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CURRENT PROBLEMS IN RESEARCH

The Planet Venus

Recent observations shed light on the atmosphere, surface, and possible biology of the nearest planet.

Carl Sagan

The launching of the Soviet interplanetary vehicle toward Venus on 12 February 1961 opens a new era in planetary studies. This article is an assessment of current knowledge of Venus at the dawn of this era.

The planet Venus is enshrouded by clouds which prevent telescopic examination of its surface. In the absence of direct observations, reasons have been adduced for proposing a variety of differing and mutually inconsistent surface conditions. Since only water clouds were familiar to terrestrial observers, the apparent thickness of the Cytherean (*1*) cloud layer seemed to argue for a great abundance of water. From there it was only a step to the assertion (*2*) that "everything on Venus is dripping wet. . . . A very great part of the surface of Venus is no doubt covered with swamps. . . . The constantly uniform climatic conditions which exist everywhere result in an entire absence of adaptation to changing exterior conditions. Only low forms of life are therefore represented, mostly no doubt, belonging to the vegetable kingdom; and the organisms are nearly of the same kind all over the planet."

After many unsuccessful spectroscopic attempts to discover water vapor in the Cytherean atmosphere, the hypothetical Carboniferous swamp was generally abandoned, to be replaced by an arid planetary desert, overlain by clouds of dust from the wind-swept surface (*3*) (Fig. 1). The arid surface also explained the great abundance of carbon dioxide [which was accidentally discovered (*4*) in a search for water vapor]; for, in the absence of water, the Urey equilibrium pressure of carbon dioxide will not be established (*5*). Hoyle (*6*) explained the lack of water by assuming a great excess of hydrocarbons over water on primitive Venus, and subsequent oxidation of the hydrocarbons to carbon dioxide, until all the water was depleted. He suggested that the surface is now covered with the remainder of the hydrocarbons, and that the cloud layer is composed of smog.

Menzel and Whipple (*7*) replaced the wind-swept desert and the planetary oil field with a global Seltzer ocean; they argued that if Venus were completely covered by water (because of the high atmospheric content of carbon dioxide, the water would, of course, be carbonated), the access of carbon dioxide to silicates would be impaired, and for this reason the Urey equilibrium would not be established. The state of our knowledge of Venus is amply illustrated by the fact that the Carboniferous swamp, the wind-swept desert, the planetary oil field, and the global Seltzer ocean each have their serious proponents, and those planning eventual manned expeditions to Venus must be exceedingly perplexed over whether to send along a paleobotanist, a mineralogist, a petroleum geologist, or a deep-sea diver. But new information has recently become available which probably eliminates three of the four proposed surface environments; taken together with some of the earlier data, it points the way to a consistent picture of the atmosphere and surface of Venus.

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Composition of the Atmosphere

Only the portions of the Cytherean atmosphere which are above the cloud layer are accessible to spectroscopic investigation. Since the cloud layer may be situated tens of kilometers above the surface (see the discussion below), the spectroscopic data are not necessarily directly applicable to the lower atmosphere. It is possible that gases present above the cloud layer in undetectable amounts are abundant in the lower atmosphere. By laboratory intensity-matching of the Cytherean carbon dioxide intercombination bands near 8000 angstroms, the abundance of carbon dioxide (above the atmospheric level at which an 8000-angstrom photon is effectively reflected) is estimated to be 1 kilometer-atmosphere (km-atm) (*8*). The only other possibly identified atmospheric constituent is water vapor, marginally detected on Venus recently by high-altitude balloon spectroscopy. The abundance of water vapor (above the atmospheric level at which a 1.13-micron photon is effectively reflected) is estimated by Strong to be about 2×10^{-3} gm/cm^2 (*9*). Kozyrev reports observing several features in the aurora and night sky of Venus corresponding in wavelength to known emission bands of N_2, N_2^+, and CO^+ (*10*). From considerations of cosmic abundance and from terrestrial analogy, we would expect to find N_2—which has no permitted absorption spectrum in the presently accessible wavelength region—on Venus, and we would expect to find carbon monoxide from the photodissociation of carbon dioxide. [It is a curious incidental fact that at one time Kozyrev (*11*) believed the spectral features discovered by him were due to microorganisms in the Cytherean atmosphere.] Nevertheless, Newkirk (*12*) found no evidence of many of the strongest features reported by Kozyrev and found strong emission at a neighboring wavelength (4505 A) not reported by Kozyrev and corresponding to no known molecular emission. The only features common to both observations are unidentified emission bands at 4415 and 4435 angstroms (*13*).

One might attribute the absence of, for example, the N_2^+ first negative system in Newkirk's spectra to low magnetic activity at the time of his observations, but the absence of the feature at 4505 angstroms in Kozyrev's spectra then remains puzzling. Unsuccessful searches for carbon monoxide absorption place the amount of carbon monoxide above the relevant reflection level at less than 100 cm-atm (*14*). At the present writing, it must be concluded that there is no convincing direct evidence for nitrogen or carbon monoxide on Venus. The present upper limit on oxygen in the high Cytherean atmosphere is 100 cm-atm (*3, 15*); the limit is 100 cm-atm for N_2O, 4 cm-atm for NH_3, 20 cm-atm for CH_4, 3 cm-atm for C_2H_4, and 1 cm-atm for C_2H_6 (*14*). None of these gases has been identified. The last few abundances argue effectively against the hypothesis that the cloud layer is composed of hydrocarbons (*6, 16*); at the observed temperature of the cloud layer, the vapor pressures of gaseous hydrocarbons are greater by orders of magnitude than the spectroscopic upper limits.

Nature of the Cloud Layer

Visual observations of Venus generally show very little detail, owing to the uniformly high albedo of the cloud layer. During daylight telescopic observations, when comparisons with terrestrial clouds can be made, it is evident that the planet is a pale lemon yellow. The yellow coloration of Venus is also observed photometrically (*17*). Under the best seeing conditions, faint dark markings can be perceived on the illuminated part of the disk. A broad band of shade adjoining the terminator sometimes appears brown (*18*). Other markings, both bright and dark, can be observed; occasionally dark bands are seen extending perpendicularly from the terminator onto the disk. The difficulties encountered in making visual observations of Venus are illustrated by the fact that the outstanding American observer at the turn of the century, in over a decade of regular observation of Venus, was able to see distinct markings only once. On that occasion shading was evident, parallel to the terminator but not perpendicular to it (*19*). Danjon and Dollfus (*20*) have constructed planispheres from their visual observations which show dark markings with little relative displacement over periods of weeks. In some drawings the markings tend to radiate from the subsolar point. Danjon and Dollfus interpret these dark markings as surface features seen through stable gaps in the cloud layer. The apparent constancy in the position of the markings suggested to the French astronomers that the period of rotation of Venus is equal to its period of revolution, 225 days. However, Kuiper (*21*) has pointed out that on a slowly rotating planet, cloud patterns near the terminator will bear an approximately constant relation to the terminator, just as characteristic cloud patterns appear at a given time of day on the earth.

Photographic detail of Venus is most evident in the near-ultraviolet region and least evident in the infrared. It is impossible to explain this circumstance by an inverse-power scattering law and the hypothesis that the observed detail is below the visible cloud layer. Detail on Mars becomes more evident toward the longer wavelengths. It is tempting to suggest the presence around Venus of high-altitude clouds which are opaque to ultra-violet light and more transparent in the infrared. An alternative explanation is that the cloud layer is billowy, so that low-lying clouds appear darkened in the violet because of the increased scattering of light by the overlying atmosphere (*14*). The classic ultraviolet photographs by Ross (*18*) (Fig. 2) show time-variable bright and dark areas, sometimes stretching, bandlike, perpendicularly from the terminator onto the disk. Generally there is a dark shading adjacent to the terminator, as in visual observations. Perhaps the most striking features of Ross's photographs are the departures of the crescent from a symmetric form. Especially where there are bright features the planetary limb protrudes markedly. On the other hand, when there are nearby dark features, the terminator has a serrated appearance. The bright protruding features are prominent near the apparent poles, especially near the southern pole; they were also detected visually by such early observers as Schröter and Trouvelot, who explained them as enormous mountains, 60 or more kilometers high. Ross proposed the more likely explanation that the protrusions are areas of atmospheric haze surrounding the planetary poles, such as exist around Mars. This, in turn, implies an appreciable difference in temperature between the equator and the poles. It would be of interest to determine the composition of the polar haze. More recent ultraviolet photographs show three bright and three dark bands, roughly perpendicular to the terminator and extending across the entire visible hemisphere of Venus. The inclination of these bands to the plane of the Cytherean orbit is estimated by Kuiper (*22*) at 32° and by Richardson (*23*) at 14°. The difference between these values emphasizes the observational difficulties.

Ross attributed the presence of band structure to atmospheric circulation, as has been suggested for the Jovian planets. If the explanation is correct, then the speed of rotation at the equator must exceed the speed of random atmospheric winds (*17*), giving a maximum period of rotation of a few weeks. The minimum period is obtained from the absence of a rotational Doppler shift at the planetary limb (*24*). The true period of rotation is probably between 5 and 30 days.

A potentially effective method of studying the Cytherean cloud layer is the determination of the polarization of sunlight reflected from Venus to Earth, as a function of the phase of Venus. The polarization curve of Venus in integrated light was first obtained by Lyot (*25*), who attempted to reproduce it in the laboratory, employing a wide range of substances. He found that for fine mists of water, decreasing the size of the droplets caused the polarization curve increasingly to resemble that of Venus. However, before even a rough fit was obtained, the droplets became unstable. Lyot therefore prepared colloidal suspensions of bromonaphthalene, which have the same differential index of refraction as water in air, and found that droplets of 2-micron radius were required to give an approximate fit with the Venus observations. However, this fit was rather poor; for certain phase angles, even the signs of the laboratory and Cytherean polarizations disagreed. Furthermore, the near-infrared polarization curve of Venus differs markedly from the theoretically predicted curve for liquid water droplets (*26*). The polarimetric evidence argues against a liquid water cloud layer on Venus, but at the same time no substance is known which provides a better fit to the polarization curve of Venus than do droplets of water. More work is needed, both on the polarimetry of laboratory suspensions of liquids and crystals at low temperatures and in providing the Venus polarization as a function of wavelength (*27*).

The polarization varies over the disk of Venus. Regions of high (negative) polarization are localized in the apparent polar regions, and correlation of high polarization with the bright visual and photographic features in the same regions is tempting. However, there appears to be no consistent difference in polarization between the poles (*28*), while the bright areas near the apparent south pole are usually more brilliant than those near the apparent north pole. Indeed, comparison of visual and polarimetric observations made on the same day shows no clear correlation, and it is possible that the particles responsible for the polarization are different from those responsible for the visual and photographic cloud layer.

The problem of the composition of the clouds has been approached in other ways. The visual albedo of Venus, corrected for yellow coloration, has been estimated to be 0.68 ± 0.04 (*26*). The only common condensable or sublimable substance which is known to have such high reflectivities at the temperatures of the Cytherean cloud layer is water, either as droplets or as ice crystals. Carbon dioxide sublimation is unlikely in the Cytherean atmosphere, because at the carbon dioxide pressures of the cloud layer, temperatures of about 165°K are required for saturation; even in the polar regions there is no evidence for cloud temperatures so low as this. A condensable or sublimable cloud layer is suggested by the polar haze. Noncondensable substances which have sufficiently high reflectivities include quartz, Al_2O_3, CaO, $MgCO_3$ and a number of other geochemically less abundant materials, but it is improbable that there is large-scale preferential production of such substances on Venus (*29*). A variety of molecules has been suggested to explain the yellow coloration, among them polymerized carbon suboxide (*26*), ammonium nitrite (*30*), and nitrogen dioxide. Because these substances have low reflectivities, it is unlikely that the clouds are composed primarily of any of them.

The presence of large quantities of polymerized carbon suboxide is further

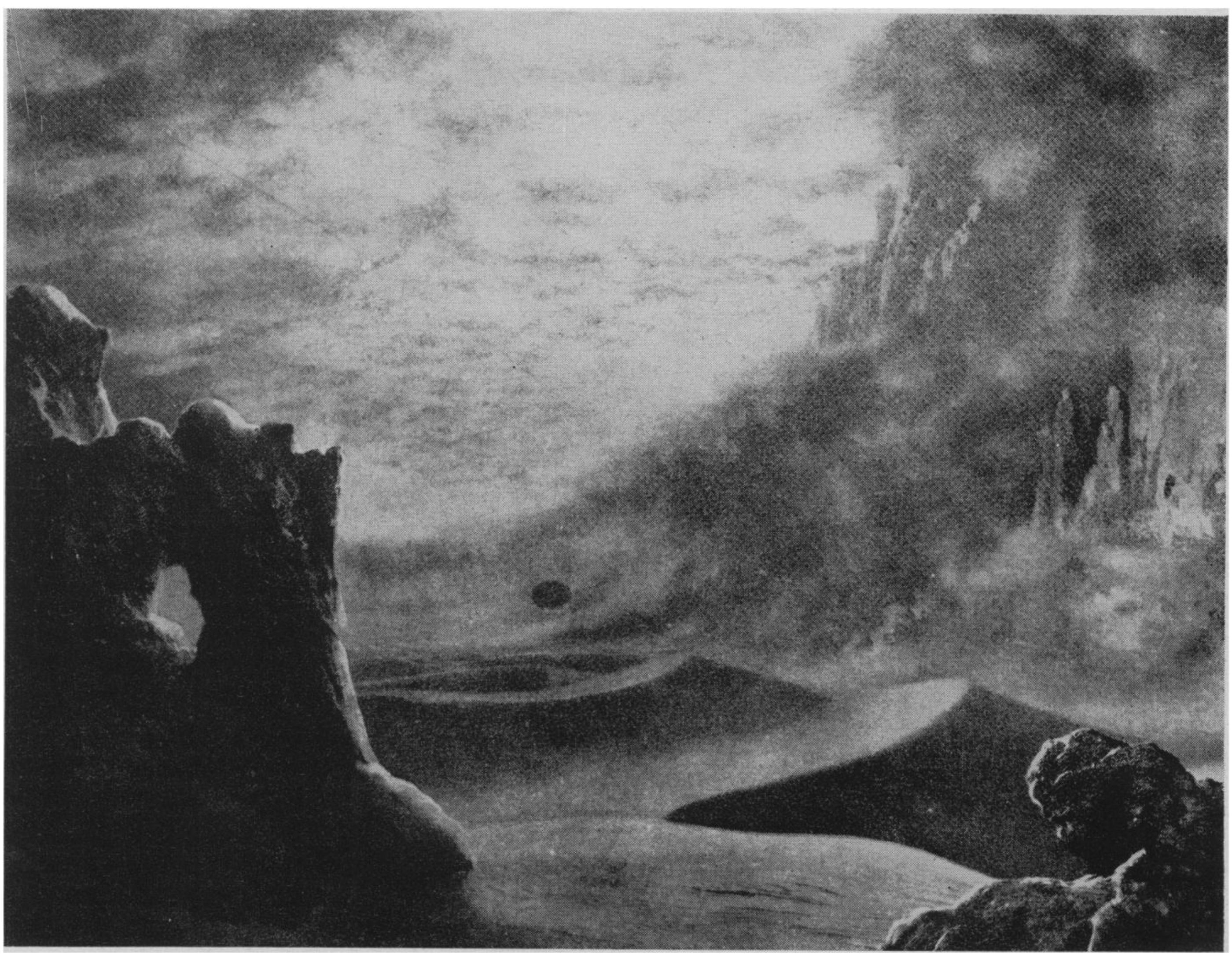


Fig. 1. A painting by Chesley Bonestell showing possible surface conditions on Venus according to the dust-bowl hypothesis. [From a painting by C. Bonestell, in *The Conquest of Space* (Viking Press, New York, 1950)]

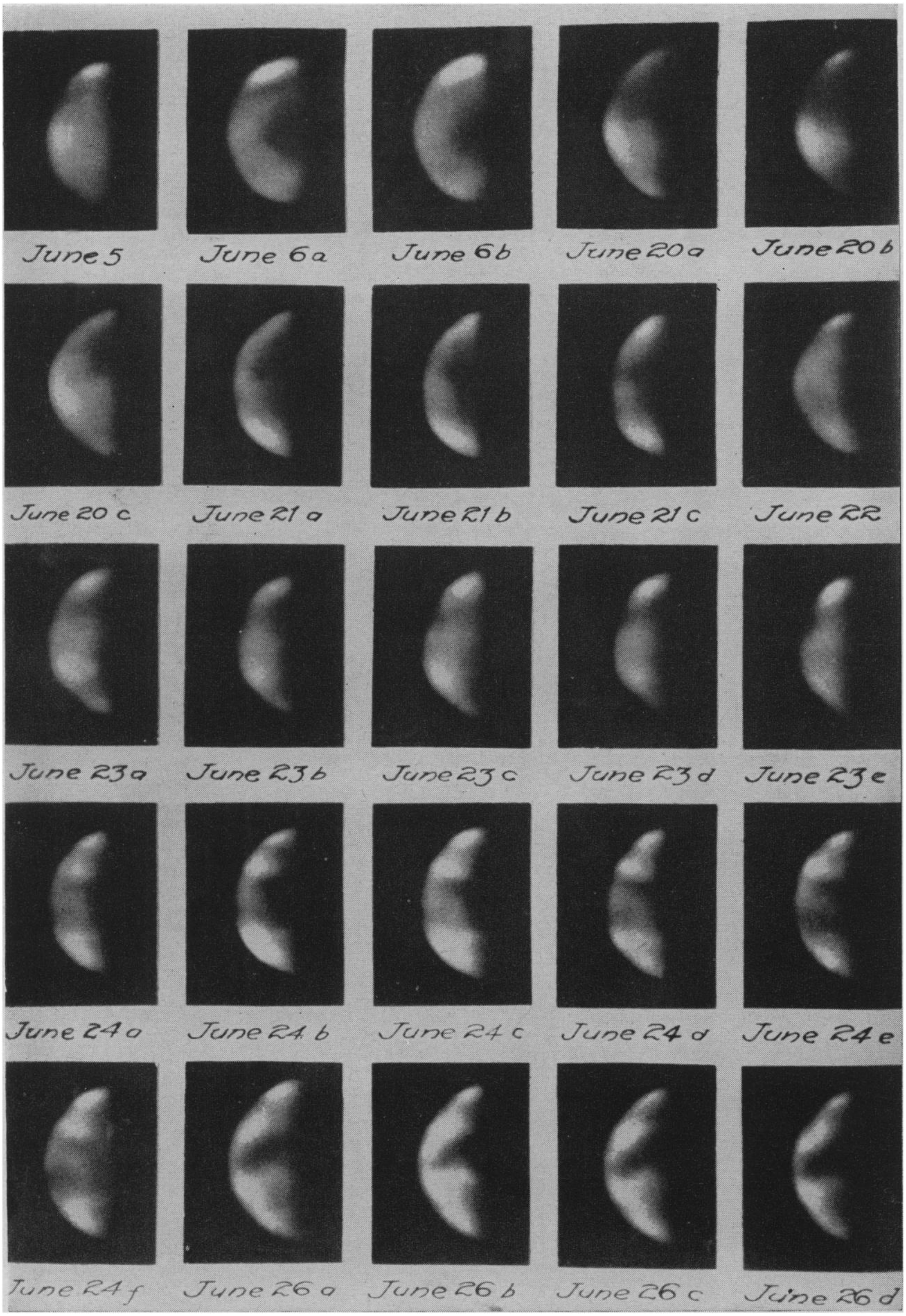
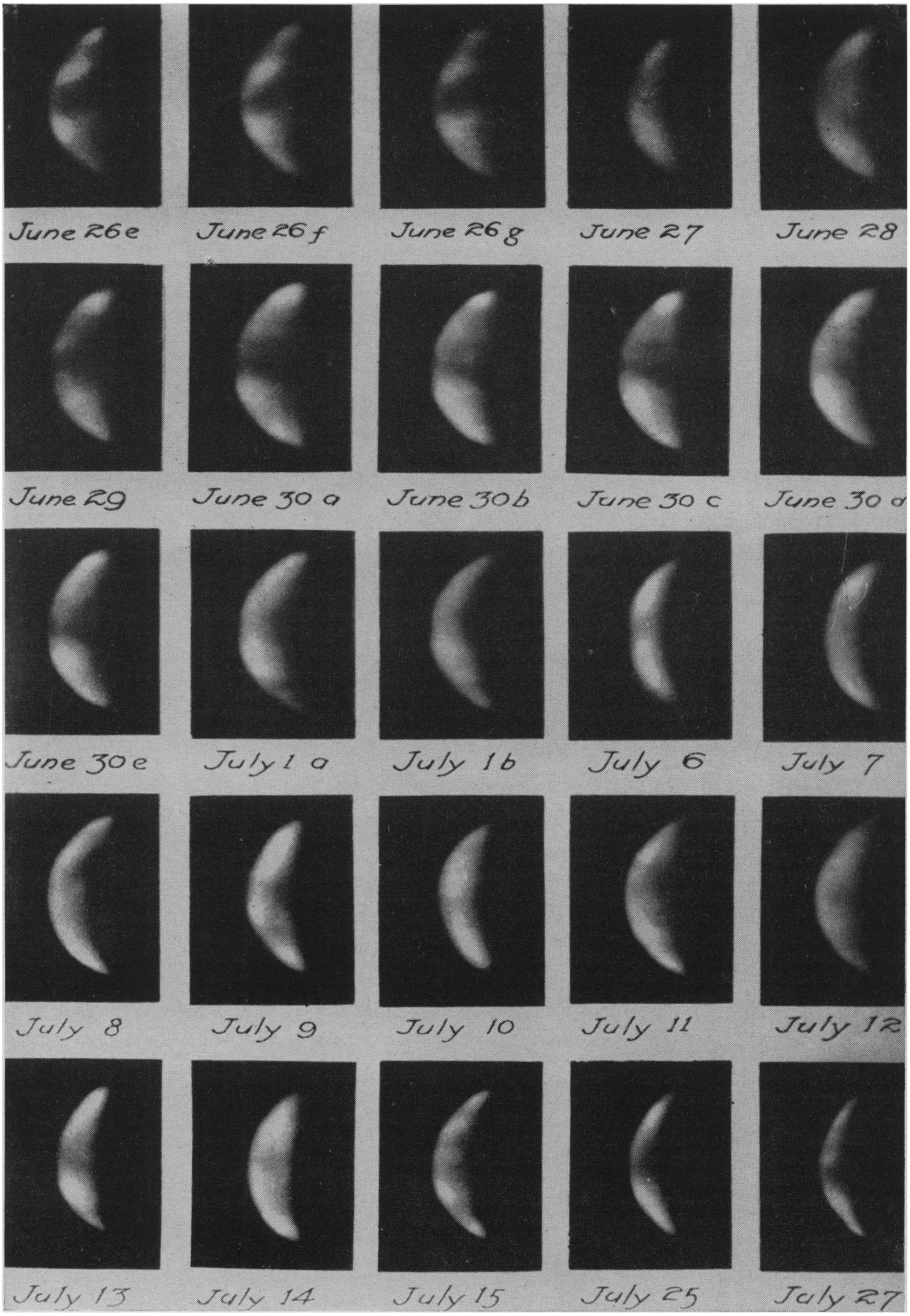


Fig. 2. Sequence of ultraviolet photographs of Venus taken with the 60- and 100-inch reflectors at Mount Wilson Observatory by F. E. Ross, in June and July 1927. [From *Astrophys. J.* **68**, 57 (1928), with permission from the University of Chicago Press. Copyright 1928 by the University of Chicago]


June 26e
June 26f
June 26g
June 27
June 28
June 29
June 30 a
June 30b
June 30 c
June 30 d
June 30e
July 1 a
July 1b
July 6
July 7
July 8
July 9
July 10
July 11
July 12
July 13
July 14
July 15
July 25
July 27

improbable because the monomer has a set of fairly strong absorption features extending to wavelengths just short of 3350 angstroms, while all ultraviolet spectra of Venus for this region have been negative; and also because in the photoproduction of each monomer by

$$2\,CO + CO_2 + h\nu \rightarrow C_3O_2 + O_2$$

a molecule of oxygen is formed, while searches for molecular oxygen have also been unsuccessful. On the other hand, small amounts of polymerized carbon suboxide $(C_3O_2)_n$ must certainly be produced and may contribute to the coloration of the clouds. The surprisingly low intensity of the carbon dioxide absorption bands in the 8- to 13-micron region (*31*) suggests the presence of a substance which is transparent to the photographic infrared and opaque to the thermocouple infrared; although it is possible that $(C_3O_2)_n$ can serve this function, the lack of unambiguous laboratory spectra of the polymer (*31*) precludes a more definitive identification. Since polymerized carbon suboxide absorbs in the near-ultraviolet, it is also a likely candidate for the hypothesized high-altitude dark clouds (*32*). Heyden, Kiess, and Kiess (*33*) have called attention to a broad continuum in the near-ultraviolet spectrum of Venus, which they attribute to N_2O_4. Since nitrogen tetroxide is readily dissociated, at wavelengths of less than 3000 angstroms, to the dioxide and to atomic oxygen, it might be thought that a plentiful source of NO_2 is available. However, the identification of the tetroxide must be regarded as extremely tentative, since Kiess and Corliss (*34*) have announced a very similar feature in the spectrum of Jupiter, where so highly oxidized a molecule as N_2O_4 certainly could not escape reduction at all atmospheric levels.

If the surface temperature of Venus is near 600°K (see the discussion below), the theory of the radiation balance implies an ice-crystal cloud layer some 30 or 40 kilometers above the surface (*35*). The predicted cloud temperature is equal to the thermocouple temperature, and the theoretical saturation abundance of water vapor above the clouds agrees with the balloon abundances of water. The reflectivity of such a cloud layer is high enough to explain the Cytherean albedo, but insufficient data are available on the polarization of ice crystals to make comparisons with the Venus polarization curve.

Optical Temperatures

The radiation emitted from Venus at various wavelengths has been analyzed, and corresponding temperatures have been obtained. However, the radiation at a given wavelength may be the integration of emission from many altitudes in the Cytherean atmosphere, and for this reason considerable caution must be exercised in relating these temperatures to specific atmospheric levels. Thermocouple observations in the 8- to 13-micron window in the terrestrial atmosphere yield mean temperatures for the disk of Venus of about 234 ± 10°K (*31, 36*). The fact that the 10-micron carbon dioxide bands are probably not opaque above the cloud layer (*32*) implies that the cloud temperature is close to the thermocouple temperature. The unilluminated hemisphere has almost the same temperature as the illuminated hemisphere; this circumstance has suggested (*18*) that the period of rotation must be much less than the period of revolution—otherwise the bright side would grow much warmer than the dark side. However, this conclusion is not necessarily valid if violent interhemispheric circulation exists, as indeed the banded structure in ultraviolet photographs would seem to indicate. It is also possible that the temperature at a given atmospheric depth is much lower on the dark than on the bright side but that the observer sees to greater depths in the unilluminated hemisphere because of a sinking of the cloud layer, and so obtains misleadingly high composite temperatures. Evidence exists that the bright ultraviolet clouds in the apparent polar regions are colder than clouds in neighboring areas (*31*), as would be expected if the clouds originate from the condensation or sublimation of a gas.

Thermocouple tracings of the disk of Venus show distinct limb darkening, the intensity falling off approximately as $(\cos\,\theta)^{\frac{1}{2}}$, where θ is the angle between the line of sight and the planetary vertical (*31*). From this law of limb darkening, the vertical temperature distribution immediately above the cloud layer can be computed; the atmosphere turns out to be nearly isothermal above the cloud layer, the temperature decreasing only as the one-eighth power of the optical depth (*37*). The true lapse rate is only about half the adiabatic lapse rate. In the absence of an ozone layer (there should be little ozone in an atmosphere with no free oxygen) the temperature will remain roughly constant above the cloud layer until dissociation and ionization by short-wavelength solar radiation become significant.

Carbon dioxide will begin to dissociate above unit optical depth with light of wavelengths of less than 1692 angstroms, and the atomic oxygen produced will be ionized in the Schumann-Runge continuum. The absorption cross-section of carbon dioxide just short of the photo-dissociation threshold is about 10^{-19} square centimeters; therefore, the temperature commences to increase, and the Cytherean ionosphere begins at the level above which there is about 1 cm-atm of carbon dioxide. From observations of the occultation of Regulus by Venus (*38*) it is known that there is about 1.7 cm-atm of atmosphere at an altitude of some 70 kilometers above the cloud layer. From the same observations a scale height of 6.8 kilometers has been obtained for this level. Thus, if there is negligible photodissociation at this altitude, the ambient temperature is about 300°K; if carbon dioxide is completely photodissociated, the temperature is about 150°K. The limb-darkening evidence that the atmosphere is approximately isothermal above the cloud layer suggests that the temperature 70 kilometers above the cloud layer probably lies a few tens of degrees below 230°K. An intermediate level of photodissociation is therefore indicated, as would be expected for such a transition region. (It should be mentioned, however, that the $T \propto p^{\frac{1}{8}}$ law inferred from limb darkening cannot apply high above the cloud layer and still be consistent with the occultation data.) If the cloud layer is a few tens of kilometers above the surface, then the Cytherean ionosphere begins at altitudes comparable to those of the terrestrial ionosphere.

Molecular vibration bands show rotational fine structure, which, if a Boltzmann distribution of energy levels is assumed, can be used to derive temperatures. If equipartition exists between rotational and translational energies, the rotational temperature so derived will be the appropriate gas kinetic temperature. On the basis of an assumed radiative transfer in an optically thick Cytherean atmosphere which scatters radiation isotropically, a composite rotational temperature of 285 ± 9°K has been derived from the carbon dioxide bands in the 8000-angstrom region (*39*). From considerations of pressure broadening of the spectral lines in an adiabatic atmosphere, the temperature at the bottom of the layer emitting the 8000-angstrom features is estimated at 320°K (*26*). The rotational temperatures must arise from deeper levels than the thermocouple temperatures, probably from beneath the visible cloud layer. This is then evidence for the transparency of the visible cloud layer in the near infrared; accordingly, observations at near-infrared wavelengths which lack molecular absorption features should provide information on the lower Cytherean atmosphere.

Microwave Temperatures

Since the 1956 inferior conjunction, when Mayer, McCullough, and Sloanaker (*40*) made their first observations at 3.15 centimeters, measurements have been made of the absolute intensity of the microwave radio emission from Venus. If one assumes *ad hoc* that the signal is due to black-body radiation, a brightness temperature can be derived from the Planck distribution. If the assumption of black-body emission is correct, the brightness temperature should be independent of frequency. Between 3 and 21 centimeters, the brightness temperature proves to be constant within limits of experimental error, and the Venus radio spectrum is inconsistent with known sources of nonthermal emission, such as cyclotron or synchrotron radiation from charged particles trapped in a Cytherean Van Allen belt (*35*). The mean black-body temperature for these wavelengths is approximately 600 ± 50°K, possibly depending somewhat on the phase of Venus. On the other hand, observations near 8 millimeters appear to give significantly lower brightness temperatures; at 8.6 millimeters, observations with the 10-foot radio telescope of the Naval Research Laboratory give a brightness temperature of 410 ± 160°K (*41*), while observations at 8 millimeters with the 22-meter telescope of the Lebedev Institute of Physics yield a mean brightness temperature of 350 ± 70°K (*42*). The Lebedev data also show a marked phase effect, increasing from about 315°K near conjunction to about 430°K two months later.

There are two possible explanations of the thermal radiation at centimeter wavelengths and two corresponding explanations of the lower temperatures at millimeter wavelengths. In the first case, the thermal emission might arise from free-free transitions in a Cytherean ionosphere at an electron temperature of 600°K. To explain the low temperatures near 8 millimeters we must assume that the ionosphere becomes transparent at a wavelength less than about 1 centimeter, so that in the millimeter region we are observing the Cytherean surface at its temperature of about 350°K. From the required opacity and temperature of the ionosphere it follows that the electron density must be at least 10^9 per cubic centimeter (*43*), higher by a factor of 1000 than the electron density of the terrestrial ionosphere. If the electron density is about ten times greater in the illuminated hemisphere, the phase effect can be accounted for exactly (*43*).

Such high electron densities are very difficult to explain. Preliminary calculations indicate that the ionization rates are too low and the recombination rates too high for such electron densities to be produced by solar ultraviolet radiation in a Cytherean atmosphere composed of carbon dioxide, nitrogen, and water vapor. If the electrons are to be produced by solar corpuscular radiation, the strength of the Cytherean magnetic field must be as low as 10^{-2} gauss for ionization by solar protons to be effective; if the field strength is greater, the solar wind will be magnetically deflected. If the ionization is produced by solar protons, there is still a difficulty in accounting for the low recombination coefficients, but the difficulty is not so severe as in the case of ionization by ultraviolet radiation. In addition, there is evidence that the magnetic activity on the earth declines during inferior conjunctions of Venus (*44*); if this phenomenon is interpreted as the deflection of solar protons by the Cytherean magnetic field, it follows that the field strength on Venus is of the order of a few gauss, and that the Cytherean ionosphere cannot arise from the solar wind. However, these measurements of the Cytherean magnetic field are very marginal. There is some radar evidence for the existence of a dense Cytherean ionosphere (*43*), but it is also marginal. For these reasons it appears somewhat unlikely but not entirely impossible that the 600°K emission arises from the ionosphere of Venus.

The alternative explanation is that the surface of Venus is at 600°K, or perhaps at a somewhat higher temperature if allowance is made for phase effects and for the possibility that the surface emissivity differs from unity. Molecular absorption and particle scattering would decrease the apparent temperatures in the millimeter region. The 8-millimeter phase effect would then be attributable to a condensable or sublimable cloud layer, which, if analogous to terrestrial clouds, is transparent at centimeter wavelengths but has a nonzero opacity in the millimeter region. In the illuminated hemisphere it must be supposed that cloud vaporization increases, and the attenuation of emission from the surface declines.

However, the existence of such high surface temperatures must be explained before this model is acceptable. The radiation temperature of an airless planet with the albedo and distance from the sun of Venus is about 250°K, if the period of rotation is a few weeks. The high surface temperature must be due to a very efficient greenhouse effect: Visible radiation strikes the surface and increases its temperature, but the infrared radiation emitted by the surface does not readily escape to space, because of atmospheric absorption. If the atmosphere is assumed to be in convective equilibrium below the effective reflecting layer in the 8000 angstrom bands, there are 18 km-atm of carbon dioxide above the surface; however, this is still insufficient by many orders of magnitude for producing the required greenhouse effect (*35*). Absorption is required in the region between 20 and 40 microns, and the only likely molecule which absorbs in this wavelength interval is water. The requisite total abundance of water vapor in the Cytherean atmosphere is between 1 and 10 grams per square centimeter; saturation and ice-crystal cloud formation occur at the thermocouple temperature of the Cytherean cloud layer and give approximately the balloon water-vapor abundance above the clouds (*35*). Despite an absolute water-vapor abundance of the same order as the earth's, the surface temperature is so high that the relative humidity would be about 10^{-3} percent. On the other hand, if the surface temperature were 350°K, a total abundance of about 0.1 gram per square centimeter would be required for the greenhouse effect; saturation and ice-crystal cloud formation would occur at about 195°K, and it would follow that the clouds are not composed of water, and that the balloon spectroscopy results (*9*) are incorrect. Thus if the visible cloud layer is condensible or sublimable, the ionosphere model of the origin of the microwave emission becomes untenable. Only with surface temperatures of about 600°K or greater can the requisite greenhouse effect be explained consistently. The Venus overcast is high, not because the cloud bank is very thick, but because breaks in the clouds are very rare. There is no possibility of precipitation reaching the surface; precipitation is always vaporized in the hot lower atmosphere, and ice crystallization occurs again at the cloud layer.

From the equations of radiation balance it follows that 1 km-atm of carbon dioxide is sufficient to raise the ambient temperature some 30°K in the absence of other absorbing gases (*35*). Since 1 km-atm is the abundance of carbon dioxide above the effective reflecting level in the 8000-angstrom bands, the temperature at that level should be raised about 30°K above the radiation temperature, or to approximately 280°K. This is in excellent agreement with the rotational temperature for the same bands, 285 ± 9°K (*39*). The argument also provides strong evidence that the 8000-angstrom bands originate from below the visible cloud layer; otherwise the greenhouse effect would raise the cloud temperature to approximately 280°K.

In Fig. 3, the data given in the foregoing discussion are collected, and the two alternative atmospheric models are presented. The altitudes of the cloud layer—12 and 37 km, respectively, for surface temperatures of 350° and 600°K—are based on an assumed adiabatic lapse rate of 10°K per kilometer in the Cytherean troposphere. Because of the difficulty in accounting for the ionospheric electron densities, the cloud temperatures, and the water-vapor abundance with a surface temperature of 350°K, the higher surface temperature is to be preferred at the present time. A definitive choice between the two models could be made by comparing accurate phase-brightness temperature curves at 8 millimeters and at 3 centimeters with each other and with the occurrence of solar activity, or by scanning the disk of Venus with a fly-by probe. In the latter experiment, strong emission peaks should be detected at the planetary limbs if the radiation at centimeter wavelengths is ionospheric in origin. An experiment to detect limb-brightening near 1 cm is now scheduled by the National Aeronautics and Space Administration for the Mariner A Venus fly-by probe, which will probably be launched in 1962.

Early History and Present Surface Conditions

If the surface temperature is 600°K and the adiabatic lapse rate prevails in the troposphere, the surface pressure of carbon dioxide is about 3 atmospheres. From arguments on general abundance it appears that the value for the partial pressure of nitrogen should be of the same order as the terrestrial value; the total surface pressure on Venus would then be approximately 4 atmospheres. The partial pressure of carbon dioxide is so much greater than the equilibrium partial pressure (less than 10^{-5} atm) that it is clear that the Urey equilibrium fails on Venus.

At these temperatures and pressures there can be no global oceans of water (*7*) or of hydrocarbons (*6*, *16*) to limit the access to silicates of outgassed carbon dioxide. The essential point would seem to be that liquid water is required for the Urey equilibrium, both as a catalyst and as a weathering agent to expose fresh silicates, and that, because of the high temperatures, there is no liquid water on Venus (*45*). This explanation was originally proposed by Urey (*5*) at a time when the surface temperatures were thought to be sufficiently low for liquid water to be present but when all spectroscopic searches for water vapor had been fruitless. It now appears that water is

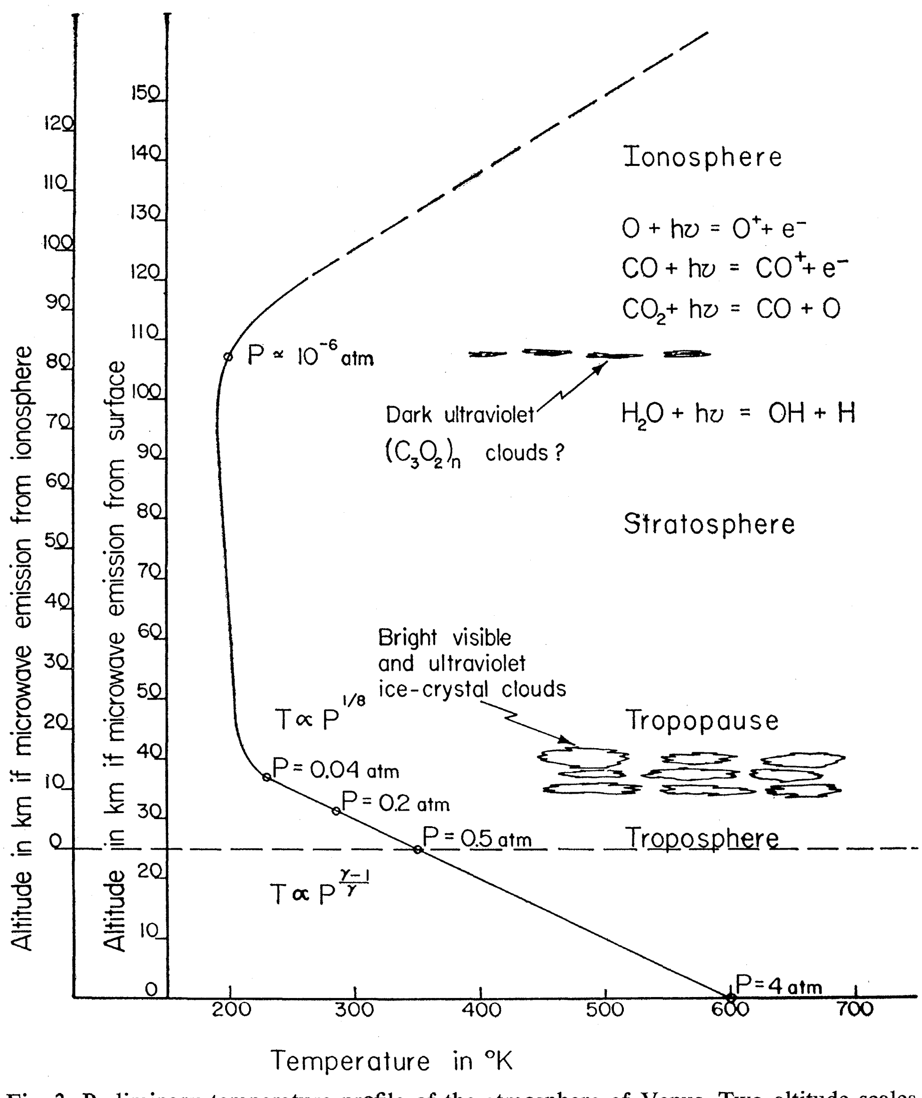


Fig. 3. Preliminary temperature profile of the atmosphere of Venus. Two altitude scales are given, corresponding to the two alternative sources of the 600°K microwave brightness temperatures. Troposphere pressures are computed from the 8000-A band intensities and the adiabatic gradient; the pressure at the base of the ionosphere is derived from occultation data. The altitude of the tropopause cloud layer is bracketed as shown, but the depth of the clouds should be much less than is indicated. On the ionospheric model, the tropopause cloud layer could not be composed of water. If there is nitrogen in the Cytherean atmosphere, nitrogen ionization should occur in the higher atmosphere in addition to the processes shown. The slope of the ionospheric temperature profile is schematic only.

present, but not in the liquid phase. The total abundance of carbon dioxide on Venus is of the same order of magnitude as the total abundance of carbon dioxide in the crust of the earth (*35*); hence, roughly equal amounts of carbon dioxide have been outgassed from the interiors of the two planets during their history, but on the earth the carbon dioxide has been sedimented, while on Venus it has remained in the atmosphere. The ultimate source of the oxygen in Cytherean carbon dioxide must be water (*29*). Through diffusion of water vapor to high altitudes, its photodissociation by solar ultraviolet radiation, and the escape of hydrogen to interplanetary space, enough oxygen has been released during the last 5×10^9 years to account for the present abundance of Cytherean carbon dioxide by the oxidation of reduced carbon compounds (*29, 35*). The oxygen in terrestrial carbonates, atmospheric oxygen, and the oxygen in water are similarly derived. If much of the primordial Cytherean water had been present at one time on primitive Venus, a very efficient greenhouse effect would have been quickly established and the surface temperature would have risen, vaporizing the water. Thus, it appears that extensive bodies of liquid water and low temperatures could not have occurred together for any appreciable period in the history of Venus.

Consequently, weathering by water must not have occurred, and the present surface erosion on Venus must be due mainly to wind and high temperatures. In the greenhouse model, solar radiation absorbed during the Cytherean day goes mainly into heating the massive atmosphere. As a result the troposphere should be less convective than on Earth, and surface winds should be mild breezes. Such aeolian erosion and the moderate thermal erosion suggested by the microwave phase data suggest that the surface of Venus closely resembles terrestrial desert wastelands. The temperatures are too high for the Carboniferous swamp, the planetary oil field, or the global Seltzer ocean, but, the desert of St. John and Nicholson (*3*) is still roughly consistent with the data (See Fig. 1). From the surface of Venus we might see the sun only dimly; the sky would be completely overcast perhaps 90 percent of the time (*35*), and the high-altitude white clouds would sometimes appear reddened by dust in the lower atmosphere. The Cytherean atmosphere may be transparent in the near ultraviolet. Hot, arid, calm, and overcast, the surface of Venus appears inhospitable for human habitation at the present time.

Life

No known terrestrial microorganisms can survive more than a few minutes' exposure to 600°K; proteins are denatured, deoxyribonucleic acid is depolymerized, and even small organic molecules are dissociated in short periods of time. Temperatures at the poles of Venus are probably not more than 100°K cooler than the mean planetary temperature, and it appears quite certain that terrestrial organisms deposited on the surface of the planet would quickly be killed. Consequently there seems little danger of biological contamination of the surface of Venus (*46*). However, conditions are much more favorable at higher altitudes, especially just beneath the cloud layer, and there is the distinct possibility of biological contamination of the upper Cytherean atmosphere. At such high temperatures, and in the absence of liquid water, it appears very unlikely that there are indigenous surface organisms at the present time. If life based upon carbon-hydrogen-oxygen-nitrogen chemistry ever developed in the early history of Venus, it must subsequently have evolved to subsurface or atmospheric ecological niches. However, since, as has been mentioned, there can have been no appreciable periods of time when Venus had both extensive bodies of water and surface temperatures below the boiling point of water, it is unlikely that life ever arose on Venus.

After the physical enviroment has been thoroughly investigated and if, indeed, Venus proves to be without life, there will exist the prospect of microbiological planetary engineering. To prepare Venus for comfortable human habitation, it is necessary to lower the surface temperature and to increase the partial pressure of molecular oxygen. Both ends could be accomplished if a means were found to dissociate carbon dioxide to oxygen and elemental carbon. The essential difference between the Cytherean and the terrestrial greenhouse effects is the great abundance of carbon dioxide on Venus; the quantities of water vapor in the two atmospheres are approximately equal. Even if ordinary green plants could grow on the surface, the problem would not be solved, because the oxygen evolved in photosynthesis derives from water, and the amount of carbon dioxide in the Cytherean atmosphere is more than 1000 times greater than the amount of water vapor. An organism is needed which can photosynthesize in the high atmosphere of Venus according to the symbolic equation

$$CO_2 + H_2O + \text{light} \rightarrow (CH_2O) + O_2,$$

the oxygen arising from the water. In time, the organisms would be carried to lower atmospheric levels, where, because of the higher temperatures, they would be roasted, decomposing ideally according to the symbolic equation

$$(CH_2O) + \text{heat} \rightarrow C + H_2O$$

Although the oxygen is derived from water, the over-all effect would be to restore the water metabolized in photosynthesis to the atmosphere, and to dissociate carbon dioxide to carbon and oxygen.

Before such a scheme can be seriously considered, much more information must be acquired about the composition and meteorology of the Cytherean atmosphere, and extensive laboratory biological investigations must be performed. Nevertheless, some tentative specifications can be entertained at the present time. In order to have appreciable photosynthesis before thermal dissociation, the life form deposited must be a microorganism. Since there is no liquid water anywhere on Venus, the organism must be able to utilize water vapor (from the atmosphere) or ice crystals (from the cloud layer). The only known microorganisms which photosynthesize evolving molecular oxygen are the algae. It would be desirable to have an organism with resistance to extremes of temperature. Blue-green algae are known to survive immersion in liquid nitrogen, and some forms ordinarily live in hot springs at 80°C. Since there is little likelihood that the microorganisms would find nitrogen in the form of nitrates or ammonia in the Cytherean atmosphere, they would have to be able to fix molecular nitrogen from the atmosphere. The only photosynthetic, nitrogen-fixing, oxygen-evolving, temperature-resistant aerial microorganisms are the blue-green algae, primarily of the Nostocaceae family.

Extensive laboratory experiments should be performed on the ecology of the algae in simulated Cytherean environments. It is necessary to know whether the algae will be able to reproduce prior to thermal decomposition; whether a complete aerial existence is possible, or if they require the cloud ice-crystals as a substratum; whether a strain can be found which will photosynthesize at low temperatures and high ultraviolet fluxes: whether trace metal requirements can be supplied by meteoritic infall, or whether metals must be provided artificially; and what the products of slow thermal decomposition may be. But it is conceivable that these problems can be solved, and that the microbiological re-engineering of Venus will become possible. Such a step should be taken only after the present Cytherean environment has been thoroughly explored, to prevent the irreparable loss of unique scientific information. It might be advisable to find suitable controls for the algae, because in the absence of predators and competitors the algae might reproduce at a geometric rate and the entire conversion of carbon dioxide would then be accomplished in relatively short periods of time.

Ideally, we can envisage the seeding of the upper Cytherean atmosphere with appropriate strains of Nostocaceae after exhaustive studies have been performed on the existing environment of Venus. As the carbon dioxide content of the atmosphere falls, the greenhouse effect is rendered less efficient and the surface temperature falls. After the atmospheric temperatures decline sufficiently, the decreasing rate of algal decomposition will reduce the water abundance slightly and permit the surface to cool below the boiling point of water. At this time, the original mechanism becomes inoperative, because the algae are no longer thermally decomposed, but now surface photosynthesis becomes possible. At somewhat lower temperatures, rain will reach the surface, and the Urey equilibrium will be initiated, further reducing the atmospheric content of carbon dioxide to terrestrial values. With a few centimeters of precipitable water in the air, surface temperatures somewhere near room temperature, a breathable atmosphere, and terrestrial microflora awaiting the next ecological succession, Venus will have become a much less forbidding environment than it appears to be at present. Hopefully, by that time we will know with more certainty whether to send a paleobotanist, a mineralogist, a petroleum geologist, or a deep-sea diver (*47*).

References and Notes

1. In the literature one sometimes finds the adjective *Venusian*. This is incorrect; we do not say "Sunian," or "Moonian," or "Earthian." The appropriate adjective would be *Venerean* or *Venereal*, but at least the second of these has been pre-empted by other areas of human activity. The Greek goddess corresponding to Venus is Aphrodite, but the appropriate adjective here, *Aphrodisian* or *Aphrodisiac*, must be excluded for similar reasons. Since diseases and love-philters preceded modern astronomy, we must be content with *Cytherean*, an adjective which has been used by astronomers for more than a century. Cythera is the Ionian island onto which Aphrodite is said to have emerged from the sea.
2. S. Arrhenius, *The Destinies of the Stars* (Putman, New York, 1918), chap. 7.
3. C. E. St. John and S. B. Nicholson, *Astrophys. J.* **56**, 380 (1922).
4. W. S. Adams and T. Dunham, *Publs. Astron. Soc. Pacific* **44**, 243 (1932).
5. H. C. Urey, *The Planets; Their Origin and Development* (Yale Univ. Press, New Haven, 1952). Urey proposed that on a planet having both surface silicates and surface water, the partial pressure of CO_2 is maintained by a sequence of equilibrium reactions, which can be summarized by such over-all reactions as

$$MgSiO_3 + CO_2 \underset{}{\overset{H_2O}{\rightleftarrows}} MgCO_3 + SiO_2$$

and

$$CaSiO_3 + CO_2 \underset{}{\overset{H_2O}{\rightleftarrows}} CaCO_3 + SiO_2$$

If, at equilibrium, the abundance of CO_2 increases (for example, through volcanism), the rate of carbonate sedimentation also increases; if the abundance of CO_2 decreases, the reactions reverse, and silicate deposition increases. The partial pressures of CO_2 on the earth are within about an order of magnitude of the equilibrium pressures, at room temperature, resulting from the reaction to dolomite given above.
6. F. Hoyle, *Frontiers of Astronomy* (Harper, New York, 1955), pp. 68–72.
7. D. H. Menzel and F. L. Whipple, *Publs. Astron. Soc. Pacific* **67**, 161 (1955).
8. G. Herzberg, in *Atmospheres of the Earth and Planets*, G. P. Kuiper, Ed. (Univ. of Chicago Press, Chicago, rev. ed. 1952), chap. 13. One centimeter-atmosphere (cm-atm) is the amount of gas corresponding to a path 1 cm long at atmospheric pressure and room temperature. Centimeter-atmospheres can be converted to molecules per square centimeter by multiplication with Loschmidt's number. One kilometer-atmosphere (km-atm) equals 10^5 cm-atm.
9. J. Strong, private communication (1960). The value of 20 microns of precipitable water is derived for one atmosphere pressure. Because of lower pressure broadening, if the pressure at the relevant Cytherean reflecting level is, for example, 0.2 atmospheres, the water vapor abundance would be about 4×10^{-2} gm/cm^2. This corresponds to the saturation vapor pressure of water above a convective cloud layer at about 240°K. However, it should be noted that the probable error of the balloon measurements exceeded the absolute value of the results; and that there was no astronomical calibration—for example, against the Moon—so the possibility remains that some of the water detected was in the terrestrial atmosphere.
10. N. A. Kozyrev, *Bull. Crimean Astrophys. Observatory* **12**, 169 (1954); H. C. Urey and A. W. Brewer, *Proc. Roy. Soc. (London)* **A241**, 37 (1957). B. Warner, *Monthly Notices Roy. Astron. Soc.* **121**, 279 (1960) has shown that the agreement in wavelength of many of Kozyrev's features with known bands of N_2, N_2^+, O, and O^+ is greater than would be expected by chance. However, many inconsistencies remain.
11. N. A. Kozyrev, *Akad. Nauk S.S.S.R. Astron. Circ.* **175**, 26 (1956).
12. G. Newkirk, *Planetary Space Sci.* **1**, 32 (1959).
13. It may not be irrelevant to mention that perhaps the outstanding unidentified interstellar absorption feature is one about 40 A wide, centered at 4430 A.
14. G. P. Kuiper, in *Atmospheres of the Earth and Planets*, G. P. Kuiper, Ed. (Univ. of Chicago Press, Chicago, rev. ed. 1952), chap. 12. Kuiper's maximum abundances have not been corrected for pressure-broadening.
15. See also T. Dunham, *ibid.*, chap. 11.
16. Y. Mintz, "Temperature and Circulation of the Venus Atmosphere," *RAND Corp. Rept. No. P-2003* (1960).
17. See, for example, E. J. Öpik, *Irish Astron. J.* **4**, 37 (1956).
18. F. E. Ross, *Astrophys. J.* **68**, 57 (1928).
19. E. E. Barnard, *ibid.* **5**, 300 (1897).
20. A. Danjon, *L'Astronomie* **57**, 161 (1943); A. Dollfus, *ibid.* **68**, 413 (1955).
21. G. P. Kuiper, private communication (1960).
22. ———, *Astrophys. J.* **120**, 603 (1954).
23. R. S. Richardson, *Publs. Astron. Soc. Pacific* **67**, 304 (1955).
24. V. M. Slipher, *Lowell Observatory Bull. No. 3* (1903).
25. B. Lyot, *Ann. Observatoire Meudon, Univ. Paris* **8**, 66 (1927).
26. G. P. Kuiper, *The Threshold of Space*, M. Zelikoff, Ed. (Pergamon, London, 1957), pp. 78ff.
27. T. Gehrels (private communication) has recently found that the Venus polarization curve departs markedly from the curve of Lyot at several different wavelengths. Laboratory duplication of these observations would represent a major step toward understanding the Cytherean cloud layer.
28. A. Dollfus, *Ann. d'Astrophys. Suppl.* No. 4 (1957).
29. H. C. Urey, in *Handbuch der Physik*, S. Flugge, Ed. (Springer, Berlin, 1959), vol. 52, p. 363.
30. A. Dauvillier, *L'Origin Photochimique de la Vie* (Masson, Paris, 1958).
31. W. M. Sinton and J. Strong, *Astrophys. J.* **131**, 470 (1960).
32. L. Kaplan (private communication) has recently shown from new laboratory data that the observed intensity of the Cytherean far infrared carbon dioxide bands is approximately the intensity to be expected above the cloud layer. The need to hypothesize a high level infrared absorbing layer above the visible cloud layer is thereby diminished. Weaker bands of carbon dioxide, such as those in the 8000-angstrom region, must come from greater depths, probably from beneath the visible cloud layer.
33. F. J. Heyden, C. C. Kiess, H. K. Kiess, *Science* **130**, 1195 (1959).
34. C. C. Kiess and C. H. Corliss, *Sci. News Letter* **75**, 229 (1959).
35. C. Sagan, "The Radiation Balance of Venus," *Calif. Inst. Technol. Jet Propulsion Lab. Tech. Rept. No. 32–34* (1960).
36. E. Petit and S. B. Nicholson, *Publs. Astron. Soc. Pacific* **67**, 293 (1955).
37. J. I. F. King, "Probe Observations of Venus at Close Range," *Johns Hopkins Univ. Rept.*, J. Strong, Ed. (1960), appendix 3.
38. D. H. Menzel and G. deVaucouleurs, *Astron. J.* **65**, 351 (1960); private communication.
39. J. W. Chamberlain and G. P. Kuiper, *Astrophys. J.* **124**, 399 (1956).
40. C. H. Mayer, T. P. McCullough, R. M. Sloanaker, *ibid.* **127**, 1 (1958).
41. J. E. Gibson and R. J. McEwan, in *Paris Symposium on Radio Astronomy*, R. N. Bracewell, Ed. (Stanford Univ. Press, Stanford, Calif., 1959), p. 50.
42. A. D. Kuz'min and A. W. Salomonovich, *Astron. Zhur.* **37**, 297 (1960).
43. C. Sagan, K. Siegel, and D. Jones, in preparation.
44. J. Houtgast, *Nature* **175**, 678 (1955).
45. Even if the Urey equilibrium did apply in the absence of liquid water at 600°K, the partial pressure of CO_2 would be less than 3 atm by several orders of magnitude.
46. See, for example, C. Sagan, *Proc. Natl. Acad. Sci. U.S.* **46**, 396 (1960).

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