11. D. E. Anderson, Jr., *ibid.* **81**, 1213 (1976).
12. I. Ferrin, thesis, University of Colorado (1976); S. Kumar, D. M. Hunten, A. L. Broadfoot, *Planet. Space Sci.* **26**, 1063 (1978).
13. V. I. Oyama, G. C. Carle, F. Woeller, J. B. Pollack, *Science* **203**, 802 (1979).
14. This work was performed under NASA contracts NAS 2-8816 and NAS 2-9477. We acknowledge the contributions to this experiment of the Pioneer Project Office, our colleagues on the Pioneer Venus Science Steering Group, and especially our colleagues and staff at the University of Colorado's Laboratory for Atmospheric and Space Physics. The false-color image on the cover of this issue was made at Infomap, Inc., Boulder, Colo.

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Infrared Remote Sounding of the Middle Atmosphere of Venus from the Pioneer Orbiter

Abstract. *Orbiter infrared measurements of the Venus atmosphere in the 60- to 140-kilometer region show very small diurnal temperature differences near the cloud tops, increasing somewhat at higher levels. The seasonal (that is, equator to pole) contrasts are an order of magnitude larger, and the temperatures unexpectedly increase with increasing latitude below 80 kilometers. An isothermal layer at least two scale heights in vertical extent is found near the 100-kilometer altitude, where the temperature is about 175 K. Structure is present in the cloud temperature maps on a range of spatial scales. The most striking is at high latitude, where contrasts of nearly 50 K are observed between a cold circumpolar band and the region near the pole itself.*

The Venus orbiter radiometric temperature experiment (VORTEX) on the Pioneer orbiter is an infrared radiometer with ten spectral channels in the wavelength region from 0.2 to 60 μm, similar in concept to Earth weather satellite instruments. Its principal attribute is the ability to measure thermal emission from the atmosphere at eight different, distinct height levels, and thus allow the vertical temperature structure to be recovered. Previous radiometers on U.S. and Soviet missions were simple cloud top mappers, without the ability to discriminate true atmospheric temperature structure from cloud morphology, and with little or no vertical coverage. The height range covered by VORTEX, in contrast, is about 60 to 140 km. This includes the "Earth-like" range of temperatures and pressures; the region of the ultraviolet markings, which exhibit much dynamical activity including the "4-day" circulation; the peak of the ionosphere, and the base of the exosphere. The temperature sounding channels all are in or near the ν_2 fundamental band of carbon dioxide. Two other channels measure reflected solar energy in the near infrared, and one is located in the far infrared near 50 μm. The instrument and its measurement capabilities have been described (*1*, *2*).

Since orbital insertion on 4 December, the radiometer has been activated in all three of its operating modes: global mapping, local imaging, and limb scanning. Excellent performance has been obtained in each case. The second and third of the modes listed require very high data rates and therefore can be used only infrequently without impacting the return from the other science experiments. Consequently, most of the VORTEX data so far are in the relatively low spatial resolution mapping mode (maximum spatial resolution approximately 20 km), and our report deals exclusively with this. The presentation of results from the solar reflectance channels is also deferred until a preliminary analysis has been performed.

Data from orbit 1 are presented in several forms in three figures. Figure 1 shows temperature profile retrievals for selected regions representing dayside (afternoon) equatorial, nightside (predawn) equatorial, and polar soundings. Figure 2 shows a cross section of the atmosphere in the northern hemisphere, consisting of measurements of the temperature at six different height levels from equator to equator over the pole. This plot was made by selecting from the data set those soundings with near-nadir viewing geometry. Figure 3 is a rectangular coordinate map of Venus which has been enhanced in the image processing laboratory to bring out the structure of the cloud tops. The data shown represent a ratio of the intensity in the 11.5-μm window channel to that measured in the wing of the 15-μm CO_2 band, which measures the atmospheric temperature above the clouds near 80 km altitude. This ratio process removes, to first order, horizontal atmospheric temperature differences and viewing geometry effects, and leaves inhomogeneities in cloud opacity or height in the presence of a vertical temperature gradient as the principal source of contrast. The narrow strip to the bottom left is the data taken near periapsis, the width of the strip representing the distance between the horizons to either side of the spacecraft as it passes close to the planet.

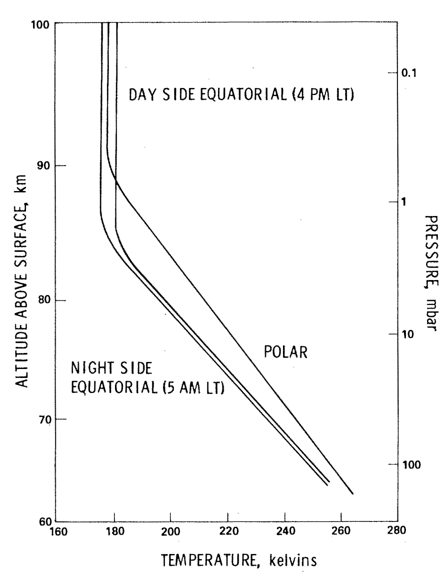

Fig. 1. About 4000 vertical temperature profiles were measured on orbit 1; these three are typical of the equatorial and polar profiles at the local times of day shown. The 11.5-μm window temperature, corresponding approximately to the temperature at unit optical depth in the clouds, occurs at an altitude of approximately 68 km on the dayside and about 0.5 km lower on the nightside. The altitude scale is derived, assuming a reference height of 52 km at 1 bar. [From *NASA SP-8011* (1972)]

The principal conclusions so far from these and similar data from the first few orbits are as follows:

1) Over the limited range of longitudes observed so far, day-to-night temperature contrasts are very small. From about 65 to 80 km, the differences appear to be about 1 K on average at all heights. Between 80 and 100 km, about 5 K of contrast is observed, with the dayside warmer.

2) Pressure modulator radiometer measurements (*1*) near 100 km at the equator show virtually no limb darkening. This implies temperatures constant to within 1 K over a vertical range of at least two scale heights (about 8 km) in this region.

3) The source function for cooling to space at altitudes near 125 km and above is extremely low, at least near the poles where the orbital geometry allows us to measure it (*1*).

4) The cloud top brightness temperatures are about the same on average for measurements made near 5 a.m. and 4 p.m. Venus local time. This result should be compared with figure 8 of Ksanfomality *et al.* (*3*), who interpreted Venera 9 and 10 measurements in terms of 10 K higher equatorial cloud temperatures all over the nightside, relative to the day.

5) Equator-to-pole temperature con-

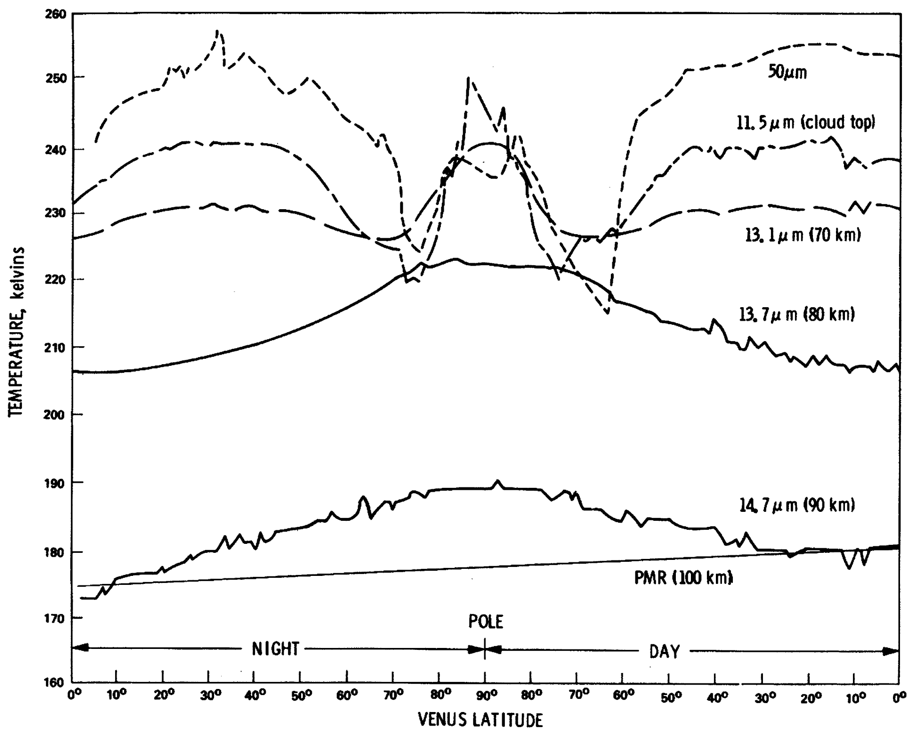

Fig. 2. A scan from equator to equator through the north pole, showing the latitudinal dependence of temperature observed in six of the channels. The approximate height in the atmosphere associated with each channel is also shown, except for the two (11.5 and 50 μm) for which the height is determined by the cloud properties, rather than the atmospheric pressure. The detailed structure is real, being well above the instrument noise, which is on the order of 0.1 K. Exceptions to this are the 50-μm and pressure modulator channels; the curve for the latter (*PMR*) has been smoothed by averaging a large data set from several orbits.

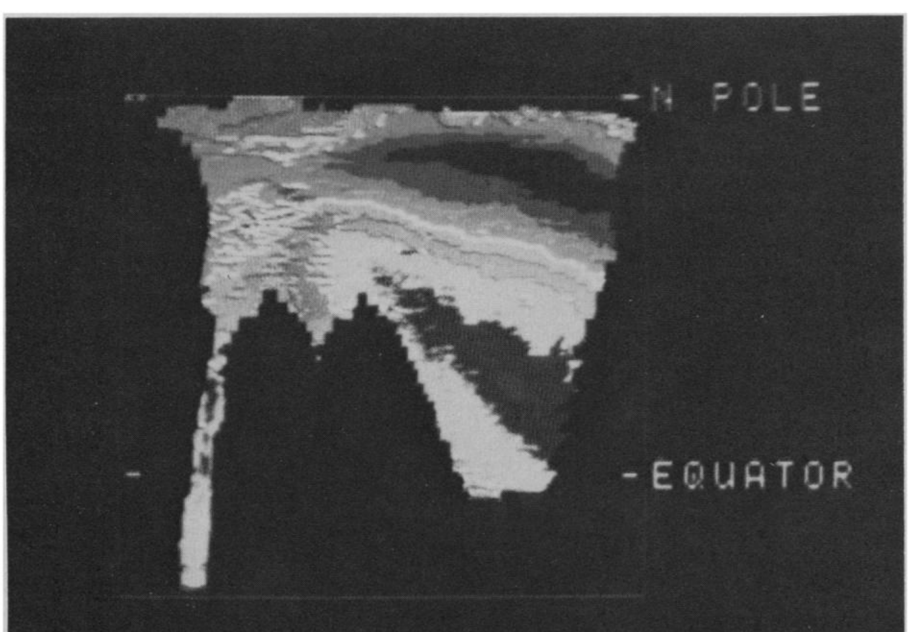

Fig. 3. Image of the Venus clouds obtained during orbit 1 on 5 December 1978. The different levels represent the ratio between the emission from the cloud tops near 65 km, measured at 11.5 μm, and that of the atmosphere about 15 km higher, measured at 13.7 μm. The coldest clouds have a temperature of about 215 K, and are represented by the dark band at 70°N latitude. Each of the eight levels shown represents a change in cloud opacity equivalent to a brightness temperature difference of about 3 K. There is a monotonic decrease in cloud opacity between the cold polar band and the diagonal dark gray feature at mid-latitudes, the latter characterized by a cloud top temperature of 240 K. Our coverage extends from the north pole to 30°S, and from 160° longitude at the left to 90° longitude at the right (referenced to a Venus-centered Aries/ecliptic coordinate system), although not all areas are observed because of the orbital geometry. Meridians and parallels are linearly spaced. The subsolar longitude was 269°, and the tick marks in the lower half of the image indicate the location of the equator.

trasts of about 10 K are observed in the altitude range 65 to 80 km. The sense is that of gradually increasing temperatures when moving from equator to pole. This contrast is smaller at 90 km and is essentially absent at 100 km.

6) The polar clouds show large temperature contrasts and an organized, quasi-permanent structure characterized by an intense, cold band of cloud surrounding the pole and a warm depression in the cloud at the pole itself.

7) A great deal of variable structure has been observed, superimposed on the global scale phenomena described above. This appears on a variety of scales, some suggesting planetary waves and others showing less organized structure presumably associated with the Venus meteorology in ways not yet understood.

The low day-night contrasts are presumably a manifestation of the efficient redistribution of solar heating near the cloud tops by the rapid zonal circulation. The winds are smaller above 80 km (see below), allowing a somewhat larger thermal gradient to be sustained. Also, the heating rates are expected to be greater at these levels than below (*4*).

The cold polar band appears to be poleward of the bright ring observed in the ultraviolet, and may be associated with the dark ultraviolet feature seen inside the polar ring in Mariner 10 images (*5*). The band appears to have a wavelike structure (see Fig. 3). A similar infrared feature has been observed at both poles from ground-based telescopes (*6*, *7*). Diner (*7*) has suggested that such features are solar-related, such that the coolest point always occurs between local midnight and dawn on Venus. The Pioneer data so far are consistent with this hypothesis, although we must wait for more complete phase angle coverage from later orbits to test it completely.

The fact that the Pioneer observations do not show the day-night asymmetry in cloud top temperature reported by Venera experimenters (*4*) may also be explained by additional longitude coverage, especially of the evening terminator. This is where the Venera data were concentrated; ground-based measurements (*7*) show contrasts in this region which do not, as suggested in (*3*), extend to all local times.

The more favorable viewing geometry of the Pioneer orbiter shows much higher temperatures at the poles than might have been expected from ground-based observations. During a high resolution pass over the north pole, temperatures in excess of 260 K were measured in the 11.5-μm window channel. This is more than 45 K higher than the polar band cloud temperature in the same channel, and must mean a substantial depressing or clearing of the clouds at the pole, since the cloud temperature rises much more than that of the overlying atmosphere. This, in turn, implies strong descending motion.

Apart from the pole itself, the most striking warm feature is seen at mid-latitudes on the right-hand side of Fig. 3. This is suggestive of the Y-shaped features that are prominent in ultraviolet pictures of the planet (*4*). If a correlation can be established, the infrared measurements will provide strong constraints on theories of the origin of the ultraviolet markings. In any event, the complex structure of the cloud top temperatures suggest, in general, an equally complex circulation pattern.

Theoretical models and measurements at levels near 150 km predict higher temperatures than those implied by the very low brightness temperatures we observe at 125 km. This result is almost certainly due to the breakdown of local thermodynamic equilibrium (LTE) at low pressures, rather than to kinetic temperatures lower than 170 K. Non-LTE conditions at these levels on Venus have been predicted theoretically (*4*). Below 110 km (pressures greater than 10^{-6} bar), the infrared brightness temperature may safely be interpreted in terms of kinetic temperature (*4*).

The higher temperatures observed at the pole relative to the equator imply either a substantial haze at high altitudes near the equator, or a real increase in gas temperature with latitude on constant pressure surfaces. Although the Mariner 10 and Pioneer Venus ultraviolet imaging experiments both report high equatorial hazes, these seem to be very tenuous even at visible wavelengths (*8*). It is unlikely that they could provide enough opacity at 12 μm to account for the large contrasts observed; further analysis is needed to confirm this. Higher polar stratospheric temperatures, relative to the equator, imply several constraints on the atmospheric dynamics. Any poleward transport of heat in the stratosphere must be thermally indirect, that is, against the temperature gradient. This type of situation is encountered in Earth's stratosphere, where the motions are driven from below. On Venus, the mean meridional circulation, planetary scale waves, and small-scale eddies may all play a role in transporting heat poleward.

In addition, if the zonal wind is cyclostrophically balanced (*9*), higher polar temperatures would imply that the strength of the zonal wind decreases with height in the stratosphere. Our preliminary data then indicate that the 4-day circulation falls off above the cloud tops and is much reduced by the 80 km level. Ground-based spectroscopic data (*10*) suggest that the zonal circulation also varies in both time and longitude. Continued VORTEX data should distinguish between symmetric Hadley circulations, tides locked to the solar heating, and time-varying eddies, in producing this effect.

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References and Notes

1. F. W. Taylor, F. E. Vescelus, P. B. Forney, G. T. Foster, J. R. Locke, J. T. Houghton, J. Delderfield, J. T. Schofield, "Pioneer Venus orbiter infrared radiometer. I: Instrument description," in preparation.
2. F. W. Taylor, R. Beer, D. J. McCleese, J. V. Martonchik, M. S. Hanner, P. B. Forney, "The Pioneer Venus orbiter infrared radiometer. II: Calibration," in preparation.
3. L. V. Ksanformality, E. V. Dedova, L. F. Obukhova, V. M. Pokras, N. V. Temnaya, G. F. Filippov, *Sov. Astron.-AJ*. **20**, 476 (1976).
4. R. E. Dickenson, *J. Atmos. Sci*. **29**, 1531 (1972).
5. M. J. S. Belton, G. R. Smith, G. Schubert, A. Del Genio, *ibid*. **33**, 1394 (1976).
6. D. J. Diner, J. A. Westphal, F. P. Schloerb, *Icarus* **27**, 191 (1976).
7. D. J. Diner, "Simultaneous ultraviolet and infrared imaging of Venus," thesis (part 2), California Institute of Technology (1978).
8. B. O'Leary, *J. Atmos. Sci*. **32**, 1091 (1975).
9. C. Leovy, *ibid*. **30**, 1218 (1973).
10. W. A. Traub and N. P. Carleton, "Retrograde winds on Venus: Possible periodic variations," preprint.

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Orbiter Cloud Photopolarimeter Investigation

Abstract. *The first polarization measurements of the orbiter cloud photopolarimeter have detected a planet-wide layer of submicrometer aerosols of substantial visible optical thickness, of the order of 0.05 to 0.1, in the lower stratosphere well above the main visible sulfuric acid cloud layer. Early images show a number of features observed by Mariner 10 in 1974, including planetary scale markings that propagate around the planet in the retrograde sense at roughly 100 meters per second and bright- and dark-rimmed cells suggesting convective activity at low latitudes. The polar regions are covered by bright clouds down to latitudes approximately 50 degrees, with both caps significantly brighter (relative to low latitudes) than the south polar cloud observed by Mariner 10. The cellular features, often organized into clusters with large horizontal scale, exist also at mid-latitudes, and include at least one case in which a cell cuts across the edge of the bright polar cloud of the northern hemisphere.*

One major objective of the orbiter cloud photopolarimeter (OCPP) experiment is to determine physical properties (size, shape, and refractive index) of the haze and cloud particles on Venus, and to measure the vertical distribution of these aerosols. The diurnal, altitudinal, and latitudinal variations obtained for these properties should contribute to our understanding of the processes of formation and decay of the aerosols that form a ubiquitous veil around Venus.

The second major objective is to obtain images in ultraviolet light and to use these to study large-scale cloud morphology, measure cloud-tracked winds, and determine characteristics of wave propagation in the atmosphere of Venus. The geometry for imaging from the orbiter will yield nearly full-disk images for approximately 80 days beginning in the middle of January 1979, thus permitting extension of the time scales for dynamical studies by an order of magnitude over that obtained by Mariner 10 imaging, which lasted for 8 days (*1, 2*). The planned extended mission for Pioneer Venus will permit study of physical processes occurring on time scales up to several hundred Earth days (*3-7*).

The overall purpose of these studies is to better understand basic atmospheric and climatic processes. Improved knowledge of the life cycle of aerosols on Venus, together with analysis of their effect on atmospheric structure, may contribute to determination of the role of atmospheric aerosols in terrestrial climate. Similarly, the information obtained on the general circulation and

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