was also found to have a response at 745 nm with a passband of 30 nm full width at half maximum and a response of about 28 percent of that of the 365-nm channel when exposed to a source whose power output was constant with wavelength.

The radiation data obtained as a function of altitude for the day probe and sounder probe are shown in Fig. 2 for the UV and the visible channels. Work is in progress on the absolute scales of the radiances, and, at present, such values should be used with caution. The relative behavior of these radiances, however, is as shown. As a first approximation, the altitude dependence of the UV intensity in the 365-nm passband has been determined by assuming that the altitude behavior of the portion of the signal in the UV channel attributed to 745-nm light is identical to that of the 530-nm radiation. Making this correction to the signal in the UV channel for the day probe, we obtain the data of Fig. 3, which indicate that very little UV light remains at altitudes below 25 to 30 km. For the remainder of the probe descent, it is thus possible to consider that the signal in the UV channel is due to 745-nm radiation, and its behavior may be compared with the visible channel behavior.

From the ambient radiation data, the following conclusions can be inferred.

1) The strong variations at the cloud tops are attributed to probe rotation and cloud patchiness.

2) In the cloud region, the stronger interaction of near-UV (as compared with visible) light is apparent. The variation of the slopes and of the second derivatives of the data agree with the general structure for the cloud regions determined from the backscatter data. The strongest rate of extinction occurs in the region extending from the highest altitudes measured down to 58 km. High extinction rates are also observed in the region from 56 to 50 km in the main cloud bank (regions C and B). Because of the apparent absence at the day probe location of the upper part of region B—so prominent at the sounder probe location—more UV light appears to penetrate to below the cloud at the day probe location than at the sounder probe location, as inferred from the fractional decrease in the UV signals passing through the cloud regions.

3) Below the clouds, extinction of the 365-nm channel radiation occurs down to about 26 km; near-UV light is present in all this part of the atmosphere. The near-UV light which had not been absorbed by heavy region B clouds is now propagated through and attenuated by the atmosphere down to about 26 km. Multiple

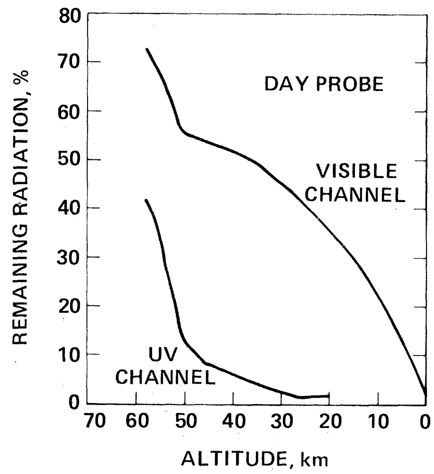

Fig. 3. Percentages of readings remaining for the UV (365-nm) channel of the day probe after correction for the 745-nm contribution. Also plotted are percentages of the readings remaining at each altitude for the 530-nm channel of the same probe; the assumed behavior for the 745-nm contribution (valid down to 25 to 30 km) to the UV channel follows this curve.

scattering calculations are in progress (*7*) to help elucidate these data.

4) If the radiation remaining at 26 km as detected by the UV channel is primarily at a wavelength of 745 nm, the faster rate of change with altitude of the 530-nm radiance compared to the 745-nm radiance is evident. Golovin *et al.* (*8*) have observed that radiation in spectral regions below 600 nm is strongly absorbed starting below 20 km, an extinction perhaps attributable to molecular vapors such as sulfur or bromine. Calculations are in progress for our data to separate the Rayleigh scattering contributions to our signals in order to confirm this absorption.

JACQUES BLAMONT

Service d'Aeronomie du Centre National de la Recherche Scientifique, 91 Verrieres, France

BORIS RAGENT

NASA Ames Research Center, Moffett Field, California 94035

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15 May 1979

Clouds of Venus: A Preliminary Assessment of Microstructure

Abstract. *The multimodal microstructure of the Venus cloud system has been examined. In addition to confirmed H_2SO_4 droplets and suspected elemental sulfur, a highly concentrated aerosol population has been observed extending above, within, and below the cloud system. These aerosols appear to cycle through the cloud droplets, but can never be removed by the weak precipitation mechanisms present. All cloud particles are likely laced with aerosol contaminants. Sedimentation and decomposition of H_2SO_4 in the droplets of the lower cloud region contribute more than 7 watts per square meter of heat flux equaling one-fourth of the solar net flux at 50 kilometers.*

The particle-size distribution measurements by the Pioneer Venus large cloud particle size spectrometer (LCPS) revealed that the Venus cloud populations were inherently multimodal (*1*). Three modes are observed in the raw data centered approximately at 1, 3, and 8 μm diameter in the number density spectra. Table 1 summarizes the populations observed in each of three cloud and one haze regions. We have indicated that the observed multimodal size distributions were of fundamental importance with each mode suggesting different chemical composition or at least a different origin (*2*). Continuing reduction of Pioneer Venus results requires only slight adjustment of our ideas on the identities of the three groups of particles. It has become apparent, with final data on the descent profile of the probe, that temperatures are higher than was originally supposed, which raises questions of just how dilute the H_2SO_4 can be in the lower cloud region. Optical absorption data from the large probe solar net flux radiometer (LSFR) have provided additional constraints on the probability that mode 3 in the middle cloud region is elemental sulfur.

We have sought to separate and examine these modes in detail, treating them as distinct sizes as well as combined populations. The analysis involves removing the known LCPS instrumental broadening of narrow spectral features (for example, the mode 2 H_2SO_4 peak in the middle cloud region); separating the broader spectra of merged populations into their likely modal subsets (for example, particles in the upper cloud region into two populations of mode 1 and mode 2 particles); developing analytical descriptions of the populations; and examining the behavior of each population as influenced by changes in thermodynamic equilibria, cloud dynamics, and microphysical interactions throughout their vertical extent.

The results of this current analysis strengthen the identification of the narrow mode 2 particles in the middle (and now upper) cloud regions as H_2SO_4, enhance our arguments for a broad distribution of H_2SO_4 droplets in the lower cloud region, and reveal an underlying aerosol population throughout the entire cloud system. However, evidence from other measurements [from, for example, the LSFR (*3*) and the nephelometer (*4*, *5*)] reduce the grounds for identifying

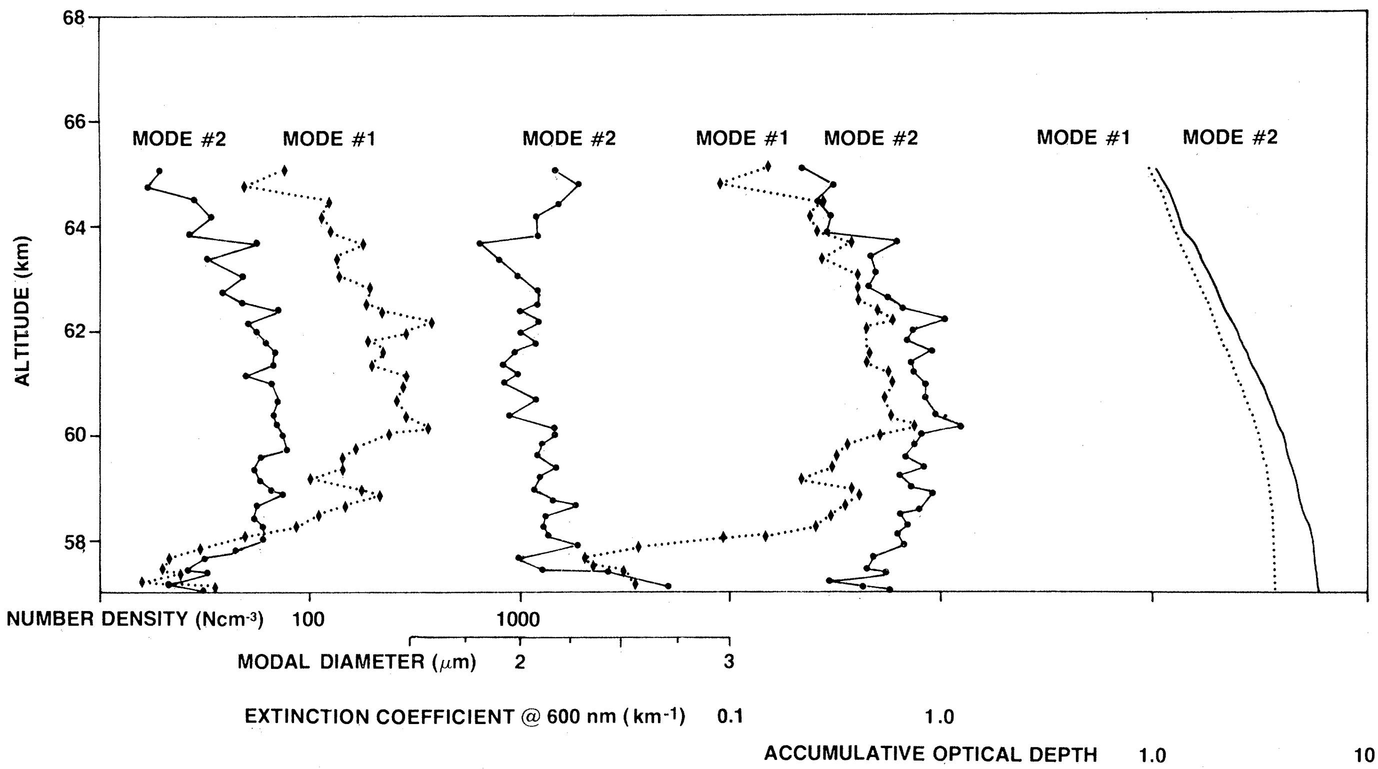

Fig. 1. Modal parameters of the upper cloud region. The accumulative optical depth was initialized at a value of unity for modes 1 and 2 at 65 km.

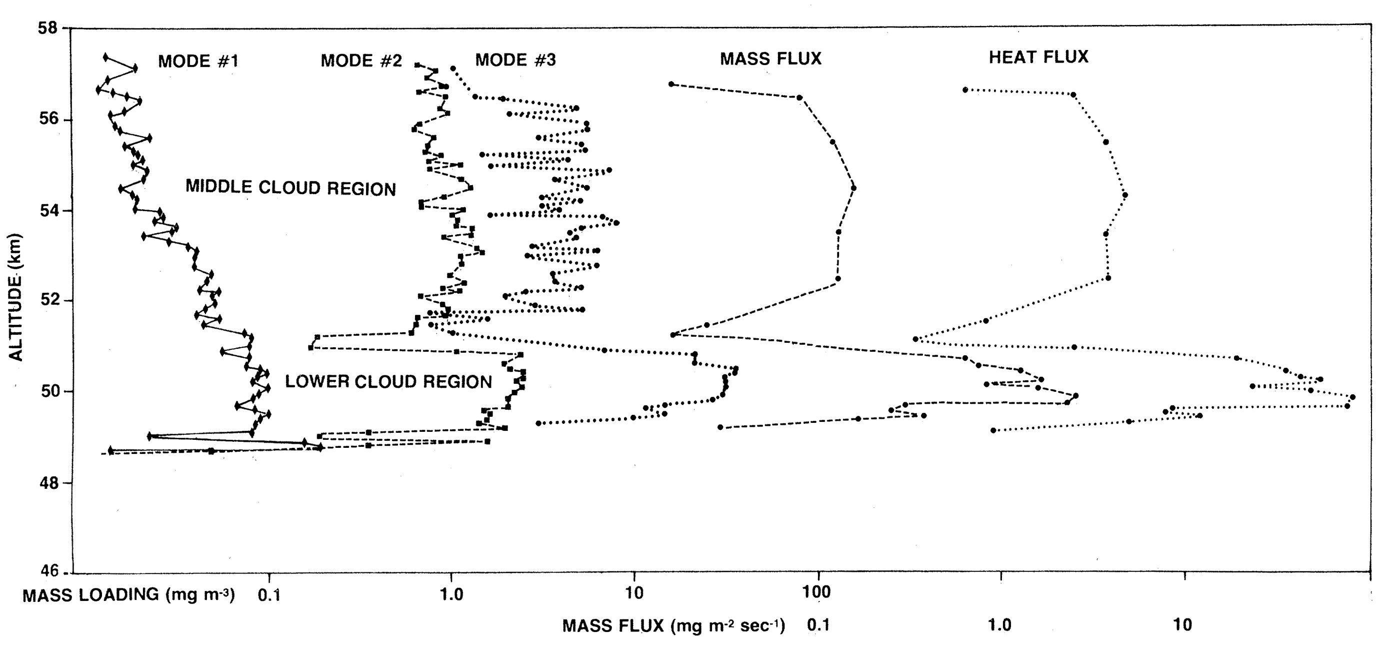

Fig. 2. Modal parameters for middle and lower cloud regions. The mass and heat fluxes have been smoothed in the middle cloud region over 1-km intervals. For heat flux computations, the lower cloud region is assumed to be H_2SO_4 and the large mode 3 particles of the middle cloud region are assumed to have heats of vaporization equivalent to that of water. The heat of decomposition of $H_2SO_4 \cdot H_2O$ is 690 cal g^{-1} under the assumption that H_2O, SO_2, and O_2 are produced at 90°C.

large mode 3 particles as elemental sulfur in the middle cloud region. The modal properties of the three cloud regions (Figs. 1 and 2) emphasize optical properties in the upper cloud region and mass properties in the middle and lower cloud regions.

Sizes and compositions. Resolution of the spectral features of size is best in the middle cloud region. The narrow mode 2 previously identified as H_2SO_4 provides the sharpest feature observed. However, the finite LCPS resolution does not reveal the true spectral width. The average LCPS size distribution observed (Fig. 3) for the entire 53- to 57-km region is most easily described as Gaussian with a modal diameter of 2.7 μm and σ = 1.35 μm; the actual distribution is much narrower ($\sigma \leq 0.65$) once the instrumental errors in sizing, which generate spectral broadening, are removed. The upper limit on the standard deviation has been established by laboratory tests based on preflight calibration data with monodispersed spheres and by tests with the LCPS flight spare.

At any one altitude, the H_2SO_4 droplet distribution is still narrower. Actually, the existing spread is due to slight shifts in modal size during descent from 57 to 53 km. Mode 2 in this region contains approximately three optical depths. If we average over only one optical depth, the standard deviation is typically 0.2 μm, which is less than the value of 0.26 μm suggested by Hansen and Hovenier (*6*). At any one altitude, the H_2SO_4 is essentially monodispersed with the modal size decreasing from 2.8 μm at 57 km to 2.3 μm at 51 km. It is difficult to imagine a cloud of particles varying only 20 percent in size throughout 5000 m of vertical depth. These particles can only be liquid droplets, and the refractive index (m = 1.42 to 1.44) (*7*) matches concentrated H_2SO_4 (80 to 85 percent).

The clear separation of modes 1 and 2 observed in the middle cloud region begins to disappear in the upper cloud region; bimodality is observed at several altitudes, however, even as high as 64.8 km. The addition of all of the missing data between 56 and 58 km since our earlier publication (*1*) shows the gradual merging of modes 1 and 2 through simultaneous increases in mode 1 concentration and decreasing size in mode 2 until the LCPS resolution is insufficient to show the strong bimodality. In order to separate modes 1 and 2 in the upper cloud region, the spectral variance observed for mode 2 in the top of the middle cloud region was assumed to apply to the largest particles in the upper cloud region; this subset was removed as a continuation of the mode 2 H_2SO_4 droplets. The result is that the modal size decreases from 2.5 μm at 58 km to about 2 μm at 65 km, with most of the decrease occurring in a fairly sharp transition between 57 and 58 km (Fig. 1). This transition region appears to be a dynamical or chemical cloud regime boundary in that changes occur in all three modes: size and concentration change in modes 1 and 2, with mode 3 particles emerging below this level. A second possible similar cloud regime boundary is suggested by similar reasoning as separating the lower and middle cloud regions.

Sulfuric acid is also the best candidate for the bulk of the lower cloud region. Mode 2 is clearly resolved only near the top and bottom, which supports previous arguments (*1*) that some mode 2 H_2SO_4 droplets grow into mode 3 and reappear when mode 3 evaporates. It might also be explained, however, by the mixing of two different H_2SO_4 clouds. The base of the lower cloud is a dominant planetwide feature [compare (*1*, *4*, and *8*)]. Trimodality exists only when averaging over the entire lower cloud, requiring a multifunctional fit to the spectrum (Fig. 4).

Refractive indices were derived by Ragent and Blamont by comparing their nephelometer data with our particle-size distribution data (*4*). At 50 km they found m = 1.37 [revised to 1.33 more recently (*7*)], which suggests very weak acid. However, it is necessary to correct for both wavelength and temperature. The nephelometer operates at 900 nm, and the temperature in the lower cloud is about 350 K. The index of concentrated H_2SO_4 drops by about 0.02 per 100 K temperature rise, and probably by 0.01 between 600 and 900 nm (*9*). The computed indices are therefore consistent

Table 1. Venus cloud summary. Altitudes of each cloud region and corresponding temperatures are: upper (U), 68 to 58 km, 230 to 288 K; middle (M), 58 to 52 km, 288 to 346 K; lower (L), 52 to 48 km, 346 to 364 K; and lower haze (H), 48 to 31 km, 364 to 493 K.

Mode	Modal diameter (μm)	Size range (μm)	Cloud region	Identity	Concentration (cm^{-3}) U	M	L	H
1	*	? to 1.5	U, M, L, H	S, various aerosols	150	25	100	10
2	2 to 3	1.5 to 5	U, M, L	H_2SO_4, inclusions or impurities	50	50	50	
3	7 to 8	5 to 35	M, L	M: S?, H_2SO_4? L: H_2SO_4		10	30	

*Power law distributed; no modal value can be specified.

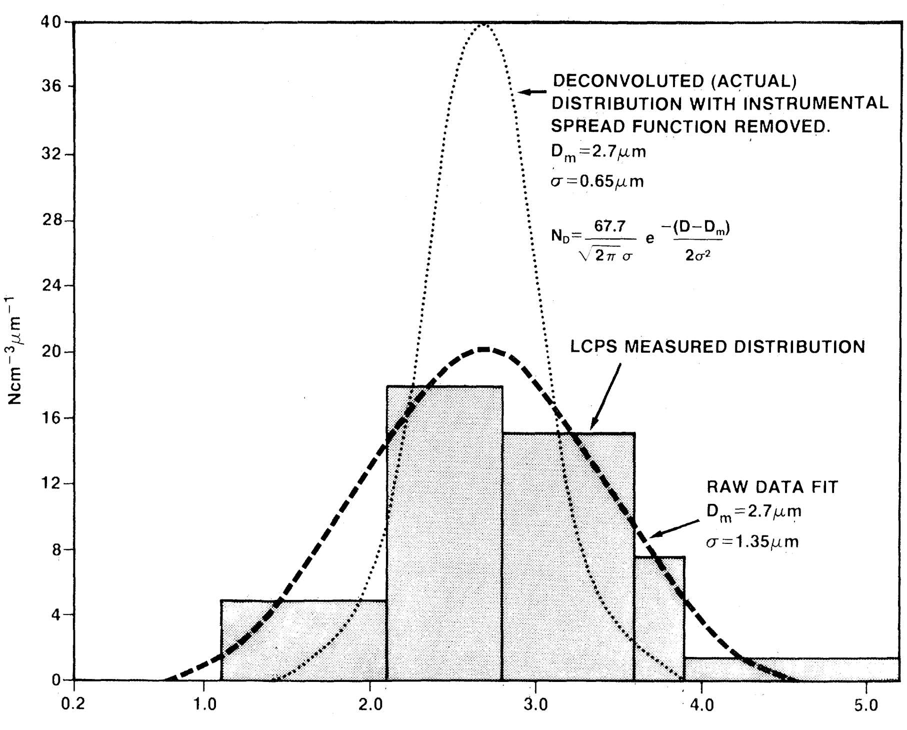

Fig. 3. Average mode 2 size distribution from 53 to 57 km.

with somewhat stronger acid but still not as strong as required to maintain H_2SO_4 stability at 90°C. We believe the discrepancy is within the possible combined sources of error in the LCPS and nephelometer measurements and the approximations in the computations.

As was the case with the lower cloud H_2SO_4, the mode 3 particles in the middle cloud are difficult to fit analytically; this difficulty thereby supports a possible irregular shape factor. We have previously suggested sulfur as a mode 3 middle cloud prospect. We have verified by tests in our laboratory that sulfur will easily supercool to temperatures below 80°C in quantities of near raindrop size without any special preparation. If mode 3 particles were liquid sulfur droplets, however, the nephelometer scattering signals would be much larger than those observed. Solid sulfur in some complex morphology might be permissible at upper levels where vapor requirements for equilibrium are small. However, one must assume that whatever ultraviolet it could absorb had been absorbed above since no additional reduction in net solar flux is observed (*3*).

Young (*10*) has suggested that large particles of liquid sulfur are present down to 20 km and assumes a large quantity of sulfur vapor in equilibrium. This hypothesis is based on the existence of a backscatter signal in the nephelometers of Venera 9 and 10 (*8*, *11*), but absent in the other three channels. No such particle was seen by our instrument, and the large amount of sulfur vapor has not been seen by any analytical instrument. Although it is possible that Venus is highly inhomogeneous, the low-altitude signal was measured at only the one angle, and the gain in this channel is 1000 times higher than in the forward-scattering channel. We feel the evidence for these large, low-altitude particles is weak.

The smallest particles. We previously suggested that the mode 1 particles might be H_2SO_4 and elemental sulfur in some mixture (*1*); arguments about ultraviolet absorption favor a large percentage of elemental sulfur in the upper cloud region (*12*). Our current thinking is that, in general, the particles are simply aerosol debris. They are most likely polyparticles having both volatile and involatile composition. What the data reveal is the large size tail of an underlying aerosol population (truncated by the 0.6-μm LCPS lower size cutoff) whose resolved concentration varies with altitude but whose distribution fits a power law with similar slope throughout the entire cloud region. The slope varies from d^{-3} to d^{-4} throughout the cloud region and is similar to that observed with terrestrial aerosols (*13*). The overall concentration is, however, one to two orders of magnitude higher and by terrestrial standards would be considered filthy. Such a high concentration of aerosol at first seemed surprising; we now believe, however, that there can be no precipitation on Venus to scavenge and carry aerosol to the surface, cleansing the atmosphere. The only precipitation is in the form of virga which simply carries scavenged aerosol to somewhat lower layers, where the most volatile constituents evaporate leaving smaller involatile aerosol, which are then recycled. The preferred argument is that the mode 1 aerosol distribution is the product of cloud activity and not in competition with it. There is also reason to believe that the submicron aerosol fraction exists well above the H_2SO_4 cloud tops as well as below their base, perhaps being responsible for the Mariner 10 haze layers at 75 to 85 km and the reported high-altitude planetwide haze inferred from cloud photopolarimeter measurements (*14*).

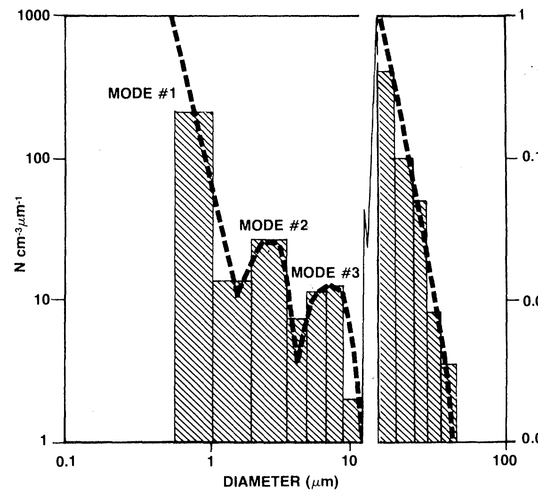

Fig. 4. Average size distribution of the lower cloud region. The LCPS raw data histogram is an average for the entire lower cloud region and can be fit with the following three reduced analytical functions. Mode 1, $n(d) = 108\,d^{-4.3}$; mode 2, $n(d) = 27.5e^{-6.2(d-\bar{d})^2}$ where $\bar{d} = 2.7$ μm; and mode 3, $n(d) = 111e^{-2.8(\ln d/\bar{d})^2}/d$ where $\bar{d} = 7$ μm.

The involatile aerosol constituent may be from extravenusian sources. Such submicron particles could be generated by the recondensation of meteoric vapors (*15*). The mass influx at Earth is 10^{-16} g cm^{-2} sec^{-1} or 40 metric tons per day, and number densities are expected to be a few thousand per cubic centimeter at stratospheric heights. Similar numbers should apply to Venus. These particles, too small to be detected by the LCPS, are nevertheless scavengeable nuclei, which may contribute some absorption to an otherwise transparent particle. Below 30 km the meteoric particles must still be present in some form, but they are again probably too small to detect. Particles ejected by volcanoes or raised from the surface by winds are evidently too scarce to be detected. If present, they would be most concentrated near the surface, just the region where nothing is detected. Vapors, especially sulfur, are another matter. Sulfur is ejected on Earth and Io and can be present in amounts much greater than would be expected in equilibrium with the surface; it would thus be a likely aerosol component.

In the cloud regions a certain portion of the aerosol population must serve as condensation nuclei for the H_2SO_4 droplets. Nucleation depletes only a small portion of the nuclei, however. The remaining fraction may interact with the cloud droplets through scavenging processes. The growth and decay of patches of cloud can effectively reconstitute large nuclei, which become the preferred condensation nuclei and further the next growth cycle. Such a process occurs in all terrestrial clouds, and there is direct evidence for it on Venus; here we note the strong correlation of the number of mode 1 aerosol with cloud droplet size and density (Figs. 1 and 2). One might interpret this to mean that they are both in equilibrium with the same parent vapors and thus both cloud particles. The aerosol population, however, is less volatile and persists when H_2SO_4 droplets decrease in size or rapidly evaporate.

Optical appearance. Other questions require consideration of the full particle spectrum. The upper cloud region is of obvious interest since it must be the site of all the scattering, polarization, and absorption (particularly ultraviolet) observed at and near visible wavelengths. The optical depth that can be probed from Earth is no more than 4 to 6, and the upper cloud region has a depth of at least 10. Moreover, all the attenuation observed by the LSFR occurs in the upper cloud. We identify the mode 2 in this region as H_2SO_4; the absorption might therefore reside in some combination of mode 1 and inclusions or impurities in mode 2. Tomasko *et al.* (*12*) found that mode 1 alone is not sufficient if the particles are sulfur, and that some absorption must reside in mode 2. Inclusions might be solid sulfur or meteoric dust, and impurities in solution might be derived from the latter. It is unlikely that any cloud particle remains pure given lengthy residency with the highly concentrated mode 1 aerosol.

Young (*16*) has generated a convincing fit to the reflection spectrum of Venus by postulating the presence of large particles of solid sulfur at and below an optical depth of 4. Further, a statistical association of dark areas with decreasing CO_2 absorption has been interpreted by Crisp and Young (*17*) as an association with rising cloud tops and therefore upward motion. They have suggested that the updraft carries the (large) particles up to a level where they are more visible. At least at the sounder probe entry location we found no sign of such large particles until we reached such large optical depths that they could have no effect on the reflected radiation. We were at first puzzled by the discrepancy until we realized that small particles are carried up at least as efficiently as large ones. The mechanism can perhaps be rescued if the absorbing particles are smaller than the scattering ones. An essential element of Young's fit to the optical absorption was a specific height (and therefore temperature) distribution of the sulfur particles. It remains to be shown that such a fit can be recaptured with the different distribution that seems to be implied by the Pioneer Venus results.

Mass loading and fluxes. The mass balance is of particular interest in the middle and lower cloud regions. The partitioned mass loading is presented in Fig. 2 with the mass flux for mode 3 in the middle and lower cloud regions. In converting the measured particle-size distributions to profiles of mass loading, we have assumed the particles to be spherical, of density 1.8 g cm^{-3}, and falling at Stokes velocities with zero updraft; a value of 2.5 cm sec^{-1} is computed for the mean mass size. The mode 3 particles in the middle cloud region are most likely nonspherical and could even be needlelike, if sulfur. If so, the mass loading could be overestimated by factors as large as 2.

The peak computed mass flux of 2.8×10^{-3} g m^{-2} sec^{-1}, if representative of the whole planet, must be balanced by a similar upward flux in the gas phase. Values of a few centimeters per second are required; similar values are typically computed from the convergence of the low-level flow associated with terrestrial stratiform clouds.

The mass flux observed also gives rise to a significant heat flux (involving heats of formation as well as latent heats) of 8 W m^{-2}, which equals one-fourth of the solar net flux input at the same altitude range (*3*). Because our computations are so sensitive to size ($\sim r^5$), the values computed must be regarded as estimates (*18*); it is clear, however, that this heat flux may be a thus-far overlooked major component of the overall atmospheric thermal balance, especially when computations indicate the possibility of growth by coalescence to sizes a factor of 2 larger than those actually observed. This comparison is even more significant if it is assumed that our measurements are representative of the whole planet since the planetwide net solar flux would average about 20 percent less than typical measurements by the sounder probe (*3*).

Although the general morphological features of the cloud system are as yet unclear, they appear to be more like stratiform than cumuliform clouds. The potential for mist and drizzle is there, but heavy precipitation is extremely unlikely. Intriguing microphysical questions remain: Can solid elemental sulfur be made to fit all constraints on the mode 3 middle cloud particles? What possible growth mechanisms can force H_2SO_4 droplets to be monodispersed planetwide over great depths? What kind of charge separation processes can operate in clouds of strong electrolyte, and are these clouds really involved in the observed lightning and atmospheric electrification processes? It appears likely that laboratory experimentation will be necessary to provide positive answers to such questions.

ROBERT G. KNOLLENBERG
Particle Measuring Systems, Inc., Boulder, Colorado 80301
D. M. HUNTEN
University of Arizona, Tucson 85724

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21 May 1979

Cloud Images from the Pioneer Venus Orbiter

Abstract. *Ultraviolet images of Venus over a 3-month period show marked evolution of the planetary scale features in the cloud patterns. The dark horizontal Y feature recurs quasi-periodically, at intervals of about 4 days, but it has also been absent for periods of several weeks. Bow-shaped features observed in Pioneer Venus images are farther upstream from the subsolar point than those in Mariner 10 images.*

The earliest ultraviolet images of Venus obtained by the cloud photopolarimeter on board the Pioneer Venus orbiter were at moderately large phase angles, thus showing substantially less than the full disk (*1*). The imaging during a nearly 3-month period beginning in early January 1979 has had much more favorable illumination conditions and permits an examination of not only the 4- to 5-day quasi-periodicity but also the long-term variation in the global cloud morphology. We present a representative set of enhanced (*2*) images selected from that period. A list of the seven images, their dates of acquisition, and the time, phase angle, and latitude (*3*) corresponding to the disk center are given in Table 1.

The series of five images shown in Fig. 1 covers a 6-day period and illustrates the recurrence of the dark horizontal Y feature. Although the second image (Fig. 1B) resembles the images from Mariner 10, the rest of this series shows a rapid evolution of the large-scale cloud patterns. Changes in appearance on even