VENUS THROUGH A SPECTROSCOPE

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INTRODUCTION

Venus is the earth's twin in size, with a comparable density of 4.9. I shall speak only on the spectroscopic observations and the closely related techniques of analysis of the radiation coming from our sister planet. I shall, of course, endeavor to avoid topics such as the radar investigations which have been considered by my colleagues. I shall enter into some detail, only in the case of the new techniques which might possibly, some day, provide information on the possibility of detecting extraterrestrial life. Optical work on the planetary atmospheres added to the space experiments such as those on board the American Mariners and the Russian space probes will eventually lead us to definite data on life or the absence of it on the other planets. The discovery of life or remnants of life would of course be a scientific event of the greatest importance.

While the space vehicles such as Mariner 5 and Venera 4 provide a real breakthrough there is nevertheless no doubt that many observations from the earth may bring substantial contributions.

Apart from a few exceptional important observatories such as Harvard, Lowell and Pic du Midi which always retained great interest in planetary observations, the solar system was rather neglected during the first half of the twentieth century. But the situation changed radically a decade ago with the launching of the first sputnik.

I have no competence either to discuss the techniques envisaged to search for life on other planets or even to formulate an operational definition of life. The oxygen that we breathe is classified as an "inorganic" chemical; yet it is essential to life.

Wonderful spectroscopic work has been performed in recent months on the trace components of the atmosphere of Venus, down to a few parts per billion of the main component (CO_2); I shall give some detail on these investigations.

In the earth's atmosphere we find as rare components, methane (1.5 p.p.m.), hydrogen (0.5 p.p.m.), carbon monoxide (0.05 p.p.m.) and traces of nitrous oxide and complex hydrocarbons. We shall see that the Venus atmosphere contains traces of hydrogen chloride and hydrogen fluoride as well as carbon monoxide, but the abundant element is carbon dioxide, in great contrast with the earth. Despite the great differences between the atmospheres of the earth and Venus, comparisons of the chemical and physical processes, based on the spectroscopic observations and leading to discussions on their evolutions, are of great help. In particular it is very fruitful to examine the possible relations between the terrestrial and venusian meterology, as was done by F. S. Johnson in his review of the second Tucson conference. This applies in particular to the discussions on the tropospheric lapse rate and on the differences between the bright and dark sides of the tropopause.

The spectroscopic observations are still incomplete; for example there is still a great need of additional "local" spectra, such as those of the polar and equatorial regions as well as of the regions which appear dark in the ultraviolet.

The spectroscopic investigations provide the material on which to base our understanding of the physical state of the planets. Both the expensive space explorations and the relatively inexpensive observations from the earth are essential to a logical program of planetary investigations.

One of the most striking mysteries of Venus, her rotation period, was recently solved by radar observations made by teams of the Massachusetts Institute of Technology, California Institute of Technology (Caltech), and the U.S.S.R. This rotation is retrograde with a sidereal period of 243.09 days, the pole lying within 3° of the orbital pole. This topic is covered in other reports in the present symposium.

For 200 years the astronomers have had observational evidence that Venus possesses an atmosphere. Indeed the presence of a thick atmosphere, coupled with the similarity in size and density, has long led to the common belief that Venus may have followed an evolution similar to that of the earth, culminating in the existence of life. When the planet is near inferior conjunction the illuminated hemisphere appears as a thin crescent which has often been observed to exceed 180°. Indeed the horns appear sometimes to extend much more than half around the disk. When Venus lies nearly in the line between the earth and the sun a circular ring of light can be seen around the whole disk. This phenomenon is due to the deep atmosphere which deflects the sunlight around the edges of the disk by scattering and refraction.

The transits of Venus have been observed four times in 243 years. The next one will take place thirty-five years from now, on 8 June, 2004. The first description of a transit dates from 1639; the black body was clearly projected on the sun's disk. Two centuries ago, in 1761, Edmund Halley used the transit of Venus for determination of the solar parallax. At the time of entry of Venus on the sun's disk, as soon as about 70 per cent of the planet's body is in front of the sun the remaining fraction is completely outlined by a narrow border of light.

The occultations of stars by Venus provide very reliable data on the density of the upper atmosphere of the planet. The most interesting investigation in this field has been performed by Professor Donald H. Menzel in collaboration with Dr. G. de Vaucouleurs when Regulus was occulted by Venus on July 9, 1959. Indeed this observation provided the first reliable data on the density of the atmosphere of Venus. It is most gratifying that this excellently organized observational campaign gave results which were confirmed by several investigators in recent years. Indeed the occultation results obtained by Professor Menzel provided a wonderful opportunity to discuss current models of the Venus atmosphere. The density found in 1959 was 6×10^{13} cm.$^{-3}$ at a radial distance of 6,169 ± 2 km. In a recent paper by Donald M. Hunten and Michael B. McElroy entitled "The Upper Atmosphere of Venus: The Regulus Occultation Reconsidered," the results of the occultation have been compared in great detail with the most recent models of the Venus atmosphere.

Despite the fact that Venus was known to have a thick atmosphere no characteristic absorption band was found spectroscopically before 1932, in contradistinction with the major planets. The two best pioneering observers of the second half of the last century, Sir William Huggins in London and Father Secchi in Rome, who had no difficulty in seeing dark bands (due to CH_4 and NH_3),[1] in the spectra of the major planets could not see any absorption feature in Venus. In his George Darwin Lecture of 1933 on "Spectrographic Studies of the Planets" the remarkable observer V. M. Slipher, of the Lowell Observatory, mentioned that he could not discover any absorption band in his photographs of the spectrum of Venus. The reason for this failure is simple; there is no absorption band in the blue-violet region of Venus, and Slipher used a prism spectrograph having too low a resolution in the red region on account of the low sensitivity of his photographic emulsions.

Actually, prior to 1926 the visual observations and the photographs in the blue to the red region did not reveal any feature on the surface of the planet. It was only in 1926 that F. E. Ross, at the Mount Wilson Observatory, succeeded in obtaining photographs revealing distinct features on the disk of Venus. These photographs were taken in the ultraviolet, to everyone's surprise, because ultraviolet light is markedly useless for photographing clouds on the earth.[2] Ross's photographs showed that the hazy dark patches changed from day to day; they were assumed to be clouds floating in the sky of Venus, not permanent features of the planet's surface. I believe that I have found an explanation for the dark clouds. Indeed the "darkness" of certain regions is possibly due to the presence of the absorption bands of CO_2^+ (see Appendix).

The rotation period (if there is any!) of these clouds is still controversial. Several rotation periods have been suggested but are not convincing; they differ greatly from the rotation period of the surface found by radar.

The dark and light spots change so rapidly that they cannot be studied at a single station, but require an international collaboration. Such a cooperative venture between eight or ten observatories was organized by the International Astronomical Union and was very successful. For example, 300 good photographs were taken between

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[1] The assignment of the absorption bands of the major planets was made only in 1932 by R. Wildt in Göttingen. In Uranus the bands are so strong that they are seen all the way from the red to the blue region.

[2] Photographs taken in the near infrared were unsuccessful for registering details, notwithstanding the well-known haze-penetrating power in the infrared.

March 16 and August 1, 1962. Many series of photographs cover the evolution of the clouds over several days, with intervals of only a few hours. This collaboration continues. Very good photographs have been obtained recently, especially by G. H. Herbig in 1962 with the 120-inch telescope of the Lick Observatory. Actually useful observations have been made with instruments as small as a 25-cm. telescope in Brazzaville. The 107-cm. instrument of the Pic du Midi has been of very great help. Series of observations by H. Camichel and C. Boyer from 1953 onward (including daylight ultraviolet observations) have been collected under the auspices of Commission 16 of the International Astronomical Union.

Until 1932 all the spectrographic information on Venus was of a negative nature. It was demonstrated at Mount Wilson that the sunlight reflected from Venus passes through less than the equivalent of one meter of oxygen at sea-level pressure. Water vapor above the clouds of Venus amounts to less than 10^{-1} of that in our atmosphere. We shall discuss these amounts of O_2 and H_2O later on.

In 1932 Walter S. Adams and Theodore Dunham, Jr., found strong absorption bands on high dispersion spectrograms of Venus taken in the red and near infrared region with the 100-inch telescope on Mount Wilson. On the other hand Adams and Dunham were unable to find lines of oxygen and water vapor on account of the very strong lines of these molecules due to telluric absorption. The measurement and classification of the rotational structure of the newly observed absorption bands, which had never been found in the laboratory, indicated that the responsible molecule was probably CO_2. To check this possibility Dunham filled a 20-meter tube with CO_2 compressed to 10 atmospheres. The coincidences were perfect and demonstrated that the Venus atmosphere contains an enormous amount of CO_2, much greater than that of the earth. A considerable part of the present report will be devoted to the role of CO_2.

In the study of the absorption bands of Venus, advantage was taken of the Doppler shift due to radial velocity, and of the recurrence of cloud patterns, essentially for two purposes: to obtain, if possible the rotation period, and especially to separate the venusian lines of molecules such as H_2O and O_2 from the strong telluric lines due to the same compounds. The search for a rotation period by use of the Doppler effect was very disappointing. One may indeed expect the atmospheric features to have a rotation period different from the solid planet, for example on account of prevailing winds, but astronomers have been disconcerted by how large the difference has turned out to be. The cloud patterns tend to recur after 4 or 5 days, as was shown by several French observers and by a team at New Mexico State University. Guinot in Paris used a Fabry-Perot interferometer and found a retrograde rotation of period 4.1 ± 0.7 days for the atmospheric level to which his measurements refer. A comparison of the radial velocities at opposite sides of the visible disk was tried as long ago as 1903 by V. M. Slipher, who found a practically null value for the rotation effects; on the other hand Belopolsky in Pulkovo found "distinct evidence" of rotation!

At the time of near elongation the radial velocity effect is greatest and has been applied by various astronomers to a search for H_2O and O_2. We shall return to this problem later on.

Other optical techniques of great importance are polarimetry, radiometry and photometry or rather colorimetry with narrow filters. Polarization measurements of great precision were first performed by Bernard Lyot, then by his pupil, Audoin Dollfus. Recent work has been carried out by T. Gehrels, who used six colored filters and made measurements at phase angles from 28° to 120°. Like Lyot, Gehrels found that the particles of the clouds have diameters of the order of a few microns. Deirmendjian claims that the particles are dielectrics, plus some absorption and finds diameters around 1 μ. Monochromatic phase curves and albedos have been measured photoelectrically by W. M. Irvine in ten narrow bands between 3,150 Å and 1.06 μ. His interference filters had half widths between 50 and 200 Å. He also covered the standard U-B-V bands. The spectral reflectivity is strongly dependent on λ and phase angle. The albedos are determined as functions of λ. This three-year program of multicolor photoelectric photometry under the direction of the Harvard College Observatory was conducted at the Boyden Station in South Africa.

The absolute spectrum of Venus from 2.8 to 14 μ has been determined at the Lunar Planetary Laboratory with a resolution of approximately 50. The germanium bolometer was cooled to 2° K. The results agree with independent photometric work carried out at Caltech by Professor Murray and his collaborators in the window from 8 to 14 μ. On the other hand these results do not agree with earlier work by Sinton and Strong, who found a somewhat higher surface brightness. A few puzzles remain outstanding, namely what property of the clouds causes the low brightness temperature between 8 and 10 μ; what mechanism accounts for the strong absorption of sunlight in the 3 to 5 μ region?[3]

Thanks to rockets the spectrum of Venus has been extended toward the ultraviolet, as we shall see later, but only a beginning has been accomplished in the ultraviolet region below λ 3,000. Much more information in the ultraviolet is required to discuss the possibilities of Raman diffusion of solar L_α by CO_2 (no quantitative estimate has been made as yet but the probability seems low), and of fluorescence. One may hope to obtain more detailed spectra once orbiting telescopes become available.

It should be clear, however, that while interplanetary probes like Mariner 5 and Venera 4 have led to a real breakthrough in our knowledge of Venus[4] many observing techniques using the traditional telescopes or other instruments such as radar and radio lead to extremely important discoveries. As was stressed by the panel on planetary astronomy of the National Academy of Sciences' Space Science Board, there is a great need for ground-based planetary astronomy, especially in the Southern Hemisphere. The panel on planetary astronomy recommended observations from sites of superior seeing such as those now being developed in the mountains of Northern Chile. Recent observations in the infrared region, which we shall describe later on, revealed the great potentialities of this spectral domain for studying planetary atmospheres, especially from an arid, high-level site where the water vapor absorption is considerably reduced. High mountain sites such as the Jungfraujoch, and Görnergrat in Switzerland, and Mauna Kea in Hawaii may also be advantageous. These astronomical installations are inexpensive, compared to space probes; both are really needed. For the infrared, specialized telescopes of relatively low cost may be constructed. A 1,000-inch telescope devoted to infrared studies and collecting as much flux as possible may cost less than a single fly-by mission to Venus. There is at present a lack of telescopes specialized in infrared studies. Yet we know that the 60-inch infrared collector at Caltech has led to exciting discoveries. A 4-meter infrared collector is being planned in France, while a 60-inch infrared telescope is being designed by the Hull University group for observing at their Testa Grigia station. The ultimate goal of several astronomers is the installation of an infrared 1,000-inch collector: a field of tremendous importance would thus be open. These endeavors should be coupled with observations from aircraft and from high-altitude balloons.

Great progress in planetary astronomy has been made recently with traditional telescopes on the ground, thanks to gratings of higher efficiency and resolution, to Fabry-Perot interferometers, and especially to Michelson interferometers with Fourier transform.

The extension of the sensitivity of photographic emulsions (going now to 1.4 μ) has been coupled with the availability of gratings which are efficient in any selected region. Excellent high-dispersion (5.4 Å/mm.) spectrograms of Venus in the region near 1 μ have been obtained with the Struve Memorial Telescope of McDonald Observatory by L. D. Gray and R. A. Schorn. They correspond to three phase angles (26°, 111° and 116°), and give a rotational temperature of 200–250° K. with little variation with phase. New detectors of greater sensitivity are being adapted to infrared spectroscopy, advantage being taken of the atmospheric windows or the reduced infrared absorption on high mountains, in aircraft or on balloons.[5] The image tubes and electron cameras prove most useful in the near infrared.

The Fabry-Perot interferometer is able to give very high resolution but covers a narrow spectral region.[6] I shall stress especially the recent work carried on with the Michelson interferometer and Fourier transform. This instrument is due to the greatest American specialist in physical optics, Albert Michelson, but it has become a tool of tremendous possibilities thanks to Pierre Jacquinot in France and to Peter Fellgett in the

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[3] Could this absorption be due to the vibration-rotation bands of CO_2^+ in Venus? According to Sagan absorption by CO_2^+, CO^+ and N_2^+ cannot explain the blue haze of Mars.

[4] It may be interesting to notice that it will be possible in 1973 and 1975 to use the gravitational field of Venus to assist a combined Venus-Mercury fly-by. The opportunity will not repeat itself until 1980, and to study Mercury otherwise would need a much larger booster.

[5] This point will be discussed later.

[6] Outstanding applications have been made by G. Courtès at the Observatoire de Haute Provence and by the Mount Wilson group.

United Kingdom, followed by Janine and Pierre Connes and their collaborators in France, by A. Gebbie in the U.K., L. Delbouille and G. Roland in Belgium, Lawrence Mertz, Gerard P. Kuiper, John Strong, Woolf and other American astronomers. The new technique reached all its potentialities through the use of the large digital computers. I shall now illustrate these potentialities by describing a few wonderful results on the spectrum of Venus obtained by Janine and Pierre Connes.[7] The method is particularly fruitful in the infrared region. The very high resolving power which may be reached reveals elements of extremely low abundance.[8]

RECENT APPLICATIONS OF FOURIER SPECTROSCOPY

A great advantage of the interferometric method is to accept radiation from a source of comparatively large area and over a comparatively large solid angle (the "Jacquinot advantage"); light enters through a hole instead of a narrow slit. Moreover all the spectral elements in a wide spectral range may be measured at the same time ("Fellgett advantage"). In the infrared no photographic emulsion is available; the normal procedure is to scan the spectrum and to examine each spectral element at a time by means of an exit slit followed by a detector. On the contrary, Fourier spectroscopy handles information concerning many spectral elements simultaneously with a single detector. The success of this technique is due to the modern methods of frequency analysis. Actually an interferogram contains in a coded form all the information needed to reconstruct the spectrum. Since the key to the code is known, the decoding can be done by performing a frequency analysis, but large digital computers are essential to this procedure. We shall see what spectacular progress may be due to an increase in resolution and to new techniques of analysis of the electromagnetic radiations issued from a planet.

An errorless spectrum can be extracted from a perfect interferogram by digital computation. But errors in the interferogram can lead to considerable distortions in the spectrum. Fourier transform spectroscopy is very sensitive to periodic, slow progressive or random inaccuracies in the displacement device. "Noise" may be due to fluctuations of the source intensity, of receiver sensitivity or amplifier gain, and lack of linearity of the receiving system. Sophisticated methods now available permit the elimination of all essential errors. On all interferograms the path difference is controlled by an accurately known monochromatic line, for example, the green line of Hg^{198} (λ_{air} 5,460.7532 according to Meggers and Kessler; or $\nu_{vac} = 18{,}307.406$ cm^{-1}). Corrections are applied for the Doppler effect, including the earth rotation. The difficulties due to the atmospheric turbulence have been solved by the development of a special modulation method by Lawrence Mertz.

Before 1965 no published Fourier transform spectrum had a resolving power greater than 3,000.[9] J. and P. Connes now obtain immensely greater resolutions. In the laboratory, using a displacement of 11 cm., they have an instrumental width smaller than 0.07 cm.$^{-1}$, a ratio signal/noise greater than 10^4, a reproducibility of intensities better than 1/400 and a reproducibility of positions better than 1/500 instrumental width. Incidentally J. Pinard uses now a displacement of 2 meters, and gets a resolution of 0.005 cm.$^{-1}$

The first spectrum of Venus recorded by J. and P. Connes (September, 1964) in the infrared windows at 1.25 μ, 1.6 μ, and 2.2 μ using the 91-cm. telescope of the Steward Observatory on Kitt Peak gave a resolution which was 5 to 10 times better than Kuiper's best spectrograms taken at McDonald. In 1966 modifications of their interferometer gave them a resolution of 0.08 cm.$^{-1}$ about 100 times that of the best previous spectra of Venus. These most recent interferograms were taken at the Coudé focus of the 193-cm. reflector of the Observatoire de Haute Provence (O.H.P.).

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[7] These examples concern high resolving power; but even with moderate resolving powers (order of 1,000) Fourier spectroscopy may prove more efficient than the classical techniques of dispersion, especially for extended objects such as the nightglow, the planets, the comets, and the nebulae.

[8] The gases that are most likely to be indicative of biological processes are those that are clearly in disequilibrium with the environment (Lewis D. Kaplan).

[9] Simple devices may give good results for sources having a very low luminosity, such as the nightglow, but much more elaborate systems are necessary for high resolution planetary spectroscopy. J. Connes and H. P. Gush were the first to resolve the rotational structure of an infrared nightglow band of OH; the resolving power of 900 was better than anything obtained before. Interesting interferograms of Venus have been made with the 61-inch Harvard telescope with a resolving power of 1,000. They cover the region 8–13 μ, and may be compared with the observations of Sinton and Strong. Here are a few equivalences at 2 μ (or 20,000 Å): 1 cm.$^{-1}$ = 4 Å; precision of 0.01 cm.$^{-1}$ = 0.04 Å; precision of 10^{-3} cm.$^{-1}$ = 0.004 Å; resolution of 0.08 cm.$^{-1}$ = 0.32 Å.

These Venus O.H.P. spectra of highest resolution were taken during the daytime in three atmospheric windows: 2.53–1.89 μ (3,950–5,300 $cm.^{-1}$), 1.82–1.39 μ (5,500–7,200 $cm.^{-1}$) and 1.32–1.18 μ (7,600–8,500 $cm.^{-1}$). For comparison solar spectra were obtained in the same region with the same resolution, 0.08 $cm.^{-1}$, which is 3 times better than the resolution in the Michigan atlas. The signal/noise ratio was about the same for the solar spectra taken at Michigan and O.H.P. Corrections were automatically made for telluric absorption, the Fraunhofer lines, and the characteristics of the filters, account being taken also of the change in zenith distance and radial velocity in the course of each observing run. Many thousands of lines originate in the atmosphere of Venus, most of them being due to the principal constituent CO_2 in its various isotopic modifications. In the region 1–2.5 μ J. and P. Connes found that the half width of the CO_2 lines is $\leqslant 0.03$ $cm.^{-1}$, indicating a total pressure inside the absorbing layer not exceeding 0.3 atm. On their interferograms the CO_2 bands are rotationally resolved, and show plainly the isotopic lines.

The vibration-rotation spectrum (1st overtone, transition 2–0) of HCl appeared strikingly in the region 1.79–1.72 μ (5,600–5,800 $cm.^{-1}$). In the R-branch there was only a slight interference from the telluric lines of H_2O and CH_4 and from a weak venusian CO_2-band. Two series of sharp lines with intensity ratio 3 to 1 could be assigned to HCl^{35} and HCl^{37}; the comparison of the wave lengths in Venus to those measured in the laboratory by Rank, Rao, and their collaborators showed that the precision of the venusian wave lengths was better than 0.01 $cm.^{-1}$ The P-branch fell in a less favorable region, but two lines could nevertheless be measured accurately.

It is difficult to relate spectroscopically observed amounts of absorbing gases to their absolute concentration on Venus on account of the uncertainties and variabilities in the height of the clouds, the amounts of reflection and scattering within them and the averaging of these over the disk. The synthetic model spectra, as established by Belton, Hunten and Goody in the spectral region 8,000–11,000 Å are based on line formation in a homogeneous semi-infinite scattering atmosphere. On the whole these lead to more convincing conclusions, especially since the rotational structure of the CO_2 bands generally exhibits a great deal of overlapping. It is thus difficult to obtain precise values of the equivalent widths of the individual lines.

The pressures derived by Belton are all larger by a factor of 2 or 3 than the effective pressures found by the Connes using the Ladenburg and Reiche curve of growth. According to Belton, a pressure of 0.2 atm. near the cloud tops is the most reasonable working hypothesis, and the mean scattering free path in the clouds is about 1.4 km. When the line formation is dominated by multiple scattering as is presumably the case for Venus the usual curve-of-growth technique may lead to serious errors in pressure and chemical abundances.

If HCl is distributed uniformly with CO_2 the HCl/CO_2 abundance ratio on Venus is approximately 0.6×10^{-6}, a value probably accurate to ± 20 per cent.[10] For the comparison of HCl and CO_2 abundances, the observers used a "hot" band of $C^{12}O^{16}$ near 5,687 $cm.^{-1}$ (1.73 μ) and an ordinary transition of $C^{12}O^{16}O^{18}$ at 5,858 $cm.^{-1}$ (1.71 μ). As will be seen later the O^{16}/O^{18} abundance ratio is the same on Venus and in the laboratory. On the basis of the intensity distributions and the profiles the effective temperature was found to be 270 ± 30° K and the effective pressure $80 \pm \begin{cases}100\\40\end{cases}$ mb.

The second rare gas which was discovered by its vibration-rotation bands is HF. The fundamental transition v_0 at 3,961 $cm.^{-1}$ (2.52 μ) lies at the long wave length limit of the observations and is badly overlapped by strong telluric H_2O and CH_4, also by telluric and venusian CO. However an unblended line found at 4,039 $cm.^{-1}$ (2.47 μ) is R(1); its wave length agrees perfectly with the laboratory value. The region of overtone band is better. If we assume a uniform mixing with CO_2 as we did for HCl the abundance ratio HF/CO_2 is 5×10^{-9} (accuracy within a factor of two).

The third definitely identified rare molecule is CO, whose first overtone (2–0) at 2.35 μ is convincingly present. Until June, 1966, not only was the amount of CO in the Venus atmosphere unknown, but even its very existence was questionable. Observations by Sinton (1963) and by Moroz (1964) seemed to indicate a broad outline of the band, but it appeared little deeper than

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[10] It has been argued that rough upper limits could be estimated for the atmospheric abundance of liquid water on the basis of the discovery of HCl in the Venus atmosphere. However such a calculation would be invalid for the small droplets which might be present in the clouds.

the noise level. Kuiper (1962) found no convincing evidence of CO absorption on his best spectra and concluded that the upper limit for CO abundance was 10 cm. atm. By increasing the spectrum resolution by two orders of magnitude J. and P. Connes were able to measure the amount of CO and to obtain information about its location in the atmosphere; they used an interference filter from 3,950 to 5,300 cm.$^{-1}$ (2.53 to 19. μ) and a resolution of 0.08 cm.$^{-1}$ The unblended 39 lines of CO found in the regions P(1) to P(25) and R(0) to R(25) are sharp, intense and symmetrical. From a comparison with 38 laboratory wave lengths near 4,200 cm.$^{-1}$ (2.4 μ) (Rao, Humphreys and Rank, 1966) the r.m.s. scatter of the Venus wave lengths is smaller than 10^{-8} cm.$^{-1}$, i.e., of the order of the uncertainty of the corrections for the diurnal Doppler shift, which varies by 4×10^{-8} cm.$^{-1}$ during one tracing. There is good evidence for the isotopic combinations $C^{13}O^{16}$ (from P(9) to R(13)) and $C^{12}O^{18}$ (from P(7) to R(9)), the maximum equivalent width being 0.005 cm.$^{-1}$ $C^{12}O^{17}$ was not found, while "hot" bands were observed. From the intensities of the lines it appears that CO is present, not only in the photochemical region (very high atmosphere where an appreciable fraction of CO_2 may possibly be photodissociated), but rather well mixed with CO_2 in the whole atmosphere. As in the case of HCl and HF the path length through the scattering layer is not well determined. The ratio CO/CO_2 appears to be 46×10^{-6}. The mean value obtained for the temperature of CO is 240° K and the mean pressure 60 mb. The temperature agrees with that of CO_2 but is slightly lower than that of HCl (270° K and 80 mb.).

Summarizing we may say that the abundances relative to CO_2 are:

- for HCl less than one part per million;
- for HF a few parts per billion;
- for CO 45 parts per million.

The discovery of the two gaseous hydrogen halides in the upper atmosphere of Venus[11] was made possible by the high resolving power of the interferometer and by the high specific strength of the lines of these light linear molecules.

No other H-containing gas was detected. Among those which should have appeared on the spectra if present to more than one part per million are CH_4, CH_3Cl, CH_3F, C_2H_2, and HCN. H Br and H I fall in unfavorable spectral regions. The evidence concerning H_2O on Venus was not strengthened; observations from a drier, higher site than O.H.P. would help considerably.[12]

GROUND OBSERVATIONS DURING THE PRE 1967-PERIOD

In March, 1967, the KPNO and Goddard groups inaugurated the Tucson Symposia on Planetary Physics. The papers presented at the first conference have been edited and published in the volume "The Atmospheres of Venus and Mars." We shall first consider the period ending with this conference. Commission 16 of the I.A.U. devoted to "Etude physique des planètes et satellites" had always done its utmost to insure coordination, continuity of research and documentation centers, as well as the study and selection of instruments (micrometers, polarimeters, photometers, cameras, spectrometers, etc. . . .). Previous international symposia had been devoted to topics in or close to planetary physics and substantial parts of these conferences had always been concerned with Venus. The 1956 Liège Conference on "Les Molécules dans les Astres" contained various important contributions to our knowledge of Venus by Dollfus, Kozyrev, Link, etc. . . ., but most of them are completely outdated now. The 11th Liège Symposium (1962) on "La Physique des Planètes" in which Menzel, Kuiper, Minnaert, Spinrad, Suess, Gebbie, Sagan, Öpik, etc. . . . took an active part, was in fact the last international conference on planets prior to the space experiments. At this 1962 meeting we all were aware of the fact that the study of the planets, which had been on the whole rather neglected in comparison to the investigations on extragalactic nebulae, nucleogenesis, etc. . . . was going to come into the limelight again soon. Indeed, our main aim in organizing the 1962 symposium was to get us prepared for the exciting space experiments which were in the making. We knew the necessity of increasing our knowledge of the atmosphere and surface of Venus in order to derive models for the structure (temperature, pressure, ionization, etc.). We also realized that there were considerable difficulties involved at many stages, especially in the interpretation of the

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[11] As early as 1964 Suess sems to have anticipated the presence of significant amounts of gaseous halides on Venus.

[12] A search for the vibration-rotation bands of CO_2^+ and CO^+ is desirable and promising. The rotational structures may be easily predicted, on the basis of the well-known structures of electronic transitions. See Appendix.

spectroscopic observations in terms of abundances. Radiation in the microwave region was beginning to be used to probe the atmosphere and the surface of Venus. A high surface temperature[13] of 580° K was already considered by the radio-astronomers, who also envisaged a surface pressure of the order of 30 atm., but such estimates assumed that the atmosphere contained a large amount of nitrogen in addition to CO_2. There were controversial statements regarding, for example, two distinct cloud layers; a dense one at 30–40 km. and a hazy region at about 100 km. from the surface. Many materials were suggested as composition of the clouds; polymerized formaldehyde, ammonium nitrite, microorganisms, water droplets, ice particles, silica particles, sodium and magnesium chlorides, calcium and magnesium carbonates, volatile low-molecular-weight organic compounds. It was generally assumed that the primitive atmospheres of the inner planets had been of similar composition (CH_4, NH_3, H_2O, etc.).

What did we know of the spectrum of Venus in 1962? The most important and detailed information had been obtained by G. P. Kuiper, mainly at the McDonald Observatory. The spectrum beyond the photographic range had been obtained first with prism spectrometers, the resolution being approximately 250 at 1.8 μ and 80 at 2.5 μ. Later on Kuiper used a grating spectrometer from 1.0 to 2.5 μ with resolutions 250, 700, 800, and 1,500. At the same epoch Gebbie, Delbouille, and Roland utilized a Michelson interferometer with a similar resolution from 1.2 to 2.5 μ. Sinton observed the region 8 to 14 μ with a resolution of 30. We have seen the tremendous progress in resolution made a little later by application of Fourier spectroscopy.

Kuiper found 40 bands in the region 1.0–2.5 μ, all due to CO_2, including $^{13}CO_2$, $^{12}C^{18}O^{16}O$ and "hot" bands. By comparison of the laboratory bands and those of Venus it appeared that the strong bands are stronger in the laboratory, while the reverse is true for the weaker bands. This behavior may be explained by reduced penetration into the Venus atmosphere with increasing band strength. This effect has also been studied by Spinrad. For the weak bands the Venus spectrum corresponds to about 2 km.-atm. of CO_2, but the intensities vary with phase, from day to day, and even from region to region.[14] Anyway the determination of abundances is difficult: we have already stressed this point, and we shall return to it later on. Within 20 per cent, the abundance ratio $^{13}C/^{12}C$ based on the CO_2 (and later on the CO) bands is the same on Venus and the earth.

A similar result is found for $^{18}O/^{16}O$ on the basis of the 2 ν_3 band of $^{12}C^{18}O^{16}O$ at 4,639 cm.$^{-1}$ (2.16 μ). On the earth the $^{13}C/^{12}C$ ratio is 1/89 while it may reach 1/2 in the late carbon stars. Fowler, Greenstein, and Hoyle attribute the low terrestrial isotope ratio to an incomplete nuclear process occurring in the T Tauri stage of the solar nebula. On this basis one might have expected the isotope ratio on Venus to be different because of its greater proximity to the sun.

The CO band at 2.35 μ was not observed by Kuiper, who concluded that the upper limit of CO is of the order of 3 cm. We have seen earlier that CO has now been observed by J. and P. Connes. The Venus spectrum from 1.88–1.93 μ and the peak at 1.98 μ seems to be incompatible with the ice bands at 2.0 μ. This point will be discussed further on. Using a compact Mertz interferometer Kuiper found that water vapor is extremely scarce above the Venus clouds; it would at the most be equivalent to a layer of liquid water only one micron thick.

W. M. Sinton made infrared observations of Venus with the 42-inch Lowell reflector, using a lithium fluoride prism spectrometer with a liquid-nitrogen-cooled lead sulfide detector. The presence of CO was not convincing, in contrast with the Connes' observations. The albedo depends strongly on the wave length. Using an infrared pyrometer in the region 8–13 μ, the temperature obtained is 236° K, close to the previous values of Pettit and Nicholson and of Strong and Sinton. The temperature is actually found to be variable.

Spinrad observed the weak band of CO_2 at 7,158 Å and concluded that the abundance of CO_2 above the clouds corresponded to 2 km. atm. Spinrad found also that nitrogen tetroxide, N_2O_4, suggested by Hayden, Kiess and Kiess and formaldehyde, HCHO (suggested occasionally), were absent. Cruikshank found upper limits to the mixing ratios $COS/CO_2 < 10^{-6}$ and $H_2S/CO_2 < 2 \times 10^{-4}$. Kozyrev had found two discrete absorption bands at λ 4,372 and λ 4,120. These

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[13] The radio-emission emanates from a hot surface and from the lower hot atmosphere. The maximum brightness corresponds to a wave length of 6 cm.

[14] One may expect a similar variability of the CO_2^+-bands. Dr. Kuiper mentioned to me that photographs of Venus taken in CO_2-regions reveal weak features, which differ from those in the ultraviolet.

were not confirmed by Richardson and by Heyden and collaborators. Spinrad and T. Owen also found no trace of the bands.[15]

The investigation of Spinrad and of Sinton and Strong have been discussed by L. D. Kaplan, who suggests that there are two intensity maxima in the bands of CO_2, one corresponding to T (rotational) = 300° K, the other to T = 700° K. G. Münch and Th. Dunham, Jr., have also examined high resolution spectra in the photographic region.[16]

A more recent search for minor constituents has been carried by Tobias Owen. The H_2O band at 8,200 Å was photographed with a dispersion 2.2 Å/mm. at the Kitt Peak 84″ coudé. He doubts the presence of water vapor and places the upper limit at 16 μ precipitable water. Carbon suboxide, C_3O_2, which has been suggested as a candidate for the cloud particles, did not reveal itself in a favorable region, $\lambda < 3{,}300$ Å, with dispersions 1 Å/mm. and 2 Å/mm.

The spectrum of the nightglow of Venus has also been rediscussed by Owen, Shimizu, Meinel, Donahue, McElroy and others. Kozyrev (1954) had announced positive results which were only partly confirmed by Newkirk (1959) and eventually entirely disproved by Weinberg and Newkirk (1961) and by Owen (1962). New attempts made in September '67 at a favorable inferior conjunction did not lead to the detection of any emission. No trace of emission was found at the positions of the lines of Na, N_2^+, OH and C II.

After these results Kozyrev reported that he had also found no evidence of any emission line in the course of observations made during the same period.

Shimizu discussed the glow which may possibly be produced by the recombination of CO and O. He stressed the fact that the contribution of the solar wind to the upper atmospheric phenomena may be affected by the absence of a magnetic field on Venus.[17] He estimates that the airglow may have an intensity between 0.5 and 20 kilorayleighs (1 kR. = 10^9 photons cm.$^{-2}$ sec.$^{-1}$).

Meinel also discussed the nightglow, which may be produced by the creation of CH_2O and C_3O_2 as a result of lightning in the obscure hemisphere. There may also be electrical discharges between dust particles near the surface.

The dayglow and the nightglow should reveal vacuum ultraviolet emissions. Indeed a sounding rocket launched by Moos, Fastie and Bottema seemed to reveal a bright feature near 1,300 Å. They estimated the intensity of the corresponding dayglow emission to be 5 kR. and to be assigned to the resonance lines of the oxygen atom. A weak glow had been detected just beyond the terminator. On the other hand Mariner 5 and Venera 4 did not appear to have detected any airglow emission at λ 1,304. In fact it appears that the abundance of atomic oxygen in the upper atmosphere of Venus is less than in the earth atmosphere by many orders of magnitude.

McElroy has suggested that the dissociative recombination of CO_2^+ may lead to CO in the electronic state $A^1\Pi$

$$CO_2^+ + e \rightarrow CO\ (A^1\Pi) + O\ (^3P)$$

CO would then emit the $A^1\,\Pi \rightarrow X^1\,\Sigma^+$ system and the corresponding dayglow may have an intensity as great as 25 kR.

The understanding of phenomena on Venus may be helped by a comparison with other astronomical bodies, by meteorology on the earth, and by laboratory experiments. On account of the high abundance of CO_2 one might expect the presence of CO_2^+; this ion is abundant in comet tails. This question is discussed in the Appendix.

Moreover a dissociative recombination of CO_2^+

$$CO_2^+ + e \rightarrow CO + O$$

may play an important role in the ionosphere or the induced magnetosphere of Venus.[18]

On the basis of all the pre-1967 observations and of the theoretical and experimental works four models were being considered until a year or two ago.

(*i*) The hot ionosphere model: free-free emission of electrons in a very dense ionosphere would be responsible for the radio-emission in the microwave region. This model is now excluded as a result of the radar experiments, and of the brightness found at different wave lengths of the centimeter region. Moreover, the microwave emission of Venus is fairly steady as is normally the

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[15] Kozyrev had also observed these bands in the smoke from volcanic eruptions. One may not exclude a telluric absorption which would vary in intensity in some irregular fashion. This problem is under investigation in several institutions.

[16] See also the work by L. D. Gray and R. A. Schorn, p. 232.

[17] See pp. 243–244.

[18] This has been discussed by McElroy and others.

case for thermal sources. On the contrary non-thermal sources are generally erratic.

(*ii*) The aeolospheric model (E. Öpik): the high ground temperature would be due to a dense dust layer; very strong friction of the wind on the soil would create the high temperature. This model is now also abandoned. A similar model by Goody and Robinson (*Ap. J.* 146 (1966): p. 339, is now rather promising).

(*iii*) The hothouse model, essentially developed by C. Sagan: the atmosphere would be transparent in the visual region but fully absorbing in the infrared from 5 to 12 μ. Very convincing radio observations at λ 21 cm. have been made by Branson, using a one-mile radio telescope giving the brightness distribution across Venus.

(*iv*) The electrical discharge model: electrical discharges[19] between adjacent liquid droplets in the clouds would be responsible for the Venus microwave emission. This proves to be inconsistent with the scans in the 19 mm. channel of Mariner 2.

MARINER 2, BALLOONS, SOUNDING ROCKETS, VENERA 4, AND MARINER 5

Many essential problems remained pending before the Mariners and the Veneras. The values obtained by the investigators for the surface pressure ranged all the way from 3 to 1,000 atmospheres! Most "models" were neither sufficiently well defined, nor thoroughly analyzed. D. Deirmendjian stressed the fact that even the definition of what are the "lower" and "upper" atmospheres is not clear. Their separation is the "visible" cloud layer. But visible to what? The human eye, infrared detectors, a telescope on earth or in space, radio waves?

A few months after the last pre-space planetary symposium in 1962, the real space age started for Venus with the Mariner 2 fly-by mission and by the experiments from balloons (stratoscopes of the Princeton University and John Strong's balloons at Johns Hopkins). Mariner 2 passed within six planetary radii (41,000 km.) of the surface of Venus on December 14, 1962. Professor Murray proceeded to an infrared photometric mapping of Venus through the 8–14 μ window on December 14, 15, 16, 17, 1962, about at the time of the Mariner 2 encounter. The infrared instruments on Mariner 2 observed at 8.4 μ (a transparent region) and at 10.4 μ (strongly absorbed by CO_2); the values obtained for the temperature were 200° K at the center of the disk and 220° K at the limb. These values are in agreement with the temperature of 208° K found by Murray at the center of the disk. There was no difference in temperature between the illuminated and the dark sides. The success of the United States spaceship was considerable. For example the absence of a Van Allen belt of energetic particles and of an appreciable magnetic field were results of great importance. The radio measurements at λ 13.5 and λ 19 cm. could be localized in areas approximately 1/8 of the diameter of the planet so that the variation in temperature across the disk could be measured. Had there been a thick ionosphere the apparent radio temperature near the edges would have been equal to or greater than the average. It thus became more and more evident that the surface of Venus is very hot. Mariner 2 also scanned the high atmosphere in the infrared at 8.4 μ and 10.4 μ and found no irregularities across the terminator. Mariner 2 opened possibilities of accurate discussions of the limb-darkening, thanks to the observations of the dark side, the terminator and the bright side with a 19 mm.-channel and antenna polarization, combined with radar at 3.8 cm.

Stratoscope II examined the CO_2 bands. Other balloons equipped by a team under the direction of Professor J. Strong examined particularly the H_2O bands. It was found that the amount of H_2O is between 3 and 12×10^{-3} g.cm.$^{-2}$ In another expedition the spectral distribution of the reflecting power of the clouds in the region 1.7–3.4 μ was examined.

Despite this success many puzzles remained. Vigorous discussions of the nature of the clouds

TABLE 1

PUBLISHED VALUES OF H_2O AMOUNTS

Band (μ)	Amount (μ)	Reference
$1 < \lambda < 2\ \mu$	<20	Connes *et al.* (1967)
0.82	<16	Owen (1967)
1.38	70	Dollfus (1965)
1.4 and 1.9	10 ?	Kuiper (1967)
1.13	98	Strong (1965)
0.82	<70	Spinrad (1962)
0.82	$10^{-4} \times CO_2$	Belton, Hunten, and Goody (1968)
0.82	60	Spinrad and Shawl (1966)

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[19] The synchrotron radiation from presumed Van Allen belts and the glow discharges resulting from charge separation are now also excluded.

now began. Lyot in 1929 had interpreted the clouds as due to water droplets; so did Deirmendjian (1954). The balloon observations by Strong's team and the laboratory experiments on the reflectivities of many possible cloud particles led to the conclusion that the clouds of Venus were probably ice. The reflection of the clouds appears to agree relatively well with that of ice particles from 1.7 to 3.4 μ. Sinton also concludes that ice crystals give a satisfactory solution in the region 1–3 μ. Comparison with calculations based on the Mie theory and with reflection spectra of water, silica, sand, oil, frozen CO_2, etc. . . . did not provide an agreement comparable with that of ice crystals.

Sagan and Pollack concluded from several theoretical arguments that the clouds of Venus were ice, in agreement with Strong's group. However, the infrared spectra obtained by Kuiper from the ground and from high altitude aircraft give strong evidence against the ice hypothesis. Rea and O'Leary (1968) argue that the reflectivity minima at 1.5 and 2.0 μ are due to CO_2 absorption. Actually there seem to be combined effects of small particle reflectivities and absorptions in the near infrared. Dust grains had been considered by Öpik (1961) in his aeolosphere hypothesis and also by Matsushima (1967). We shall describe only very summarily the scores of papers which have been published in this field in the course of the last years.

Let us consider first the evidence in favor of the ice crystals. Certain observers claim to have found evidence for H_2O absorption, and temperatures near 230° K at the top of the cloud or haze layer argue for ice crystals. These according to Sagan would have mean radii between 7.5 and 10 μ and would match the infrared albedo and the polarimetric observations. The ice clouds can also provide the additional opacity desired to build consistent hothouse models. According to Sagan clouds made primarily of ice crystals with water droplets towards their bottoms may account for the general mm. spectrum, the mm. phase effect, the Mariner 2 microwave limb-darkening and the infrared limb-darkening. Clouds made primarily of ice (not necessarily clean ice!) allow a sizable fraction of the incident sunlight to penetrate to the surface, but are very opaque to radiation thermally produced by the surface of the planet. The vapor pressure of ice at a temperature of 230° K is quite low.

The objections raised by Rea and O'Leary against the ice crystal hypothesis are considered as invalid by Sagan and Pollack who showed that ice crystals a few microns in diameter are consistent with all the observations of Venus near $\lambda\lambda$ 1.5–, 2–, and 3 μ. According to Sagan the Venera 4 water-vapor observations, if reliable, would demonstrate the existence of ice clouds, but some dust may be mixed with the ice.

An important argument against ice crystals is the low H_2O vapor content observed spectroscopically. Belton, Hunten, and Goody in agreement with Kuiper consider that the cloud particles are unlikely to be composed of ice. Actually the clouds of Venus must be quite tenuous. Clouds containing an appreciable amount of carbon suboxide (C_3O_2) do not seem likely, despite a few arguments in favor. W. F. Libby suggests clouds made of liquid water droplets in which CO_2 and other volatile materials are dissolved. Actually scattering by a very thick molecular atmosphere has been suggested to explain the occultation measurements of Mariner 5. Such scattering may contribute to the high albedo of the planet. The comparison of the phenomena in the atmospheres of Venus and the earth, associated with the observations from Mariner 5 and Venera 4, does not lead to unambiguous conclusions. The particles in the cloud layer must be of micron size or larger and highly transparent. The scattering properties of the cloud particles on Venus resemble those of water droplets, ice particles, or particles of transparent minerals such as quartz. It seems rather likely that a perfectly convincing solution will be found only when a space probe samples the particles themselves.

In his review of the Second Tucson Conference, F. S. Johnson discussed the temperature above the cloud level. This temperature must be approximately constant (about 245° K) up to the 10^{-8} atm. pressure. This level may be significantly higher than that at the cloud tops: it is estimated to be located at a planetocentric distance of about 6,144 km.

In an as yet unpublished paper, Peter Fabian, Takashi Sasamori and Akira Kasahara, working under Professor Libby, have discussed the radiative convective equilibrium temperature calculations of the venusian atmosphere. They also calculate the vertical temperature distribution. They assume that CO_2 is by far the major constituent. The temperatures which they obtained are given in table 2.

TABLE 2

A Few Published Values of the Temperatures

T surface (°K)	Authors	Technique
653 ± 40	Radio-astronomers	6 cm. (max. of T)
590	Radio-astronomers	2 cm.
750	Radio-astronomers, Mariner 5, radar	Radio, radar, Mariner 5
554 ± 10	Venera 4	Probes on Venera 4
580	Pre-Mariners, radio-astronomers	Microwaves[1]
700	L. D. Kaplan	Rotational structure CO_2 (2 maxima); near infrared
670, equator, daytime 580, 80° lat., daytime 620, equator, nighttime 500, 80° lat., nighttime	P. Fabian *et al.*	Theory

T above cloud level (°K)	Authors[7]	Technique
190–245	F. S. Johnson	Review, comparison with the earth's atmosphere[2]
230	J. Strong *et al.*	Near infrared
230	W. B. Sinton	Infrared pyrometer (8–13 μ)
300	L. D. Kaplan	Rot. struct. of CO_2 (2 maxima); near infrared
200–250	L. D. Gray and R. A. Schorn	Rot. struct. of CO_2 near 1 μ
200 center of disk 220 limb	Mariner 2	Infrared (8.4 and 10.4 μ)
208 center	Murray	Infrared (∼10 μ)
250 noon 170 (midnight)	P. Fabian *et al.*	Theory
240	J. and P. Connes *et al.*	CO, CO_2 (rotat. distrib.)[3]
270 ± 30	J. and P. Connes *et al.*	HCl (rotat. distrib.)[4]
220–440	H. Spinrad	CO_2 (λ 7,820, rotat. distrib.)[5]
235	Various	Infrared, radio
300	Various	3 mm.
270	Belton *et al.*	Theory[6]

[1] Pressure ∼30 atm.

[2] T constant, up to 10^{-3} atm. pressure level.

[3] p (CO) = 60 mbars.

[4] p (HCl) = 80 mbars $\left|\begin{matrix}+100.\\-40\end{matrix}\right.$

[5] Function of phase; p values parallel with T.

[6] p ∼0.2 atm.

[7] The first measurement of the thermal emission of Venus was made in 1924 by E. Pettit and S. B. Nicholson.

THE CORONA OF VENUS

Photometers for the detection of L_α and λ 1,304 O I have been placed on board Zond 1, Venera 2-3-4, and Mariner 5.[20] The photometers placed on the Soviet space vehicles were sensitive in two spectral ranges: 1,050–1,340 Å and 1,225–1,340 Å; they were directed at the night side of Venus. They found the distribution of the L_α

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[20] On October 19, 1967, at 17 h. 34 m. 55.3 sec. U.T. Mariner 5, which had been launched from Cape Kennedy on June 14 at 6 h. 01 m. 00 sec. U.T. and whose orbit had been corrected on June 19, passed by Venus at a distance 10,151 km. from the center of the planet. The distance from the earth was 79,764,370 km., corresponding to a transit time of 266 seconds for the radio signals. Venera 4 landed near the equator on the night side of Venus. The Russian Venera 4 and the American Mariner 5 flew by the atmosphere of Venus within an interval of 34 hours. These space probes complemented each other. The essential information on chemical composi-

radiation, but the O I triplet was extremely weak or absent. On the basis of the observations from Venera 4 the atomic hydrogen concentration is approximately 50 cm.$^{-3}$ at a distance of 10,000 km. from the planet's center on the night side. This hydrogen may be due to photodissociation of H_2O or HCl. The intensity of the L_α nightglow exceeds the galactic background by several hundred rayleighs. Venus has daytime and nighttime ionospheres at the positions probed by the radio occultations. The magnetic dipole moment of Venus is smaller than that of the earth by a factor of the order of 1,000. The absence of magnetic field may presumably be attributed to the very slow rotation.

The experiments placed on board Mariner 5 by C. A. Barth and his team, to observe the L_α and O I emissions included three U.V. photometers with a long λ cutoff at 2,200 Å and short λ cutoffs, respectively, at $\lambda\lambda$ 1,050, 1,250, and 1,350 Å. The photometer adjusted for λ 1,304 revealed that the upper atmosphere is very deficient in atomic oxygen, but the other photometers showed a strong hydrogen corona.[21] For the L_α signal the galactic background of 0.59 kR. was substracted; this galactic background was observed several days before and after encounter of Mariner 5 with Venus. The remarkable measurements of L_α intensities as a function of planetocentric distance (6,000 to 13,000 km. from center) could not be explained with a model having a single scale height: a two-component L_α model is required. Three hypotheses may be considered to explain such a two component L_α model: an atomic hydrogen-two temperature distribution, an atomic H-deuterium model and a model containing a mixture of atomic and molecular hydrogen.

No DCl has been found on the Venus interferograms taken by F. and J. Connes; according to L. D. Kaplan the unsuccessful search for the (2, 0) band of DCl at 2.43 μ sets an upper limit D/H smaller than 0.1 by atoms. No HDO band is favorable for high sensitivity on Venus. L. D. Kaplan did not see the (110) and the (030) bands of HDO; the ν_3 fundamental (001) should be a good candidate for aircraft spectroscopy, although the albedo above 2.7 μ is low. McElroy and Hunten find that a large deuterium component in the exosphere is the least objectionable explanation of the L_α-data from Mariner 5: the enrichment of the D/H ratio may be produced by the diffusive flow. The deuterium model is ruled out by C. A. Barth, who favors the H and H_2 model, but several key questions remain pending. Among them: where does the abundant H_2 come from and where does it go? How does it affect the thermal structure of the upper atmosphere? How can the recombination proceed at the required rate? The solar ultraviolet below 845 Å dissociates H_2 into 1s^{2}S and 2p^{2}P°, the transition between these two states giving L_α. However the U.V. dayglow observed in the bright limb of Venus may have been the Lyman bands of H_2 ($B^1\ \Sigma_u^+ - x^1\ \Sigma_g^+$) excited in a fluorescence process by solar radiation (between 845 and 1,108 Å) and re-emitting between 1,200 and 1,600 Å. We have mentioned earlier that McElroy suggested the possible emission in the fourth positive bands of CO as a result of dissociative recombination of CO_2^+.

The deuterium model and the H/H_2 model are working hypotheses. A crucial test requires a new planetary probe equipped for mass spectroscopy and optical spectrometry. Important data may also be eventually obtained with high resolution measurements from an orbiting observatory.

IS THERE WATER VAPOR IN THE ATMOSPHERE OF VENUS?

To illustrate the drastic evolution of our ideas on the physics of Venus in recent years it may be interesting to mention a hypothesis put forward in 1955 by Menzel and Whipple. This hypothesis was perfectly logical in 1955. The authors suggested that the whole surface of Venus was covered with water, and that the gases (H_2O, CO_2, and CO) had been produced by volcanoes. A number of puzzles could be explained in this way.

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tions, magnetic field, and corona, and the comparison between bright and dark sides were on the whole in fair agreement. Nevertheless certain important information on the temperature and pressure at the surface and the height of the cloud region seem to be contradictory. This point will be discussed later.

The first direct measurements in the venusian atmosphere were provided by the descent stage of the canister of Venera 4 on October 18–19, 1967. Among the instruments for investigating the lower layers were a radio altimeter, a barometric device, a thermometer and an atmospheric density gauge.

[21] As Mariner 5 approached Venus the photometers viewed the galactic background. Moving past Venus, the photometers observed successively the outer atmosphere on the night side (a faint ultraviolet nightglow of unknown origin was also observed), the dark planet, the terminator and finally the day side. The field of view then passed off the bright limb and measured the outer atmosphere until the galactic background only was again observed.

We know now that such a hypothesis is inconsistent with the high temperature of the surface. We shall later say a few words about a somewhat similar view developed recently by Professor Libby, who favors the existence of very extensive polar ice caps.[22]

Actually the spectroscopic detection of water vapor and of oxygen is difficult from the ground on account of the high intensities of the telluric bands of H_2O and O_2. Experienced observers like Adams and Dunham could find neither H_2O nor O_2. The best way to advance our knowledge of the abundance of H_2O on Venus is by using the Doppler shift in the most favorable circumstances, and to try to place the spectrographs at a high altitude. Moreover the conversion of observed intensities into abundances is complex and may lead to serious errors. Pressure effects and line formation in a scattering atmosphere may account for discrepancies between weak and strong bands.

The first seemingly convincing evidence in favor of H_2O was found by John Strong in 1952.[23] Strong sent a 16-inch telescope with a recording spectrometer up in a balloon to an altitude of approximately 20 km., where it was above 98 per cent of the terrestrial H_2O. This balloon experiment was repeated under improved instrumental conditions in 1964. Bottema, Plummer and Strong observed the water vapor band at 1.13 μ; the intensity observed is equivalent to 98 μ of precipitable water at 1 atm. pressure. This result coincided fairly closely with that of Dollfus.

In 1966 Belton and Hunten, using the radial velocity shift from a ground observatory found an absorption equivalent in 125 μ of precipitable water. Measurements were made by photoelectronic scanning with the 40-foot spectrograph of the McMath Solar Telescope at Kitt Peak.

Owen in 1967 obtained high resolution spectrograms of Venus (2.2 Å/mm. at 8,000 Å; Doppler shift: 0.33 Å). He found only one Doppler-shifted companion to the telluric H_2O absorptions near λ 8,200. He suggested that this feature is actually a solar line. He concluded that the upper limit on the equivalent precipitable water is 16 μ.

Hunten, Belton, and Spinrad did not accept Owen's conclusion. They found ten H_2O companion lines and expressed the view that the companion line observed by Owen is not a solar line. The Kitt Peak observations have been further discussed by Hunten, Belton, and Goody who found an equivalent width of 15 mÅ for λ 8,189.27 and 8,193.00, the Doppler shift being 0.35 Å. Spinrad and Shawl confirmed the results of Belton and Hunten; their observational material consisted of Lick Observatory spectrograms with a dispersion of 1.9 Å/mm. The equivalent width was 15 mÅ, corresponding to an amount of H_2O in the line of sight equal to 60 μ precipitable water.

The most recent observations by Belton and Hunten were made at Kitt Peak on the solar telescope with photoelectric detection. Water vapor absorption in the Venus spectrum was detected, the mixing ratio H_2O/CO_2 being 15 parts per million. This fraction, which is much greater than that of HCl/CO_2 is definitely smaller than the value to be expected for water vapor in equilibrium with ice at the observed temperature of the CO_2 bands. The authors therefore conclude that the cloud particles are almost certainly neither ice nor water. On the basis of two high-altitude flights, (11.3 km.) Kuiper and his associates found that the Venus atmosphere is essentially devoid of water vapor and ice crystals. The upper limit of the mixing ratio H_2O/CO_2 is 10^{-5}, but Kuiper favors a ratio of 10^{-6}.

The Connes and collaborators failed to detect H_2O in the strong band region using interferograms of high resolution. The recent determinations of abundance of water vapor are summarized in table 1, giving the equivalent amounts of precipitable water in microns. It seems difficult to escape the conclusion that the H_2O-content is variable with time and location on the disk; there may be "dry" or "humid" periods.

Several authors have stressed the value of using the region between 1 and 1.4 centimeters for the detection of water vapor; this region is indeed sensitive, as the center of a water-vapor line lies at 1.35 cm. From a comparison of theoretical and observed microwave brightness temperatures at 1.35 cm., Pollack and Wood obtain an upper limit of 0.8 per cent for the water-vapor mixing ratio in the lower atmosphere. This limit is consistent with the mixing ratio of water vapor detected by Venera 4, the existence of aqueous ice clouds and

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[22] Fifteen years ago many conjectures were made as to the surface environment of Venus: oceans, hot deserts, swamps, lakes of oil, etc. All these models are inconsistent with the now fairly well-known atmospheric composition. J. S. Lewis has discussed the equilibrium between the lithosphere and the atmosphere of Venus.

[23] Water vapor in the atmosphere of Venus was possibly discovered in November, 1950, by Moore and Ross with a manned balloon-telescope system at an altitude of 24 km.

a greenhouse effect caused by carbon dioxide and water vapor.

IS O_2 PRESENT?

The presence of oxygen was investigated by Prokofjev and Petrova who used a high dispersion (1 Å and 0.25 Å per mm.) in the bands λλ 6,300, 6,900, 7,600 when Venus had an appreciable Doppler shift. They concluded in favor of the probable presence of weak O_2 lines in the atmosphere, but could not give a quantitative estimate.

Belton and his collaborators obtained a Doppler-shifted spectrum in the middle of the A band of O_2. There is no evidence for any expected planetary feature. Lines of 3 mÅ equivalent width should be readily detected. There may be a weak (4 mÅ) unassigned venusian line at λ 7,637.89 but this may be sheer coincidence. The upper limit to the mixing ratio O_2/CO_2 is 4×10^{-5} if the unobserved lines are formed within a scattering cloud or haze. If the lines are formed in a clear atmosphere above a reflecting cloud layer the mixing ratio is less than 1.0×10^{-5}. At any rate these values are in sharp disagreement with the value 4×10^{-3} published as a preliminary result of the Venera 4 probe. It appears that this larger amount must be in error. It has been suggested that the oxygen may have been produced during the entry of the probe, or that the chemical-sampling technique used ran into difficulties.[24] It has also been suggested that the fine 800° K tungsten filament used on Venera 4 may have burned out for some other reason than the presence of O_2. This measurement should be repeated.

A similar disagreement appears for water vapor: Venera 4 gives much greater values than spectroscopy, but this case is not so clear, as the mixing ratio for the amount of H_2O may depend on height (condensation of the water vapor into the clouds).

TWO SOMEWHAT RELATED CONTROVERSIES: THE ICE CAPS OF VENUS AND THE ALTITUDES OF THE VENERA 4 CANISTER

If the origin and the evolution of Venus resemble those of earth, we may wonder where its water ejected by the volcanoes has gone. Notwith standing the high temperatures measured for the surface of Venus Professor W. F. Libby has suggested that water is locked up in giant polar ice caps extending to 30° latitude. The observations of the radio astronomers generally indicate polar temperatures around 470° K while the surface temperatures must be around 700° K. However, if the measurements performed by Venera 4 have been correctly interpreted by the Soviet investigators, the polar temperature might possibly be low enough to allow ice to form huge ice caps presumably covered by a solid hydrate of CO_2. The existence of plant life around the periphery of the ice caps may not be excluded.

This hypothesis has been criticized by several scientists, especially by Tobias Owen and Carl Sagan who consider that the polar temperature is certainly too high. Following J. A. Businger and J. R. Holton the atmospheric structure which would be required would create extraordinarily violent winds.

I shall not enter into details and only express the hope that a canister will land some day in the polar region of Venus.

This hypothesis is closely related to a controversy regarding the value of the radius of Venus. The radius deduced from the combination of observations made from Venera 4 and Mariner 5 is 6,081 km. On the other hand the value obtained by earth-based radar measurements is 6,055 ± 1 km. In the discussions the assumption that Venera 4 actually reached the main surface is of crucial importance. One must either disregard the evidence that Venera 4 did indeed land or accept the conclusion that the radar results are erroneous by a factor of 25 times their probable error. The controversy affects of course the values of temperature and pressure at the surface and the whole problem of the distributions of all the physical characteristics as functions of altitude.

Johnson's review summarizes the situation as follows:

> Thus, the surface pressure and temperature remain in doubt. The Soviet results are 18.5 atm and 544°K, but the Mariner 5 results, combined with radar data, indicate that this particular pressure level and temperature occur at an altitude near 35 km. The surface pressure and temperature, therefore, may be in excess of 100 atm and 700°K.

UPPER ATMOSPHERE, IONOSPHERE AND EXOSPHERE

The atmosphere of Venus consists predominantly of CO_2 (abundance greater than 90 per cent) with the possible presence of N_2 (probably less than 2.5 per cent); HCl, HF, CO, O_2 and

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[24] The Soviet canister was carrying 11 gas analyzers adapted to CO_2, N_2, O_2 and H_2O.

H_2O are minor constituents. The ion which plays the major role in the ionosphere of Venus is CO_2^+ although not more than 2 per cent of the CO_2 is ionized, according to R. W. Stewart. In the daytime ionosphere the peak is approximately at an altitude of 82 km. above the point at which Mariner 5 indicates a pressure of 1 atm. Venus has daytime and nighttime ionospheres at the positions probed by radio occultations in the S band; the nocturnal ionosphere presents difficult problems.

The model for the daytime ionosphere adopted by McElroy is based on the production and removal of electrons by the reactions

$$CO_2 + h\nu \rightarrow CO_2^+ + e \rightarrow CO + O$$

Two peaks are identified as F_1 and E layers, by analogy with their terrestrial counterparts.

According to investigations by P. Cloutier, McElroy, and F. C. Michel, by Dessler, by the Mariner Stanford Group and by others, the ionosphere produced by solar ultraviolet radiations induces a magnetosphere which protects the atmosphere against direct bombardment by the solar wind. I refer to Johnson's review for some detail on this matter.

The absence of a magnetic field on Venus has often led to the simplified conclusion that the solar wind interacts directly with the venusian atmosphere, as it does with the atmosphere of a comet whose nucleus has no magnetic dipole. The possible existence of an induced magnetosphere complicates the problem of the structure of the ionosphere of Venus. Leverett Davis, Jr., has recently compared the shock wave produced by the solar wind in the atmospheres of the earth and Venus.

The values given for the temperature of the exosphere are approximately: 708° K (McElroy), 700 ± 100° K (Stewart) and 650 ± 50° K (Barth). The last value obtained by the photometry of L_α assumes the presence of H_2 in order to explain the puzzling features in the measurement of L_α. Before the launching of Mariner 5 and Venera 4 exospheric temperatures ranging from 600° K to 3,000° K were quoted, depending essentially on the concentration adopted for CO_2. The situation has definitely improved in this case.

ULTRAVIOLET OBSERVATIONS FROM SOUNDING ROCKETS

Important results have been obtained, especially by D. C. Evans and by D. C. Morton, E. B. Jenkins and A. V. Sweigart. According to Evans, who used rocket-borne objective grating spectrographs, a drop in albedo occurs below λ 3,000 Å and a reflectivity minimum occurs at 2,500 Å; this behavior may be interpreted by Rayleigh scattering, added to reflectivitiy by the cloud surface. Initially the influence of an ozone layer was envisaged, but this suggestion is not consistent with later observations.

TABLE 3

A FEW PUBLISHED VALUES OF THE PARTIAL PRESSURES OF COMPOUNDS IN THE CLOUD LAYER

Compound	Pressure in bars	Reference
CO_2	0.1	J. and P. Connes *et al.* (1967)
CO	9×10^{-6}	Kaplan (1967)
H_2O	1.1×10^{-5}	Strong *et al.* (1965)
	$<1.3 \times 10^{-5}$	Belton and Hunten (1966)
	6×10^{-6}	Spinrad and Shawl (1966)
	$10^{-6} - 10^{-7}$	G. P. Kuiper (1967)
HCl	6×10^{-8}	J. and P. Connes *et al.* (1967)
HF	5×10^{-10}	J. and P. Connes *et al.* (1967)

Jenkins and his collaborators have described their rocket spectra in the region λ 2,100 to λ 3,070. The resolution of their f/2 objective grating camera was approximately 1 Å. Weak unidentified absorptions may possibly exist near λ 2,174 and λ 2,450 Å, and broad variations in albedo seem apparent between λ 2,470 and λ 2,650. An overall depression of albedo near λ 2,200 Å could be due to the presence of a trace of carbonyl sulfide (COS). The upper limits for the abundances in the upper atmosphere of Venus, as provided by lack of detectable absorption, are:

5×10^{-4} cm. – atm. O_3 (ozone);
9×10^{-3} cm. – atm. NH_3 (ammonia);
10^{-3} cm. – atm. SO_2 (sulfur dioxide);[25]
6×10^{-2} cm. – atm. NO_2 (nitrogen dioxide);
10^{-1} cm. – atm. NO (nitric oxide);
5×10^{-1} cm. – atm. C_3O_2 (carbon suboxide).

The low ozone abundance is consistent with the almost complete absence of oxygen. On the basis of photochemical equilibrium calculations Libby and Fabian stated that the ozone layer above the clouds is equivalent to 0.05 cm. – atm., an amount ten times greater than the upper limit found observationally by Jenkins and collaborators. Libby's estimate was based on the high abundance (0.4 to 1.6 per cent) of oxygen measured by

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[25] Cruikshank and Kuiper found an upper limit of 5×10^{-3} cm.-atm. with the band near 3,000 Å.

Venera 4, but we have seen earlier that the Venera 4 determination faces strong objections.

A good start has been made in the spectroscopy of Venus. Much remains to be done from the ground as well as with balloons, high altitude aircraft, sounding rockets, satellites, and space probes. I hope that the American Philosophical Society will organize another series of reports on Venus, five or ten years from now. Many of the topics described in this report will certainly have become obsolete by then! But Mars may appear more exciting at that time.

On account of the large number of references I indicate only the most recent volumes or periodicals where the references may be found:

Journal of Atmospheric Sciences **25** (July 1968).

The Atmospheres of Venus and Mars, ed. J. C. Brandt and M. B. McElroy (New York, Gordon and Breach, 1968).

Communications of the Lunar and Planetary Laboratory, The University of Arizona, Ed. G. P. Kuiper (Tucson, Arizona, 1967-1968).

La Physique des Planètes (11th Liège Astrophysical Symposium, 1962).

APPENDIX

CONSIDERATIONS REGARDING THE POSSIBLE PRESENCE OF CO_2^+ AND CO^+ IONS IN VENUS

Until 1926 visual observations and photographs in the blue to the red region had not revealed any feature on the surface of Venus. It was only in 1926 that F. E. Ross, at the Mount Wilson Observatory, succeeded in obtaining photographs revealing distinct features on the disk of the planet. The successful photographs were taken in the ultraviolet, to everyone's surprise, because ultraviolet light is markedly useless for photographing clouds on the earth. Photographs taken in the red and near infrared region had been unsuccessful for registering details, notwithstanding the well-known haze-penetrating power in the red and near infrared.

As far as I know no really convincing explanation has been found yet for the fact that observations in the ultraviolet region reveal dark and bright regions on Venus. One may wonder whether the atmosphere of Venus may not contain molecules (neutral or ionized) which would fulfill the following conditions:

(*i*) have a resonance electronic transition in the region λ 3,300 – λ 3,900 Å;

(*ii*) have the adequate abundance and transition probability.

The CO_2^+-ion fulfills these conditions. Its spectrum has been analyzed by S. Mrozowski and is characterized by a strong electronic system $^2\Pi_u \rightarrow {}^2\Pi_g$ in the near ultraviolet. Another strong double band λ 2,883 – λ 2,896 is due to a $^2\Sigma_u^+ \rightarrow {}^2\Pi_g$ transition of CO_2^+. I discovered CO_2^+ in the spectrum of comet tails twenty years ago. Actually several authors, especially M. D. McElroy, have suggested that CO_2^+ plays the leading rôle in the ionosphere of Venus.

In 1957 H. C. Urey and A. W. Brewer had pointed out that a number of bands, claimed to have been observed by Kozyrev in the nightglow of Venus can be assigned to CO^+, and that absorption bands of Venus near λ 4,120 and λ 4,372, also announced by Kozyrev, may be due to CO^+ and CO_2^+. It seems now that these emission and absorption features of Venus do not really exist. Urey and Brewer also suggested that absorption bands of CO^+ and CO_2^+ may be responsible for the color of Venus.

In comet tails the strongest transitions of CO_2^+ are the 0, 0 (λ 3,509), 0, 1 (λ 3,674), and 1, 0 (λ 3,378); one may expect that the same low-temperature transitions would be the strongest absorptions of CO_2^+ in Venus. In hot laboratory sources many additional CO_2^+ bands are observed; the comparison of the spectra of Venus and of comet tails is more appropriate.

If solar radiation (whether electromagnetic or corpuscular is immaterial) is able to ionize the CO_2 molecules of comets, it could just as well ionize CO_2 in Venus, since the heliocentric distances of Venus and of certain comets are of the same order. CO_2 is by far (90–95 per cent) the most abundant constituent of Venus; part of it is ionized.

The transition probability of the ultraviolet resonance system of CO_2^+ is presumably *much* greater than that of the vibration-rotation transitions of neutral CO_2 in the infrared. Even if the abundance of CO_2^+ is much lower than that of CO_2 (which is probable) the presence of strong ultraviolet bands of CO_2^+ is far from excluded, on account of the high transition probability of CO_2^+.

The electron densities in the ionosphere of Venus have been estimated theoretically; they should be approximately equal to the densities in CO_2^+. The values thus obtained seem too low to explain the clouds of Venus. However there still seems to be some uncertainty with regard to the electron densities in Venus.

Two fairly easy observations should be made. Photographs with narrow filters near λ 3,509, λ 3,674, or λ 3,378 should reveal enhanced features if the "darkness" of certain regions of the disk is due to a higher local abundance of CO_2^+. Spectrograms of local features of Venus (dark and bright regions) in the near ultraviolet region should be obtained with high resolution and compared with solar spectrograms having the same resolution.

It is known that the very high resolution of Michelson interferometers with Fourier transform employed in the infrared region can reveal elements of extremely low abundance relative to CO_2, such as HF and HCl. It is probable that vibration rotation bands of CO_2^+ and CO^+ corresponding to the infrared-active frequencies will also be found, in the fundamental or first overtone transitions. An accurate prediction of the rotational structures of these bands may be made on the basis of the known data of CO^+ and CO_2^+. Of course the rotational resolutions of these oxides are not as easily observed as those of hydrides such as HF or HCl, but the abundances of CO^+ and CO_2^+ are probably much greater than those of HF and HCl. The material on Venus obtained by P. and J. Connes may be adequate.

If my suggestion is correct the clouds are irregularities in the CO_2^+ region, possibly due to irregularities of the solar wind and to the effect of relaxation times. The intensities of the CO_2-bands vary with phase, from day to day, and even from region to region. One may expect a similar variability of the CO_2^+-bands.

The clouds of Venus have been (and still are) a source of many speculations. We may possibly have to revise our views as to their nature.