28 June 1968, Volume 160, Number 3835 **SCIENCE**

The Planet Venus

Information received from Mariner V and Venera 4 is compared.

Robert Jastrow

The U.S. spacecraft Mariner V and the U.S.S.R. spacecraft Venera 4 were launched within 2 days of one another in June 1967. They traversed elliptical paths of approximately 200 million miles, and arrived in the vicinity of Venus 5 months later (Fig. 1).

En route to the planet, the two spacecraft sampled conditions in the interplanetary medium, including magnetic field strengths and concentrations of charged particles of various energies. Approximately 50,000 kilometers from Venus, and approaching it from outside the planet's orbit, that is, away from Sun, the spacecraft crossed a standing shock or bow wave created by the obstacle which Venus presents to the flow of the solar wind (Fig. 2). Penetrating the bow wave, the spacecraft began the phase of their flights in which data were collected on the ionosphere and upper atmosphere of Venus.

The histories of the spacecraft diverged as they drew nearer the planet. Mariner V moved across the dark side, penetrated the bow wave again on the sunlit side, and receded into space (Fig. 2); Venera 4 curved downward and ejected a capsule which parachuted to what appeared to be a soft landing on the dark side of the planet near the equator.

The following discussion is based on information contained in Mariner V reports published in *Science* (29 December 1967), on translations of Venera 4 results which appeared in *Pravda* (22 October 1967) and in *Izvestia* (31 October 1967), and on reports presented on 7 and 8 March 1968 at the Second Arizona Conference on Planetary Atmospheres, sponsored by the Kitt Peak National Observatory.

Conditions in the Interplanetary Medium

Both spacecraft contained magnetometers for measuring the interplanetary magnetic field en route to Venus and the planetary field, if any, of Venus. They also contained particle detectors for the measurement of the concentration and velocity of the low-energy particles constituting the interplanetary plasma, and detectors sensitive to particles of higher energy, including Van Allen belt particles and cosmic rays.

The principal interest in these measurements lies in the comparison they provide between the current state of the interplanetary medium, as the sunspot cycle climbs to its maximum, and the state of earlier spacecraft flights in 1962 (Mariner II), 1964 (Mariner IV), and 1965 (Venera 2) when the sunspot cycle was at or near its minimum.

Venera 4 magnetometers recorded interplanetary magnetic field strengths of about 7 gamma (1 gamma is 10^{-5} gauss), and occasionally stronger fields during increases of the magnetic activity index on Earth. Mariner V recorded interplanetary magnetic fields in the neighborhood of 8 gamma. These values are close to those measured by Mariner II in 1962.

The Soviet reports mention that the flux of 1-Mev solar protons has increased 100-fold from the quieter solar conditions in 1965 to the more active solar conditions in 1967.

Interaction between Venus and the Solar Wind

As the spacecraft approached the neighborhood of Venus, each detected its first indication of disturbances created by Venus in the interplanetary medium. Data received by Venera 4 during this period are mentioned as being under study, but no indication of the scientific results has been given as yet. Mariner V reports contain a detailed discussion of conditions observed in this portion of its flight, and provide an extremely interesting picture of the effects produced on the solar wind as it flows past a planet which is, in this case, surrounded by an ionosphere but no magnetosphere. These effects differ significantly from those observed by spacecraft near Earth, which is protected from the solar wind by a magnetosphere, or those observed near Moon, which has no protecting envelope at all and is directly exposed to solar wind bombardment. According to Mariner V data, when the spacecraft was 50,000 kilometers from Venus it entered a zone in which conditions were appreciably different from those encountered in the interplanetary medium up to that point. Plasma density and magnetic field both showed substantial increases, and the direction of the magnetic field fluctuated rapidly and violently. Similar phenomena are observed when a spacecraft penetrates the Earth's magnetopause, that is, the boundary of the magnetosphere surrounding Earth. It is natural to look to this phenomenon—the penetration of a magnetospheric boundary—for an explanation of the changes detected by Mariner V. However, other particle detectors on board Mariner V,

The author is director of the Institute for Space Studies of the Goddard Space Flight Center, National Aeronautics and Space Administration, New York.

designed to record the presence of magnetospheric particles (Van Allen belts), gave a null result which was confirmed by similar detectors on Venera 4. Within the sensitivities of these detectors, no evidence was found for a Venus magnetosphere.

Although a Venus magnetosphere appears to be missing, other Mariner V and Venera 4 measurements, described below, indicate that Venus is surrounded by an ionosphere, that is, a layer of electrons and ions resulting from ionization of the upper atmosphere by solar ultraviolet radiation.

Can an ionosphere protect Venus from the solar wind? At first thought, it seems that an ionosphere should offer no substantial obstacle to a plasma; that is, the charged particles of the solar wind should be able to penetrate the charged particles of the ionosphere with relative ease. But this is not the case, because the solar wind carries with it a small interplanetary magnetic field, dragged along by the solar wind as it streams outward from the surface of Sun. This interplanetary field was measured by magnetometers on board both Venera 4 and Mariner V.

When the solar wind comes into contact with the Venus ionosphere, the magnetic field which it carries with it is unable to penetrate the "foreign" plasma of the ionosphere. As a result, the solar wind is deflected and flows over and around the boundary of the ionosphere, encapsulating it, just as the magnetosphere of Earth is encapsulated. The bounding surface of the ionosphere may be called the Venus ionopause.

Measurement of the Planetary Magnetic Field

The negative results of the search for magnetospheric particles permit an upper limit to be placed on the strength of the Venus magnetic field. According to the interpretation of the Mariner V data, the strength of the field, if it exists, is certainly less than one-hundredth of the strength of the Earth's field, and probably less than one-thousandth.

More direct limits on the field are also obtained from the magnetometer data. The limits quoted in the Mariner V and Venera 4 reports are, respectively, two one-thousandths and three ten-thousandths of the strength of the Earth's fields.

It is not known whether a slowly rotating planet like Venus should exhibit a weak dipole field, or no field at all. That is, does a critical threshold value exist for the rate of rotation of the planet, below which a planetary magnetic field is not generated? Also, theories of the origin of the Earth's field relate it not only to the Earth's rotation but also to the motions of the molten material within the planet's core, about which nothing is known concerning either Earth or Venus. It does not seem possible to make useful interpretations of the results of the measurement of the Venus magnetic field at the present time.

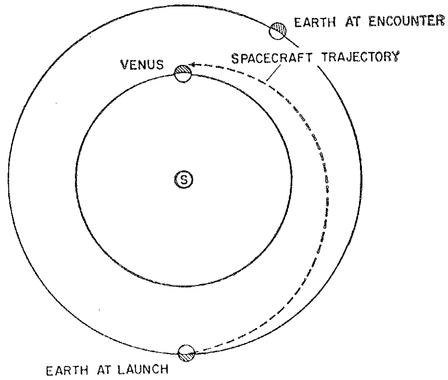

Fig. 1. Interplanetary trajectories of Venera 4 and Mariner V. The spacecraft followed semielliptical paths, falling inward toward the Sun from the orbit of Earth to the orbit of Venus.

Upper Atmosphere: Data from Venera 4 and Mariner V

No concrete information regarding the Venus upper atmosphere and ionosphere existed before the 1967 flights. The literature contained one theoretical study of upper atmosphere temperatures which concluded that they might range from 100° to 3000°K, depending on the proportion of CO_2 assumed in the atmosphere. Also, there were speculations on the possibility that the ionosphere could contain peak densities as high as 10^9 electrons per cubic centimeter, or a thousand times more than the peak density in the Earth's ionosphere. These speculations were motivated by the hope of accounting for the intensity of microwave emission from Venus without recourse to alternative explanations requiring a very high surface temperature.

Mariner V reached its point of closest approach to Venus, 10,000 kilometers from the center of the planet and 4000 kilometers from its surface, 2½ hours after its initial penetration of the ionopause. Twenty minutes later, Mariner V crossed the ionopause for the second time and emerged again into the solar wind (Fig. 2). During the corresponding segment of its flight, Venera 4 presumably crossed the ionopause also, and then approached the surface on the dark side of the planet. Both spacecraft collected information concerning the upper atmosphere in this period.

Venera 4 and Mariner V contained ultraviolet photometers, sensitive to the Lyman-alpha hydrogen line at 1216 angstroms and the oxygen line at 1304 angstroms, for detecting the concentrations of neutral hydrogen and oxygen atoms along their paths. On approaching the planet, photometers on both spacecraft showed a rise in the concentration of neutral hydrogen, signifying the presence of a hydrogen envelope or corona around the planet, held there by its gravitational attraction.

The Venera 4 reports specify an interplanetary hydrogen density of 0.01 atoms per cubic centimeter and a density of 1000 atoms per cubic centimeter at an altitude of 1000 kilometers above the planetary surface. Mariner V reports at the Kitt Peak conference indicate comparable values. Ten thousand kilometers above the surface, the hydrogen density is appreciably less than in the hydrogen corona of Earth at comparable distances, presumably because the upper atmosphere temperature is lower and the rate of decrease of density is more rapid on Venus than on the Earth.

According to Mariner V data, the number of hydrogen atoms in the upper atmosphere of Venus is comparable to the number in the upper atmosphere of Earth. However, the hydrogen envelope around Venus is much less extended than that around Earth, implying substantially lower temperatures in the outer atmosphere of Venus than in the outer atmosphere of our planet. Neither spacecraft reported a measurable concentration of oxygen atoms. This negative result confirms the analysis of the dayside ionosphere data, discussed below.

Mariner V contained radio propagation experiments which provided information on electron densities in the dayside and nightside atmospheres, on upper atmosphere temperatures, and on temperature and pressure profiles in the lower atmosphere. The radio propagation experiments depended on the fact that the Mariner V trajectory carried the spacecraft behind Venus. As a result, signals from the spacecraft to

Earth were blocked for about 20 minutes. Prior to the passage of the spacecraft behind Venus, and again just after its emergence on the other side of the planet, the signals from Mariner V traversed the Venus atmosphere en route to Earth. As the spacecraft approached the edge of the Venus "shadow," the signals swept through all of the atmosphere (Fig. 3). Passage through the atmosphere produced changes in the wavelength and velocity of the signals, which were easily detected on Earth as a change in the phase of the waves. The sign of the phase change differs for passage through the neutral atmosphere and through the charged-particle ionosphere, respectively; hence it was possible to construct separate density profiles for the atmosphere and the ionosphere. We postpone the discussion of the information gained in this way on the properties of the lower atmosphere, and confine ourselves in this section to a discussion of the ionosphere results.

The first result of the experiment is that the peak density is 5×10^5 electrons per cubic centimeter for the daytime ionosphere. This density is close to peak densities observed in the daytime ionosphere of Earth. The altitude of the peak is surprisingly low, being approximately 100 kilometers above the surface in contrast to an altitude of 250 to 280 kilometers for the peak in the Earth's ionosphere. A secondary peak, or shelf, occurs in the profile approximately 15 kilometers below the principal peak.

The narrowness of the Venus ionosphere is a third feature of interest. The half-width of the electron-density profile is approximately 20 kilometers, in comparison with a half-width of approximately 300 kilometers for the Earth's ionosphere.

The Mariner V data lead to an important conclusion concerning the degree of dissociation of carbon dioxide into carbon monoxide plus oxygen (*1*). As seen below, carbon dioxide is the principal constituent of the Venus atmosphere. Laboratory studies of the reaction rates for dissociation of carbon dioxide indicate that it should be largely or entirely dissociated under conditions prevalent on Venus. Since atomic oxygen, one of the products of the dissociation, is a much lighter gas than carbon dioxide, it is less tightly bound by the gravitational pull of the planet and should "float" above the heavier molecular constituents, extending the atmosphere to higher altitudes than would be the case if the carbon dioxide were not dissociated.

That is, a layer of oxygen, created as the product of the photodissociation of carbon dioxide molecules, will form an upper layer of the atmosphere, extending to higher altitudes than the carbon dioxide molecules themselves. This layer of oxygen at high altitudes will be ionized by solar ultraviolet radiation, creating ions and electrons. Thus, if carbon dioxide is extensively dissociated, there should be a substantial density of electrons at high altitudes.

The Mariner V data, however, do not show the predicted electron densities at high altitudes. According to these data, the electron densities on Venus fall off much more rapidly with increasing altitude than would be expected if carbon dioxide were dissociated. Apparently the predicted dissociation of carbon dioxide, and the formation of a high-altitude layer of atomic oxygen, do not occur.

Detailed studies indicated that no more than 2 percent of the carbon dioxide on Venus can be dissociated if agreement is to be maintained with the Mariner V data. It is difficult to reconcile this conclusion with laboratory measurements on carbon dioxide dissociation.

The implications regarding the photodissociation of carbon dioxide, derived from the Mariner V data, will be

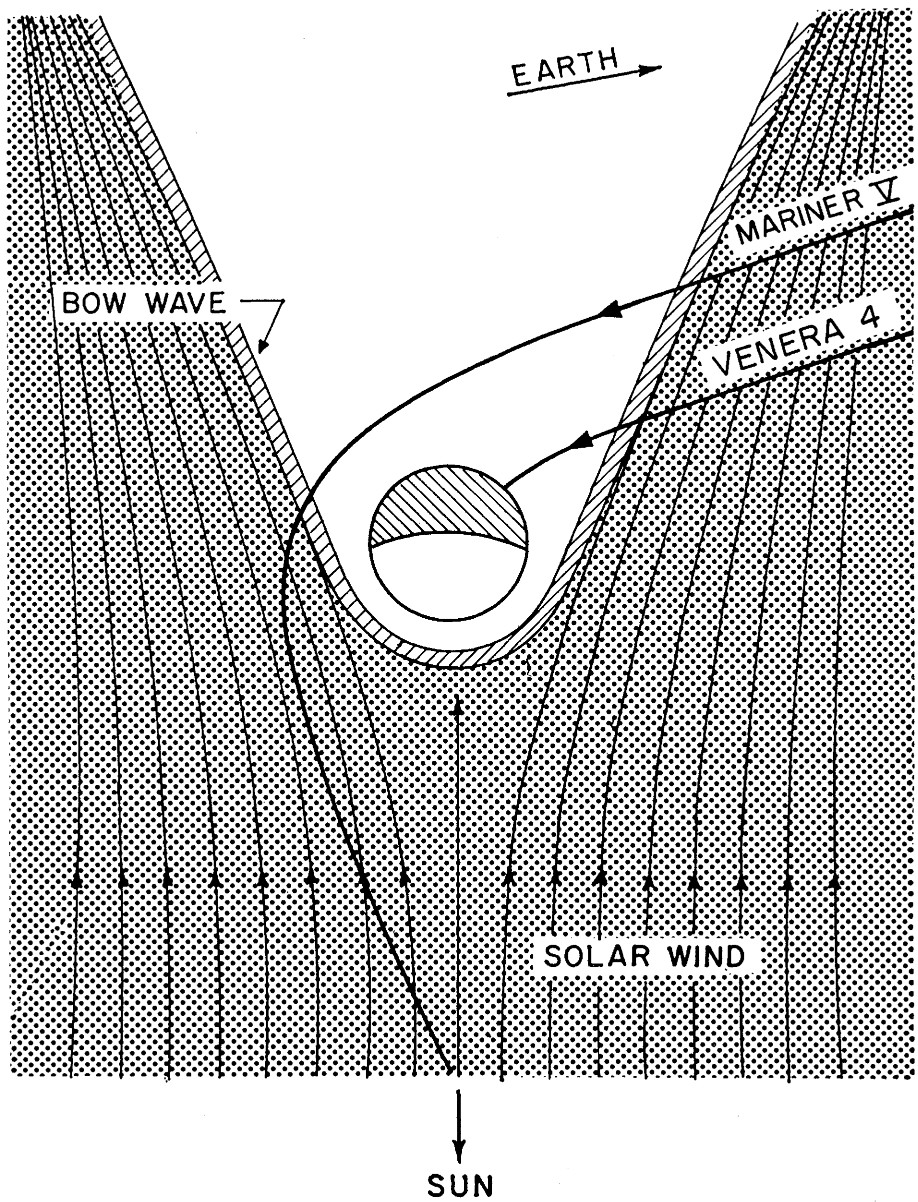

Fig. 2. The trajectories of Venera 4 and Mariner V near Venus, projected onto the orbital plane. Both spacecraft penetrated the bow wave apparently marking the Venus ionopause. Venera 4 landed on the dark side; Mariner V swerved around the planet under the pull of its gravity and reentered the solar wind. The Mariner V radio occulation experiments were performed as the line of sight from the spacecraft to Earth cut through the Venus ionosphere and atmosphere.

of basic importance in subsequent analyses of the Venus atmosphere. They are important also in analyses of the atmosphere of Mars, which, like that of Venus, consists principally of carbon dioxide.

Ionospheres of Earth and Venus Compared

The principal peak in Earth's ionosphere is an F2 or Bradbury layer. The F2 layer is a type of ionosphere that exists when atoms rather than molecules are the major constituents of the atmosphere. This is generally the situation at high altitudes in the atmosphere because the molecules, being relatively heavy, are pulled down toward the surface of the planet by gravity, as already mentioned, while the lighter atoms "float" above them. The absence of molecules eliminates the possibility of dissociative recombination and allows electron removal solely by the process of radiative recombination. Because radiative recombination is slow, electrons produced by ionization of atoms at high altitudes remain where they are produced until, under the attraction of gravity, they slowly diffuse downward to the lower levels of the atmosphere, in which molecules are found in abundance. There they disappear rapidly by dissociation recombinations.

Electron densities in an F1 layer, which are controlled by the density distribution of low-lying, relatively heavy molecular constituents, usually display a peak at a lower altitude than in the F2 layer, and fall off more rapidly at high altitudes than those in an F2 layer; that is, an F1 type of ionosphere is lower and narrower than an F2 type.

The Venus ionosphere differs from an F2 layer in precisely the characteristics—altitude of peak and breadth of layer — that usually differentiate F1 from F2 layers. Detailed theoretical studies reveal that an F1 layer on Venus, formed by ionization of carbon dioxide, yields approximately the right value of the peak electron density: it reproduces the secondary peak in the data, which turns out to be similar to the E layer in the Earth's atmosphere; and it is a narrow layer in agreement with the data. Ultraviolet photometer data from both spacecraft, showing no evidence of atomic oxygen, support the conclusion that carbon dioxide is not dissociated in the upper atmosphere.

Surface and Lower Atmosphere

Among the planets of the solar system, Venus is closest to Earth in distance from Sun and most nearly identical to Earth in size and weight. The planet is completely covered by clouds that have frustrated our attempts to observe its surface. In spite of the obstacles interposed by the heavy cloud cover, Earth-based studies of Venus, with the methods of optical, radio-, and radar-astronomy, have yielded several facts of importance regarding its surface and atmosphere. These facts have an interest beyond their contributions to knowledge of an uncharted territory. The additional significance lies in the fact that they describe conditions on a planet which should be very similar to Earth, and yet, as discussed below, is completely different.

The question of understanding the differences between Earth and Venus focuses our attention on the history of the solar system and the history of Earth. Why did two similar planets, probably formed out of similar materials, and situated at distances from Sun which are not too greatly different, evolve along different paths? Why does one planet offer an excellent climate for living organisms, while the other offers conditions hostile to terrestrial life? Is it possible that planets with life are rare objects in the universe? These questions, stated or implied, stimulate much of the scientific discussion on the properties of Venus; with them in mind, we concentrate the discussion of Venera 4 and Mariner V data on the information they provide regarding the lower atmosphere and the surface of the planet.

Knowledge Gained by Venera 4 and Mariner V

The spacecraft experiments contributed four basic points of information regarding the Venus atmosphere. These are surface temperature, surface pressure, bulk composition, and concentration of certain minor constituents including water vapor. Information regarding the first three quantities—surface temperature, surface pressure, and bulk composition—was obtained by direct measurement by Venera 4 and indirectly by Mariner V. In addition, Venera 4 acquired information on the concentration of certain minor constituents of the atmosphere, including, in particular, the water content.

Microwave Temperature Measurements

Prior to the flights, the global average of the temperature at the surface of Venus appeared to be in the neighborhood of 700°K (800°F), hot enough to melt lead, and far hotter than the temperature of the Earth's surface. This estimate was derived from measurements of the intensity of the energy radiated to space from the planet. Most of the energy radiated by a planet is concentrated in the infrared region of the electromagnetic spectrum. However, small amounts are radiated at other wavelengths, including those in the microwave region. The microwave radiation is of special interest to observers of Venus because it passes relatively unhindered through the clouds over the planet, and can therefore be detected by radio telescopes on Earth. It is our only means of obtaining information about the surface of Venus from a great distance.

According to theories on the radiation of energy from a heated surface, the intensity of the microwave radiation should be proportional to the first power of the temperature of the surface. Thus, the temperature of the surface of Venus can be deduced from the microwave measurements. In this way, it was found that the surface temperature of Venus was approximately 650°K on the nightside of the planet, approximately 750°K on the dayside of the planet, and approximately 700°K as an average over day and night conditions.

The foregoing interpretation of the microwave measurements depended on the assumption that there was no source of microwave emission other than the surface of Venus. If the surface emission were supplemented by emission of microwaves from the atmosphere, the derived value of the surface temperature would have to be reduced accordingly.

Mariner II performed an experiment, during its Venus flyby mission in 1962, which indicated that most, if not all, of the microwave radiation was emitted from the surface of the planet, and that little, if any, was emitted from the atmosphere and ionosphere. The Mariner II experiment supported the interpretation that the surface of Venus is very hot. However, a measure of doubt remained, perhaps because of the importance of this result for speculation on the existence of life on Venus.

Venera 4 Data on Temperature Pressure and Surface Conditions

The reports on Venera 4 state that the temperature was 544°K at the time of the final transmission of the data from the probe. This result removes the last remaining uncertainty regarding the high temperature of Venus.

It is not definitely established that the probe had reached the surface of the planet at the time of transmission of the final data. However, in the U.S.S.R. reports and subsequent discussion at the Kitt Peak conference, facts were mentioned which tend to support this conclusion. The discussion revealed that the Venera 4 altimeter gave an altitude measurement at one point during the descent. The measured altitude at this point was 26 ± 1.3 kilometers. At approximately the same altitude, the parachute opened and the spacecraft began transmission of atmospheric data. Thereafter, no further altimeter data were obtained, but temperature data were transmitted back at frequent intervals throughout the ensuing parachute descent of the spacecraft, and pressure and density data were transmitted down to a level at which the pressure was 7 atmospheres.

In spite of the lack of subsequent altimeter data, the descent profile, that is, altitude as a function of time, could be calculated from the Venera 4 atmospheric data. This calculation was made in two independent ways. First, the equation of hydrostatic balance was integrated to yield the altitude z at time t_0:

$$z(t) = z(t_0) - \int_{t_0}^{t} \frac{dp}{\rho(z)g}$$

with Venera 4 data used for pressure p and density ρ. Second, the course of the descent was calculated from the aerodynamic drag coefficient, area of the spacecraft, and density profile of the atmosphere.

The two methods provided descent profiles $z(t)$ which agreed closely. According to the average of the calculated profiles, the spacecraft descended 28 ± 0.7 kilometer between the time at which the parachute opened and the time at which the transmission of spacecraft signals ceased. The agreement between this result and the altimeter measurement of 26 ± 1.3 kilometers supports the interpretation that the spacecraft was lying on the surface of the planet at the time of cessation of signals.

In most of the discussion that follows, we assume that the final data received from Venera 4 represent surface conditions.

The Venera 4 landing site was on the nightside of the planet. If the final Venera 4 temperature of 544°K represents surface conditions, this temperature may be compared directly with the nightside microwave values of 650°K.

The discrepancy of approximately 100°K may reflect the fact that the Venera 4 datum was observed at a specific site on the surface, whereas the microwave value is an average over the disk of the planet. For example, if the Venera 4 probe landed on a mountain or a plateau, it would indicate a lower temperature than the microwave value. Venera 4 and Mariner V data indicate that the temperature falls off with increasing altitude above the surface at the rate of 10°K per kilometer, hence a variation of 100°K would mean that the landing site of the Venera 4 capsule is 10 kilometers above the mean level of the Venus surface. This explanation was suggested by Kuzmin in his analysis of Venera 4 data presented at the Kitt Peak conference.

Elevations of 10 kilometers above the mean surface level are conceivable on Venus if it has a mantle and crust similar to those of Earth. In that case, the surface of Venus, like that of Earth, should be marked by large blocks of light-weight granitic rocks, floating in the denser rocks of the underlying mantle. The maximum elevation of these blocks above the mean surface of Earth is about 10 kilometers.

Prior to the flights, the surface pressure of the atmosphere was believed to be larger than the pressure at the surface of Earth. Estimates ranged from several to several hundred atmospheres. The Venera 4 data indicate a surface pressure of 18.5 ± 3.5 atmospheres at the landing site of Venera 4. If the spacecraft landed on an elevation 10 kilometers above the mean surface of the planet, as suggested by Kuzmin, the mean surface pressure, obtained when the Venera 4 pressure data are extrapolated downward another 10 kilometers, turns out to be about 40 atmospheres. This result is of interest because of the differences—a factor of 100—in estimates of surface pressure prior to the spacecraft flights.

Finally, Venera 4 measured atmospheric properties away from the surface. According to U.S.S.R. reports at the Kitt Peak conference, about 50 readings of density, pressure, and temperature were obtained as the spacecraft parachuted downward. The temperature data indicated a lapse rate of about 10°K per kilometer.

Temperature and pressure data extended to the regime of pressure and temperature values measured by Mariner V. Apparently the two spacecraft sampled conditions in overlapping regions of the atmosphere.

Mariner V Temperature and Pressure

Although Mariner V did not send a probe to the surface of Venus, or approach closer to the surface than 2600 miles (4160 kilometers) during its flight past the planet, it acquired information on conditions deep in the atmosphere by an indirect method, based on the effect of the atmosphere on the propagation of radio signals from the spacecraft to Earth. This method, described above, should, in principle, determine atmospheric conditions down to the surface of the planet. However, because of the high density of the Venus atmosphere the radio signals from the spacecraft were bent or refracted through so large an angle, as they passed through the lowest layers of the atmosphere, that they never reached Earth. As a consequence, conditions at and near the surface were not determined.

Nonetheless, data acquired on atmospheric conditions at intermediate altitudes were sufficiently accurate so that they could be extrapolated downward to the surface with reasonable reliability. But, in the extrapolation of the Mariner V data to the surface, a question arises which also arose in the discussion of the Venera 4 data; namely, where is the surface?

Tracking data determine the position of Mariner V with respect to the center of the planet; consequently, the atmospheric conditions are known only in terms of this distance. The distance to the center can be converted into an altitude above the surface, provided the radius of the planet is known.

A value of the radius is provided by radar observations of Venus from Earth. The radar observations yield accurate determinations of the motion of Venus in its orbit around Sun, and also yield the radius of the planet as a by-product of the orbital studies. The radius determined in this way is 6056 ± 1 kilometers (*2*).

If the Mariner V data are extrapo-

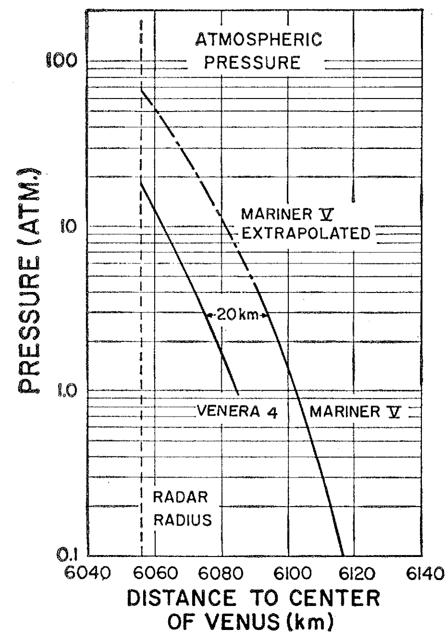

Fig. 3. Atmospheric pressure data from Venera 4 and Mariner V. The two sets of data agree if the altitude scales of the measurements are displaced by a total of 20 kilometers. The profiles in Figs. 3 and 4 are based on the assumption that carbon dioxide makes up approximately 90 percent of the atmosphere.

lated downward along an adiabat to 6056 kilometers to obtain surface conditions, the results are a surface temperature in the neighborhood of 700°K and a pressure in the neighborhood of 65 atmospheres.

These results are based on data received just before the spacecraft entered occultation, that is, as it passed behind Venus. During this portion of the trajectory, the signals from Mariner V traversed the nightside atmosphere. As the spacecraft emerged from behind the planet, its signals traversed the dayside atmosphere, but results from the analysis of occultation data received during this portion of the trajectory are not yet available.

Discrepancy between Mariner V and Venera 4 Results

Figures 3 and 4 show the Mariner V data on nightside temperature and pressure versus distance to the center of the planet; they also show the Venera 4 data on temperature and pressure versus altitude above the surface, plotted on the assumption that 6056 kilometers is the radius of the planet.

The figures indicate that the Venera 4 values of temperature and pressure are considerably lower than those deduced from the occultation experiment. However, the discrepancy would be removed throughout the entire region of overlap if the Venera 4 results were shifted upward in altitude by 20 kilometers.

It is possible that the two spacecraft sampled regions differing by 20 kilometers in elevation, since a difference of about 20 kilometers exists between the highest and lowest points of the Earth's crust, and may also exist on Venus.

Other possible explanations of the discrepancy are the following: (i) radio transmission from the Venera 4 spacecraft ceased before the spacecraft reached the surface of the planet; (ii) values given for the distance from Mariner V to the center of the planet are too large; or (iii) the planetary radius is greater than 6056 kilometers.

On the basis of the 100°K difference between the microwave brightness temperature and the Venera 4 temperature measurement, the most probable explanation seems to be that the 20-kilometer gap is made up of an elevation difference of about 10 kilometers plus errors of several kilometers each in the quoted values of the above quantities.

Composition: Venera 4 results. Prior to the flights, the Venus atmosphere was considered to have an abundance of carbon dioxide, the concentration of this gas being at least a thousand times greater than the concentration of carbon dioxide in the atmosphere of Earth. The presence of carbon dioxide was revealed by absorption bands in the spectrum of sunlight reflected from the cloud tops of Venus and recorded by telescopes on Earth. Gas analyzers on the Venera 4 probe confirmed the abundance of carbon dioxide in the Venus atmosphere and indicated, furthermore, that it constituted 90 to 95 percent of the total atmosphere. The bulk of the remaining 5 to 10 percent presumably consisted of nitrogen, for which the Venera 4 gas analyzers indicated an upper limit of 7 percent. The next most probable component of the atmosphere is neon, which, although rare in Earth's atmosphere, has a high intrinsic abundance in the cosmic distribution of the elements.

The Venera 4 results on bulk composition were a surprise to many observers, the majority view having been that carbon dioxide constituted only a few percent of the Venus atmosphere.

Mariner V data on bulk composition. The Mariner V radio propagation experiment gives the variation of density with altitude. From the rate of

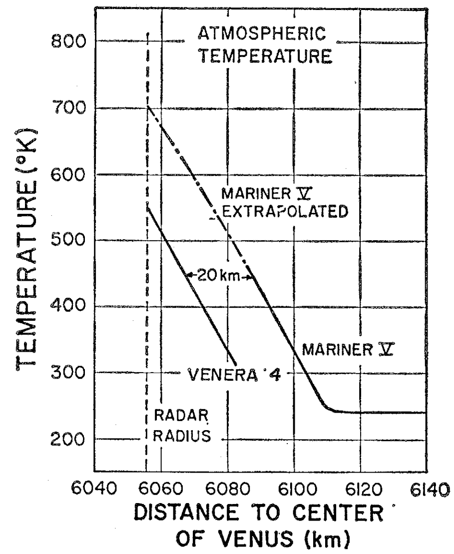

Fig. 4. Atmospheric temperature data from Venera 4 and Mariner V.

change of density with altitude, it is possible to deduce the ratio of temperature to average molecular weight of the gases composing the atmosphere. If the average molecular weight is known, the temperature and pressure profiles follow. The average molecular weight, which depends on the composition, is not known from the Mariner V data alone; however, an upper limit for the average molecular weight can be deduced from the Mariner V data by an indirect argument. The upper limit is 42, which corresponds to an atmosphere composed of 87 percent carbon dioxide, if the balance of the atmosphere is assumed to consist of nitrogen; or 92 percent carbon dioxide if the balance of the atmosphere consists of neon.

A considerable degree of uncertainty would remain in the interpretation of the Mariner V data on the lower atmospheres if no other information were available. However, as already noted, direct measurements of composition were carried out by the Venera 4, indicating that carbon dioxide constituted 90 to 95 percent of the atmosphere. Since a carbon dioxide concentration of 90 percent is both the lower limit of the Venera 4 data and the approximate upper limit of the results indirectly obtained from the Mariner V data, it seems reasonable to take 90 percent as the best carbon dioxide concentration yielded by the combination of the two sets of data. With this assumption, temperature and pressure profiles can be obtained from the Mariner V data. These profiles, shown in Figs. 3 and 4, have been used as the basis for the discussion of Mariner V data.

Differences in Composition between Earth and Venus

The measurement of the abundance of carbon dioxide on Venus is of great interest because it brings out the vast differences between the histories of Venus and Earth. Like most other gases in Earth's atmosphere, carbon dioxide probably came from the interior of the planet through fissures in the crust. Presumably, the carbon dioxide in the atmosphere of Venus also came from its interior. Presumably, also, it was emitted into the atmosphere at the same rate. Yet carbon dioxide is a thousand times less abundant on the Earth than on Venus. What is the explanation for the scarcity of this gas in our atmosphere?

The answer is believed to be that chemical reactions transform atmospheric carbon dioxide into carbonates that are subsequently deposited in the sedimentary rocks of the Earth's crust. Evidence for this assertion is found in the fact that the amount of carbon dioxide near the surface of Earth, in the form of carbonates in sedimentary rocks, is the same, within a factor of 2 or 3, as the amount of carbon which Venus contains in the carbon dioxide of its atmosphere.

The carbonates are formed partly by marine animals as a product of their metabolism, and partly by chemical reactions not involving living organisms. In the latter case, however, liquid water must be present; otherwise the reactions proceed very slowly. It is unlikely that a substantial amount of carbon dioxide would have been removed from the Venus atmosphere in the absence of life and liquid water on the planet.

Nitrogen. Gas analyzers carried on the Venera 4 spacecraft yielded an upper limit of 7 percent by volume for the abundance of nitrogen. Translated into absolute amounts, this upper limit on the percentage of nitrogen represents 1 or 2 atmospheres. If the abundance of nitrogen is close to the quoted upper limit, we conclude that the amount of nitrogen on Venus is approximately the same as the amount of nitrogen in the atmosphere of Earth. This result would be consistent with the premise that the two planets have similar interiors, and that their atmospheres have evolved similarly from components exhaled through the planetary crust.

Oxygen. Venera 4 sensors indicated an oxygen concentration greater than 0.4 and less than 1.6 percent, with a probable value of about 1 percent. According to reports at the Kitt Peak conference, spectroscopic evidence obtained with Earth-based telescopes indicates an oxygen concentration of no more than 0.001 percent. This discrepancy between Earth-based values and those of Venera 4 is unresolved at present.

The oxygen concentration obtained from the Venera 4 sensors, if translated into absolute amounts, is approximately the same as the amount of oxygen in the atmosphere of Earth. An oxygen concentration of this order of magnitude is puzzling, since oxygen in the Earth's atmosphere is produced by plant life, and plants seem to be excluded from most of the surface of Venus by the high temperature. Furthermore, oxygen is not exhaled to the atmosphere from the interior of Earth, and probably is not exhaled from the interior of Venus either, because it is very active chemically. All the iron in the interior of the planet, for example, would have to have been oxidized to its highest valence state if molecular oxygen were to be exhaled from the crust.

Water. The attempt to detect water on Venus was one of the most important experiments made on the Venera 4. The water concentration has a bearing on the nature of the Venus clouds and the possible existence of life on Venus. Prior to the flights, ground-based spectroscopic observations provided evidence for some water vapor in the atmosphere above the clouds, perhaps as much as is present in the Earth's atmosphere above the clouds; also, the clouds themselves were believed by some, although not by all observers, to be composed of liquid or frozen water droplets. The amount of water below the clouds of Venus was unknown, but it seemed possible that a substantial amount of water might exist on the surface or in the lower atmosphere.

This is the case on Earth, which contains an abundance of water on or near the surface, some of it in the atmosphere, but most—99.99 percent—in liquid form in the oceans.

It is believed that the water on the surface of Earth was originally trapped in the interior of the planet. This water was one of the substances in the cloud of gas and dust out of which Earth and other planets condensed 4.5 billion years ago when the solar system came into existence. During the course of the Earth's history, part of the water rose to the surface and escaped through cracks and fissures in the crust. This water slowly accumulated in the natural basins of the crust to make up the modern oceans.

According to current theories on the origin of the solar system, it is reasonable to assume that the materials out of which Venus was formed contained about as much water as the materials out of which Earth was formed. As in the case of Earth, the water within Venus should have risen to the surface during the past 4.5 billion years, and should now form a layer on the surface as deep as the layer of water on the surface of Earth.

The average thickness of Earth's oceans, if spread uniformly over the globe, would be 8000 feet (2.7 kilometers). Therefore, an amount of water equivalent to a thickness of several kilometers should be present on Venus. However, the layer of water should not be in liquid form on the surface; if present on Venus, it should be in the atmosphere in the form of water vapor, because of the high temperature of the Venus surface.

Prior to the flights of Venera 4 and Mariner V, there was indirect evidence against the presence of the equivalent of an ocean of water in vapor form in the Venus atmosphere. The evidence was based on radio-astronomical observations of the intensity of microwave emission from Venus. Water vapor is a strong absorber of microwaves at 1.35 centimeters, hence a small concentration of water vapor in the Venus atmosphere would produce a dip in the emission at that wavelength. No dip is discernible, from which it is deduced that at most about 20 grams per square centimeter of water vapor can exist in the atmosphere. This is about one ten-thousandth of the amount of water on the surface of Earth. Thus, the available evidence indicated that Venus is a dry planet in comparison to Earth.

Venera 4 Detection of Water

Venera 4 sensors obtained positive indication of the presence of water in the lower atmosphere below the cloud layers, and bracketed its concentration between 0.1 and 0.7 percent. The lower limit was set by a measurement of the change in electrical resistivity of phosphorus pentoxide, while the upper limit was set by observations of the change in partial pressure produced through absorption by calcium chloride.

The Venera 4 measurements support the indications that Venus is a relatively dry planet. The Venera 4 lower limit of

0.1 percent is approximately the same as the upper limit of 20 grams per square centimeter deduced from the microwave-emission data, hence 0.1 percent may be taken as the best value yielded by the combination of earth-bound and spacecraft observations. As already mentioned, this is 10^{-4} times less water than is present on the surface of Earth.

Why is water scarce on Venus? The most probable explanation is that solar ultraviolet radiation has extensively dissociated water molecules during the planet's history, liberating hydrogen, which, being too light a gas to be held by the gravitational attraction of the planet, has escaped. The same processes of dissociation and escape would have occurred on Earth, but at a much lower rate because of the following circumstances: The temperature of the Earth's atmosphere falls off with increasing altitude until it reaches a minimum of about 200°K at a height of 10 kilometers. At altitudes of 10 kilometers and higher, the vapor content of the atmosphere is limited to the saturated vapor density of water at 200°K, which is about 10^{-9} gram per cubic centimeter or one-thousandth of the average water vapor content near the ground.

In this way, the temperature minimum acts as a cold trap, condensing water vapor out of the atmosphere and effectively confining Earth's water to altitudes below 10 kilometers. However, solar ultraviolet radiation does not reach the 10-kilometer level. It is absorbed at higher altitudes by the dissociation of oxygen molecules in the Earth's atmosphere, and very little of it penetrates below 100 kilometers. Thus, the Earth's water is protected from the destructive effects of solar ultraviolet radiation by the combination of a cold trap in the stratosphere and a shielding layer of oxygen above.

The Venus stratosphere is also a cold trap, but a less effective one because it is warmer. According to Mariner V measurements, the temperature of the Venus stratosphere is about 240°K. The saturated density of water vapor at 240°K is 200 times greater than that at 200°K, hence the water vapor content at high altitudes, and therefore the rate of escape of water from the planet, should be greater on Venus than on Earth by approximately the same factor.

A factor of 200 is not enough to account for the dryness of Venus. The rate of escape of water from Venus must be about 10^6 times greater than on Earth, in order to remove the water as rapidly as it is released from the interior of the planet. However, this still larger escape rate might be realized if the shielding layer of oxygen were missing from the Venus upper atmosphere (*3*).

Since the Earth's abundance of atmospheric oxygen is the consequence of plant life, which is presumed to be rare or missing on Venus, it seems at first that the shielding layer of oxygen would, in fact, be absent from Venus. Unfortunately for this argument, the dissociation of water itself may provide enough oxygen to constitute a shielding layer, since this element remains behind as a product of the dissociation after the liberated hydrogen atoms have escaped. In this case, if Venus has lacked plant life throughout its history its rate of loss of water by dissociation may have been large for a brief period at the beginning of the planet's history, but would have tapered off later on, as the shield of oxygen built up. Thus, the reasons for the absence of water on Venus remain a mystery.

Nature of the Venus Clouds

If the water content of the Venus atmosphere is close to the upper limit quoted from the Venera 4 measurements, it is likely that the clouds on Venus are composed of water droplets. Assuming a water vapor mixing ratio of 0.7 percent, and comparing this concentration of water vapor at various altitudes with the saturated water vapor pressure corresponding to the Mariner V temperature profile, we find that the saturation level is reached at 250°K. The Mariner V temperature profile levels off to a nearly isothermal regime at approximately 240°K, which should mark the top of the convective layer, and, therefore, the top of the cloud layer. Since the temperature rises at the rate of 10°K per kilometer below the isothermal region, it may be concluded that the cloud layer is of the order of 1 kilometer in thickness. This statement rests on the assumption that the water vapor concentration is at the upper limit of the range quoted for the Venera 4 measurements. A cloud layer of this thickness is adequate to explain the visible appearance of the planet.

If the water vapor mixing ratio is 0.5 percent or less, the vapor pressure does not reach saturation level at any point in the lower atmosphere, and water clouds do not form. Since the combination of data from microwave brightness and from Venera 4 favors 0.1 percent for the water vapor concentration, the burden of the evidence seems to be against a water (or ice) composition for the Venus clouds.

References and Notes

1. The discussion in this section is based on calculations communicated privately by R. W. Stewart. Similar calculations were reported at the Kitt Peak conference by M. B. McElroy.
2. *Note added in proof*: Recent analyses yield an improved radius value of 6050 ± 5 kilometers [M. E. Ash, D. B. Campbell, R. B. Dyce, R. P. Ingalls, R. Jurgens, G. H. Pettengill, I. I. Shapiro, M. A. Slade, T. W. Thompson, *Science* **160**, 985 (1968); W. G. Melbourne, D. O. Muhleman, D. A. O'Handley, *ibid.*, p. 987].
3. S. I. Rasool, private communication.

Bibliography

Mariner 5 Results

C. W. Snyder, *Science* **158**, 1665 (1967).
H. S. Bridge, A. J. Lazarus, C. W. Snyder, E. J. Smith, L. Davis, P. J. Coleman, D. E. Jones, *ibid.*, p. 1669.
J. A. Van Allen, S. M. Krimgis, L. A. Frank, T. P. Armstrong, *ibid.*, p. 1673.
C. A. Barth, J. B. Pearce, K. K. Kelly, L. Wallace, W. G. Fastie, *ibid.*, p. 1675.
Mariner Stanford Group, *ibid.*, p. 1678.
A. Kliore, G. S. Levy, D. L. Cain, G. Fjeldbo, S. I. Rasool, *ibid.*, p. 1683.
J. D. Anderson, G. E. Pease, L. Efron, R. C. Tausworthe, *ibid.*, p. 1689.

Venera 4 Results

V. S. Avduevsky, M. Ya. Marov, M. K. Rozhdestvensky, "Model of the atmosphere of the planet Venus based on results of measurements made by the Soviet automatic interplanetary station Venera 4," *J. Atmos. Sci.*, in press.
A. D. Kuzmin and Yu. N. Vetukhnovskaya, "Venera 4 and the interpretation of the radio astronomical measurements of Venus," *ibid.*, in press.
V. M. Vakhmin, "A review of the Venera 4 flight and its scientific program," *ibid.*, in press.
A. P. Vinogradov, U. A. Surkov, C. P. Florensky, "The chemical composition of the Venus atmosphere based on the data of the interplanetary station Venera 4," *ibid.*, in press.