Abstract. The current state of knowledge of the Venusian clouds is reviewed. The visible clouds of Venus are shown to be quite similar to low level terrestrial hazes of strong anthropogenic influence. Possible nucleation and particle growth mechanisms are presented. The Pioneer Venus experiments that emphasize cloud measurements are described and their expected findings are discussed in detail. The results of these experiments should define the cloud particle composition, microphysics, thermal and radiative heat budget, rough dynamical features and horizontal and vertical variations in these and other parameters. This information should be sufficient to initialize cloud models which can be used to explain the cloud formation, decay, and particle life cycle.

1. Introduction

In earth-based observations, Venus has always appeared to be covered by an optically thick cloud canopy. The recent high resolution images obtained by Mariner 10 confirmed that the veil of clouds is unbroken. In the visible portion of the spectrum, these clouds appear as a featureless, uniform layer without temporal or geographical changes in contrast suggesting any morphological structure. Further evidence of cloud continuity and homogeneity is reflected in the lack of thermal hot spots in the infrared (IR). In search of cloud structure, only observations in the near ultraviolet (UV) have been productive. The earliest of these, by Ross (1928), showed cloud features with recognizable temporal changes on the scale of days. These features are produced by a UV absorber which remains to be identified. Although particular suggested UV absorbers are consistent with some observations, inconsistencies generally arise with others.

Our current knowledge of the mysterious clouds of Venus has developed from earth-based spectrophotometer and polarimeter measurements, the Venera entry probe series results, and the Mariner 5 and 10 flyby experiments. However, at least prior to Venera 9 and 10, the more direct measurements of the Venera and
Mariner missions produced as many questions as answers regarding the definition of these ubiquitous clouds.* While the earth-based observations are restricted to the upper visible cloud levels, it is these measurements that first brought us closer to understanding the nature of these clouds. Such measurements showed the clouds to be a very diffuse haze region. Quantitative interpretation of the particle characteristics in these clouds has only been possible with analysis of polarization data taken by various observers. Arking and Potter (1968) performed comparative analyses of the angular distribution of reflected light using multiple-scattering computations with polarization neglected. The work of Coffeen (1968, 1969) concerned the polarization of reflected sunlight and involved comparison with single-scattering computations for spheres. These first efforts were consistent with particles of mean radii of 1 μm and real refractive indices between 1.33 ≤ n_r ≤ 1.70 (Arking and Potter) and 1.43 ≤ n_r ≤ 1.55 (Coffeen). With the work of Hansen and Arking (1971) the refractive index was more accurately defined and the implied assumption of spherical particles was removed. The most definitive and exhaustive study involving multiple-scattering computations was by Hansen and Hovenier (1974). The essential results of that work have defined the following cloud properties:

- **Particle shape:** Spherical.
- **Refractive index:** 1.44 ± 0.01 μm.
- **Effective radius:** = 1.05 μm (mode radius = 0.86 μm).
- **Size distribution:** Narrow with 0.07 μm effective variance† (σ = 0.26 μm).
- **Cloud altitude:** For optical depth = 1 the pressure is ≈ 50 mb.

Kawabata and Hansen (1975) have added the following:

- **Cloud particle number density:** ≈ 30 cm⁻³ at 50 mb.

The narrow tolerances given are required to explain several polarization features. The particles responsible for the observed polarization must be spherical for the glory and rainbow to be observed and the size distribution must be exceedingly narrow in order to produce the anomalous diffraction‡ feature. The

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* The Nephelometer Experiment aboard Venera 9 and 10 appears to have provided the first clear indication of in situ cloud optical properties. The early preliminary results of Marov et al. (1976) generally confirm the diffuse haze cloud model and predicted cloud microphysical properties. Any thorough discussion of the Venera 9 and 10 results must await more detailed analysis.

† The effective radius and variance as defined by Hansen and Hovenier refer to mean cross-section particle sizes as opposed to arithmetic means. Because of the narrow distribution, the difference between mean cross-section and modal size is small.

‡ Anomalous diffraction refers to the observed resonance behavior in scattering due to interference of diffracted and refracted light in forward scattering.
distribution of polarization with phase angle is extremely sensitive to the refractive index. The dispersion of the refractive index was defined from multiwavelength measurements (0.99, 0.55 and 0.36 μm) and the cloud height at optical depth unity from analysis of the Rayleigh scattering contribution at 0.365 μm.

Because the data from which these results were interpreted were from the entire visible part of the planet, it follows that the particle size is very uniform for essentially the complete planetary cloud. It must further be added that the size distribution parameters appear quite consistent for measurements over a period of years. Thus, we conclude that the size distribution parameters as provided are characteristic of an unchanging planetary cloud and exhibit no major seasonal variations.

Following the definition of the physical particle parameters, the reduction of candidates for the cloud particle composition came swiftly. The list was long and included a number of modestly exotic materials, e.g., mercury compounds (Lewis, 1969; Rasool, 1970), polywater (Donahue, 1970), and hydrated ferric chloride, FeCl₂ • 2H₂O (Kuiper, 1969). It is, however, certain today that only sulphuric acid in fairly concentrated form is compatible with the properties as defined by polarization data, spectroscopic observations, and most models for thermal emission. H₂SO₄•H₂O was suggested as the likely candidate for the visible cloud particle composition independently by Sill (1972) and Young (1973) on the basis of the particle properties at the cloud tops and from chemical equilibrium considerations. Pollack et al. (1974, 1975), using aircraft measurements of low resolution infrared spectra of Venus and assuming the particle size deduced from polarization measurements, conclude that of 14 suggested cloud particle materials only concentrated sulphuric acid could account for the absorption features at 3 μm. They also interpret the observed phase angle variations of the radiance observed in the 1 to 6 μm region as implying that H₂SO₄ is present to many tens of optical depths below the cloud tops. Taylor (1975) finds that opacity profiles at two spectral intervals near 11 and 45 μm are consistent with 1.1 μm H₂SO₄ droplets with a small amount of water vapor. Martonchik and Beer (1975) also find good agreement between their 3 to 4 μm reflectivity measurements and an H₂SO₄ cloud. However, they have difficulty in reconciling their observations of IR flux as a function of phase angle with a homogeneous cloud of 1.1 μm droplets. Landau (1975), in particular, cannot reconcile certain of his IR polarization data with the absorption properties of H₂SO₄. The number of these near IR observations is small, however, so further measurements are needed.

Because optical measurements are necessarily limited to the examination of the upper regions of the Venusian clouds, the structure of the bulk of the clouds is unknown. Larger particles or denser clouds (higher concentration) seem probable at lower levels. The simplest model of the H₂SO₄ cloud deck is a homogeneous model wherein the concentration of cloud particles (Nₚ) is proportional to pressure (P) and thus the scale heights for the particles and gas are identical.
However, there is considerable evidence from a number of different types of observations for an increase of \( N_p \) in descending through the cloud mass which is more rapid than linear in \( P \).

The most definitive study of the vertical structure of cloud optical depth was by Lacis (1975). He summarizes evidence on cloud particle properties predicted by a variety of observers and observations (photometry, absorption line analysis, thermal emission spectroscopy, etc.). Defining the ratio of the gas scale height to the particle scale height, \( m = H_g/H_p \), he deduces an increase in turbidity with depth and finds that values of \( m = 2 \) above 50 mb and \( m = 1.5 \) below 50 mb are more realistic than a homogeneous \((m = 1)\) model. Based on Venera 8 measurements he infers a probable decrease in turbidity below 40 km with a relatively clear region between 10 and 30 km. The increase in turbidity beneath the cloud tops is more rapid than in a homogeneous atmosphere and, in fact, at 600 mb he predicts a mean free path of approximately 100 m which is approaching the optical density of certain terrestrial clouds. The results of Venera 9 and 10 reported by Marov et al. (1976) appear to verify Lacis analysis, although the apparent cloud base is higher. The cloud base might well have changed between observations.

There is increasing evidence that \( \text{H}_2\text{SO}_4 \) cloud droplets exist to considerable depths. It is, however, also probable that there are cloud particles other than \( \text{H}_2\text{SO}_4 \); for example, sulphuric acid cannot by itself yield the low UV albedo of Venus. The Venera 8 measurements also suggest considerable cloud structure at depths beneath the range of remote measurements, although a unique interpretation of the Venera 8 measurements is not possible. The ambiguity is largely the result of the fact that only downward solar flux measurements were made by the entry probe. Had upward or net flux measurements been performed as well, confusion as to cloud base levels would not exist.

The amount of absorption of solar UV radiation is only about 4% of the incident solar flux (Lacis, 1975), but the absorption is patchy over the disk giving rise to the UV contrasts. The embedded UV features, which under contrast enhancement resemble terrestrial cirrus clouds, have been a continual source of frustration to investigators. The features do not correlate with such measurable properties as cloud top temperature, pressure, condensation levels, etc. Since the level at which the contrasts arise cannot be defined (cf. Travis, 1975) their association with the \( \text{H}_2\text{SO}_4 \) cloud is also dubious. From an analysis of Mariner 10 result, Hapke (1975) believes that the UV absorbers are well mixed vertically but incompletely mixed horizontally, thus causing the UV markings.

The particle composition responsible for the UV markings may be some form of elemental sulphur. Prinn (1973a, b; 1975) and Hapke and Nelson (1975) have suggested an abundance of mechanisms for liberating elemental sulphur, sulphur oxides, sulphur acids and COS near the surface. In Prinn's work, the photochemically produced \( \text{H}_2\text{SO}_4 \) clouds contain small amounts of UV-absorbing sulphur at lower levels. Prinn believes that COS would be produced near the surface but
Hapke and Nelson emphasize the possible roles played by liquid, solid, and vapor sulphur phases in the meteorology of Venus, similar to the role of \( \text{H}_2\text{O} \) in the terrestrial atmosphere. Another possible UV coloring agent is \( \text{HBr} \), suggested by Sill (1975). This cannot be rejected on the basis of existing evidence, although the requirement for high water mixing ratios \( (10^{-3}) \) is near the upper limits of water abundance estimated by Rossow and Sagan (1975) from microwave emission studies. If the particles are large, differential sedimentation (similar to virga in terrestrial cirrus) and cloud motions could be responsible for the UV markings. Large nonspherical particles would tend to produce a featureless polarization contribution, and thus a significant fraction \( (\sim 25\%) \) of the scattering in the cloud tops could be from particles with physical properties different than those specified above.

Additional evidence of vertical cloud structure is found in Mariner 10 high resolution photographs of the limb. These indicate several layers of tenuous haze at altitudes of 70 to 80 km. Analysis of orange/ultraviolet pairs (O'Leary, 1975) indicates a pressure of 4 mb for the level at which the slant optical path equals unity. These thin haze layers are not to be confused with the lower visible clouds which are themselves more like a haze than like terrestrial clouds. The thin haze layers are not recognizable from earth and have negligible vertical optical depth. It is quite possible that the limb haze layers coincide with the temperature inversions detected by the radio occultation experiment aboard Mariner 5 (cf. Kliore, 1975).

Another interesting feature of the UV clouds is the observed white polar caps (Dollfus, 1975). Based on earth-based photographs, the polar cap clouds are transitory in nature, usually lasting several weeks to months, evolving independently at each pole, and sometimes not being observed for periods of years. It is interesting that regional IR measurements by Coffeen (1968) indicate the same particle size and refractive index at the poles and the equator.

Finally, we must mention the possibility of aeolian transport of dust within 10 km of the Venusian surface. Because of the very dense atmosphere in this region, surface wind velocities less than 0.5 m s\(^{-1}\) (corresponding to frictional velocities of 1 to 2 cm s\(^{-1}\)) are all that is required to lift dust from the surface (Hess, 1975; Sagan, 1975). However, the surface photographs of Venera 9 (Zigel, 1976) indicate low turbidity values.

In all cloud systems there are important couplings between cloud microphysics and dynamics. On Venus, the primary measurements of winds are those obtained from displacements of the UV markings. From Mariner 10 images, Suomi (1975, 1976) finds zonal winds of 90 m s\(^{-1}\) with meridional components of only a few meters per second. The Venera 8 probe measured velocities which decreased from 50 m s\(^{-1}\) at \( \sim 45 \) km altitude to essentially zero at the ground (Marov et al., 1973). Turbulence is strongest at 60 km (in the vicinity of maximum solar heating) with a secondary level at 45 km (Woo, 1975). In general, the cloud dynamics of Venus are poorly understood.
Fig. 1. The diagram depicts our best estimate of the vertical structure of the Venusian clouds. The references cited refer to the adjacent cloud regions. The heating rate is for a nonhomogeneous cloud model, as are the number density estimates. The visual range was calculated by inverting Lacis’s (1975) estimate for particle concentration. Since the number density has as its data base an estimate of particle cross-section, the visual range estimates are more reliable than the number density, which requires assumptions about particle size.

Figure 1 summarizes the variety of the best evidence describing the Venusian clouds. In most cases, the reliability of the information decreases rapidly with depth into the H₂SO₄ cloud canopy. The visual ranges are calculated from the concentrations of Lacis (1975) and are more reliable than the concentrations which depend on an assumed particle size.

The cloud experiments aboard Pioneer Venus will provide an opportunity to obtain information on these clouds at greater depth. The entry probe experiments carrying in situ measuring devices will penetrate all cloud layers between the level of the visible clouds and the surface, thus providing detailed vertical profiles of cloud particle parameters. Experiments aboard the orbiter, through remote measurements at multiple wavelengths and high spatial resolution, can be combined to assess cloud properties at greater depths and define horizontal cloud structure. The entry probe measurements will provide only a fleeting glance of the visible clouds at four locations. If the clouds of Venus were of the same patchwork characterizing terrestrial clouds, chances of success would be inhibited. However, Venus has a planet wide cloud cover of great optical thickness.
which intensive observations have never penetrated, and the planned experiment grouping should indeed return significant data. It is true that the entry probe measurements will define the atmosphere at only one particular time; however the probe will be correlated with nearly simultaneous orbiter data and the continuous orbiter measurements will provide coverage to observe weather related cloud changes.

How well the Pioneer Venus mission succeeds in defining the cloud properties will depend to a large extent on the overall success of the mission. Correct interpretation relies upon substantial integration of data from many experiments. The in situ measurements carried by the entry probes provide the cloud truth from which we can remove constraints and provide atmospheric reference points (calibration) for the model-dependent interpretations of cloud parameters determined from other experiments. The orbiter experiments provide global coverage and tell us how representative the local entry point measurements are.

Some comparative aspects of Venusian and terrestrial clouds is given in the next section. In the third section, the primary cloud and cloud-related experiments are discussed followed by the expected scientific results. A detailed description of the experiment instruments is given elsewhere (Colin and Hunter, 1976, this issue).

2. Some Comparative Venusian and Terrestrial Cloud Physics

From Figure 1, it is obvious that the visible Venusian clouds are not clouds by terrestrial standards at all. They have visual ranges through great depths which are greater than that required of aircraft for noninstrument flight conditions and their total columnar mass amounts to only about 1 mm of precipitation. They appear to be stagnant and their potential for precipitation must be nearly negligible even though the particle lifetime is probably many times longer than that in terrestrial clouds. What then are they?

The closest obvious terrestrial counterpart to the Venusian clouds has to be the Junge layer of stratospheric aerosols which exists at a pressure level of approximately 50 mb and at temperatures similar to those of the upper levels of the Venusian clouds (Hunten, 1971). The average particle size and the variance of the size distribution for the visible Venusian clouds are similar to these terrestrial stratospheric aerosols (Hansen and Hovenier, 1974) and indeed the particle composition is apparently highly concentrated sulphuric acid in both cases. However, the similarity does not hold for the total optical thickness of the aerosols. The terrestrial stratospheric Junge layer usually has an optical thickness of ~0.01 to 0.05 while Marov et al. (1976) estimate 20 to 55 for Venusian clouds.

However, there is a different terrestrial comparison which emphasizes the current relevance of studying the Venusian H$_2$SO$_4$ cloud system. The following observations of Braham (1975) are timely. During periods of pollution alerts, such as that which occurred on 28 June, 1975 for the entire state of Illinois, it has been
observed that the visibility is very poor over large state-wide regions without any
direct association with one source region. In the example cited, the meteorological
regime was characterized by a stagnating anti-cyclonic mixing layer capped by a
subsidence inversion. Direct observations in this multistate haze layer revealed
that the upper part of the mixed layer was characterized by isolated scud type
stratocumulus with minimum visibility in the upper half of the haze layer. This
haze layer was characterized by 3 to 4 μm diameter solution droplets with
perhaps 1 cm⁻³ as large as 10 μm in size. There was sufficient correlation between
total vertical SO₂ measurements and Aitken nuclei measurements to infer that the
particles were at least sulphates in solution if not indeed solution droplets of
H₂SO₄.*

It is theorized that the H₂SO₄ droplets in this type of cloud-haze system are
concentrated by recycling within the small scud cloud layers near the top of the
haze. Thus, the growth of fairly large concentrated solution droplets requires
hours rather than days. The H₂SO₄ droplets formed have the ability to survive
advection over large distances as well as substantial vertical convection, and an
observed feature of these dispersed particles is that the visibility is totally
decoupled from the source region. It is clear that this haze, or disperse cloud,
ever produces precipitation. One further note is that sulphate measurements in
rain are consistent with an atmospheric half-life for scavenged SO₂ of only 4 to
5 hr. One can easily speculate as to the resultant atmospheric state were it not for
the scrubbing that natural rainfall gives our terrestrial atmosphere.

Thus, we do have Venusian type clouds in our terrestrial atmosphere and one
does not have to go to the stratosphere to find them. The particle size, opacity,
chemical composition and morphology are indeed quite similar. The similarity in
chemical composition is particularly intriguing. There is an increasing amount of
research on anthropogenic sources of cloud nuclei and lower tropospheric haze
particles (both of which are predominantly sulphates). Sulphates are the primary
condensation nuclei of all terrestrial clouds including those of remote areas. Fenn
et al. (1963) have reported that about 40% of the mass of the aerosol in air above
the Greenland ice cap is sulphates and Cadle et al. (1968) found 50% of Antarctic
air particulates were sulphates. Sulphates normally co-exist with ammonia and by
inference it is supposed that they are ammonium sulphate; however, H₂SO₄ is
also often found. In general, chemical analysis suggests less NH₄⁺ relative to SO₄²⁻
than (NH₄)₂SO₄ stoichiometry requires (see Junge and Manson, 1961 and Lazrus
et al., 1971). Electron microscopy of collected particles often shows evidence of
liquid phase suggestive of sulphuric acid (Mossop, 1963, 1965). The role of
ammonia will be discussed further; however, the primary point to make is that the
visible Venusian clouds are quite similar to the solution droplets characterizing

* Braham (1975) further suggests that the Junge layer may be enhanced through low level terrestrial
pollution by the role of strong vertically developed clouds. He cites as evidence the preference of
tallest echos during thunderstorms for formation over or just downwind of cities such as St. Louis.
Strong vertical motions within thunderstorms would thus transport sulphates to the Junge layer
enhanced by the high concentration of SO₂ associated with metropolitan regions.
terrestrial haze, precloud, and the disperse clouds of strong anthropogenic influence. It is instructive to cross-fertilize as much as possible between these areas, particularly in the area of microphysics, which is least known for Venus.

One area of microphysics where we may benefit from current terrestrial cloud studies with regard to the Venusian clouds is in formation processes. There have been detailed photochemical models (Prinn, 1974, 1975) presented for the production of various cloud constituents and their parent vapors. However, at the present time, we know nothing of the possible mechanisms which generate the embryonic cloud nuclei from which the H₂SO₄ droplets must evolve. In our own terrestrial atmosphere, cloud water droplets form on aerosol particles which are predominantly sulphates and are typically several hundred Angstroms in diameter. Common terrestrial clouds form when a slight supersaturation of water vapor is present although terrestrial haze layers never reach saturation. Typical transitions from the embryonic state to the growing cloud droplet follow what is known as a Kohler (1926) curve, an example of which is shown in Figure 2. The regions

![Equilibrium Saturation Ratios for H₂SO₄ Droplets](image)

Fig. 2. Curves of equilibrium saturation ratios of H₂SO₄ droplets containing the stated initial masses of H₂SO₄ compared with Kelvin curve for pure water droplets. Note the scale change at 0.99 saturation ratio and the initial rapid change in size at low saturation ratios, which is particularly applicable to the Venusian H₂SO₄ cloud system.
to the right of the curve maxima are regions of stable droplet growth. The phenomenon of passing through the supersaturation barrier is known as activation. Cloud droplets are generally not activated unless there is a supersaturation typically ≤1%. Even so, close cloud observations invariably reveal a precloud layer well below, and haze layers outside of, the nominal optical cloud boundaries.

Soluble nuclei are the preferred cloud condensation nuclei (CCN) since even higher supersaturations are required for droplet formation on insoluble particles or by homogeneous nucleation from the vapor. Because the nuclei are in general quite small, the solution droplets are quite dilute at the time of activation. Giant nuclei (0.1 μm) reach activation at larger sizes and at elevated heights above cloud base.

Using the above background to examine the formation and nature of the Venusian H₂SO₄ clouds, one first concludes that these clouds are composed of particles resembling terrestrial unactivated (giant) cloud nuclei growing within a parent water phase (H₂SO₄ droplets are closest to being in vapor equilibrium with water since at all concentrations <95% H₂SO₄, water has the higher partial pressure and is nearly 100 times the vapor pressure of H₂SO₄ at concentrations below 65%). They differ largely in the concentration parameter. It has also been asked why the size spectrum of the Venusian H₂SO₄ cloud is so narrow (Young, 1975; Hunten, 1975). Steady-state coagulation processes produce size spectrum narrowing and, additionally, there is a narrowing of the size distribution during initial cloud formation in terrestrial clouds produced by diffusional growth (see cloud physics texts e.g., Fletcher, 1962). This narrowing from an initial broad size spectrum of condensation nuclei available in the atmosphere is the result of the fact that the growth rate is proportional to \(1/r\). As long as the vapor supply lasts, the spectrum narrows. While there is an extremely low vapor density in equilibrium with the Venusian clouds and the growth rate is very slow, the same result could be expected. It is sometimes misconceived that, because of the very slow growth and decay rates of H₂SO₄ droplets, they are in equilibrium; however, they can easily exist in nonequilibrium. The time scale can simply be very long due to the small vapor density gradients. For example, an ice crystal evaporates more slowly at -50°C and 0% relative humidity than at 0°C and 99% humidity.

There is one subtle feature of the H₂SO₄ droplet curves in Figure 2. At very low saturation ratios there is a sharp increase in size with increasing saturation ratio. This is primarily due to the two orders of magnitude change in H₂O chemical activity, and thus in equilibrium vapor pressure for concentrated solution droplets, with a concentration change of only 20% (e.g., 85% to 65%). The activity of water in H₂SO₄ increases above 0.5 only at concentrations <45% H₂SO₄. Conversely, the activity and partial pressure of H₂SO₄ increase with increasing concentration. Thus, a growing H₂SO₄ droplet may grow at high concentrations by adding H₂O molecules and at lower concentrations by adding H₂SO₄. Natural gradient fluctuations could thus provide continuous growth as
long as the droplet remained highly concentrated. The growth rate from $\text{H}_2\text{SO}_4$ molecules is extremely slow due to the small $\text{H}_2\text{SO}_4$ gradient but we must keep in mind that a droplet's in cloud residency is extremely long.

On both Venus and Earth the $\text{H}_2\text{SO}_4$ molecule is presumably produced through reaction of $\text{H}_2\text{O}$ and $\text{SO}_3$, with $\text{SO}_3$ possibly produced as suggested by Cadle and Powers (1966):

$$\text{SO}_2 + \text{O} + \text{M} = \text{SO}_3 + \text{M}.$$ 

Prinn (1975) has shown rapid conversion using OH or HO_2 intermediates, but their existence is uncertain. Scott and Hobbs (1967) show that $\text{SO}_4^-$ production from $\text{SO}_3$ is 500 times faster in the presence of $10^{-5}$ mb of NH_3 (undetectable by spectroscopic earth-based measurements). Laboratory investigations by Friend et al. (1973) favor intermediate ammonium salts. Laboratory mixtures of ammonia, $\text{H}_2\text{O}$, $\text{SO}_2$, and UV rapidly produce $\text{H}_2\text{SO}_4$ Aitken particles. However, except for noting the interesting possibility of explaining both the Russian NH_3 measurements using chemical methods (Surkov et al., 1973) and the lack of spectroscopic evidence for NH_3 by western observers, we offer no suggestion of the details of $\text{H}_2\text{SO}_4$ production.

The initial formation of $\text{H}_2\text{SO}_4$ droplets on Venus may well be quite similar to terrestrial $\text{H}_2\text{SO}_4$ droplet formation. All such processes are model dependent, and the one suggested here may not be valid, but it offers a convenient nucleation path. We previously mentioned that the growth of water droplets from a pure vapor phase generally involves intermediate nuclei (heterogeneous nucleation). Homogeneous nucleation of water requires a saturation ratio of 4 which is in many ways a reflection of the small molecular size of $\text{H}_2\text{O}$. $\text{H}_2\text{SO}_4$ is, however, a much larger molecule with greater embryo stability and nucleation while homogeneous is also probably heteromolecular (water vapor plus $\text{SO}_3$). Free energy calculations show that $\text{H}_2\text{SO}_4$ particle sizes of 50 Å are comparatively more stable than 5000 Å water droplets. In fact, Kiang and Stauffer (1973) have calculated critical radii of approximately 8 Å for stable $\text{H}_2\text{SO}_4$ droplet embryos at 50% humidity.

Pure $\text{H}_2\text{SO}_4$ is a colorless liquid, as are its aqueous solutions; however, the phase diagram of the $\text{H}_2\text{SO}_4$-$\text{H}_2\text{O}$ binary is complicated by the formation of eutectic hydrates.* The most common hydrates, $\text{H}_2\text{SO}_4 \cdot \text{H}_2\text{O}$ (mp 8.5°C) and $\text{H}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$ (mp -38°C) would be expected in the Venusian upper atmosphere. Further hydration by $\text{H}_2\text{O}$ ($\text{H}_2\text{SO}_4$ hydrates up to $\text{H}_2\text{SO}_4 \cdot 8\text{H}_2\text{O}$ are known) produces embryos of sufficient size to be relatively stable and result in fairly rapid

* $\text{H}_2\text{SO}_4$ droplets will also supercool and supersaturate well below their eutectic or freezing points. Because of the lowered volume free energy of solution droplets they will supercool more than water droplets. Pure water homogeneously nucleates ice at $-40^\circ$C. One can approximate the additional supercooling of $\text{H}_2\text{SO}_4$ droplets by subtracting the bulk freezing point depression from $-40^\circ$C (see Knollenberg 1969 for computational details). Nucleation temperatures of from $-80^\circ$C to $-100^\circ$C would be expected unless the $\text{H}_2\text{SO}_4$ supersaturates enough to enhance nucleation of crystalline $\text{H}_2\text{SO}_4$. 


coagulation. Within a few days the size distribution would approach the self
preserving distribution resulting from steady-state coagulation. This process can
be qualitatively explained by small particles, having higher mobilities and collision
rates, colliding with themselves or larger particles, rather than larger particles with
each other. In such a case, the large particle end of the spectrum is essentially
unchanged, whereas the amount of loss at the small particle end is proportional to
time. The coagulation rate increases rapidly for broad initial distributions; how-
ever, it would not be expected to produce micron sized H₂SO₄ droplets in less
than days and diffusional mechanisms are probably faster.

The macro-molecular-sized hydrated sulphuric acid embryo is the easiest way
for H₂SO₄ to retain water molecules at small sizes (<0.01 μm) and low humidity.
The formation of larger embryos proceeds through further hydration and coagula-
tion prior to the formation of H₂SO₄ solution droplets. The onset of H₂SO₄
solution droplet formation is H₂O vapor dependent but requires particle sizes of
the order of 0.1 μm for 1% humidity at 0°C. With increased relative humidity or
droplet size, the droplets grow not only by condensation of water vapor, but by
the condensation of solute molecules or hydrated embryos (heteromolecular
condensation).

That H₂SO₄ droplets are stable is irrefutable. How large they grow and to what
depth in the Venusian atmosphere they remain stable and highly concentrated is
open to question. The Pioneer Venus experiments will provide detailed measure-
ments of the cloud particle size distribution. With the added measurements of the
equilibrium vapor constituents, the formation of these clouds can be approached.

As opposed to terrestrial clouds, it is most likely that Venusian cloud particles are
not generated at the cloud base. It is quite clear that the production of SO₃,
H₂SO₄, and H₂SO₄ hydrates occurs at high altitudes where UV radiation is
plentiful. Embryonic particle formation continues through coagulation until small
stable solution droplets are grown. These solution droplets grow through diffusion
of both solute and solvent molecules. They grow to increasing size and/or
increasing concentration with depth most likely because of enriched parent
vapors.

3. Proposed Pioneer Venus Cloud Experiments and Expected Scientific Results

3.1. Proposed experiments

Determination of the physical, chemical, and optical parameters characterizing
the cloud and haze particles of the Venusian atmosphere will be accomplished by
direct in situ measurements from the probes entering the atmosphere, as well as
inferred from indirect measurements made from the probes and the orbiter. Principal in situ measurements will be accomplished during descent by the
instruments carried on the one large probe, and supplementary in situ measure-
ments of planetary variability of some of the parameters will be derived from the
experiments delivered to different parts of the planet on the small probes. Orbiter
A summary listing of the objectives of the proposed Pioneer Venus cloud experiments is given in Table I. The listing differentiates between primary cloud experiments and cloud related experiments. Cloud related experiments are those which provide measurements from which cloud properties are to be inferred. These include \textit{in situ} optical and state parameter measurements and orbiter optical measurements. It should be pointed out that almost all experiments in one way or another can contribute to our understanding of the clouds. For instance,
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<td></td>
<td>Rng#1 = 0.5–5 μm</td>
<td>Rng#1 = 0.5 μm</td>
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<td></td>
<td>Rng#2 = 5–50 μm</td>
<td>Rng#2 = 5 μm</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Rng#3 = 20–200 μm</td>
<td>Rng#3 = 20 μm</td>
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<td></td>
<td></td>
<td>Rng#4 = 50–500 μm</td>
<td>Rng#4 = 50 μm</td>
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<td></td>
<td></td>
<td>Practically unlimited</td>
<td>Practically unlimited</td>
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<td></td>
<td>2. Particle concentration</td>
<td>Practically unlimited</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Particle aspect ratio</td>
<td>~20%</td>
</tr>
<tr>
<td>Cloud Photopolarimeter Orbiter Imaging Experiment (OCPP)</td>
<td>Spin-scan mapping of planet and vertical scanning of limbs</td>
<td>Horizontal: ~500 km (sub-satellite)</td>
<td>1. Photopolarimetry:</td>
<td>Intensity: ~5%</td>
<td>Imaging S/N ~100</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>· Degree of polarization</td>
<td>Polarization: ~0.1–0.3%</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>· Direction of vibration</td>
<td></td>
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<td></td>
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<td></td>
<td>· Intensity</td>
<td></td>
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<td></td>
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<td></td>
<td>Horizontal: ~30 km</td>
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<td></td>
<td>2. Imaging: Intensity in 300–390 nm spectral band</td>
<td>Mapping: One full planetary image in $3\frac{1}{2}$ hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vertical: ~0.5–1 km</td>
<td>Imaging S/N ~100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Limb scanning: Intensity in 650–750 nm passband</td>
<td></td>
</tr>
<tr>
<td>Experiment</td>
<td>Vehicle</td>
<td>Measurement profile</td>
<td>Spatial resolution</td>
<td>Measurements performed</td>
<td>Dynamic range</td>
<td>Resolution</td>
</tr>
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</tr>
<tr>
<td>Solar Net Flux Radiometer (LSFR)</td>
<td>Large Probe</td>
<td>Vertical profile from 67 km to surface</td>
<td>Vertical: 300 to 800 meters</td>
<td>Sunlight intensity in narrow angular and spectral bands at fixed zenith and azimuthal angles plus broadband flux measurements</td>
<td>150 db</td>
<td>Narrow band ~ ±2% Flux ~ 4%</td>
</tr>
<tr>
<td>Orbiter Infrared Radiometer (OIR)</td>
<td>Orbiter</td>
<td>Slant range profiles down to 50 km</td>
<td>Horizontal: ~5-50 km Vertical: ~3-300 km</td>
<td>Temperature field and water vapor distribution providing 3-dimensional structure maps</td>
<td>Vertical coverage: Temperature: 60-160 km 0.5 K at 240 K Water vapor: 10 precip. μm</td>
<td></td>
</tr>
<tr>
<td>Orbiter Ultraviolet Spectrometer (OUVS)</td>
<td>Orbiter</td>
<td>Horizontal non-overlapping scans</td>
<td>Horizontal: 3×0.5 km max.</td>
<td>Backscattered sunlight in UV</td>
<td>512 steps in spectral range of 1900-3400 Å 1.5 Å</td>
<td></td>
</tr>
<tr>
<td>Neutral Particle Mass Spectrometer (LNMS)</td>
<td>Large Probe</td>
<td>Vertical profile from 67 km to surface</td>
<td>Vertical: approximately 60 mass spectra during descent</td>
<td>Measure abundances and identify atmospheric gas constituents</td>
<td>1-208 AMU</td>
<td>1 ppm resolution 20% accuracy</td>
</tr>
<tr>
<td>Gas Chromatograph Analyzer (LGC)</td>
<td>Large Probe</td>
<td>Vertical: 3 complete samples during descent</td>
<td>Vertical: 56-142 meters</td>
<td>Abundances of heavier gases. Relevant to clouds are CO2, NH3, COS, H2S, SO2, H2O, C2H6 and HCl</td>
<td>10⁵</td>
<td>8-54 ppm</td>
</tr>
</tbody>
</table>

* In this table we have included only the portions of the experiments which relate to clouds.
the atmospheric structure experiment (LAS/SAS) provides the required pressure-altitude reference and ambient temperature from which we will tag cloud levels. Such experiments are not, however, necessarily sensitive to the presence of clouds and are not discussed in detail here. Tables II and III are listings of the descriptive data and parameters characterizing the cloud experiments.

3.2. Expected scientific results

3.2.1. Cloud Particle Parameter Measurements

The principal particle parameters to be measured directly or inferred from indirect measurements are those which characterize the cloud microphysics, as well as the changes in these quantities associated with larger scale cloud behavior. In this group are: (1) particle size distribution (2) shape (3) concentration and (4) optical parameters—especially the scattering cross-section. Larger scale cloud behavior will be interpreted from changes detected in the vertical or horizontal homogeneity in any of these parameters.

3.2.1.1. Size distribution. The most significant size distribution data is expected from the direct in situ measurements obtained from the cloud particle size spectrometer (LCPS). Data will be obtained in four major size ranges covering 34 size classes. Data will be transmitted from each size range at least once every eight seconds from the time of jettison of the main probe aeroshell to impact, i.e., from an altitude of approximately 67 km to the surface. Vertical resolution for the measurement will thus vary from about 800 m at first to about 100 m at impact.

The radiation scattering experiments on the probes will obtain data which can be used to constrain the particle size distribution. The narrow-band solar net flux radiometer (LSFR) channel measures the intensity of the radiation field as functions of zenith and azimuth angles from the sun. The form of the azimuth dependence at optical depths less than about 5 must be consistent with that computed from the size distribution measured by the LCPS.

The Nephelometer (LN/SN), carried on all four entry probes, incorporating two background detectors operating in spectral ranges of 320 to 390 nm and 460 to 580 nm and viewing the ambient scattered radiation at zenith angles of 85° on the large probe and 80° on the small probe, will provide a series of azimuthal data at the higher elevations. These data, in turn, will be compared with scattering functions computed from trial distributions measured on the large probe and inferred from other data.

Several experiments on the large and small probes will obtain data on ambient radiation fluxes and changes in these fluxes with altitude. Especially at altitudes where the optical depth into the atmosphere is modest (<5), these data will provide consistency tests for any particle properties determined by other means.
For example, total attenuations of solar radiation measured as a function of altitude must be compatible with particle concentrations, size distributions and particle optical constants determined from other experiments. The flux experiments on the large probe include the infrared radiometer (LIR), the LSFR, and the LN. The small probes will carry the net flux radiometer (SNFR) and the SN.

The LN/SN will obtain, at a wavelength of 900 nm a measure of the product of $N(d\sigma/d\Omega)$ where $N$ is the particle density and $(d\sigma/d\Omega)$ the effective particle differential scattering cross-section in the backward direction. These measurements when combined with particle concentration data again yield cross-section data for comparison with those determined from experimentally measured size distributions. The scattering phase functions can also be computed from LCPS size spectra and inferred refractive indices.

Three instruments carried on the orbiter, the cloud photopolarimeter (OCPP), the ultra-violet spectrometer (OUVS), and the infrared radiometer (OIR), will yield significant information from which particle parameters may be inferred. All of these experiments, with various angular resolutions measure radiation arriving from the planet in various spectral bands, at various angles with respect to the roll axis, and in one mode, the OCPP measures the polarization of the reflected radiation. Scans across the planet or the atmospheric limb are accomplished by utilizing the spin of the orbiter and along track scanning is accomplished by the orbital motion of the orbiter. The OUVS and OIR look angles will be fixed at 60° and 45° respectively while the OCPP telescope is pointable to allow the possibility of observations throughout the orbit; this pointing capability will permit simultaneous measurements of a given location on the planet with either the OUVS or OIR as well as repeated measurements of a given location from several points in the spacecraft orbit.

The photopolarimetry and limb scanning modes of the OCPP are of primary interest for particle parameterization. Remote sensing of reflected sunlight to measure cloud and particle properties relies on the dependence of the polarization of the measured light on the particle properties. In addition, the polarization is also dependent on scattering properties of the atmospheric gases and on the distribution of particles in the atmosphere. Comparison of such measured polarization data taken at several scattering angles and zenith angles and in four spectral regions, with theoretical calculations involving particle size distribution, shape, optical properties, and vertical distribution will yield best-fit inferences about these quantities.

The OIR will, in addition to other measurements, give data from which the relative opacities of the higher cloud layers (i.e., above a pressure of about 100 mb), at 2, 15, and 45 μm are expected to be inferred. In addition, the vertical and horizontal distribution of cloud opacity at 15 μm will be obtained. These data, while not uniquely identifying particle composition or size distribution, will strongly constrain these parameters so as to act as a further input for the analyses of data from the OCPP and the OUVS.
3.2.1.2. **Particle shape.** The length of time for a particle to pass through the sensitive volume of the LCPS along with the measured large probe descent velocity and measured particle size for that particle, form the basis for an aspect ratio measurement in the 50 to 500 μm size range. Such a measurement will distinguish between highly asymmetric solid particles and more spherically shaped solids or liquids.

Highly aspheric or crystalline particles will also strongly affect particle angular scattering functions, especially at large scattering angles since surface wave scattering is suppressed in the case of scattering by nonspherical particles. Therefore, the data on the single-scattering functions will also contain information on particle shape.

3.2.1.3. **Particle concentration.** The only direct measurement of total particle concentration as a function of altitude will be obtained from the data collected by the LCPS on the large probe. These data are available by summing the number of particles per unit volume for all of the size channels measured by the instrument. Very small particles of diameters less than about 0.5 μm will not be counted. Particle concentration will, thus, be available from about 65 km to the surface with a vertical resolution of from 800 to 100 m.

If the particle size distribution and optical properties are available as a function of altitude from the results of any of the experiments described below then the data from a number of other experiments on the probes may be used to obtain the local particle concentration. From the LN/SN effective cross-section measurements, the particle concentration is easily computed. Similarly, several experiments will measure the optical opacity of the clouds as a function of altitude in several wavelength intervals. Once the total effective cross-section of the particle is known, then the local particle concentration may be derived from the change in opacity with altitude.

3.2.1.4. **Optical parameters.** Besides the obvious computation of cloud particle optical properties from LCPS data, the particle optical parameters will be inferred from radiation scattering experiments. The principal data obtained, as described above, involve as a function of altitude: (a) the angular-scattering functions for sunlight as a function of wavelength, (b) spectral measurements of ambient radiation, (c) net flux measurements in several spectral ranges, and (d) the backscatter or lidar cross-section at a fixed wavelength.

At altitudes such that the optical depth of the atmosphere is small (on the order of one or less) the angular-scattering functions measured may be assumed to be due to single scattering and are thus accurate representations of the scattering properties of the particles. If the detection geometry is accurately determined and the detector is absolutely calibrated and since the incident solar flux is well known, it is also possible to derive an absolute (as well as relative) differential
scattering cross-section by using the measured concentration of particles. Attempts may then be made to fit these angular functions of intensity or polarization, using either the measured or trial particle size distributions, assumed indices of refraction (including imaginary components), and assumptions concerning sphericity or non-sphericity of the particles. Such calculations thus yield best-fit values for the indices of refraction of the particles, strongly hinting at their composition and also may indicate sphericity or non-sphericity of the particles. Such calculations may also test the particle size distribution for best fit. Techniques for making these calculations are discussed by Hansen and Travis (1974) and Kerker (1969). The experiments that are expected to obtain such angular data include the LSFR on the large probe, the OCPP and the OUVS on the orbiter and perhaps the LN/SN on all the probes.

The attenuation of solar flux with depth into the atmosphere may also be used to determine the total cross-section of the particles at altitudes such that offsets due to multiple scattering are unimportant. For this measurement, as well as the net flux experiments, the quantity measured depends on $N\sigma_T \Delta \chi$ where $\Delta \chi$ is a distance over which the change in solar flux is measured (including slant path effects), $N$ is the particle concentration derived from other experiments, and $\sigma_T$ is the total cross-section. Experiments included in this category include the LSFR, LIR and LN on the large probe, the SNFR and SN on the small probes, and the OCPP and OUVS on the orbiter.

Finally, the calibrated LN/SN on all of the probes also measures the light backscattered from an on-board light source. If the particle density is determined from another experiment, the effective particle differential cross-section at $\sim 175^\circ$ is immediately obtained.

3.2.2. Vertical and Horizontal Distributions of Clouds and Haze

Information from several experiments on the Pioneer Venus orbiter and probes should provide a large improvement in our knowledge of the spatial distribution of atmospheric particulates.

At levels above the main visible cloud layer (i.e., above 65 to 70 km altitude) information on the haze particles will be obtained by remote sensing from the orbiter, primarily by the OCPP, OUVS, and OIR experiments. The vertical distribution of particles for altitudes 75 to 90 km should be revealed by the visual limb scans of the OCPP, in a manner analogous to the detection of limb hazes by Mariner 10 (O'Leary, 1975): the resolution of the OCPP limb-scan will be $< 1$ km for latitudes between $\sim 60^\circ$N and $\sim 20^\circ$S. The OUVS will also be sensitive to scattering by particles at these high altitudes, and in addition it may be possible to relate thermal structure observed by the OIR to aerosol layering.

The level of the visible clouds (60 to 70 km altitude) will be sensed at least in part by instruments on both the orbiter and probes, providing an important overlap for cross-calibration. The OCPP will derive information on the vertical structure by means of polarization observations of particular local areas from
different zenith angles, and information on the particle microstructure from the variation of polarization with phase angle.

The OIR will obtain the temperature field and the water vapor distribution with a resolution ~5 km. Global coverage at high spatial resolution will result in three dimensional structure maps which will be informative as to the chemical processes of cloud formation and atmospheric circulation. As an additional aid in constructing such maps, there is a spectral channel for measuring all radiation shortwards of 4 μm which will be used to detect spatial variations in the reflectivity of the clouds for solar radiation. It can function in the downward-looking mode to monitor horizontal variations and also in a limb-scanning mode to obtain information on vertical cloud structure. An additional channel, centered in the 2 μm band of CO₂, will be sensitive only to a cloud layer existing well above the main cloud deck, thus allowing an independent check on cloud layer results obtained from temperature sounding measurements.

On the large probe the LCPS will directly measure cloud particle size for particle diameters between 0.5 and 500 μm, and the LSFR will indirectly obtain information on the vertical cloud structure by measuring the change in solar flux with depth into the atmosphere. The LN/SN, on both the large and three small probes, will measure the atmospheric transparency at ~900 nm wavelength; in addition to information on the vertical structure, the measurements at four sites will yield information about horizontal variations on a very large scale. The microwave propagation experiment (MPRO) will provide information on the structure of the microwave absorbing clouds of Venus which apparently extend downward from an altitude of about 50 km to at least 37 km, which is the critical refraction limit depth in the Venus atmosphere. The possible existence of these microwave absorbing layers was established by the S-band (13 cm) radio occultation experiment of Mariner 5 (Fjeldbo et al., 1971) and confirmed by the observation of higher absorption of the X-band (3.5 cm) signal during the Mariner 10, S- and X-band occultation experiment (Howard, 1974).

The most obvious task which the cloud investigations must address is to determine the cause of the markings (contrasts) in UV planetary images. Without such knowledge it is not possible to unambiguously interpret the images and the apparent cloud motions. Although it seems highly probable that the direct information to be obtained on the clouds, as well as indirect information such as the gaseous composition as a function of altitude from the gas chromatograph (LGC) will reveal the origin of the UV features, there is in fact no assurance of that. Many potential causes of UV brightness variations will be examined; for example, cloud height variations and particle size and number density variations, but other potential causes of the contrasts such as slight variations in cloud particle impurities (cf. Travis, 1975) may escape detection.

Planetary cloud morphology at the cloudtop level will be indicated by the UV images of the OCPP. The spatial resolution (~30 km) in the images will be sufficient to show most of the observable detail (cf. Murray et al., 1974). In the
pericentral portion of the orbit, the OIR and OCPP will observe horizontal cloud morphology with resolution of a few kilometers, but the data will be in the form of strips rather than images. The LSFR on the large probe will obtain some data on cloud morphology by observing at a few zenith angles and at all azimuth angles as the probe spins. Information on the vertical cloud morphology will be obtained by instruments on the descending probes, such as the LCPS and the LN/SN.

3.2.3. Impact of Cloud Truth on Modeling and Theory

3.2.3.1. Radiative transfer. The information to be obtained by Pioneer Venus on the distribution of atmospheric particles and on the particle properties should considerably improve our ability to model the atmospheric radiation field, for both solar radiation and planetary radiation. This, in turn, will improve the realism of models for the atmospheric circulation.

The deposition of solar radiation depends strongly on the location and properties of clouds, and the present uncertainty in cloud properties makes the distribution of solar heating very uncertain (cf. Lacis and Hansen, 1974). Much of this uncertainty should be removed by the direct radiative flux measurements on the probes, but global data on the cloud particle properties will allow global modeling of the solar radiation field. Basically the same considerations apply to the planetary thermal radiation field.

It should be emphasized that the identification of the UV absorbing particulate matter can yield interpretation of absorption features only when combined with particle size data. Solid and liquid materials (particles) in general yield wide absorption bands whose spectral features are dependent upon particle composition, phase, and size, in contrast to simpler gaseous absorption features.

Furthermore, even the local radiation modeling required for the interpretation of certain experimental data can be aided by combined measurements. For example, the determination of optical depth (τ) and single-scattering albedo (ω) from the narrow-band LSFR data requires the single-scattering phase function of the particles. The phase function can be computed from the particle size spectrum as measured by the LCPS and the index of refraction of the particles.

On the other hand, the different transmission and scattering properties of the atmosphere are obtained independent of the phase function and are of greater fundamental importance than the optical depth and single-scattering albedo for problems which require modeling radiative energy transport in the atmosphere. The fact that it is possible to reproduce these scattering properties by more than one combination of phase function, optical depth, and single-scattering albedo hardly lessens our ability to use any one of the models which could duplicate our observations to reasonably predict the scattering properties of the atmosphere under other conditions.

3.2.3.2. Cloud particle composition and microphysics. The composition of the cloud particles, in comparison with the composition of the surrounding gases, and
whether the particle is in chemical and thermal dynamical equilibrium with its environment, are of importance in determining the origin of the particles, their distribution and ultimate fate. Appropriate models for the cloud chemistry and microphysics do not now exist but their underpinnings can be established by the Pioneer Venus measurements.

The atmospheric composition data will be obtained principally from the Neutral Mass Spectrometer (LNMS) and LGC on the large probe, as well as the mean molecular weight measurement of the LAS/SAS on all of the probes. The gas composition as determined from the LNMS and LGC, will probably determine the cloud particle composition, especially at lower altitudes where equilibrium is more rapidly achieved. At high altitudes, the particles may have long residences without vapor equilibrium. It will be of considerable importance if we are able to identify small amounts of hydrated $\text{H}_2\text{SO}_4$. The LNMS may be capable of identifying hydrates up through $\text{H}_2\text{SO}_4 \cdot 6\text{H}_2\text{O}$, which could define possible regions or levels of cloud particle formation if abundances are several ppm. The particle composition inferred from the ambient atmospheric gaseous composition combined with measurements of the particle size distribution must be compatible with data on radiation scattered from the cloud particles. From such experiments it is possible to obtain, as one result, best-fit computational comparisons which include as parameters the optical constants of the particles. These optical constants impose constraints on the particle composition and, if they are compatible with the composition measured for the ambient gases, the particle may be assumed to be of that composition if in dynamic equilibrium with the surrounding atmosphere. Such intercomparisons provide several indirect approaches in equilibrium assessment.

In the event that the UV absorbing layer is characterized by large particles, their composition can be inferred partially from cloud particle size spectral characteristics. Of additional importance here is the ability of the LCPS to determine whether large particles are nonspherical. At the present time, the growth of elemental sulphur crystals (rhombohedral or monoclinic) is a distinct possibility. One would not expect such crystals to be restricted to near micron size.

The cloud particle size spectrum is essential to any discussion of cloud microphysics. The LCPS will provide detailed particle size spectra from the approximate top of the $\text{H}_2\text{SO}_4$ cloud layer to the planetary surface. The limited LCPS spatial coverage can be extended by LN/SN measurements to all entry points in at least a qualitative fashion. The spectral characteristics (mean or modal size, variance, changes in distribution moments, etc.) provide necessary inputs from which calculations of particle growth rates can be made or examined. The roles of particle coagulation vs. coalescence and diffusional growth will be assessed by estimating and comparing computed growth rates for such processes based upon measured size spectra.

The Pioneer Venus mission provides an opportunity to measure the degree of
equilibrium reached in the cloud growth process by accurately measuring the cloud droplet mass content and its parent vapor constituent abundances. The particle mass content as a function of altitude coupled with size spectral parameters, will define whether the clouds are layered and their vertical structure. Estimates of H$_2$SO$_4$ concentration can be made, enabling growth rate computations. The lower cloud regions, being hotter, would be expected to require higher vapor pressures for equilibrium accompanied by faster growth (decay) rates of the droplet population.

3.2.3.3. Cloud growth and dissipation processes. The determination of operative cloud processes will require the integration of many measurements from the Pioneer Venus mission. Specific information as to mean particle size and mass, along with integrated cloud parameters such as cloud particle mass content, optical depth, single-scattering albedo, and size spectral properties will provide clues as to basic cloud formation processes and their thermal-radiative interactions. Cloud layering, for instance, would suggest condensation products as the cloud particles. The shape of the particle size spectrum always provides clues as to particle origin, e.g., whether by condensation or dust scoured from the planet's surface. The variation of the size spectrum with depth can indicate operative diffusional growth, chemical growth, or coalescence mechanisms. An encounter with precipitation sized particles would be of fundamental importance. Combined with temperature measurements, the vertical profile of particle mass content can indicate cloud type – particularly the presence or absence of convective activity or mixing processes.

Certain aspects of cloud particulates are simpler if formed by condensation from a relatively pure parent phase as characterized by terrestrial clouds. Likewise, the latent heat released from condensation drives vertical motions and turbulent mixing processes causing a high variability of cloud properties in space and time. At least the visible Venusian clouds cannot be described as forming through simple phase change processes. Because they are formed through chemical change, the problem is much more complex. To a first approximation, the estimated total cloud particle mass would not contribute significant latent heat exchange in the Venusian atmosphere. However, chemical heats of formation for substances like H$_2$SO$_4$ are many times greater than latent heat values (even for water). Even the heat of hydration of H$_2$SO$_4$·H$_2$O is twice as high as the latent heat of vaporization of water. Coupled with the relatively low CO$_2$ pressures at significant cloud density, the heat exchange during cloud particle formation may well be significant. Thus, one result of the mission should be a determination of the role of latent heats and heats of formation in the cloud and planetary heat budgets. The energetic input from cloud particle radiative exchange processes should also be obtained. Larger scale mass transport processes will be examined using wind and turbulence data provided by radio science experiments (MWIN and MTUR). Rough estimates of eddy coefficients or vertical velocities can be
made from the accelerometer and descent data from all entry probes. Combined with particle mass content, a first attempt at determining the life cycle of the cloud particulates can be made.

4. Conclusions

It should be apparent that any investigation of planetary phenomena as perplexing as the Venustian clouds must allow for a few surprises. From their visible appearance, the H$_2$SO$_4$ clouds seem to be extremely homogeneous; however, we must remember that H$_2$SO$_4$ was only identified three years ago and at least one other constituent is yet to be identified (the UV absorber). We have little knowledge of the clouds at depth and much of our current knowledge about these clouds must be regarded as speculative. It is thus important that we do not cling to preconceived ideas too strongly. Rather, the cloud data from the Pioneer Venus mission will be examined on its own integrity with its interpretation only modestly tempered by prior observations.

Much of the data that will be obtained from the mission are of a singular nature, unattainable by earth-based remote measurements. Not only are the vertical profiles of cloud parameters unique, but the opportunity to perform orbiter measurements at otherwise unattainable scattering geometries, fields of view, resolution, time scales, etc., will provide vastly improved remote measurements. Most of the cloud data will be obtained during a short intensive period avoiding the familiar problem of comparing nonsimultaneous observations.

We expect the successful completion of the Venus mission to answer many of the first order questions about the Venustian clouds. Some of these have already been addressed in the previous sections. The development of definitive conclusions must await the analysis of the actual data we obtain. Our attempt here was not to predict our results but rather indicate the kinds of analyses we plan to perform on the data and draw attention to known similarities in appearance of the Venustian planetary cloud layer to certain terrestrial cloud forms. From all appearances, the visible Venustian clouds are analogous to haze layers of unactivated terrestrial cloud nuclei characteristic of disperse clouds in polluted regions. If our data in fact show this to be true and the cloud system has extensive vertical homogeneity we may be dealing with a very elementary cloud form in terms of basic cloud processes. Such conclusions must, however, await the analysis of the data and the development of appropriate predictive cloud models.

References