Precipitation on Venus: Properties and Possibilities of Detection[1]

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ABSTRACT

Mariner 10 occultation measurements have provided evidence of a dense cloud deck in the lower atmosphere of Venus with a peak liquid content of about 1 g m^{-3}. This, in conjunction with other measurements—such as turbulence, updrafts and the presence of aerosol—seem to favor the possibility of precipitation on Venus. Modeling of droplet growth in the Venusian environment shows that precipitation size drops can be formed over periods of only a few hours, similar to growth rates on Earth. The precipitation region, if it exists, would extend from the cloud base at about 50 km to the 38 km level where most of the droplets will have evaporated. Precipitation regions can be detected with a variety of remote sensing radar and radio techniques.

1. Introduction

Recent results from Mariner 10 have provided evidence of a dense cloud deck in the lower atmosphere of Venus at an altitude of about 50 km, with a peak liquid content of about 1 g m^{-3} and an average liquid content of 0.5 g m^{-3} (Kliore, *et al.*, 1979). Preliminary results from the Pioneer probe mission seem to verify the presence of a lower cloud deck at 50 km with a liquid content of about a factor of 3 less than the Mariner 10 peak measurement. It is conceivable that precipitation in the form of sulfuric acid solution is produced by this cloud deck. In a recent paper by Knollenberg and Hunten (1979), which presented the data from the Pioneer Venus cloud particles size spectrometer, they stated that, "Significant particle mass loading and size spectral features suggest that precipitation is likely produced and a peculiar aerosol structure beneath the lowest cloud layer could be residue from a recent shower." Knowledge of the factors necessary for the formation of precipitation (vertical wind velocity, liquid content, turbulence, presence of nucleating particles and general atmospheric conditions) is very limited in the lower cloud region of Venus. The hypothesis of rain is based largely on one set of data derived from the Mariner 10 occultation measurements for the liquid content of the clouds; however, several other factors are definitely favorable to the existence of precipitation, including recent Pioneer Venus results. These factors are discussed in this paper as well as the growth and evaporation rates of cloud and rain particles, and the expected extent of the precipitation. The growth and evaporation modeling show rates similar to those on Earth, as well as a rain layer extending from the cloud deck (at ~50 km in altitude) down to a level of about 38 km above the surface of Venus. In addition, several methods of detecting rain on Venus using various radar techniques are proposed and briefly discussed.

2. Possibility of existence

In recent papers by Kliore *et al.* (1977, 1979), the liquid content of the clouds of Venus was determined using Mariner 10 radio occultation data. As the radio link signal was occulted by the planet, it encountered excess attenuation beyond the absorption by atmospheric gases. This attenuation was attributed to cloud layers. The absorption coefficient derived from the dual-frequency occultation data was used to determine the liquid content of the clouds. Assuming an 85% sulfuric acid solution [in agreement with the results of Pollack (1975) and Pollack *et al.* (1978)] the liquid contents of these clouds were calculated. Of particular interest was a lower cloud deck centered at about 49 km (assuming a Venus radius of 6050 km) which was found to have a liquid content of 1 g m^{-3} at its peak and 0.5 g m^{-3} average. The liquid content and atmospheric environment (1.2 atm., 365 K) are similar to those for clouds on Earth which range from 0.3 to 2.0 g m^{-3} in liquid content. The high liquid content of this lower

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Venusian cloud is the basis of our investigation of the possibility of rain on Venus.

Comparison of the different atmospheric characteristics deduced by other scientists may give additional insight into some of the parameters necessary to predict rainfall. First, there is good agreement between the Mariner 10 cloud and the Mariner 5 cloud (Kliore *et al.*, 1979). Although each have similar liquid contents, the Mariner 10 cloud has a denser more pronounced peak, while the Mariner 5 cloud appears to extend to greater depths with a gradually increasing liquid content. As discussed by Kliore *et al.* (1979), the Mariner 10 cloud does not account for all of the opacity predicted by Muhlemen *et al.* (1979) and therefore it is possible that this cloud extends below 43 km where the occultation signal was lost. It is also possible that Mariner 5 detected a vertically thick cloud deck while Mariner 10 detected a thinner cloud deck and a rain region. The less dense rain region, then, would not have produced as high an attenuation as the denser cloud deck in the microwave region.

There appears to be good correlation between the occultation data and the Venera 9 and 10 nephelometer experiment (Keldysh, 1976) in terms of the existence of a lower cloud deck. However, the results of the nephelometer experiment gave a fairly uniform cloud particle size falling within the range 0.5–2.5 μm with a concentration ranging from 400–500 cm^{-3} (Keldysh, 1976). These results give a maximum liquid content of about 10^{-2} g m^{-3}—nearly two orders of magnitude less than the occultation results. Local variations in the weather could explain such differences. However, the most probable explanation is that the Venera experiment was not sensitive to drops of large radii. It is possible that 5% of the particles had a radius >10 μm and 0.5% had a radius >15 μm. Also, any particles larger than 50 μm would not be detected. In order to account for a liquid content of 1 g m^{-3} only 0.2% of the drop population would require a radius >50 μm. Thus the available data on drop size in the lower Venus cloud do not contradict the formation of large cloud and rain droplets.

In addition, the Venera 9 and 10 nephelometer profile showed a sharp decrease at precisely the peak of the Mariner 10 profile. It is possible that the cloud base is at 49 km and the liquid content detected by Mariner 10 below 49 km was indeed a region of large rain particles. Particles of drop size $\gtrsim 150$ μm would not be detected by the nephelometer but would be more visible to the radio occultation wavelengths.

Preliminary results from the recent Pioneer Venus probe mission verify the presence of a fairly dense cloud layer from about 49 to 51 km. The particle size spectrometer (Knollenberg and Hunten, 1979) detected droplets up to 35 μm in size with the Sounder probe on the day side of Venus. Knollenberg and Hunten (1979) estimate the liquid content of this lower cloud to be about 0.1–0.2 g m^{-3} depending on the droplet concentrations. This is slightly lower than the Mariner 10 results which gave an average liquid content of 0.5 g m^{-3}. In addition, they suggest that the aerosol structure detected below the main cloud deck (49–31 km) could be the residue from a recent rainshower.

The gas chromatograph (Oyama *et al.*, 1979) found water vapor concentrations of less than 0.06% at 54 km, and equal to 0.52% at 44 km and 0.14% at 24 km. There appears to be a significant increase in water vapor content below the cloud region (44 km) which decreases with decreasing altitude. This may suggest the presence of evaporating sulfuric acid water droplets (rain) below the cloud.

The Pioneer Venus nephelometer data (Ragent and Blamont, 1979) produced vertical profiles at four points on the planet. Although preliminary results suggest the cloud above 51 km is a planetary feature, the lower cloud region (below 51 km) varies from location to location and from day to night in terms of particle size and liquid content. It appears that the liquid content changes by a factor of about 2 between the day and the night side profiles. More detailed Pioneer Venus results will be valuable in understanding the properties of the lower cloud region.

It is interesting to compare the vertical wind velocity profiles of Venera 7 (Kerzhanovich *et al.*, 1971) and the turbulent regions found by Woo (1974, 1975), Kerzhanovich *et al.*, (1972) and Stone (1977). A plot of the liquid content profile derived by Mariner 10 and the profiles of the wind velocity (measured by determining the relative descent speed of the Venera probe as derived from the Doppler shift in the frequency of the radio signal received on Earth) and turbulent regions is shown in Fig. 1. Below about 44 km there is a fairly strong updraft reaching 1.5 m s^{-1} as determined by Venera 7. Above 44 km, the vertical wind profile changes directions and reaches a downdraft velocity of about 2 m s^{-1} at its peak. Toward the center of the cloud the downdraft velocity again approaches zero. The turbulent regions found by Woo, Stone and Kerzhanovich occur in the cloud region between 50 and 44 km. There appears to be some kind of turbulent downfall below about 50 km. Inasmuch as clouds are supported by updrafts, it is possible that the downdrafts seen by Venera 7 are due to a region of falling rain.

The presence of precipitation would have important implications in understanding the dynamics of the Venus atmosphere. The precipitation would evaporate well above the surface (the lowest altitude that 85% sulfuric acid could survive evaporation is 28 km) and would play no rule in surface erosion. However, the evaporation and condensation of the

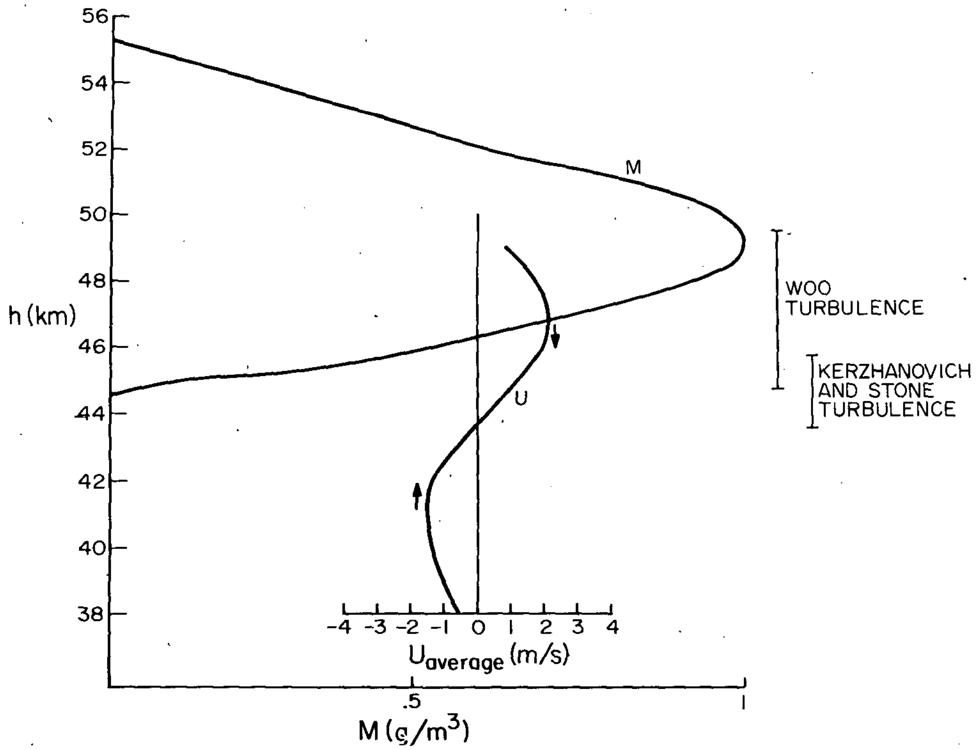

FIG. 1. Liquid content, turbulence and vertical wind velocity profiles of Venus. The liquid content *M* is taken from Kliore *et al.* (1979), the vertical wind velocities are from Kerzhanovich *et al.* (1971) and the turbulence regions are from Woo (1974) and Kerzhanovich *et al.* (1972).

clouds through cycling by rainfall would lead to heat transport from the region around 38 km where evaporation occurs (see Section 3) to the region around 50 km where condensation occurs. The condensation of a sulfuric acid cloud of an average liquid content of 0.5 g m^{-3} will increase the atmospheric CO_2 temperature by 1 K. The presence of precipitation will also be a mechanism of material transport. Large droplets of sulfuric acid solution falling from the cloud layer evaporate at lower altitudes where sulfuric acid is thermally converted to COS (Hunten, *et al.* 1977) or SO_2 (Oyama *et al.*, 1979) and recycled back up into smaller particles at the top of the cloud. While photochemistry dominates the production of sulfuric acid in the upper atmosphere (at ~70 km), the appropriate photodissociating radiation cannot penetrate to the depths of the lower clouds. The mechanism of sulfuric acid formation in this region is unknown.

3. Properties of precipitation on Venus

In this section the growth of cloud drops by condensation and coalescence in the Venusian environment will be studied. Specifically, the minimum drop size necessary to produce rainfall and the vertical extent of the rainfall region are derived. The following initial parameters are used in these calculations:

1) LIQUID CONTENT. A liquid content of 1 g m^{-3} is used in the coalescence calculations. This is the peak value derived from the Mariner 10 occultation data.

2) UPDRAFTS. An updraft of 1 m s^{-1} is used. This is consistent with the updraft determined by Venera 7 (Kerzhanovich *et al.*, 1971) in the 38–44 km region.

3) CONCENTRATION. 85% sulfuric acid is used. Pollack *et al.* (1978) presented evidence that at least two-thirds of the total cloud optical depth is 85% sulfuric acid within a few percent. It is likely that the lower parts of the cloud become more concentrated as more water evaporates; however, slightly higher concentrations will not change the results significantly. Recent Pioneer results are also consistent with high concentrations of sulfuric acid-water solutions (Oyama *et al.*, 1979).

4) SUPERSATURATIONS. Growth rates and evaporation rates are highly dependent on the subsaturation and supersaturation of the cloud environment. The best estimates of the water vapor mixing ratio on Venus are given by the Pioneer Venus gas chromatograph experiment. Preliminary results show 0.06% H_2O at about 54 km, 0.52% H_2O at 44 km and 0.14% at about 24 km (Oyama *et al.*, 1979). Apparently, the Venus atmosphere contains a higher mixture of H_2O below the clouds, suggesting the evaporation of water from possible sulfuric acid rain. We have

assumed a water vapor mixing ratio of one to several times $\times 10^{-3}$ within the cloud region which is consistent with an 80–95% sulfuric acid solution. Below the clouds, the vapor pressure seen by Pioneer Venus is rich in H_2O, but less than the saturated vapor pressure. Thus subsaturations[3] are assumed to be (−1).

5) TEMPERATURE AND PRESSURE PROFILES. A revised temperature profile from Mariner 10 (Kliore, unpublished) and the profile calculated by Muhleman *et al.* (1979) are averaged for the temperature profiles. Mariner 10 pressure profiles are used.

a. Droplet growth

Droplet growth in clouds is a complex process involving condensation and coalescence (Fletcher, 1962; Mason, 1971; Hamill, 1977). Depending on the droplet size, the number density and the droplet distribution, one of these processes usually dominates.

The initiation of either of these processes is highly dependent on the presence of aerosols or ions. In an atmosphere free of such particles, a supersaturation of several hundred percent is necessary to initiate droplet growth, while in an atmosphere containing these particles, supersaturations of only a few percent can initiate cloud particle growth. Such aerosols are usually formed by reactions of atmospheric gases due to heat and radiation, by volcanic dust, and by surface dusts uplifted into the atmosphere by winds. In view of the recent Pioneer Venus results, it is most likely that a photochemical substance such as sulfur is the source of nucleating particles. For the purposes of this paper we will assume the atmosphere of Venus contains sufficient particulate matter to easily initiate condensation.

Condensation is responsible for initial growth. We have assumed that heteromolecular condensation dominates in which two or more vapors condense onto liquid or solid particles. This process has been described in detail by Hamill *et al.* (1977). Briefly, the water vapor pressure of the sulfuric acid droplet is equal to the partial pressure of water vapor in the surrounding atmosphere. The droplet will grow as long as the atmosphere is supersaturated in sulfuric acid vapor. Any sulfuric acid vapor that collides with a solution particle is absorbed. This absorption changes the solution concentration, resulting in a droplet which is undersaturated in water vapor. Water is therefore absorbed and the droplet is again in equilibrium. The rate determining factor then is the frequency of H_2SO_4 molecular collisions. The growth equation is (Hamill *et al.*, 1977)

TABLE 1. Condensation table.

H_2SO_4 [%]	80	85	90	95
P_a [g cm^{-1} s^{-2}]	4.6	16	39	72
$\bar{\nu}$ [cm^3 mol^{-1}]	5.1×10^{-23}	5.6×10^{-23}	6.4×10^{-23}	7.4×10^{-23}
r (μm)		τ (s)		
2	2.1×10^1	6.0	2.2	1.1
5	1.7×10^2	4.8×10^1	1.8×10^1	9.0
10	7.1×10^2	2.0×10^2	7.4×10^1	3.7×10^1
50	1.8×10^4	5.0×10^3	1.9×10^3	9.4×10^2
80	4.6×10^4	1.3×10^4	4.8×10^3	2.4×10^3

h = 50 km; T = 365 K; P (total atmosphere) = 1.2 atm; D = 0.12 cm^2 s^{-1}; r_1 = 1 μm.

$$\frac{dr}{dt} = \frac{DP_a\bar{\nu}}{kTrX(1 + \lambda \mathrm{Kn})}, \tag{1}$$

where r is the droplet radius, $\bar{\nu}$ the average volume per molecule in the droplet, P_a the H_2SO_4 vapor pressure (Gmitro and Vermeulen, 1964), k Boltzmann's constant, T the temperature, X the weight fraction of the solution, Kn the Knudsen number and

$$\lambda = \frac{1.333 + 0.71\ \mathrm{Kn}^{-1}}{1 + \mathrm{Kn}^{-1}} + \frac{4(1-\alpha)}{3}, \tag{2}$$

where α is the sticking efficiency and is taken to be 1 (Hamill, 1977).

Results are shown in Table 1 and Fig. 2. Droplets can reach their critical radii[4] in from 1 to 12 h, depending on the sulfuric acid concentrations. Depending on the updrafts, it is possible for droplets to reach these radii while being uplifted from the bottom to the top of the cloud. For faster updrafts, some turbulent mixing may be necessary in order for droplets to reach their critical radii before being lifted out of the cloud region.

Condensation alone cannot account for droplets of rain size. Coalescence begins to dominate when droplets reach critical radii of about 20 μm under Earth conditions or 80 μm under Venus conditions (see the Appendix). The equation which governs this process (developed from equations in Mason, 1971) is

$$U\int_{r_0}^{r_1}\frac{dr}{EV} - \int_{r_0}^{r_1}\frac{dr}{E} = \frac{1}{4\rho_L}\int_{z_0}^{z_1}M'dz, \tag{3}$$

where U is the updraft velocity, V the terminal fall velocity (see Fig. 3), r_0 and r_1 are the initial and final droplet radii, E the collision efficiency, ρ_L the liquid droplet density, M' the cloud liquid content, and z_0 and z_1 are the initial and final heights the droplet falls or rises as it grows from r_0 to r_1. Terminal fall velocities are calculated using Stokes' law for small drops. Large droplet fall velocities are taken from velocities measured by Gunn and Kinzer

[3] Subsaturation = $(S - 1)$, where S is the ambient vapor pressure divided by the saturated vapor pressure.

[4] The critical radius r_c is the radius at which coalescence begins to dominate over condensation. This is not a strict boundary, but rather a means of simplifying the equations.

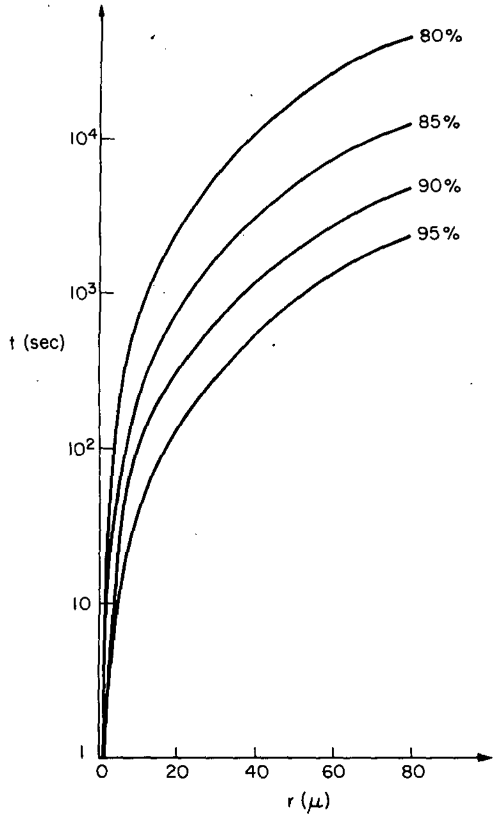

FIG. 2. Time of growth by condensation as a function of drop radius at several sulfuric acid concentrations.

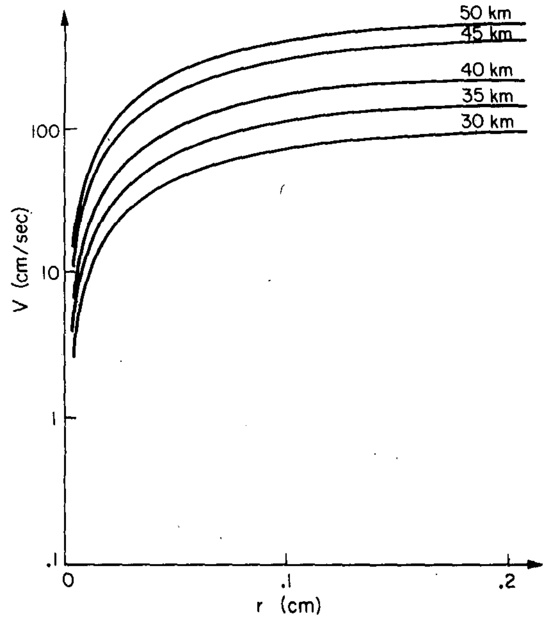

FIG. 3. Terminal fall velocities as a function of drop radius for the large drop case plotted at different heights in the atmosphere from 30 to 50 km.

(1949) with corrections made for temperature, pressure and molecular weight. Collision efficiencies have been calculated in detail by Lin and Lee (1975) for water droplets under Earth conditions. They found that for radius ratios (small to large drops) of from 0.1 to 0.8 and for large drop radii $\gtrsim 40$ μm, the collision efficiency is centered around 1. Since the surface tension decreases as the sulfuric acid concentrations increase (*Handbook of Chemistry and Physics*, 1977), we assume the collision efficiencies on Venus to be also centered around 1. The cloud liquid content is assumed to be 1 g m^{-3}.

The results of these calculations are shown in Fig. 4 for updraft velocities of U = 10, 50, 100, 200 and 500 cm s^{-1}.

As expected, the droplets are first uplifted because their terminal velocity is smaller than the updraft. As their size increases by coalescence, their terminal velocity increases. When the droplet terminal velocity is greater than the updraft velocity, the drops start falling back down through the cloud, continuing to grow. For high updraft velocities, the droplets reach the top of the cloud before they can grow to a size large enough to start falling down. In that case, the formation of precipitation size droplets is unlikely.

The time of growth from the critical radius to the raindrop is a useful calculation for comparing the physics of the Venus clouds to those on Earth. The following equation was used in this calculation (Mason, 1971):

$$4\pi r^2 \rho_L \frac{dr}{dt} = \pi r^2 E V' M', \qquad (4)$$

where V' is the velocity difference between the large and small drops. Fig. 5 shows the radius of the drop due to growth by coalescence as a function of time

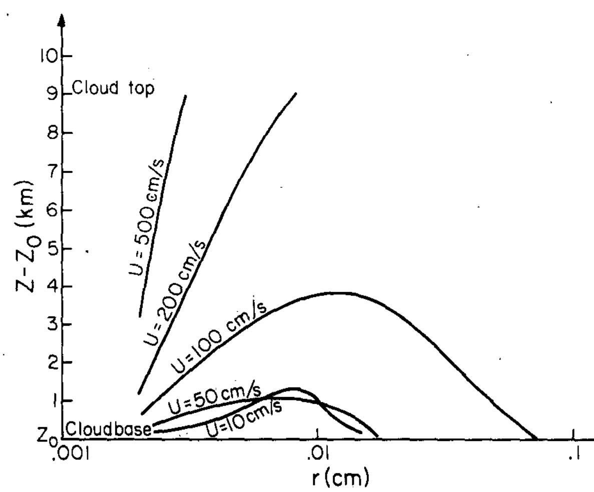

FIG. 4. Drop radius due to coalescence as a function of height from the cloud base $(Z - Z_0)$, where Z_0 is the cloud base. The curves correspond to different updraft velocities U.

for Venus and Earth. For a drop to grow to raindrop size, a period of from 30 min (time for a drop to grow to the minimum fallout radius of 150 μm) to several hours is necessary, depending on how long the updraft sustains the particle in the cloud. Cloud droplets grow only slightly slower (by a factor of about 0.7) on Venus under similar environmental conditions and in clouds of the same liquid content as on Earth. This can be explained with Eq. (4). The gravity on Venus is slightly lower, and the drop density slightly higher than on Earth.

b. Extent of rain region

The vertical thickness of the rainfall may be calculated using the equation (developed by Mason, 1971)

$$-\int_{R_i}^{R_f} \frac{(V-U)rdr}{1+F\sqrt{\mathrm{Re}}} = \int_0^H \frac{(S-1)dh}{X}, \qquad (5)$$

where R_i is the radius of the droplet as it falls out of the cloud and R_f the radius at which the updraft overpowers the fall velocity and the drop is carried up again. F is a ventilation coefficient (Mason, 1971), Re Reynolds' number, h the height below the cloud base, $(S - 1)$ is the subsaturation and

$$X = \left\{\frac{L\rho_L}{KT}\left(\frac{LM}{RT}-1\right) + \frac{RT\rho_L}{DMP_s(T)}\right\},$$

where L is the latent heat, K the thermal conductivity, R the gas constant, M the molecular weight and P_s is the saturated water vapor pressure. If the cloud base is set at $H = 0$, the vertical extent of the rain region will be H. For small increments of radial decrease, the above equation reduces to

$$\frac{dh}{dr} = \frac{XR(V-U)}{1+F\sqrt{\mathrm{Re}}} \times 10^5\ [\mathrm{km\ cm^{-1}}]. \qquad (6)$$

A plot of radius versus height for several initial drop radii is shown in Fig. 6.

An updraft of 1 m s^{-1} will produce droplets 80 μm in radius by coalescence (see Fig. 4). An 80 μm droplet will fall 12 km below the cloud base according to Fig. 6. Thus, the results of these calculations show that the cloud deck on Venus can produce a fairly extensive rain layer—up to 12 km in vertical thickness. This is more than twice as thick as layers on Earth. However, those on Earth are bounded by the solid surface.

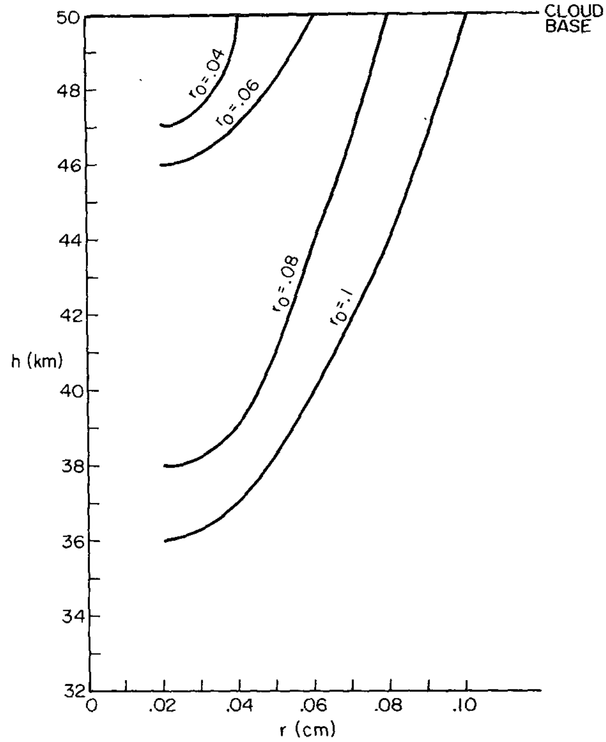

FIG. 6. Drop radius vs height for rain drops falling from the clouds at an initial height of 50 km. Each curve corresponds to a different initial radius r_0 (cm).

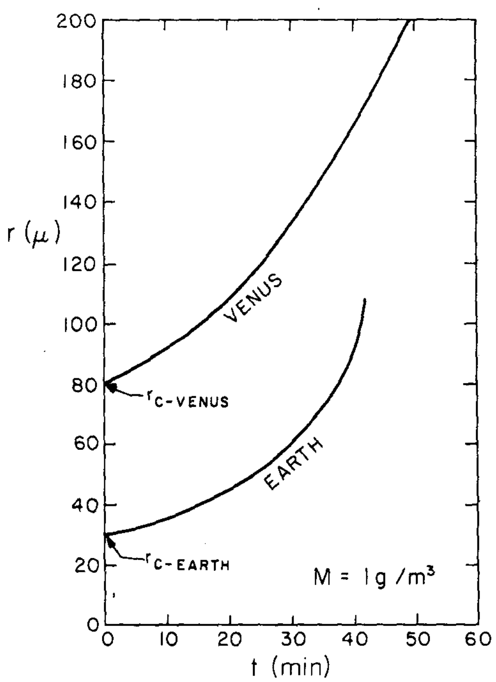

FIG. 5. Drop radius due to coalescence as a function of time for Venus and Earth conditions. A liquid content of 1 g m^{-3} and an updraft of 1 m s^{-1} are used for both planets.

4. Methods for detection of precipitation in the atmosphere of venus

a. Introduction

The cloud particle size spectrometer which was flown on the Pioneer Venus (PV) large probe is capable of measuring particle sizes up to 500 μm (Knollenberg *et al.*, 1977). Thus, precipitating particles could be detected. However, because of the *in situ* nature of the measurement and the limited time during which the probe is in the atmosphere, it is highly probable that no precipitation will be detected even if it usually exists. The possibility of detecting precipitation on Earth at a specific point over a period of a fraction of an hour even if the sky is overcast would similarly be very low.

To obtain a definite answer on the presence of precipitation, a global, long-term remote sensor is necessary. This implies the use of an Earth-based or orbiting spaceborne sensor.

In the remote sensing of Earth precipitation, the most commonly used sensor is radar (Battan, 1973). Meteorological radars are commonly used on commercial aircraft and by meteorologists for precipitation detection and extensive mapping. Passive microwave radiometers are also being used to a limited extent (Allison *et al.*, 1974). In this section we will discuss the possibility of detecting rain on Venus with an Earth-based radar (i.e., such as Goldstone), and briefly touch on the possibility of detection using spaceborne sensors.

When an electromagnetic signal encounters a volume of precipitation particles, energy is scattered in all directions including backward. For a precipitation region with a thickness H along the radar line of sight, the backscatter cross section is given by (Battan, 1973)

$$\sigma = \frac{\pi^5}{\lambda^4} C^2 H Z, \quad (7)$$

where λ is the radar wavelength, Z the reflectivity factor, $C = (\epsilon - 1)/(\epsilon + 2)$ and ϵ is the dielectric constant of the particles' constituents. Most meteorological radars operate in the wavelength regions from 1 to 10 cm. Based on a wide variety of measurements of Earth precipitation, it was found that Z can be expressed as

$$Z = 300 R^{3/2},$$

where R is the rain rate [mm/hr] and Z is in mm^6 m^{-3}. This is a statistical approximation. We will assume that it is still valid for Venus precipitation. For sulfuric acid (and water), the dielectric constant is much larger than unity. This implies that C^2 is approximately equal to 1.

b. Earth-based radar

The backscatter cross section of any reasonable precipitation is appreciably smaller than the backscatter cross section of a planetary surface. At first look, it seems that the echo from the surface will completely overshadow the echo from any precipitation region. However, two favorable factors, unique to Venus, will allow the detection of a return echo from the precipitation.

At X-band frequencies (i.e., 3.5 cm wavelength), the atmospheric roundtrip attenuation at the radar subpoint is in the range 13–18 dB. This attenuation increases nearer to the planet limb because more atmosphere is traversed by the electromagnetic wave. Practically all of the absorption occurs in the lower 45 km of the atmosphere. Thus, the surface echo is appreciably attenuated by the atmospheric absorption while the precipitation echo is only attenuated by the clouds themselves.

The second favorable factor is that the atmosphere, at the level where the precipitation occurs, moves with a horizontal velocity of about $v_p = 50$ m s^{-1} (Antsibor, 1976) while the surface rotates at a much slower rate which give a radar line of sight velocity of $v_s = \pm 2$ m s^{-1} at the equator. Thus, the surface echo will have a Doppler spectrum width at X-band of

$$f_s = \pm \frac{2v_s}{\lambda} = \pm 114 \text{ Hz}, \quad (8)$$

while the precipitation echo could be anywhere over a much wider spectral width of

$$f_p = \pm \frac{2v_p}{\lambda} = \pm 2850 \text{ Hz}. \quad (9)$$

In Fig. 7 we have sketched the relative position of these spectra. It should be pointed out that rain would most likely occur only in limited regions at any specific time. Thus, the spectrum of the rain probably will be patchy as sketched in Fig. 7. The precipitation also has a vertical velocity component of a few meters per second (see Section 3). However, this component is much smaller than the horizontal velocity, and it could be neglected in a first-order calculation.

We now calculate the signal-to-noise ratio of the echo from a patch of precipitation of linear dimension ΔX as seen from the Earth (see Fig. 7). The radar equation is

$$P_r = \frac{P_t G}{4\pi r^2} \sigma \frac{(\Delta x)^2}{4\pi r^2} \left(\frac{\lambda^2 G}{4\pi}\right) \quad (10)$$

and the signal-to-noise ratio

$$\text{SNR} = \frac{P_r}{kT\Delta f} \sqrt{\zeta \Delta f}. \quad (11)$$

The different parameters are defined, and their values given in Table 2. Δf is the Doppler spread which corresponds to ΔX, where ΔX is projected on a plane orthogonal to the Venus-Earth line of sight, i.e.,

$$\Delta f = \Delta x f_p / \rho, \quad (12)$$

where ρ is the radius of Venus. The above three equations give

$$\text{SNR} = \frac{P_t}{(4\pi)^3 kT} \left(\frac{\lambda G}{r^2}\right)^2 \sqrt{\left(\frac{2\rho\zeta}{f_p}\right)} \quad \sigma(\Delta x)^{3/2}. \quad (13)$$

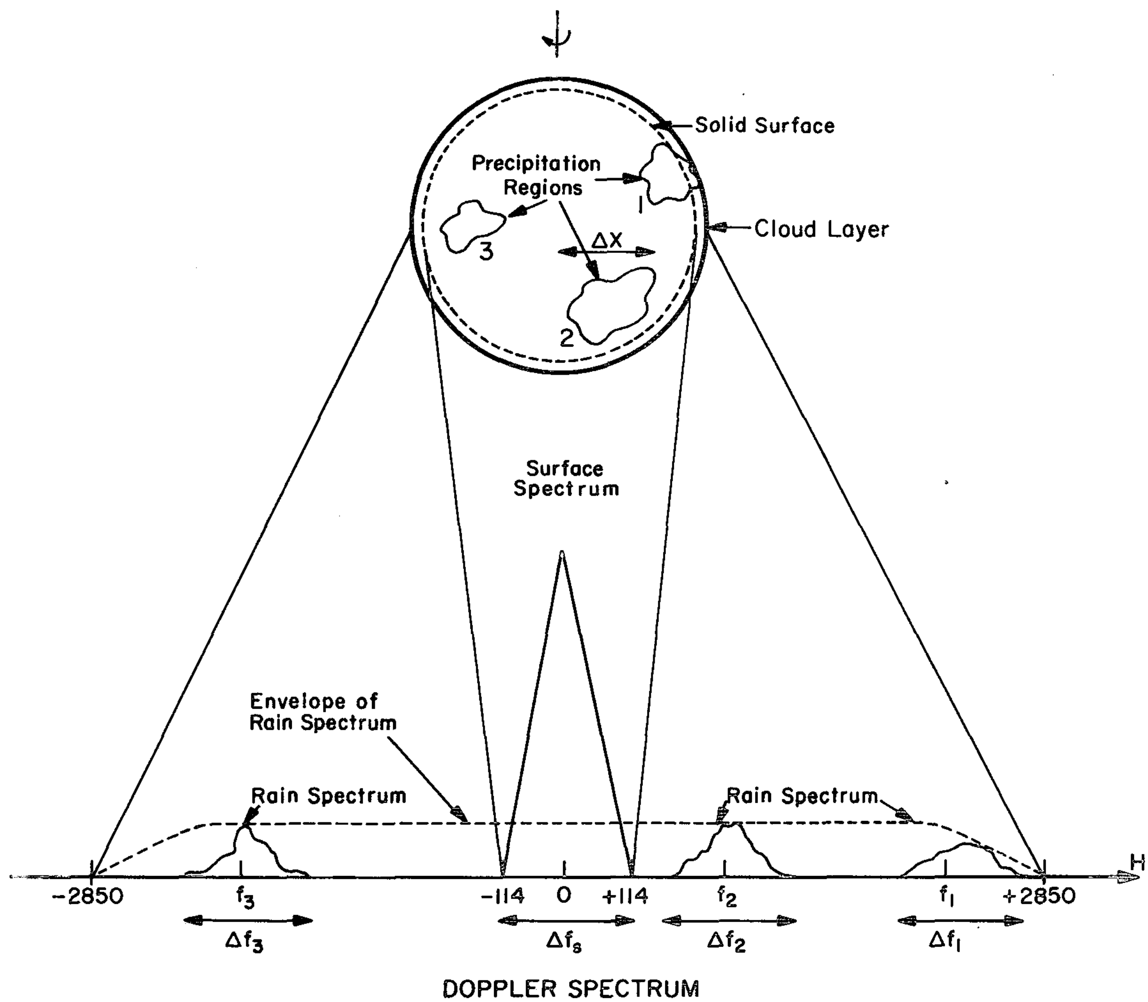

FIG. 7. Illustration of the spectrum of the Earth-based radar returned echo in the presence of localized rain regions. In the center of the spectrum (i.e., $\Delta f_s = \pm 114$ Hz) is the return from the rotating solid surface of the planet. The precipitation regions, if they exist, will be moving with a high tangential velocity because of the atmospheric circulation. Their echos would have a much larger Doppler shift and the corresponding spectrum could be anywhere between ±2850 Hz depending on their location (see text for details).

Using the values in Table 2 and Eq. (7) for the backscatter cross section (i.e., $\sigma = 1.6 \times 10^4 R^{3/2}$), we find that

$$\text{SNR} = 5 \times 10^{-4} (R\Delta X)^{3/2}, \quad (14)$$

where R is in millimeters per hour and ΔX in kilometers. Assuming a minimum detectability SNR of 10 dB, then we obtain

$$R\Delta X \gtrsim 750. \quad (15)$$

This establishes the minimum precipitation region that could be detected with the Goldstone radar. For a weak rate of $R = 1$ mm h^{-1} (i.e., drizzle by Earth standards), the precipitation region must have an extent of at least 750 km on a side as seen from Earth. This corresponds to $f = 360$ Hz. For a rain rate of $R = 10$ mm h^{-1} (average storm by Earth standards), a linear extent of $\Delta X = 75$ km (i.e., $\Delta f = 36$ Hz) is necessary for detection. The extent of these precipitation regions is realistic by Earth standards.

It should be pointed out that the wind velocity will probably be variable over the planet. For the visible clouds, the analysis of the Mariner 10 ultraviolet images gives retrograde zonal velocities of about 80–100 m s^{-1} (Schubert, *et al.*, 1977). The

TABLE 2. Earth-based radar parameters.

Transmitted peak power	P_t = 400 kW
Antenna gain	$G = 1.5 \times 10^7$
Distance (Earth–Venus)	$X = 4.5 \times 10^{10}$ m
Operating wavelength	λ = 3.5 cm
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ W K^{-1} Hz^{-1}
Receiver noise temperature	T = 40 K
Total observation time	ζ = 3600 s
Backscatter cross section	σ = [see Eq. (7)]
Thickness of the precipitation layer	H = 2.5 km

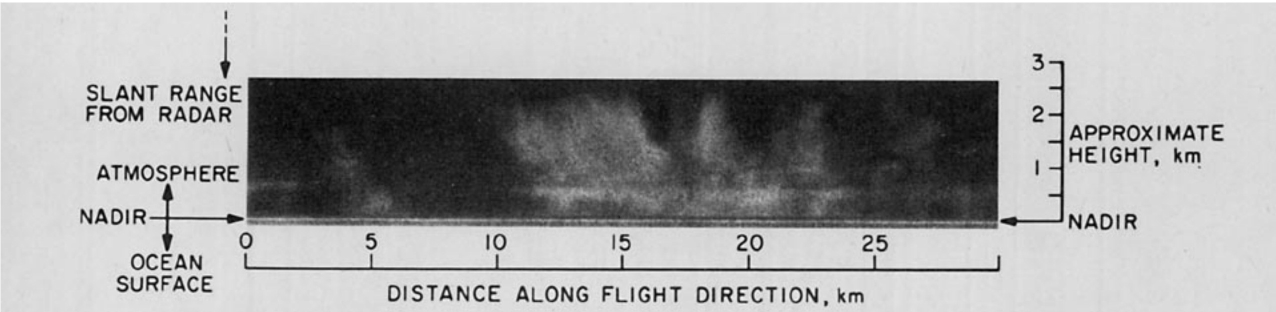

FIG. 8. Example of a vertical profile of an Earth precipitation region obtained with an airborne X-band downlooking radar. The precipitation region extends all the way down to the surface. The upper edge of the precipitation can be easily and accurately measured. The brightness of the image of the rain is directly proportional to the backscatter cross section which in turn is related to the rain rate.

zonal velocities at latitudes between 0° and 45° are comparable, and they decrease at higher latitudes. This suggests a tendency toward conservation of angular momentum equatorward of about 45° latitude, and solid body rotation poleward of this latitude. Similar behavior of the wind probably occurs just below the clouds in the precipitation region with smaller velocities (40–50 m s^{-1}). Thus, the interpretation of precipitation echoes will not be straightforward.

c. Spaceborne sensors

The Earth-based radar technique is the obvious approach to attempt the first detection of rain and give gross estimates of its characteristics. However, it cannot provide high-resolution (in three dimensions) information about the precipitation. This can be accomplished with a bistatic (Earth-spacecraft) technique, a monostatic spaceborne radar sensor or a passive microwave sensor.

A monostatic spaceborne sensor is the most appropriate approach for high resolution mapping of the precipitation. With a downlooking sensor, the precipitation along the spacecraft track could be mapped with high vertical resolution. In Fig. 8 we show an example of precipitation mapping with an airborne X-band radar. Similar capability can be achieved with a Venus orbiting radar. With such a sensor, the location, vertical extent and approximate intensity of the precipitation can be determined. Three-dimensional mapping over a wide swath (hundreds of kilometers) around the flight track can also be achieved with a mechanically or electrically across track scanning beam.

Passive microwave imaging sensors have also been used on airborne and spaceborne platforms to delineate regions of precipitation in the Earth's atmosphere and to determine an approximate value of the rain rate (Allison *et al.*, 1974). The 19.35 GHz scanning radiometer (ESMR), which was flown on Nimbus 5, recorded and mapped the passive microwave emission data to delineate rain areas. Precipitation regions have a high microwave temperature T_B because large droplets with radii >1 mm emit strongly due to the enhanced absorption effect. This effect is caused by the effective size dimension of the droplets being comparable to the wavelength divided by the large index of water at microwave frequencies. A similar sensor could be used on an orbiting platform to detect and delineate the regions of precipitation in the atmosphere of Venus. Because of the very high absorption of the lower atmosphere in the high microwave region (about 40 dB one-way absorption at 20 GHz), the thermal emission from the surface will be completely absorbed and a major source of error eliminated.

The passive microwave radiometer gives wide spatial across-track coverage of the integrated information over the whole thickness of the precipitation region. It does not provide direct information on the thickness or vertical location of the precipitation. In that sense, it complements the radar which can provide accurate height information over a limited across-track spatial swath.

5. Conclusion

One of the main requirements for the possible presence of precipitation on Venus is a large liquid content of the clouds. The calculations in this paper were based on the liquid content derived from the radio occultation measurement on Mariner 10, which is two orders of magnitude larger than the values detected by Venera. However, the Pioneer Venus probe data seem to support the presence of a low cloud deck (~50 km) with liquid content of about 0.1 g m^{-3}. Our results show that precipitation on Venus is not unlikely, and the environmental factors are as favorable as on Earth.

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APPENDIX

Calculation of Critical Radius

When the rate of growth by condensation is the same as the rate of growth by coalescence, a critical radius r_c is reached and coalescence dominates. This radius may be calculated by

$$4\pi r_c D[\rho(a) - \rho] = \pi E r_c^2 V M',$$

where $\rho(a)$ is the vapor density at the drop surface, ρ the vapor density in the atmosphere, E the collection efficiency, V the velocity of the large drop relative to the small drop, m' the liquid content of the cloud and D is the diffusion coefficient. It is assumed that $E \approx 1$ and $r > 1\ \mu$. Drops are assumed to fall at Stokes velocity. Thus, r_c is given by

$$r_c = 3\left[\frac{18D\rho(a)\eta}{\rho g M'}\right]^{1/2},$$

where η is the viscosity of the atmosphere and g the gravity. This gives a value of r_c of about 80 μm for the lower cloud layer.

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