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Venus: The Next Phase of Planetary Exploration

The atmosphere and clouds of Venus are ripe for direct exploration by means of entry probes.

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Venus is our nearest neighbor; its dense atmosphere, its high surface temperature, and its uniform cloud cover make it the strangest of the inner planets. To explore and understand this planet and its atmosphere should be an item of continuing priority in any planetary exploration program adopted by the United States. The scientific importance of Venus is at least equal to that of any other target in the solar system.

Atmospheric studies generally divide into lower-atmosphere (meteorological, concerned only with thermodynamic equilibrium), upper-atmosphere (aeronomical, concerned with the ionization and photolysis of the outer skin of the atmosphere), and plasma investigations. The interplanetary plasma has rather small influence on the ionosphere, and the ionosphere probably has no significant effect on the lower atmosphere. On the other hand, the lower atmosphere is the source of chemical species and the anchor for upper-atmosphere temperatures; it provides the source of dynamical disturbance energy and the thermal radiation environment for the outer layers. Despite the scientific interest of upper-atmosphere and plasma research, we cannot claim to understand an atmosphere unless the physics, chemistry, and dynamics of its main bulk have been adequately studied. It is regrettable that on Venus, in contrast to the earth, the accessibility of the three regions mentioned does not reflect their importance to a reasonably complete understanding of the atmosphere. Very little is known about the lower atmosphere at present. Most observational methods cannot penetrate the clouds, and measure only the upper 0.1 percent of the atmospheric mass. The U.S.S.R.'s Venera 4 may have penetrated the upper 20 percent, but most of its measurements were made at higher altitudes. The U.S. Mariner 5 made only two temperature soundings in the upper 5 percent of the atmosphere.

There are three areas in which we need information before studies of Venus can advance: the chemistry, physics, and structure of the clouds; the atmospheric motions; and the thermal structure. Of these three, we have some limited knowledge only of the last. Useful cloud measurements can be made only by instruments carried right into the atmosphere, and many other types of atmospheric measurement, difficult or impossible to perform remotely, become straightforward with instruments in the atmosphere. Until recently there has been, in the United States, reluctance to undertake to send entry probes (as opposed to flybys), because of possible biological contamination of the planet. But we are now certain that surface temperatures, at least in equatorial regions, are much higher than any contemplated in sterilization programs. It is thus reasonable to relax sterilization requirements greatly (*1*).

Given the scientific problems of greatest current interest, we can devise an orderly and definable scientific strategy. Though this strategy will have to change from time to time, it should not be merely a response to one pressure after another. The U.S.S.R. probe Venera 4 (*2*) provides an example of effective scientific planning; the measurements it obtained are the basis for a substantial part of the definite knowledge that we now have of the Venus atmosphere below the clouds.

At the time the U.S.S.R. probes were planned (about 1963) little was known for certain about the lower atmosphere of Venus, but three fundamental questions had been raised: (i) Is the surface temperature between 500° and 700°K, as indicated by microwave measurements? (ii) What is the surface pressure? (iii) What is the concentration of CO_2, the only known constituent of the atmosphere? What other gases are present, and in what concentrations? The problem of the Venus atmosphere was then, and still is, on the watershed between speculation and the possibility of using the complex methods of geophysics to seek a rather detailed understanding. Before the flight of Venera 4 there was a general consensus concerning the answers to the foregoing questions, but there were enough doubts to produce reluctance about investing time and effort in the elaborate process of geophysical modeling of the lower atmosphere.

The aim of Venera 4 was to provide conclusive answers to these key questions, and it used the simplest feasible instrumention for this purpose. It carried probes for determining temperature, pressure, and density and a set of simple chemical sensors to define the general composition. These sensors showed that the major gas is CO_2, and they indicated the presence of small amounts of O_2 and H_2O. The following day, by less direct method, Mariner 5 confirmed the dominance of CO_2.

With the clarity of hindsight, we can easily point out additional features that

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should have been included. The most important is some means of indicating that the descent was terminated by a solid surface. Since there was no such indicator, we are faced with a basic uncertainty about the surface pressure and temperature. Venera 4 gave values of 19 atmospheres and 544°K; radar measurements from the earth, combined with Mariner 5 data, strongly indicate that the radius is 25 kilometers lower than the last data point from Venera 4, and the surface pressure and temperature would then be 100 atmospheres and 700°K (*3*), respectively. The O_2 measurement obtained by direct chemical analysis from Venera 4 is incompatible, by a large factor, with ground-based spectroscopy (*4*). There is a similar discrepancy in the H_2O measurements, discussed below, but this could perhaps be reconciled, because the *in situ* measurements were made below the cloud tops, whereas the spectroscopic values refer to a region near and above that level.

Table 1. Some basic data about Venus.

Length of year, 224.70 days
Synodic year, 583.92 days
Sidereal day (retrograde), 243.09 days*
Solar day, 116.77 days
Radius, 6053 km†
Height of visible clouds, 57 km‡
Surface temperature, 700°K†
Surface pressure, 100 atm†

* See (*15*). † See (*3*). ‡ See (*32*).

[This paper was submitted before the results of the probes Venera 5 and 6 were announced. They confirm the presence of water vapor, but do not detect O_2. An improved altimeter gives a radius in good agreement with earth-based radar and the inferred surface temperature is about 740°K.]

Despite these uncertainties we now know that the surface temperature in the tropical night is high (550° to 750°K); that the lapse rate in the clouds is almost adiabatic (about 9°K per kilometer); that the surface pressure is high (20 to 110 atmospheres); and that CO_2 is the major atmospheric constituent some 25 to 50 kilometers above the surface (the precise concentration is open to debate, but there seems little likelihood that it can be less than 80 percent). The temperature distribution at pressures from 30 to 5000 millibars has been confirmed by Mariner 5, and the results (together with some theoretical expectations) are summarized in the preliminary temperature profile of Fig. 1. Other data of interest are presented in Table 1.

The only important data which could not be confirmed by Venera 4 or Mariner 5 are the indications of a microwave phase effect (implying a higher surface temperature during the day than during the night) and a relatively low temperature near the poles (*5*). Both of these observations, if valid, are highly significant for atmospheric dynamics.

It is interesting to note how close the Venera 4 data were to expectations. The ground temperature is close to that indicated by microwave measurements for the night side; the adiabatic lapse rate could be confidently anticipated because of the high surface temperature and the presence of cloud cover; the ground pressure was thought by most investigators to be between 3 and 300 atmospheres, even though a few favored higher or lower values; several authors had proposed large CO_2 concentrations, and a combination of spectroscopy and photometry had shown that 30 percent was a lower limit (*6*).

It might have been tempting to suggest that, with the data available before the flight of Venera 4, the Soviet probe was unnecessary. Fortunately, no such view prevailed, and as a result the basic data are now well enough established to make it worth while to construct elaborate models of the lower atmosphere. These models point clearly to the next generation of measurements that must be made before we can understand the physics, chemistry, and dynamics of the lower atmosphere of Venus. The high surface temperature, the complete cloud cover, and the low rotation rate ensure that, in all respects, Venus will differ widely from the earth. The reexamination of ideas that a study of Venus will stimulate can lead to a much better understanding

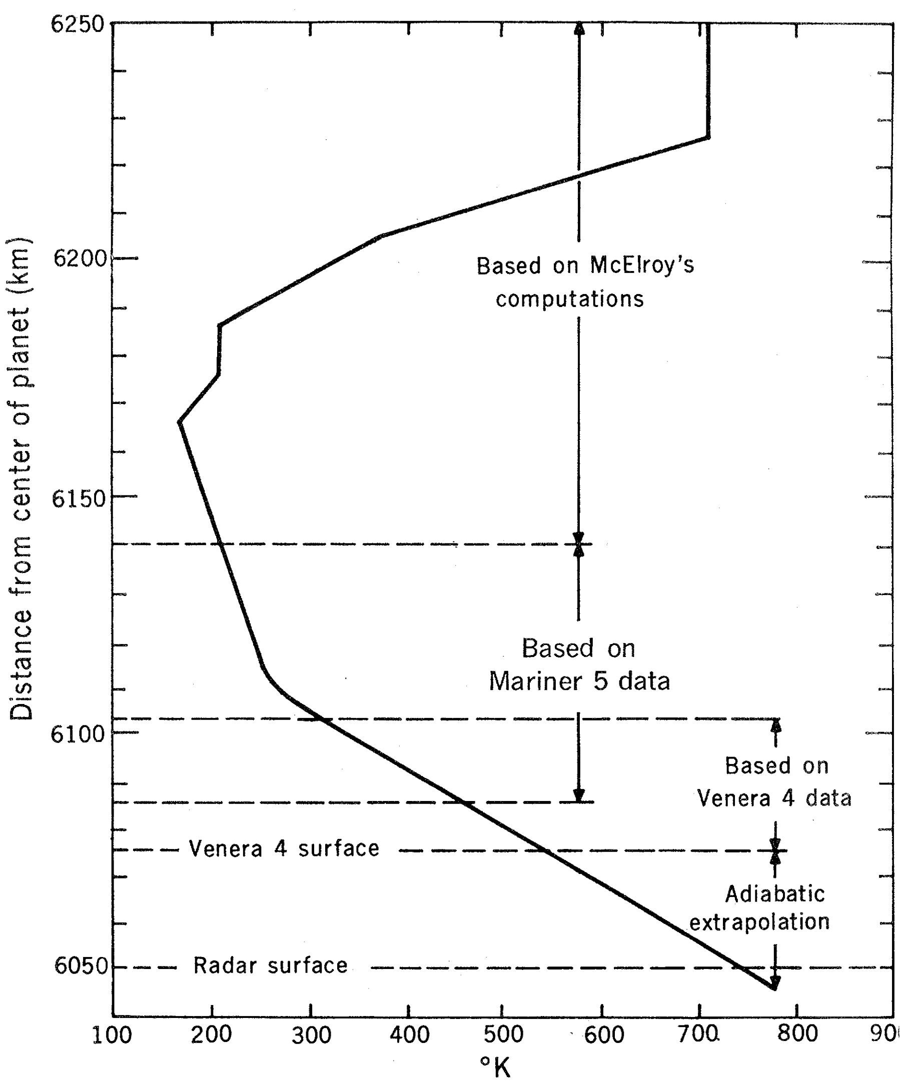

Fig. 1. Venus atmospheric temperature profile.

of the earth's atmosphere as well as to a new and fascinating field in atmospheric science.

Clearly, the major qualitative questions that must next be answered refer to the clouds. We must know their composition and, especially, whether or not they are condensable; their vertical distribution; and their optical properties for both solar and planetary radiation. Any serious study of atmospheric radiation and dynamics will require answers to these questions. We see no means of answering them from a flyby or orbiting spacecraft. We are therefore led inevitably to suggest direct probing of the atmosphere as the only way to obtain the essential information. In the remainder of this article we describe the current problems in more detail and, finally, return to the question of how to attack them.

The Greenhouse Model

A surface temperature as high as 700°K is not easy to explain, and it is not surprising that all available models run into difficulties. The simplest, and thus far most popular, model is a greenhouse model. It is supposed that the atmosphere transmits some solar radiation but is extremely opaque in the infrared spectrum, so that outgoing thermal radiation from the surface is trapped; emission to space then takes place from the cold outer layers of the planet's atmosphere or clouds. The earth's atmosphere provides a greenhouse effect of about 30°K; much effort has been put into studies of how powerful the effect could be on Venus.

Let us examine the greenhouse model in greater depth, not because it is necessarily correct, but because its simplicity exposes many of the essentials. Alternative models involve an internal source of heat on the planet, which must be larger than the earth's to be significant, or deep adiabatic currents driven by differential insolation. The latter model is discussed below.

The problems of the greenhouse model can be readily illustrated by a simple radiative-equilibrium treatment based on a gray atmosphere—one whose absorption coefficient is independent of wavelength for planetary radiation. The relation between the surface temperature T_S and the infrared optical depth τ^* is given by the Milne-Eddington approximation (*7*)

$$T_S^4 = F(2 + 3\tau^*/2)/2\sigma,$$

where σ is Stefan's constant and F is the outgoing radiation flux, which we set equal to the effective solar flux. To obtain a value for F, we average the incident radiation over the whole planet, day and night, and allow for the 77 percent that is observed to be reflected (*8*); the result is $F = 1.6 \times 10^5$ erg cm^{-2} sec^{-1}. We then find $\tau^* = 60$ for 600°K and $\tau^* = 113$ for 700°K. [With internal heat we may take $F = 100$ erg cm^{-2} sec^{-1}, roughly the terrestrial value; τ^* is then 2×10^5, slightly greater than the value obtained by Hansen and Matsushima (*9*).] The infrared opacity required by the greenhouse model is in no way unreasonable, and this is the model's intrinsic appeal.

Closer examination of greenhouse models reveals several serious problems; many of these are present in other types of models, but the simplicity of the greenhouse model exposes them.

1) The atmosphere must be extremely opaque throughout the infrared; part, or even most, of the opacity is probably contributed by the clouds. Yet visible radiation must penetrate to great depths.

2) Heat transfer by convection, both free and forced, must be added to the model.

3) The clouds, if of dust, must be supported, presumably by turbulent motions. If the material is condensable, the problem is less serious, but there are strong objections to the obvious possibility, water vapor.

4) Advection of heat by circulations of planetary scale must be considered.

Infrared Opacity

Carbon dioxide is the principal constituent of the atmosphere of Venus, although traces of H_2O, HCl, HF, and CO may have some influence on the transfer of radiation. At high temperatures and high pressures many transitions from thermally excited states and pressure-induced bands appear in the spectrum. These bands may possibly be able to block all gaps in the thermal spectrum of the atmosphere; if they do not, they cannot be responsible for a substantial greenhouse effect. All these gases are transparent to visible radiation, and they would therefore transmit the solar energy required to heat the "greenhouse."

While the role of gases is uncertain, the importance of the cloud layer as a screen for thermal radiation can hardly be doubted. Infrared spectra of the emitted radiation show no bands or lines, suggesting that all or most of the outgoing radiation is from the clouds. And thermal maps of the planet show no "hot spots" where the ground could be radiating through holes in the cloud (*10*). Analysis of the visual albedo (*11*) suggests an optical thickness, for the cloud, of 30 or so in the visible spectrum; greater optical thickness may be anticipated in the infrared region, and we have seen that an optical thickness of 60 is highly significant.

There is, therefore, strong evidence that the cloud plays an essential role in the transfer of radiation; it may well be the most important source of opacity at every level.

If clouds are essential to the physics of the lower atmosphere of Venus, three questions must be answered before further progress is possible.

1) Do the clouds consist of dust or condensate, and what substance or substances are involved?

2) Since clouds generally require motions, since motions require heat sources, and since heat sources depend on the clouds, what is the general nature of this interaction?

3) Clouds interact with solar as well as with terrestrial radiation, and solar radiation will usually be strongly attenuated before it reaches the surface. Is there, therefore, sufficient heat flux at low levels to maintain the high ground temperature?

This last question can be asked in the framework of radiative equilibrium, and according to Samuelson (*12*) the answer is negative. Any cloud material that one might reasonably propose would scatter and absorb too much solar radiation to permit average equatorial ground temperatures to reach a value near 600°K, even without other adverse circumstances such as heat convection. The maximum equatorial temperature that Samuelson could obtain for any acceptable cloud properties is 507°K. The question could be investigated with much more confidence if we knew the optical properties of the cloud, or the chemical composition, so that theoretical estimates could be made with some assurance. Alternatively, if the vertical flux of solar radiation could be measured *in situ*, we would be able to deduce the heat deposition as a function of height and circumvent to some degree the problem of the optical properties of the cloud.

Convection

In radiative equilibrium most of the increase in temperature with depth takes place in the lowest scale height of the absorbing material. A substantial "greenhouse effect" is likely to lead to superadiabatic lapse rates near the surface and therefore to convective instability. It is thus expected, and observed as well, that the lower atmosphere of Venus is close to convective equilibrium, with an adiabatic lapse rate. Local thermal convection, alone, can only carry heat upward. Thus the solar flux penetrating to low levels must be greater (for a given surface temperature) in the presence of convection than it would be for radiative equilibrium.

Gierasch (*13*) has made computations for an atmosphere similar to Samuelson's but with a convective interior. In order to achieve a high temperature, a large opacity is required, but, if the opacity is increased above a certain level, turbulent heat flux at low levels has to be *downward*, and this cannot be the case for free convection. According to preliminary calculations it may be very difficult to obtain a surface temperature of more than 500°K in a radiative-convective model.

Thaddeus (*14*) and others have made the point that the thermal inertia of a deep atmosphere is too great to respond strongly to diurnal changes on Venus (which have a period of about 120 earth days). For a surface pressure of 100 atmospheres the characteristic time constant (τ_c) associated with the mean solar flux F used above, a thermal capacity mc_p (7.5×10^{11} erg cm^{-2} deg^{-1}), and a temperature T (700°K), is $\tau_c = mc_pT/F = 38{,}000$ earth days, or 320 Venus days. The peak-to-peak variation of temperature in half a Venus day is $T/2\tau_c = 1$°K, even if all the solar flux reaches the surface. In fact, most of the solar radiation is probably deposited fairly high in the cloud layer; such diurnal changes as do take place are likely to occur well away from the surface.

Time-dependent calculations by Gierasch confirm the view that there is almost no diurnal variation of temperature in the lower atmosphere of Venus. The calculations also show that, in such a deep atmosphere, surface and atmosphere are so strongly coupled thermally that only a negligible boundary layer can develop. Thus a convective-radiative model leads to the conclusion that there would be no diurnal variation of surface temperature. Any resulting microwave phase effect must be far below the threshold of detection, and indeed the latest measurements indicate no significant change (*5*). Nevertheless, there is a simple alternative explanation of the positive effect indicated by earlier work (*5*), now that the rotation of Venus is known to be in close resonance with its synodic motion (*15*). The time between successive inferior conjunctions is 5 Venus days, as accurately as we can tell from present measurements. Phase and position on the planet are thus closely coupled; a region may radiate more or less microwave energy than the average by virtue of an unusually high or low emissivity. It would be interesting to check the radio data for a periodicity of one-fifth the synodic period.

The Cloud Layer

The cloud must be created either by dust blowing from the surface or by condensation. Cloud particles must then be suspended by mixing processes. It is of critical importance to know whether the aerosol is dust or condensation particles. The former would have to reach all the way to the surface, but with the latter there could be a clear region underlying the cloud.

In view of the high temperature and pressure near the surface, a number of condensable vapors may exist, and there may be several layers of cloud of different composition (*16*), one of which could be water or ice. A priori, one would say that ice is by far the most probable material, for we know that ice clouds exist on earth. But observations designed to confirm or refute the presence of ice seem to point both ways. Two kinds of spectroscopic information are available: (i) reflection spectrum of the clouds, and (ii) sharp absorption lines of water vapor, which should be present in a predictable amount.

Ice clouds show broad absorption bonds at wavelengths of 1.5 and 2.0 μ, and reflect very poorly above 2.7 μ (*17*). Two suitable sets of Venus spectra are available: those of Kuiper and Forbes, obtained from an aircraft, and that of Bottema, Plummer, Strong, and Zander, obtained from a balloon; the latter is of lower resolution but extends to longer wavelengths (*18, 19*). The 1.5-μ and 2-μ features are both difficult to distinguish, because of strong CO_2 absorption in the Venus atmosphere. Nevertheless, the aircraft spectra have sufficient resolution to show that any dip has a depth of less than a few percent; Kuiper and Forbes conclude, in agreement with an earlier analysis by Rea and O'Leary (*20*), that the clouds are not ice. If the particles are sufficiently small, the absorptions become very weak, and some authors (*21, 22*) feel that the case is not yet closed. The balloon observations show that the planet reflects very little from 2.7 μ to the limit at 3.4 μ. The initial drop can again be attributed to CO_2, but, from 3.0 to 3.3 μ, some other absorber is required, and ice fits the specifications perfectly. Pollack and Sagan (*21*) consider this to be the strongest piece of evidence for ice clouds. But ammonium chloride, discussed below, absorbs strongly in just the required region (*23*) and appears to be an equally satisfactory candidate.

There is considerable evidence that the region of the cloud top is hazy, and that reflected solar radiation has traversed a long, contorted path within the haze. At the known temperatures of about 240°K, there must be a predictable partial pressure of water vapor in equilibrium with any ice particles. The sharp absorption lines of water vapor are hidden by their counterparts in the earth's atmosphere, but measurements are possible under special conditions. From the ground, one can observe with high dispersion at times when the relative orbital motions produce the largest Doppler shift (*6, 24*); or one can observe from balloons or from high-altitude aircraft (*18, 25*). Several ground-based observers have seen weak absorption; some find it variable, and some do not see it at all. But even the highest values (a mixing ratio of 10^{-4}) are far smaller than would be expected for ice clouds. The high-altitude observations refer to much stronger bands, whose absorption is pressure-dependent; because of this pressure dependence, interpretation is rather difficult. Most striking are the recent observations from aircraft, which suggest an upper limit of 10^{-6} for the mixing ratio. Thus, neither the broad bands of the solid nor the sharp lines of the vapor seem to be present in the intensity expected for ice clouds.

On the other side of the argument are the measurements obtained by Venera 4, which indicated an H_2O mixing ratio of around 1 percent at a level some 15 kilometers below the visible region. Water at such concentrations would indeed condense and form a cloud layer (*21, 22*). However, Lewis (*16*) has shown that the particles would have to consist of rather strong hydrochloric acid. The spectroscopic evidence suggests that the visible cloud surface has a different composition; if there are hydrochloric acid clouds, they must be hidden from view by a higher layer of different composition.

The presence of free HCl encourages consideration of transparent chlorides, and Lewis (*16*) has suggested ammonium chloride. The excess of HCl would ensure a very small amount of free NH_3 at the cloud tops. An attractive feature of NH_4Cl is the fact that the particles, as they fall, must dissociate into NH_3 and HCl, which can then mix upward to regenerate fresh particles (*26*). As noted above, the low cloud albedo near 3 μ is expected for NH_4Cl. And the refractive index of 1.64 agrees better with the observed polarization and intensity of the planetary light than the index of 1.33 for ice does (*27*). Very recently, G. P. Kuiper has advocated a composition of $FeCl_2 \cdot 2H_2O$.

Dust Clouds

In view of the difficulty of finding a suitable condensable substance for the clouds, we must consider dust as a serious candidate. Several lines of evidence suggest that there is no sharp cloud-top of the type seen in terrestrial clouds; rather, there seems to be a very hazy region many kilometers in extent (*6*, *28*). Though dust clouds may have such an appearance, they present a serious theoretical difficulty: the problem of keeping them suspended. Fallout under gravity gives a downward flux of material which, in a steady state, must be balanced by an upward turbulent flux. This can only be achieved if there is a simultaneous upward heat flux. Thus, depending on the particle size, there must be an upward turbulent heat flux of calculable size, and this must be balanced by a downward flux of solar radiant energy. We have seen that obtaining an adequate heat flux at low levels is a fundamental difficulty for "greenhouse" models.

The same problem probably arises for the internal heat model of Hansen and Matsushima (*9*). If there is enough dust, an internal heat source of the same magnitude as the earth's can produce the observed surface temperature. But the heat flux proposed is very small (100 erg cm^{-2} sec^{-1}), and the opacity is very large ($\tau^* \simeq 10^5$, corresponding to 10 g cm^{-2} of dust for particles of 1 μ radius). It is questionable whether this large amount of dust can be supported by the turbulence generated by such a small heat flux.

For a condensing cloud the problem is less difficult because we only need to mix vapor upward, and this requires a much smaller intensity of turbulence, at least in the region beneath the clouds.

Calculations by Gierasch show that, if the cloud absorbs solar radiation, conditions may arise whereby turbulence ceases in the middle of the cloud layer. Time-dependent clear layers are therefore a possible phenomenon to be looked for in the Venus clouds.

Throughout most of the cloud layer, turbulence may be sufficient to preserve a constant mixing ratio (either of dust to CO_2 or of total condensable vapor to CO_2). However, the position is more complex near the top of the cloud, where the interdependent equations for heat and mass flux have to be considered. Preliminary calculations indicate that this may be a rather complex region for which a steady-state solution is impossible. Occasional upheavals may be followed by a long period of quiescence in which solid matter falls out, and the process starts over again.

Finally, it is important to point out, terrestrial experience indicates that condensation clouds are exceptionally complicated. Convection tends to occur preferentially in columns (cumulus towers), and the processes of condensation, coalescence, freezing, and precipitation involve physical, chemical, and dynamical phenomena in little-understood ways. At the safe distance of the earth we can speculate about generalities relating to the Venus clouds, but local measurements *in situ* may reveal a situation differing greatly from expectation.

Planetary Circulations

The different average insolation at the equator and the poles will give rise to horizontal temperature gradients. Such a situation is unstable and, if rotation is slow enough, will give rise to large-scale convection, possibly to a Hadley cell: air rising in the tropics, moving poleward at high altitudes, then sinking and returning near the surface. The Hadley circulation is not of major interest for terrestrial meteorology except in the tropics, because of the fast rotation and the instabilities that arise in zonal mid-latitude circulations. The Venus atmosphere has, however, revived interest in this classic problem.

Stone (*29*) has investigated a group of models with heat-flux boundary conditions. For the special case in which input and output heat fluxes are both at the upper surface, Stone's work does not differ in fundamentals from a model proposed by Goody and Robinson (*30*); the general features of this model are shown in Fig. 2. Goody and Robinson thought in terms of a very slowly rotating model with a relatively rapid response to solar heating; their source and sink are therefore at the subsolar and antisolar points, respectively. If the solar radiation is deposited at the cloud tops, this picture may be valid. But if it penetrates to any great depth (as in Gierasch's and Samuelson's models), the temperature contrast is between pole and equator rather than between subsolar and antisolar points, because of the long thermal time constant of the dense atmosphere.

The model predicts velocities on the order of 30 meters per second in a narrow upper boundary layer, with a very slow circulation in the deep atmosphere. The numerical values are based on exceedingly uncertain data, but two qualitative features of the solution may be of significance. First, the circulation is sufficient to destroy almost all the horizontal temperature contrast to be expected from a radiative-convective model. This feature agrees well with observation. Second, the deep currents, although very slow, could be adiabatic, creating an adiabatic lapse rate without penetration of solar radiation. It may well be that a deep circulation of this nature is needed to explain completely the high surface temperatures.

These Hadley models do not account for the 100-meter-per-second retrograde circulations reported by some observers (*31*). The evidence in favor of these circulations is weak at present, but their existence cannot be questioned on the basis of present theory. If correct, these observations suggest the existence of two independent dynamical regimes.

The Upper Atmosphere

Considerable work has recently been done on the structure of the Venus stratosphere and upper atmosphere, stimulated by the availability of two electron-density profiles from Mariner 5 (*32*). McElroy, in particular, has calculated the temperature profile (see Fig. 1) and also the ionospheres to be expected for various compositions. The unexpected result, also found for Mars, is that the CO_2 atmosphere apparently must remain essentially undissociated at great heights. This stability is in marked contrast to the behavior of O_2 on the earth, where solar radiation produces oxygen atoms at a rate sufficient to make O the dominant form above 90 kilometers. The dissociation of CO_2 into CO and O is expected to proceed at about the same rate as O_2 dissociation on the earth; just as we find a region of atomic oxygen on the earth, we might expect a region on Venus where CO and O replace CO_2. Despite considerable discussion, we have no satisfactory solution of this puzzle. The intervention of radicals containing hydrogen has been suggested, but the suggestion does not stand up to quantitative study. There is a strong suspicion that a metastable CO_3 molecule may be involved. Mass-spectrometer measurements of the neutral gas and the positive ions could readily be made during entry into Venus' upper atmosphere. Such measurements give a far better insight into the physics of the ionosphere than mere electron densities, as has been amply demonstrated on the earth.

Another curious implication of Mariner 5 data is a ratio of deuterium to light hydrogen in the neighborhood of unity (*33*). This result, if true, has a bearing on theories of atmospheric evolution by escape of light atoms. Direct measurement by mass spectrometer will be difficult, but an entry mission gives a fine opportunity to repeat the observations of scattered Lyman-alpha radiation in a favorable geometrical situation.

Required Measurements

According to the foregoing discussion the primary present uncertainties concerning the physics of Venus pertain to (i) the nature of the clouds and (ii) the heat balance and circulation. The first uncertainty involves the chemistry, the microphysics, and the macrophysics of the clouds, their optical properties, their motions, and their structure in the vertical and geographically. The second involves all of the first and also a knowledge of the chemistry of the hot, dense lower atmosphere, knowledge of the thermal structure at a number of critical locations, and an understanding of the global winds.

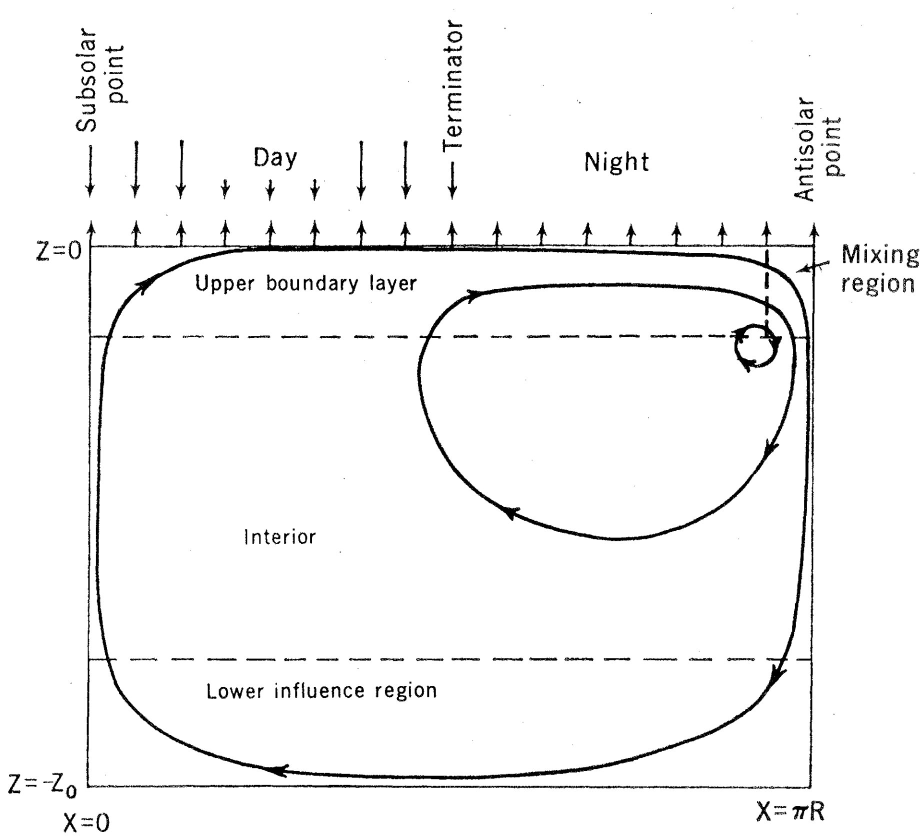

Fig. 2. Schematic diagram of planetary circulation. (Z_0) Depth of the cloud layer; (R) radius of the planet. [After Goody and Robinson, courtesy University of Chicago Press]

Are the state of the art in instrumentation and the U.S. capability in planetary exploration sufficient to throw new light on all or most of these problems? Preliminary studies make it clear that, if we start from the idea of a mission designed around the science need, Mariner has the capability to accomplish an investigation relevant to every science question that can be asked at this stage.

The missions that we can envisage include flybys, orbiters, and entry probes. Although flybys, in the past, provided the best means for early exploration, they are inferior to orbiters and can be regarded as having been superseded.

The idea of small, relatively cheap orbiters, capable of missions to all the inner planets, is one that has been strongly endorsed by the Space Science Board (*1*) of the National Academy of Sciences. Simplicity is achieved by means of spin-stabilization; transmission to the earth is achieved by means of a contrarotating antenna pattern. The main purpose of a small orbiter will be investigation of the interplanetary plasma and of its interaction with an ionosphere or a magnetic field, but some investigations of the Venus atmosphere are possible. High-resolution visual and thermal mapping could provide information about the nature and dynamics of the cloud, although the results might be difficult to interpret. Surface temperature can be explored geographically by microwave imaging. Temperatures can be measured down to the 5-atmosphere level by radio occultation (*2*). If on-board propulsion is supplied, an occasional low perigee would provide the opportunity to make a mass analysis of the upper atmosphere.

Such data are of undoubted value, and would be most welcome. Nevertheless they hardly approach what is needed for solving the major problems discussed in this article. These problems can be tackled only by means of probes which would enter the atmosphere and penetrate to the surface of the planet. The precise capability of a Mariner mission, launched on an Atlas-Centaur rocket, for placing probes in the Venus atmosphere has been estimated, and these preliminary assessments indicate that it is extensive.

We can visualize four different types of probes.

1) Large probes could carry about 60 pounds (27 kilograms) of instruments

to the surface. The science capability of such a probe is impressive; it could (i) make complex and redundant composition measurements; (ii) obtain some wind information and information on pressure, temperature, and density of the atmosphere; (iii) perform a variety of cloud physics and chemistry experiments; and (iv) directly measure the solar and planetary heat balance.

2) Small probes could carry about 2 pounds of instruments to different geographical locations of interest. Their purpose would be to measure temperature, and to obtain some information on the cloud structure and on winds, near the poles and near the subsolar and antisolar points.

3) Balloons could be large or small. In early investigations a small balloon would probably be used for wind measurements, floating in a pressure area between 50 and 100 millibars. Later investigations might make greater use of this type of platform.

4) Upper-atmosphere probes would be a dividend from a lower-atmosphere mission. Sophisticated upper-atmosphere experiments could be attached either to the bus (if this impacts) or to heat shields and other structures, being destroyed when the main ablation took place.

5) Bus experiments might or might not impact the atmosphere. Television, infrared, and microwave mapping would provide valuable geographical information in the vicinity of the individual probes.

With an Atlas-Centaur, at least one probe of each of the above types could be sent into the Venus atmosphere; with larger boosters, now available, the mission weight could be doubled. A single mission can therefore contribute to almost every science objective. If doubts must be expressed, they apply more to the instruments, and to the number of scientific groups with the ability to exploit the opportunity offered. For example, an instrument capable of collecting and analyzing aerosol particles has not been developed for terrestrial use, nor, surprisingly, has *any* cloud-physics instrument capable of operating from a dropsonde been developed. The problem of making wind measurements is also a difficult one. But sophisticated instrumentation is precisely the area in which the U.S. space program can claim its greatest achievements; the challenge is one that we should not want to avoid.

Conclusion

Ten years ago Venus was a topic for speculation alone. The change since then has been dramatic. Some fundamental data are available; quantitative theories have been stated; well-posed questions about the atmosphere can be answered by feasible missions; and, above all, the geophysical profession has had its interest aroused and offers the specialized knowledge needed to understand the complex processes. Venus, the least understood of the inner planets, should be a first-priority target for the U.S. space program. Nevertheless, NASA has no present plans for investigating its lower atmosphere.

Often cited as a reason for giving Venus a lower priority in the U.S. space program is uncertainty about Soviet intentions. We tend to speculate that the Soviets will probably do "this" and not "that" tending to favor our own projects. But in fact we do not know, for example, that the Soviet Union will not enter the race for a Mars landing, which is the mainstay of our present space effort in the early 1970's. Collaboration with the Soviet Union and with European countries in unmanned space experimentation is both feasible and highly desirable; if the current political tensions can be reduced, it is even likely that collaboration will come about. Until then, however, we have no choice but to base our judgment upon our own scientific and technical abilities and desires. Our program should be flexible enough to accommodate new information from any source; if it stretches our capability and imagination to the limit, we need not fear for its ultimate value.

References and Notes

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