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2. Features of the atmosphere of Venus according to remote observations

Introduction

Venus is covered with a fairly dense atmosphere. Its atmosphere was discovered by M. Lomonosov in 1761 when the planet passed (Fig. 2.1) in front of the Sun's disk. Since the long-term visual observations conducted after that could not detect any optical inhomogeneities on the visible disk, even the answer to the question of the period of its rotation around its axis remained unknown until the second half of the 20th century [6, 30]. And only thanks to radar observations conducted in 1964-1970, it was possible to determine its value equal to 243.1085 Earth days. This value is very close to the resonant value calculated for the Earth-Venus planetary system [20], equal to 243.18 Earth days.

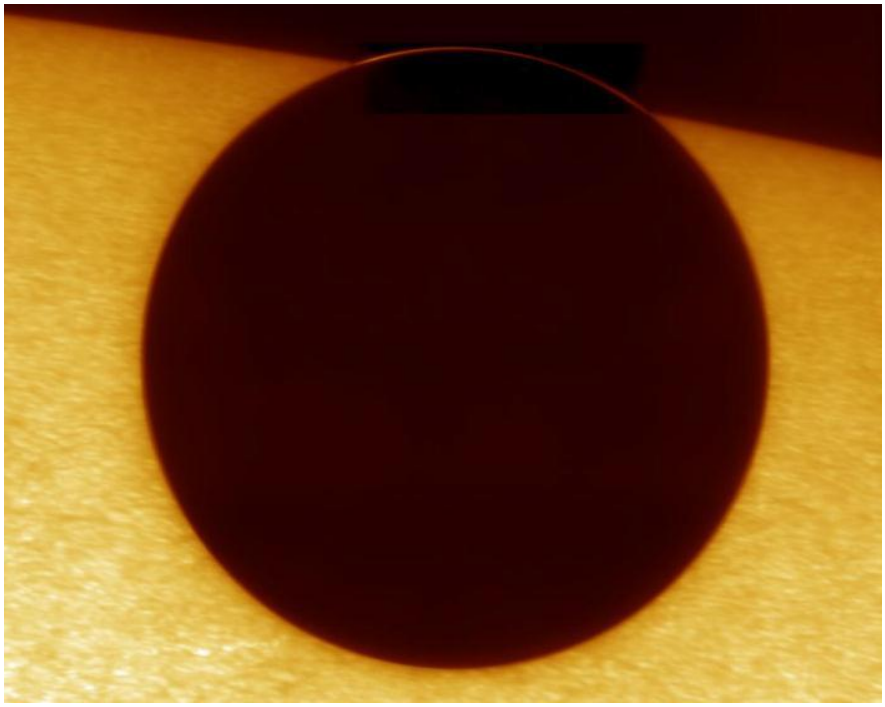

Fig. 2.1. Image of Venus passing across the Sun's disk on June 8, 2004. Along the edge of the planet, a bright stripe is visible against a dark background, resulting from the refraction of sunlight in the planet's atmosphere. The image was obtained with the Swedish Solar Telescope located on the island of La Palma (photo by Mats Lofdahl).

Moreover, the direction of rotation turned out to be opposite to the Earth's; that is, clockwise, if viewed from the North Pole of the World. The superposition of rotational movements around the Sun and around the axis led to the fact that the solar day on Venus lasts as long as 116.8 Earth days. The properties of sunlight diffusely reflected by the gas cloud layer of the planet, and the physicochemical properties of the atmosphere of Venus have been considered in detail based on observational data in a number of works [1, 4, 9, 10]. Therefore, below we recall some of its main characteristics.

2.1. General characteristics

The main physicochemical properties and celestial-mechanical characteristics of the planet's atmosphere are given in Table 2.1. To determine the period and direction of rotation around its own axis, radar observations of Venus were started only in 1958 at the Lincoln Observatory at the Massachusetts Institute of Technology in the USA [15].

But the very first estimates of these values, although with a rather large error, were made only in 1961. This was independently obtained by three groups of researchers using radio observations at wavelengths $\lambda = 4.3$ cm, 12.5 cm [7] and 68 cm [10]. Such a large error in determining specific digital data was due to the very weak reflected radio signal. Therefore, extraordinary efforts had to be made to increase the power of radio transmitters and to increase the sensitivity of the receiving equipment.

For example, the sensitivity of the radio telescope in Yevpatoria in 1962 was improved by as much as 6 times. Such efforts allowed to double the error in determining the rotation period of Venus. And in the frequency spectrum of the radiation reflected by the planet's surface [17, 18] it was possible to detect some anomaly, which was attributed to a topographic detail on the planet's surface [21, 22, 26-29]. By the displacement of this detail, it was possible to determine the value of the rotation period, equal to 240±60 Earth days, and establish the reverse direction of this rotation [2, 5, 14].

Table 2.1.

Main physical and orbital characteristics of the planet Venus [24].

Parameter name	**Its value**
Average diameter	12 103.6±1 km
Volume	$9.38 \cdot 10^{11}$ km³
Mass	$4.8685 \cdot 10^{24}$ kg
Density	5.204 g/cm³
Compression	~0.0002
Surface area	$4.60 \cdot 10^{8}$ km²
Acceleration of gravity	8.87 m/s², or 0.904·g
Sidereal rotation period	224.70069 days
Synodic rotation period	583.92 days
Rotation period	243.0185 days
Length of solar day	116.75 days
Average surface temperature	735 K
Average distance from the Sun	108 208 930 km
Perihelion	107 476 259 km
Aphelion	108 942 109 km
Average orbital velocity	35.02 km/s
Orbital eccentricity	0.0068
Albedo	0.65
Apparent magnitude	-4.7^{m}
Orbital inclination to the plane of the Sun's equator	≈ 3.86°
Angular size	9.7-66.0″
Elongation	< 48°
Surface pressure	9.3 MPa
Atmospheric composition	Carbon dioxide 96.5 % Nitrogen 3.5 % Sulfur dioxide 0.015 % Argon 0.007 % Water vapor 0.002 % Carbon monoxide 0.0017 % Helium 0.0012 % Neon 0.0007 %

Every year, the accuracy of the determination of the rotation period of Venus became more and more accurate, and in 1970, at a meeting of the International Astronomical Union (IAU), it was decided to consider the value of the rotation period of Venus around its axis equal to 243 Earth days. At the same time, the values of the

initial positions of the planetocentric coordinate system were also approved; the North Pole was considered to be directed from the ecliptic plane to the north to a point with the following coordinates: right ascension 273.0° and declination +66.0°. A certain position of it was taken as the zero meridian, which intersects the Alpha region with a center at latitude -30°S. From ground-based radar observations, the angle of inclination of the rotation axis to the perpendicular to the plane of Venus's orbit was determined. The obtained value is slightly less than 3°. Therefore, seasonal changes [19] on Venus are almost absent. The value of the radius of the solid surface of Venus (6057±55 km) was first determined only in 1965.

This was done during radio interferometric observations at a wavelength of λ=10.6 cm at the Owens Valley Observatory. From observations from the Pioneer Venus spacecraft, it was possible to establish that the figure of the solid surface of Venus can be described by a three-axis ellipsoid with the following values of its semiaxes: 6050.99±0.14 km and 6052.02±0.10 km in mutually perpendicular directions in the equatorial plane, and 6051.54±0.10 km in the polar plane [8, 23, 25]. At the same time, it was found that the position of the center of the Venus figure deviates from the center of mass by 430±120 m.

2.2. Optical properties of the atmosphere

The very first images of Venus in the ultraviolet spectrum were obtained in 1924 by W. Wright. They indicated the presence of darker Y-shaped details on the planet's disk, which were oriented symmetrically with respect to the equator (Fig. 2.2). More thorough studies allowed us to establish that these details begin to be noticeable starting from the wavelength λ<500 nm. Their photometric contrast reaches maximum values of K~45% at wavelengths less than 350 nm. Studies of changes in photometric contrast from the phase angle were carried out using images obtained by the Pioneer Venus spacecraft. They showed an increase in contrast to the values of the phase angle α=(40-60)°. And with a subsequent increase in the value of the phase angle, the contrast K decreased sharply.

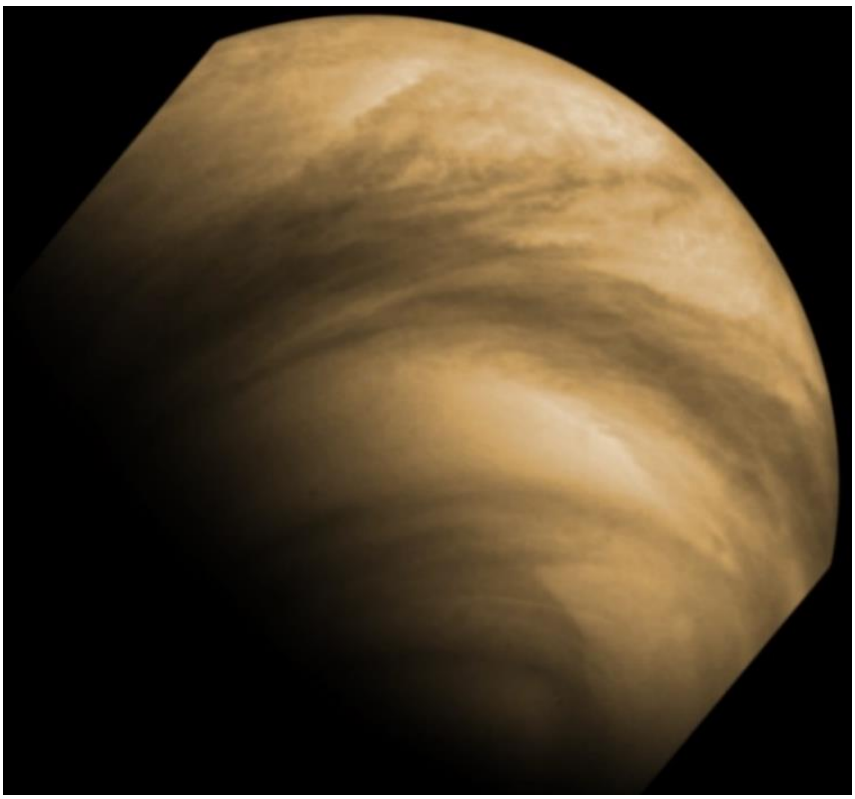

Fig. 2.2. Appearance of Venus in ultraviolet rays (https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2013/superhurrica.jpg).

The differences in the polarization properties of the parts of the disk of Venus were studied in detail by photopolarimetry from the “Pioneer-Venus” spacecraft. It was found that in the far ultraviolet at λ=270 nm the degree of polarization for dark parts is greater than for light parts in almost the entire interval of phase angles α. While in the near infrared range of the spectrum at λ=935 nm, differences in the degree of polarization began to appear only at phase angle values α>80°. But the degree of polarization P at these wavelengths became greater for light parts. The spectral phase dependences of the value of P in the polar regions practically coincide. However, in the northern region, changes in polarization P over time were much greater. The most complete data on changes in the phase dependence of the total brightness of Venus were obtained by V. Irwin and colleagues during observations at wavelengths of 314.7-1063.5 nm. Certain parts of the spectrum were cut out with broadband UBV filters and ten narrowband ones. Fig. 2.3 shows a fairly detailed phase dependence of the colors.

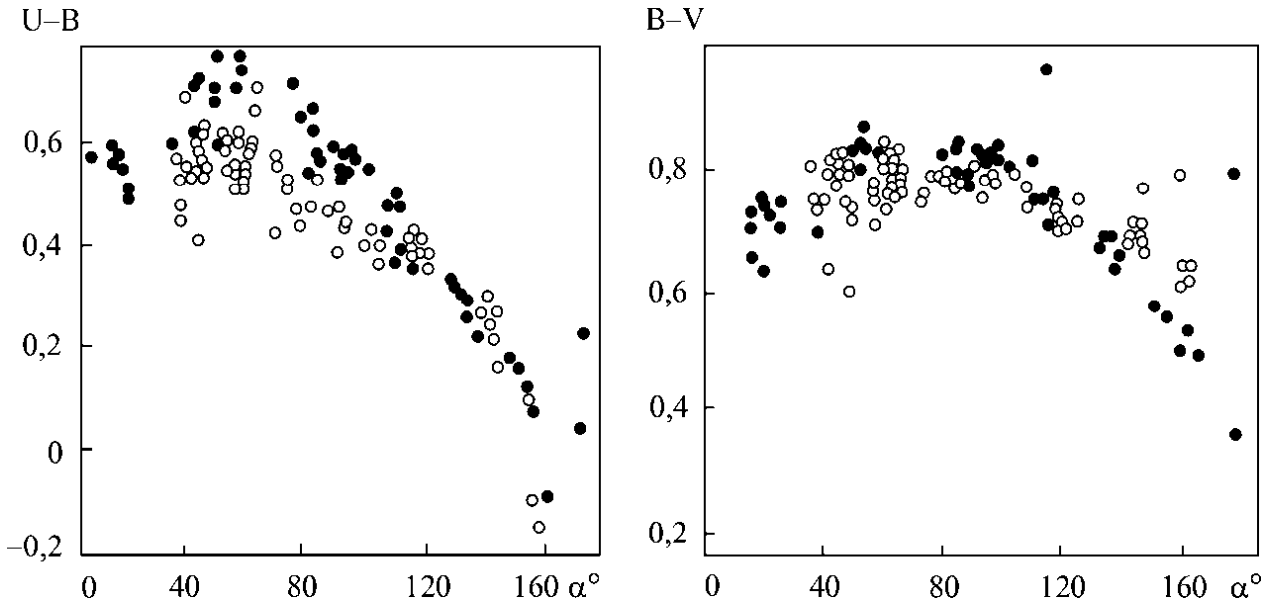

Fig. 2.3. Changes in the U-B and B-V color indices for the brightness of Venus depending on the phase angle α according to the observational results of various authors [10]

Back in the 1920s, B. Lio began to investigate the polarization properties of the entire disk of Venus using a visual polarimeter. Then he was able to obtain the phase dependence P(α), which still remains the most complete in terms of the range of phase angles. In the second half of the 20th century, observers supplemented the phase dependences in the spectral range 0.325÷4.8 μm. The dependence P(α) for individual parts of the disk of Venus in the far UV was determined from the board of the Pioneer-Venus spacecraft. The appearance of the phase dependence changes with wavelength, which determines the specific dependence P(λ) (Fig. 2.4).

For different values of the phase angles, the obtained dependences also turned out to be very different. This is clearly demonstrated by the data in Fig. 2.5, built on the results of observations by O.V. Morozhenko. In the 1960s, B. O'Leary pointed out the possibility of observing a 22-degree halo caused by ice crystals and water droplets in the phase dependence of the magnitude of Venus m(α) at the value α=157.5°. At that time, it had an amplitude of up to 7%. Later, it was observed by a number of other observers.

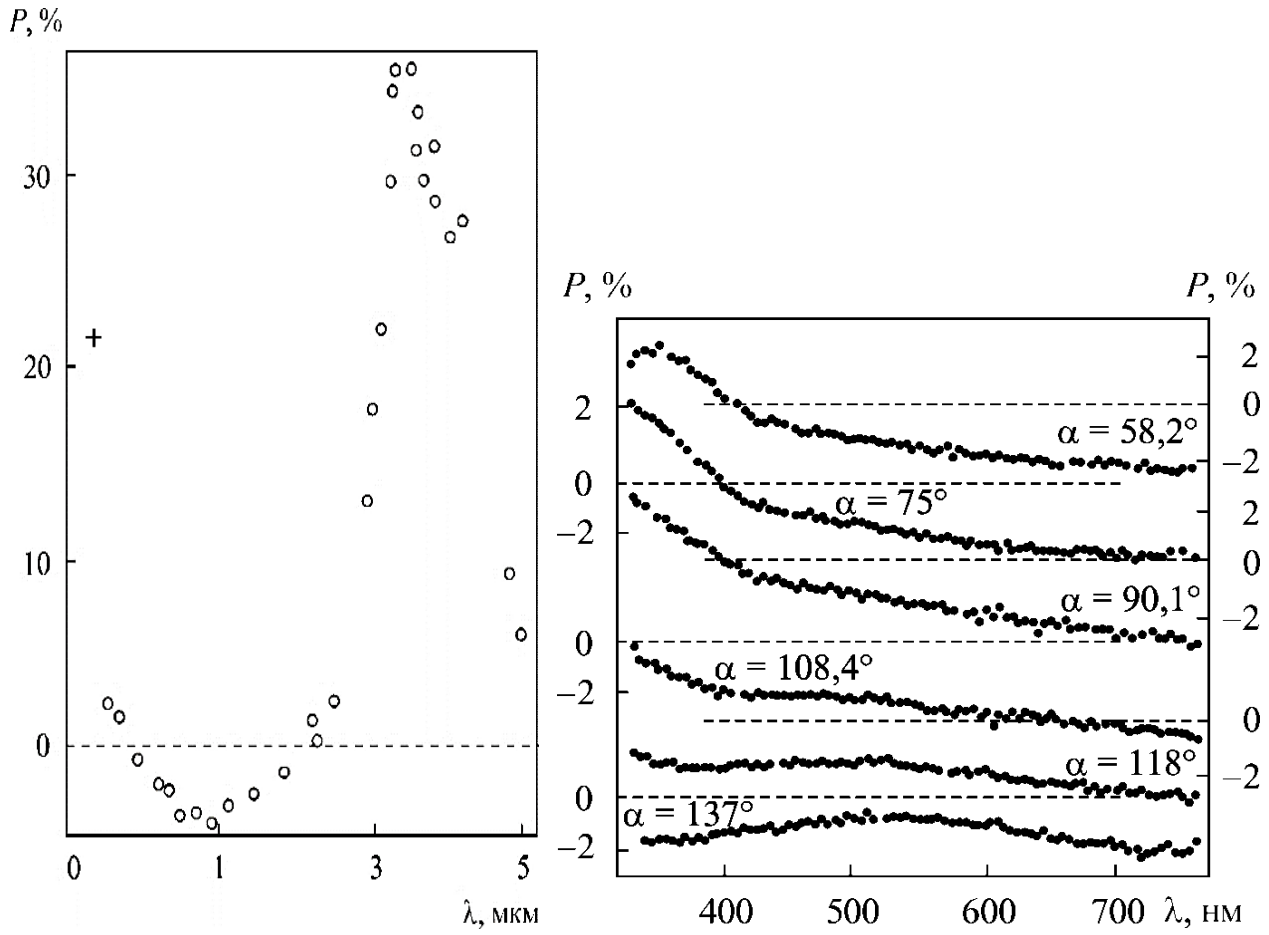

Fig. 2.4. Changes in the degree of polarization with wavelength for the disk of Venus at α = 103° (○) and 98° (+) [10].

Fig. 2.5. Results of spectropolarimetric observations; the ordinate scale for the results at a=58.2°, 90.1°, 118° is located on the right, and for a=75°, 108.4°, 137° – on the left [10]

In the 1930s, W. Adams and T. Dunham discovered carbon dioxide absorption bands in the spectrum of Venus. Only they appear quite clearly there. The equivalent width (W) of these bands depends on the phase angle α and has a noticeable maximum at a value of α≈60°.

2.3. Physical characteristics of aerosol particles in clouds

Comparing the phase dependence P(α) of radiation from the disk of Venus with the dependence P(α) obtained in laboratory conditions for water fog, B. Lio made the first attempt to determine the size of particles in the clouds of Venus. The best match

was observed for particles with a size r=1.25 μm. Later, other researchers obtained almost the same value.

They compared observational data with calculations for aerosol particles of different physical nature, different sizes, using the single scattering model, etc.

Very thoroughly, strictly taking into account multiple scattering by the method of doubling atmospheric layers was first performed by J. Hansen with A. Arking, and then by J. Hansen and D. Hovenir.

Using the model of a semi-infinite layer of gas and aerosols, they obtained the following parameters: the real part of the refractive index n_r=1.43±0.02 at a wavelength of 990 nm, and 1.46±0.02 at a wavelength of 365 nm; the value of the aerosol radius r_{ef}=1.1±0.1 μm; the ratio of the volume scattering coefficient of aerosol and gas at a wavelength λ=365 nm was f=0.45; the upper boundary of such a cloud layer was located at a pressure of 50 mbar. Fig. 2.6 shows the sensitivity of the observation results to changes in the input values of the quantities nr and ref.

J. Katavar and colleagues also performed an analysis of the same observational data; but they used different laws of particle size distributions when applied to three homogeneous Monte Carlo models, as well as to one model of as many as three layers. When analyzing the observational data obtained at a wavelength of λ=550 nm, the best agreement was found for a homogeneous model with the following values: n_r=1.45 and r_{ef}=1.1 μm.

Using the obtained value of the refractive index n_r=1.44 in visual rays, A. Young proposed a model of a cloud layer, the main component of which is sulfuric acid. As can be seen from Fig. 2.7, this value of nr corresponds to a 75% solution in water of sulfuric acid for a mass ratio f′.

The opposite direction of the arrows in this figure indicates the possibility of the existence of acid in liquid in the form of droplets and in solid in the form of crystals. The infrared spectrum of such a solution agrees quite well with the spectrum of Venus in the wavelength ranges of 3.0-3.6 and 8-14 microns.

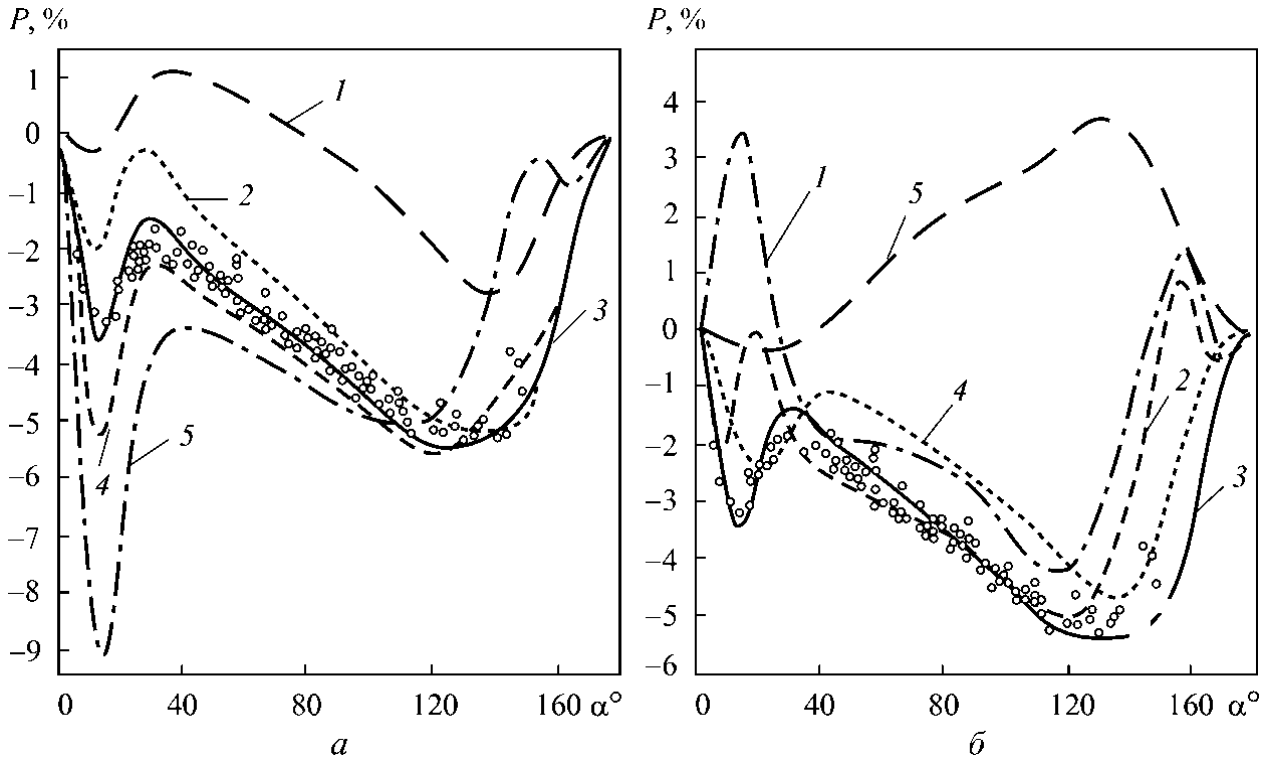

Fig. 2.6. Comparison of model calculations and observational (○) dependence of the degree of polarization on the phase angle P(α) at l=990 nm: (a) 1– at n_r=1.33 (r_{ef}= 0.8), *2* – at n_r=1.40 (r_{ef}=1.0), *3* – at n_r=1.43 (r_{ef}=1.05); *4* – at n_r=1.45 (r_{ef}=1.1), *5* – at n_r=1.50 (r_{ef}=1.2); (*б*) – at n_r=1.43 and r_{ef}=2 (1), 1.5 (2), 1.0 (3), 0.7 (4), 0.4 μm (5) [10]

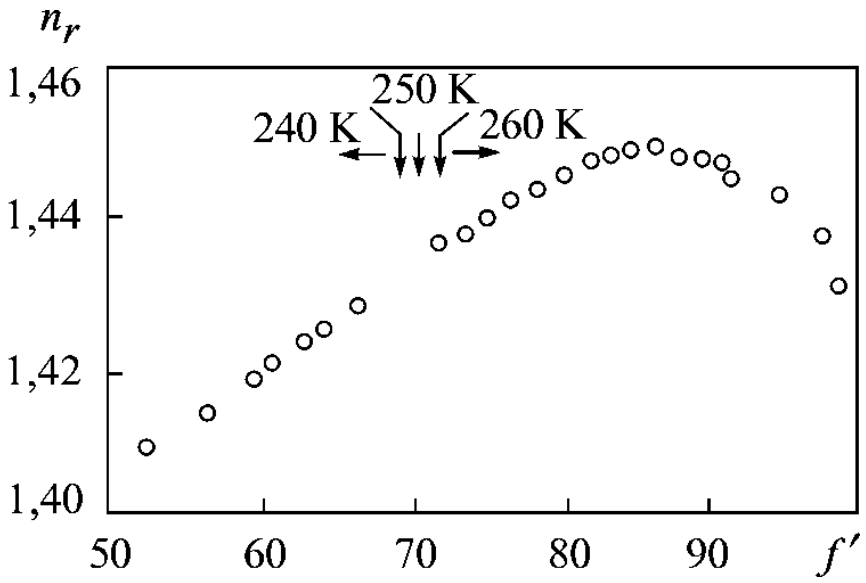

Fig. 2.7. Changes in the real part of the refractive index of an aqueous solution of H_2SO_4 with a mass ratio f' [10].

Some decrease in the reflectivity of Venus with a decrease in the wavelength from 2.3 to 1.2 microns can be explained by the pollution of the cloud layer. After all, in the spectrum of a 75% solution of H_2SO_4 in pure water, such a decrease is not observed. When studying the characteristics of the atmosphere of Venus, very little attention was paid to the values of the albedo of single scattering in the continuous spectrum. Namely, these data are used to determine the imaginary part of the refractive index.

The spectral values obtained from observations regarding the phase changes of the degree of polarization $P(\lambda, \alpha)$ for the disk of Venus satisfy the calculations performed when applying the model of a homogeneous gas-aerosol layer. However, when processing images transmitted from the “Mariner-10” spacecraft, obtained in directions perpendicular to the planet's limb, they indicated the presence of at least two more layers above the clouds with several kilometers of a purely gas gap between them.

Even higher, at altitudes of 78-90 km, there is a very thin fog, which covers the pressure range from 0.5 mbar to almost zero. The particles in such a fog can also be droplets of a concentrated solution of sulfuric acid in water.

The presence of such a fog with a particle radius of less than 0.3 μm was confirmed by subsequent experiments on other spacecraft. It follows that the physical parameters of fog particles above the main cloud layer, obtained from the analysis of ground-based polarimetric observations for the entire disk of the planet and for individual parts on this disk, showed somewhat different results [16].

Although the reality of changes in the altitude of the upper level of the cloud layer was independently confirmed by the analysis of the results of infrared sounding in tens of wavelengths for most of both hemispheres of the planetary disk, performed by the infrared radiometer of the “Pioneer-Venus” spacecraft from 04.12.1978 to 14.02.1979.

Starting with the launches of the “Venera-9 and -10” spacecraft, the vertical structure of the clouds began to be studied using nephelometric instruments. They illuminated a certain volume of the atmosphere with radiation at a wavelength of λ_{ef}=920 nm; the radiation scattered by the atmosphere was recorded by special

receivers at three values of phase angles. Processing of the obtained observation results made it possible to register that at altitudes of 18-63 km the clouds actually consist of separate layers, and the gaps between these layers are also not purely gaseous.

The studies conducted by the “Pioneer-Venus” spacecraft were unique. Four separate probes were dropped from this spacecraft to different regions of Venus: near the equator, at high northern latitudes, and at mid-southern latitudes on the day and night sides of the planet. All of these probes operated at λ=630 nm. As the results of these studies showed, no particles larger than 35 μm could be detected in the clouds. Analysis of the results taken from all four probes showed that most likely the particles in the clouds are spherical. A similar experiment was also performed by probes from the “Venera-15 and -16” spacecraft.

Since the value of the imaginary part of the refractive index (especially in the UV) turned out to be somewhat greater than for a 75% solution of H_2SO_4, the possible presence of SO_2 in the gaseous state in the atmosphere of Venus was suggested in [13]. Its presence was also confirmed by spectrophotometric observations of the Venusian atmosphere by the equipment of the probes of the spacecraft "Venera-15 and -16".

However, the same effect can be exerted by some more complex sulfur molecules, which are called allotropes: S_2, S_3, S_4 and S_8. Since such a chemical element as sulfur does not dissolve in sulfuric acid, and sulfur condensates do not penetrate into the middle of the droplet, the size of these particles does not increase. X-ray radiometric and gas chromatographic analysis of these droplets carried out on the probes "Venera-15 and -16" allowed us to find there also such chemical elements as chlorine and fluorine [3].

2.4. Gaseous components of the atmosphere of Venus

From ground-based spectrophotometric observations, it was possible to reliably detect only the absorption bands of carbon dioxide CO_2. The remaining atmospheric components of the planet Venus were determined using gas chromatographs and mass spectrometers installed on various spacecraft. From the results of these observations, it was possible to confirm that the main component of the atmosphere is ≈96.5% CO_2;

nitrogen there is ≈3.5%, while molecules of other elements were found only in “trace” quantities. SO_2, H_2S, H_2O, CO, He, Ar, HCl, etc. were found there. The concentrations of these gases and their isotopic composition noticeably depend on the height above the surface.

It is believed that in the atmosphere of Venus the main source of CO_2 is its release from the planetary crust during the degassing process. Calculations of the total mass of CO_2 in the planet’s atmosphere alone give a value of $4.7 \cdot 10^{20}$ kg. This is almost 300 thousand times greater than the mass of the same gas in the Earth’s atmosphere [11, 12]. However, when we also take into account the reserves of carbon dioxide on Earth associated with water in the ocean and with compounds in the crust, these reserves are almost the same.

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