National Aeronautics and Space Administration
Goddard Space Flight Center
Contract No.NAS-5-12487

ST-LPS-RA-10753

"VENERA-4" AND THE INTERPRETATION OF RADIO ASTRONOMICAL MEASUREMENTS OF VENUS

by

A.D. Kuz'min
&
Yu.N. Vetukhnovskaya

(USSR)

24 SEPTEMBER 1968

ST-LPS-RA-10753

"VENERA-4" AND THE INTERPRETATION OF RADIO ASTRONOMICAL MEASUREMENTS OF VENUS

Kosmicheskiye Issledovaniya
Tom 6, vyp. No.4, pp 590-597
Izd-vo "NAUKA, 1968

by
A.D. Kuz'min and
Yu.N. Vetukhnovskaya

SUMMARY

The result of AIS "Venera-4" measurements are used for interpreting radio astronomical ground observations. It is shown that radio astronomical data are in good agreement with the model of venusian atmosphere designed on the basis of AIS "Venera-4" data. Water and water vapour content in the atmosphere of Venus is estimated. Some assumptions on the possible physical condition of Venus are submitted.

*
* *

Studies of Venus started more than 300 years ago. In 1761 M.V. Lomonosov discovered the existence of an atmosphere of Venus. However, up to the end of our century's fifties the knowledge accumulated about Venus did not match the general rapid development of science and technology. It was only established that at the level of the cloud layer the temperature of the atmosphere is about 240°K and remains virtually unchanged from day to night. It was also established that the atmosphere of Venus has a high carbon dioxide content. However, even such fundamental characteristics of the planet as its temperature, surface properties and pressure in its atmosphere remained unknown.

This scarcity of factual data resulted in various hypotheses and phantasies with diameterically opposite supposition as to the existence on Venus of a total ocean or of an arid desert.

A considerable progress in investigations of Venus was achieved in the last ten years mainly through the use of radar and radio astronomical methods of investigation.

Radio astronomical investigations have shown that Venus has a dry and hot surface surrounded by a colder atmosphere. Radar investigations of Venus made it possible to determine the elements of its rotation. However, many problems of planet's physics, especially of its atmosphere, remained open. In view of the limited possibilities of ground methods of investigation of Venus' atmosphere, the data on its composition, pressure and temperature were often limited to very rough estimates.

A new stage in the investigation of Venus originated with the successful descent of the Soviet automatic interplanetary station "Venera-4" in the atmosphere of the planet. In the course of this experiment, direct measurements of temperature pressure and chemical composition were carried out in the atmosphere of Venus for the first time and unique scientific data were obtained. The results of these measurements are reported in [1,2]. The subject of this article is the comparison of the results of measurements of AIS "Venera-4" with the data of radar and radio astronomical ground measurements.

ALTITUDE DISTRIBUTION OF TEMPERATURE AND PRESSURE IN THE ATMOSPHERE

A comparison with the data of radio astronomical and radar measurements of Venus and the solution of a number of other problems necessitates the knowledge of the altitude distribution of temperature and pressure in the atmosphere of the planet. The measurement data of AIS "Venera-4" yield such a distribution from the planet's surface up to the altitude of 28 km [1]. We have determined the distribution of temperature and pressure from $h = 28$ km up to the upper boundary of the cloud layer by interpolating the dependence $p(T)$ obtained on the basis of measurement data (in infrared rays) of temperature $T = 240°K$ and pressure $p = 0.1$ atm obtained at the level of the upper boundary of the cloud layer [3,4]. For tying in altitude, the interpolation curve $p(T)$ (Fig.1) was divided into a series of temperature intervals ΔT. Within each interval the atmosphere was assumed to be polytropic, and consequently, the dependence $\log p = f(\log T)$ was assumed to be linear. Then, on the basis of the inclination angles of the thus separated line segments we have determined the polytropic exponent, equal to $\mu g/\beta R$, the temperature gradient β, and the altitude $\Delta h = \Delta T/\beta$ variation corresponding to the selected ΔT. Here μ is the molecular weight, g is the gravitation acceleration on Venus and R is the universal constant. The altitude of the upper boundary of the cloud layer was found to be $h_{cl} = 40$km. The distributions of $p(h)$ and $T(h)$ are in agreement with those obtained on "MARINER-5" [5], provided the radius of the planet surface is 6085 km. The distribution of temperature and pressure in the atmosphere for $h < 28$ km which was determined by an analogous method for control purpose is in good agreement with that obtained in [1]. In the region from 50 to 90 km above the cloud layer, i.e. from 90 to 130 km above the surface, the distribution

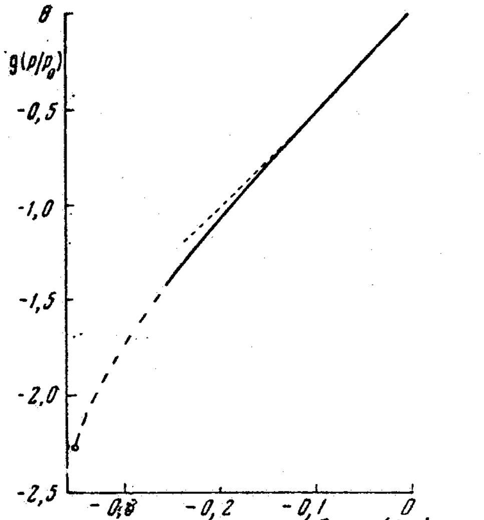

Fig.1

Dependence of pressure p on temperature T in the atmosphere of Venus relative to pressure p_0 and temperature T_0 near the planet surface.

Solid line) "Venera-4" data; broken line) calculated dependence for the adiabatic atmosphere; circle) measurement results in infrared; dashed line) result of interpolation between "Venera-4" measurements and measurements in infrared.

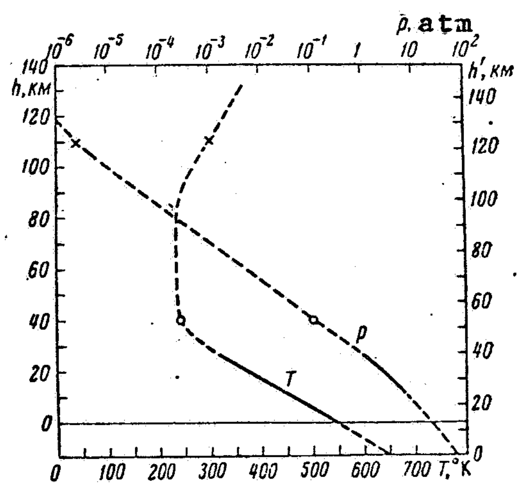

Fig.2

Distribution in height h of temperature T and pressure p in Venus' atmosphere.

Solid lines) results of "Venera-4" measurements; circles) data of measurements in infrared; crosses) results of Regulus eclipse measurements; h) altitude scale for a hypothetical model with p_0 = 50 atm.

of temperature and pressure was determined on the basis of the observation data on the Regulus eclipse [6,7] processed for a carbon dioxide atmosphere. The region between h = 40 and h = 90 km was assumed to be isothermic with a temperature of 235°K. The altitude distribution of temperature and pressure in the atmosphere of Venus is thus plotted in Fig.2.

COMPARISON WITH THE RESULTS OF RADIO ASTRONOMICAL AND RADAR MEASUREMENTS

In recent years, as a result of numerous radio astronomical measurements, the dependence on wavelenth of brightness temperature $\bar{T}_{я♀}$ of Venus' intrinsic radioemission was investigated in sufficient detail [4,8-10]. The most characteristic peculiarity of this spectrum is the approximate constancy of $T_{я♀}$ in the 20 to 2 cm wavelength range and its substantial decrease in shorter wavelenghts. Subsequently, it was established [11] that the high-temperature emission in the centimeter band originates from the hot surface of the planet, and the decrease in $\bar{T}_{я♀}$ in shorter wavelengths is due to this band's radiowave absorption by a colder atmosphere. However, the nature of this absorbing agent remained unclear. According to various hypotheses it could be a cloud layer consisting of drops of a "polar" liquid (for instance, of supercooled water or some hydrocarbons), a dust cloud, or a nitrogen atmosphere with pressure of 100-200 atm at the surface, etc. The results of AIS "Venera-4" measurements make it possible to solve this problem unambiguously. Fig.3 shows tha computational dependences $\bar{T}_{я♀}(\lambda)$ which we have calculated. The brightness temperature was determined by solving the radiation transfer equation. The absorption coefficient was determined from the relation

$$\alpha = \alpha_n + \alpha_{res}$$

Here α_n is the nonresonance absorption in carbon dioxide and water vapour. According to [12]

$$\alpha_n = p^2\nu^2(273/T)^5(15{,}7f^2_{CO_2} + 1330 f_{H_2O})\cdot 10^{-8}.$$

According to [2], the content in CO_2 and water vapours was assumed to be $f_{CO_2} \simeq 1$, $f_{H_2O} = 0{,}004$. The quantity α_{res} is the resonance absorption in the water vapour line λ = 1,35 cm equal to

$$\alpha_{res} = 7{,}2\cdot 10^4(1 + 3{,}182 f_{H_2O}) f_{H_2O}\nu^2\cdot e^{-644/T}\frac{p^2}{T^{4,125}} \times$$

$$\times\left[\frac{1}{(22{,}235-\nu)^2+\Delta\nu^2} + \frac{1}{(22{,}235+\nu)^2+\Delta\nu^2}\right].$$

The emissive power of the planet E = 1 - R was assumed to be 0.9 and identical over the entire disk, while the surface was assumed to be isothermic. The calculation was carried out for three values of the surface temperature: T_S = 550°K, that is equal to the temperature of the near-surface part of the atmosphere, T_S = 600°K and 650°K. Comparison with the results of radio astronomical measurements plotted in Fig.3 shows a good agreement between calculation and experiment.

The agreement existing between experimental and computational data for the atmosphere determined on the basis of AIS "Venera-4" measurements eliminates the necessity of including other agents absorbing the millimeter radioemission and makes it possible to estimate the upper limits of their possible content. Fig.4 shows the calculated spectra of Venus' radioemission in the presence of droplet-liquid water in the cloud layer.

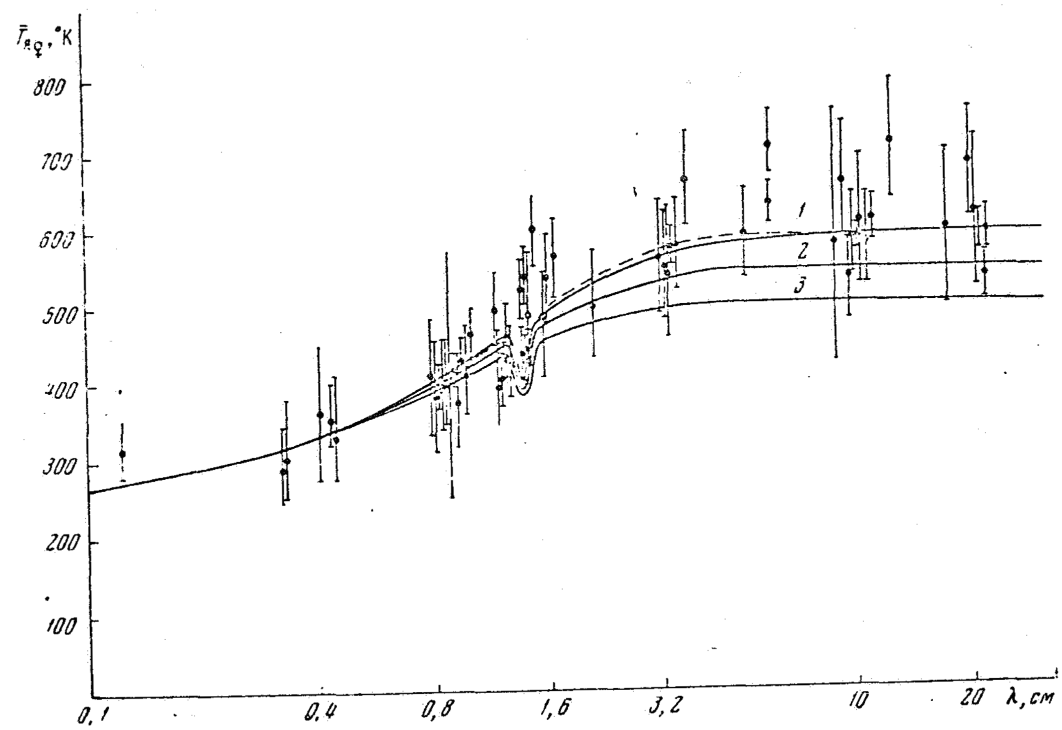

Fig.3

Calculated and measured dependences $\bar{T}_{я♀}(\lambda)$

The calculation is made for $f_{CO_2} \simeq 1$, f_{H_2O} = 0.004 and three values of surface temperature:
1) for T_S = 650°K; 2) for T_S = 600°K;
3) for T_S = 550°K; the dashed curve corresponds to the hypothetical model with p_0 = 50 atm; the dots are the measured values.

The calculation of the absorption coefficient was carried out on the basis of the approximate formula

$$\alpha_B = \alpha M_0/\lambda^2$$

where M_0 is the water content of the cloud and a is a coefficient depending on temperature. In the -20 to ∓ 20°C temperature range it can be approximated by the analytic relation $\alpha = 2{,}2\cdot\exp[0{,}04(273° - T)]$. In connection with the dependence of absorption on temperature, the quantity,

$$B = \int_{h_1}^{h_2} M_0(h)\exp[0{,}04(273° - T)]\,dh.$$

represents the parameter for evaluating the water abundance in the layer located between the altitudes h_1 and h_2.

Comparison of calculated spectra for B = 0.1; o.3; 1; 3 and 10 g/cm^2 shows that B > 0.3 g/cm^2 is not in agreement with the results of radio astronomical measurements. For a thickness of the cloud layer of the order of several kilometers this corresponds to the upper limit of the mean water content of the clouds of $M_0 < 0.1$ g/cm^3.

Comparison with radio astronomical observation data in the vicinity of λ = 1,35 cm allows us also to make more precise the water vapour content in the atmosphere of Venus. To this end we have calculated the spectrum for two values of the relative water vapour content, namely $f_{H_2O} = 0.004$ and 0.002. The fact that on λ = 1.35 cm a decrease in $\bar{T}_{s♀}$ predicted in calculations, was absent in the majority of radio astronomical measurements, shows that in the atmosphere of Venus the water vapour content is closer to the lower limit (0.1%) than to the upper limit (0.7%) determined on the basis of AIS "Venera-4" measurements.

We have also calculated the radio brightness distribution over the disk of Venus. In the 1.9 cm wavelength we have obtained a decrease in brightness temperature near the edge of the disk by approximately 100°K, which is in good agreement with the results of measurements by "MARINER-2" [13]. The corresponding calculation for the 3 cm wavelength was in good agreement with the results of measurements of radiobrightness distribution in this wavelength carried out at the Main Astronomical Observatory (Pulkovo), USSR [14].

Summing up the foregoing it may be said that the results of the radio astronomical measurements are in good agreement with the data obtained by AIS "Venera-4". At the same time it should be noted that the best agreement between the calculated spectrum $\bar{T}_{s♀}(\lambda)$ and the radio astronomical data takes place for $T_S \simeq 650$°K, i.e. at a surface temperature higher by approximately

100° than the atmosphere temperature measured by "Venera-4". This fact requires additional investigations and, apparently, it will be elucidated only in the course of further measurements. For the time being it is possible to formulate only some suppositions on the possible cause of the indicated diversity. Since AIS "Venera-4" measurements are related to a local region of Venus, while radio astronomical measurements yield parameters averaged over the entire visible disk, it may be assumed that AIS "Venera-4" landed in a mountainous region where surface temperature and the near-surface atmosphere temperature, which is equal to it, is by about 100°K lower than the average temperature of the surface. A calculation carried out under this assumption shows that in this case, the atmospheric pressure at the level of the mean surface may attain 50 atm.

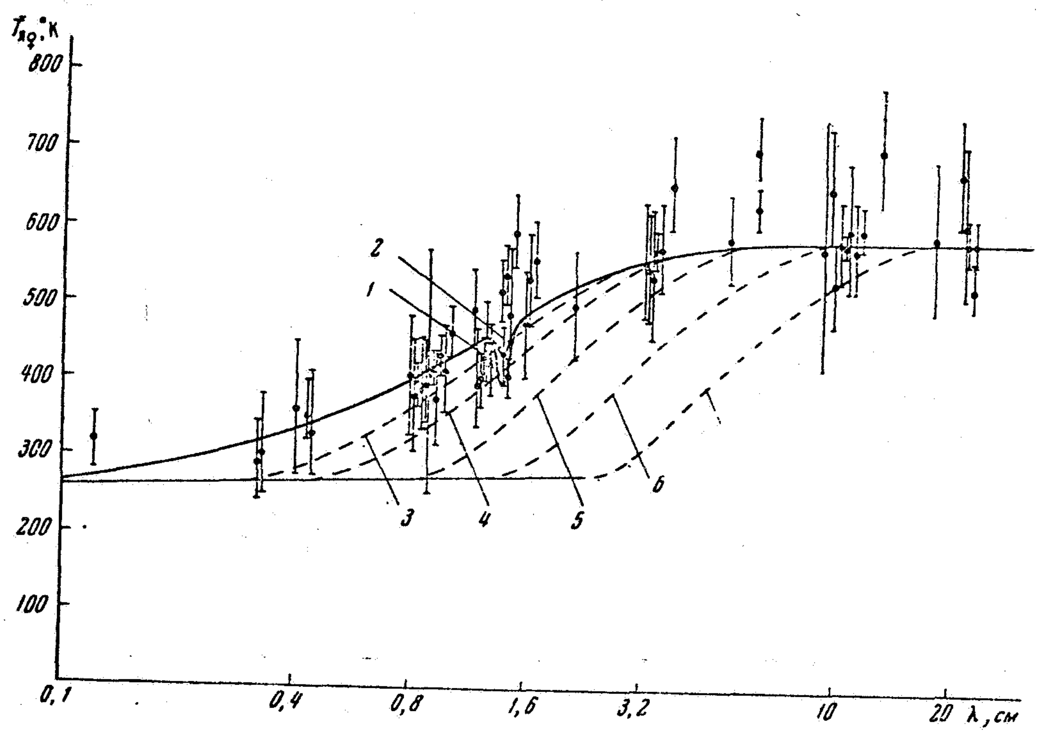

Fig. 4

Calculated and measured dependences $T_{я♀}(\lambda)$.

For various water vapour concentrations:
1) for f_{H_2O} = 0.004; 2) for f_{H_2O} = 0.002
for various droplet-liquid water contents
3) for B = 0.1 g/cm^2; 4) for B = 0.3 g/cm^2;
5) for B = 1.0 g/cm^2; 6) for B = 3 g/cm^2;
7) for B = 10 g/cm^2.

The distribution of temperature and pressure in height can be obtained by shifting the zero level by 10-15 km (right-hand scale of altitudes in Fig.2). The calculated spectrum of $\bar{T}_{я♀}(\lambda)$, computed under the aforementioned assumptions on temperature and pressure is plotted in Fig.3 by a dashed line. It can be seen that it is in good agreement with the experiment.

In such a model the taking into account of the absorption effect in the atmosphere increases the dielectric constant ε of the matter of Venus' surface, determined from radio astronomical polarization measurements [11] up to $\varepsilon = 3$, which is in agreement with radar measurement data corresponding to $\varepsilon = 3.1 - 4.7$.

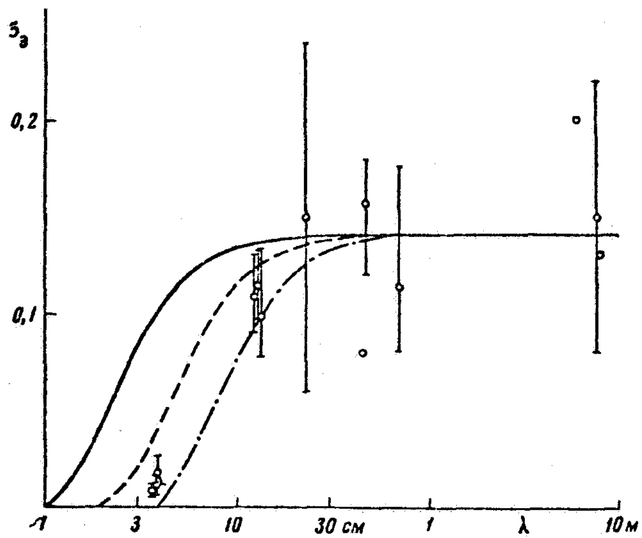

Fig. 5

Calculated and measured dependences $\sigma_{eff}(\lambda)$

Passing to the analysis of the radar measurements data on Venus, let us investigate the dependence of the effective cross-section of planet reflection σ_{eff} on wavelength. The quantity σ_{eff} is approximately constant and is equal to about 0.14 in the 70 to 20 cm wavelength range. It decreases down to about 0.015 in the 3 cm range (Fig.5) [4, 15-17]. Such a sharp variation of σ_{eff} can hardly be explained by the frequency dependence of the reflection factor $\rho(\lambda)$ of the matter of planet's surface. The short wave absorption in the planet atmosphere seems more natural.

Let us see whether the Venus' model atmosphere, based on AIS "Venera-4" data, can ensure the required absorption. The calculation was based on formula

$$\sigma_{eff}(\lambda) = \sigma_{eff\,0}[-2\tau(\lambda)],$$

in which it was assumed that $\lambda_{eff_0} = 0.14$. The results of the calculation are shown in Fig.5. The solid line corresponds to the calculation for a pressure of 20 atm at the surface with 0.4% of water vapour. In this case the absorption in CO_2 and in water vapour is insufficient for the agreement with the experimental data, and the presence must be assumed of some additional, still undetected agent in the atmosphere, strongly absorbing the electromagnetic radiation in the 3 cm band. Such an agent could be dust. However, to obtain the required absorption in the lower atmosphere of Venus dust should amount to about 1 kg/cm^2 [18].

The dashed line in Fig.5 shows the results of calculation for a pressure of 50 atm at the surface with 0.4% of water vapour It can be seen that at p_0 = 50 atm the model atmosphere of Venus based on AIS "Venera-4" measurements data is in agreement with the results of radio astronomical and radar measurements without having to involve any hypothetical absorbing agents.

A great interest is also offered by the comparison of radio astronomical and radar data with the "MARINER-5" measurements [5]. Unfortunately, the temperatures and pressures, measured by "MARINER-5", are referring to the distance from the planet's center of gravity. Therefore, in order to reduce them to the altitude above the surface it is necessary to know the radius of the surface. With $R_♀$ = 6056 km [19], determined by radar measurements, the extrapolation of "MARINER-5"'s measurement data along the adiabat yields a temperature and pressure of the atmosphere at the planet surface which are approximately 800°K and 150 atm. The obtained temperature of the atmosphere exceeds by 150°K the surface temperature which is the best agreement with the data of radio astronomical measurements. A still greater divergence occurs in the case of radar measurements data The calculated dependence $\sigma_{eff}(\lambda)$ for p_0 = 150 atm is shown in Fig.5 by a dot-dash line. The absorption of radioemission in the 3 cm band in the atmosphere of CO_2 at 150 atm pressure is so high that the calculated value of the effective cross-section of the radar reflection σ_{eff} = 0.14% must be one order lower than the measured -1.7%. On the other hand, for a planet surface radius equal to 6070-6085 km, the results of "MARINER-5" measurements are in good agreement with the data of radio astronomical and radar measurements (with the determination of $\sigma_{eff}(\lambda)$ in particular). In this case there exists a complete agreement between the results of measurements by "MARINER-5" and "VENERA-4"

The astronomical, radioastronomical and radar measurements, and especially the measurements carried out on AIS "Venera-4", have broadened considerably our knowledge of Venus' atmosphere and have considerably reduced the field of hypotheses concerning the physical conditions on the planet.

The solution of new and more spacific problems that have now arisen, will necessitate further investigations, in which a major role will be played by subsequent flights towrd Venus.

* * * THE END * * *

Manuscript received on
24 of April, 1968.

Contract No.NAS-5-12487
Volt Information Science, Inc.,
1145 19th Street, NW
Washington, D.C. 20036
Telephone: [202] 223-6700 X 36-37

Translated by
Mr. Daniel Wolkonsky
Sept 16, 1968
Revised by
Dr. Andre L. Brichant
Sept.19, 1968

LAB/ldf

REFERENCES

1. V.S. AVDUYEVSKIY, N.F. BORODIN, V.V. KUZNETSOV, A.I. LIFSHITS, M.Ya. MARKOV, V.V. MIKHNEVICH, M.K. ROZHDESTVENSKIY, and V.A. SOKOLOV: Dokl. AN. SSSR, 179, 310, 1968.
2. A.P. VINOGRADOV, Yu.A. SURKOV, K.P. FLORENSKIU, and B.M. ANDREYCHIKOV; Dokl. AN SSSR, 179, 37, 1968.
3. P. CONNES, J. CONNES, W.C. BENEDICT, L.D. KAPLAN: Astrophys. J., 147, No.3, 1230, 1967.
4. A.D. KUZ'MIN: - Radioastronomicheskiye Issledovaniya Venery. Izd-vo VINITI, 1967.
5. A. KLIORE, G.S. LEVY, D.L. CAIN, G. FIELDBO, S.I. RASOOL: Science, 158, 1683, 1967.
6. G. DE VAUCOULEURS, D.H. MENZEL: Nature, 188, No.4744, 28, 1960.
7. D.Ya. MARTYNOV, M.M. POSPERGELIS: Astron. Zh., 38, No.3, 558, 1961.
8. J.R. DICKEL: - Icarus, 6, No.3, 417, 1967.
9. M.P. HUGHES: - Planet. Space Sci., 14, No.10, 1017, 1966.
10. D.H. STAELIN, E.C. REIFENSTEIN: Preprint, 1966.
11. A.D. KUZ'MIN, V.D. KLARK: Astron. Zh., 42, No.3, 595, 1965.
12. W. HO, I.A. KAUFMAN, P. THADDEUS: J. Geophys. Res., 71, No.21, 5091, 1966.
13. F.T. BARATH, A.H. BARRETT, J. COPELAND, D.E. JONES; A.E. LILLEY: Astron. J., 69, No.1, 49, 1964.
14. D.V. KOROL'KOV, Yu.N. PARIYSKIY, Yu.N. TIMOFEYEVA, and S.E. KHAYKIN: - Dokl. AN SSSR, 149, No.1, 65, 1963.
15. J.V. EVANS, R.P. INGALLS, L.P. RAINVILLE, R.R. SILVA: Astron. J., 71, No.9, 902, 1966.
16. J.V. EVANS: - - Report at the 2nd Arizona Conference on Planet Atmosphere, Tucson, 1968.
17. J.C. JAMES: - - Astron. J., 72, No.8, 1047, 1967.
18. Yu.N. VETUKHNOVSKAYA, A.D. KUZ'MIN: Astron. Vestnik, 1, No.2, 85, 1967.
19. M.E. ASH, I.I. SHAPIRO, W.B. SMITH: Astron.J., 72, No.3, 338, 1967.