delayed data for the small probes, it appears that region C is a planetary feature, whereas regions tentatively identified as A and B may differ from one location to another. No data on region D is, as yet, available for the small probes.

A consideration of the sounder probe nephelometer response at a given altitude and comparison with the particle size distribution measured by the LCPS experiment at the same altitude makes possible best-fit analyses for the indices of refraction of the particles at those altitudes, assuming that the particles have very little or no absorption at 900 μm and that they are spherical or that the shape factor is known (*5*). The assumption of low absorption is supported by the results of the solar net flux radiometer (LSFR) experiment (*6*), and supporting evidence for the sphericity or lack of sphericity for the particles, especially for large particles, is obtained from the LCPS experiment. These data support the hypothesis that the particles are spherical in all of the regions except possibly region C. The comparisons and analyses have yielded the following results.

In region D, the curves of nephelometer reading and total particle concentration are similar, especially at the higher altitudes, which implies that the distribution function of particle sizes is relatively constant, as is also directly verified from the LCPS measurement. From our preflight calibration without renormalization, the nephelometer data can be derived directly from the measured particle size distribution by assuming spherical particles and an index of $n = 1.44$, in agreement with the properties of a 75 to 85 percent concentration of H_2SO_4. Figure 3 shows the sensitivity of the calculation to the choice of index of refraction. We conclude that in region D the particles are essentially composed of a concentrated solution of H_2SO_4.

In region C, our early calculations indicate that it is not possible to fit the nephelometer data with values of index greater than 1.40 for the larger particles (assuming sphericity) while retaining a value of $n = 1.44$ for the smaller particles and that our best fit occurs when we use a value of 1.33. We are not in a position, however, to definitively exclude high-index, irregularly shaped particles such as sulfur from this region, since such particles may well have backscattering cross sections much smaller than spheres of equal volume and refractive index.

In region B, again in accord with the results of the LCPS and LSFR measurements, we assume liquid (spherical) particles and conservative scattering; from the particle size distributions measured by the LCPS, we compute that in all parts of this region the nephelometer data cannot be fit by assuming an index as large as 1.44 for the large particles ($d > 5$ μm), and by assuming $n = 1.44$ for smaller particles. The largest value of index (under the assumption that the large particles are spherical), which provides rough agreement with our data, is $n = 1.37$. Further refinement of our calculations may change this value slightly. We tentatively conclude that in this region it is not necessary to invoke large sulfur particles in order to explain the data.

Region A appears to be composed of particles similar to those of region D with a slightly broader distribution. The very narrow peak appearing in the nephelometer data at an altitude of about 1500 m below the major structure of region A is evident in the data of both the nephelometer and cloud particle sampling experiment and is, again, apparently similar in its physical properties to region D. Nephelometer signals from region A may be explained by using the measured particle size distribution results from this region, corrected for the integration time differences between the LCPS and large probe nephelometer experiments, by assuming particles of $n = 1.44$ (H_2SO_4). Because of the similarity in particle size distributions between the lower portion of region B and region A, we infer that region A has been detached from region B by local weather.

Finally, we report the nephelometer signals observed during the impact of the day probe (Fig. 4). We have inferred that this probe landed in loosely compacted material so that a small amount of fine "dust" was ejected from the surface into the atmosphere in the vicinity of the probe. This dust subsequently settled out onto the surface over the next few minutes until the atmosphere in the vicinity of the probe was again free of particulate matter.

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References and Notes

1. L. Colin and D. M. Hunten, *Space Sci. Rev.* **4**, 451 (1977).
2. L. Colin and C. F. Hall, *ibid.*, p. 283.
3. M. Ya. Marov *et al.*, *Kosm. Issled.* **14**, 729 (1976).
4. R. G. Knollenberg and D. Hunten, *Science* **203**, 792 (1979).
5. J. B. Pollack and J. N. Cuzzi, Proceedings of the 3rd Conference on Atmospheric Radiation, Davis, Calif., 28 to 30 June 1978.
6. M. Tomasko, L. R. Doose, J. Palmer, A. Holmes, W. Wolfe, N. D. Castillo, P. H. Smith, *Science* **203**, 795 (1979).
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Clouds of Venus: Particle Size Distribution Measurements

Abstract. *Data from the Pioneer Venus cloud particle size spectrometer experiment has revealed the Venus cloud system to be a complicated mixture of particles of various chemical composition distinguishable by their multimodal size distributions. The appearance, disappearance, growth, and decay of certain size modes has aided the preliminary identification of both sulfuric acid and free sulfur cloud regions. The discovery of large particles > 30 micrometers, significant particle mass loading, and size spectral features suggest that precipitation is likely produced; a peculiar aerosol structure beneath the lowest cloud layer could be residue from a recent shower.*

The cloud particle size spectrometer flown on the large sounder probe (hereafter LCPS) during the Pioneer Venus mission provided detailed microstructural data on the Venus cloud system. Aircraft-mounted particle-size spectrometers are currently widely used in terrestrial cloud physics, air-quality studies, and research programs involving the sizing of airborne particulates (*1*). However, this is the first time a particle size spectrometer has flown on a space mission.

The LCPS measured particle size and number density in the clouds and lower atmosphere of Venus as a function of altitude. The LCPS is an in situ measuring device capable of high-resolution measurements of particle size in the range of 0.5 to 500 μm. It makes single-particle measurements even at high concentrations (10^3 to 10^4 cm^{-3}) and is relatively insensitive to particle shape and orientation.

In the primary measurement, the shadows of laser-illuminated particles are imaged onto a linear photodiode array. The number of photodiode elements interrupted by each particle is counted as a specific size. Three different magnifica-

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tions give size ranges of 5 to 50, 20 to 200, and 50 to 500 μm. In the smallest range, the light scattering which is also measured extends the resolution down to 0.5 μm (*2*). The result is a vertical profile of particulate concentration for 38 size classes from 0.5 to 500 μm with cloud levels resolved to a minimum of ± 400 m. The measurements were initiated at 67 km and continued to the planetary surface.

Data from two regions (67 to 62.5 km and 58 to 56.5 km) were not yet available at the time of this writing, and time has yet to allow integration with the data from other experiments. Therefore, the descendent profiles presented are based on best estimates of altitude. For comparisons with other results, ground receipt times are also given at significant cloud layer boundaries. Finally, the LCPS data provide only one vertical profile, and although the Venus cloud system appears planetary in nature, we cannot automatically presume that our results can be extended planet-wide.

This comment sets the tone for the discussion that follows. Terrestrial cloud physicists find it difficult to comprehend the homogeneity already known to exist in the Venus cloud system, and meteorologists are equally amazed at the lack of temperature variation in the lower atmosphere. There appears to be no weather at the surface and probably no geographical climatic variations. The cloud particles are themselves not simply phase variations of condensation from a single parent vapor phase, but particles formed by chemical reactions. Like terrestrial clouds of anthropogenic influence (for example, the metropolitan brown cloud), these chemically formed clouds are difficult to destroy. In the terrestrial case, these particles are more often simply diluted and eventually scavenged by precipitation hydrometeors. Particles formed in this way may easily have lifetimes of days to weeks; given the extent of development of such clouds on Venus and the lack of sufficient precipitation, their global extent and persistence are not so extraordinary.

The general features of the Venus cloud system as observed by the LCPS are best illustrated in terms of integrations involving the first three size distribution moments. Figure 1 depicts the observed concentration, computed extinction coefficient, and mass loading as functions of altitude during the large probe's descent. A cursory examination of these data shows four distinctly different cloud regions, the upper three of which we have designated upper, middle, and lower cloud regions with an underlying lower thin haze. Below 31 km no particles whatever were detected. Perhaps the most striking of the results is the multimodal size distributions (insets, Fig. 1).

A narrow size mode near 2 μm in diameter was already known from Earth-based polarimetry, and larger particles of sulfur (10 μm) have been invoked to explain Venus's yellow coloration (*3*). Size modes attributed to both of these particles were observed, but, unexpectedly, a third size mode around 1 μm and another region of large particles (~ 10 μm) were also observed. From their location at an optical depth of 5 to 10, the large particles in the middle cloud region may be identified with the expected sulfur; however, our analysis showed the large particles in the lower cloud region to probably be H_2SO_4.

The upper cloud region is a region of small particles of 0.6 to 4 μm diameter with a fairly high concentration (300 to 400 cm^{-3}) but a relatively low mass loading (1 mg m^{-3}). The extinction coefficient averages slightly above 1 km^{-1}, which, if integrated over this vertical layer from 62.5 to 58 km, includes six optical depths. If the region from entry (67 km) to 62.5 km is of similar composition, the optical depth could double.

Earth-based observations of Venus have shown the particles in the tops of the Venus clouds to be H_2SO_4 in fairly concentrated form (*4*). A striking feature of the cloud particles that aided the identification of the particle constituents was that the size distribution was narrow and consisted of droplets about 2 μm in diameter, allowing refractive index matching with H_2SO_4. Unfortunately, we do not yet have data from the large probe at regions high enough to overlap the depth of coverage afforded Earth-based measurements. At the highest regions where data are available, the size spectrum appears broad, although a slight bimodality can be observed at a couple of levels. The modal droplet size is about 1.2 μm diameter. Prior analyses (*5*) were consistent with modal sizes of 1.6 μm. At this stage of analysis the disagreement should not be considered large; the earlier work may have assumed too simple a cloud model (with respect to size distribution).

The middle cloud region between 51 and 56 km shows a decrease in concentration to about 100 cm^{-3} but increases in both extinction coefficient and mass loading to 2 km^{-1} and 5 mg m^{-3}, respectively. Both increases are the result of the presence of larger particles (5 to 25 μm) in the middle cloud region. This region has an integrated optical depth of 12.5. The overall size distribution is trimodal with a very narrow 3.5-μm mode separating small (1-μm) particles and the larger particles.

The lower cloud region between 49 and 51 km is the most dense. The concentration is not noticeably greater than in the upper cloud region, but the extinction coefficient and mass loading are one and two orders of magnitude higher, respectively. This is the region of largest particle sizes observed. Just beneath this thick layer is a distinct thin layer of somewhat reduced opacity and mass which we have tentatively designated as a pre-cloud layer, which we believe to be of similar composition but smaller sizes. The combined thick and thin layers have roughly 13 optical depths and nearly half the total cloud mass. The second size distribution mode observed at 3.5 μm in the middle cloud region essentially disappears, and the large size mode (≈ 10 μm) strengthens in the lower cloud region, leaving mostly the very small and very large particle modes.

The region from 32 to 48 km below these clouds is a thin haze of particles nearly a micrometer in size, with concentrations of 1 to 20 cm^{-3}; the upper part from 45 to 47 km is most dense. It contains negligible mass and optical depth but is of interest because of its persistence with altitude.

The various modes observed in the size distributions at lower altitudes undoubtedly reflect distinct populations of particles. Further information is obtained from the sample-to-sample variability. A rough mass profile (for example, in the middle cloud region) and broad size spectra usually indicate solid particles traversing the photodiode array in different orientations. Smooth profiles and narrow size distributions indicate spherical particles, almost certainly liquid. By both criteria, we feel that the 3.5-μm peak is liquid, and the larger particles are solid (or possibly an unusually broad spectrum of liquid droplets). As already mentioned, solid sulfur is an excellent candidate. The narrow 3.5-μm peak is surely H_2SO_4. The data gap at 57 km currently precludes positively tracing it into the upper cloud region where the droplet size may have simply decreased and merged with smaller particles of 1 μm, producing the spectrum observed. The slight bimodality indicated supports this conclusion; however, the increase in particles near 1 μm in size requires explanation. Again the data set to be received will help; they may be H^3SO^4, elemental sulfur, or some mixture of both.

The general behavior of all popu-

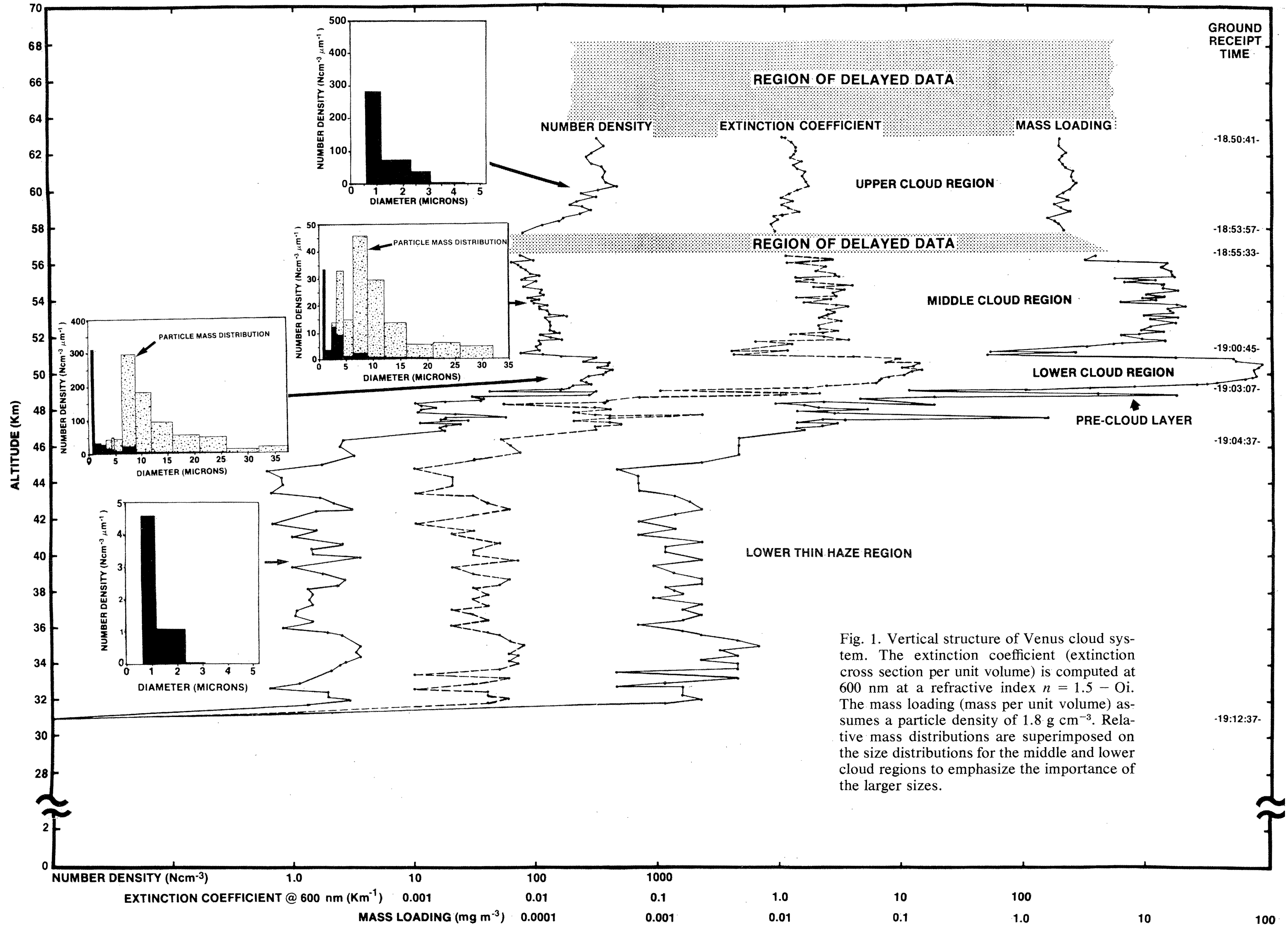

Fig. 1. Vertical structure of Venus cloud system. The extinction coefficient (extinction cross section per unit volume) is computed at 600 nm at a refractive index $n = 1.5 - 0i$. The mass loading (mass per unit volume) assumes a particle density of 1.8 g cm^{-3}. Relative mass distributions are superimposed on the size distributions for the middle and lower cloud regions to emphasize the importance of the larger sizes.

lations is to show a concentration independent of height or decreasing somewhat at lower altitudes. This behavior is characteristic of a source at the top and a sink at the bottom, with downward flow by mixing and by gravitational settling. It seems to follow that there is a source of sulfur and H_2SO_4 at or above 57 km, the top of the middle cloud region. The source is presumably photochemical in nature, requiring ultraviolet radiation that does not penetrate far into the sulfur cloud.

We suggest the following working interpretation of the middle and lower clouds and the lower haze. The large sulfur particles created near 57 km are slowly descending. As they reach the region of 51 km, they begin to evaporate, and near 48 km the residues melt to form the particles of the lower haze. The slow evaporation of these particles is a problem; perhaps it is retarded by the presence of sulfur vapor, or perhaps we are seeing the residue of a recent local shower. The large particles (> 30 μm) observed in the middle and lower cloud layers are nearing mist sizes and would double their size by coalescence, falling through the 49- to 51-km layer. There is every reason to believe precipitation sizes could be produced in these clouds.

The H_2SO_4 droplets (peak 3.5 μm) present from 56 to 51 km appear traceable into the lower cloud region. The modal size decreases somewhat toward the bottom of the middle cloud region, and then it largely disappears while a large size mode (of similiar concentration) rapidly increases in the lower cloud region. This appears consistent with H_2SO_4 droplets, which first lose water on the way down but then encounter increased H_2O (and perhaps SO_2 and SO_3) growing to form the lower cloud region of dilute acid and the densest layer. This layer must incorporate some of the 0.2 percent of water vapor observed at lower altitudes by the large probe gas chromatograph (*6*). Its base is the dominant planetary feature at the several planetary locations observed by the Pioneer Venus nephelometer (*7*) as well as by the Soviet nephelometer aboard Venera 9 and 10 (*8*).

It is clear that the Venus cloud system is far more complicated than we expected. Both H_2SO_4 and sulfur particles seem identifiable, but other particles must be explained (for example, 1-μm particles at 51 to 56 km). The Venus clouds are quite tenuous at certain altitudes, but because of the vertical extent, the total cloud optical depth integrates to more than 32 (and should increase to 36 to 40 when all data is received) and the particle mass is equivalent to 0.1 to 0.2 mm of precipitation. Most importantly, the large sizes (> 10 μm) encourage the possibility of precipitation on Venus, either in the dilute H_2SO_4 lower cloud region or initiated by sulfur from the middle cloud region, which would pick up the dilute H_2SO_4 when falling below 51 km. The significance of these large particles in returning mass downward cannot be overemphasized.

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References and Notes

1. R. G. Knollenberg, *Proceedings of the International Cloud Physics Conference* (American Meteorological Society, Boston, 1976), pp. 554–561.
2. L. Colin, *Space Sci. Rev.* **20**, 249 (1977).
3. A. T. Young, *Icarus* **32**, 1 (1977); B. Hapke and R. Nelson, *J. Atmos. Sci.* **32**, 1212 (1975).
4. A. T. Young, *Icarus* **18**, 564 (1973); J. B. Pollack *et al.*, *ibid.* **23**, 8 (1974).
5. J. E. Hansen and J. W. Hovenier, *J. Atmos. Sci.* **31**, 1137 (1974).
6. V. I. Oyama, G. C. Carle, F. Woeller, J. B. Pollack, *Science* **203**, 802 (1979).
7. B. Ragent and J. Blamont, *ibid.*, p. 790.
8. M. Ya. Marov, V. N. Lebedev, V. E. Lysteev, I. S. Kuznetsov, G. K. Popandopulo, paper presented at the 19th meeting of the Committee on Space Research (of the International Council of Scientific Unions), Philadelphia, 14 to 19 June 1976.
9. We thank Ball Brothers Research Corporation, Boulder, Colo., for building the excellent LCPS instrument.

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Preliminary Results of the Solar Flux Radiometer Experiment Aboard the Pioneer Venus Multiprobe Mission

Abstract. *The solar flux radiometer aboard the Pioneer Venus large probe operated successfully during its descent through the atmosphere of Venus. Upward, downward, and net fluxes from 0.4 to 1.0 micrometers were obtained at more than 390 levels between 185 millibars (at an altitude of ~ 61 kilometers) and the surface. Fluxes from 0.4 to 1.8 micrometers were also obtained between 185 millibars and about the level at which the pressure was 2 atmospheres. Data from 80 to 185 millibars should be available after additional decoding by the Deep Space Network. Upward and downward intensities in a narrower band from 0.59 to 0.66 micrometers were also obtained throughout the descent in order to constrain cloud properties. The measurements indicate three cloud regions above the 1.3-atmosphere level (at an altitude of ~ 49 kilometers) and a clear atmosphere beneath that level. At the 67° solar zenith of the probe entry site, some 15 watts per square meter are absorbed at the surface by a dark ground, which implies that about 2 percent of the solar energy incident on the planet is absorbed at the ground.*

Although Venus resembles Earth in size, mass, and distance from the sun, conditions at its surface are completely different from those at the surface of Earth. In particular, a remarkably high surface temperature near 750 K has been measured by several techniques. It is generally assumed that absorbed sunlight provides the energy that maintains the high surface temperature of Venus despite the planet's complete coverage by a highly reflective cloud layer. An understanding of the thermal balance of Venus requires a detailed knowledge of the amount of sunlight absorbed at various levels in its atmosphere and at the planet's surface. The planned contributions of the Pioneer Venus mission in this and other areas affecting the thermal balance have been outlined previously (*1*).

To obtain measurements of solar flux near the cloud tops where the sun is still visible from a spinning probe suspended beneath a parachute, the measurement scheme adopted used narrow fields of view (5° full width at half maximum response). When the sun was visible, the instrument determined the spin period of the probe and sampled the radiation field at known azimuth angles relative to the sun. When the sun was no longer directly visible (at optical depths greater than about 7 at the entry site), the instrument sampled as rapidly as the data rate allowed (every 8 seconds). Each measurement set contains data in two broad spectral channels, from 0.4 to 1.0 μm and from 1.0 to 1.8 μm, in three upward-looking directions at angles of 27°, 60°, and 83° from the zenith and two downward-looking directions at angles of 102° and 142° from the zenith. In addition, data were collected in a narrower spectral channel from 0.59 to 0.66 μm at zenith angles of 60° and 142° (Fig. 1). Thus, except near the cloud tops where azimuthal information was obtained, the data consist of sets of 12 intensity samples obtained at 8-second intervals during the descent. The broad-band upward-looking samples are used in a three-point Gaussian quadrature for the downward flux, and the downward-looking chan-

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