The Clouds of Venus


by


Andrew T. Young

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Department of Physics
Texas A & M University
College Station, Texas   77845


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## Abstract

The physical and chemical properties of the clouds of Venus are reviewed, with special emphasis on data that are related to cloud dynamics. None of the currently-popular interpretations of cloud phenomena on Venus is consistent with all the data. Either a considerable fraction of the observational evidence is faulty or has been misinterpreted, or the clouds of Venus are much more complex than the current simplistic models. Severals lines of attack are suggested to resolve some of the contradictions. A sound understanding of the clouds appears to be several years in the future.

## 1. Introduction

The visible "surface" of Venus is formed by an optically thick, un-broken cloud cover. The major constituent of these clouds has only recently been discovered to be sulfuric acid, and the exact composition is still uncertain. The approximate depth of the cloud-filled region has been revealed by Venera-8 data (Marov et al., 1973), but even these are not capable of a unique interpretation (Lacis and Hansen, 1974). Further-more, photographs taken in near-ultraviolet light show cloud features that change markedly from day to day (Ross, 1928), due to some as-yet un-identified absorber. Finally, there is conflicting evidence about the cloud motions and the general atmospheric circulation (Young, 1975).

Because so much remains unknown or in doubt about the clouds of Venus, it is impossible to give a unified interpretation of the observa-tional data. The best that can be done at present is to review the ob-servational evidence, and show what can and what cannot be inferred from it. A few conceptual models can also be compared with the data, and the numerous conflicts pointed out.

## 2. Relatively "Hard Facts"

The general chemical composition of the Venus atmosphere has been reviewed by L. Young (1972). Over 90% of the atmosphere is $CO_2$. The only uniformly-mixed minor constituent is CO, with a mixing ratio of $5.1 \times 10^{-5}$. Water vapor is known to be variable, typically in the range $10^{-5} - 10^{-6}$, corresponding to about 1% relative humidity at the mean temperature of the absorbing gas ($250 \pm 10$ K). HCl appears to be concentrated within the lower part of the cloudy region, and the same is probably true of HF; typical

mixing ratios in the region we can observe are roughly $4 \times 10^{-7}$ for HCl and $10^{-8}$ for HF, but these are derived from a single spectrum and the actual amounts may vary as much as water does. Upper limits for various other gases are given by Owen and Sagan (1972); these are on the order of $10^{-7}$ for $NH_3$ and for the sulfur-bearing gases $H_2S$ and COS, $10^{-8}$ for $SO_2$, and $3 \times 10^{-9}$ for ozone. According to Traub and Carleton (1972), the upper limit for the $O_2$ mixing ratio is $5 \times 10^{-6}$. If $O_2$ and CO were produced by photodissociation of $CO_2$, we should observe at least 5 times more oxygen than this upper limit.

Notice that HCl is about 40 times as abundant as HF, although these two halogens have similar cosmic abundances. Furthermore, the sum of the upper limits for sulfur-bearing gases is lower than the HCl abundance, although sulfur is about 60 times as abundant as chlorine in general. I shall return to these points later.

Let us now turn to the cloud particles themselves. The bulk of what we know about the clouds has been found by Hansen and his associates from a very detailed analysis of very extensive and accurate polarization observations made by several other workers. The definitive results of Hansen and Hovenier (1974) are that (1) the particles are spherical, and hence probably liquid; (2) the visual refractive index is 1.44 ± 0.015, with a normal dispersion curve; and (3) the effective radius of the size distribution is 1.05 ± 0.10 microns, with a small effective variance (0.07 ± 0.02). Furthermore, from the small amount of Rayleigh scattering observed, they find that the average "cloud-top" pressure (i.e., the pressure at unit optical depth in the cloud) is 50 millibars, in good agreement with L. Young's (1972) value of 30-60 millibars for the pressure of $CO_2$ line formation.

All of the above results appear to be well established, and I shall accept

them as the basic data for further discussions. However, it should be remembered that all the values quoted depend on certain assumptions and laboratory values used in interpreting the actual observational data, so that some revisions, hopefully only minor ones, will eventually have to be made.

## 3. Preliminary Results

What can be made of these facts? The first conclusion drawn from them was that the cloud particles were composed of a strong sulfuric-acid solution (Sill 1972; Young and Young 1973). This explains the following facts: (1) the extreme dryness of the atmosphere, a result of the reaction

$$H_2O + H_2SO_4 = H_3O^+ + HSO_4^-,$$
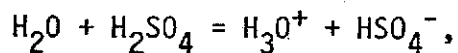
which is strongly exothermic and goes very nearly to completion. The great decrease in the number of $H_2O$ molecules in sulfuric acid solutions accounts for the corresponding decrease in their vapor pressure. Sill (1972) suggested that 86% (by weight) acid would be required to explain the low average humidity. However, any additional acids dissolved in the drops, such as HCl and HF, would further lower the vapor pressure, so that such a high concentration is not required. (2) Liquid drops are possible, not only because sulfuric-acid solutions generally have lower freezing points than water, but also because they supercool so readily that it is difficult to measure the freezing points accurately. The mixture in the range of interest that freezes at 250 K contains 75.9% $H_2SO_4$ by weight. Higher concentrations have higher freezing points, up to the monohydrate $H_2SO_4 \cdot H_2O$, which is 84% sulfuric acid and freezes near 281.7 K; but any additional acids in the solution should lower the freezing points. (3) The refractive index of 1.44, and the dispersion curve, are very

well explained by sulfuric acid of 70 - 75% concentration (Young 1973; Hansen
and Hovenier 1974). According to recent refractive-index measurements by
Palmer and Williams (1974), the best-fitting concentration is 70.5%; however,
all higher concentrations lie within the range of permitted refractive indices
for the Venus aerosol. It should be pointed out that water solutions of HF
have even lower refractive indices than water itself, so that the addition
of some HF to the acid droplets should lower the refractive index appreciably;
this would favor a concentration somewhat higher than 70%. Furthermore, HF
is highly soluble in $H_2SO_4$ because it reacts to form fluosulfonic acid:

$$HF + H_2SO_4 = H_2O + HSO_3F.$$
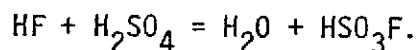
On the other hand, HCl, which is highly soluble in water because it dissociates,
is only weakly soluble in strong sulfuric-acid solutions; thus HCl, which might
tend to increase the refractive index, is less likely to dissolve in the
strongly-acid aerosol than HF, which tends to lower the refractive index.
Indeed, this may help explain why HF is some 40 times less abundant in the
gas phase than HCl, even though the two halogens have similar cosmic abundances.
(4) Some of the previously unexplained features of the infrared spectrum of
Venus, such as the 11.2 micron band and the extreme blackness of the planet
near 4 microns, are in good agreement with the spectrum of strong sulfuric
acid solutions (Young and Young, 1973). Furthermore, the spectrum of Venus in
the thermal infrared is explained in detail by 75% sulfuric acid drops with the
size distribution found by Hansen and Hovenier (1974), if the aerosol is
homogeneously mixed with the gas and the stratospheric lapse rate is 3 or 4
degrees per kilometer, as found by Mariner 5 and 10 radio occultations (Young
1974; Samuelson et al. 1974). The uniform stratospheric mixing ratio is

supported by other data as well (Young 1974). Both the infrared data and the requirement that the optical depth in the visible be unity at the 50 millibar level lead to a mass mixing ratio of $5 \times 10^{-6}$, or a numerical mixing ratio of $2.3 \times 10^{-6}$ for $H_2SO_4$ molecules relative to $CO_2$. This is comparable to typical mixing ratios for water vapor.

The spectra of sulfuric acid solutions change only slowly with concentration between 75% and 84.5% (the monohydrate). However, marked changes appear at higher concentrations, due to undissociated sulfuric acid molecules. These allow us to exclude concentrations appreciably higher than 85%. On the other hand, the low relative humidity appears to rule out any concentration much lower than 75%. A small concentration of some other acid will help bring the freezing point, vapor pressure, and refractive index closer to the observed values; HF is the most likely candidate. It seems reasonable at present to say the sulfuric acid concentration in the aerosol is about 80 ± 5%.

The effect of HF on the physical properties of this acid at 250 K needs to be investigated in the laboratory. If we imagine that as much HF as HCl were in the gas phase before adding the sulfuric-acid aerosol, which then dissolved the bulk of the HF, then between 1 and 2 per cent of the molecules in the liquid would be HF. As only about 1% of the molecules are water (as is shown by the relative humidity of about 1%), and as HF has such a powerful affinity for $H_2O$ that there is no chemical substance known that will dry it, even this small amount of HF may have an appreciable effect in lowering the water-vapor pressure of the aerosol. Thus we might expect the vapor-phase abundance of water to vary inversely with that of HF. Such a negative correlation should be looked for, although it will be difficult to measure with present techniques.

Although sulfuric acid explains the infrared spectrum of the Venus clouds

very well, it is as incapable of explaining the yellow color of the planet as water. For years this color, due to an absorption in the blue and ultraviolet, was used as an argument against water clouds, and the same argument is equally good (or bad) against sulfuric-acid clouds. The usual argument contains a fallacy, however: while it is true that pure water (or sulfuric acid) is non-absorbing at the short wavelengths where Venus absorbs, there is no reason why there cannot be some other material present, perhaps as a minor contaminant dissolved in the cloud aerosol, which does absorb at short wavelengths. We can only rule out a proposed cloud material if it absorbs where Venus is highly reflecting, not the other way around. Both water and $H_2SO_4$ are acceptable cloud constituents on this basis.

Indeed, there are indications that some other material must be present. For, if the ultraviolet absorber were a major cloud constituent, the absorption should be fairly uniform across the disc, and there should be no ultraviolet markings. (The argument, first made by Ross (1928), that the markings could be due to variations in the Rayleigh-scattering optical depth above a uniform yellow cloud, was based on a misunderstanding of Russell's interpretation of twilight phenomena on Venus; the layers visible at the limb and terminator have a normal optical depth less than 0.02 and are therefore so transparent as to be invisible on the disc. Furthermore, the polarization analysis (Hansen and Hovenier, 1974) shows that the Rayleigh optical depth is only about 5% at the wavelengths where the UV markings have maximum contrast, roughly 20 - 30%. As the ultraviolet albedo of Venus is near 50%, the very low Rayleigh optical depth cannot contribute enough light to account for the brightness variations on UV photographs. Finally, a preliminary look at possible correlations between UV markings and $CO_2$ absorption variations over the disc (shown in Fig. 1) indicates that the mean difference

between UV light and dark markings is only $(1 \pm 3)\%$. Thus, spatial variations in the concentration of UV absorber are the easiest means of explaining the UV features.)

## 4. Cloud Microstructure

To get a more detailed picture of the cloud, let us look at some additional quantities that can be deduced from the basic data. The projected surface density is about 3 g/m$^2$ of $H_2SO_4$, or 4 g/m$^2$ of total mass, in the aerosol above unit optical depth, which we take to occur at 50 mb pressure. At this pressure and a temperature of 250 K, the mean free path in $CO_2$ is about a quarter of a micron. This is smaller than the size of the droplets, but not enormously so; if we assume that Stokes' law is valid, we find that the aerosol deoplets can fall about $3 \times 10^{-4}$ m/sec or about 25 meters/day at the 50 mb level. The number density of droplets is about $1.6 \times 10^8$ m$^{-3}$, corresponding to an average separation of about 1.8 mm.

If the gas were perfectly still, these figures would correspond to a downward flux of $5 \times 10^4$ particles per square meter per second (5 per cm$^2$), or a mass flux of 1.5 micrograms per cm$^2$ per day. This flux must be compensated by a similar upward flux of either aerosol particles in regions of higher number density, or sulfur-bearing gases, depending on whether the sulfuric acid is produced below or above the 50 mb level. If it is produced below, then turbulent mixing must account for the nearly-constant aerosol mixing ratio. If it is produced above, in the region of free molecular flow, then the rate of fall is inversely proportional to the gas density, and a constant production rate will give a constant mixing ratio in still air (an argument first proposed by Link (1969) for the Earth's high scattering layer.) In the Stokes'-law region, the

speed of fall is (nearly) constant and the aerosol number density, rather than the mixing ratio, becomes constant. However, the region below the 50 mb level is probably strongly convective and turbulent, so that a nearly-constant mixing ratio can be expected there too. In any case we know that the aerosol extends with nearly constant mixing ratio up to the level of about 5 mb, or about 2.5 scale heights above our reference level (Young, 1974).

The narrow size distribution is evidence that the aerosol we see has not been subjected to much coalescence. As a rough indication of what is involved, note that a particle must travel about a scale height, on the average, to collide with another similar particle at the level of unit optical depth. If we assume that differential velocities of neighboring particles are comparable to the Stokes velocity (due to a spread in particle sizes), it will take a particle about 200 days to collide with another. However, because of the narrow size distribution, the Brownian motion may be more important. The thermal velocity for a sulfuric-acid droplet, which has a mass of about $10^{-11}$ g, is about a millimeter per second -- about four times faster than the Stokes velocity at 50 mb. This reduces the coalescence time scale to about 60 days. If the mixing ratio remains constant, the time scale is reduced in proportion to the pressure increase at greater depths (e.g., about 1 day at the 3-atmosphere level.) Of course, if the droplets are electrically charged, the whole problem is much more complicated.

These long time scales expected for significant evolution of the cloud structure at the levels we see are in marked contrast to the time scales of significant changes in ultraviolet cloud structure and in $CO_2$ absorption strength observed in the near infrared. Unlike terrestrial weather phenomena, in which clouds can rapidly appear and disappear as water condenses and evaporates, short-term

weather on Venus cannot be explained by a simple phase change of the major cloud constituent: sulfuric acid has a completely negligible vapor pressure[*] at 250 K. Once an aerosol droplet forms, there is no way to get rid of it without transporting it to much deeper levels of the atmosphere than those we see. Yet, according to Mariner occultation data, the region we see has a very low lapse rate (about 1/3 of the adiabatic lapse rate) and is therefore very stable against convection.

If, as is widely supposed, the 4-day periodicities in the UV features and the IR absorptions are due to a rapid rotation of the atmosphere, it is hard to understand how the periodic phenomena can survive in the face of the wind shears and turbulent mixing that should accompany the necessary 100 m/sec winds. Furthermore, there is a considerable body of data that are incompatible with the supposed 4-day rotation (Young, 1975). These data include both long-lived limb-terminator asymmetries in $CO_2$ absorption and some of the most reliable Doppler measurements of rotational velocities.

Finally, let us look at the behavior of one of our sulfuric acid droplets as it moves up and down in the cloud. In the region near the cloud top, the lapse rate is 3 or 4 degrees per kilometer (15 or $20^0$ per scale height), and the major effect should be a change in composition as water is cooked out of the droplet (going downward) or as more condenses (going up). For example, Fig. 3 of Young (1973) shows that a $7^0$ change in temperature at constant water-vapor pressure, or a $15^0$ change at constant mixing ratio (allowing for the 30% change in total pressure), corresponds to a 3% change in acid concentration. Suppose

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[*]The expected mixing ratio of $H_2SO_4$ in the gas phase in equilibrium with 75% acid droplets is about $10^{-13}$.

the droplet has fallen to a warmer region, so that water evaporates; this represents a 3.8% mass loss. The increase in temperature causes a slight expansion (a few tenths of a per cent loss in density), which is overwhelmed by the effect of the change in composition on density (about a 2% increase). Thus the volume of the drop is smaller due to both a drop in mass (3.8%) and a smaller increase in density; the net result is slightly over 5% decrease in volume. This corresponds to a radius decrease of just under 2%, or a change in projected area (or optical depth, if this happens to all the cloud particles) of about 3½%. The change in refractive index is an increase of about 0.002, again mainly due to the change in composition.

We can sum up these changes by noting that they are dominated by the loss (or gain) of water, due to the temperature dependence of the vapor pressure; the effects of thermal expansion are quite minor. Furthermore, the changes to be expected in one scale height are much smaller than the changes in either radius or refractive index that can be detected with present-day polarization data. Thus the natural vertical inhomogeneity of the cloud does not contribute sensibly to the apparent width of the size distribution, for example.

The above discussion does not take account of possible complications due to HF or other contaminants. However, they are all likely to be much more volatile than sulfuric acid itself, and to be lost with the water as the temperature rises. Hence, at the bottom of the cloud, we should have nearly pure sulfuric acid. Figure 8 of Young (1973) shows the vapor-pressure curve for the azeotropic mixture of water and sulfuric acid (98.3% by weight); for a cloud-bottom temperature of 400-450 K, the range indicated by the Venera-8 data, the expected water-vapor mixing ratio is near $10^{-4}$. This is quite consistent with various radio- and radar-astronomical upper limits near $2 \times 10^{-3}$, but is less than some model

atmospheres have required to account for the greenhouse effect. However, these models did not allow for the large opacity of the cloud itself. For example, if we assume the same aerosol droplets remain uniformly mixed from unit optical depth at 50 mb down to the cloud base at about 5 bars, the total cloud optical depth is equal to the pressure ratio, 100. This is consistent with estimates of the optical depth required to account for the Venera-8 light measurements, also.

When sulfuric acid boils, the vapor is generally a mixture of $H_2SO_4$, $H_2O$, and $SO_3$ molecules. Thus we should not expect much molecular sulfuric acid in the lower atmosphere. On the other hand, $HSO_3F$, which has a much lower boiling point than sulfuric acid and should therefore distil out of the aerosol well above the cloud base, is stable in the vapor phase up to $900^{\circ}C$, and may therefore be a minor constituent of the lower atmosphere.

## 5. Cloud Thermal Balance and Dynamics

Because of the very high thermal-infrared opacity of the cloud, solar radiation absorbed within or below the cloud cannot be directly re-radiated to space. We can expect that this energy will have to be transported by convection, and indeed the Mariner temperature profiles show a lapse rate that is almost exactly adiabatic in the cloud-filled region. Venus absorbs about 20% of the incident sunlight; about half of this is taken up by the mysterious ultraviolet absorber (See Fig. 2) which means it is absorbed in the upper part of the cloudy region. About 10% of the rest (1% of the original sunlight) reaches the surface, according to the Venera-8 data. Because of the increasing absorption in near-IR and visible $CO_2$ bands with increasing temperature and pressure, there must be some sunlight absorbed at every level in the atmosphere. However, according to Lacis and Hansen (1974), the Venera-8 data do not uniquely determine the vertical distribution of the deposited energy. On the other hand, one can make the following argument: because the aerosol particles are large compared to visible

and near-IR wavelengths, the cloud optical depth is practically independent of wavelength between 3000 $\overset{o}{A}$ and a few microns. The near-IR $CO_2$ bands show that the reflected sunlight penetrates, on the average, to about the level where the temperature is 250 K. The ultraviolet absorber (and hence the region where half of the total heat is absorbed) must lie at, or above, this level -- otherwise the UV absorber would not be seen, and the albedo would be near unity in the ultraviolet. Thus about half of the total absorbed energy is deposited near the cloud top, at a pressure no greater than one or two tenths of an atmosphere.

But the absorbed heat does not remain at the cloud top. If it did, the sunlit side of Venus would be appreciably warmer than the night side; in fact, the reverse appears to be true (Ingersoll and Orton, 1974). Apparently, convective mixing is sufficiently strong to store the absorbed energy deeper in the atmosphere.

L. G. Young (1972) has pointed out the remarkable constancy of the $CO_2$ rotational temperatures measured in different bands over several years. In spite of the fact that the strength of the absorptions, and hence the cloud-top pressure, varies considerably with time, no corresponding variation in the temperature has been observed. Therefore, I thought that the "thermostat" involved might be a phase change, such as freezing or melting, of the aerosol droplets (Young, 1973). However, in our most recent data, a small (8 or 9 degrees RMS) but apparently real temperature variation exists.

If an entire column of the Venus atmosphere were heated by $7^o$, the previous section shows that an increase in the amount of gas visible should result from the 3.7% decrease in optical depth, due to shrinkage of the aerosol particles as water evaporates from them. As the standard deviation of the amount of $CO_2$ absorption in this set of data (Young et al., 1974) is only about 5%, of which about half is due to random noise, we should expect to find a strong positive

correlation of the temperatures with the $CO_2$ variations, if the above picture is correct. In fact, there is practically no correlation of the temperature and the amount of gas; about 20% negative correlation is observed between the absorption strength and temperature variations, but this is mainly due to the temperature dependence of the (primarily low-J) lines we measured (see Fig. 3). Furthermore, the temperatures do not show a detectable 4-day variation. Instead, they seem to vary from place to place on the planet, with the mean being about the same from one day to the next.

My first reaction to this was that it proved that the clouds could not be sulfuric acid! However, it is possible to save the acid-cloud model if one assumes that the cloud-top temperature, and indeed the whole atmospheric temperature profile in this region, is determined by an equilibrium between the heat flux convected up from below and the flux radiated away. Then the near-constancy of the cloud-top temperatures means that the convective flux is nearly constant. This picture also explains why the top of the convective region coincides with about optical depth unity in the cloud: at the point where the cloud can radiate its heat away to space, convection is no longer needed to transport the upward flux. (This coincidence is even closer if we use the optical depth in the thermal infrared, which is a few times smaller than in the visible.) Finally, the near-constancy of the convective heat flux is explained by the depth of the convective cloud, whose base is in contact with the large heat capacity of the lower atmosphere.

The spatial variations in cloud-top temperature invite a comparison with the only two other spatially-variable quantities known, the water vapor abundance (Barker, 1974) and the ultraviolet features. Unfortunately, there is hardly any overlap between our data and Barker's water measurements. However, we do have

good ultraviolet coverage, largely supplied by the New Mexico State and Paris observatories. The detailed comparisons will be presented elsewhere; our preliminary result (Fig. 4) is that there is no difference between the mean temperatures of light and dark UV features. However, there does appear to be a real difference in the temperature <u>variations</u>: the light regions all seem to have nearly the same temperature, while the largest temperature variations all occur in the dark features. The interpretation of this discovery would be easier if we understood what the light and dark features are, physically.

They are clearly <u>not</u> "clearings" in an "upper cloud layer", for we find exactly as much $CO_2$ absorption in light features as in dark ones (Fig. 1). Indeed, such clearings probably cannot exist: if the cloud top is (nearly) a surface of constant temperature, large variations in cloud-top pressure would mean large temperature variations along a surface of constant pressure, which would produce mass motions tending to remove the imbalance. The clearer parts of the atmosphere, where we see more $CO_2$, are the colder at a given pressure level. But, as we find no mean difference between light and dark UV features, they are neither hot nor cold. This is even more surprising because the UV absorber is responsible for a large fraction of the total solar heating; one might expect to find dark areas a little warmer because of this.

It even seems difficult to determine whether the absorbing material is above or below unit optical depth. The generally lighter shade of the cusps, where we see to a smaller optical depth because of oblique illumination and viewing, suggests that the dark stuff is underneath. Then it should be more visible -- i.e., we might expect the dark markings to be larger and more contrasty -- when we see deeper in (more $CO_2$). Unfortunately for this argument, the days of maximum contrast and extent of the dark markings are the days when

we see the <u>least</u> $CO_2$. This is why we once suggested more $CO_2$ over light regions (Young and Young, 1973).

About the only regularity detected in the cloud structure is the tendency for the clouds to be less dense (and hence, for the isothermal surfaces to lie deeper in the atmosphere) at higher latitudes. The polar clearing has been observed at all four transits since 1761; the pressure at which a fixed optical depth (and hence, a fixed temperature) occurs is about a factor of two higher at the poles than at the equator (Link, 1969; pp. 209-214). The same effect is visible at much greater depths in the $CO_2$ data: spectra taken at higher latitudes show stronger absorptions (cf. Fig. 3 of Young et al., 1974), although one would expect to see less because of the oblique illumination and viewing. According to Barker (private communication), the effect is quite prominent at inferior conjunctions. A factor of two difference in pressure at constant temperature corresponds to a polar cooling of 10 - 15$^o$ along a constant-pressure surface. Are the cloud tops lower at the poles because the aerosol is produced at low latitudes and has time to fall out before the general circulation carries it to the poles, or because the aerosol is produced photochemically and there is less sunlight available to manufacture it at high latitudes?

Finally, although it is the four-day weather cycle on Venus that has attracted most attention, there is ample evidence of longer weather patterns with larger amplitudes. For example, Scott and Reese (1972) have pointed out the UV features "appear to be randomly distributed and quite ephemeral in nature, rarely enduring in a recognizable pattern for more than 20 days and usually much less." The spectroscopic observations show much larger variations from one year to the next than are seen within a 3-week interval of continuous and intensive observation; indeed, the general trend of the 3-week sequence (Young et al., 1974) opposes that of the average variation with phase angle (Young, 1972).

Furthermore, the 4-day cycle appears to come and go, or at least to vary from pronounced regularity to apparent chaos; Ross himself looked for periodic variations and was unable to find any, although his pictures cover several 4-day intervals well enough to show the repetition if it had been present. As Venus has a very low orbital eccentricity and a small equatorial obliquity, seasonal effects should be minor. What, then, is the nature of the long-term variations in weather?

## 6. Conclusions

I must conclude that we don't really understand the clouds of Venus very well. However, there are some obvious lines of investigation that would help clarify the situation, possible allowing us to ask the right questions the next time around. For example:

1. How do the trace constituents $H_2O$, HCl, and HF vary? How are these variations related to the temperature variations? Good spatial resolution over the disc is essential. Such an investigation may be possible at present if a sustained cooperative observing program can be conducted with several large telescopes simultaneously, using the highest-dispersion spectroscopic equipment available. The HF is the most difficult, but probably the most interesting after water. At present there is no prospect of getting enough spectral resolution from an orbiting spacecraft, which would obviously solve the spatial-resolution problem.

2. We need to know more about the physical chamistry of the $H_2O - H_2SO_4 -$ HF system at conditions like those at the Venus cloud tops. This is a fairly straightforward laboratory investigation, though the corrosive nature of the materials and the low concentrations of HF may pose difficulties in getting the measurements.

3. What is the general circulation pattern of the Venus atmosphere? Doppler measurements of wind velocity from Earth are very difficult, but should be repeated, using as many different techniques as possible to eliminate systematic errors. Meteorological probes, such as constant-pressure balloons, have been very useful on Earth and should be tried on Venus; the corrosive aerosol presents problems in maintaining a long lifetime, however.

4. Most frustrating of all, what is the ultraviolet absorber, and what is the nature of the UV features? All the "obvious" explanations conflict with at least some of the data. The lack of correlation of UV features with any easily-measurable quantity (cloud-top temperature, pressure, etc.) is baffling. I would guess that we won't understand the features until we know what the UV absorber is, and where it comes from. Until the features are understood, I think it is dangerous to interpret their motions as wind speeds, especially in view of the conflicting data on winds.

5. What is the average vertical structure of the clouds? In other words, how do the aerosol composition, size distribution, and mixing ratio vary with altitude? At present, high-resolution thermal-infrared spectra seem to offer the best handle on the mixing-ratio problem in the upper parts; enough observations should be made to separate long-term averages from short and long weather cycles. The techniques that have been tried in the past -- interpretation of the spectroscopic phase curve and line profiles in the near infrared -- require higher spectral resolution, and are intrinsically less sensitive to the vertical structure, and more difficult to analyze because of multiple scattering.

Finally, a word of caution: Because of long-term changes in the atmosphere of Venus, a restricted set of data, no matter how refined, cannot present a "typical" picture of the clouds. There is particularly the danger that data from

flyby spacecraft get entrenched in the literature as "definitive", while they actually show only a snapshot of the weather at a particular time. A good example of this is shown by the Mariner 5 temperature profiles: because the entry and exit data agreed well, they were regarded as a very accurate model by many people. Now we see important differences between Mariner 5 and Mariner 10 data, such as an appreciably different stratospheric lapse rate. Of course, neither set of results is "wrong", but Venus is different at different times and places. (The sampling of the atmosphere at just one point by an entry probe exemplifies a further complication of the same kind.) We cannot separate the "weather" from the "climate" until a large body of data, extending over a long period of time, is available. Both ground-based patrols and long-lived orbiters will be needed to solve these problems.

## 7. Acknowledgments

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## Figure Captions

Fig. 1.   Relation between the relative amount of $CO_2$ absorption and the relative
          brightness of the corresponding part of the planet in ultraviolet
          light.  To remove the effect of daily variations in $CO_2$ absorption,
          the ratio of the amount observed in a particular area to the average
          for the standard slit position (parallel to the line of cusps and
          midway between limb and terminator), which averages over a large part
          of the the disk, is used.  The estimated brightness of each area on
          UV photographs runs from 1 (very bright) to 5 (very dark).  The $CO_2$
          absorptions are taken from Young et al. (1974) and the UV pictures
          were taken at the New Mexico State and Table Mountain Observatories
          on the same days as the infrared spectra.

Fig. 2.   Spectral distribution of the solar energy absorbed by Venus.  Upper
          curve:  solar energy distribution;  bottom curve:  fraction of sun-
          light absorbed $(1 - A_\lambda)$ at each wavelength;  middle curve:  energy
          absorbed by Venus.  Note that the absorbed energy is mostly in the
          region around 4000 $\overset{\circ}{A}$.

Fig. 3.   Relation between $CO_2$ rotational temperatures and amount of absorption
          in the 7820 $\overset{\circ}{A}$ band.  Curve 1 shows the variation to be expected
          if the aerosol number density varies in an atmosphere of fixed
          temperature-pressure profile.  Curve 2 is the relation expected from
          temperature variations in a 75% $H_2SO_4$ aerosol, as described in the
          text.  Curve 3 is the effect of temperature alone on the equivalent
          widths of the $CO_2$ lines measured, for a fixed amount of gas.  This
          last effect appears to be present, but is hard to see because of large,
          uncorrelated variations in the amount of $CO_2$.  The two light, unlabelled

lines are the two regression lines; note that only curve 3 is contained

between them. The heavy cross is centered at the means of R and T,

and indicates ± one internal standard error in each coordinate.

Fig. 4.  Relation between ultraviolet cloud features and $CO_2$ rotational

temperatures. Although there is no systematic variation of mean

temperature with light or dark UV features, the darker features appear

to show more temperature variation than the lighter ones. The

scatter in the light-feature temperatures is comparable to their

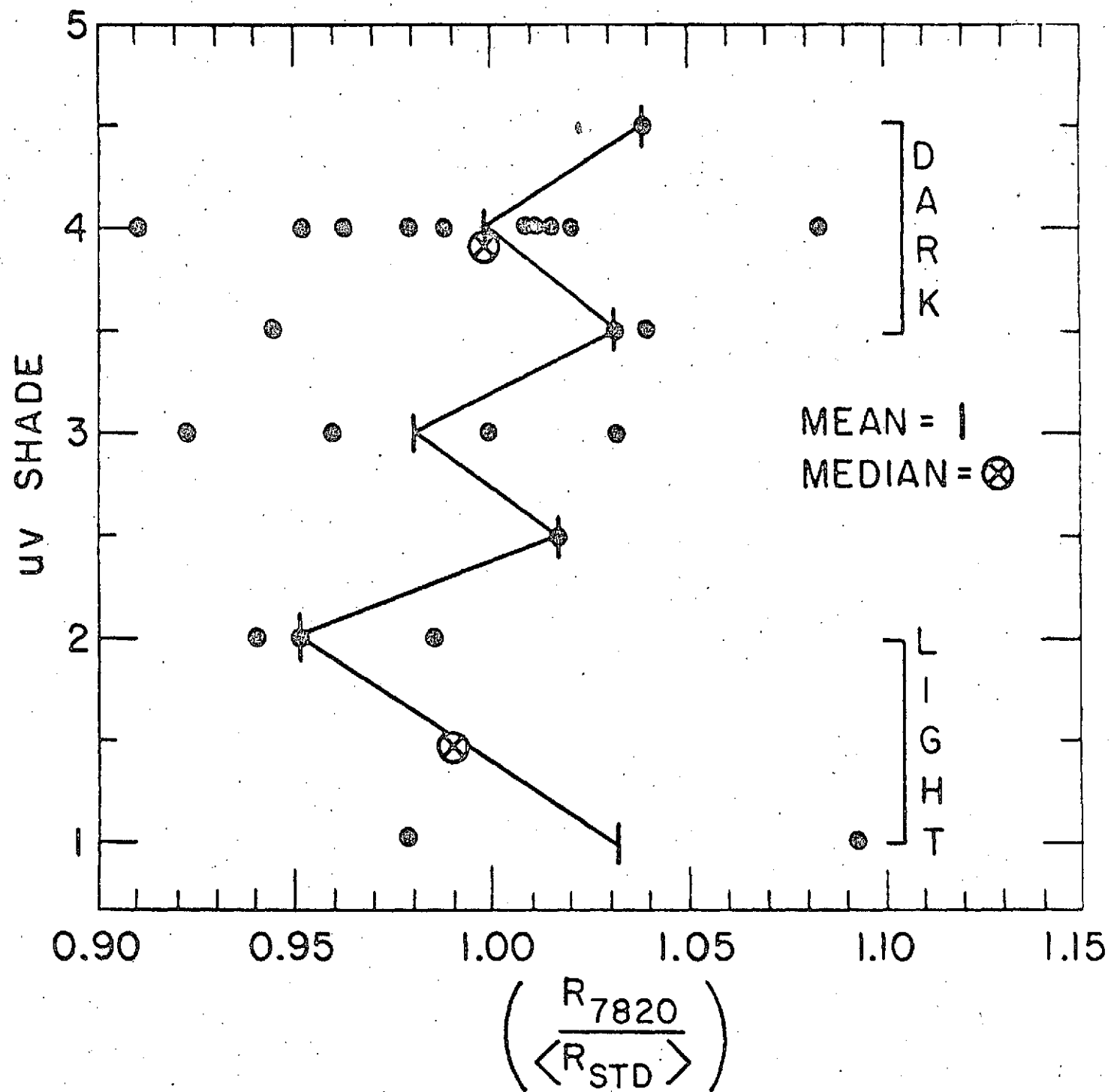internal errors (3 or 4 degrees), so they may be nearly isothermal.
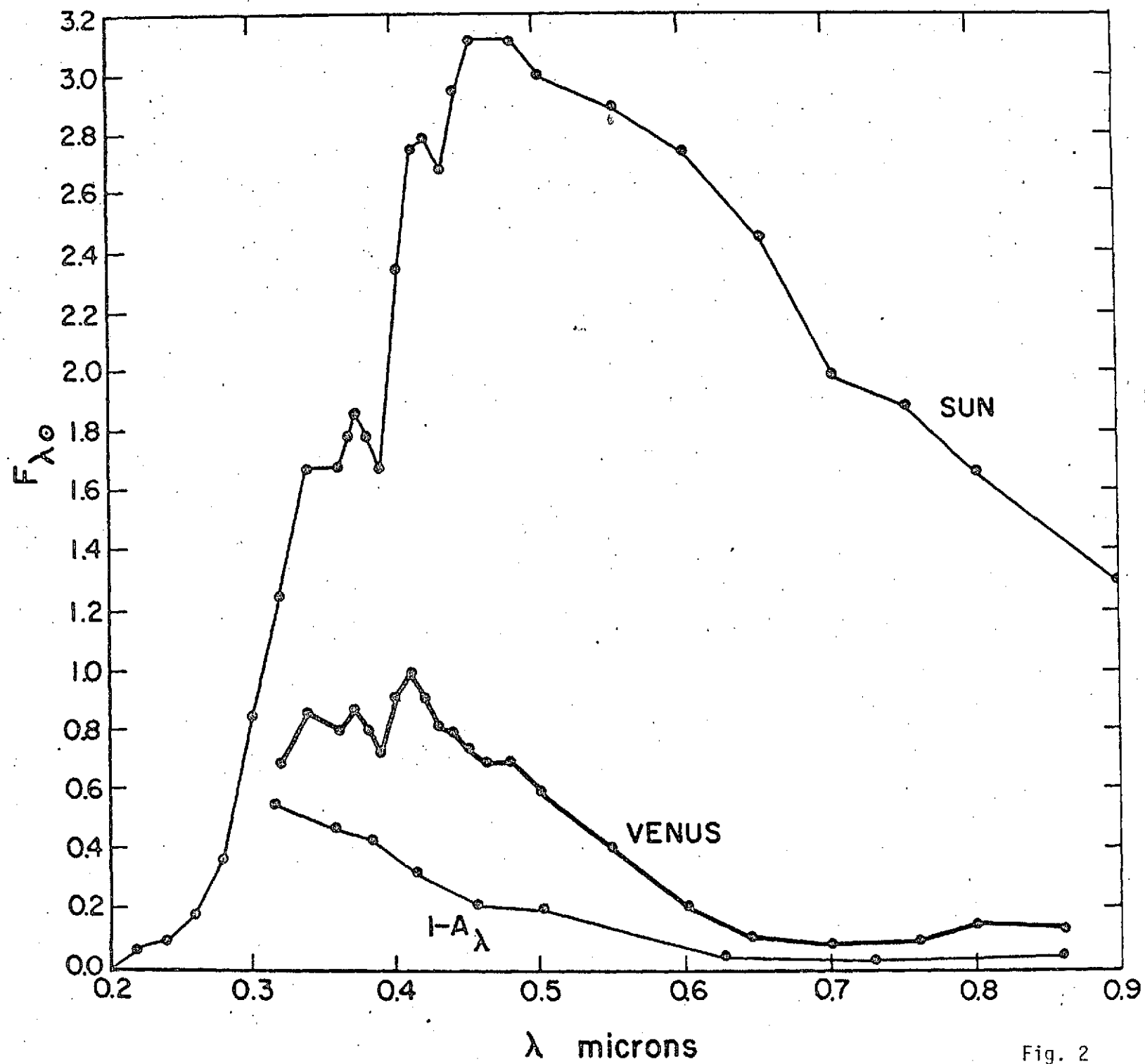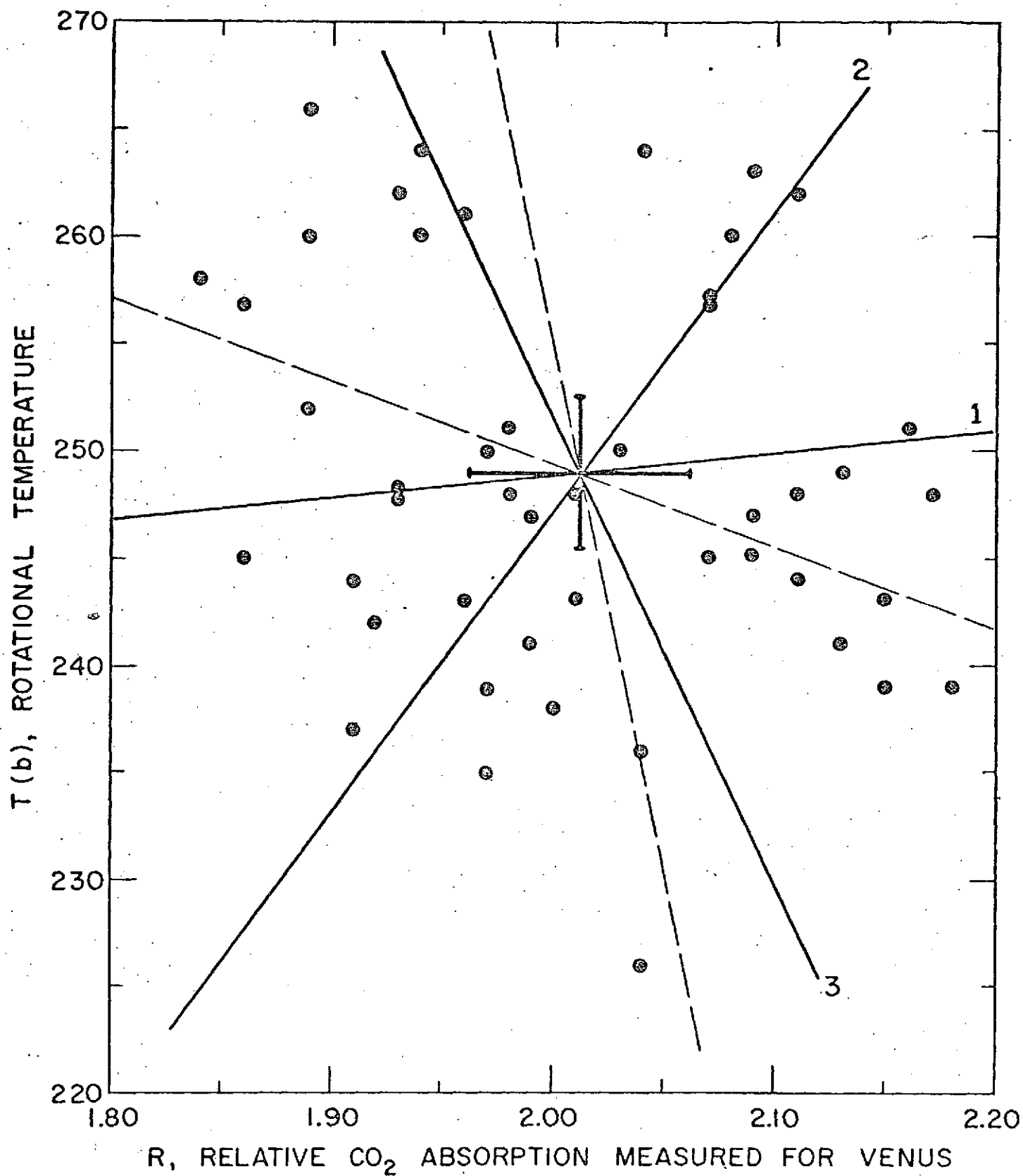
Fig. 1

Fig. 2

Fig. 3

Fig. 4