two vapor pressures and for the three selected temperatures the concentrations of HCl in solution and the conductivities of the resulting solutions were found from the International Critical Tables.

The data for 273°K and 283°K came directly from the tables and the data for 240°K from an extrapolation of the tabular values. The results appear in the table. The real and imaginary parts of the dielectric constant of pure water are given by the familiar Debye formulae for a liquid in which there is dipolar relaxation. With $\epsilon = \epsilon' + i\epsilon''$,

$$\epsilon' = \frac{\epsilon_{\infty} + \epsilon_{o}\left(\frac{\lambda_c}{\lambda}\right)^2}{1 + \left(\frac{\lambda_c}{\lambda}\right)^2}, \quad \epsilon'' = \frac{(\epsilon_{\infty} - \epsilon_{o})\left(\frac{\lambda_c}{\lambda}\right)}{1 + \left(\frac{\lambda_c}{\lambda}\right)^2} \tag{1}$$

Values for the three parameters, ϵ_o, ϵ_{∞}, and λ_c, were obtained from Buckley and Maryott (1957) and appear in the table. For 240°K the parameters were obtained by extrapolating the tabular values in the Circular. In terms of the dielectric constants and conductivity the attenuation of the solution is

$$\beta\,(\mathrm{cm}^{-1}) = \frac{8.88}{\lambda} \left\{ \left[(\epsilon')^2 + (\epsilon'' + 60\,\lambda\,\sigma)^2 \right]^{1/2} - \epsilon' \right\}^{1/2}, \tag{2}$$

where λ is in cm. This formula is plotted in the figure for the parameters in the table for T = 273°K. The results for the other temperatures are nearly the same. The attenuation of pure water is also shown for comparison.

The radar observations of Venus, which span the wavelength interval 3.8 cm to 8 m, are reviewed by Evans, Ingalls, Rainville, and Silva (1966). At 3.8 cm the radar cross section is 1.2% of the geometric cross section, at 12 cm it is about 12%, and for wavelengths 20 cm and longer it lies in the range 15 - 18%. The most recently reported experiment at 23 cm (Evans, Brockelman, Dupont, Hansen, and Reid, 1966) yielded a cross section of 18% the geometric cross section of the planet. This is a strong echo, comparable to the echoes that are obtained from typical terrestrial materials, and implies that the mean surface dielectric constant is of the order of 7 or more. It appears that, although there is clearly atmospheric absorption at 3.8 cm, and possibly some absorption at 12 cm, at wavelengths 20 cm and longer the atmosphere is essentially transparent. We will suppose that the two way atmospheric absorption at 20 cm is not more than 20% and therefore $\tau_{20} \lesssim 0.1$. From the calculations we find that $\beta_{20} \cong 10\ cm^{-1}$ in nearly every case. Hence for $\tau_{20} \lesssim 0.1$, the mass of liquid water clouds must be less than .01 gm/cm^2. This amount of water cloud of average density 1 gm/m^3, typical of terrestrial water clouds, would be just 100 m thick.

An even smaller upper limit on the liquid water content of the Venus atmosphere may be obtained by an argument which is also based on microwave observations of the planet, but which is a little less direct than the above. Consider the microwave emission spectrum of the planet which would result from a cool acid cloud above the warm surface. Let the surface emission temperature be T_s, the cloud temperature T_c, and the cloud optical depth τ_λ. The brightness of a pencil of radiation leaving the surface at an angle $\cos^{-1}\mu$ with respect to the surface normal and passing through the cloud is

$$T_B(\tau_\lambda, \mu) = T_s e^{-\tau_\lambda/\mu} + T_c(1 - e^{-\tau_\lambda/\mu}). \quad (3)$$

The disk temperature of the planet is $T_D = 2\int_0^1 T_B\, \mu\, d\mu$, and for small values of τ_λ we find

$$T_D \cong T_s - 2\tau_\lambda\,(T_s - T_c). \quad (4)$$

From an extended series of measurements, Drake (1964) obtained an average disk temperature of 622°K at 10 cm, and from a similar series of measurements Mayer, McCullough, and Sloanaker (1963) found an average disk temperature of $621^{\circ}K$ at 3 cm. The absolute error in each series is probably not greater than 10%. As is evident in figure 1, an acid cloud absorbs more at 3 cm than at 10 cm, and, if such a cloud were present in the Venus atmosphere in great abundance, the disk temperature should be relatively lower at 3 cm than at 10 cm. Considering the measurement errors, let us suppose that the 3 cm disk temperature is really about 70° lower than the 10 cm disk temperature and calculate the thickness of an acid cloud which would produce this difference. Alternatively, we may take the disk temperature to be the same at both wavelengths (as is probable according to the measurements) and suppose that an increase in T_s by about 70° at 3 cm over what it is at 10 cm is compensated by the absorption of the water cloud. This increase in T_s is about the maximum that might be expected from the effect of an increase in the surface emissivity at 3 cm over that at 10 cm. We assume here that the surface emissivity is 0.85 - 0.90 at 10 cm, a plausible value derived from the radar experiments (Pollack and Sagan, 1965) at 12 cm and longer wavelengths. The emissivity can at most increase to 1.0 at 3 cm, and the resulting increase in T_s is about $70^{\circ}K$. Let $T_s \cong 620^{\circ}K$ and $T_c \cong 270^{\circ}K$. Then $2(\tau_3 - \tau_{10})(T_s - T_c) = 2(\tau_3 - \tau_{10})(350) \lesssim 70$, and $\tau_3 - \tau_{10} \lesssim 0.1$. For the acid cloud we find $\beta_3 = 26\ cm^{-1}$ and $\beta_{10} = 12$ for $p_{HCl} = 10^{-4}$ mb, and $\beta_3 = 31\ cm^{-1}$ and $\beta_{10} = 15\ cm^{-1}$ for $p_{HCl} = 10^{-3}$ mb. For $(\tau_3 - \tau_{10}) < 0.1$, the mass of liquid water clouds must be less than 0.007 g cm^{-2} for both values of p_{HCl}.

Liquid water clouds have been suggested for Venus to explain the microwave spectrum (Deirmendjian, 1964; Griffith et al., 1967). If the temperature of the liquid cloud is much above $273^{\circ}K$, the large amount of water vapor that must lie beneath the cloud in the lower atmosphere will produce too strong a specific absorption at 1.35 cm to fit the available data (Barrett and Staelin, 1964). If the cloud is cooled to temperatures of the order of 240 - $260^{\circ}K$, the resulting water vapor in the lower atmosphere is consistent with the observed 1.35 cm disk temperatures. Then a cloud mass of 0.2 - 0.3 gm/cm^2 of pure water is needed to fit the microwave data (Basharinov and Kutuza, 1965) in the neighborhood of 0.4 - 3 cm. With the increase by a factor of 2 in the attenuation near 1 cm wavelength of the HCl solution over that of pure water, a cloud mass of only 0.1 - 0.2 gm/cm^2 is required. However, this is still 10 times the larger upper limit obtained above. Consequently, liquid water clouds cannot be invoked to explain the microwave spectrum.

These upper limits must also be borne in mind when constructing atmospheric models for calculations of the greenhouse effect and interpretations of the infrared and visible spectra.

Acknowledgments

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REFERENCES

Barrett, A. H., and Staelin, D. H. 1964, Space Sci. Revs., 3, 109.

Basharinov, A. E., and Kutuza, B. G. 1965, J. Res. NBS, 69D, 1580.

Buckley, F., and Maryott, A. A. 1957, National Bureau of Standards Circular 514.

Connes, P., Connes, J., Benedict, W. S., and Kaplan, L. D. Ap. J. (in press).

Deirmendjian, D. 1964, Icarus, 3, 109.

Drake, F. D. 1964, A. J., 69, 62.

Evans, J. V., Brockelman, R. A., Dupont, E. N., Hansen, L. B., and Reid, W. A. 1966, A. J., 71, 897.

Evans, J. V., Ingalls, R. P., Rainville, L. P., Silva, R. R. 1966, A. J., 71, 902.

Griffith, P. H., Thornton, D. D., and Welch, W. J. 1967, Icarus (in press).

Mayer, C. M., McCullough, T. P., and Sloanaker, R. M. 1963, in Physics of the Planets, Proc. XIth Intern. Astrophys. Symposium, Liege, Belgium, 1962.

Pollack, J. B., and Sagan, C. 1965, Icarus, 4, 62.

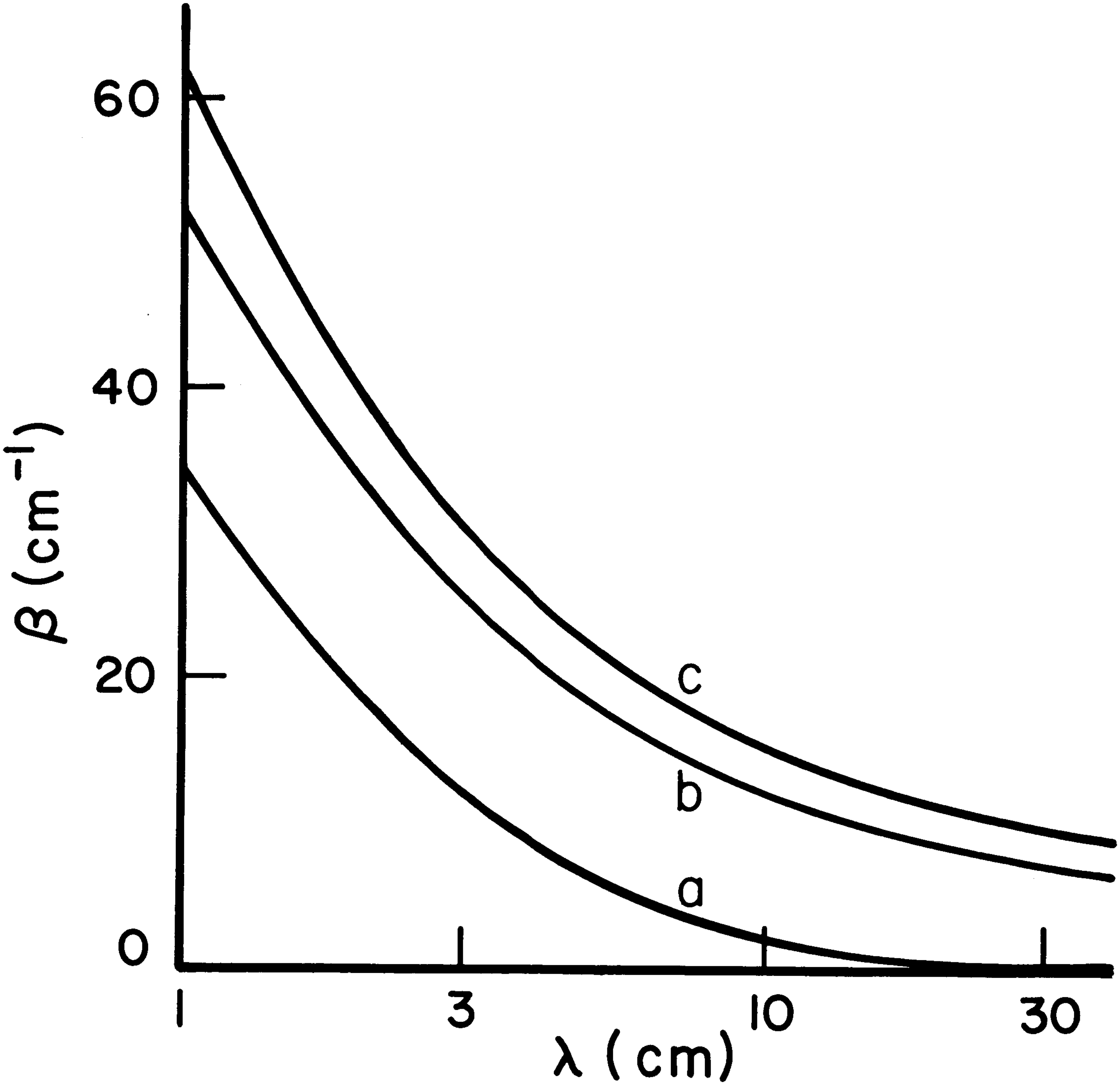
TABLE

The concentration, C, and D.C. conductivity, σ, of HCl solutions, and the parameters ϵ_o, ϵ_∞, and λ_c of pure liquid H_2O.

T (°K)	P_{HCl} (mb) 10^{-4}		P_{HCl} (mb) 10^{-3}		ϵ_o	ϵ_∞	λ_c (cm)
	C (Moles L^{-1})	σ (Mhos cm^{-1})	C (Moles L^{-1})	σ (Mhos cm^{-1})			
240	4.1	0.40	5.5	0.52	4.8	101.4	8.14
273	1.9	0.38	3.0	0.58	5.0	88.2	3.34
283	0.8	0.21	1.9	0.47	5.0	84.0	2.43

FIGURE CAPTION

The absorption coefficient, β, as a function of wavelength, λ, for pure water (a), and HCl solutions at partial pressures of HCl of 10^{-4} mb (b) and 10^{-3} mb (c).


60
40
20
0
β (cm⁻¹)
c
b
a
1
3
10
30
λ (cm)