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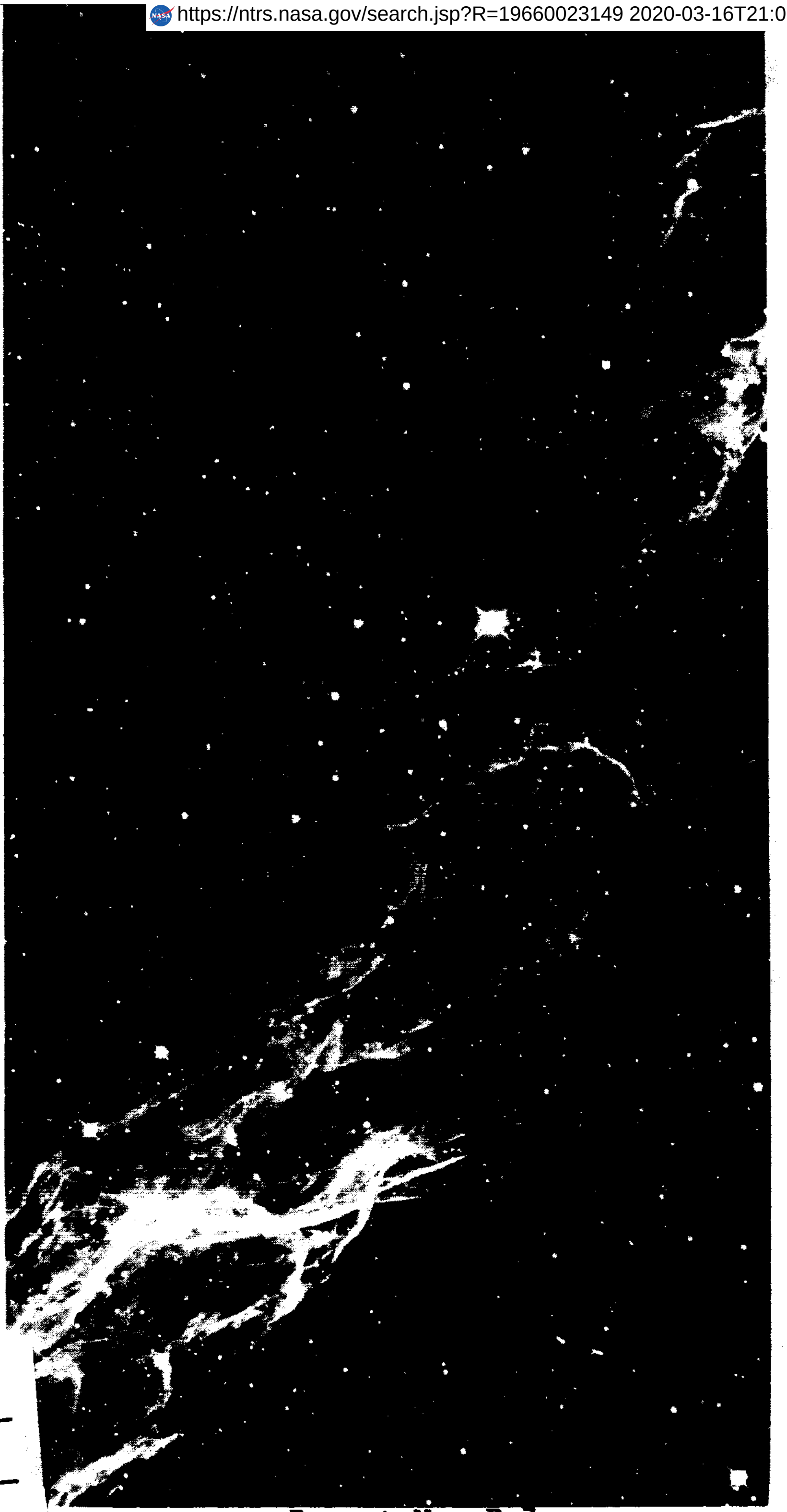

Report No. P-7

# SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS - VENUS

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# SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS - VENUS

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# SUMMARY

A review of our present knowledge of Venus suggests that it is a scientifically interesting planet for detailed exploration by space probes. The interest is due to a variety of reasons, but arises primarily because of the apparently totally different nature of its atmosphere as compared to those of Mars and Earth, our lack of understanding of the atmosphere and surface conditions, and the controversies due to conflicting data. No single area of study has yet been investigated completely, so that much additional data are required to complete our understanding of this planet.

A general description of Venus based on results of past investigations can be summarized briefly in the following statements. The planet is very similar to the Earth in mass, size, and density, so much so that it can be made to fit almost any theory for the interior structure of the Earth. It is widely held that Venus is chemically equivalent to the Earth, having a distinct iron-rich core with a central pressure of roughly one megabar. The surface seems to be at a temperature of ≈700°K, with a pressure exceeding 10 atm and possibly as high as 100 atm. Any liquid areas that do exist are probably small,

and may be expected to be turbulent oceans of hydrocarbons. $CO_2$ is the only atmospheric constituent whose identification is at present undisputed, but it apparently comprises less than 10 percent of the atmosphere. Disputed identifications have been made for $O_2$, $N_2$, $H_2O$, $H_2CO$, and CO. Negative results were obtained in searches for $N_2O$, $CH_4$, $C_2H_6$, and $NH_3$. The composition of the clouds is unknown; the most that can be said is that the upper portions consist of fine droplets or dust. If Venus has a magnetic dipole field, the dipole moment is less than 0.1 that of the Earth's. The existence of Venusian charged particle radiation belts is uncertain.

A detailed evaluation of this current knowledge indicates that answers must still be found for a great many questions. These answers are of importance beyond the additions they would provide to our present knowledge of Venus. In particular, studies of the very dense atmosphere may lead to a better understanding of the evolution of planetary atmospheres and planetary physics in general. Further, despite the apparently extreme surface conditions, Venus is still biologically interesting, since life forms may exist in suspension at various levels of the atmosphere and because of the possible existence of localized, highly elevated, cooler surface regions.

The measurements which are suggested for missions to Venus may be briefly categorized as follows:

1) Ultraviolet, infrared and radiometric observations for determination of atmospheric constituents,

atmospheric circulation, and planetary energy balance. Polarimetry may be incorporated for cloud layer studies.

2) Microwave radiometry to provide detailed thermal profiles and to establish accurate brightside and darkside temperature values.

3) Radar measurements to obtain detailed topographical information and to determine certain physical properties of the surface material.

4) Magnetometry and charged particle counting for a precise definition of the Venusian magnetosphere.

5) Direct lower atmosphere and surface measurements using an atmospheric entry probe. Included are atmospheric pressure, temperature and density, and surface composition determinations.

6) Biological experiments for detection of bio-molecules, life forms, or evidence of life in the past.

The following table summarizes the data expected from each suggested measurement and indicates the minimum suitable mission modes.

# PARTIAL LIST OF BASIC MEASUREMENTS FOR VENUS MISSION

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Atmosphere | Determination of species present in the atmosphere | UV and visible grating monochromator | Flyby or Orbiter |
| | Spatial distribution of these species in the atmosphere | | Orbiter |
| | Aurora and airglow observations | | Flyby or Orbiter |
| | Detection of ozone | | Flyby or Orbiter |
| | Spatial and temporal variations of atmospheric temperature and pressure | IR spectrometer | Orbiter |
| | Determination of $CO_2$ partial pressure | | Orbiter |
| | Determination of presence of $H_2O$ | | Flyby |
| | Thermal mapping of atmosphere | IR radiometer | Orbiter |
| | Accurate determination of planetary energy balance | | |
| | Identify possible atmospheric absorbers in the mm-wave region | Microwave radiometer | Flyby or Orbiter |

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Atmosphere (Cont'd) | Definition of cloud structure | TV cameras and multicolor photometers | Orbiter |
| | Detection of motion and turbulence in the atmosphere | | Orbiter |
| | Star occultation data to determine atmospheric mean molecular weight | | Orbiter |
| | Pressure, temperature variations and composition of the lower atmosphere | Aerodynamic-type sensors and light-absorption instrumentation | Atmospheric probe |
| | Optical thickness and polarizing properties of the lower atmosphere; fluxes of radiation as function of height | Zenith-pointed skylight analyzer | Atmospheric probe |
| | Atmospheric density and density gradients | Orbiter tracking of atmospheric probe | Atmospheric probe |
| | Identification of lower atmosphere constituents | Mass spectrometry | Atmospheric probe |
| | Detection of bio-molecules and life forms | Video microscope; gas chromatograph | Lander or atmospheric probe |
| Surface | Determination of surface features | Radar | Orbiter |
| | Improvement on accuracy of present temperature estimates and determination of thermal profiles | Microwave radiometer | Orbiter |

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Surface (Cont'd) | Visual identification description of surface conditions | TV camera | Lander or atmospheric probe |
| | Description of surface texture | Impactometer or penetrometer | Lander or atmospheric probe |
| Magnetic field | Measurement of the magnitude and configuration of the magnetic field | Rubidium vapor, helium vapor magnetometer | Flyby or Orbiter |
| | Determination of the magnetosphere | | Flyby or Orbiter |
| | Orientation of the magnetic equator | | Orbiter |
| | Determination of both short and long period variations in the planetary field | | Orbiter |
| | Detection of possible field variations due to surface features and anomalies | | Orbiter |
| Charged particles | Detailed study of particle energy spectrum, pitch-angle distribution, and time variations in any existing trapped radiation belts | Solid state detectors; shielded Geiger counters | Orbiter |

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# SCIENTIFIC OBJECTIVES OF DEEP SPACE INVESTIGATIONS - VENUS

## 1. INTRODUCTION

Venus, in some respects, is very similar to the Earth. It has about the same mass, volume, density, and surface gravity and has for these reasons often been considered a twin planet of the Earth. When one looks beyond these basic features, however, the similarity ends rather abruptly. Most observations have indicated a very different atmospheric composition and surface condition. In addition, many parameters are not clearly defined, since the very heavy Venusian cloud cover causes difficulties in the interpretation of certain data. Thus, one is faced with the double problem of establishing a model for a planetary environment which has unfamiliar characteristics and of reconciling conflicts arising from what otherwise appear to be reliable data.

In this report, significant data obtained in the past are reviewed and related to models for the planetary environment. The scientific objectives of space missions to Venus which would resolve present uncertainties and directly add to our understanding of the planet are then formulated. Section 2 tabulates the physical data and orbital elements, most of which are well known at the present time. Section 3 reviews the existing data and is divided according to observational technique for maximum clarity. Section 4 shows the manner in which these data can be used to construct models for the planetary environment and interior. Section 5 provides a summary list of basic scientific questions which missions to the planet should answer. Section 6 describes a set of measurements which are based on these questions and certain other uncertainties and gaps in our knowledge which are indicated throughout the report.

## 2. PHYSICAL DATA AND ORBITAL CHARACTERISTICS

The Venusian astronomical and orbital characteristics which are well known at the present time (Allen 1963, Moore 1957, Evans 1962, and Brereton 1965) are summarized in Table 1.

Several parameters require additional comments. First, the mass of Venus is not known quite as precisely as the mass of certain other planets, an error of $0.022 \times 10^{27}$ grams out of $4.869 \times 10^{27}$ grams being the commonly accepted uncertainty. The lack of satellites precludes any more accurate Earth-based mass measurements. Second, the diameter given in Table 1 refers to the visible disk, since the surface itself cannot be seen. The most precise measurements, obtained during the occultation of Regulus by Venus are within the range of ± 20 km. No observations have ever detected any polar flattening or planetary

## Table 1

## GENERAL DATA FOR VENUS

| | |
|---|---|
| Distance from the Sun | |
| Aphelion | $108.9 \times 10^6$ km |
| Perihelion | $107.5 \times 10^6$ km |
| Mean | $108 \times 10^6$ km<br>or 0.723 AU |
| Sidereal period | $224^d16^h48^m$ (.62 years) |
| Orbital eccentricity | 0.0068 |
| Orbital inclination | 3°24' |
| Mean synodic period | 583.92 days |
| Axial rotation period | 242.6 ± 0.6 days, retrograde |
| Diameter | .97 Earth (12,200 km) |
| Mass | 0.81 Earth ($4.85 \times 10^{27}$ grams) |
| Density | 0.89 Earth ( 5.15 g/cm$^3$) |
| Surface gravity | 0.85 Earth |
| Escape velocity | 10.2 km/sec |
| Albedo | 0.76 (at 5500 Å) |

oblateness. Third, in estimating the density value, the mass of the atmosphere is assumed insignificant compared to the mass of the entire planet. Finally, the axial rotation period is that based on data reported by Goldstein in 1966.

## 3. REVIEW OF EXISTING DATA

Very little is known with any certainty about Venus, in spite of the fact that numerous measurements have been made using a variety of methods and types of instrumentation. In order to provide for increased clarity, this section briefly reviews the existing data and is divided according to technique so as to best illustrate the relations between various past investigations. A brief summary of the available environmental information is given in Table 4 at the end of the section.

### 3.1 Visual and Photographic Observations

Telescopic studies of Venus fail to reveal any sharp, well-defined markings such as are evident on Mars or the moon. The disk is often entirely featureless; when markings are seen, they are invariably diffuse and obscure, so that their positions are difficult to establish with any accuracy. The more prominent of the features take the form of dusky shadings with indefinite boundaries. They are generally short-lived, as are certain bright patches observed from time to time. The best known bright areas are seen near the cusps of the planet. However, they also vary in position and visibility and attempts to detect some regularity in their appearance have not been successful.

Somewhat more distinct features were observed in ultraviolet photographs, but could not be interpreted in terms of any definite planetary features. Subsequent photography has also failed to reveal any essential information about the planet.

## 3.2 Photometry

An important planetary constant and one which is relatively easy to obtain is the albedo or reflectivity of the disk as a function of wavelength and phase angle. This quantity is useful in determining composition of clouds and surface, and in computations designed to determine the planetary heat balance.

Photometric investigations show that the reflectivity of Venus increases toward the red, in keeping with the visual observation that it has a definite yellow tint (Rea and Welch 1963). The source of increased absorption in the blue has been attributed to cloud particles rather than to gaseous components (Opik 1962). Several reasons for this argument are advanced. First, ultraviolet photographs show dark bands of such a nature that if absorption were due to gases, a most unnatural atmospheric circulation would be present, rising at the poles and descending at the equator. The second argument is the failure to detect absorption lines which one would expect if the absorption were due to rotation-vibration-electronic bands of the gas molecules. Finally photometry across the disk has been carried out for phase angles near 90° which shows brightening toward the limb. This analysis indicates the absorption is due to cloud material.

A value for the albedo of 0.76 (at 5500 Å)is the one normally quoted, with a variation between 0.55 and 0.90 from the visible through the photographic infrared.

## 3.3 Polarimetry

The original and one of the most extensive sets of polarization measurements of the planet Venus were made by Lyot (1929). Extensive laboratory experiments performed during the same period ruled out numerous possible interpretations for the Venus cloud cover, but there were some similarities of the observed curve with the polarization curve of water droplets. Many other possible explanations exist, however. An earlier idea that the clouds may not be water droplets or ice particles was strengthened by Kuiper's (1957) infrared measurements. He countered with the suggestion that carbon suboxide ($C_3O_2$) might well be the substance in the cloud layer. This substance easily forms in an atmosphere containing CO and $CO_2$ exposed to ultraviolet radiation. Also, the production of $C_3O_2$ provides a satisfactory explanation for the apparent low $CO_2$ abundance. However, it has never been detected spectroscopically and further, the occasional clearings noted by some observers (Urey 1959) indicate that the clouds might precipitate as rain or evaporate, and neither could be expected if they consisted of these resinous suboxides. Thus a unique solution based on present data is clearly difficult. Sagan and Pollack (1966) however, have recently proposed that ice crystals with mean radii of approximately 7.5μ are consistent with polarimetric observations. They have calculated the visible and near-infrared albedo for an atmosphere containing such crystals and claim agreement with the data of Strong and others.

## 3.4 Spectroscopy

With one or two possible exceptions, all of the numerous spectroscopic observations that have been made of Venus provide information concerning only the planet's upper atmosphere. The Venusian cloud cover along with the strong absorptions in the terrestrial atmosphere conceal most of the atmospheric content of Venus. Careful study and analysis of existing data, however, has led to identification of several atmospheric constituents and permits estimates to be made for certain other parameters of interest. The chief atmospheric constituent, on the other hand, has not yet been determined.

### 3.4.1 Composition

The first constituent of the Venusian atmosphere to be detected was carbon dioxide ($CO_2$), observed by Adams and Dunham (1932). After comparisons with laboratory data, Dunham estimated the amount of $CO_2$ above the cloud layer of Venus as 400 meter atmospheres. Adel and Slipher (1934), using low resolution plates of $CO_2$ laboratory data, estimated the Venusian content to be 3000m atm. This estimate is considered to be too high by most investigators, since a significant amount of succeeding work by Herzberg (1951, 1952), Kuiper (1952), and Kaplan (1961) has always yielded values which lie between 300 m atm and 1000m atm. Spinrad (1962a), however, in a very recent analysis, obtained an estimate of 2000m atm of $CO_2$ above the cloud layer. Differences here arise largely due to assumptions (in data interpretation) as to whether or not the $CO_2$ is mixed with the atmospheric light scattering material, or whether there is a $CO_2$ atmosphere lying above a sharp cloud deck. It is necessary to obtain some idea of the scattering coefficient and distribution with height of the particles producing the opacity before a more precise abundance can be determined. At present, the abundance is accepted as being between 100 and 1000 m-atm, with the lower values most widely held.

Considering this rather large amount of $CO_2$, one might expect to find at least some $O_2$ (Rea 1962). St John et al (1922) and Dunham (1952), however, have used the Doppler shift technique on the A band at 7600 Å and have detected no $O_2$, setting an upper limit of 80 m atm. Prokofjev and Petrova (1962), on the other hand, report a tentative identification of $O_2$ using this same technique. Additional investigations are obviously needed for confirmation in this instance.

Carbon monoxide (CO), if present on Venus, should produce absorption in its 2-0 band at 2.345μ. Sinton (1962) took a number of spectra covering this region and then made comparisons with laboratory spectra. While it appeared definite that something was absorbing at this wavelength, the shape of the band was in poor agreement with the laboratory spectra. Moroz (1965) obtained similar results, so that this should probably be classed as a possible identification, with further work needed for confirmation.

Kozyrev (1954) and Newkirk (1959) have reported a visible emission in the night sky due to $N_2^+$. The observations were tentative and were not confirmed by a more recent study of Weinberg and Newkirk (1961). Further work is thus required to allay doubts that these observations may be due to an instrumental or terrestrial sky effect (Rea 1962).

There also exists conflicting evidence concerning the quantity of $H_2O$ on Venus. Recent work by both Dollfus (1963) and Bottema, Plummer and Strong (1964) has indicated the presence of approximately 10-100μ of precipitable water vapor, with independent observations at 1.4μ and 1.13μ, respectively. Spinrad (1965), on the other hand, working at 8200 Å, has been unable to detect any water vapor and set an upper limit of roughly 10μ precipitable water. Since different spectral bands were used, it is possible that results are conflicting due to a strong wavelength dependence of the atmospheric opacity in the near infrared (Owen 1966).

An additional observation which should be mentioned was reported by Kozyrev (1961) for formaldyhyde, $H_2CO$. He observed a constant emission from the lower layers of the atmosphere and attributed it to chemiluminescence of $H_2CO$. This observation was not confirmed however, either by Newkirk (1961) or Spinrad (1962a), and so should be substantiated by other observers before receiving general acceptance.

Upper limits on several other gases have been set by Kuiper (1952) from spectra in the 1.5 to 2.2μ region. These are $N_2O$, 100 cm atm; $CH_4$, 20 cm atm; $C_2H_4$, 3 cm atm; $C_2H_6$, 1 cm atm; $NH_3$, 4 cm atm. An attempt to detect the $H_2$ quadrupole line at 8150 Å also failed, but that is not surprising since the minimum observable absorption would correspond to a path of about 12 km atm.

A brief summary of the results obtained by spectroscopic observations to date is given in Table 2.

### 3.4.2 Temperature and Pressure

The vibration-rotation bands of $CO_2$ in the near infrared have been widely used to infer a Venusian atmospheric temperature. Two possible ways to determine the $CO_2$ rotation temperatures are by the ordinary Boltzmann equation method, assuming a clear atmosphere, and by the procedure of Chamberlain and Kuiper (1956), where the light scattering particles are assumed to have the same distribution as the absorbing $CO_2$ molecules. In this latter case, the visible cloud layer would be regarded as the altitude at which the optical thickness due to scattering is about unity in the continuum outside the absorption bands in the visible.

In general, the rotational temperatures given by the usual application of the Boltzmann equation are higher than those derived with the modification. The most reliable estimates appear to range between 250 and 450°K (Spinrad 1962a). An important consideration, however, is that these rotational lines

Table 2

## SPECTRAL FEATURES ON VENUS

| Molecule | Wavelength | Comments |
|---|---|---|
| $C^{12}O_2$ | 7158 Å<br>7828<br>7891<br>8698<br>Numerous identifications between 1 and 10μ | Verified by many observers as being present at between 100 and 1000 m-atm. |
| $C^{13}O_2$ | 1.475μ | Identification of spectral features reported by several observers |
| $C^{12}O^{16}O^{18}$ | 2.15μ | Identification confirmed by several observers |
| $O_2$ | | Disputed identification. Abundance estimated as less than 80 m-atm. |
| $N_2$ | 4300 Å region | Reported emission in night sky, unconfirmed by later work. |
| $H_2O$ | 1.13μ<br>8200 Å | 100μ of precipitable water reported from 1.13μ observations. Conflicting negative results at 8200 Å set upper limit at 10μ. |
| $H_2CO$ | Visible region | Broad emission feature, not confirmed by subsequent work. |
| CO | 2.345μ | Tentative identification, further work needed for confirmation. |
| $N_2O$<br>$CH_4$<br>$C_2H_4$<br>$C_2H_6$<br>$NH_3$ | | Negative results obtained in searches for these molecules. |

probably absorb over a region with a large temperature gradient, as indicated by this large range of temperatures. The relative weighting of the high, cool gas and lower hotter layers varies with rotational quantum number. The effect is to make the rotational temperature an average quantity that applies directly to some unknown but intermediate level in the $CO_2$ absorbing region. Therefore even the highest values of T ($\simeq$ 450°K) are still integrated averages. This method, then, suggests that surface temperatures may be well over 500°K.

Spectroscopic pressure determinations have been made assuming the $CO_2$ absorption lines have the characteristic Lorentz shape, which is valid for the case where the absorption coefficient is governed predominantly by collisions. In this work $N_2$ is assumed to be the predominant atmospheric constituent, so that the atomic parameters are taken as characteristic of $CO_2$-$N_2$ collisions. Like the rotational temperatures, the Venus individual pressures are mean values integrated over the $CO_2$ absorbing layers. Depending on the quantum number of the rotational line used in the analysis, pressures between 1 and 6 atmospheres have been obtained. Subsequent refinements lead to a range of 2 to 5 atmospheres, corresponding to the temperature range of 250-450°K. Using a further approximation, Spinrad (1962a) estimates that the pressure at the bottom of the $CO_2$ absorbing layer is near 10 atmospheres, which is then taken as a lower limit for the Venusian surface pressure.

## 3.5 IR Radiometry

Radiometric work has been carried out by several investigators over a period of many years. The earlier work in the 8-13μ terrestrial atmospheric window has been reviewed by Pettit (1961) and Sinton (1961a). This work showed several important features. First, the temperature at the sub-Earth point was found to be approximately 240°K, nearly independent of phase. Second, limb darkening exists and very nearly obeys a $\cos^{1/2} \theta$ law. Third, the temperature at the poles is some 20°K less than at the equator, where a line joining the poles is taken as approximately perpendicular to the orbital plane.

More recently, Murray et al. (1963) used an interference filter with the 200 in. telescope and, because of the improved sensitivity, made use of a diaphragm only 1/30 the diameter of the disk. An interesting result of this work is the 215°K temperature for the center of the disk, considerably lower than previous results and lower than calculated radiation temperatures, which were in good agreement. This discrepancy has not been directly resolved; additional measurements in other parts of the spectrum, however, have seemingly verified the older data. Sinton (1962) observed an emission at 3.75μ which corresponded to a temperature of 236°K. Also, of course, the radiometer measurements from the Mariner flyby in 1963 are in agreement with the older data. Observations in two channels, 8.1 - 8.7μ and 10.2 - 10.5μ, gave temperatures which were on the order of 240°K at the center of the disk. A definite limb-darkening was observed, the radiation temperatures showing a monotonic decrease of approximately 20°K between the central region and the limbs.

Since both the 8 and 10μ temperatures were the same, it has been assumed that there was little $CO_2$ absorption in the light path, and that the measured temperatures were cloud temperatures. The light and darkside temperatures were qualitatively the same. One anomaly was noted in the southern part of the terminator scan, which was about 10°K cooler than expected on the basis of symmetrical limb-darkening. The clouds were here perhaps locally higher or more opaque, or the effect may be associated with a large surface feature.

### 3.6 Microwave Radiometry

Venus, near inferior conjunction, subtends a larger angular diameter than any other planet. Its radiation is thus relatively easily detected and it was therefore the first planet from which microwave emission was measured. These first observations, made by Mayer et al. (1963), revealed an effective disk temperature of 595° ± 55°K at a wavelength of 3.15 cm, a most surprising result in the light of the much lower infrared temperature of the planet. Subsequent observations verified these findings, showing a disk temperature rising from ~ 350°K at 4 mm to a value near 600°K for wavelengths from 3 cm to 21 cm.

A rather large number of observations were made during the 1962 conjunction and data were obtained over an increased wavelength range. Table 3 incorporates some of these results along with certain other data to show representative temperature values for the entire wavelength range which has thus far been investigated. Further results are also available for most of the wavelengths given; for simplicity, however, only the reference providing the mean value of the temperature is listed. In addition to these data, of course, the microwave radiometers aboard Mariner II provided for high-resolution scanning of the disk. The spacecraft contained a two-channel microwave radiometer operating at wavelengths of 13.5 and 19 mm. Data obtained indicate a brightness temperature of some 450°K, with little or no change between the dark and light side values. Limb darkening was clearly apparent, and is a very strong indication that the emission (and high temperature) is characteristic of the planetary surface or very deep atmosphere.

While the latter is not surprising, the equality of light and dark side temperatures does not seem to agree with interpretations of ground-based measurements. In a detailed study of phase effect and limb-darkening, Pollack and Sagan (1965) concluded that there should be a difference of some 200°K in the brightside and darkside temperature. This disagreement bears on the problem of determining the heating of a slowly rotating planet both by direct insolation and by radiative and convective transport from the atmosphere. Of course, atmospheric absorption at wavelengths near 1 cm is possible, which would tend to reduce the difference between brightside and darkside temperatures.

Table 3

## VENUS MICROWAVE BRIGHTNESS TEMPERATURES

(mean values for each wavelength)

| | | | |
|---|---|---|---|
| 3.2 mm | 300° | $^{+57^\circ}_{-27^\circ}$ | Tolbert and Straiton (1962) |
| 4.3 mm | 350° | $^{+50^\circ}_{-30^\circ}$ | Grant, Corbett and Gibson (1963) |
| 8 mm | 374° | ± 75° | Kuz'min and Salomonovich (1963) |
| 8.35 mm | 395° | ± 60° | Thornton and Welch (1964) |
| 8.5 mm | 380° | $^{+72^\circ}_{-34^\circ}$ | Lynn, Meeks and Sohigian (1964) |
| 8.6 mm | 375° | ± 52° | Tolbert and Straiton (1964) |
| 1.18 cm | 395° | $^{+75^\circ}_{-55^\circ}$ | Staelin, Barrett and Kusse (1964) |
| 1.35 cm | 520° | ± 40° | Gibson and Corbett (1963) |
| 2.07 cm | 500° | ± 70° | McCullough and Boland (1964) |
| 3.15 cm | 616° | ± 40° | Haddock and Dickel (1964) |
| 10 cm | 622° | ± 6° | Drake (1964) |
| 21 cm | 595° | ± 6° | Davies (1964) |
| 21.4 cm | 528° | ± 33° | Drake (1964) |
| 40 cm | 400° | ± 60° | Drake (1964) |

## 3.7 Radar Reflectivity

The first radar contact with Venus was reported by the Lincoln Laboratory at the time of the 1958 inferior conjunction (Price et al. 1959) at 68 cm. Since that time, many other groups have carried on work in this area on a rather continuing basis, providing new data on the value of the astronomical unit, the Venusian rotation rate, surface features or roughness, and to a lesser extent the ionospheric structure.

Before the advent of radar astronomy techniques, it was generally felt that the astronomical unit was known to within some 96,000 km, an uncertainty much too large for planetary exploration. Since 1961, however, data from Lincoln Labs, Jodrell Bank, and the Goldstone facility have reduced this uncertainty to a much more acceptable value. Thompson et al. (1961) at Jodrell Bank, using a 73 cm signal, obtained a value for the astronomical unit of 149,599,755 km, with a radio albedo larger than the moon's. The MIT observers (Millstone staff 1961), at 68 cm, obtained a value of 149,597,700 km for the astronomical unit (within 1500 km). Operating at a wavelength of 12.6 cm with a more sensitive system, the Goldstone experimenters (Victor et al. 1961 and Goldstein et al. 1963) obtained a value of 149,599,000 ± 1500 km. This refinement of the astronomical unit represents an important step in terms of future space missions.

A very good estimate for the Venusian rotation period was also obtained during the 1962 conjunction from a study conducted over a two month period. If a large surface feature is present on the planet that scatters more energy back to the radar than surrounding areas, it will show up as an irregularity on the spectrum. On close examination, such an irregularity was found to persist from day to day and to slowly change its position. The relative permanence suggests that it is caused by a surface feature and that its motion was the result of the planet's rotation. If it is assumed that the axis of Venus is perpendicular to its orbit, then the measured angular velocity corresponded to a sidereal rotation period of 1200 days forward or 230 (+40, -50) days retrograde (Carpenter 1964).

A second and independent method of measuring the rotation period is by observing the broadening of the returned radar signal. Since the broadening is due to both the Venusian orbital motion and rotational motion about its own axis, and since the orbital motion is well known, a careful analysis of the difference in width between the transmitted and received signals can yield a magnitude and direction for the rotational period. These data provide a 250 day retrograde period for Venus and, in addition, suggest that the coordinates of the axis of Venus are 119° right ascension and -78° declination (Goldstein 1964). A comparison of 1964 data (Carpenter 1966) with the features observed in 1962 suggests that the rotation of Venus may be nearer to 244 days retrograde rather than the 250 days given by the earlier base bandwidth measurements.

This has been confirmed by recent measurements reported by Goldstein (1966) from which a rotation rate of 242.6 ± 0.6 days was obtained. The coordinates of the axis of rotation were found to be 98° ± 5° right ascension and -69 ± 2° declination. These observations are also reported to reveal "conspicuous topographic prominences on the surface of Venus".

Further analysis of these and additional data can provide a rather preliminary concept for the Venusian surface. Muhleman (1963), in analyzing the observed echo power at 12.5 cm and 68 cm, found an average dielectric constant for the surface material between 3 and 7, with no large upward variations. This low value, along with the absence of measurable variations, was interpreted as an indication that there are no large bodies of water on the Venusian surface.

Comparisons of the polarization of the transmitted and received signals can also be used to deduce certain characteristics of the reflecting body. The Goldstone polarization data (Victor et al. 1961) have been interpreted to suggest that the roughness of the Venus surface is similar to that of the moon, but with a dielectric constant of nearly 3.6. Other data suggest a rough surface also, but don't provide any quantitative information. The only conclusion that can be drawn then is that the dielectric constant is probably less than 7, consistent with dry terrestrial soils and there is an absence of large bodies of water.

Possible Venusian ionospheric effects were also noted during the 68 cm observations at the 1961 conjunction (Muhleman 1963). On the basis of a correlation between radar echo characteristics and solar activity an electron density at Venus of the order of $10^7/\text{cm}^3$ was inferred, corresponding to a plasma frequency of about 27 Mc/sec. Interpretations such as this, however, are difficult because of the presence and effect of the solar plasma.

### 3.8 Magnetometry

Magnetometer data, obtained as Mariner II passed Venus, gave no evidence of a Venusian field at any point on the trajectory. The sensitivity of the magnetometer was such that a field change of about 4 gamma on any axis would have been detected. During encounter, a slow change no larger than about 10 gamma was observed. This change, however, did not have the character of a planetary field (Smith et al. 1963) and was attributed to a temporal change in the interplanetary magnetic field. The continuous fluctuations with periods from 1 to 60 seconds and amplitudes of the order of 3 gammas that seem characteristic of regions near the geomagnetic field were not observed. Simultaneous measurements by other Mariner experiments also failed to reveal any effect associated with a planetary field, such as trapped particles or a modification in the flow of solar plasma.

Table 4

## SUMMARY OF INFORMATION ON VENUSIAN ENVIRONMENT

| Observational Technique | Remarks |
|---|---|
| 1. Visual & photographic observations | Banded features appear in ultraviolet. Rather faint patterns are sometimes seen at subsolar point in yellow light. Vague, varying features noted in infrared. Surface cannot be seen optically because of extensive cloud cover. |
| 2. Photometry | Albedo is between 0.5 and 0.9 dependent upon wavelength. Occultation of Regulus gives atmospheric scale height of 6.8 km. Pressure at occultation level is $\approx 2.5 \times 10^{-3}$ mb. |
| 3. Polarimetry | Cloud top pressure on sunlit side is 0.1 to 1 atm. Clouds are composed partially of particles in micron size range. Water droplets and ice crystals give approximate, but not detailed, agreement with observed polarization curves. |
| 4. Spectroscopy | 7820 Å band of $CO_2$ shows, with some uncertainties, (P,T) values ranging from (1 atm, 210°K) to (5.6 atm, 430°K). Estimated amount of $CO_2$ is 2 to 10%; remainder of atmosphere unidentified. Spectroscopic searches for water vapor inconclusive. Unsuccessful searches for $N_2O$, $CH_4$, $C_2H_4$, $C_2H_6$ and $NH_3$. Disputed identification of CO, $O_2$ and ice crystals. |

Table 4 (Cont'd)

| Observational Technique | Remarks |
|---|---|
| 5. IR radiometry | Radiation temperatures are approximately 240°K for both bright and dark sides at 3.75$\mu$ and 8-13$\mu$. Distinct limb-darkening of 20-30°K. Thermal maps have shown at least one isolated cold feature. |
| 6. Microwave radiometry | Temperatures from 0.8 to 10.3 cm vary from 315 to 600°K at inferior conjunction. Strong evidence exists for limb darkening and hence surface origin of emission. Mariner data yielded temperatures of 460, 570 and 406°K for darkside, terminator, and brightside, respectively. |
| 7. Radar | Reflectivity near inferior conjunction at wavelengths of 12.5, 43, and 68 km is 0.10. A retrograde sidereal rotation of 242 days is estimated. The rotational axis appears to be within 10° of the orbit pole. |
| 8. Magnetometry | Magnetometer data from Mariner II gave no evidence of a Venusian magnetic field. The planetary dipole moment is less than 1/10, or perhaps even 1/20, that of the Earth. |

These results do not necessarily mean the absence of a magnetic field, but if one does exist, it does not extend out to the 41,000 kilometer distance of closest Mariner approach.

## 4. SUMMARY OF EXISTING KNOWLEDGE

### 4.1 Atmosphere

During recent years, and particularly since the discovery of clouds in the Venusian atmosphere, a number of attempts have been made to construct models of the Venusian atmosphere which would interpret the observed data. Ideally, such a model should be self-consistent and physically reasonable, and must explain all observations. While this has not yet been achieved, it has become possible to discard some previously held hypotheses and to recognize, to a degree, which characteristics are more likely to be verified by future detailed experiments.

One of these model atmospheres, much discussed during recent years, is the aelosphere model proposed by Opik (1961) as a possible mechanism for the maintenance of the observed microwave temperatures of $\approx 600°K$. It is suggested in this case that the atmosphere below the clouds is an extremely dry, dusty region kept in motion and stirred by the winds above the clouds, resulting in a strong frictional interaction at the surface. The winds transfer momentum downward, and since an atmosphere that is stirred will maintain an adiabatic lapse rate, the temperature will increase with increasing depth below the clouds. The winds cause a perpetual dust storm. The dust particles, perhaps made of calcium and magnesium carbonates, have been ground together and are extremely fine, remaining suspended almost indefinitely. At the surface there is no sunlight, only dust and heat and wind.

Many additional details of this model have been worked out, but it is sufficient to simply say here that the model has several inherent difficulties. Circulation features (Sagan et al. 1961) were never well described and it has not been demonstrated that the momentum transport necessary to heat the surface is feasible. In particular, the model is inconsistent with the observed phase effect in the microwave emission. This microwave phase effect renders the model implausible by the following inconsistencies: (a) the surface is unheated by sunlight and yet the brightside temperature appears higher than that of the darkside and (b) the heat source is located beneath the cloud cover, but the lowest temperatures are observed at inferior conjunction, which is when such a heat source should be most apparent.

The ionosphere model (Jones 1961 and Priester et al. 1966) was proposed as a means of providing a nonthermal source for the observed microwave emissions. The model is based on an argument that the Venusian ionosphere is highly ionized and contains a large number of free electrons, so that it is opaque to long radio waves and transparent to shorter (infrared) waves. The high microwave temperatures are attributed to free-free electron transitions so that a moderate surface temperature of about 300°K might then be acceptable.

It is, however, becoming increasingly difficult to reconcile this model with observed data. First, Spinrad's analysis of the $CO_2$ 7820 Å band showed temperatures of approximately 440°K and pressures of nearly 10 atmospheres, presumably in the lower atmosphere. Extrapolation of these data, coupled with other measurements, results in very high surface temperatures and pressures, in complete disagreement with various details of the ionospheric model. An even more serious objection can be offered in the light of Mariner II's microwave data. If the high temperatures originate in the ionosphere, limb-brightening should have been observed as the planet was scanned. Instead, however, a definite limb darkening was observed, which supports the contention that the high temperatures exist at the surface. In addition, Mariner II indicated that the solar wind flux in the region of Venus was too low to sustain the electron density required for the ionospheric model.

What appears to remain then as the most plausible concept of the atmosphere at the present time is a modification of the greenhouse model, which was first proposed by Sagan (1960). At that time, Sagan assumed that some visible solar radiation penetrates the cloud cover and strikes the surface, which upon being heated radiates in the infrared. The infrared radiation is then trapped in the lower atmosphere because of molecular absorption and light scattering at the cloud cover. The required opacity for this model cannot be due to $CO_2$ alone, but if 10 $gm/cm^2$ of water vapor is assumed, the necessary infrared opaque conditions are achieved. Such an amount of water, mixed thru the atmosphere, would result in ice crystal clouds at a temperature of some 235°K, roughly that observed by studying the far infrared radiation. This is interpreted as an ice crystal layer at an altitude of about 35 km. Near infrared spectrophotometry by Sinton (1961b) shows absorption features attributed to ice at this same temperature level from which the far infrared thermocouple radiation arises.

In addition to this work, Strong's balloon observations indicated that the required amount of water vapor existed above the cloud layer. The ice crystals and water vapor may well provide for the greenhouse effect. The ice crystals would also explain an otherwise unidentified emission at 10$\mu$ (Kaplan 1961) and account for the observed Venusian albedo. The temperature differences observed between the dark and light sides at some wavelengths can be explained, at least in part, by condensing clouds. For example, observed changes in the intensity of 8 mm radiation with phase might be the result of a cloud layer which appears opaque at millimeter wavelengths and transparent at centimeter wavelengths and either condenses or sublimes.

Some difficulties with this model arose, however, when Spinrad's (1962b) data indicated that the amount of water vapor in the atmosphere is insufficient to maintain the greenhouse effect. Either it had to be assumed that pressure broadened absorption lines and induced dipole absorption in $CO_2$ can increase the opacity to the necessary level, or modifications to the model were required.

Several other incongruities also indicate that modifications are necessary. It is not known, for example, if the steep temperature gradient between surface and clouds could be maintained, since vertical and horizontal mixing should tend to equalize the temperature. Estimates by Opik (1961) indicate the greenhouse effect cannot support high surface temperatures, since radiation both to and from the surface is so impeded by the atmosphere that the mechanism cannot operate effectively. Also there is no direct spectroscopic data on the required long paths, high temperatures, and moderately high pressures. Recent observations, however, indicate that there is a phase variation in which the surface temperature difference between the dark and light sides is at least 70°K (Drake 1963). Interpretation of this fact produced a second greenhouse model (Owen 1965), some of the essential features of which are given in Table 5. Under the conditions mentioned here, it is assumed that an insignificant amount of water vapor exists in the lower atmosphere. The high temperatures and pressures would provide the necessary opacity by thermal

Table 5

## PARAMETERS FOR VENUSIAN ATMOSPHERIC MODEL

| Parameter | Minimum | Maximum | Most Probable (Owen 1965) |
|---|---|---|---|
| Surface temperature (darkside) | 540°K (near pole) | 640°K | 610-640°K |
| Surface temperature (lightside) | 700°K | 800°K | 750°K |
| Temperature at cloud level | -- | -- | 235°K |
| Albedo (λ5500 Å) | 0.6 | 0.76 | 0.76 |
| Cloud altitude | 60 km | 100 km | 80 km |
| Surface pressure | 30 atm | 100 atm | 50 atm |
| Cloud top pressure | 90 mb (darkside) | 600 mb (lightside) | -- |

excitement of low-lying rotational states, pressure broadening of line contours, pressure induced dipole transitions and perhaps volatilization of surface material.

## 4.2 Planetary Interior and Surface

The variation in the mean densities of the terrestrial planets is sometimes taken as an argument for the inhomogeneity of this part of the solar system. MacDonald (1962) and Urey (1952) agree that these planets differ both in abundances of heavy elements and radioactive elements, so that they are chemically distinct. Others, including Ramsey (1948), Bullen (1957), and Levin (1964) have maintained that the terrestrial planets have the same composition, and that the cores are composed of a high-density state of silicates. Thus the two opinions regarding the interiors of terrestrial planets have been (1) if the Earth's core is chemically distinct from the mantle, the terrestrial planets cannot all have the same composition, and (2) if the terrestrial planets all have the same general composition, their cores result from pressure phenomena and are not chemically distinct.

Recent work by Kovach and Anderson (1965), however, indicates that it is possible to construct models for Venus and Mars that are identical in composition to the Earth without violating the hypothesis of a chemically distinct, i.e., iron-rich, core. These latter authors investigated the same planetary models which were used in previous studies, but which were modified to be in accord with more recent data on the moment of inertia of the Earth and with free oscillation and shock wave data. The change from low-density surface material to mantle material and the change to an inner core were assumed to be pressure controlled, although inclusion of a chemically distinct crust and inner core is not critical for any of the principal conclusions. For the case of Venus, a coefficient of thermal expansion of $4 \times 10^{-5}/°K$ was used in view of its assumed high surface temperature. This temperature correction is small, amounting to a 1.6% increase in the effective mean density for Venus.

If the ratio of core mass to planetary mass is taken as 0.3, the mass of Venus gives an external radius of 6100 km. The actual radius of the Venusian solid surface is not known; however, computed models for Venus which have cores containing 30 to 32% of the total planetary mass are entirely compatible with all observational data. In fact, the planet appears so similar to the Earth that it can be made to fit almost any theory that accounts for the Earth. It thus seems most reasonable to assume at present that Venus is chemically equivalent to the Earth, having a distinct iron-rich core with a central pressure of roughly one megabar.

The Venusian temperatures cause no problem within such a model, although they do suggest a most dreary surface condition. Since the melting points of aluminum, lead, tin, magnesium, zinc, etc. may be reached, pools of molten metal could possibly cover portions of the surface. The high pressures may produce low-lying clouds of unusual materials that would ordinarily be gases at such temperatures. The temperature of the dark pole has been estimated by Drake to be about 540°K, so that with the high surface pressures several constituents of the lower atmosphere may condense out in that region. Thus seas containing such things as liquid benzene, liquid acids, and, if the pressure exceeds some 60 atmospheres, possibly some small amounts of liquid water may exist.

Any liquid areas that do exist are probably small in size, however, since Muhleman found the dielectric constant of the Venus surface to be $3 < \epsilon < 7$, values characteristic of very dry terrestrial soil. In particular, $\epsilon$ is too small to permit extensive smooth oceans of water and too large to permit extensive smooth oceans of hydrocarbons. Turbulent water oceans and uncommon liquid hydrocarbons are not excluded on this basis, however, nor are combinations of $H_2O$ and hydrocarbons, such as might exist if oil were floating in patches on water.

### 4.3 Magnetosphere

For several hours in December 1962, the Mariner II fluxgate magnetometer measured magnetic fields in the vicinity of Venus, to within a distance of 41,000 km at the point of closest approach. The encounter occurred during relatively quiet conditions in the interplanetary medium (Kern and Vestine 1963), so that no abnormal compression of the magnetosphere of Venus could be expected. Neither the magnetometer nor the radiation counters aboard gave any evidence that the vehicle penetrated into a region of a planetary magnetic field, nor is there evidence that it passed through a hydromagnetic shock wave such as exists in front of the Earth's magnetosphere.

These negative results permit an estimate of an upper limit for the magnetic dipole moment of Venus. Theoretical models of the interaction of the solar wind with a dipole magnetic field, including a crude estimate of the extent of the disturbed region outside the magnetosphere, indicate that the dipole moment of Venus, if it is approximately perpendicular to the Sun-Venus line, is less than 1/10 that of the Earth. Comparison of the measurements made near Venus with those made by other spacecraft near the Earth leads to the conclusion that the dipole moment of Venus is less than 1/10, or even 1/20, that of the Earth (Smith et al. 1963). If the dipole moment of Venus is the dominant contribution to the field, the magnitude of the surface field is less than 5 to 10% of the geomagnetic surface field. Of course, if Venus has a more complicated magnetic structure than the Earth, so that higher-order multipoles are important, the surface field in places could be larger than the Earth's field without increasing the strength of the field along the Mariner trajectory to an observable value.

The above conclusions are consistent with the expectations based on the dynamo theory of the Earth's field

(Smith et al. 1965). Although no detailed theory is available, the rotation of the planet is usually assumed to be an essential feature. Since Venus apparently has a much slower rotation, it is plausible that it may have a much smaller magnetic moment than that of the Earth. In fact, on this basis, the Venusian field ($M_V$) would be much less than one percent of the Earth's field ($M_E$). If it had been found that the two fields were approximately equal, it would then appear that the magnetic moment is insensitive to rotation rate or that the core of Venus has properties very different from those of the Earth.

If the Venusian field is about 0.1 times the Earth's field, the cosmic-ray flux everywhere above the atmosphere of Venus will be similar to that above the polar regions of the Earth. If it turns out that the Venusian field is substantially smaller than this, particles of much lower energy could reach the atmosphere, but this is not considered too important since the flux of cosmic particles drops off rapidly with energy. Of course, the cosmic-ray intensity at the surface of Venus is probably much less than at the Earth's surface due to the increased atmospheric absorption produced by the much greater atmospheric mass per unit area.

A high-energy radiation zone similar to the Earth's is also possible under the present assumptions, but it may well have a much different structure and energy density. The energy density of trapped particles cannot exceed the energy density of the planetary magnetic field, which would be at most $10^{-2}$ that of the Earth. If $M_V$ is reduced much below 0.1 $M_E$, there will be correspondingly less possibility of trapping particles in the correspondingly small magnetosphere. However, $M_V$ would have to be reduced to about $M_E/750$ before the magnetopause would be lowered to the top of the atmosphere. For smaller $M_V$, the solar wind and interplanetary field could interact directly with the atmosphere. This would not be expected to have any significance except at the very highest levels of the atmosphere.

## 4.4 Biology

A likely pattern of molecular evolution on Venus is based on the assumption that the environments of Earth and Venus were very similar at the time of their origin, since the values of their present density and mass are nearly the same. The position of Venus results in a slower planetary cooling process and approximately twice the flux of ultraviolet radiation on the upper atmosphere. With an enhanced rate of photodissociation of water in the upper atmosphere and a somewhat lower escape velocity for hydrogen, Venus would lose water at a greater rate than Earth. Further, larger amounts of carbon would appear as atmospheric carbon dioxide instead of carbonaceous rock. The excessive water loss tends to sustain higher temperatures in view of the lack of evaporative cooling from surface oceans.

Such processes, even though they by now may have resulted in complete desolation, would have allowed for a wide range of possibilities for biotic evolution. These include the evolution of advanced forms of anaerobic (non-oxygen consuming) life unknown to man, thermal forms capable of subsisting on the hot surface, and microenvironmental biota resembling terrestrial forms which could survive in the atmosphere. In spite of the unity of biochemistry seen in terrestrial biotic evolution, the diversity of environmental conditions capable of supporting life is startling. In spite of the enrichment of the terrestrial atmosphere with oxygen, the persistence of anaerobic microbial forms is apparent on the Earth. The opportunity for the evolution of advanced anaerobic forms may well have been present on Venus. The higher temperatures either would drive the planet to an arid condition, or promote the rapid evolution of carbonaceous biotic forms unique to the particular planetary environment.

## 5. BASIC SCIENTIFIC QUESTIONS

The following is a list of important scientific questions, some of which have been raised by past experiments and all of which bear directly on the establishment of consistent models for Venus and its environment.

1. What is the chief constituent of the atmosphere?
2. Are important minor constituents, such as $H_2O$ and $O_2$, present and what is their concentration?
3. What is the constitution of the cloud layer?

4. What is the depth of the atmosphere?
5. What is the variation of pressure and temperature in the lower atmosphere?
6. What are the circulation patterns in the atmosphere?
7. Is there evidence of life in the past? Do life or pre-life forms now exist?
8. What are the correct mass and moments of inertia of Venus?
9. What is the topography and constitution of the Venusian surface?
10. What is the value of the surface pressure?
11. What is the difference between the brightside and darkside surface temperatures and what are their correct values?
12. What is the significance of the southern hemisphere cold spot as observed by Mariner II?
13. What is the strength of the magnetic field?
14. Is there a trapped radiation belt?
15. Do any atmospheric effects exist which may contribute to the observed radio emissions?
16. Do ionospheric and auroral phenomena exist?
17. What is the nature of the Venusian interior? If a distinct core exist, what is its composition?

## 6. BASIC MEASUREMENTS

It is difficult to find any major area of investigation with regard to Venus which has been studied exhaustively. Thus a significant amount of additional information is required before our knowledge of this planet can be considered much more than speculative.

The experiments selected for Mariner '67 are designed to measure certain properties of the Venusian atmosphere as well as to check for the existence of radiation belts and a magnetic field. If successful, the flight will improve our present estimates for temperature and density in the upper atmosphere, determine the energy of trapped radiation (if any), and either lower our present upper limit for the magnetic field or actually determine the field strength. Much, however, will still remain to be learned about the upper atmosphere and environment and virtually all parameters associated with the lower atmosphere and surface will still have to be determined. Thus it is meaningful to plan for additional space missions.

The following suggestions are concerned with classes of experiments which are felt to be needed for future Venus exploration. Some of the data may be provided by Mariner '67 but it is difficult to judge at this time to what extent this will be true.

It may be noted that many of the classes of measurements given here are discussed in the recent Space Science Board Study (1965) as those in need of support during the next ten years. In the present case, however, the concepts have been carried one step further, resulting in specific experimental recommendations wherever possible. In other instances, the use of recent data has led to a modification of certain previous suggestions.

## 6.1 Ultraviolet Spectrometry

This instrumentation will permit the determination of the composition and pressure of the Venusian atmosphere by analysis of the spectrum in the 1000 Å to 5000 Å region with at least a 10 Å resolution. A scanning monochromator could provide the continuum and absorption spectral features from the dayside scans and emission features (airglow and aurora) from nightside scans.

An important consideration here is the determination of the hydrogen distribution in the atmosphere, which could be obtained by scanning the planet at 1216 Å. the Lyman-$\alpha$ wavelength. Such data would be most helpful in answering questions on the rate of escape of the atmosphere and the development of the atmosphere into its present state. A set of measurements in the 2000-3000 Å ozone band system is equally important, since the ozone content can be related to the concentration of atmospheric oxygen and certain oxides. At least qualitative results for other atmospheric constituents (particularly nitrogen) might also be obtained in the search throughout the above-mentioned spectral region.

Finally, detection of aurorae could provide valuable information on atmospheric composition, the planetary magnetic field, and the existence of trapped radiation.

## 6.2 Infrared Spectrometry

While much additional IR spectroscopy remains to be done from the Earth's surface, it is also true that measurements from a space probe will provide the increased spatial resolution necessary to permit detailed atmospheric structure determinations. Monitoring several $CO_2$ bands from an orbiter would ultimately yield spatial and temporal variations for temperature, pressure, and $CO_2$ partial pressure which would be most useful in defining atmospheric conditions. A search for $H_2O$ bands should also be conducted with this instrumentation.

## 6.3 Radar

Some measure of the distance of the spacecraft from the planet is needed in order to make the results of certain other experiments meaningful. In addition, an altimeter would provide valuable data on surface features in general, the existence of mountains in particular, and the possibility of oceans. While these latter features should be partially observable from Earth-based radar, detailed surface resolution requires a Venus orbiter.

### 6.4 Infrared Radiometry

A radiometer aboard an orbiter can be used to provide improved spatial resolution of the radiation from the atmosphere. This is essential if the planetary energy balance is to be accurately determined. In addition, air mass temperature distributions and atmospheric circulations can be detected along with a determination of how complete the cloud cover is over most of the planet.

### 6.5 Microwave Radiometry

A microwave experiment would improve on the accuracy of the present temperature estimate, provide for detailed thermal profiles and clearly distinguish between brightside and darkside temperature values. These determinations are necessary if a theoretical model is to be uniquely fitted to experimental data.

Further, mm-wave radiometry, made difficult by terrestrial atmospheric absorption, could be pursued with the possibility of determining unidentified atmospheric absorbers which may be responsible for the lower temperatures in this wavelength region. It might be learned if dusts, aerosols, etc. are present or if certain gases exist in sufficient quantity to cause absorption in this region.

## 6.6 Occultation

Two types of occultation experiments might readily be performed. The first of these is a measurement of the changes in the spacecraft radio signal resulting from attenuation by the Venusian atmosphere. These data can be related to the density of the atmosphere.

The second type of observation is represented by the case when a star is occulted by the planet. The parallel rays of the star are refracted by the density gradient in the planet's atmosphere, resulting in a divergence which is well-defined theoretically. Such measurements could be used to provide data on the atmospheric mean molecular weight, as they were in the case of the Regulus occultation observed from Earth.

## 6.7 Polarimetry

The intensity of sunlight reflected from each point on a planetary disk is the sum of the light reflected from the surface (or cloud decks), light scattered by the molecules of the atmosphere (Rayleigh scattering), and the light scattered by particles of dust or thin clouds (Mie scattering). By carefully mapping the intensity of the light from various parts of the disk at several wavelengths, and also by measuring the polarization, it is possible to theoretically fit a model of the clouds and atmosphere, including such things as ice or dust content.

In the same way, important data can be obtained from scanning the terminator, or twilight zone. The exact way in which fading from the sunlit to the darkened hemisphere takes place depends upon light scattering in the atmosphere, which is determined by the depth and density distribution and by dust or high clouds. Observations of this region may provide a way of separating the effects due to dust or clouds and permit tentative identification of these constituents. The polarimeter could well be incorporated in the UV and visible spectrometer.

## 6.8 Photography (TV camera)

Since meteorological subjects, such as cloud structure and motion, are of interest to the study of Venus, photoimaging should be considered to provide much higher resolution and more detailed pictures than can be obtained from Earth. Multispectral viewing could be used in attempting to distinguish features in the cloud cover.

## 6.9 Trapped Particle Counting

Any orbiter or flyby mission that approaches a distance of one planetary radius from Venus should include instrumentation to identify and determine the spatial and energy distribution of any trapped radiation in the vicinity of Venus. This can provide information concerning the magnetic moment of Venus and the relation between solar phenomena and magnetic storms.

## 6.10 Magnetometry

The data obtained from the Mariner II magnetometer experiments revealed general information on the interplanetary medium and established an upper bound for the magnetic moment of Venus. It is now clear that a considerable advantage would be gained if a much reduced miss distance (5000 km or less) could be achieved. Such a close approach, to within about one planetary radius, could significantly reduce the upper limit of the magnetic field which might remain undetected. Further, in passing on the darkside, the spacecraft would very likely pass through the magnetic tail region, where interesting variations in the field strength might well be observed.

## 6.11 Pressure, Temperature, and Composition Determinations in Lower Atmosphere

The pressure and temperature variations should be established as functions of height in the lower atmosphere. Instrumentation used here would also provide data at the surface if it survived the landing. The atmospheric density may either be derived from other measurements made during descent, or from a backscatter experiment using a radioactive source.

Quantitative data regarding the lower atmosphere composition is also of great importance to a number of planetary considerations. This information might be obtained by means of a mass spectrograph or by observing the absorption of sunlight at specific wavelengths as a probe descends through the atmosphere. Substances such as A, $CO_2$, $H_2O$, $N_2$, $O_2$ and $O_3$ should be considered initially.

### 6.12 Determinations of Surface Conditions

A succession of low-resolution TV pictures taken downward during probe descent may identify the landing place, give some information on wind drift, and provide information on the detailed surface conditions in the landing area. It is not yet certain whether this would be completely practical below the Venusian cloud deck.

A penetrometer or impact accelerometer should also be included to distinguish between rock-like surfaces, softer soils, or liquids. Simple devices have been suggested which provide signals as the capsule is being deformed and crushed upon impact.

### 6.13 Biology

One of the most convincing life detection techniques would consist of video telescope and video microscope observations. A Surveyor-type camera with variable focal length could be adapted for this purpose. The "abbreviated microscope" such as that developed at Stanford University could be used in searching for bacteria, fungi, algae, protozoans, pollen grains, bacterial spores, etc.

Gas chromatography and mass spectrometry can be utilized to search for molecules of biological interest. Various amino acids and carbohydrates have been detected using these techniques. Optical rotation and fluorescence techniques could provide for the detection of biopolymers and their building blocks.

### 6.14 Summary of Measurements

In reviewing the basic measurements, it may be noted that there is no one mission mode that can be considered to the complete exclusion of the others. Because of the dense, opaque atmosphere, it is necessary to plan for the use of an atmospheric probe or lander if much direct evidence is to be gained of surface conditions and lower atmosphere composition. An orbiter, on the other hand, is equally important since such topics as planetary energy balance, structure of the upper atmosphere, exospheric temperature, magnetosphere, etc. must still be studied.

For convenience, the type of data expected from each measurement is listed in Table 6 along with the minimum mission mode required to make the measurement.

Table 6

## PARTIAL LIST OF BASIC MEASUREMENTS FOR VENUS MISSION

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Atmosphere | Determination of species present in the atmosphere | UV and visible grating monochromator | Flyby or Orbiter |
| | Spatial distribution of these species in the atmosphere | | Orbiter |
| | Aurora and airglow observations | | Flyby or Orbiter |
| | Detection of ozone | | Flyby or Orbiter |
| | Spatial and temporal variations of atmospheric temperature and pressure | IR spectrometer | Orbiter |
| | Determination of $CO_2$ partial pressure | | Orbiter |
| | Determination of presence of $H_2O$ | | Flyby |
| | Thermal mapping of atmosphere | IR radiometer | Orbiter |
| | Accurate determination of planetary energy balance | | |
| | Identify possible atmospheric absorbers in the mm-wave region | Microwave radiometer | Flyby or Orbiter |

Table 6 (Cont'd)

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Atmosphere (Cont'd) | Definition of cloud structure | TV cameras and multicolor photometers | Orbiter |
| | Detection of motion and turbulence in the atmosphere | | Orbiter |
| | Star occultation data to determine atmospheric mean molecular weight | | Orbiter |
| | Pressure, temperature variations and composition of the lower atmosphere | Aerodynamic-type sensors and light-absorption instrumentation | Atmospheric probe |
| | Optical thickness and polarizing properties of the lower atmosphere; fluxes of radiation as function of height | Zenith-pointed skylight analyzer | Atmospheric probe |
| | Atmospheric density and density gradients | Orbiter tracking of atmospheric probe | Atmospheric probe |
| | Identification of lower atmosphere constituents | Mass spectrometry | Atmospheric probe |
| | Detection of bio-molecules and life forms | Video microscope; gas chromatograph | Lander or atmospheric probe |
| Surface | Determination of surface features | Radar | Orbiter |
| | Improvement on accuracy of present temperature estimates and determination of thermal profiles | Microwave radiometer | Orbiter |

## Table 6 (Cont'd)

| Category | Type of Data | Instrumentation | Mission Mode |
|---|---|---|---|
| Surface (Cont'd) | Visual identification description of surface conditions | TV camera | Lander or atmospheric probe |
| | Description of surface texture | Impactometer or penetrometer | Lander or atmospheric probe |
| Magnetic field | Measurement of the magnitude and configuration of the magnetic field | Rubidium vapor, helium vapor magnetometer | Flyby or Orbiter |
| | Determination of the magnetosphere | | Flyby or Orbiter |
| | Orientation of the magnetic equator | | Orbiter |
| | Determination of both short and long period variations in the planetary field | | Orbiter |
| | Detection of possible field variations due to surface features and anomalies | | Orbiter |
| Charged particles | Detailed study of particle energy spectrum, pitch-angle distribution, and time variations in any existing trapped radiation belts | Solid state detectors; shielded Geiger counters | Orbiter |

# REFERENCES

Adams, W. L. and Dunham, T. 1932, Pub. Astron. Soc. Pacific, 44, 243.

Adel, A. and Slipher, V. M. 1934, Phys. Rev. 46, 240.

Allen, C. W. 1963, "Astrophysical Quantities," U. of London, Athlone Press.

Bottema, M., Plummer, W. and Strong, J. 1964, Ap. J. 139, 1021.

Brereton, R. G. 1965, JPL Engineering Planning Document No. 328.

Bullen, K. E. 1957, M. N. Roy. Astron. Soc. Geophys. Suppl. 7, 271.

Carpenter, R. L. 1964, Astron. J. 69, 2.

Carpenter, R. L. 1966, Astron. J. 71, 142.

Chamberlain, J. W. and Kuiper, G. P., 1956, Ap. J. 124, 399.

Davies, R. D. 1964, Paper presented at the Intern. Astron..Union, XIIth Assembly, Hamburg.

de Vaucouleurs, G. and Menzel, D. H. 1960, Nature, 88, 28.

Dollfus, A. 1963, Compt. Rend. 256, 3250.

Drake, F. D. 1963, NRL Report No. 5937.

Drake. F. D. 1964, Astron. J. 69, 62.

Dunham, R. 1952, "The Atmospheres of the Earth and Planets," ed. by G. Kuiper, U. of Chicago Press.

Evans, D. C. 1962, Douglas Aircraft Co. Rept. No. SM-41506.

Gibson, J. E. and Corbett, H. H. 1963, ONR Report No. 5937, Washington, D. C.

## REFERENCES (Cont'd)

Goldstein, R. N. 1964, Astron. J. 69, 12.

Goldstein, R. N. 1966, Seventh International Space Symposium (COSPAR).

Goldstein, R. N. and Carpenter, R. L. 1963, Science, 139, 910.

Grant, C. R., Corbett, H. H. and Gibson, J. E. 1963, Ap. J. 137, 620.

Haddock, F. T. and Dickel, J. R. 1964, private communication.

Herzberg, G. 1951, J. Roy. Astro. Soc. Can. 45, 100.

Herzberg, G. 1952, Ap. J. 115, 337.

Jones, D. E. 1961, Planetary and Space Sci., 5, 166.

Kaplan, L. D. 1961, Planetary and Space Sci., 8, 23.

Kern, J. W. and Vestine, E. H. 1963, Space Science Reviews, 2, 136.

Kovach, R L. and Anderson, D. L. 1965, Journal Geophys. Res. 70, 2873.

Kozyrev, N. A. 1954, Izv. Krym. Astr. Obs. 12, 169.

Kozyrev, N. A. 1961, Pravda, July 15.

Kuiper, G. P. 1952, "Atmospheres of the Earth and Planets," U. of Chicago Press.

Kuiper, G. P. 1957, The Threshold of Space (ed. by M. Zelikoff) Pergamon Press, London.

Kuzmin, A. D. and Salomonovich, A. E. 1963, Soviet Astron. A. J. 6, 518.

Kellogg, W. W. and Sagan, C. 1961, "The Atmospheres of Mars and Venus, NAS-NRC Publ. 944.

## REFERENCES (Cont'd)

Levin, B. J. 1964, Icarus 3, 498.

Lynn, V. L., Meeks, M. L. and Sohigian, M. D. 1964, Astron. J. 69, 65.

Lyot, B. 1929, Ann. Meudon 8, Part 1.

MacDonald, J.G.F. 1962, J. Geophys. Res. 67, 2945.

Mayer, C. H., McCullough, T. P. and Sloanaker, R.M. 1963, Proc. Intern. Astrophys. Colloq. 11th, Liege, Belgium.

McCullough, T. P. and Boland, J. W. 1964, Astron. J. 69, 68.

Millstone staff, 1961, Nature, 190, 592.

Moore, P. 1957, "The Planet Venus", The MacMillan Co. New York.

Moroz, V. I. 1965, Soviet Astronomy, 8, 566.

Muhleman, D. O. 1963, Icarus, 1, 401.

Murray, B. C., Wildey, R. L. and Westphal, J. A. 1963, J. of Geophys. Res. 68, 4813.

Newkirk, G. A. 1959, Planet. Space Sci., 1, 32.

Newkirk, G. A. 1961, private communication.

Opik, E. J. 1961, J. Geophys. Res., 66, 2807.

Opik, E. J. 1962, Prog. Astronautical Sciences, Vol. 1, Chap. VI.

Owen, R. B. 1965, NASA Report TN D-2527.

Owen, T. C. 1966, private communication.

Pettit, E. 1961, Planets and Satellites, Chap. 10.

Pollack, J. B. and Sagan, C. 1965, Icarus, 4, 62.

# REFERENCES (Cont'd)

Price, R. et al. 1959, Science, 129, 751.

Priester, W., Roemer, M. and Schmidt-Kaber, T. 1962, Nature, 196, 464.

Prokofjev, V. K. and Petrova, N. N. 1962, Mem. Soc. Roy. Sci. Liege, July, p. 311.

Ramsey, W. H. 1948, M. N. Roy. Astron. Soc. 108, 406.

Rea, D. G. 1962, Space Science Reviews, 1, 159.

Rea, D. G. and Welch, J. W. 1963, Space Science Reviews, 2, 558.

Sagan, C. 1962, in "Space Age Astronomy" Academic Press, New York, p. 430.

Sagan, C. and Pollack, J. B. 1966, Seventh International Space Science Symposium (COSPAR).

Sagan, C., Siegel, K. M. and Jones, D. E. 1961, Astron. J. Vol. 61.

Sagan, C, 1960, Jet Propulsion Laboratory Tech. Report 32-34.

St. John, C. E. and Nicholson, S. B. 1922, Ap. J. 56, 380.

Sinton, W. M. 1961a, Planets and Satellites, Chap. 11.

Sinton, W. M. 1961b, Conference on Physics of the Solar Systems and Reentry Dynamics, Virginia Polytechnic Institute, Aug. 31.

Smith, E. J., Davis, L., Coleman, P. J. and Sonett, C. O. 1963, Science, 139, 909.

Smith, E. J., Davis, L., Coleman, P. J., and Sonett, C. P. 1965, J. Geophys. Res. 70, 1571.

Space Science Board, 1965, Space Research-Directions for the Future (Part I).

# REFERENCES (Cont'd)

Spinrad, H. 1962a, Publ. Astron. Soc. Pacific, 74, 187.

Spinrad, H. 1962b, JPL Report No. 32-256.

Spinrad, H. 1965, private communication.

Staelin, D. H., Barrett, A. H. and Kusso, B. R. 1964, Astron. J. 69, 69.

Thompson, J. H. et al. 1961, Nature, 190, 519.

Thornton, D. D. and Welch, W. J. 1964, Astron. J. 69, 71.

Tolbert, C. W. and Straiton, A. W. 1962, J. Geophys. Res. 67, 1741.

Tolbert, C. W. and Straiton, A. W. 1964, Nature, 204, 1242.

Urey, H. C. 1952, The Planets, Their Origin and Development, Yale University Press, New Haven.

Van de Hulst, H. C. 1957, Light Scattering by Small Particles, John Wiley and Sons, Inc., New York.

Victor, W. K. and Stevens, R. 1961, Science, 134, 46.

Weinberg, J. L. and Newkirk, G. 1961, Planet. and Space Sci., 5, 163.