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THE INFLUENCE OF VOLCANIC ACTIVITY ON THE FORMATION OF THE VENUS SURFACE

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ABSTRACT

Due to the similarity of size, mass, average density, etc., Venus is called the “sister” of Earth. But this planet is a world with a very different geological history and surface conditions. The surface of Venus is hidden under a dense layer of sulfuric acid clouds. The temperature on this surface reaches 737 K, and the pressure is 92 times higher than on the Earth's surface. Both planets formed in almost the same part of the Solar System and should have a similar chemical composition, similar metallic cores and silicate mantle. However, Venus represents a paradoxical case of planetary evolution, and demonstrates a different path of further development from Earth.

Venus revolves around the Sun at a distance of 0.723 AU in 224.7 Earth days in an almost perfectly circular orbit. Due to the peculiarities of its orbit, Venus is the closest planet to Earth, approaching at a distance of less than 40 million km. Venus does not have a significant global magnetic dipole field, and there are no satellites around it. Its geological activity manifests itself in forms that are significantly different from Earth's plate tectonics. Studying the extreme conditions on Venus' surface and in its atmosphere can help to better understand climate processes and their possible consequences on planet Earth.

The geological history of Venus is characterized by large-scale volcanism and provides a unique opportunity to study alternative paths of evolution of rocky planets. Venus can serve as a natural laboratory for studying processes that may have occurred on the early Earth before the establishment of modern plate tectonics. Modern understanding of Venus is largely based on data obtained by spacecraft. They have allowed to obtain detailed data on the relief of the surface of Venus, to register the absence of plate tectonics and the fact that about 85% of its surface is covered with volcanic lava flows and mountains.

The atmosphere of Venus is radically different from Earth's, consisting mainly of carbon dioxide. This leads to a powerful greenhouse effect; and this heat retention heats the surface to extremely high temperatures. The evolution of Venus involves the evaporation of its primary oceans. A comparison of Venus and Earth reveals both

similarities and fundamental differences between them. This makes them ideal objects for studying the factors that determine planetary evolution.

Despite the lack of direct observations of seismicity on Venus, models of the internal structure have been developed based on its global characteristics and measurements from artificial satellites. The general model of the internal structure of Venus is similar to that of the Earth and includes three main shells: a metallic core, a silicate mantle, and an outer crust. The somewhat lower average density of Venus compared to Earth indicates the presence of lighter elements in the core, such as sulfur. The absence of a significant global magnetic field may indicate either that the core is completely solidified, or that although it is liquid, the conditions for the dynamo effect are absent. The mantle of Venus consists mainly of silicate rocks rich in iron and magnesium. The outer hard shell of Venus – the crust – is relatively thin compared to the mantle and core. Its composition, according to analyses conducted by the Venus landers at the landing sites, is mainly basaltic. And this is a typical product of volcanic activity on the planet.

Such an internal structure and processes in the bowels of Venus directly affect its surface geology. The largest details of the relief on the planet Venus are three large hills; they are peculiar continents or continents. The surface relief on Venus turned out to be very diverse in shape, in height difference and in its physical characteristics. A careful study of the surface relief confirmed the predominantly magmatic composition for the bedrock on Venus. Such volcanic features as large plains – occupy the majority of the entire surface of Venus. Analysis of the observational data obtained to date shows that approximately 500 million years ago, the crust of Venus was very volcanically active and was subject to intense deformation. The numerous, fairly evenly distributed, medium-sized impact craters indicate that the planet's surface is relatively young. And the enormous number and variety of volcanic structures indicate long-term and intense magmatic activity in the planet's interior.

Although its surface appears geologically young (average age ~0.5 billion years) and the number of volcanic structures is enormous, there has been no direct evidence of modern eruptions until recently. However, data accumulated over the past decades provide increasing evidence that volcanism on Venus may still be ongoing. Data obtained by various spacecraft have shown high concentrations of SO_2 in the upper atmosphere, which then decreased. Such fluctuations can be explained by episodic large volcanic eruptions that eject significant amounts of SO_2 to high altitudes. Observations with infrared spectrometers have revealed several areas associated with geologically young volcanic regions that have anomalously high thermal emissivity. This also suggests that the lava flows in these areas are relatively "fresh", which could be manifestations of active eruptions or fresh lava flows.

The most convincing evidence of modern volcanic activity came from the analysis of archival radar data from the Magellan mission, which mapped the same areas several times, several months apart. Analysis of these images of the area revealed distinct changes in the vent and on the slopes of the volcano. These changes are direct geological evidence of volcanic eruptions that occurred on Venus during the time of the observations. This confirmation of modern activity has important implications for our understanding of Venus. Thus, Venus, despite its similarity to Earth in size and mass, is a world with a unique geological landscape and extreme surface conditions. Its current state is the result of a complex interaction of a specific internal structure, long-term and intense volcanic activity, and a thick atmosphere.

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TABLE OF CONTENTS

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1. The main astronomical and physical characteristics of Venus and their comparison with Earth

Introduction

Because of its similarity in size, mass, and average density, Venus is often called Earth's "sister." However, this planet is a world with a very different geological history and surface conditions. The surface of Venus is hidden under a dense layer of clouds (Fig. 1.1) of sulfuric acid. And the temperature on it reaches 737 K at a pressure that is 92 times higher than on the Earth's surface.

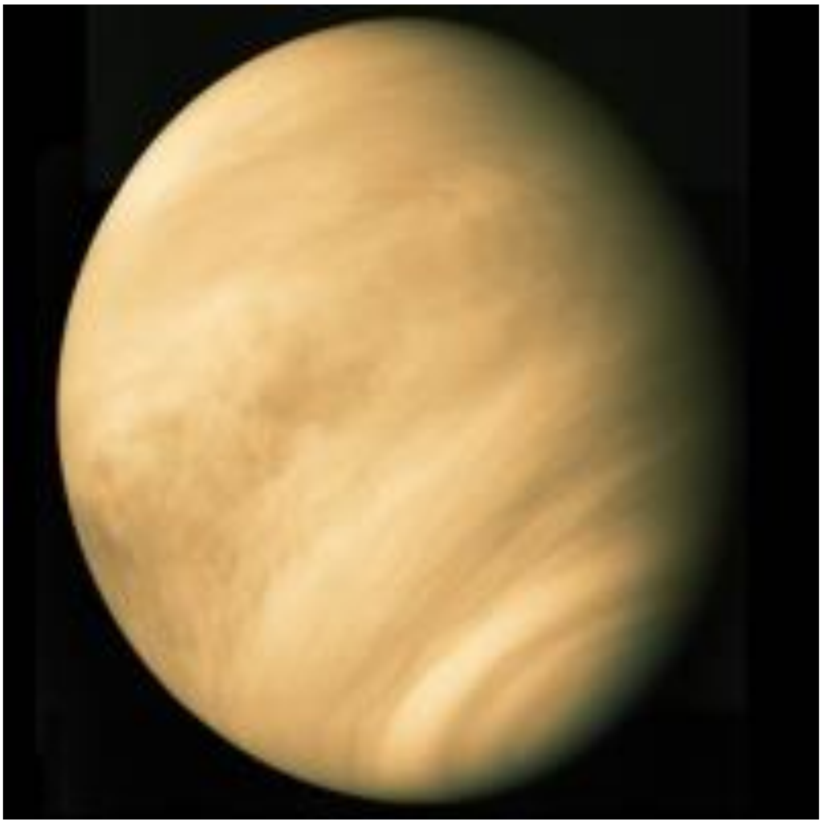

Fig. 1.1. Photograph of Venus taken by the Mariner 10 spacecraft (https://sci.esa.int/sci-images/40/ACFKIA.kay8r.jpg).

Both planets belong to the so-called terrestrial group [30]. They formed in approximately the same part of the Solar System and should have a similar overall chemical composition, similar metallic cores and silicate mantle. However, the list of similarities practically ends there. Venus represents a rather paradoxical case of planetary evolution, demonstrating a radically different path of further development from Earth. After all, its surface turned out to be red-hot to temperatures at which some metals can melt.

In terms of its size and mass, Venus is very similar to Earth. Its average radius is 6051.8 km, which is approximately 95% of the Earth's radius. The mass of Venus is estimated at $4.8685 \cdot 10^{24}$ kg, or about 0.815 times the mass of Earth. Its average density is 5.24 g/cm^3, only slightly less than the average density of Earth (5.514 g/cm^3). This high density indicates a significant proportion of metals (mainly iron and nickel) in its core and a silicate composition of the mantle and crust [29].

The gravitational force at the equator of Venus is about 8.87 m/s^2, which is approximately 91% of Earth's gravity. Venus orbits the Sun at an average distance of 0.723 AU and completes one orbit in 224.7 Earth days [1, 3]. The plane of Venus's orbit is only slightly inclined to the plane of the ecliptic: about 3.4°. Venus's orbit is almost perfectly circular, with a very low eccentricity of only 0.0067. This means that Venus's distance from the Sun varies very little during its orbital motion: from 107.5 million km at perihelion to 108.9 million km at aphelion. Due to the peculiarities of its orbit, located inside the Earth's, Venus is the closest planet to Earth, sometimes approaching a distance of less than 40 million km.

One of the most striking characteristics of Venus is its very slow and, moreover, retrograde (from east to west) rotation. Moreover, the sidereal period of the planet's rotation is 243.02 Earth days. This combination of slow retrograde rotation and relatively fast orbital motion leads to a very long solar day, which is the period between two consecutive noons. Its axial tilt is 177.36°, which is almost inverted compared to the tilt of the Earth's axis.

It is also important to note that Venus does not have a significant global magnetic dipole field [22], and there are no satellites around it; and its geological activity manifests itself in forms that are significantly different from the Earth's plate tectonics. Such significant contrasts between two seemingly very similar celestial bodies raise a fundamental question regarding the list of factors that determine the evolutionary paths of these nearby terrestrial planets [23].

1.1. The significance of Venus research

The above characteristics show that the study of Venus is of key importance for planetology. After all, the study of extreme conditions on its surface and in the atmosphere [9], in particular the powerful greenhouse effect, should help to better understand climate processes and their possible consequences on planet Earth [15]. Analysis of the geological history of Venus, which is characterized by large-scale volcanism [7, 24, 33] and the absence of plate tectonics [10] of the terrestrial type, provides a unique opportunity to study alternative paths of evolution of rocky planets and mechanisms of loss of internal heat by these bodies. And a comparison of Venus with our planet Earth will also reveal a list of critical factors that determine the suitability of a particular planet for life, and understand why Earth became an oasis of life, and its “sister” – a hellish world (Fig. 1.2). In addition, Venus can serve as a natural laboratory for studying processes that could occur on the early Earth before the establishment of modern plate tectonics.

1.2. Exploration of Venus by Space Missions

Our modern understanding of Venus is largely based on data obtained by spacecraft (SC). Since the first successful flyby of Mariner 2 in 1962, a series of subsequent space missions have revealed the planet's secrets. The Soviet "Venera" program made the first surface landings and analyzed its rocks and atmosphere. The American Pioneer Venus missions (an orbiter and atmospheric probes) provided detailed data on the atmosphere and allowed the first global topographic maps of the surface.

A revolutionary step was the high-resolution radar mapping carried out by the “Venera-15”, “Venera-16” and, especially, the American Magellan (1990-1994) spacecraft, which was able to map about 98% of the surface of Venus [18, 20]. The result of their work was the discovery of a complex world of surface structures such as volcanoes, plains, mountain ranges and unique tectonic structures [2, 11].

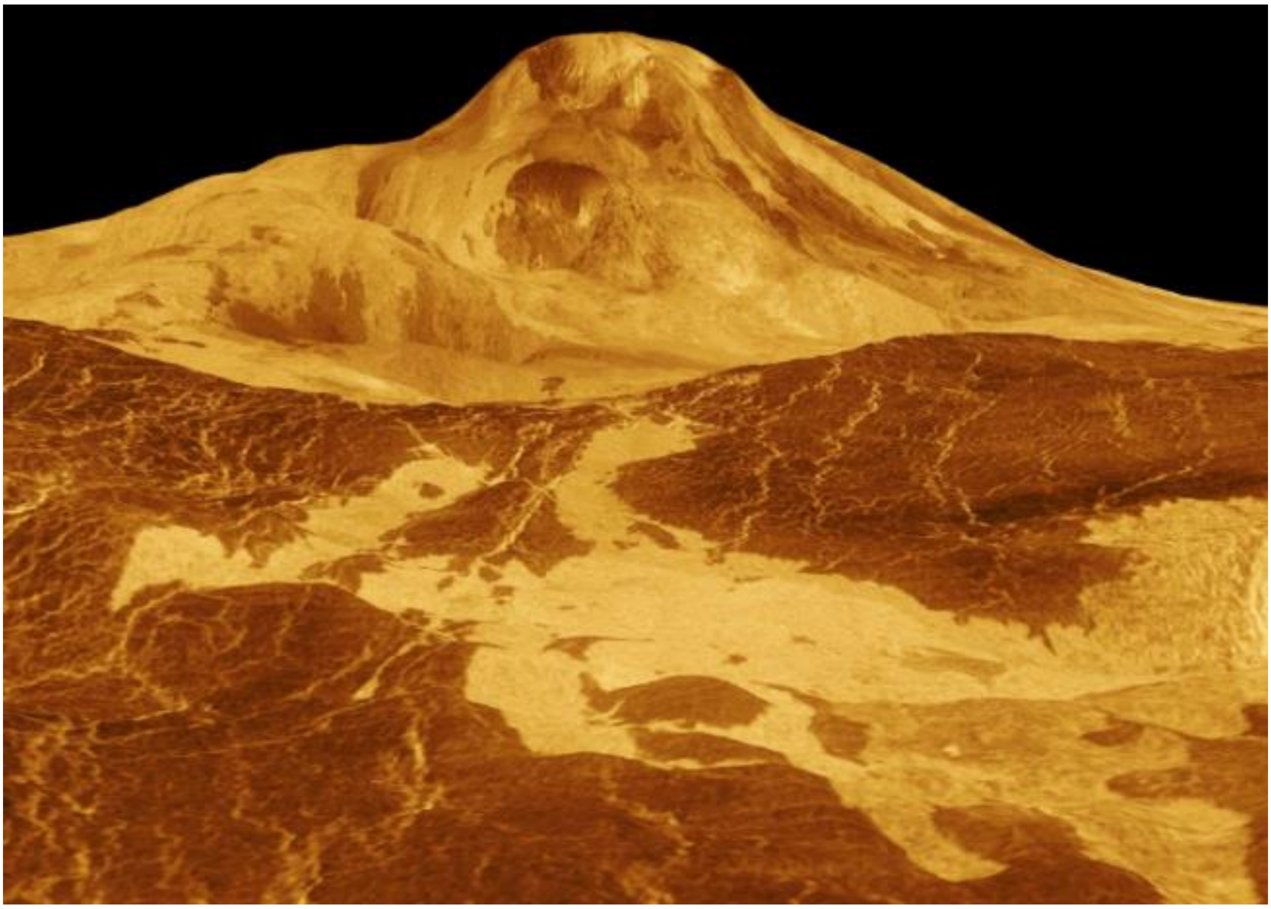

Fig. 1.2. Perspective view of Maat Mons on the surface of Venus, 1700 m above the terrain. Lava flows extend for hundreds of kilometers across fractured plains. Maat Mons is a volcano 8 km above mean surface level. Vertical scale increased by 22.5 times. Simulated shades are based on color images obtained by the "Venera-13" and "Venera-14" spacecraft (https://studfile.net/html/2706/829/html_hByup0TCgQ.cNvD/img-b7teeL.jpg).

The European mission Venus Express (2006-2014) focused on studying the atmosphere [8]. However, it was also able to provide important observational data indicating possible modern volcanic activity [32, 34]. The Japanese spacecraft "Akatsuki" continues to study the atmosphere of Venus. And future missions to Venus, such as VERITAS (NASA), DAVINCI (NASA), and "EnVision" (ESA), promise to delve even deeper into the secrets of this planet, using the latest technologies to map its surface, analyze the composition of the atmosphere and crust, and to further search for definitive evidence of modern geological activity.

Below we provide a fairly detailed list of various spacecrafts that have explored

Venus. In this, the planet is second only to the Moon and Mars. In doing so, we will use the data published in the book [30], prepared with our participation.

02/12/1961 the spacecraft “Venera-1” (USSR) was first sent to Venus. The device was equipped with a magnetometer, radiation sensors, etc. At that time, it was assumed that after landing on the planet, it would float in a vast ocean. However, a week after launch, contact with this spacecraft was lost, and the device flew 100 thousand km from the planet. On July 22, 1962, the United States launched the “Mariner 1” spacecraft. But after the rocket deviated from its intended course, an accident occurred 293 seconds after launch.

On August 25, 1962, the USSR launched another spacecraft of the “Venera” type. But when it entered Earth's orbit, problems occurred and it became “Sputnik 19”. On August 27, 1962, the United States launched a backup spacecraft “Mariner 2”. But due to problems, this spacecraft flew 34,773 km from Venus. However, its instruments were able to record thick clouds, high temperature and high pressure near the surface, the planet's very slow rotation, and the absence of a noticeable magnetic field.

On September 1, 1962, the USSR launched another spacecraft to Venus. But due to problems in Earth's orbit, it became “Sputnik 20”. On September 12, 1962, the USSR launched “Sputnik-21”, which was intended to fly by Venus; however, an accident occurred. On November 11, 1963, the USSR launched “Kosmos-21” to test the capabilities of various technologies for flying to Venus, and this spacecraft remained in Earth orbit.

On February 19, 1964, the USSR launched unsuccessfully, first “Venera-1964A”, and after half a month, on March 1, 1964, the “Venera-1964B” spacecraft. On March 27, 1964, the USSR launched “Kosmos-27” in the direction of Venus (it remained in Earth orbit). It should be noted that since 1962, the name “Kosmos” began to be given to all spacecraft that, regardless of their original purpose, remained in Earth orbit. On April 2, 1964, the USSR launched the spacecraft “Zond-1”; it also missed Venus, flying 100 thousand km from it. On November 12, 1965, the USSR launched the spacecraft “Venera-2”. It was equipped with a television system, equipment for studying cosmic rays, the magnetic field, solar plasma flows and flows of low energy charged particles and micrometeorites.

But on February 27, 1966, this spacecraft also flew 24 thousand km from Venus. On November 16, 1965, the USSR launched the spacecraft "Venera-3" with the aim of lowering it to the surface with a significant list of scientific instruments and a radio communication system. Although it was able to reach Venus in the spring of 1966, the lander was unable to transmit any information. 11/23/1965 The USSR launched the spacecraft "Kosmos-96" due to an accident in orbit.

06/12/1967 The USSR launched the spacecraft "Venera-4", designed to study Venus and Mars both from a flight path and using a lander. 10/18/1967 this device was able to enter the atmosphere and for more than an hour and a half it descended to the night side of Venus using a parachute system; it transmitted data on the pressure, composition of the atmosphere and temperature up to an altitude of 25 km; and already there it was crushed by the atmosphere. It was able to obtain information that at an altitude of 25 km the temperature of the Venusian atmosphere was 544 K with a pressure of about 20 bars. It was also possible to establish that the atmosphere of Venus consists of 96% carbon dioxide CO_2.

On June 14, 1967, the United States launched the "Mariner 5" spacecraft, which was a backup spacecraft for "Mariner 4". After the successful operation of its predecessor, the spacecraft was modified. The television cameras were removed, the solar panels were changed, and thermal insulation was added. On October 19, 1967, this spacecraft flew within 4,000 km of Venus. The updated equipment was able to determine the very high surface temperature [16] and that its atmosphere was much denser than previously expected.

On June 17, 1967, the USSR launched the "Cosmos 167" spacecraft, which again remained in Earth orbit. On January 5, 1969, the USSR launched the "Venera 5" spacecraft. A specially upgraded capsule was also parachuted into the nighttime atmosphere. But it was only able to operate there for 53 minutes and was crushed by atmospheric pressure. Sensors on the descent vehicle were able to measure atmospheric pressure in the range from 0.13 to 40 bars; gas analyzers were also able to determine the chemical composition of the components in the atmosphere, other devices determined the illumination in the atmosphere, density, and temperature in the atmosphere [26].

10.01.1969 the USSR launched the spacecraft "Venera-6"; since it was a copy of the spacecraft "Venera-4 and -5", the atmosphere also crushed this descent vehicle. But it was still possible to obtain updated results on the structure of the solar wind near Venus and it was obtained that the front of the change in plasma flows was observed at a distance of 28 thousand km from the surface of the planet.

17.08.1970 the USSR launched the spacecraft "Venera-7". The descent vehicle entered the planet's atmosphere on 15.12.1970 and first began to brake aerodynamically, and then – with the help of parachutes. He was the first to reach the planetary surface and work there for 23 minutes. Data were obtained on the chemical composition of the atmosphere, on temperature changes at different altitudes and on the surface itself, and on pressure changes with altitude.

The atmospheric pressure near the surface of Venus was found to be 90±15 bar at a temperature of 748±20 K. On 03/27/1972, the USSR launched the “Venera-8” spacecraft. Entry into the atmosphere took place on 07/22/1972. At an altitude of 60 km above the surface, a parachute with a diameter of 2.5 m was opened, and as a result, a landing was made on the day side of the planet for the first time. At altitudes of 35-30 km, a sharp decrease in illumination was registered. On 03/31/1972, the USSR launched the “Kosmos-482” interplanetary station, which did not leave Earth's orbit. On November 4, 1973, the United States launched the “Mariner 10” spacecraft, which used Venus' gravity to accelerate it to its final destination, Mercury. The closest approach to Venus was 5,770 km. The spacecraft transmitted almost 3,000 images of Venus to Earth in the ultraviolet (UV) range and visible light with a maximum resolution of up to 18 m. On June 8, 1975, the USSR launched the “Venera 9” spacecraft, and on June 14, 1975, “Venera 10”. The first landed on October 22, 1975, on the illuminated part of the planet, and the second on October 25, 1975, 2,200 km from it.

Due to its cooling system, the “Venera 9” probe was able to operate on the surface for about 53 minutes. Both spacecraft were able to transmit color panoramas of the surface to Earth for the first time. On 20.05.1978 the USA launched the spacecraft “Pioneer-Venus-1”, which on 4.12.1978 was launched into the orbit of Venus. With the help of radar equipment, certain features of the relief were obtained on a significant part of the surface of Venus [25]. This made it possible to compile maps with the presence of mountain ranges, large plateaus and lowlands. With the help of magnetometers, the absence of a magnetic field on Venus was confirmed. It was also possible to detect the presence of permanent lightning discharges, which were concentrated only in certain regions of the planet.

On 08/08/1978, the United States launched the “Pioneer Venus-2” spacecraft, which on 16/11/1978 dropped one large (with a diameter of about 1.5 m and a mass of 316 kg), and on 20/11/1978 three smaller (with a diameter of 0.7 m and a mass of 96.6 kg) descent vehicles onto the night side, the day side, and the area near the planet's North Pole. All four modules entered the atmosphere on 9 December and descended for almost an hour. One of the smaller vehicles was able to work on the surface for over an hour, although it was not designed for this. The results of this experiment confirmed the already known atmospheric chemical composition, and a thin layer of dust was detected on the surface itself. Below the cloud level, water vapor [12] and a fairly high concentration of molecular oxygen [5] were detected.

Droplets of concentrated sulfuric acid were recorded in the upper layer of clouds at an altitude of 65-70 km. In the middle layer of clouds, in addition to sulfuric acid, a large number of solid and liquid sulfur particles were found. Slightly larger sulfur particles were in the lower layer of clouds at an altitude of about 50 km. Below 30 km, the atmosphere of Venus turned out to be relatively transparent. On September 9, 1978, the USSR launched the “Venera-11” spacecraft. Its entry into the atmosphere occurred on December 25, 1978, and the landing lasted about 1 hour. The instruments of this station registered electrical discharges in the atmosphere, up to 25 lightning flashes per second. One of the thunderclaps lasted as long as 15 minutes. The occurrence of such discharges may be facilitated by the high content of sulfuric acid in these clouds.

The amount of sulfur dioxide, sulfur itself, nitrogen, carbon monoxide, water vapor, neon, argon, and their isotopic ratios in cloud particles were determined using mass spectrometry, gas chromatography, X-ray and optical spectrometry methods. To study the thermal regime of the planet, the results of the absorption and re-emission of sunlight at different altitudes in the atmosphere were refined [4].

In the upper layers of the atmosphere, about 96% of carbon dioxide and up to 4% of nitrogen were found; traces of SO_2 and carbon monoxide were also found; oxygen was practically absent, and the water vapor content under the cloud layer was within 0.1-0.4%, and above the clouds it reached 15-30%. The temperature near the surface was 735 K at a pressure of about 90 bars. 09/14/1978 the USSR launched the spacecraft "Venera-12". It descended to the surface 800 km from the “Venera-11” spacecraft and was able to register up to 1 thousand lightning flashes. On 10/30/1981, the USSR launched the “Venera-1”3 spacecraft, and 4 days later, on 11/4/1981, the almost identical “Venera-14” spacecraft.

Their landings on the surface were carried out on March 1 and 5 at a distance of 950 km between them. Color images of the landscapes were obtained at the landing sites, and soil analysis was performed on the surface of Venus (Fig. 1.3). Drilling, sampling, and chemical analysis of the soil composition were carried out at a temperature of 740 K and a pressure of 93 bars. Oxides of iron, silicon, aluminum, magnesium, calcium, potassium, and titanium were found in the soil. The measured mechanical strength of the soil and electrical conductivity were similar to terrestrial basalts present in the ocean basins on Earth.

02.06.1983 the USSR launched the spacecraft "Venera-15", and 5 days later – 07.06.1983 – "Venera-16". Their orbital modules were equipped with radar systems that transmitted images of the surface of individual parts of the planet in the northern hemisphere and the results of measurements of the height of the relief [13]. The materials obtained allowed to compile an atlas of the surface of Venus, maps of its relief, geological [18] and other special maps with a resolution of 1-2 km. These images show craters, large faults, hills, ranges and mountain ranges.

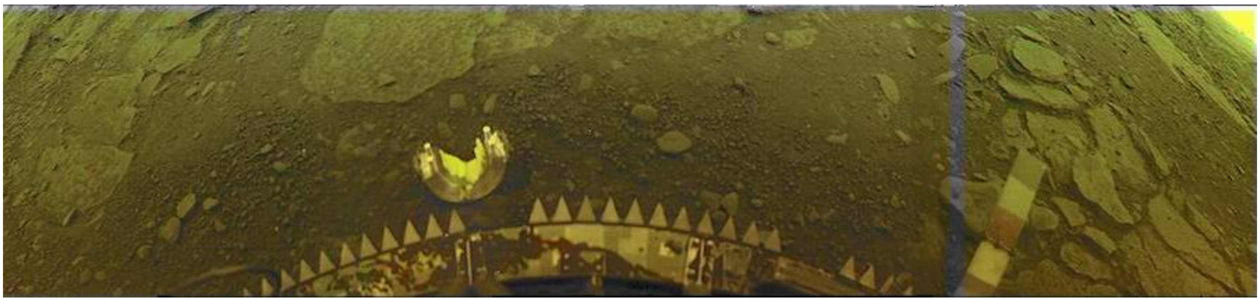

Fig. 1.3. Panoramas of the surface of Venus at the landing site of the “Venera-13” spacecraft (the second of two 180° sectors) [27].

On 15.12.1984 and 21.12.1984, the USSR launched the “Vega-1” and “Vega-2” spacecraft. Their main task was to study Halley's Comet. But the descent vehicles to the surface of Venus were also designed and manufactured using a new method. They consisted of a landing module and also had aerodynamic probes. These probes drifted for almost two days at an altitude of about 54 km and transmitted the results obtained on the studies of the atmosphere and surface of the planet. The landing modules were first equipped with UV spectrometers, with which they determined small atmospheric components and the concentration of water vapor. The balloon probes drifted for almost 9 thousand km, and when they reached the day side of Venus, they collapsed.

04.05.1989 The USA launched the Magellan spacecraft. On August 10, 1990, it reached Venus and entered a polar orbit with a rotation period of 195 minutes. Over the course of two years, the spacecraft was able to image about 98% of the surface; it operated until October 12, 1994, when communication with the spacecraft was lost. Bistatic radar provided detailed data on the relief of almost the entire surface of Venus with a resolution of better than 100 m.

At the same time, it was possible to record the absence of plate tectonics [19] and the fact that about 85% of the planet's surface is covered by volcanic lava flows [2, 6], and the remaining 15% by mountains.

A very slow erosion process was also noted and the average age of rocks on the surface was up to 500 million years. Measurements of gravitational anomalies on the planet allowed maps of the state of its interior to be constructed. 09.11.2005 The European Space Agency launched the interplanetary probe "Venus Express". Its main goal was to study in detail the environment around Venus and its interaction with the solar wind flows. Studies were also carried out on the properties of the surface, its structure and geology of the surface layer, changes in the composition and chemistry of the atmosphere, the cloud layer and fog above it. On 12.04.2006, it was possible to obtain the first image of the planet's north pole (Fig. 1.4).

Fig. 1.3. Image of two vortices in the atmosphere above the north pole of Venus obtained by the “Venus Express” spacecraft (http://www.esa.int/SPECIALS/Venus_Express/).

On August 3, 2004, the “Messenger” spacecraft was launched to study Mercury. To enter orbit around the planet closest to the Sun, the probe had to perform a series of maneuvers, which included one orbit around the Earth, two orbits near Venus, 15 orbits around the Sun, and then another 3 orbits near Mercury. During the second approach to Venus, the spacecraft transmitted a series of images to Earth and established communication with the then artificial satellite of Venus, the “Venus Express” spacecraft.

The interplanetary station of the Japanese Aerospace Exploration Agency “Akatsuki”, or “PLANET-C”, was launched on May 21, 2010. On December 7, 2010, this device unsuccessfully approached Venus and failed to enter orbit around the planet. The probe's engines were retested several times. But only on 7.12.2015 the spacecraft was able to enter the planned elliptical orbit around Venus. On 4 April this probe was able to transmit the first images of the planet in the IR range to Earth.

The spacecraft with a solar sail “IKAROS” was also created by the Japanese Aerospace Agency. It was launched on 21.05.2010; and from 3 to 10 June the solar sail with a total area of 200 m2 was successfully deployed. On 8.12.2010 “IKAROS” passed at a distance of about 81 thousand km from Venus, successfully completing the planned mission.

1.3. Briefly about the atmosphere of Venus

The atmosphere of Venus is its most prominent feature, which radically distinguishes it from the Earth. It is the densest among the terrestrial planets [23, 28] in the Solar System, and its mass is about $4.8 \cdot 10^{20}$ kg. The pressure at the average surface level reaches as much as 92-95 bar, which is almost a hundred times higher than the atmospheric pressure at sea level on Earth. The atmosphere consists mainly of carbon dioxide (CO_2), the proportion of which exceeds 96.5%.

The second most abundant gas is nitrogen (N_2), which is about 3.5%. All other components, such as sulfur dioxide (SO_2), argon (Ar), water vapor (H2O), carbon monoxide (CO), helium (He), neon (Ne), halides (HF, HCl) and various sulfur compounds (SO_2, SO, OCS, H_2S), are present only in trace amounts. Atomic oxygen (O) has been detected only in a thin layer high above the surface. Therefore, there is no significant amount of molecular oxygen (O_2) in the atmosphere of Venus. This may indicate the absence of large-scale biological processes and a different atmospheric evolution compared to the early Earth.

The dominance of CO_2 in the atmosphere leads to a powerful greenhouse effect.

After all, such an atmosphere freely transmits visible sunlight, but effectively absorbs infrared radiation in the thermal range, which comes from the heated surface. Therefore, this heat retention and heats the surface to extremely high temperatures; the average temperature on the surface of Venus is about 737 K.

This makes it the hottest planet in the Solar System; hotter even than Mercury, which is closer to the Sun. The temperature on the surface of Venus is sufficient to melt metals such as lead and zinc. At the same time, daily fluctuations in temperature on the surface are insignificant due to the enormous heat capacity of such a dense atmosphere.

Venus is completely covered with a dense multilayer cloud cover, located at an altitude of 45 to 70 km above the surface. These clouds consist mainly of small droplets of concentrated sulfuric acid (H_2SO_4).

These clouds also contain small amounts of solid sulfur, nitrosyl sulfuric acid and phosphoric acid. These components are highly reflective; therefore, Venus's albedo is one of the highest in the Solar System, about 0.77. This makes Venus a very bright celestial object in the sky, but completely obscures the planet's surface from visible light observations. Therefore, the surface can only be studied with radar or landers.

Thin aerosol hazes lie at altitudes of 30 to 90 km. And it is sulfur-containing compounds that are crucial for understanding cloud formation. Polysulfur (forms of pure sulfur, such as S_2, S_4, S_8) is suspected of forming very small particles on which sulfuric acid droplets condense.

These polysulfur molecules are formed as a result of the photochemical destruction of sulfur dioxide (SO_2) in the atmosphere; and recent studies have revealed new photochemical pathways for their formation.

The upper part of Venus atmosphere is in a state of extremely rapid global circulation, known as “superrotation”. This superrotation begins at an altitude of about 10 km and increases steadily with altitude. The upper layers of the clouds rotate around the planet from east to west with a period of about 4 Earth days. This value is much faster than the rotation of the planet itself.

The wind speed at the cloud top at an altitude of about 65 km reaches 100 m/s.

Higher up, the wind speed decreases significantly with altitude. And near the surface, the wind speed is only a fraction of m/s.

The mechanism of superrotation is quite complex, but the interaction of thermal tides with planetary Rossby waves is thought to contribute significantly to these fast winds. This phenomenon also plays a role in the uniform distribution of heat across the planet's surface. Superrotation, driven by atmospheric waves, is the primary mechanism for efficient global heat redistribution, and explains why the surface temperature remains nearly constant day and night, despite the planet's slow rotation.

This warm layer further emphasizes that the atmosphere of Venus is a highly dynamic system with significant vertical and horizontal circulation, rather than simply a static blanket for the surface layers. This complex atmospheric circulation is crucial for understanding the planet's energy balance and the stability of the global climate.

In the upper cloud layer at altitudes of about 60 km, temperatures are relatively constant, close to 230 K. Above this level, the temperature decreases, reaching about 165 K at an altitude of 95 km, where the mesopause begins. Recent observations from the Venus Express spacecraft have revealed an unexpected warm layer on the night side of the planet at altitudes of 90-120 km, in a region considered to be the cryosphere of Venus (Fig. 1.4).

Measurements have shown that this “temperature inversion” shows a temperature increase of 30-70 K, reaching a peak at an altitude of about 100 km. It is believed that such an increase may be caused by the descent of peculiar gas “pockets” from higher altitudes in the atmosphere and their heating due to compression.

This region of the Venusian atmosphere also contains light hazes of various aerosol particles, which consist mainly of sulfuric acid and water. They are very variable and can be seen from a distance as bright areas in the planet's clouds. But so far, they are poorly studied areas of the planet, as previous space probes that descended through Venus' atmosphere only began their measurements at altitudes of 60 km and below. The historical evolution of Venus involves the evaporation of its primordial oceans, which led to the release of water vapor into the atmosphere.

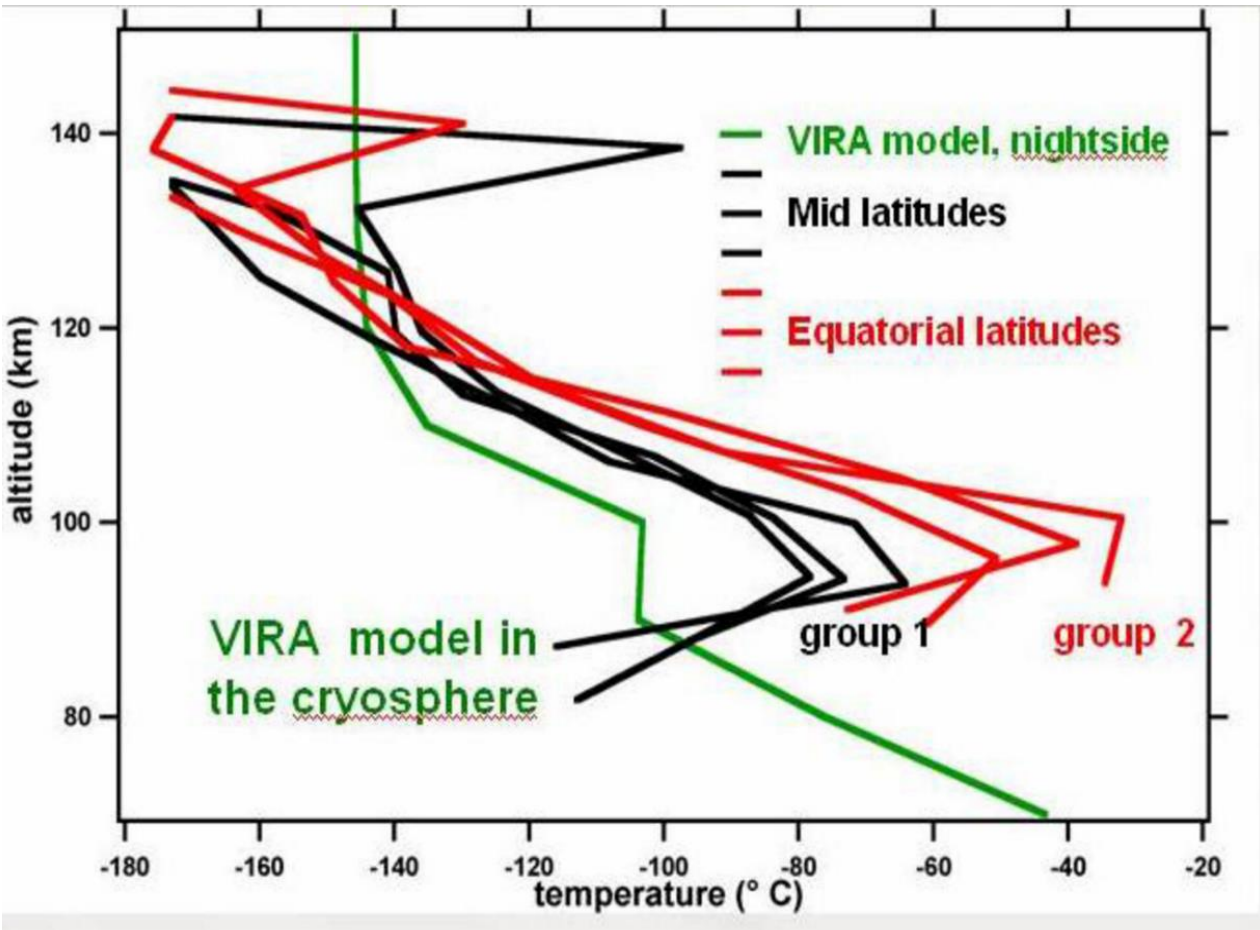

Fig. 1.4. Nighttime temperatures in the atmosphere of Venus (https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2007/11/venus_-_night-time_temperatures_in_the_atmosphere/9260274-5-eng-GB/Venus_-_night-time_temperatures_in_the_atmosphere_pillars.jpg). Venus - night-time temperatures in the atmosphere.

This, in turn, accelerated the greenhouse effect. Eventually, hydrogen, after photodissociation, escaped into space, and carbon trapped in rocks sublimed into the atmosphere; its subsequent combination with oxygen led to the formation of increasing amounts of CO_2, and to the formation of the increasingly dense, heat-trapping atmosphere observed today. Venus is a prime example of what happens when the greenhouse effect goes unchecked.

Earth's atmosphere contains only a tiny fraction of CO_2 compared to Venus, but anthropogenic emissions have increased its concentration by about 30% since pre-industrial times, amplifying Earth's greenhouse effect. Studying Venus therefore allows us to understand the consequences of extreme greenhouse effects. Venus is therefore a critical natural laboratory and a powerful warning sign for the habitability of planets and their climatic evolution.

It demonstrates how seemingly small initial differences in orbital position and internal dynamics can lead to radically divergent evolutionary paths, transforming a potentially habitable world into a hostile one. This highlights the delicate balance of planetary systems and the profound influence of atmospheric composition on surface conditions.

1.4. Comparative analysis with Earth

A comparison of Venus and Earth reveals both some similarities and fundamental differences. This makes them ideal objects for studying the factors that determine planetary evolution. As already noted, the main similarities lie in the global physical parameters: size, mass, average density and, consequently, the force of gravity. Both planets are rocky bodies with a differentiated internal structure, which includes a metallic core and a silicate mantle.

The differences are more numerous and profound. The most striking difference concerns the atmosphere and climate: Venus's extremely dense, hot, dry atmosphere, dominated by CO_2 and clouds of H_2SO_4, contrasts with Earth's moderate-pressure, nitrogen- and oxygen-rich atmosphere, with water clouds and the presence of liquid water on the surface.

Venus rotates slowly and retrogradely, while Earth rotates relatively quickly and in a direct direction. Venus has no satellites and no global magnetic field [17], unlike Earth. Geological activity on Venus also manifests itself differently: there is no terrestrial-type plate tectonics, and processes associated with mantle plumes and large-scale volcanism dominate [31, 33].

Table 1.1 below summarizes the key comparative characteristics. These tables clearly demonstrate that although Venus and Earth are very similar in size and mass, their evolutionary paths have led to the formation of very different celestial objects.

Table 1.1.

Comparative characteristics of Venus and Earth

Parameter	**Venus**	**Earth**	**Ratio (Venus/Earth)**
Average radius (km)	6051.8	6371.0	0.950
Mass (10^{24} kg)	4.869	5.972	0.815
Volume (10^{10} km³)	92.843	108.321	0.857
Average density (kg/m³)	5238	5514	0.951
Surface gravity (m/s²)	8.87	9.82 (average)	0.903
Orbital period (Earth day)	224.7	365.26	0.615
Rotation period (Earth day)	243.02 (retrograde)	0.997 (23.93 год)	~243.7
Axis inclination to orbit (deg.)	177.36 (or 2.64)	23.44	-
Average surface temperature (°C)	464	15	-
Atmospheric pressure (bar)	92 - 95	~1	~92-95
Main atmospheric components	CO_2 (>96.5%), N_2 (~3.5%)	N_2 (~78%), O_2 (~21%), Ar (~0.9%)	-
Presence of satellites	0	1 (Moon)	-
Global magnetic field	Practically no	There is (dynamo effect)	-

1.5. Relationships between the characteristics of Venus

Some key characteristics of Venus are closely related. For example, the lack of a significant global magnetic field is likely a consequence of the planet's extremely slow rotation. Even if Venus had a liquid metallic core similar to Earth's, the slow rotation would not provide a sufficiently intense dynamo effect to generate a strong field. The lack of a magnetosphere, in turn, makes Venus's atmosphere more vulnerable to interaction with the solar wind, which may have played a crucial role in the planet's loss of water during its history.

Another important relationship exists between the composition of its atmosphere and its surface temperature. Although Venus receives about twice as much solar energy as Earth, its high albedo, due to its dense clouds, means that it absorbs less energy. However, its surface is much hotter due to the dominance of carbon dioxide (over 96%) in the atmosphere. CO_2 is a potent greenhouse gas that effectively traps thermal radiation from the surface, creating a runaway greenhouse effect. This demonstrates the critical role of atmospheric composition in determining the planet's climate and serves as an important example for understanding the greenhouse effect on Earth [14].

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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.

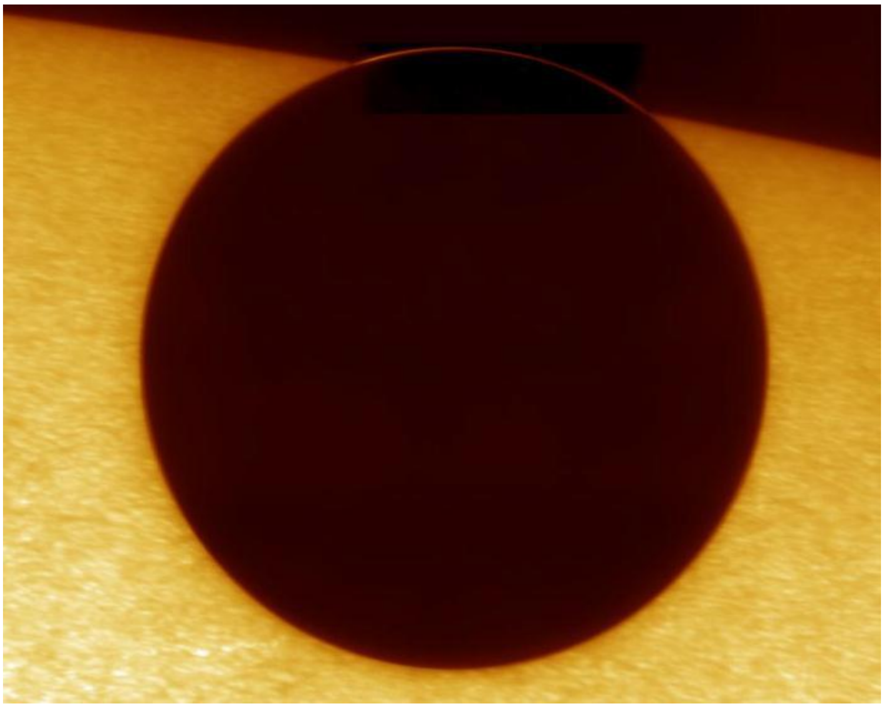


Fig. 2.1. Image of Venus passing across the Sun's disk on June 8, 2004. Along the edge of the planet, a bright stripe is visible against a dark background, resulting from the refraction of sunlight in the planet's atmosphere. The image was obtained with the Swedish Solar Telescope located on the island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

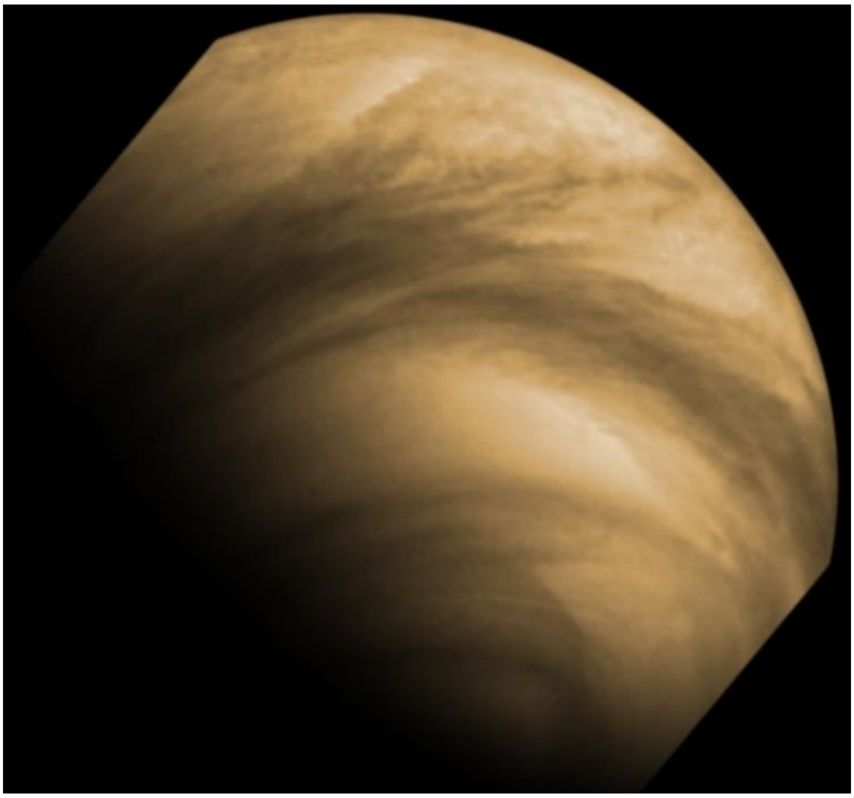


Fig. 2.2. Appearance of Venus in ultraviolet rays (https:// 3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2013/superhurrica.jpg).

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.

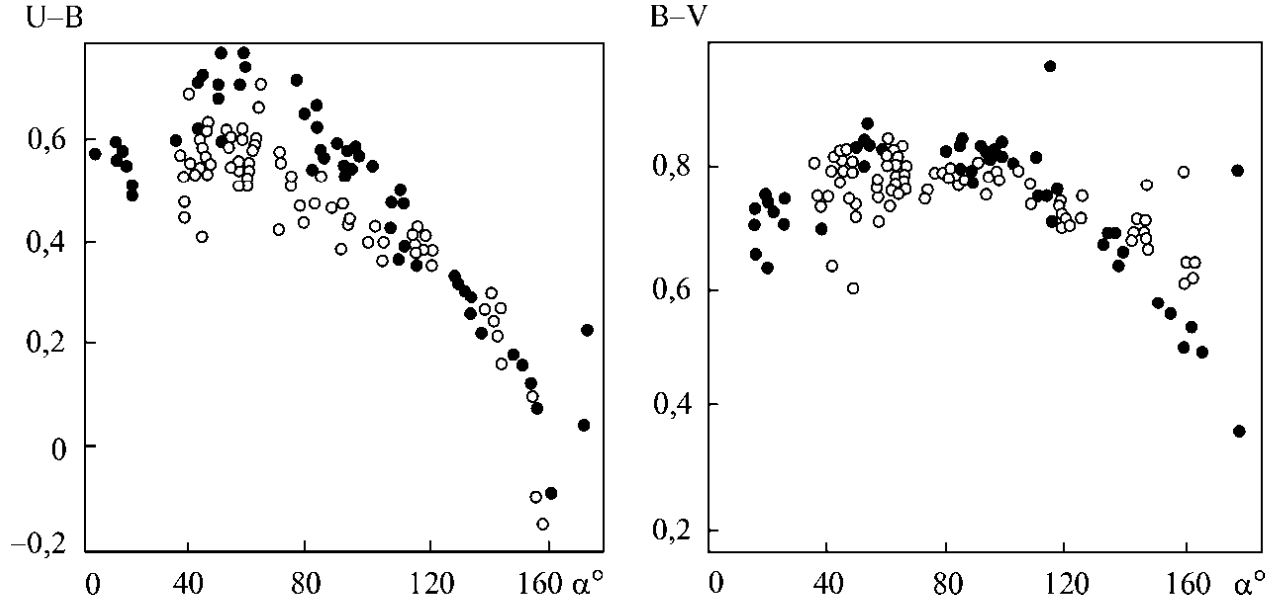
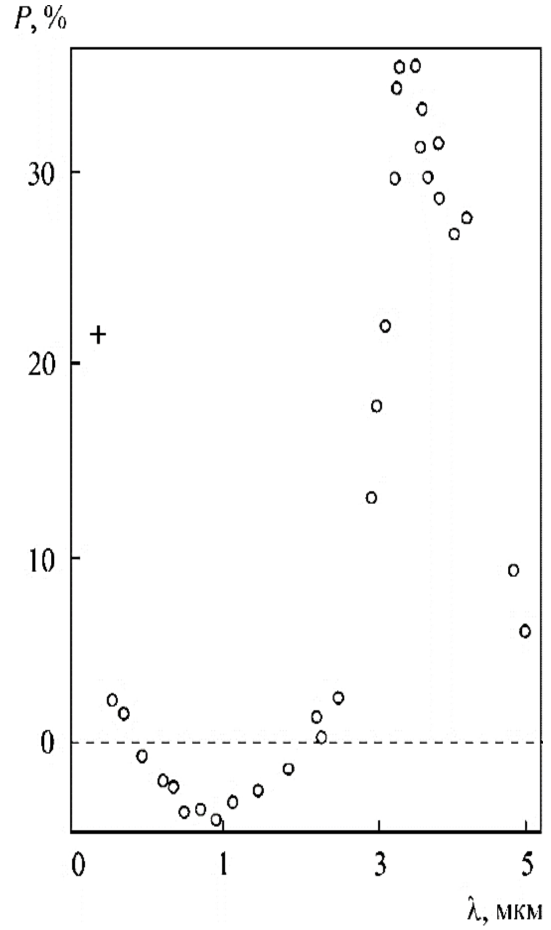


Fig. 2.3. Changes in the U-B and B-V color indices for the brightness of Venus depending on the phase angle α according to the observational results of various authors [10]

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.



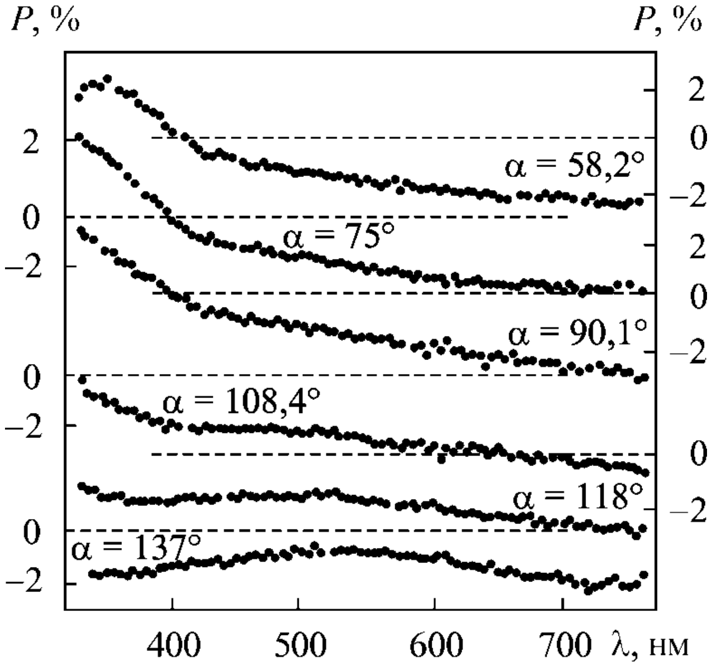


Fig. 2.4. Changes in the degree of polarization with wavelength for the disk of Venus at α = 103° (○) and 98° (+) [10].

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.

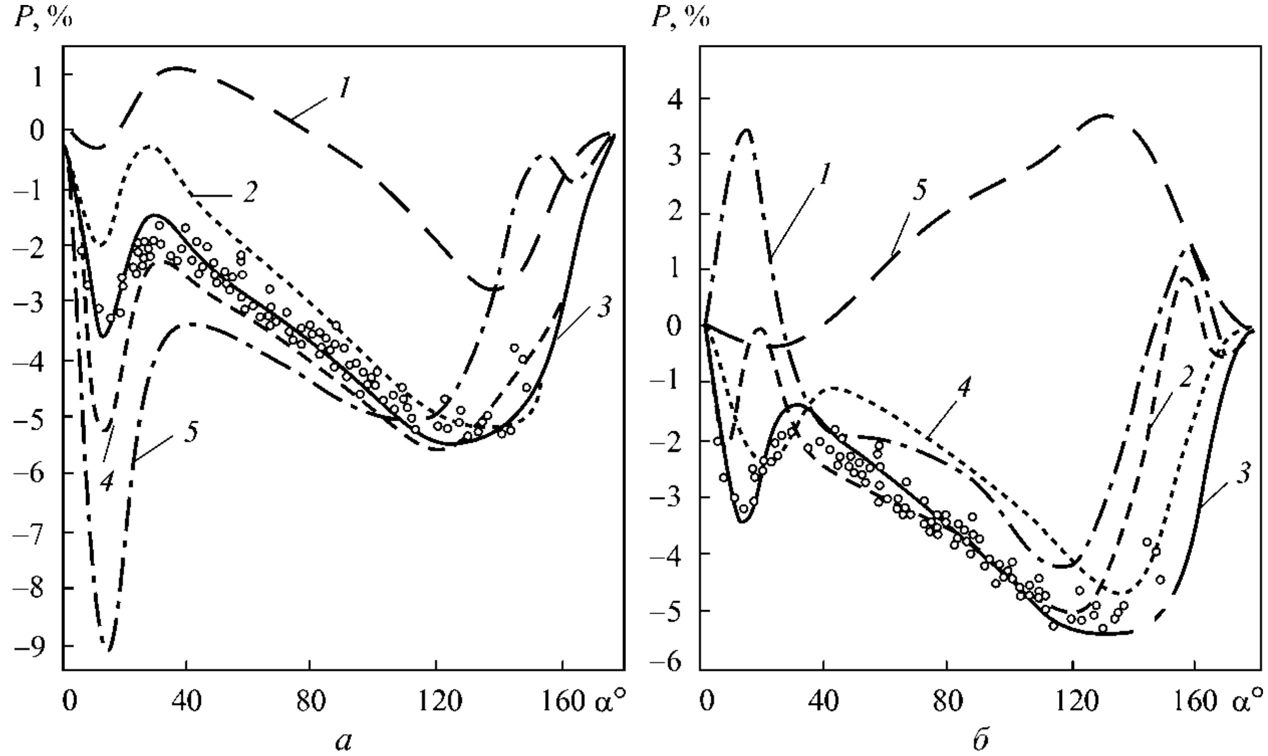


Fig. 2.6. Comparison of model calculations and observational (○) dependence of the degree of polarization on the phase angle P(α) at l=990 nm: (a) 1– at n_r=1.33 (r_{ef}= 0.8), *2* – at n_r=1.40 (r_{ef}=1.0), *3* – at n_r=1.43 (r_{ef}=1.05); *4* – at n_r=1.45 (r_{ef}=1.1), *5* – at n_r=1.50 (r_{ef}=1.2);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

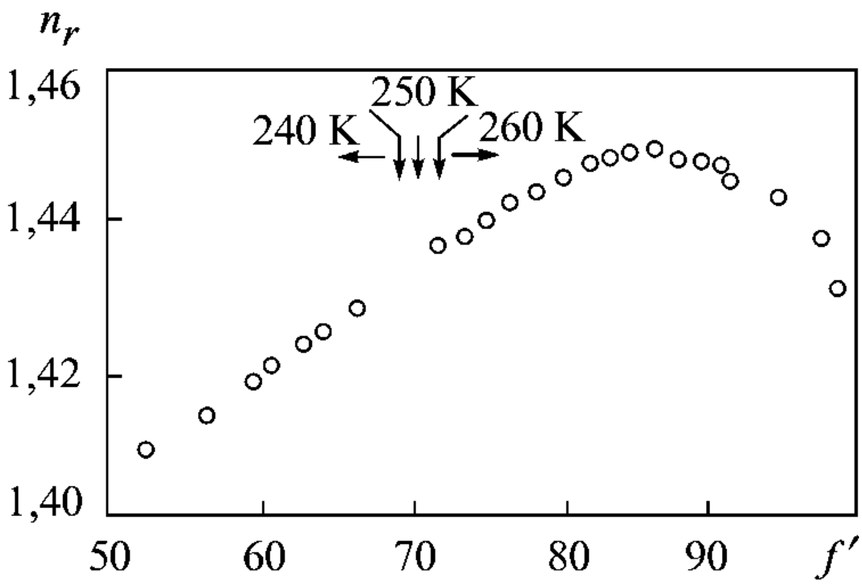


Fig. 2.7. Changes in the real part of the refractive index of an aqueous solution of H_2SO_4 with a mass ratio *f′* [10].

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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3. Model of the internal structure and characteristics of the surface relief of Venus

Introduction

The main source of information about the Earth's interior is direct seismic data. Despite the lack of direct seismic observations on Venus, models of the internal structure of this planet have been developed, based on its global characteristics, such as mass, size, average density, gravitational measurements from artificial satellites, and analogy with Earth [2].

3.1. General model

It is assumed that Venus, like other terrestrial planets [30, 33, 34], underwent a process of gravitational differentiation early in its history. This means that heavier elements sank to the center, forming the core, while lighter silicate compounds formed the mantle and crust. Thus, the general model of the internal structure [8, 12] of Venus includes three main shells: a metallic core, a silicate mantle, and an outer crust (Fig. 3.1). This structure is similar to that of Earth, as would be expected given the similarity of the two planets in size and average density. However, the details of this structure, especially the state of the core and the thickness of the layers, remain the subject of modeling and much debate.

3.2. Core

Like Earth, Venus' core is thought to be composed primarily of iron and nickel. The slightly lower average density of Venus compared to Earth may indicate the presence of a certain proportion of lighter elements, such as sulfur, in the core. Estimates of the core radius vary across models, but are generally in the range of 2,900 km to 3,500 km. This means that the core occupies a significant portion of the planet's volume; perhaps a slightly smaller fraction than the Earth's core.

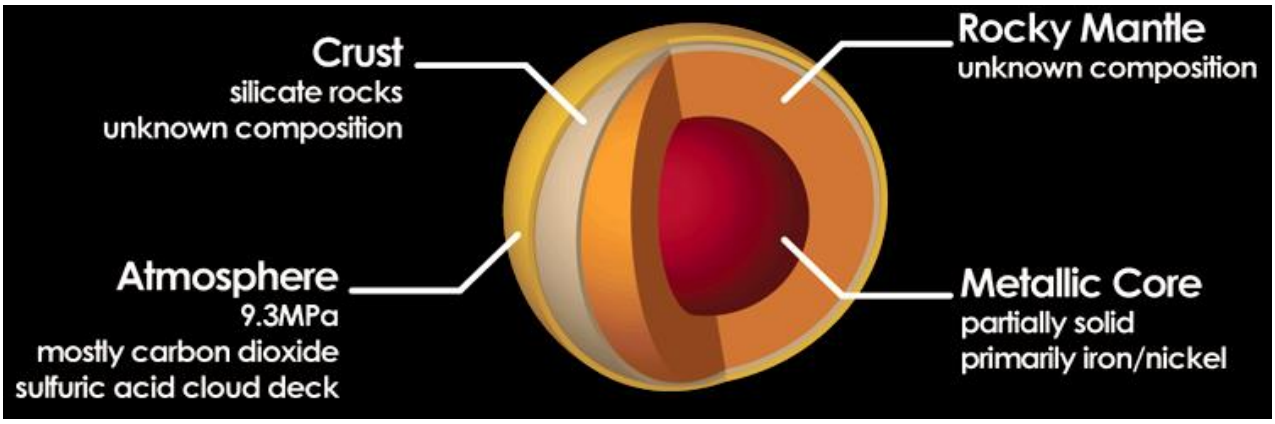

Рис. 3.1. Internal structure of Venus: the crust (outer layer), the mantle (middle layer) and the core (yellow inner layer) (http://invader-xan.pbworks.com/f/1160742297/venus-cutaway.png).

A key, still unresolved question today, is the physical state of the core of Venus [2, 25]. It is known that the Earth has a solid inner core and a liquid outer core, and convection in it generates a noticeable magnetic field [29]. For Venus, the situation is less certain. The absence of a significant global magnetic field may indicate either that the core has completely solidified, or that although it is liquid, the conditions for the dynamo effect are absent.

For example, the convection rate in the core is not suitable, or the planet rotates rapidly around its axis. Most modern models assume that at least the outer part of the core of Venus is liquid. After all, both planets are of similar size, cooled at approximately the same rate, and the Earth's core is still largely liquid today.

Analysis of the pressure in the center of Venus shows that it is significantly lower than the pressure at the boundary of the Earth's inner core. This means that the existence of a solid inner core on Venus is possible only if its core differs significantly from the Earth's in composition; for example, it contains fewer light impurities, or has a much lower temperature.

Recent analyses of gravitational data from satellites and tidal effects indicate a probable core radius of 3100–3500 km. But the data obtained so far do not allow us to unambiguously determine its state.

3.3. Mantle

The mantle of Venus, located between the core and the crust, makes up the bulk of the planet's volume. Its thickness is estimated at about 3000 km. It is assumed that, like the Earth's mantle, it consists mainly of silicate rocks rich in iron and magnesium.

Despite the extremely high temperature on the surface, the temperature inside the Venusian mantle is probably close to that of the Earth's mantle. This is due to the fact that the main mechanism of heat transfer from the interior of the planet is convection, that is, the slow movement of viscous mantle material.

If the temperature in the interior of Venus were much higher, the viscosity of the rocks would decrease, convection would accelerate, and excess heat would quickly be carried to the surface. It is believed that it is convective movements in the mantle of Venus that are the main driver of tectonic and volcanic activity [38] observed on the surface of the planet, in particular the formation of the so-called crowns and rift zones [3, 5, 7].

3.4. Crust

The outer hard shell of Venus – the crust – is relatively thin compared to the mantle and core. I

ts composition, according to the analyses carried out by the Venus landers at the landing sites, is mainly basaltic [17, 22, 27]. And this is a typical product of volcanic activity on the planet.

Estimates of the average crustal thickness vary considerably among studies. Some models based on tectonic deformation and viscous relaxation give values ranging from 10 to 30 km. Other models that take into account gravity data from orbiters suggest an average thickness of 20 to 50 km, or even up to 70 km. It is possible that the crust may be thicker under high-altitude plateaus such as tesserae.

Unlike Earth, where there is a clear division into thin (about 7 km) oceanic and thick (30–70 km) continental crust, the crust on Venus appears to be more uniform in thickness over most of the planet, according to gravity measurements.

3.5. Absence of a global magnetic field

One of the key differences between Venus and Earth is the almost complete absence of its own global magnetic field of the dipole type. Measurements show that Venus's magnetic field, if it exists, is extremely weak, at least 10 thousand times weaker than Earth's.

Instead of its own magnetosphere, Venus has only an induced one, which is formed as a result of the direct interaction of the upper layers of its atmosphere [18, 19, 28] (i.e., the ionosphere) with the solar wind.

The reasons for the absence of a strong magnetic field are still not fully understood. The most likely explanation for this is a combination of various factors.

First, this should be influenced by the extremely slow rotation of Venus (period 243 days), which does not provide sufficient Coriolis force for the effective operation of the dynamo mechanism in the core; and this is even if it is partially liquid and has some convection.

Second, it is possible that convection in the core is absent or too weak; for example, if the core is completely solidified, or if the heat flow from the core to the mantle is insufficient to support convection.

3.6. Comparison with the structure of the Earth

A comparison of models of the internal structure of Venus and the well-studied structure of the Earth allows us to highlight some key similarities and differences between them (Table 1). Thus, both planets have similar sizes, masses, and average densities; this implies a similar general differentiation into a metallic core, a silicate mantle, and a crust. The probable composition of the respective shells is also considered similar (iron-nickel core, silicate mantle, etc.).

The main differences between the planets concern the physical state of the core and the presence of a magnetic field. The state of the core of Venus (especially the presence or absence of a solid inner core) remains uncertain today, in contrast to the well-established structure of the Earth's core with a solid inner and liquid outer layer.

Table 3.1.

Comparison of models of the internal structure of Venus and Earth

Characteristics	Venus (model data, uncertainties)	Earth (seismic data)
Crust		
Thickness (km)	~10-70 (medium, possibly thicker under highlands)	~5-70 (thin oceanic, thick continental)
Composition	Mostly basaltic	Basalt (oceanic), granitic-metamorphic (continental)
State	Solid	Solid
Mantle		
Thickness (km)	~3000	~2900
Composition	Silicates (Fe, Mg)	Silicates (Fe, Mg)
State	Mostly solid, ductile (convection), possible partial melting in the upper part	Mostly solid, ductile (convection), asthenosphere (partially molten)
Outer core		
Thickness/ Radius (km)	Probably liquid, radius of entire core ~2900-3500	Liquid, thickness ~2200-2250
Composition	Fe, Ni, perhaps S	Fe, Ni, light impurities
State	Probably liquid (fully or partially)	Liquid
Inner core		
Radius (km)	Unknown, possibly absent or small	~1220-1300
Composition	Fe, Ni (?)	Fe, Ni
State	Unknown, possibly absent or small	Solid
Global magnetic field	Virtually absent	Present
Generation mechanism	No effective dynamo	Dynamo in liquid outer core

Venus does not have a global magnetic field, while Earth has a powerful magnetosphere generated by the dynamo effect in the liquid outer core. There are probably differences in the regime of mantle convection and, consequently, in the style of tectonic and volcanic activity [31, 36] at the surface (for example, the absence of plate tectonics on Venus).

There are also possible differences in the average thickness and structure of the crust between the planets [30].

The table above highlights both the similarity of the overall structure and the key differences and uncertainties, especially regarding the state of the core and magnetism, which may underlie the different geological evolution of these two planets: Venus and Earth.

3.7. The influence of internal structure on surface geology

The internal structure and processes in the interior of Venus directly affect its surface geology [6, 13]. The absence of terrestrial-type plate tectonics is likely a consequence of a combination of lithosphere properties and mantle convection. The high surface temperature may make Venus' lithosphere more plastic at shallower depths, or more buoyant than Earth's. This makes it more difficult for it to sink (so-called subduction) into the mantle.

The absence of water on Venus's surface also makes rocks stronger and less prone to the faults necessary for plate formation. However, the planet's internal heat, which is likely generated in volumes comparable to Earth's, must find an outlet to the surface.

In the absence of an effective cooling mechanism through plate tectonics, mantle plumes may play a major role in heat removal. These upward flows of hot mantle material lead to the formation of large volcanic uplifts, the formation of shield volcanoes [35], unique structures such as coronas, and large rift zones in which the lithosphere is stretched and thinned [9, 20, 24]. Thus, the geology of the surface of Venus is a direct reflection of its internal dynamics, which operate according to rules different from those of Earth.

The inability to accurately determine the state of Venus's core at present creates significant uncertainty in models of its thermal history. The state of the core (whether it is liquid, solid, or partially liquid) directly affects the planet's cooling processes and the possibility of generating a magnetic field. Crystallization of the inner core, as occurs on Earth, releases significant amounts of heat and changes the chemical composition of the outer core; together, this can sustain convection and the dynamo effect for billions of years.

If the core of Venus has a different structure, or its state, then the mechanisms of heat generation and transfer from the core to the mantle will be different. This, in turn, affects the intensity and nature of mantle convection, and therefore the long-term evolution of volcanic [14, 37] and tectonic activity on the planet's surface [32]. Understanding the state of the core is key to building accurate models of Venus' evolution and explaining its differences from the Earth.

3.8. Names on the surface of Venus

Of the classical planets, only Venus and Earth have female names. Therefore, the International Astronomical Union at one time made a unanimous decision that the names on the surface of Venus should have only female names. Thus, it was proposed that female names from the myths of different peoples of the world should be used for the names of relief details on the planet's surface. Moreover, their assignment should correspond to some specially established order.

For example, such relief details as hills, which include ridges, mountains, ridges, plateaus – will be given the names of goddesses, lowlands – heroines of various myths.

However, on Venus there was also a place for real names of women and their surnames; for example, it was proposed to use them in the names of many craters. At the same time, craters with sizes greater than 20 km should be posthumously named after famous personalities; while craters smaller than 20 km in size should receive ordinary proper names.

For example, on such a high-altitude plateau as Lakshmi, there are small craters with such names: Tamara, Lyudmila, Berta, etc.; they are located somewhat south of the mountains named after the Scandinavian goddess of fertility and love and attractiveness Freya, and east of the large crater Osipenko. In the northern hemisphere of Venus, a noticeable mountain range is crossed by a rather long canyon, which was called the Stupa of Baba Yaga; and along one of the vast plains on Venus, the Witches' Ridges stretch.

Around the north pole is the plain of the mistress of the north in Karelian and Finnish myths - Louhi, and the plain of the Snow Maiden. Next to the crown of Nefertiti is the Potanin crater, and nearby is the crater of the author of the novel "The Gadfly" - the English writer Voynich.

And the entire harem of Abdullah from the film "White Sun of the Desert" – is located all over the surface of the planet; there is also and the wife of Comrade Sukhov from the same film – "kind Katerina Matveyevna". In general, on the map of Venus you can find names from the myths of about two hundred nations from all over the world.

The largest relief details on the planet Venus are large hills; they are a kind of continents or continents; therefore, they are also called "Earths". They have diameters of more than 5-10 thousand km; they are raised 3-5 km above the surrounding lowlands.

In total, there are three Earths on the surface of Venus, which were named after the goddesses of love, taken from different mythologies. For example, near the equator is the largest Earth, which was named after Aphrodite – the Greek goddess (Fig. 3.2).

Almost at the north pole – there is an Earth, which the noses named after Ishtar – the Babylonian goddess of love; тot far from the South Pole, the Earth is named after the Slavic goddess Lada.

Recall that of the 967 impact craters found on Venus (Fig. 3.3), the vast majority (≈80%) have diameters less than 30 km. The study of radar images of the surface of Venus showed that the bottom of these craters is quite dark. This indicates their smooth surface. However, the material ejected from these craters and the ring structures around them turned out to be very light.

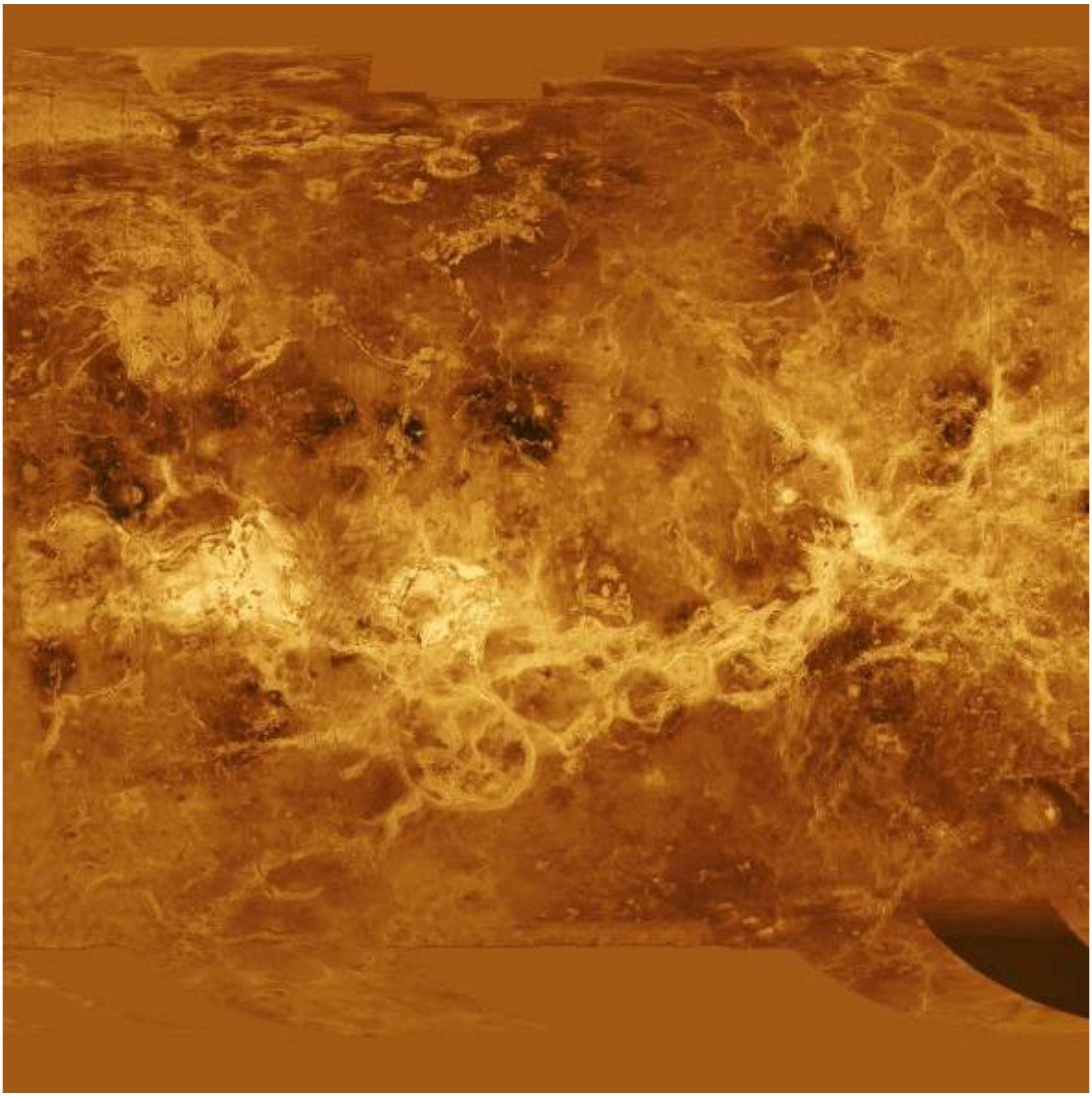

Fig. 3.2. View of the mainland of Aphrodite (http://photojournal.jpl.nasa. gov/).

This is observed due to the very strong scattering of the radar signal due to the significant roughness of these areas of the surface relief [16]; this situation is caused by the fact that the craters are surrounded by fragments of rocky material of the surface layers ejected by the explosion.

It also turned out that the most common type of surface on Venus is smoothed mountain formations in the form of ridges. They cover up to 65% of the planet's surface. Another 20% of the entire surface is occupied by flat, almost flat areas.

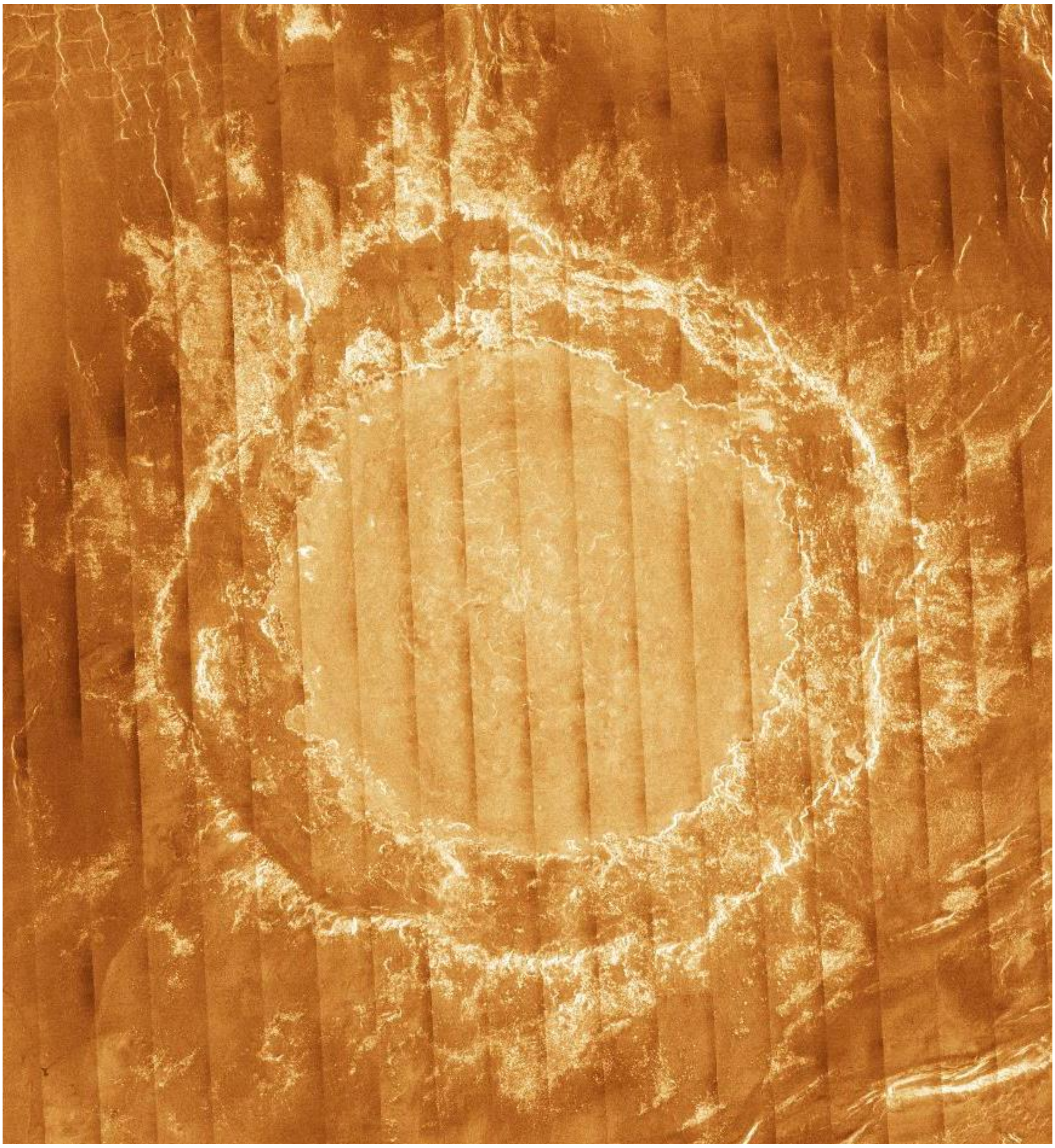

Fig. 3.3. The impact crater Mead with a diameter of 280 km has an outer and inner ring and small bright emissions around the outer ring. The surface on the slopes of the crater is morphologically very similar to the surrounding plain (http://photojournal.jpl.nasa.gov/)

3.9. Optical and chemical properties of the surface

From the landing sites of the spacecraft "Venus-9 and -10" and in October 1975, panoramic images of the planet's surface in integral light were first transmitted to Earth (Fig. 3.4). Their spatial resolution was close to 1 cm. These panoramas were transmitted for 50 and 45 minutes, respectively, from the first and second modules, which were 2000 km apart.

The observed spectral range was determined by the energy distribution from a certain artificial source with known illumination and known sensitivity of the FEP-114 photoelectron receiver.

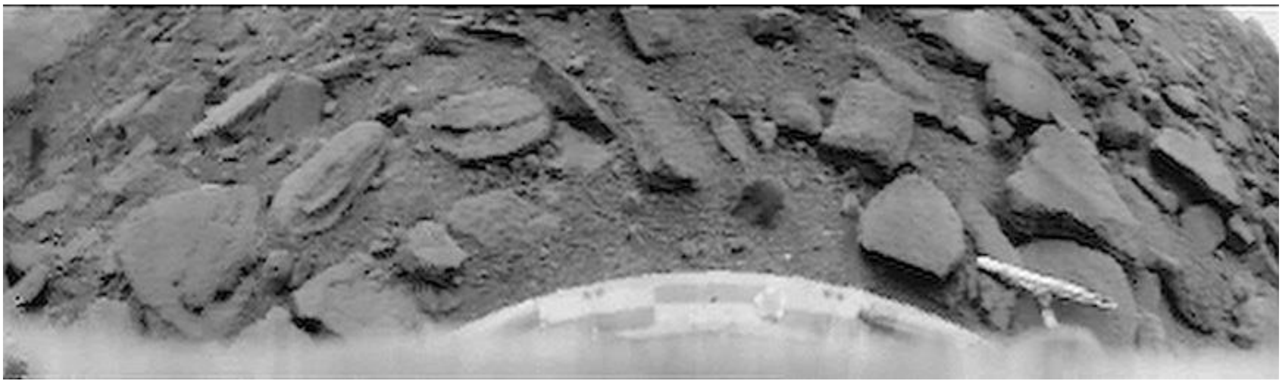

Fig. 3.4. Panoramas of the surface of Venus at the landing site of the “Venera-9” spacecraft in the 180° field of view sector, see [34].

From the results of these studies, it was obtained that the value of the surface reflectivity at the locations of the survey is very low, only 0.03-0.12 [18]. Morphological and geological analysis of the results obtained showed that the stony material in the placers around the landing modules has a flattened shape in the form of plates. The cross-section of larger stones was 50-70 cm and had a height of less than 15-20 cm. This indicated a typical ratio of their height to width of 1:3-1:6.

Seven years later, the “Venera-13 and -14” spacecraft again transmitted circular television panoramas with three times better spatial resolution from other places on the planet for 100 and 60 minutes, respectively (Fig. 3.5). These new panoramic images were obtained on March 1 and 5, 1982. They were transmitted in integral light. But they were also supplemented by three separate spectral regions in the blue, green, and red ranges. This allowed us to obtain panoramic images of the surface of Venus in color light for the first time.

Fig. 3.5. Panorama of the surface of Venus at the landing site of the “Venera-13” spacecraft (https://photomail.org/wp-content/uploads/2024/11/this-man-put-the-entire-soviet-space-program-on-his-back-he-deserves-our-respect_22-1200x248.jpg).

Morphological and geological analysis of these color images indicated that the rocks that reach the surface at the landing sites of these new spacecraft are of a significantly different nature; they have much thinner horizontal layering.

Recall that on the “Venera-8, -9, -10” landing modules, using γ - spectrometers installed there, it was possible to determine for the first time the content of such radioactive elements in the layer near the surface as uranium, potassium, and thorium (Table 3.2).

Table 3.2.

The content of radioactive elements such as thorium, potassium and uranium in the surface layer of Venus [27]

Spacecraft	Potassium, %	Uranus, 10^{-4} %	Thorium, 10^{-4} %
“Venus-8”	4	2.2	6.5
“Venus-9”	0.47 ± 0.08	0.60 ± 0.16	$3.6\ 5 \pm 0.42$
“Venus-10”	0.30 ± 0.16	0.46 ± 0.26	0.70 ± 0.34

From the landing modules of the spacecraft “Venera-13, -14 and -16” it was possible to conduct much more detailed studies of soil samples. For this purpose, a multichannel spectrometer in the X-ray range was used [26]. Soil samples were extracted from different depths and then they were irradiated with radioisotopes Pu^{238} and Fe^{55}; these elements excited fluorescent glow in the X-ray range (Fig. 4.5).

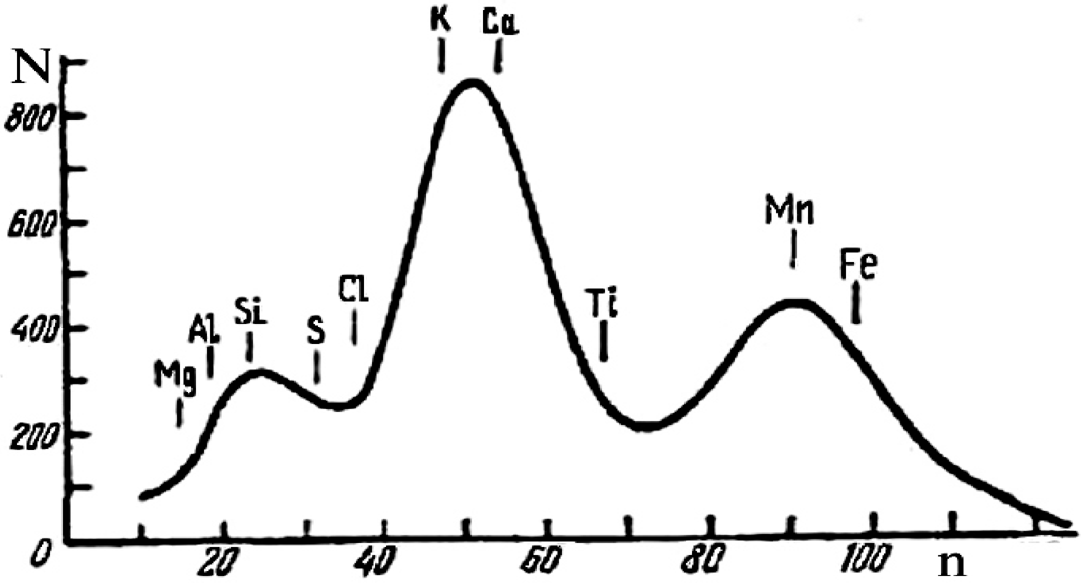

Fig. 3.6. Relative fluorescence spectrum of Venusian soil rocks at the landing site of "Venus-13" [27].

By analyzing this glow, it was possible to determine the chemical composition of the soil on the surface of Venus (Table 3.3).

Table 3.3.

Relative chemical composition of rocks on the surface of Venus [27].

Oxides of elements	«Venus-13»	«Venus-14»	«Vega-2»
MgO	11.4 ± 6.2	8.1 ± 3.3	11 ± 3.8
Al_2O_3	15.8 ± 3.0	17.9 ± 2.6	16 ± 1.9
SiO_2	45.1 ± 3.0	48.7 ± 3.6	45.6 ± 3.2
K_2O	4.0 ± 0.63	0.2 ± 0.07	0.1 ± 0.08
CaO	7.1 ± 0.96	10.3 ± 1.2	7.3 ± 0.7
TiO_2	1.59 ± 0.45	1.25 ± 0.41	0.2 ± 0.1
MnO	0.2 ± 0.1	0.16 ± 0.08	0.14 ±0.1
FeO	9.3 ± 2.2	8.8 ± 1.8	–
SO_3	–	–	4.7 ± 1.5
Fe_2O_3	–	–	8.5 ± 1.3

As follows from Fig. 3.6, the uranium-, thorium-, and potassium-rich rocks in the Venusian layer near the surface do not correspond to the primary composition for terrestrial rocks of volcanic origin. Therefore, these rocks have already undergone significant processing and are referred to as so-called secondary rocks [15].

The data obtained lead to the conclusion that on the surface of Venus there is large rubble and clastic material of very dark rocks with a density of 2.7-2.9 g/cm^3 [20]. Such an elemental composition is characteristic of basaltic rocks with volcanic lava layers. That is, on the surface of Venus the main igneous rocks that poured out from under the planet's crust are igneous rocks. And in this they are similar to similar rocks on the Moon, Mars, and Mercury.

3.10. Features of the surface relief

The very thick atmosphere of Venus [33] means that all observational data about the surface were initially obtained only by radar methods [14]. Somewhat later, and only for certain local areas, some data were obtained from panoramic images of the planet's surface transmitted from the landing sites of several modules.

Already the very first radar observations [4] allowed in the frequency spectrum with Doppler broadening of the reflected radio signal to detect two features with anomalously different reflection characteristics near the equator [32]. They were called the α and β (Alpha and Beta) regions. Later, the Beta region was morphologically divided into three separate areas, which were called features B, C and D [1]. And areas C and D were additionally called by their own names: Gauss and Hertz. After some time, another feature was discovered next to them, which was called Maxwell's Mount [9]. And in the Beta region, two more shield volcanoes were found, which were named Theia and Rhea; their height reaches 4.3 and 4.2 km, respectively (Fig. 3.7). From the intensity of the reflected radio signal, it was possible to determine the so-called effective scattering area; it changed with the longitude of the central meridian almost 4 times [6]. Using radar observations, it was also possible to construct relief maps for individual sections of the surface [5, 9, 23] with a spatial resolution of about 80 km. According to the data obtained, the surface relief on Venus turned out to be very diverse both in shape and in height differences and in its physical characteristics. For example, a cliff was found not far from the equator, the length of which reaches almost 1500 km, and the width is about 150 km with a depth of about 2 km.

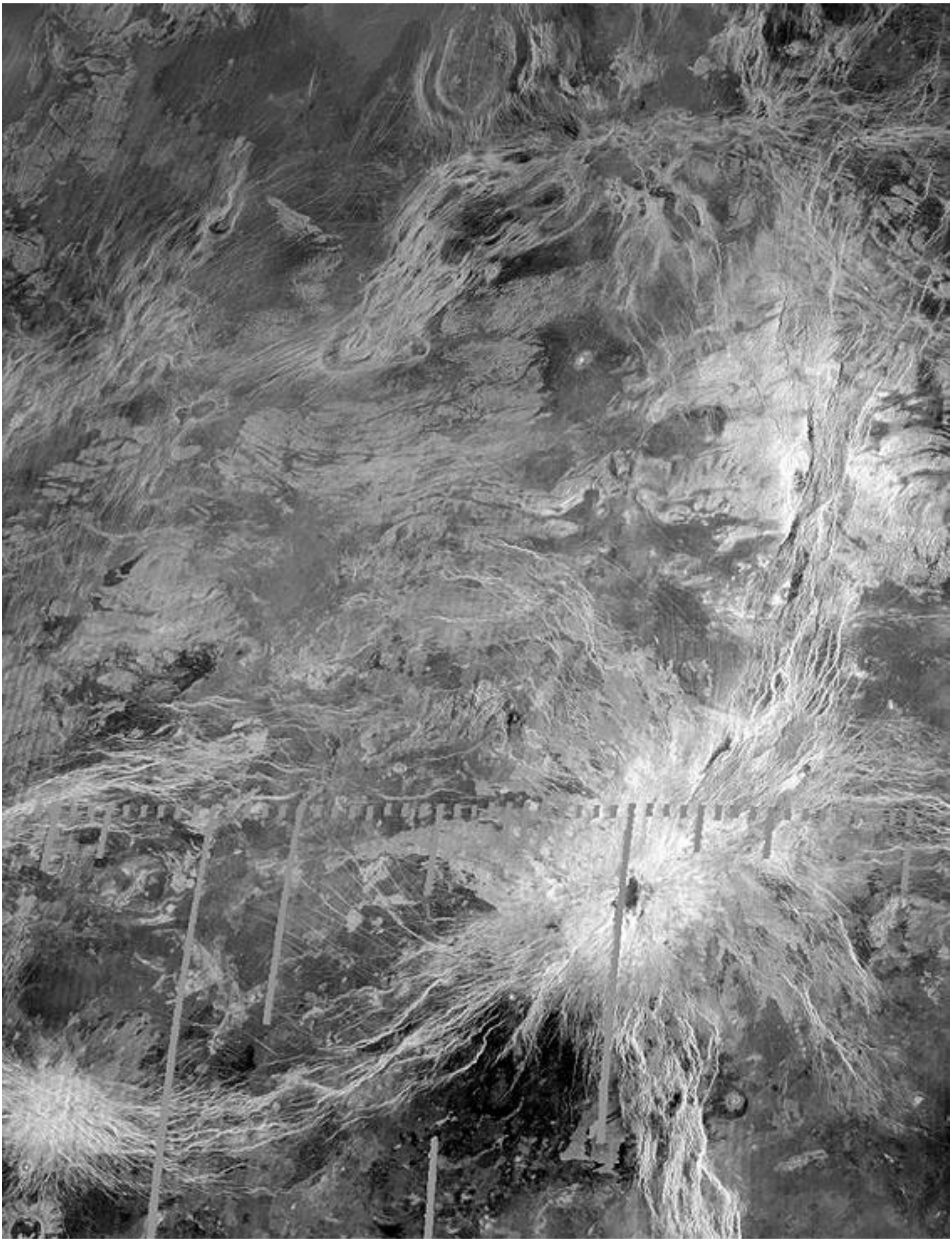

Fig. 3.7. Radar image of the Beta region from Magellan with two volcanic mountains – Theia (bottom – bright spot) and Rhea (bright spot above) (http://photojournal.jpl.nasa. gov/)

Morphologically, it is very similar to the giant system of Mariner valleys in the equatorial region of Mars. Radio interferometric observations at a wavelength of 12.5 cm over a small section of the surface of Venus with high spatial resolution allowed us to construct a map of changes in reflectivity and height of surface formations. A significant number of craters with a diameter of more than 30 km were found there; and the diameter of the largest of them exceeds 150 km at a depth of almost 500 m. A feature of this relatively small area of the surface is a significant difference in heights. Usually, this is characteristic of areas of much larger sizes.

Observations of the surface of Venus using a radio altimeter began in 1972 during the descent of the “Venera-8” spacecraft module. Then their studies were continued with orbital modules. The largest amount of data of this kind was obtained using equipment on the “Pioneer-Venus” spacecraft [17]. Based on the results of the radar images obtained by the device, cartographic data and numerous measurements of the height of surface details were prepared. The effective scattering area and the average statistical value of the angles of inclination of irregularities on the planet's surface were also determined by the power of the radio signal reflected by the surface. The data obtained of this type made it possible to calculate the reflection coefficients of the surface layer in the radio range, and the dielectric permittivity of materials on the soil surface was already determined from them.

With a surface resolution of almost 120 km, a topographic map was constructed for more than 90% of the planet's surface in the latitude range from 63°S to 74°N, based on observations made over more than one Earth year. The highest elevation value of 11.5 km is located in the Maxwell Mountains, and the lowest point was found just south of the equator in the Diana Basin, and had a depth of more than 2 km. In addition to this basin, the Atlanta and North Basin, located at latitudes (58-72)°N, are also quite deep; they also have depths of about 2 km.

This map especially highlights three large elevated plateaus, which are called continents. For example, the continent of Ishtar, located at latitudes (60-74)°N, is similar in size to Australia on Earth. Not far from it is the Lakshmi Plateau, raised to a height of 3.5-4.5 km, and the already mentioned highest mountains of Maxwell on

Venus. In the southern hemisphere at latitudes (24-36)°S there is another continent, called Aphrodite; the highest areas on it have heights of 5.5-5.7 km.

A detailed study of the relief on Venus has shown that even the largest craters are quite shallow. For example, two of them – with diameters of more than 600 km and 800 km - are located in the northern hemisphere near the equator, have a depth of only about 700 m; and another crater, located between them, has a diameter of about 400 km with a depth of only 200 m. Cracks (Fig. 3.8) of great length and width of almost 150 km have also been found on the surface of Venus; they turned out to be much deeper; several of them have a depth of about 5 km.

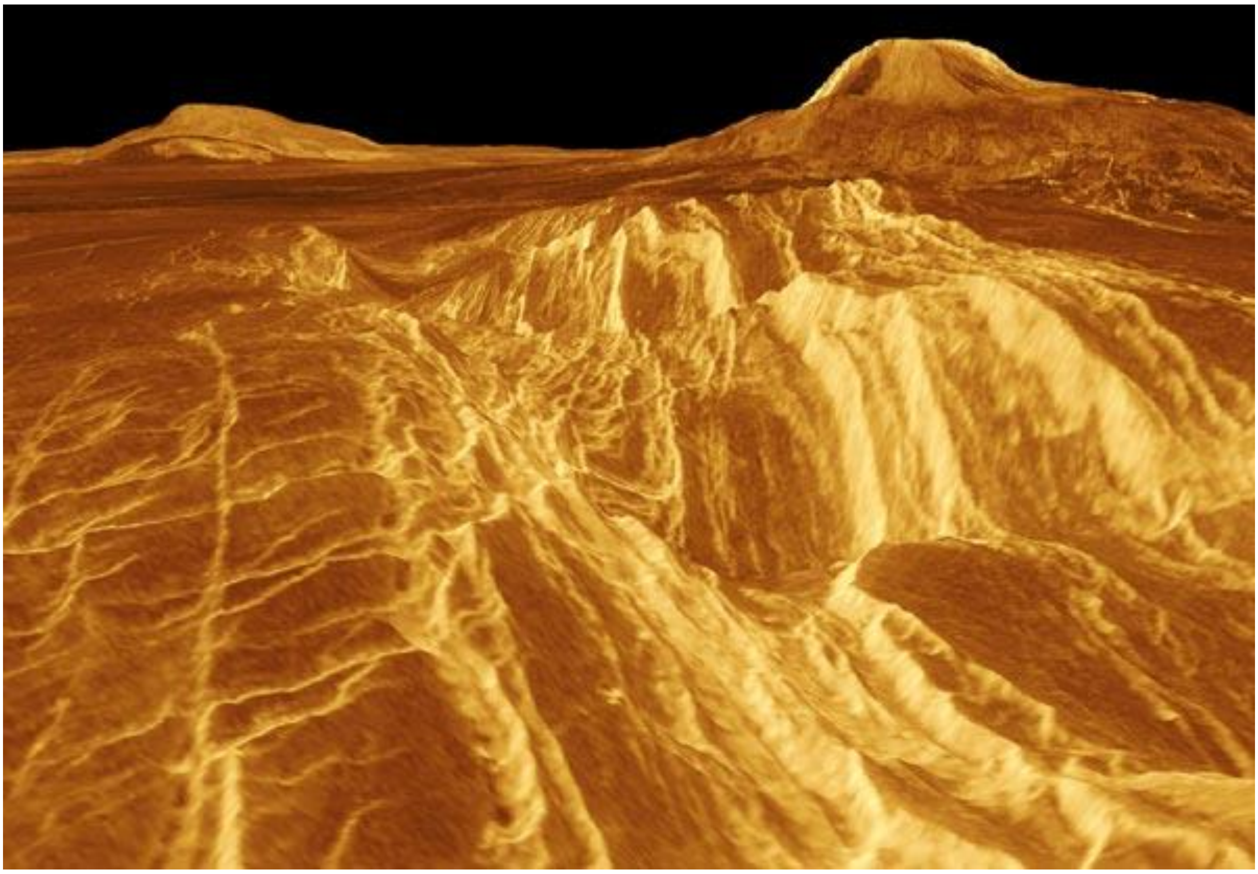

Fig. 3.8. Fissure in Eistla Regio. Lava flows spilled many kilometers down the slopes of Sif volcano (left, up to 2 km high) and Gula volcano (up to 3 km) (http://photojournal.jpl.nasa.gov/).

Using bistatic radar at a wavelength of λ=32 cm, the effective value of the dielectric permittivity (ε′=3÷11) was determined on the orbital modules of the spacecraft “Venera-9, -10” [11]. According to the results of radar measurements of altitude from the spacecraft “Pioneer-Venera” and from the spacecraft "Magellan" [3], it was possible to obtain quite complete data on changes in the angle of inclination σ_α. According to these data, it was found that the surface layer in the lower areas usually has a smaller value of the reflection coefficient. These areas are quite smooth with values of $\sigma_\alpha \approx (1-3)°$. While the mainland regions of Aphrodite, Ishtar, Beta have several times higher values of σ_α. The Maxwell Mountains, which are located on the mainland of Ishtar, are characterized by the roughest details on the entire surface of Venus; their value is 4.5-10°.

Comparison of maps of the distribution of inclination angle values with a map of changes in elevation on the surface of Venus showed a significant correlation between them for mountainous areas around the plateau. For example, for all mountainous areas – the Lakshmi and Maxwell mountains, the Aphrodite archipelago, the Alpha region – the inclination angle value increases with height. The correlation for the area on the Beta elevation is significantly less pronounced.

From the end of 1983 to mid-1984, the surface of the circumpolar regions in the Northern Hemisphere of Venus was first studied by radar with a spatial resolution of 1-2 km from the spacecraft “Venera-15 and -16". The total area of the studied surface was almost 100 million km2. Then it was possible to obtain that the diameter of the crater, called Patera Cleopatra, is almost 95 km; and in its middle another crater was found, the size of which was 55 km. From the analysis of the elevation profile, it was obtained that the depth of the larger outer crater was 1.5 km; while the bottom of the inner crater was deepened by an additional 1 km.

The most complete data on the surface relief of Venus were the results obtained from the autumn of 1990 to the autumn of 1994 by bistatic radar methods from the Magellan spacecraft. The spatial resolution of the surface images was from 120 to 180 m; altimetry was performed with a height resolution of up to 80 m. Also, radiometric temperature measurements were made with an accuracy of better than 2 K; temperature changes were recorded over more than 96% of the planet's surface area. Some of the results of the work can be found in [3, 15, 21]. Some examples of the obtained topographic maps are given in Fig. 3.9-3.11.

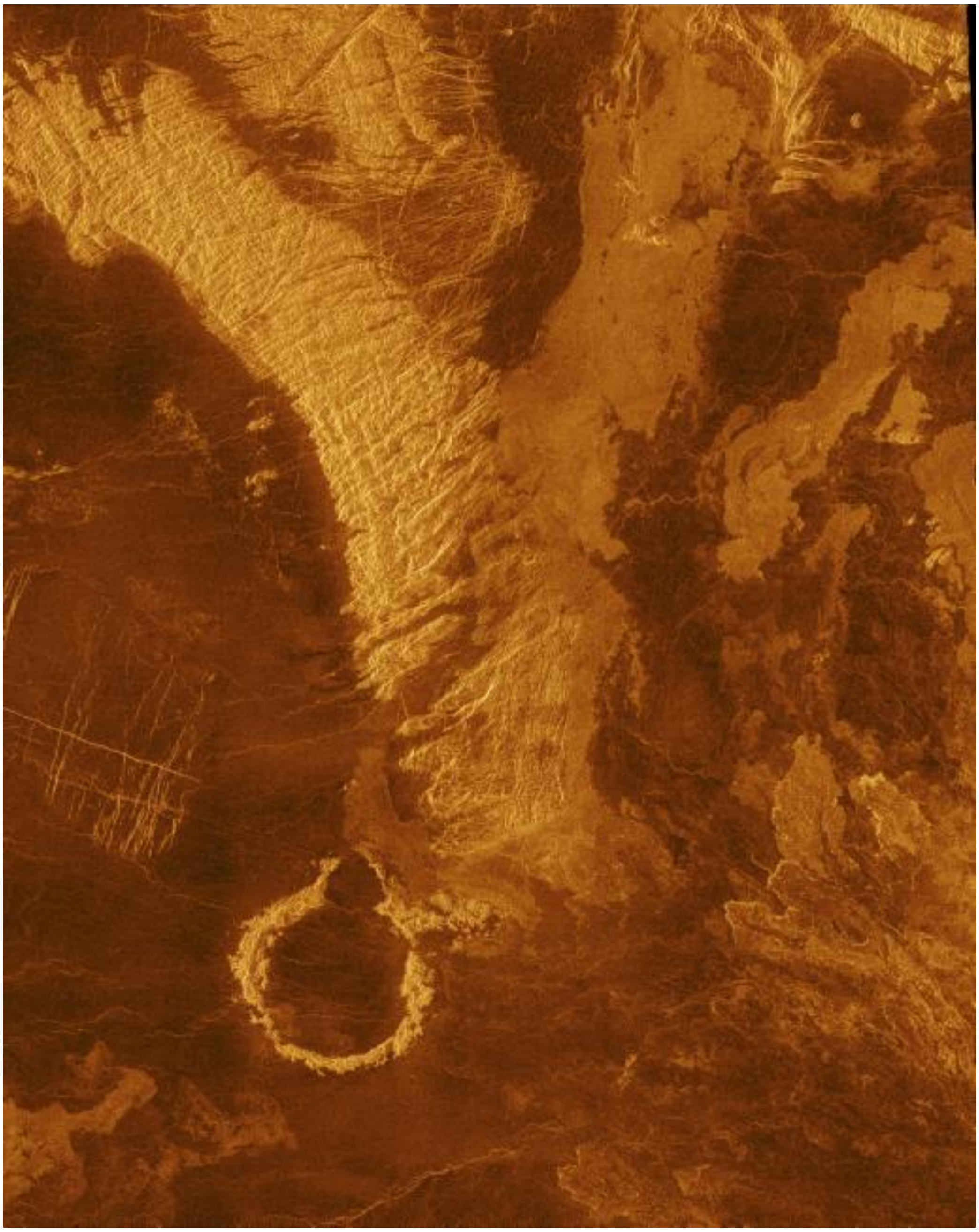

Рис. 3.9. Leda Planitia на широті 41°N – є старим геологічним ландшафтом на Венері. Показано зруйновані гори з потоками вулканічної лави. Внизу ліворуч – видно ударний кратер Елоїз з кільцевою структурою діаметром у 40 км (http://photojournal.jpl.nasa.gov/)

Fig. 3.10 shows the so-called pancake domes; Fig. 4.10 – grids of rectangular valleys, etc.

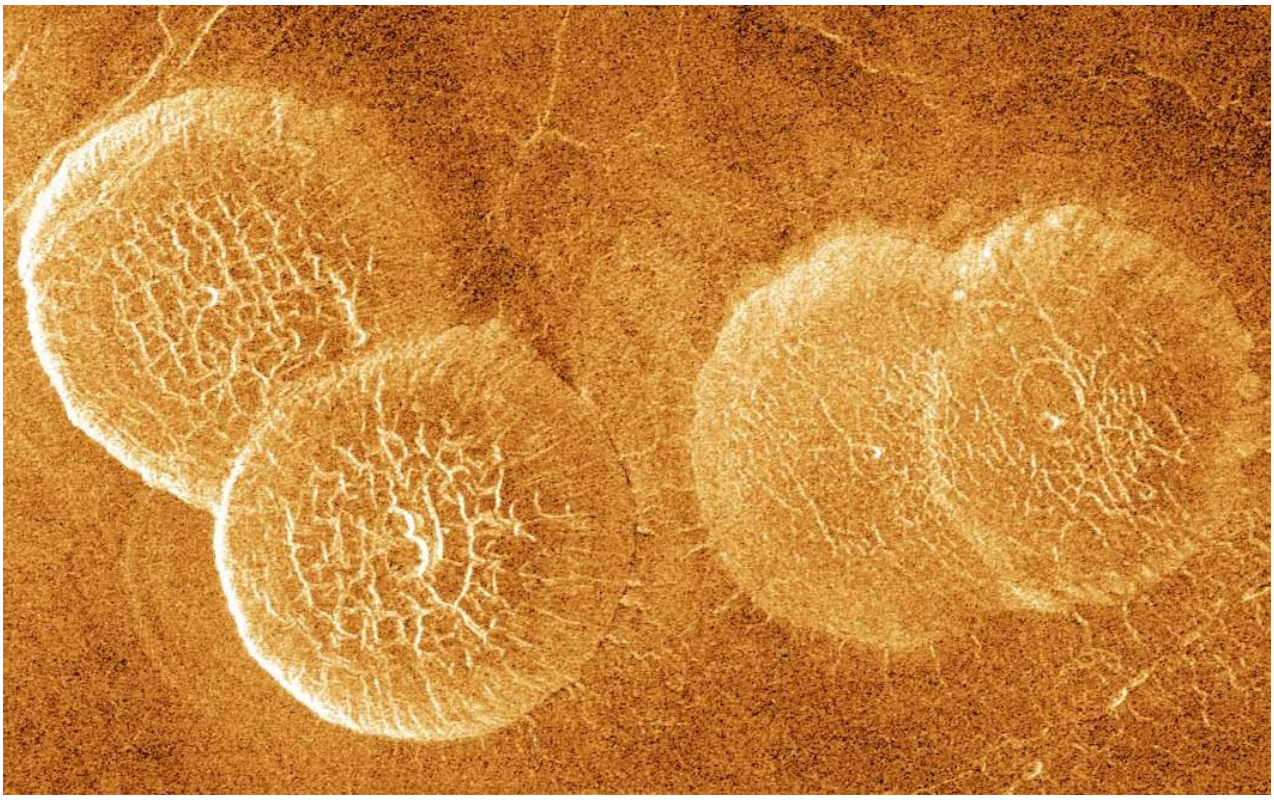

Fig. 3.10. Pancake-shaped “volcanoes” on Venus (http://photojournal.jpl. nasa.gov/).

According to the results of processing the data obtained by the “Venus-15 and -16” spacecraft, it was possible to find such specific areas, which are called tesserae (cubes). They turned out to be systems of furrows that can often intersect; they are found on almost 8% of the surface of Venus. They are somewhat higher than their surroundings and areas of plains are wedged between them.

It is believed that such systems could have arisen as a result of multiple tectonic movements in the upper layers of the planet's crust. Usually they are accompanied by uplifts, splits and subsidence of some of the areas on the surface [22, 25]. According to the data of the “Magellan” spacecraft, the structure of more than six hundred tesserae was studied in detail [10]. Table 3.4. gives the names and coordinates of some of the largest tesserae. They are located quite unevenly in latitude and longitude. The largest number of tesserae have been found near the equator in the west of the continent of Aphrodite, in the Ishtar region and in the Beta region.

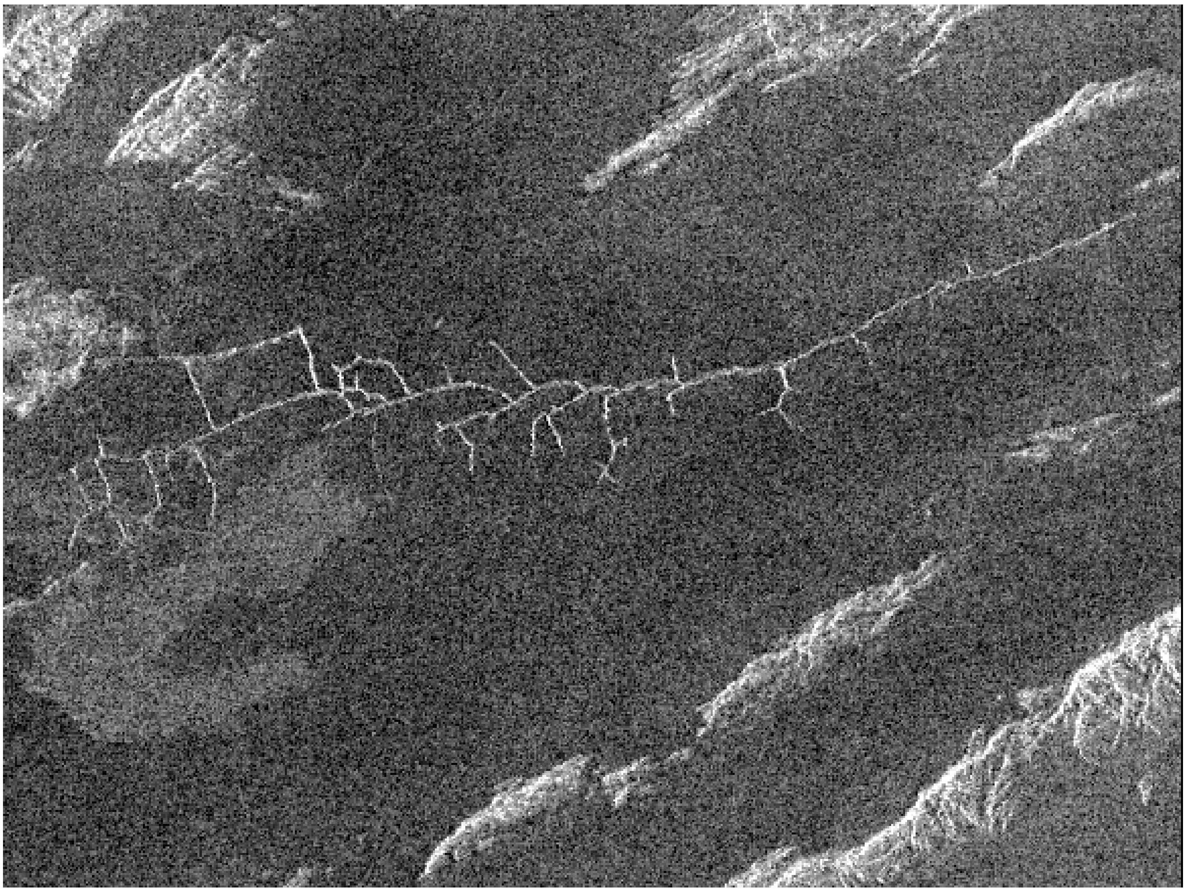

Fig. 3.11. Network of narrow (<1 km wide) bright channels (http://photojournal.jpl.nasa.gov/).

Table 3.4.

Some characteristics of large tesserae [7].

Name	Area, thousand km^2	Coordinates ψ^o	L^o	Length, km	Width, km
Ovda	9068	-5	80	5683	2083
Fortuna	3228	+67,5	35	3872	1918
Tellus	2461	+35	80	2400	1977
Thetis	2257	-8	127	2612	1447
Laima	2021	+50	47	2165	2042
Alpha	1487	-25	5	1624	1341
Phoebe	1219	-7	282	3424	812
Beta A	576	+33	277,5	1899	594

Between these relief details, about 40% of the total number of details of volcanic origin are located [2, 12, 13]. According to numerous radar observations, four main types of relief structures are distinguished in the northern hemisphere of Venus [37].

These are volcano-tectonic formations, tectonic dislocations, volcanic [37] and impact craters. A careful study of the surface relief confirmed the predominantly magmatic composition of the bedrock on Venus.

Rift regions turned out to be quite widespread. In the tropical regions of the planet, three significant areas with tectonic faults were discovered, which extend for thousands of kilometers. The largest of them runs in the direction from the Aphrodite mainland to the Beta region. Rift structures extend along the southern part at the foot of the Thetis and Ovda heights; their total length reaches 21 thousand km. From the Thetis region towards the northwestern edge of the Atlas region, another similar structure stretches over 14 thousand km long. From the Beta region to the Phoebe region in the meridional direction for 6 thousand km, a third such structure stretches.

However, the main part of the surface layer of Venus is covered by somewhat hilly plain areas. One of this type of elevations resembles the Martian volcano Olympus. It has a diameter of 300-400 km at the base. However, its height is only 1 km. In the very center of this peak there is a depression with a diameter of up to 80 km, and it is very similar to a caldera. A large number of craters have been found in the equatorial region of Venus, which in appearance are very similar to lunar ones. The vast majority of them have diameters of several tens of kilometers, and only a few of them reach almost 150 km. However, all these craters on Venus are significantly flatter than lunar ones. And the depth of even the largest of them is less than 400 m.

A significant number of fairly large tectonic structures have also been discovered on Venus. They are quite similar to the same structures on Mars and Earth. For example, not far from the equator is the large Beta Upland. It is most likely a huge basalt shield volcano. A little south of it is the Phoebe Upland.

The soil on color panoramic images of the surface of Venus looks yellow-brown. It acquires this shade due to the absorption features of the planet's powerful atmosphere [19, 30]. After all, it transmits sunlight to the surface only in the yellow and brown spectral ranges, almost completely absorbing blue rays [28]. The studies conducted have shown that the Phoebe and Beta areas should be attributed to relatively young volcanic areas with a fairly fresh surface. After all, there are practically no chemical weathering processes on it.

Volcanic features such as large plains occupy the majority of the entire surface of Venus. On such fairly smooth surfaces, bright stripes and spots ranging in size from tens to several hundred kilometers can sometimes be observed in the radio range. Systems of furrows and ridges have also been found there. And these systems are similar to similar structures on the Moon [31]. It was noted that the same older formations sometimes protruded through the upper surface material. On these same plains, many small cones and domes with a diameter of 5-10 km have also been found; often there are craters on their tops.

Tectonic formations on the surface of Venus also include the so-called dome-shaped hills (an example is Mount Rhea, Fig. 4.6) and “ovoids”. Ovoids are formations with concentric ridges and furrows that have strongly deformed ring structures. Their diameters range from 150 km to 600 km. Thin layered rocks have also been found on the surface of Venus; their formation is attributed to the deposition of volcanic ash and dust from the combustion of meteorites in the planet's atmosphere.

Observational data on the intensity of radiation in the short-wavelength region of the spectrum mainly concern the upper part of the atmosphere; while the surface layer becomes visible only at λ>3 cm.

3.11. Formation of the surface structure of Venus

The basic principles of the formation of relief structures on the surface of Venus can now be discussed only in principle. So, most likely, the primary crust of the planet should be of the basaltic type; although it may well be that its granitoid composition. Analysis of the observational data obtained to date shows that approximately 500 million years ago the crust of Venus was subjected to intense deformation. It was then that the formation of tesserae could have occurred. It is rather difficult to say anything about the possible causes of such a strong deformation. However, it can be suggested that the crust could have broken, for example, as a result of upward convective flows from the mantle of Venus. Their action could well have caused the appearance of elastic forces of compression and extension and led to the formation of the currently observed tesserae structure.

The consequences of such a step could have been the pouring out of a significant amount of basaltic lava from the upper part of the mantle. Such processes could well have led to the fact that the surface of Venus became able to preserve its original composition. This type of scenario is indicated by the increased content of uranium, potassium and thorium in the rocks. Most likely, such outpourings of basaltic lava should have been repeated [36, 38]. Therefore, during periods of reduced volcanic activity, lava plains could cool over time. And it was then that the time favorable for the formation of ridge and crack belts began.

At this stage of the events with the formation of the surface of Venus, there was a release of huge amounts of heat, the outpouring of lava flows and deformation of ancient parts of the primary crust. It is clear that such a period should have been short: no more than 300-500 million years. And the last time such a scenario took place about 500 million years ago. Traces of basaltic volcanism are visible everywhere on the modern surface of this planet, and a significant number of crustal faults indicate noticeable activity in its interior. And such high activity of the interior of Venus, most likely, is the main reason for the rather young age of the surface on Venus, compared to Earth and Mars: only 300-500 million years.

The lower mantle of Venus, or the so-called asthenosphere, consists of molten silicate rocks. The lithosphere of Venus is formed by the upper mantle, which is formed by a mixture of solid silicate rocks together with a basaltic crust. And the thickness of the lithosphere [8] of Venus, most likely, is now less than that of Earth and Mars.

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4. Evidence and forms of volcanic activity on Venus

Introduction

Volcanism is the dominant geological process that has shaped the modern appearance of Venus's surface [1, 30]. Venus was very volcanically active 300–500 million years ago. Images obtained by various probes sent to Venus have revealed many fairly evenly distributed impact craters of medium size [20]. This indicates that the planet's surface is relatively young [17]. Venus has almost no small craters [24–26]. Radar mapping data have revealed a huge number and variety of volcanic structures, indicating long-term and intense magmatic activity in the planet's interior [1, 27]. Maps created using radar data from the Magellan space probe show thousands of volcanoes with a diameter of 1.5 km or more; the largest of them reaches 280 km [2, 3, 13, 15]. 156 volcanoes with a diameter greater than 100 km have been found there.

4.1. Dominance of volcanism

Radar observations through the thick atmosphere [10, 11] show that the vast majority (about 80-90%) of the surface of Venus is covered with materials of volcanic origin, mainly in the form of large lava plains [19, 23]. The planet is literally strewn with volcanoes: more than 1600 large volcanic centers with a diameter of more than 20 km have been identified, and the total number of volcanic structures, including smaller ones, is estimated at about a million [8, 22, 28, 29]. Direct analyses of the composition of surface rocks [18], carried out by the Venus spacecraft at the landing sites, confirmed their predominantly basaltic composition, which is typical of volcanic eruptions. These facts leave no doubt that volcanism played a key role in the geological evolution of Venus [9, 14, 16].

4.2. Shield volcanoes

The most common type of large volcanic structure on Venus is the shield volcano. They are similar to their terrestrial counterparts, but often have much larger bases, reaching hundreds of kilometers in diameter. They are relatively flat, with gentle slopes and usually no more than a few kilometers above the surrounding plains. This morphology suggests that they were formed by repeated eruptions of very thin, fluid lava, probably basaltic in composition.

The highest volcano (and the second highest mountain after Maxwell) on Venus is Maat Mons (Fig. 4.1), located near the equator [12]. It rises about 8 km above mean surface level. The volcano's slope and the surrounding terrain for hundreds of kilometers are characterized by massive lava flows, which are bright in radar images.

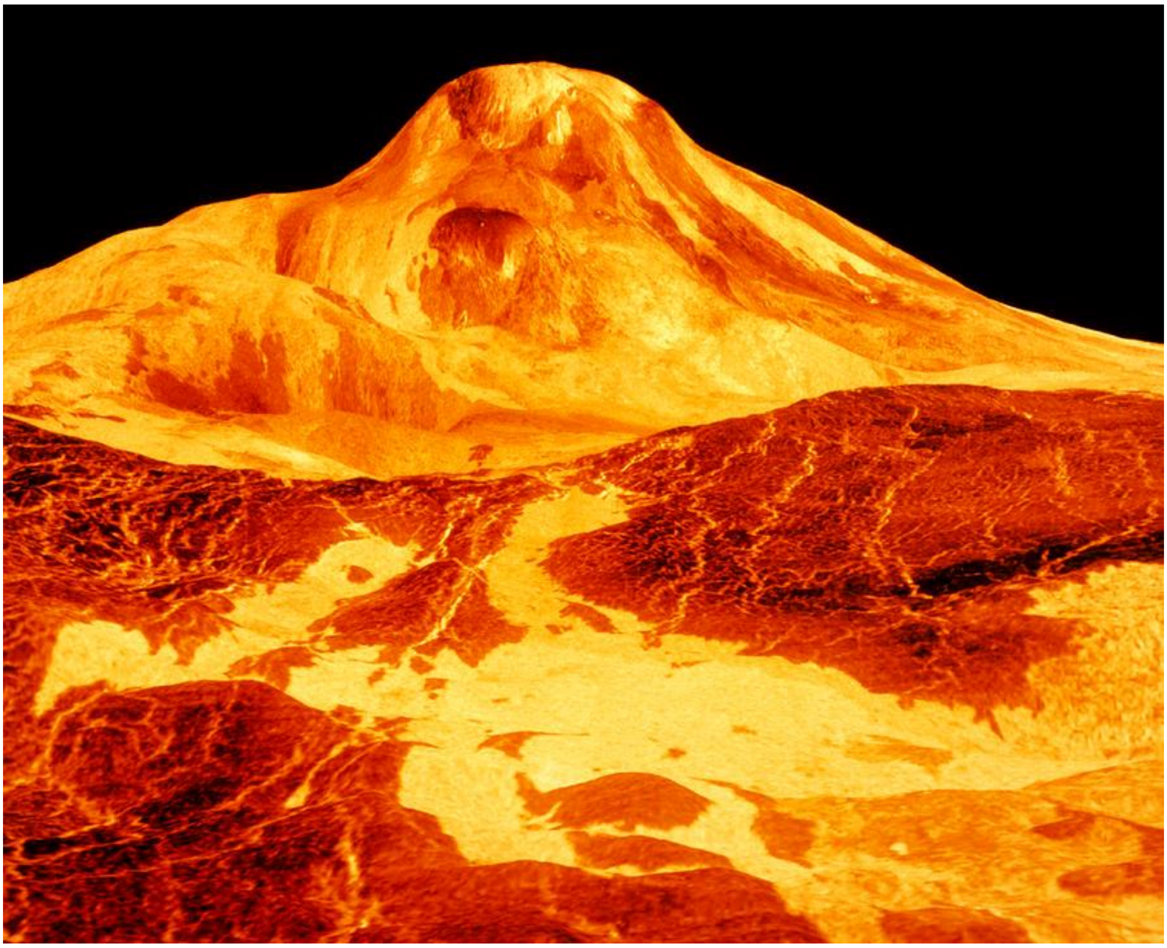

Fig. 4.1. Perspective view of Maat Mons, based on data collected by the “Magellan” spacecraft (https://images.fineartamerica.com/images-medium-large/false-colour-perspective-view-of-maat-mons-venus-nasa.jpg).

Other large shield volcanoes are Sif Mons (Fig. 4.2) and Gula Mons, located in the large volcanic regions of Eistla and Beta, respectively. Sif Mons is about 2 km high and has a base diameter of about 300 km.

A series of bright and darker lava flows extend up to 120 km from the summit. This indicates that the lava is very liquid.

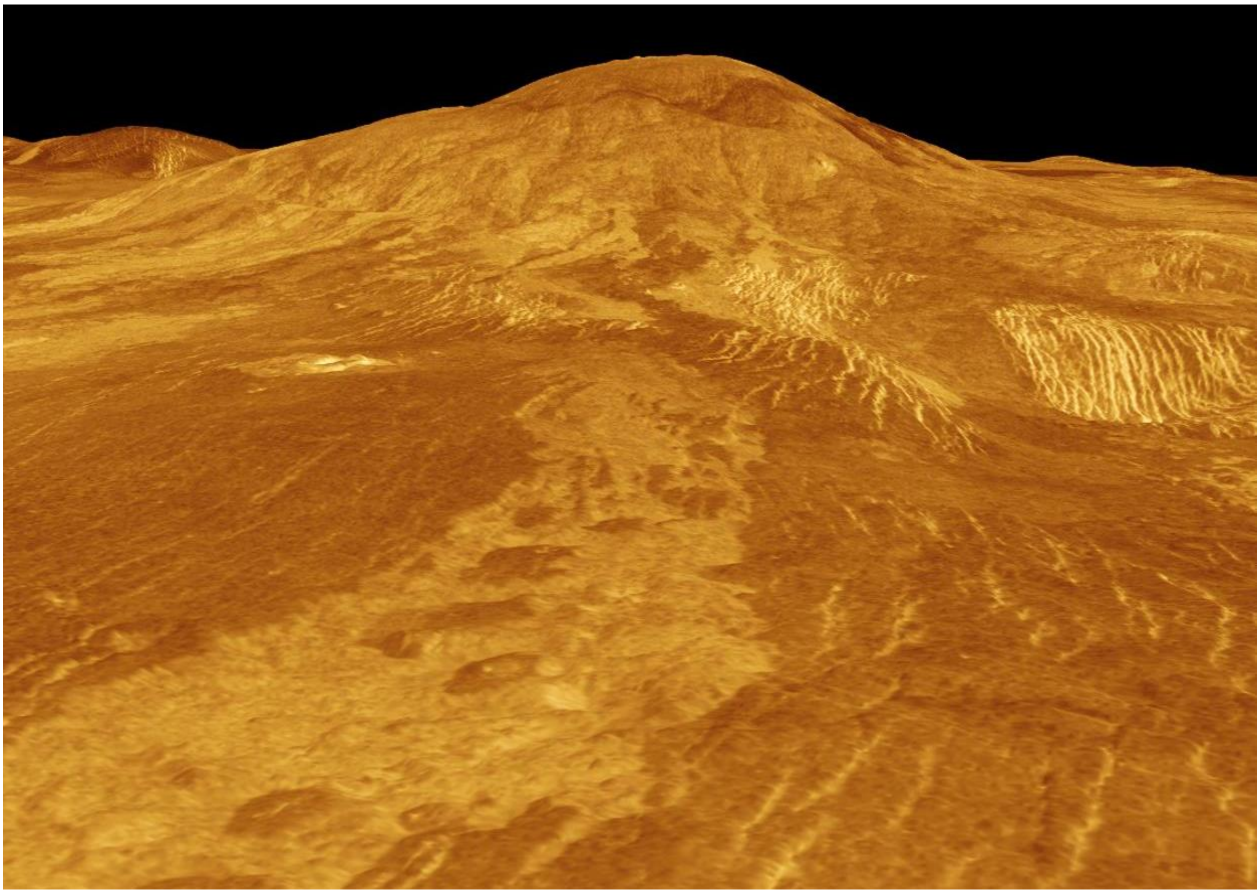

Fig. 4.2. Perspective image of Sif Mons volcano, collected by the Magellan probe with a combination of altimetry and radar measurements; vertical scale is exaggerated to emphasize the relief of the volcano (https://d2pn8kiwq2w21t.cloudfront.net/original_images/jpegPIA00108.jpg).

Unlike Earth, where shield volcanoes often form linear chains over moving tectonic plates, on Venus they are distributed more chaotically, or are concentrated in large volcanic regions [4-6]. This is associated with the absence of significant horizontal movement of lithospheric plates over stationary mantle plumes (hot spots).

4.3. Volcanic domes (Pancake Domes)

One of the most exotic and unique volcanic forms on Venus are the so-called “pancake” domes (Fig. 3.10). These are round structures with a very flat or slightly convex top and extremely steep edges. Their diameter is usually from 20 to 65 km, and their height rarely exceeds 1 km; on average, it is about 300 m. In terms of size, they are significantly (up to 100 times) larger than similar lava domes on Earth.

In total, over 152 volcanic domes have been discovered on Venus. Most of them are nearly circular in shape and have fairly steep walls. Their summits may have one to several craters, from which radial faults radiate. Their upper surfaces may range from convex to nearly flat.

The composition of domes on Venus is still unknown. Although their smooth surfaces are consistent with basaltic rock compositions; their steep walls indicate that they are composed of viscous lava, consistent with high-silica rhyolite compositions. The concentric and radial faulting pattern exhibited by many domes is consistent with stretching of the dome surfaces during their formation, as lava emerges from internal vents and spreads in all directions across the surface.

That is, the "pancake" domes are thought to have formed by the slow extrusion of very viscous lava onto the surface. The high viscosity prevented the lava from spreading over long distances, and the high atmospheric pressure on Venus probably contributed to the formation of this flat shape with steep edges.

The composition of this viscous lava is unknown, but it is assumed that it may have been richer in silica (similar to terrestrial rhyolites or dacites) compared to basaltic lavas of the plains. "Pancake" domes often occur in groups and are often associated with other volcano-tectonic structures, such as coronae and tesserae.

Coronae are another large (with a diameter of 100 km to over 2600 km, but typically 200-250 km) ring or oval structures (Fig. 4.3) that are considered unique to Venus. The morphology of coronae can be quite diverse. But a typical corona consists of a central part, which can also be raised, flat or concave, and a surrounding annular shaft, or a system of concentric ridges and faults; they are the “crown” itself. Often, an annular depression, or even a moat, is observed outside this ring.

Within the coronas, significant volcanic activity is usually observed in the form of lava flows, small shield volcanoes or domes. The general interpretation of coronas is as a surface manifestation of the so-called mantle plumes. They are upward flows of hot material from the depths of the mantle. As soon as the hot plume reaches the lower base of the lithosphere, it causes it to rise and heat. This leads to melting of rocks and to manifestations of volcanism on the surface of a particular planet [19, 21].

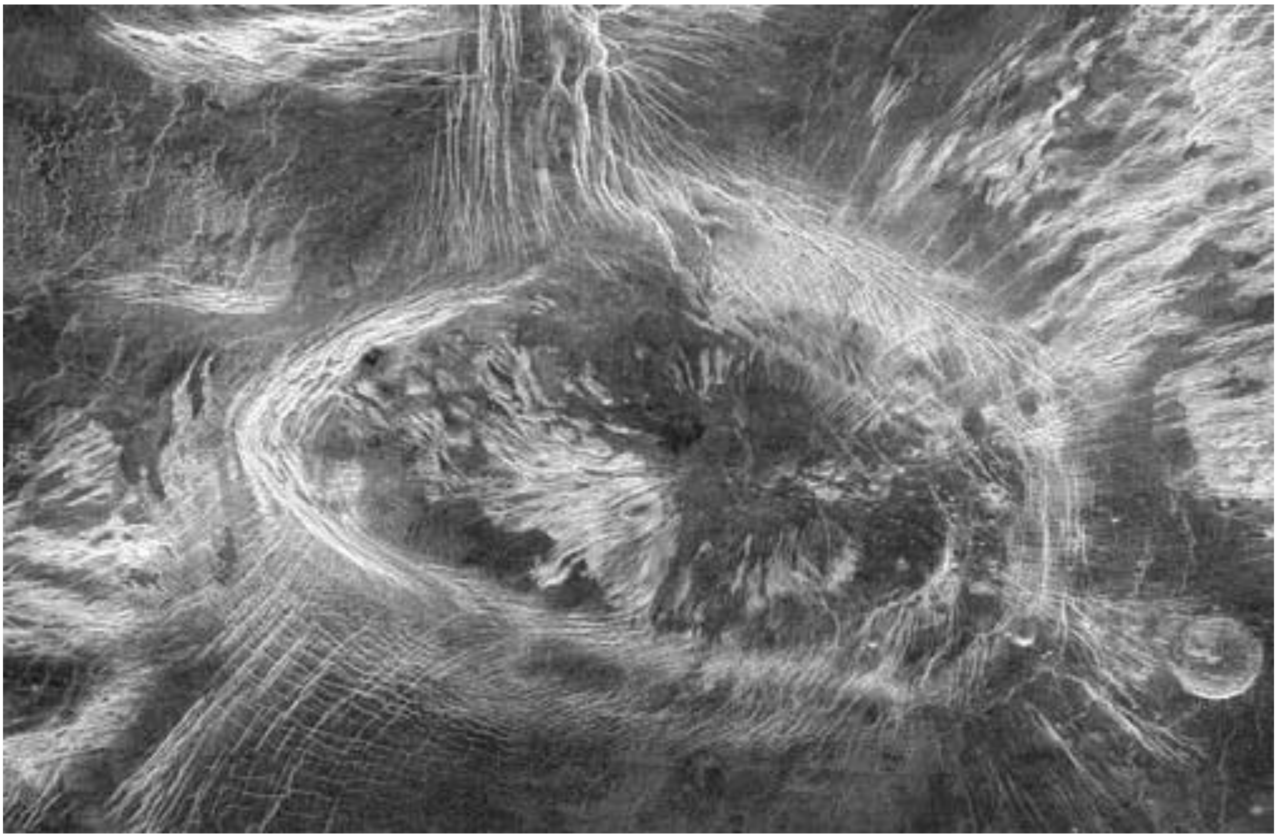

Fig. 4.3. Ba'het Corona is 230×150 km.
(https://volcanoes.sdsu.edu/Images/Planets/bahet_corona_l.jpg).

Further spreading of the plume beneath the lithosphere can cause it to stretch and break up; this is what leads to the formation of ring structures in the corona.

Over time, as the plume gradually cools or dissipates, the central part may sink due to gravitational relaxation, or even due to delamination and immersion into the mantle of the dense lower part of the lithosphere. The variety of shapes of different coronas may reflect different stages of this evolutionary process, or differences in the size and intensity of the plumes and in the properties of the lithosphere at a particular location below the surface.

Arachnoids are another type of volcano-tectonic structure, so named because of their resemblance to a spider's web (Fig. 4.4). They are usually smaller than coronas, and have diameters of 50 to 200 km; the outer ridges extend for 200–400 km. An arachnoid consists of a central, often uplifted region surrounded by one or more concentric rings of faults or ridges, from which numerous linear structures (cracks, grabens, or dikes) radiate.

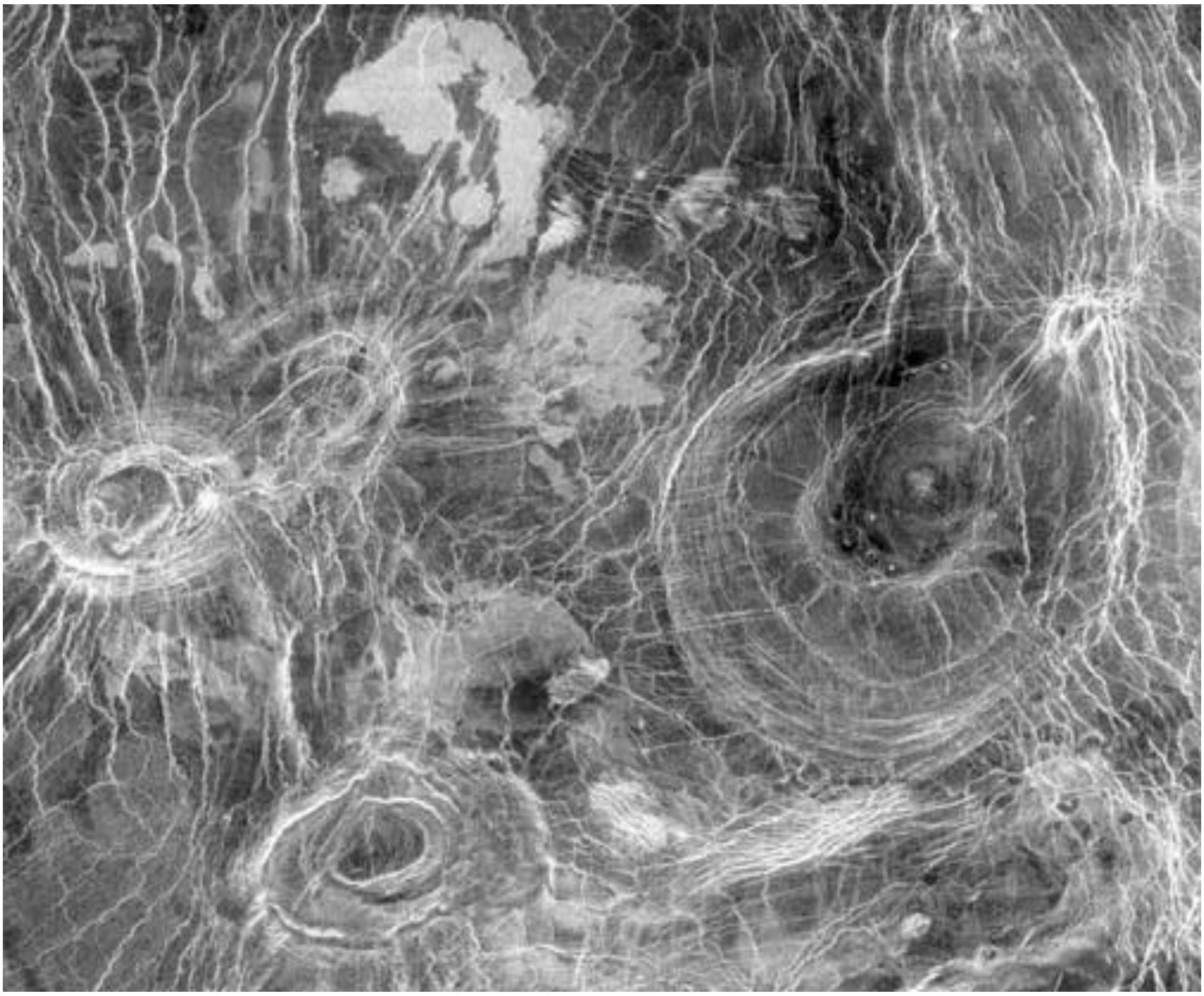

Fig. 4.4. Arachnoids are similar in form, but generally smaller than coronae. They characteristically contain radial dikes, which show up as bright lines on the image here (https://volcanoes.sdsu.edu/Images/Planets/arach_l.jpg).

More than 250 arachnoids have been found on the surface of Venus, and they are usually located near coronae and other arachnoids. Like coronae, arachnoids are rarely found on the lowest plains. Most of them lie somewhat above the low plains. Therefore, arachnoids are thought to have a similar origin to coronae and are associated with mantle plumes. However, it is possible that these plumes are smaller in size or less intense.

Radial structures are interpreted as systems of dikes or fissures filled with magma, which diverge from the center of the plume. It is possible that during the formation of arachnoids, magmatic activity was predominantly intrusive. That is, for them, magma solidified lower in the crust, without reaching the surface. Whereas during the formation of coronas, large volumes of extrusive, or extrusive, rocks are observed.

Lava channels and flows. The surface of Venus is cut by numerous channels, which, unlike terrestrial rivers, were formed by lava flows [7]. The most impressive are the so-called "canali" - extremely long (up to 6800 km in the case of Baltis Vallis), winding channels with a relatively constant width (up to 3 km) and depth [6].

They often have natural embankments (levees) along the shores. Their formation required the eruption of huge volumes of very liquid and hot lava, which could flow for thousands of kilometers along the gentle slopes of the plains. The high surface temperature of Venus (737 K) could help maintain the fluidity of the lava over great distances, slowing its cooling and solidification. The composition of this lava is a subject of debate; in addition to basalts, more exotic options have been considered, such as carbonate or sulfur lavas, which have very low viscosity.

Fig. 4.5 shows an image up to 50 km wide of part of an extremely long channel that extends across the surface of Venus from Fortuna Tessera in the north (top of the image) to the eastern part of Sedna Planitia in the south. This channel is up to 2 km wide, has numerous branches and islands along its entire length.In addition to the channels, Venus also has vast fields of frozen lava flows (flow fields, fluctus), covering millions of square kilometers, especially on the large plains. They testify to episodes of massive effusion volcanism in the planet's history. Fig. 4.6 shows one of them.

Fig. 4.5. 50 km wide image of part of the lava channel obtained by the Magellan radar (https://nssdc.gsfc.nasa.gov/imgcat/hires/mgn_f45n019_1.gif).

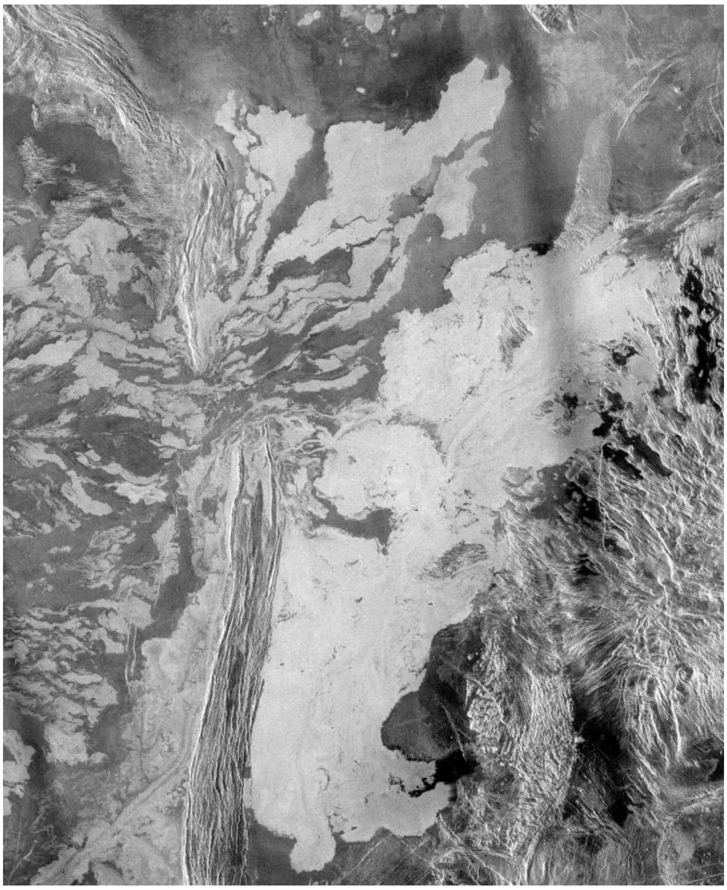

Fig. 4.6. Magellan radar image of the Ubastet Fluctus lava flow (https://upload.wikimedia.org/wikipedia/commons/4/47/VenusLava.jpg).

Ubastet Fluctus is a lava flow on Venus about 500 km wide in the Lada region;

the flow originates from Derceto Corona, located beyond the left edge of the image; a system of bright and dark lava flows destroys a belt of ridges that runs from top to bottom. After breaking through this belt of ridges, the lava reassembles into a huge, radar-bright flow with an area of almost 100,000 square kilometers on the right side of the image.

4.4. Other volcanic formations

Novae are radial systems of cracks (grabens) and dikes that diverge from a central dome-shaped rise (Fig. 4.7, left). They resemble the radial components of arachnoids and are likely related to the accumulation of magma beneath the surface and the stretching of the crust above it.

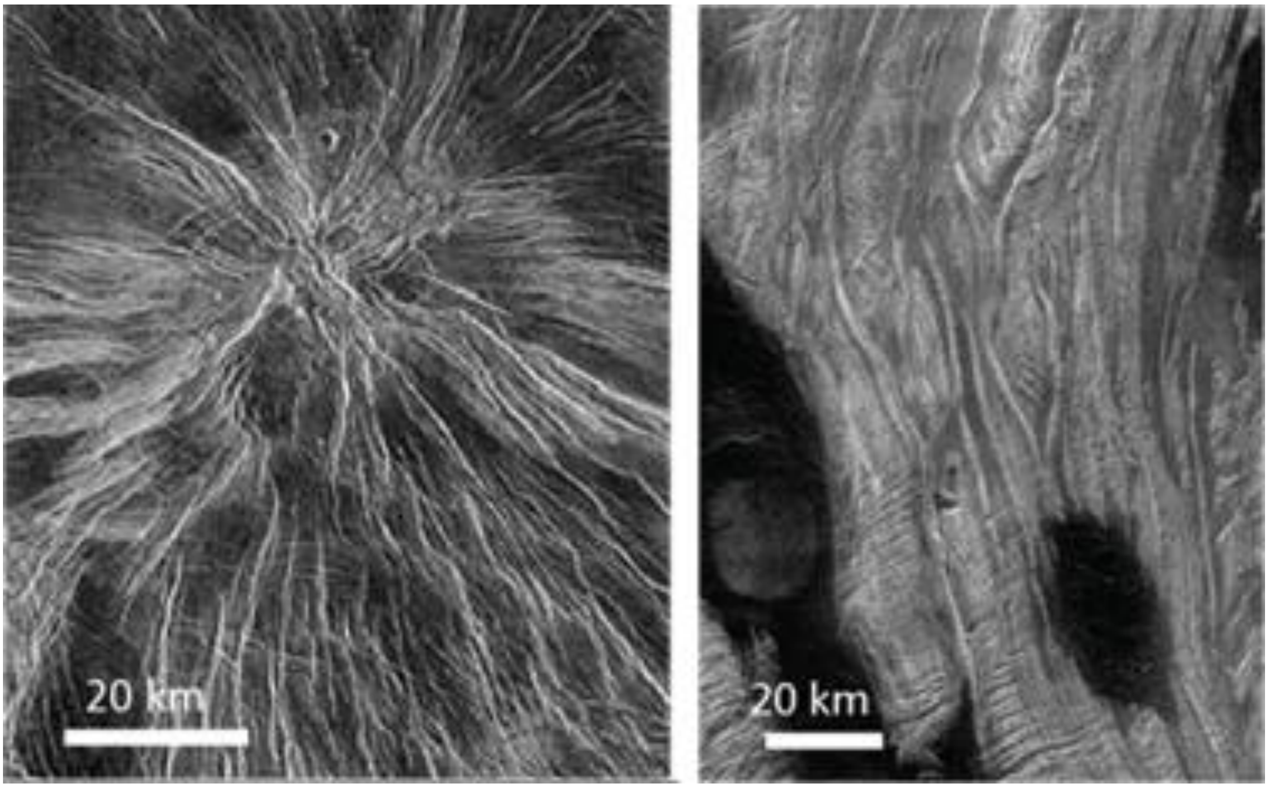

Fig. 4.8. Volcanic and/or tectonic structures on the surface of Venus: left: Nova in Themis Regio (27.2°S, 272.9°E), right: Tessera terrain in Ovda Regio (10.6°N, 90.4°E). (https://blogs.egu.eu/divisions/gd/files/2020/09/Venus_structures-2.png).

Scalped domes ("Ticks"). These are volcanic domes that are similar to "pancakes," but their edges have a scalloped, jagged shape that resembles the legs of a tick. This shape is thought to be the result of gravitational shifts and collapses on the dome's slopes after it formed.

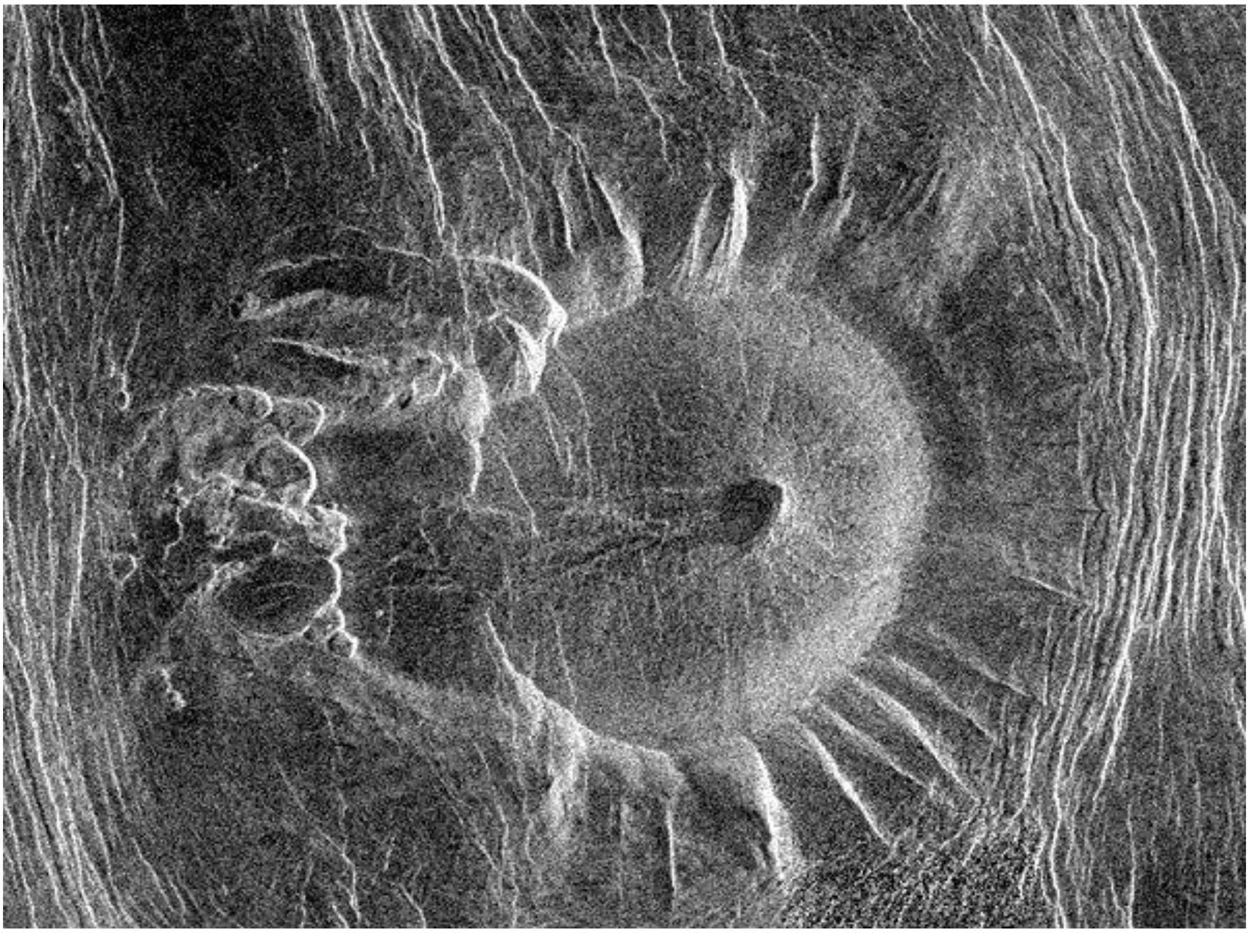

Fig. 4.9. The unusual volcanic feature Tick is shown (https://sites.uni.edu/morgans/astro/course/Notes/section4/tick.jpg).

Calderas are large (tens of kilometers in diameter) volcanic depressions formed by the collapse of the summit of a volcano, or even the surface itself above the magma chamber after a major eruption. These features are often found at the summits of large shield volcanoes.

Volcanic vents/pits. These are irregularly shaped depressions, often elongated or clustered, that do not have the raised rim around them characteristic of impact craters. They are believed to be the sources of volcanic eruptions. Some of them are surrounded by bright, diffuse deposits that are interpreted as products of explosive (pyroclastic) volcanism.

4.5. Volcanic forms as indicators of conditions

The diversity and uniqueness of volcanic forms on Venus are a direct reflection of the specific physical and geological conditions that prevail on this planet. High atmospheric pressure also affects the dynamics of eruptions, especially for viscous lavas, contributing to the formation of "pancake" domes. The high surface temperature allows even basaltic lavas to remain fluid much longer than on Earth. This feature well explains the formation of extremely long lava channels on the surface of Venus.

The absence of water in significant quantities affects the rheology (fluidity) of magma and limits erosion processes on the surface. This allows the preservation of existing volcanic forms on the surface of Venus for a long time. And the absence of terrestrial-type plate tectonics leads to the dominance of volcanism associated with mantle plumes.

This feature manifests itself in the form of large shield volcanoes, coronas and arachnoids. The latter are structures that have no direct analogues on Earth. Thus, the study of the morphology of volcanic formations allows us to reconstruct the conditions and processes that once operated and, perhaps, operate now on Venus.

The presence of evidence of explosive volcanism, although not as widespread as extrusive volcanism, is an important indicator of the presence of volatile substances (gases) in the magma on Venus. Explosive eruptions occur due to the rapid expansion of gases dissolved in magma when the pressure decreases during ascent to the surface. The identification of pyroclastic deposits around some volcanic vents indicates that the magma on Venus contained a sufficient amount of volatile components (most likely, sulfur compounds, carbon dioxide, possibly water) to ensure such eruptions.

This somewhat contradicts the idea of Venus as a completely "dehydrated" planet and raises questions about the composition of its mantle and the conditions for magma generation. The study of these deposits can provide quite valuable information about the content and role of volatile substances in the interior of Venus.

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5. The influence of volcanism on the formation of the modern surface of Venus

Introduction

As detailed studies of Venus by various spacecraft have shown, volcanism has played a major role in shaping much of the planet's present-day surface. For example, large-scale lava flows have created vast plains, and the unique nature of the crater record [16] suggests that the planet may have undergone global surface renewal in the past.

5.1. Formation of the Great Plains

Information obtained by spacecraft instruments shows that about 80% of the surface of Venus is occupied by large volcanic plains. These plains are the result of massive, repeated outpourings of lava, probably predominantly basaltic in composition, which covered vast areas, smoothing out the previous relief. This process, known as flood volcanism, is similar to the formation of lunar "seas". The lava that was poured was probably very liquid and hot, and this allowed it to spread for hundreds and thousands of kilometers. Estimates of the thickness of these lava sheets in some regions vary from hundreds of meters to several kilometers, especially within large impact basins or lowlands [15, 16].

5.2. Hypotheses of global surface renewal

One of the most intriguing aspects of the geology of Venus is its crater record. As detailed in [31], impact craters on Venus are distributed almost randomly across the surface, and the vast majority of them appear relatively young and intact [20, 30]. The average age of the surface, estimated from the density of craters, is only about 300–500 million years (Fig. 5.1). This is in striking contrast to other rocky bodies in the Solar System, which preserve crustal regions several billion years old. These observations have led to the hypothesis of a global resurfacing of the Venusian surface, which has erased much of the previous geological history.

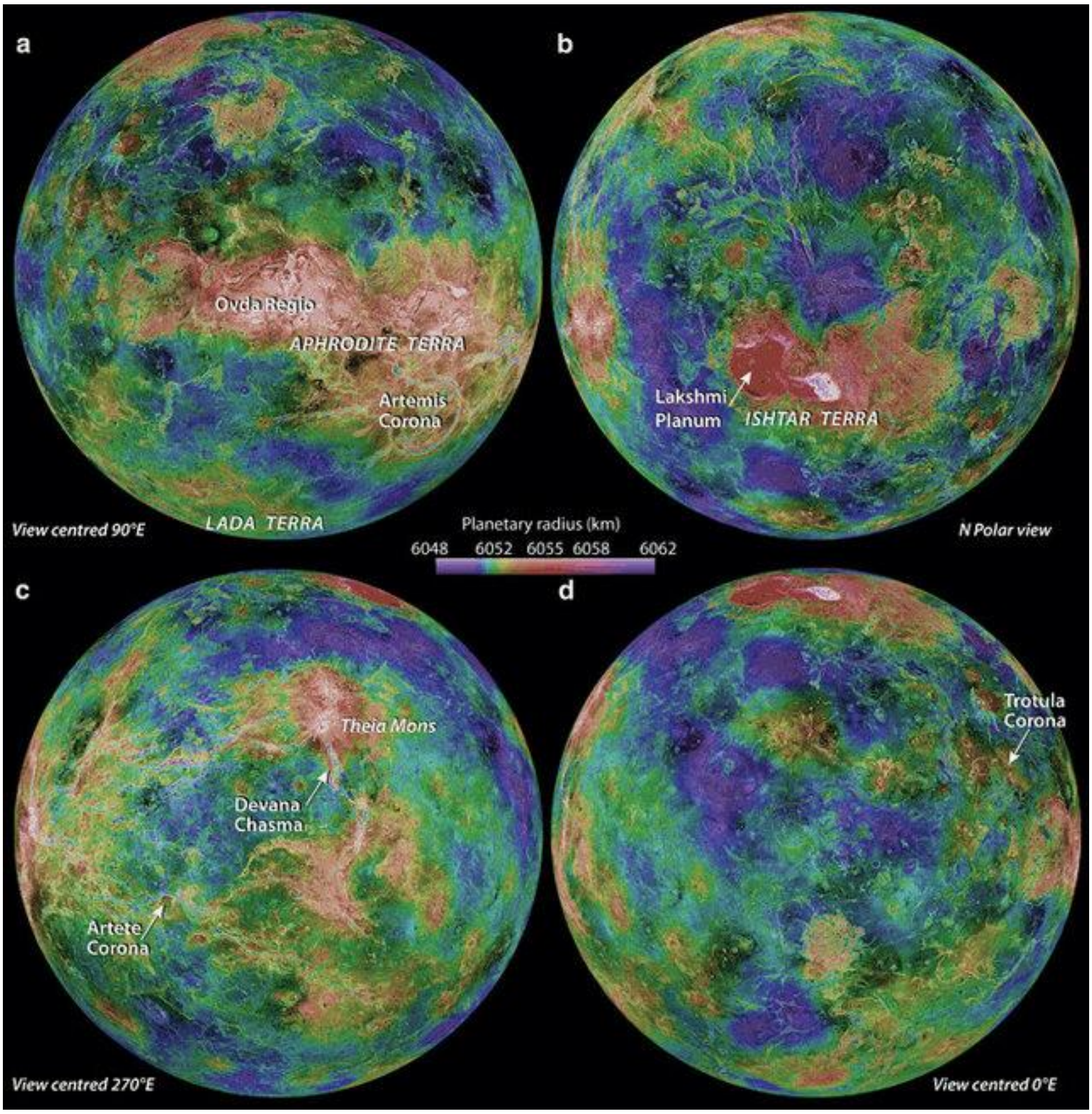

Fig. 5.1. Global topographic map of Venus derived from a mosaic of radar images by the Magellan probe [4].

There are two main models that explain this process.

1. *Catastrophic Resurfacing Model.* This model suggests that approximately 300–500 million years ago, Venus underwent a relatively short (perhaps lasting 10–100 million years) [3] but extremely intense phase of global volcanism and/or tectonism that resulted in complete or near-complete resurfacing of its surface [1, 2, 8]. After this catastrophic episode, geological activity declined sharply to a much lower level [11, 17, 20]. This model explains well the random distribution of craters and their largely intact state. The mechanisms of such a catastrophe may be related to the internal dynamics of the planet, for example, to periodic instability of mantle convection,

leading to a global mantle overturn, or to an episodic regime of subduction or plate tectonics, which suddenly becomes active and then stops.

2. *Gradual/Equilibrium Resurfacing Model*. This alternative model claims that the surface renewal did not occur catastrophically, but more gradually, through numerous but spatially limited volcanic and tectonic events; and they occurred in different places at different times over a long period. In this model, the random distribution of craters is explained by the fact that the rate of destruction of old craters and the creation of a new surface is on average balanced by the rate of formation of new craters. The surface is in a state of dynamic equilibrium [26]. This model suggests that geological activity on Venus was more prolonged and may continue to be present today [32-35], although its intensity may have decreased over time.

Current view. The debate between the proponents of the catastrophic and gradual renewal models continues. Each model has its strengths and problems. The catastrophic model better explains the low percentage of craters that have undergone modification (lava filling, deformation) [24], but requires an explanation of an extremely powerful and short-lived geological process. The gradual renewal model avoids the need for a global catastrophe, but it is much more difficult to explain why so few craters show signs of only partial destruction or lava filling if volcanic activity was constant.

Detailed geological maps compiled from data obtained by the Magellan probe show a complex stratigraphy of the planet's surface, where various volcanic and tectonic features overlap; this would indicate a long and multi-stage history [26]. This, and recent evidence of possible modern volcanic activity, shifts the emphasis somewhat in favor of models with a longer, though possibly episodic, geological activity. Perhaps the reality is a combination of both approaches: a period of particularly intense, almost global volcanism may have been followed by a phase of slower, more localized activity that continues to this day.

The current distribution of impact craters on the surface of Venus poses a fundamental dilemma. How could a planet so similar to Earth in size and mass either survive a global geological catastrophe that "reloaded" its surface in a relatively short time, or maintain a state of equilibrium renewal for hundreds of millions of years without the plate tectonics mechanism that operates so effectively on Earth?

If the catastrophic model is correct, then it is necessary to understand the physical processes in the mantle and core of Venus that could lead to such a sudden and large-scale release of energy and magma. This could be due to the peculiarities of mantle convection beneath the thick, immobile lithosphere, which leads to periodic accumulation of heat and its explosive release.

If the gradual renewal model is correct, then it is necessary to explain how local volcanic events can maintain the surface of the planet in a state where craters appear randomly distributed and mostly intact. This requires a certain balance between the rate of volcanic activity and the rate of crater formation, as well as finding mechanisms that effectively erase traces of previous activity.

Resolving this dilemma is of key importance not only for understanding the history of Venus, but also for a general understanding of the thermal evolution and internal dynamics of rocky planets, especially those without plate tectonics.

5.3. Possible modern volcanic activity

The question of whether Venus is geologically active today has long been open. Although its surface appears geologically young (average age ~0.5 billion years [20]) and the number of volcanic structures is enormous, there has been no direct evidence of modern eruptions until recently. However, data accumulated over the past decades, especially the results of the "Venus Express" mission and reanalysis of data obtained by the "Magellan" probe, provide increasing evidence that volcanism on Venus may still be ongoing [19].

The following two pieces of indirect evidence are provided.

1. *Fluctuations in the concentration of SO_2 in the atmosphere*. Sulfur dioxide is one of the main gases emitted during volcanic eruptions on Earth. Its presence in the atmosphere of Venus has long been known. Data obtained by the "Pioneer Venus" spacecraft in the late 1970s and early 1980s showed high concentrations of SO_2 in the upper atmosphere, which then decreased. Later, spectrometers on board "Venus Express" recorded a significant (almost tenfold) increase in SO_2 in the upper

atmosphere after the spacecraft arrived at the planet in 2006, followed by a gradual decrease over the following years. Such fluctuations can be explained by episodic large volcanic eruptions that eject significant volumes of SO_2 to high altitudes. Since SO_2 is relatively quickly removed from the atmosphere through photochemical reactions and interaction with surface rocks (lifetimes are estimated to range from days in the upper atmosphere to millions of years near the surface), its stable presence, and even more so significant fluctuations in concentration, require an active source of replenishment, which is most likely volcanism.

2. *Thermal anomalies*. The infrared spectrometer VIRTIS on “Venus Express” was able to “peek” through atmospheric transparency windows in the near-infrared range (about 1 μm) and measure thermal radiation from the surface itself. Analysis of these data revealed several areas associated with geologically young volcanic regions (in particular, in the Imd, Themis and Dione regions) that had anomalously high thermal emissivity. This was interpreted as evidence that the lava flows in these areas are relatively "fresh" (perhaps a few thousand to 2.5 million years old), as they have not yet undergone significant chemical weathering under the influence of an aggressive atmosphere, which over time reduces the emissivity of the surface. In addition, the VMC camera on “Venus Express” recorded several temporary bright spots in the area of the Ganiki Chasma rift zone, which could be manifestations of active eruptions or fresh lava flows, although this interpretation remains controversial due to the difficulty of calibrating the data and the possible influence of atmospheric phenomena.

5.4. Direct evidence of volcanism from surface changes

The most convincing evidence of modern volcanic activity has recently been obtained through a careful analysis of archival radar data from the “Magellan” mission, which orbited Venus from 1990 to 1994 [18]. Although the mission was not specifically designed to search for surface changes, it mapped the same areas several times, several months apart. In 2023, [6] published the results of an analysis of images of the Maat Mons area in Atla Regio, acquired in February and October 1991. Clear changes were found in the volcanic vent on the northern slope of the mountain (Fig.

5.2). The vent, which had an area of about 2.2 km² in the first image, had significantly increased (to almost 4 km²) and changed shape in the second image, taken 8 months later. In addition, the second image showed signs of new lava flows flowing down the slope from the vent. These changes have been interpreted as the first direct geological evidence of volcanic eruptions on Venus during the observation period.

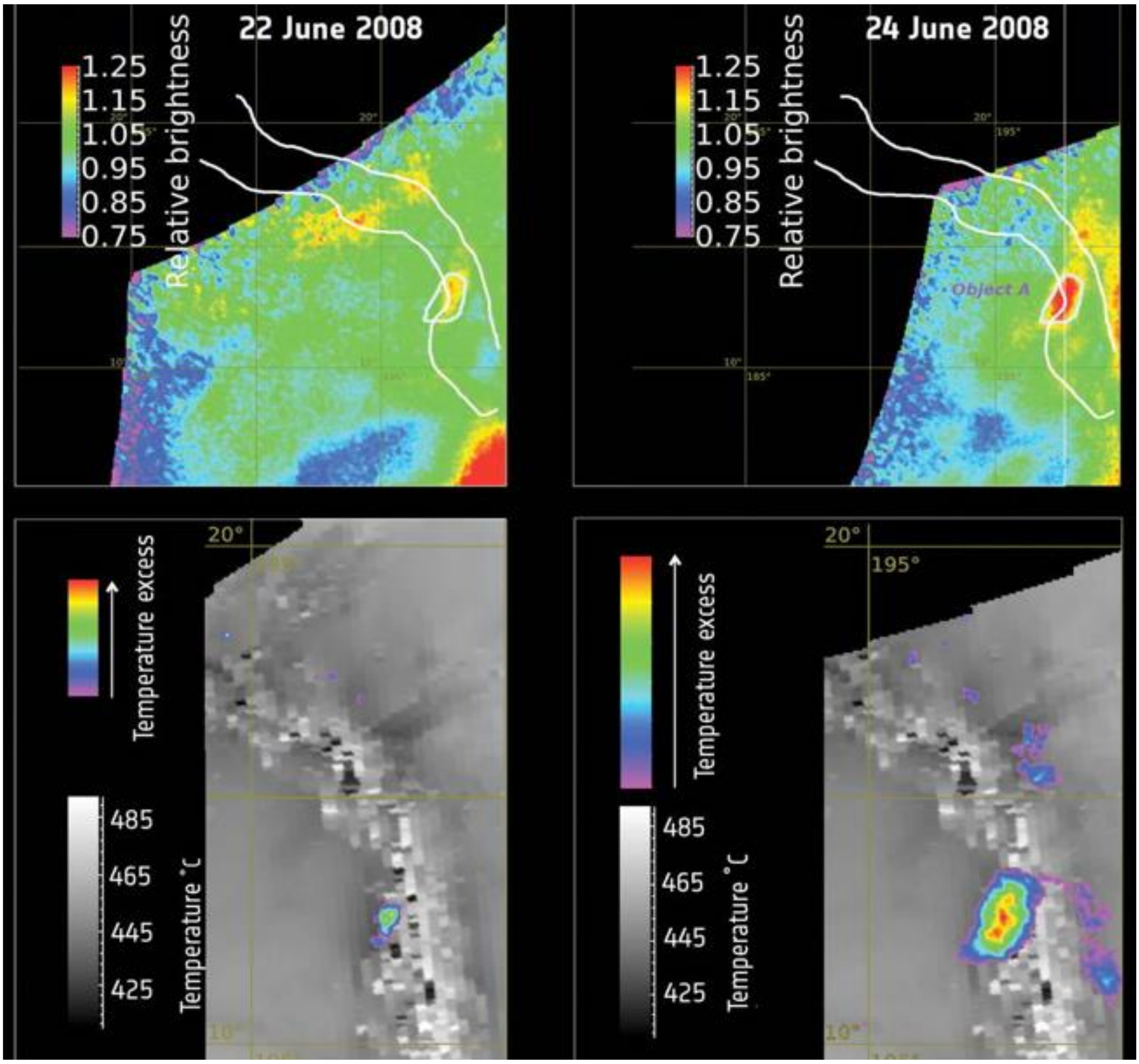

Fig. 2. Four hot spots detected by "Venus Express" in the Ganiki Chasma rift zone in Atla Regio. Relative brightness changes (top row) and temperature changes (bottom row) between 22 and 24 June 2008 are shown. The hot spot has an area of about 1 km2 with a temperature of 1100 K [22].

Estimated In 2024, two more new lava flows were reported during the Magellan mission [5, 8, 14, 15, 23]. Comparing radar images acquired 16 months apart, changes in radar backscatter were observed on the western slope of the shield volcano Sif Mons and on the western plain of Niobe Planitia. These are best explained by the appearance of new, rough lava flows [10].

The area of the new flows is about 30 km² for Sif Mons and 45 km² for Niobe Planitia, and their average thickness is from 3 to 20 m.

5.5. Significance of evidence of ongoing volcanic activity

Obtaining direct evidence of changes in the surface appearance of Venus is of fundamental importance. It has provided convincing evidence that the planet is not geologically dead, as previously believed. Volcanic activity continued at least until the 1990s and, most likely, continues today.

This confirmation of modern activity has important implications for our understanding of Venus:

● It supports models of geological evolution that predict a long, although possibly episodic, activity, rather than a single ancient catastrophe.

● It indicates that the planet's interior is still hot enough to generate magma and its emergence to the surface.

● It raises questions about the mechanisms of internal heat loss on Venus, where volcanism probably plays a much larger role than previously thought.

● Estimates of the volume of erupted lava indicate that the intensity of volcanism on Venus may be comparable to that of Earth, making it a unique laboratory for studying active geological processes on a planet without plate tectonics.

5.6. Future studies

Confirmation of current activity greatly increases the interest in future missions to Venus. The “VERITAS”, “DAVINCI”, and “EnVision” spacecraft will be equipped with instruments specifically designed to search for and study in detail signs of activity.

Radars with higher resolution and interferometry capabilities (InSAR) will be able to detect even small changes in the relief associated with lava flows or surface deformation above magma chambers [29]. Spectrometers will search for thermal anomalies and analyze the composition of volcanic gases in the atmosphere. These missions promise to revolutionize our understanding of Venus as a dynamic, active planet.

5.7. The relationship between internal processes, tectonics, and volcanism on Venus

The geological appearance of Venus, characterized by the dominance of volcanic plains, the presence of unique volcano-tectonic structures (coronas, arachnoids, etc.) [1, 16] and the absence of a global system of tectonic plates, is a direct consequence of the interaction of processes in its interior – the generation and loss of internal heat, mantle convection and lithosphere properties.

Like Earth, Venus generates heat in its interior mainly due to the decay of long-lived radioactive isotopes such as uranium, thorium, potassium, as well as due to residual heat that has been preserved since the formation of the planet. Given the similarity of size and, probably, general chemical composition, the total power of internal heat sources on Venus is expected to be comparable to that of Earth.

A fundamental question in the geology of Venus [2, 17] is how it gets rid of this internal heat. On Earth, the main cooling mechanism is plate tectonics. In this case, hot mantle material rises in the mid-ocean ridge zones, forming a new oceanic lithosphere; it then cools, moves horizontally and having become sufficiently dense, sinks back into the mantle in the so-called subduction zones, taking with it a significant amount of heat. On Venus, such a mechanism obviously does not work or works in a completely different way. Let us consider several alternative or complementary mechanisms of heat loss.

Thermal conductivity through the lithosphere. Heat can slowly seep through the stationary lithosphere by conduction. However, for a large planet with active internal heat sources, this mechanism is considered to be insufficiently effective to prevent overheating of the interior. This is the so-called “stagnant lid” regime.

Mantle plumes and volcanism. Hot upward flows of material from the depths of the mantle (i.e., plumes) can penetrate to the base of the lithosphere or even through it, carrying away heat and generating magma. Plume-related volcanism, i.e., the formation of large shield volcanoes, crowns, large lava provinces, etc., is also an important mechanism for removing heat to the surface of the planet [32].

Lithosphere delamination. The lower, denser part of the thick lithosphere can become gravitationally unstable and begin to exfoliate and sink into the hot mantle. This process, which can be triggered by mantle plumes (for example, at the edges of crowns), allows hot mantle material to rise closer to the surface, increasing heat loss.

Episodic global events. It is possible that in a stagnant lid regime, heat gradually accumulates in the mantle below the lithosphere. This can lead to periodic destabilization of the entire system, causing short-lived but extremely intense episodes of global volcanism and tectonics (the so-called catastrophic renewal), which effectively "dump" the accumulated heat. After such an event, the planet returns to a regime of slow cooling through a stagnant lid.

Venus's heat loss is likely due to a combination of the mechanisms mentioned above. Moreover, the dominant role, especially in the modern era, is played by mantle plumes and associated volcanism and, possibly, local delamination.

Lack of terrestrial-type plate tectonics. One of the most important differences between Venus and Earth is the lack of a global system of moving lithospheric plates. On its surface, there are no signs of plate tectonics characteristic of Earth: long linear chains of volcanoes above subduction zones, extensive mid-ocean ridges where new crust is formed, or large transform faults.

The reasons for this difference are not fully understood but are likely due to a combination of many possible factors. The high surface temperature (about 737 K) may make the lithosphere of Venus more ductile and less dense [22, 24] compared to the cold and dense oceanic lithosphere of Earth. This makes it difficult for it to sink (or subduct) into the mantle.

The absence of water on the surface and in the crust of Venus also plays an important role: water significantly lowers the melting point of rocks and their strength, contributing to the formation of fault zones and facilitating plate movement on Earth. The "dry" and strong lithosphere of Venus may be more resistant to fragmentation into individual plates. There may also be differences in the regime of mantle convection beneath the lithosphere.

Although there is no global plate tectonics there, the surface of Venus is still not tectonically passive. Numerous signs of local and regional crustal deformation are observed. These include the following features.

Mountain belts. Folded structures surrounding the Lakshmi Plateau (Maxwell, Akna, Freya, Danu Mountains) indicate extensive horizontal compression of the crust on Venus.

Rift valleys (chasmata). Giant systems of grabens and faults extending for thousands of kilometers (e.g., in Aphrodite Land), indicate significant crustal stretching, probably associated with mantle plumes.

Wrinkle ridges. Long, narrow ridges on volcanic plains, formed by moderate compression of the crust after lava solidified.

Tesserae. Areas of extremely complex deformation, indicating multiple episodes of compression and extension in the ancient history of the planet.

Recent studies of data from the Magellan spacecraft [6, 7, 19] have found evidence in some low-lying areas that the Venusian crust may still be broken into discrete blocks [23] that undergo minor horizontal displacements and rotations, interacting with each other like ice floes on water [26]. This regime, sometimes called a "squishy lid" or "plutonic-squishy lid," may represent an intermediate state between rigid stagnant lid and active plate tectonics.

5.8. Mantle plumes and the formation of crowns and rifts

In the absence of plate tectonics, mantle plumes play a key role in the geological activity of Venus. The unique structures of Venus, the coronas, are thought to be a direct surface manifestation of these plumes.

Modeling shows that when a hot and buoyant plume rises from the depths of the mantle and reaches the base of the lithosphere [8], it causes the lithosphere to heat up, thin, and uplift. This leads to melting of mantle and crustal rocks, which fuels volcanism at the surface, often concentrated in the center and along annular faults in the crown. The spreading of the plume head beneath the lithosphere causes tensile stresses, leading to the formation of concentric and radial cracks and grabens that form the characteristic ring of the crown [22]. Further evolution may involve gravitational relaxation of the uplifted region, leading to the subsidence of the central part, or even delamination – the separation and subduction of the cooled and thickened lower part of the lithosphere at the edge of the plume. This delamination process may be an important additional mechanism for heat loss and lithosphere recycling. The diversity of crown morphology likely reflects different stages of this complex process of plume–lithosphere interaction [22].

Large rift zones (chasmata), such as those that cross Aphrodite Land and are associated with the large volcanic uplifts of Beta and Atlas, are also thought to be the result of powerful mantle plumes. The plumes cause significant uplift and stretching of the lithosphere, which leads to its cracking and the formation of deep grabens and canyons. Volcanism is often concentrated along these rift zones.

Estimates of the thickness of the elastic lithosphere, made on the basis of analysis of gravity data and topography around crowns and volcanic uplifts, often indicate that the lithosphere in these areas is thinner than the global average. This is consistent with the idea of increased heat flow and thermal erosion of the lithosphere above active mantle plumes.

5.9. Coronas as a unique window into mantle dynamics

Because coronas are unique to Venus and closely associated with mantle plumes, their detailed study provides a unique opportunity to understand the processes occurring in the planet's mantle and the mechanisms of mantle-lithosphere interaction in the absence of plate tectonics [9].

On Earth, the manifestations of mantle plumes (hot spots) are significantly modified by the movement of lithospheric plates. On Venus, where the lithosphere is mostly stationary, the surface structures created by plumes should more directly reflect the dynamics of processes in the subsurface.5 The complex structure of coronas is the result of a complex interaction of the plume with the lithosphere, which includes uplift, melting, extension, volcanism, gravitational relaxation and, possibly, delamination or subduction.

By analyzing the morphology, gravitational anomalies, volcanic activity and possible age of various coronas, scientists are trying to reconstruct the characteristics of Venus' mantle plumes (size, temperature, lifetime) and the properties of its lithosphere (thickness, strength, viscosity). Thus, coronas serve as natural laboratories for studying mantle convection and plume volcanism under conditions that are significantly different from those on Earth.

5.10. Venus as a possible analogue of early Earth

The geological regime of Venus, characterized by the absence of plate tectonics [3, 4] and the dominance of volcanism associated with mantle plumes, may be similar to that which existed on Earth at the early stages of its evolution, in particular in the Archean era (4.0-2.5 billion years ago).

It is believed that modern plate tectonics on Earth was not established immediately after the formation of the planet. The early Earth was much hotter, its lithosphere may have been thinner, weaker and more buoyant. Under such conditions, vertical tectonic movements and intense plume volcanism [5], similar to those observed on Venus, may have dominated. Venus, due to its specific conditions (high surface temperature, lack of water), may have never been able to transition to the plate tectonic regime and was "stuck" at an earlier stage of geological evolution [11].

If so, then studying the geological processes on Venus – the formation of coronas, rifts, large volcanic provinces – can provide valuable information about how our own planet functioned billions of years ago, before the appearance of continents and oceans in their modern form. This makes Venus an extremely important object for comparative planetology and understanding the general patterns of evolution of terrestrial planets.

Conclusions

The unique geological appearance of Venus. Venus, despite its similarity to Earth in size and mass, is a world with a unique geological appearance and extreme surface conditions. Its current state is the result of a complex interaction of a specific internal structure, long-term and intense volcanic activity and a powerful atmosphere.

The key factors that determined the evolution of Venus are:

1. *Internal structure and thermal regime*. The presence of a large metallic core (probably partially liquid) and a hot silicate mantle provides a significant internal heat flow similar to that of the Earth. However, the planet's extremely slow rotation prevents the generation of a global magnetic field by a dynamo mechanism [28]. The absence of terrestrial-type plate tectonics means that the main mechanism of internal heat loss is associated with mantle plumes and volcanism.

2. *The dominant role of volcanism*. Volcanism was and probably remains the main process of formation and renewal of the surface of Venus [29-31]. Large-scale eruptions of basaltic lava have created vast plains covering about 80% of the planet. Volcanic activity associated with mantle plumes has led to the formation of unique structures such as coronae and arachnoids, as well as large shield volcanoes and rift zones. Specific surface conditions (high pressure and temperature) have contributed to the formation of exotic features such as pancake-shaped domes and extremely long lava channels.

3. *Global renewal and modern activity*. The unique distribution of impact craters [15, 26] suggests a relatively young mean age of the surface (~0.5 billion years) and the possibility of global renewal in the past, although the mechanism and duration of this process remain controversial. Recent evidence of surface changes and atmospheric composition fluctuations indicate that Venus is likely to remain volcanically active today [33-35].

4. *Extreme conditions*. The dense, CO2-dominated atmosphere has created a powerful greenhouse effect [12, 13, 25], leading to the highest surface temperatures in the Solar System. This atmosphere also plays a key role in modifying impact craters [20] and may influence the style of volcanic eruptions.

Thus, Venus appears to us as a dynamic world, whose geological history was determined by internal processes different from those of Earth. The absence of plate tectonics and the dominance of plume volcanism have shaped a landscape that has no analogues in the Solar System.

Further studies of Venus, including those by future space missions, promise to reveal even more secrets of this enigmatic planet and deepen our understanding of the evolution of terrestrial planets.

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