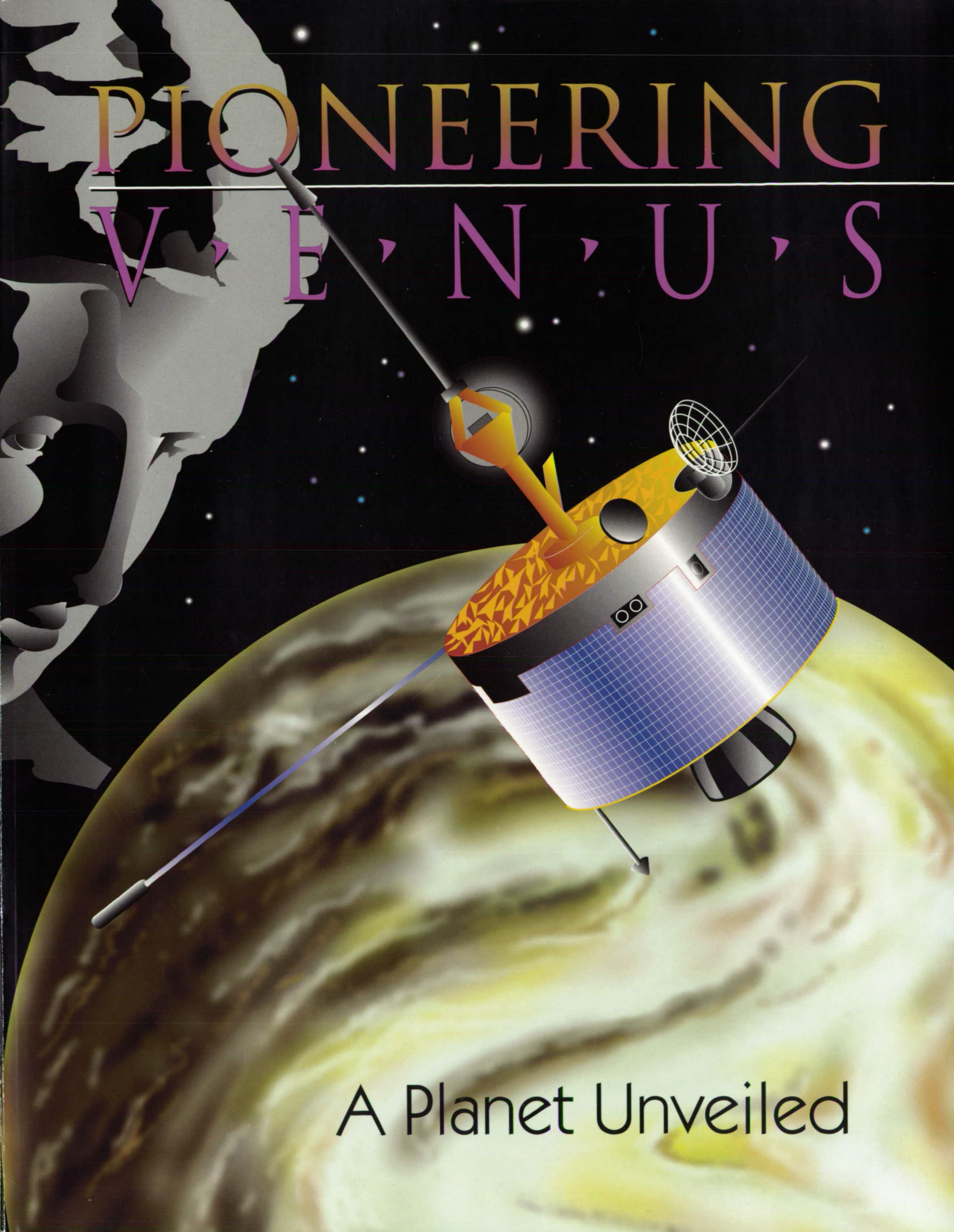
PIONEERING VENUS

A Planet Unveiled



PIONEERING V·E·N·U·S

A Planet Unveiled

The Pioneer Project and the
Exploration of the Planet Venus

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PIONEERING VENUS

A Planet Unveiled

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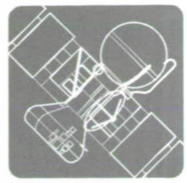
CHAPTER 7

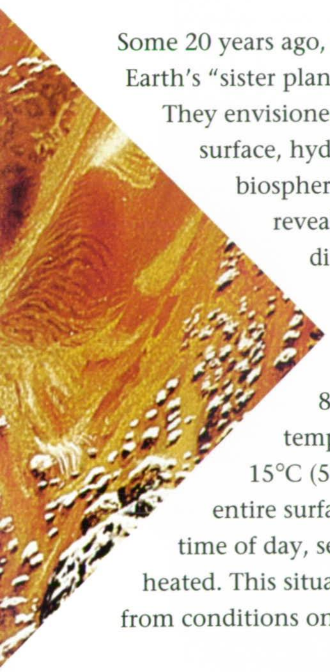


SOVIET STUDY RESULTS

R. Z. Sagdeev, V. I. Moroz, and T. Breus

Some years before NASA published the first edition of this book in 1983, Soviet space scientists graciously contributed this chapter. In it, they detailed their Venera missions 4 through 12 (1967-1978). They also mentioned the "upcoming" (1984) Vega project at the end of their text. To bring events up to date, our American authors have returned and added their own text (1994) at the chapter's end. They describe the flights of the Soviet Veneras 13 through 16 (1981-1982). They also give results of Vegas 1 and 2, including the successful Comet Halley flyby in 1986.

Venus, the planet nearest Earth, has always been of interest to the Soviet Space Program—it has sent the largest number of unmanned space probes there. The planet's many features that are similar to our own Earth has prompted this keen interest in Venus. The two planets' mass and geometry are indeed similar, and they receive roughly equal energy from the Sun.



Some 20 years ago, scientists thought that Earth's "sister planet" was its exact replica. They envisioned it with a slightly warmer surface, hydrosphere, and, possibly, biosphere. Yet, as the first studies revealed, there are drastic differences in climate. The temperature on the Venusian surface averages 735 K (about 462°C, or 864°F). However, the average temperature of Earth's surface is 15°C (59°F). Furthermore, Venus' entire surface, regardless of latitude or time of day, seems to be uniformly heated. This situation is distinctly different from conditions on Earth.

All these unique features of the Venusian atmosphere, however, have been established only in the era of space exploration.

Soviet Spacecraft

In the second half of the 1950s, radio telescopes yielded data about the high temperature of Venus' surface. So unexpected was this information, not all scientists believed it. To settle the issue, the first Soviet interplanetary automatic stations to Venus had "surface phase state" sensors onboard. These sensors could determine whether the vehicle had landed on a solid surface or if ocean waves were rocking it.

On October 18, 1967, Venera 4, the first spacecraft to descend into Venus' atmosphere with a parachute, had no such sensor onboard. However, for this mission, the spacecraft had protection against the extremely high temperatures it encountered. This protection allowed it to take actual measurements of the conditions it faced. Subsequent Venera spacecraft—Venera 5/Venera 6 (1969) and Venera 7/Venera 8 (1972)—added to the information (see Table 7-1). These probes yielded detailed information about variations in temperature, pressure, and density of the Venusian atmosphere with altitude. Venera 7 and Venera 8 made soft landings and transmitted signals directly from the planet's hot surface. Instruments aboard Venera 8 took the first scattered solar radiation measurements. They also furnished information about soil composition, including uranium, potassium, and thorium.

Table 7-1. Soviet Space Vehicles That Studied Venus, 1967 to 1978

Space vehicle		Date		Landing site			Measurements
Name	Type	Launch	Approach	Latitude	Longitude	Solar angle, deg	
Venera 4	Descent module + flyby vehicle	6/12/67	10/18/67	19	38	–20[a]	Descent module: Temperature, pressure, density, wind velocity; CO_2, N_2, H_2O content at altitudes of 55 to 25 km; ion number density in the ionosphere, magnetic field Flyby vehicle: 11_{α} — and 0I/1300Å — radiation in upper atmosphere; ion flux in region of solar-wind flow around planet; magnetic field
Venera 5	Same as above	1/5/69	5/16/69	–3	18	–27	Temperature, pressure, wind velocity, CO_2, N_2, H_2O content at altitudes of 55 to 20 km
Venera 6	Same as above	1/10/69	5/17/69	–5	23	–25	Same plasma measurements as on Venera 4
Venera 7	Descent module (soft landing)	7/17/70	12/15/70	–5	351	–27	Temperature
Venera 8	Same as above	3/26/72	7/22/72	–10	335	+5	Temperature, pressure, solar scattered radiation (from 55 km to surface), wind velocity
Venera 9	Descent module (soft landing) + artificial satellite	6/8/75	10/22/75	32	291	+54	Descent module: Temperature, pressure, wind velocity; CO_2, N_2, H_2O content, solar scattered radiation (several filters), clouds (nephelometer), panoramic survey of surfaces Satellite: TV survey of clouds, IR radiometry, spectroscopy of the day- and nightside; photopolarimetry; energy spectra of ions and electrons, electron and ion number densities and temperatures, magnetic field in region of solar-wind interaction with planet; radio occultations
Venera 10	Same as above	6/14/75	10/25/75	16	291	+62	Same as above
Venera 11	Descent module (soft landing) + flyby vehicle	9/9/78	12/25/78	–14	299	+73	Descent module: Temperature, pressure, wind velocity, composition (mass spectrometer); solar scattered radiation spectrum; nephelometer, thunderstorm activity Flyby vehicle: Upper-atmosphere UV spectrum
Venera 12	Same as above	9/12/78	12/21/78	–7	294	+70	Same as above; gas chromatograph and measurements of particle-composition of cloud layer

[a]Minus sign denotes night landing (the Sun below the horizon). First generation vehicles landed at night (except Venera 8, which landed near the terminator). It was necessary since information was transmitted directly to Earth. Since Venera 9 information was relayed via the artificial satellite from the lander and the landing was made during the day, this was widely used to study solar radiation propagation in the atmosphere (to check the greenhouse hypothesis).

Veneras 4 and 6 also obtained unexpected results in plasma and magnetic measurements. They discovered a shock wave in the solar wind near Venus like the one near Earth. The shock front of Venus, however, was much closer to its surface. Before the spaceflight to Venus, scientists hypothesized that the number density of charged particles in Venus' ionosphere could exceed by three orders of magnitude the number density of charged particles in the main peak in the terrestrial ionosphere. Ion number densities that Venera 4 measured during its descent on Venus' nightside did not confirm that suggestion, nor did Mariner 5's radio-occultation observations about electron number densities on the ionosphere's nightside and dayside. In Venus' ionosphere, the maximum number density of charged particles was about the same as on Earth. Mariner 5 observed a distinct upper boundary of the dayside ionosphere at an altitude of 500 km (310 miles). Within the boundary, the electron number density decreased by two orders of magnitude within an altitude range of only 50 to 100 km (31 to 62 miles). The boundary was similar to the plasmapause—the upper bound of Earth's thermal plasma envelope. Because of this similarity, scientists gave the name *ionopause* to the Venus phenomenon. However, Earth's plasmapause is much farther from the planet's surface, roughly 20,000 km (12,428 miles).

Although large-scale features typical of solar-wind flow around both Venus and Earth are similar, the magnetic field Venera 4 first measured near the planet seemed insignificant—only about 10 gamma (10^{-4} gauss) at an altitude of 200 km (124 miles). The surface magnetic field in Earth's equatorial region is about 50,000 gamma. Until recently, it had been thought that Venus' intrinsic magnetic field might play a significant role in forming the pattern of solar-wind flow around the planet, as it does in the case of Earth.

Operating an automatic interplanetary probe in Venus' hot and dense atmosphere was technically difficult. Nevertheless, in the 1960s, a team of scientists designed spacecraft for Venus research. The academician S. P. Korolev and then G. N. Babakin, Corresponding Member, U.S.S.R. Academy of Sciences, headed the team. NASA lauched Pioneer Venus 11 years after Venera 4, almost at the same time as Veneras 11 and 12 were launched.

It often happens in science that the solution to one problem leads to new, more complicated problems. Spaceflights to Venus were no exception. They showed that climatic and atmospheric conditions, so similar to Earth for some physical parameters, are generally quite different from those on Earth. What are the reasons for these differences? Can the climate and composition of Earth's atmosphere experience the same changes in the foreseeable future? If so, what would cause such changes: altered external conditions, environmental pollution, or something else? Such questions prompt many scientists throughout the world to consider exploration of Venus a top-priority task.

Venus can be a natural "cosmic laboratory" for studies in comparative planetology. The value of such research becomes more apparent because it is impossible to realize experiments on such a scale under Earth conditions.

Any planet's atmosphere is a complex system with many interactions and feedbacks. Its composition, for instance, is determined by how and under what conditions the planet formed, and by outgassing processes from its solid body. Other factors include reactions among atmospheric gases, the upper atmosphere's structure (from which light gases escape into the interplanetary space), and so on. The character and rate of many atmospheric processes depend on temperature, which in turn depends on the atmosphere's composition. The latter consideration is most essential for Venus. The gaseous and aerosol composition of the Venusian atmosphere allows some solar radiation to penetrate down to the surface. The opacity of the atmosphere is high, however, for infrared radiation. As a result, the surface temperature remains high. The phenomenon, which we call the greenhouse effect, is much more conspicuous on Venus than on Earth. On Earth, the greenhouse effect adds about 35°C (63°F) to the surface temperature.

A fuller understanding of what is taking place on Venus required sophisticated chemical analyses of the atmosphere and an exact knowledge of the altitudes and spectral regions where solar radiation is absorbed. Scientists also needed to study the nature of the clouds that prevent astronomers from seeing the lower layers of the atmosphere.

After the first-generation Venera probes made plasma and magnetic measurements, scientists were faced with many new problems. With theories and concepts existing at the time, it might have been possible to find solutions to some of the problems. In particular, scientists wanted to explain the weak intrinsic magnetic field near Venus. For example, they could use theories of how magnetic fields originate and maintain themselves near planets on the basis of planetary dynamos. These theories predict that a planet, if it has an intrinsic magnetic field, must rotate rapidly and have a liquid, conducting core. Scientists had used close values of mean densities of terrestrial planets to build similar models of their inner structures. Consequently, planetologists could attribute Venus' absence of an intrinsic magnetic field to its slow rotation (about 243 terrestrial days).

Scientists observed shock waves near both Venus and Earth. But Venus, they knew, had a much weaker intrinsic magnetic field than Earth. What is the obstacle—different from Earth's—that retards the solar wind and forms a shock wave near Venus?

Indeed, a strong intrinsic magnetic field protects Earth, its atmosphere, and ionosphere against the solar wind's direct effect. However, for Venus, the solar wind could interact directly with its atmosphere and ionosphere, causing ionization, compression, and heating of the ionosphere and atmosphere. The solar wind, flowing around the planet's conducting ionosphere, together with the interplanetary magnetic field, could induce electric currents in the ionosphere and thus produce induced magnetic fields. If these induced fields are strong enough, they could brake the solar wind and form an induced magnetosphere, rather than an intrinsic one, near the planet.

All these assumptions rested on the observed similarities and differences in the solar wind's pattern flowing around Venus and Earth, and they had to be verified. Much more complex and accurate measurements were needed.

To conduct more detailed experiments in the deep layers of Venus' atmosphere, interplanetary probes needed heavier and more sophisticated instruments. More importantly, the vast amount of data gathered by the instruments had to be transmitted back to Earth. Accordingly, the first-generation probes, which had not been intended to deal with such problems, were succeeded by Veneras 9 through 12 (see Figure 7-1). Whereas the earlier probes had entered the Venusian atmosphere in their entirety, the new Venera probes separated into an orbiter and a lander some time before landing. Depending on mission profile and ballistics, the orbiter either became an artificial satellite of Venus (Veneras 9 and 10) or it flew past the planet and entered an orbit around the Sun (Veneras 11 and 12) (Figure 7-2). The orbiters carried instruments to study the planet's radiation at various wavelengths, the interplanetary plasma and magnetic fields, and to conduct astronomical observations.

In 1975, Veneras 9 and 10 splendidly demonstrated the capabilities of a new generation of spacecraft. For the first time, a panoramic view of another planet was transmitted from its surface to Earth (Figure 7-3). A series of investigations looked at the atmosphere's optical properties. They determined the general features of the cloud structure. The clouds are in a layer about 20 km (12 miles) thick, with a lower boundary at an altitude of 50 km (31 miles). Radiation fluxes were measured in several spectral regions and the water vapor content was derived from the intensity of the absorption band. Scientific equipment onboard the orbital vehicles—Venus' first artificial satellites—produced important results.

A series of plasma and magnetic radio-occultation observations (Veneras 9 and 10 orbiters) made it possible to study in detail the solar-wind flow pattern around the planet, and discover a plasma-magnetic tail of the planet. The observations also allowed scientists to investigate the character of the magnetic field and the properties of the dayside and nightside ionosphere, and to identify atmospheric ionization sources in the planet's deep optical umbra.

Analyses of Veneras 9 and 10 experimental data indicated new problems. But expertise in designing sophisticated scientific equipment that could operate under very difficult conditions (enormous decelerations, high temperatures and pressures) solved most of them in the Veneras 11 and 12 probes that reached Venus late in 1978. The construction of a huge, 70-m (230-ft) diameter parabolic reflector at the Deep Space Communication Center also greatly improved data reception from the landers.

Recent scientific results from the new generation of Soviet Venera probes are discussed in the sections that follow. Table 7-1 summarizes launch dates, descent module landing coordinates, and other data.

Chemical Composition of the Venusian Atmosphere

Until 1967, scientists assumed, because of the planet's similarity to Earth, that the main chemical in Venus' atmosphere was nitrogen. Besides nitrogen, scientists expected to find a small amount (1% to 10%) of carbon dioxide, whose absorption bands they had observed as far back as the 1930s. But even simple chemical sensors on the first Venera probes proved the very opposite to be the case. The most abundant gas in the atmosphere is carbon dioxide (96.5% according to estimates), whereas nitrogen makes up just over 3%. At the time, it was impossible to get reliable information about the content of the atmosphere's many small constituents: water vapor, oxygen, carbon monoxide, sulfur compounds, and noble gases. These constituents play a tremendous part in the life of the atmosphere. They absorb solar and thermal radiation (the greenhouse effect), participate in chemical reactions, condense to form cloud layer particles, and also contribute to other processes.

The abundance of noble gases and their isotopes is of particular interest. These isotopes fall into two groups: radiogenic isotopes and primordial isotopes. The radioactive decay of elements formed radiogenic isotopes. Primordial isotopes have survived since the formation of the Solar System's planets some 4.5 billion years ago. From the absolute and relative

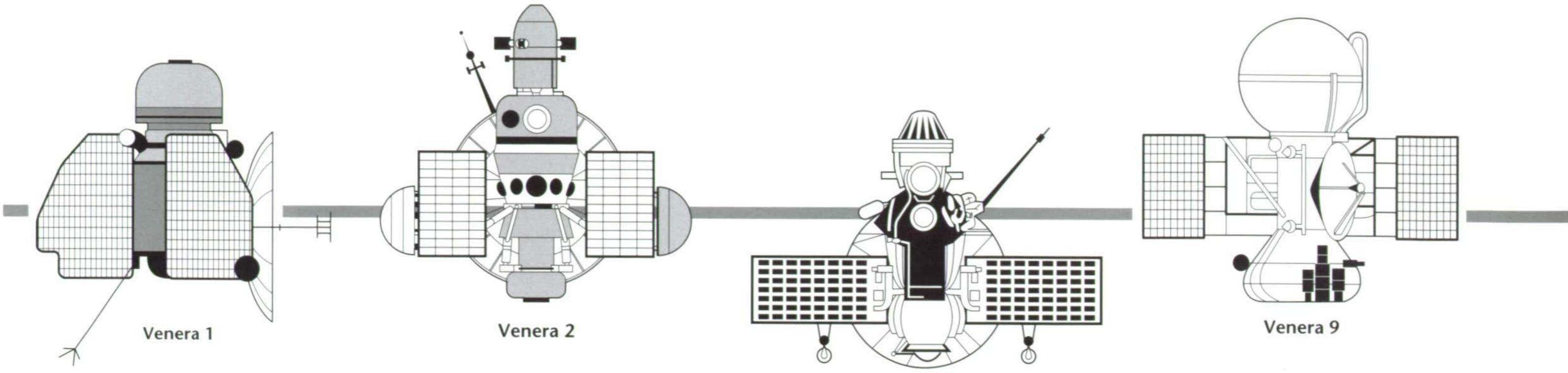


Figure 7-1. In the two decades that the United States sent four spacecraft to Venus, the Soviets attempted 29 missions (15 were successful). Although some of the failures were never officially admitted, U.S. or European sources detected them. These seven illustrations show the evolution of the Soviet spacecraft to explore Venus. It came from many sources and was not a part of the Soviet authors' contribution to this chapter. We have included it to place the U.S. and Soviet missions in perspective.

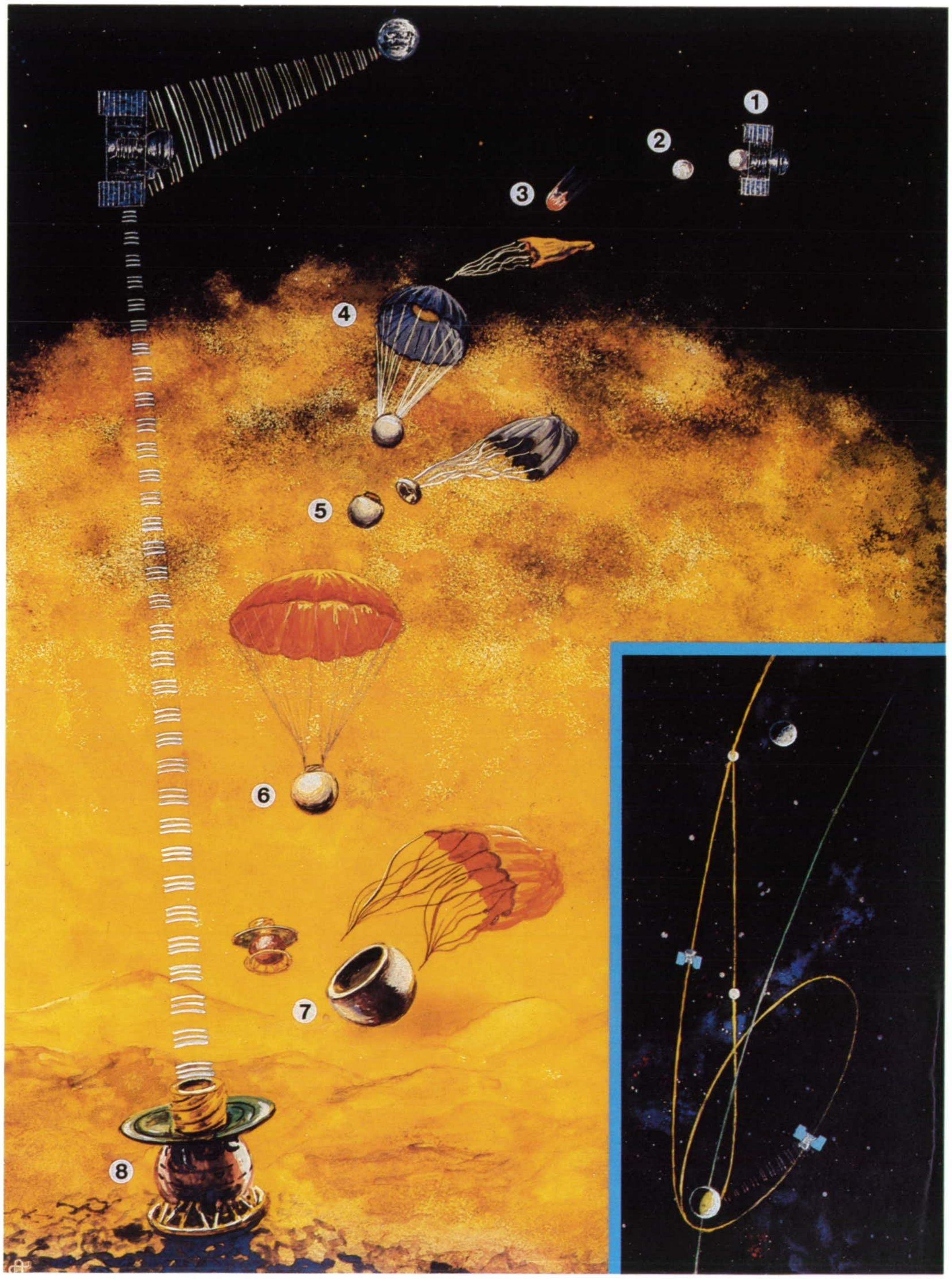


Figure 7-2. Landing scheme of the Soviet second generation automatic spacecraft (Veneras 9, 10, 11, 12).

1) Interplanetary spacecraft on Venusian orbit.

2) Separation of descender and orbiter two days before the landing.

3) Entry into the Venusian atmosphere.

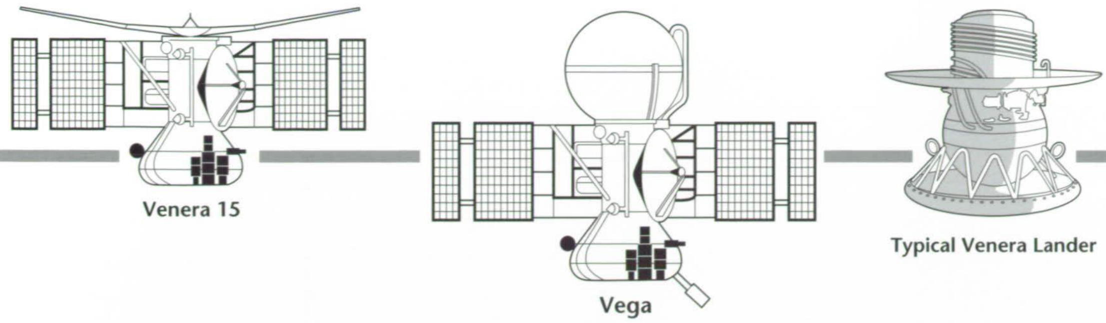
4) Deployment of auxiliary and displacement parachutes.

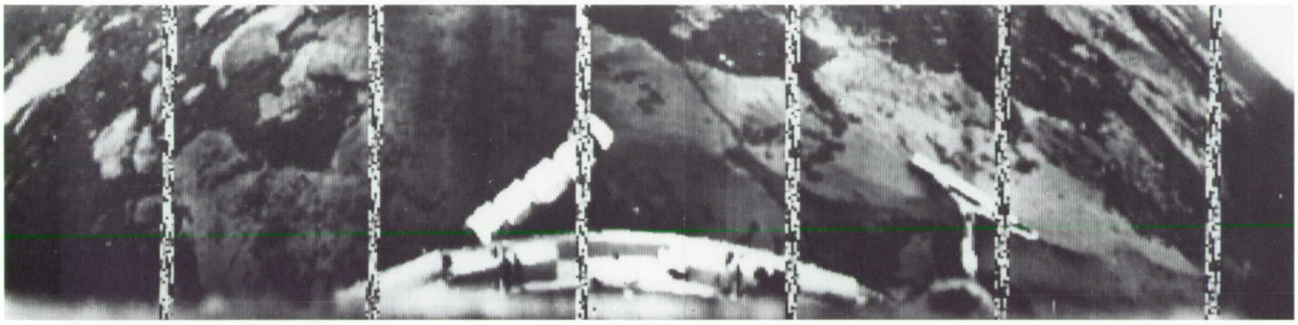
5) Jettisoning of hatch.

6) Deployment of decelerating parachute at 66 to 62 km (41 to 38.5 miles) and beginning of telemetry data transmission.

7) Jettisoning of lower sector of thermal protection shell and jettisoning of decelerating parachute at about 48 km (30 miles) altitude.

8) Landing and data transmission to Earth via the flyby bus.





content of primordial isotopes, we can gain some insight into the Solar System's history, in particular, about conditions in which the protoplanetary nebula gave rise to the planets, and about their formation process. Argon isotopes will be discussed as an example.

For fine chemical analysis of atmospheric gases, Soviet investigators used a mass spectrometer, a gas chromatograph, and an optical spectrometer. (The mass spectrometer takes microscopically small gas samples, ionizes them, and sorts them according to their mass with a high frequency electric field.) A group of scientists headed by Vadim Istomin (Institute of Space Research, U.S.S.R. Academy of Sciences) conducted the mass spectrometer experiment. The instruments (Figure 7-4) on both vehicles switched on at an altitude of about 24 km (15 miles) and operated until touchdown. These instruments scanned the mass range from 10 to 105 atomic units in 7 seconds. The gas sampling time was under 5×10^{-3} seconds, and the sampling rate was once every 3 minutes. The instruments took a total of 22 samples and transmitted about 200 mass spectra to Earth. The mass spectrum in Figure 7-5 is an average over 7 of 200 mass spectra.

The mass spectra show several peaks. These peaks correspond to the molecules carbon dioxide and nitrogen, and the atoms carbon-12, carbon-13, oxygen-16, oxygen-18, and nitrogen-14 (from decomposition of carbon dioxide and nitrogen molecules inside the instrument). Also corresponding to peaks are three noble gases: neon, argon, and krypton. Quantitative data appear in Table 7-2. The presence of krypton (about 6.5×10^{-5}%) is noteworthy. Instruments on the Pioneer Venus probe detected no krypton.

In Istomin's experiment, every single record of the mass spectrum shows krypton. Estimates averaged over tens of records showed that the relative abundances of the main krypton isotopes with atomic weights 84, 86, 83, and 82 are comparable to those on Earth. The argon results were extremely surprising. The radiogenic isotope argon-40 and the primordial argon-36 are present in Venus' atmosphere in equal amounts. On Earth, argon-40 is 300 times more abundant than argon-36.

A full explanation of this anomaly is a matter for the future, but M. Izakov (Institute of Space Research) has proposed an elegant hypothesis.

▲

Figure 7-3. Panoramic view of the Venusian surface at 291 east longitude, 32 north latitude, relayed by Venera 9 descent module. Numerous stone blocks with sharp edges are around the spacecraft, a fact testifying to their comparatively young age. On the planet's surface at the landing site, much small-grained substance resembling dust or sand is visible. After the lander's impact, a dust cloud rose that registered on a photometer for a few minutes.

He assumes that Venus derived the greater part of its atmosphere from the protoplanetary nebula. Earth (and Mars) captured relatively little gaseous material from it, and most of their atmospheres were outgassed from their interiors. According to this hypothesis, the meteorite and asteroid accumulation process, which gave rise to all the planets 4.5 billion years ago, proceeded more rapidly for Venus. This happened because the planet is closer to the Sun, and the meteorite bodies were denser there. The capture of gas also was more rapid. Before the new data, scientists believed the atmospheres of the Earth group of planets (Venus, Earth, and Mars) were of secondary origin, formed by degassing from their interiors. The argon-36 anomaly for Venus, however, casts doubt on this.

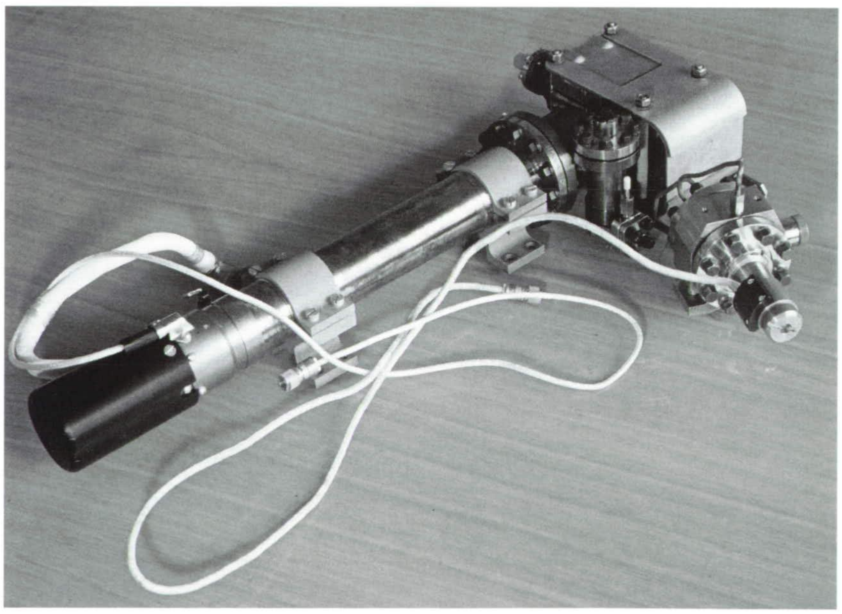


Figure 7-4. A general view of the mass spectrometer carried by the Venera spacecraft.

The atmosphere of Venus was also chemically analyzed by the Sigma gas chromatograph (Figure 7-6). Lev Mukhin of the Institute of Space Research supervised this experiment. (Gas chromatographic analysis is based on different degrees of adsorption of various gases by porous substances. The heart of the gas chromatograph is a column filled with a specific sorbent. The instrument pumps an atmospheric gas sample through the column. There the mixture separates into individual components. Various constituents of the mixture leave the column one by one, and a special ionization detector records them.)

A chromatograph was also installed onboard the Pioneer Venus Large Probe (V. Oyama at Ames Research Center supervised this experiment). Oyama (1979) reported that no carbon monoxide was found, but Venus' atmosphere contained a large amount of molecular oxygen (exceeding the upper limit from the Soviet experiment). Oyama later reported (1980) that he had misidentified the relevant chromatographic peaks, and the missing carbon monoxide was found. Oyama's data revealed another aspect that has not been explained: the presence of relatively large amounts of water vapor—approximately 0.5% at an altitude of 44 km (27 miles) and 0.1% at 24 km (15 miles).

Water absorbs light in several spectral bands, some of which (7200, 8200, and 9500 angstroms) are quite distinct in the spectra from the optical spectrophotometer (Figure 7-7) onboard the Veneras 11 and 12 descenders. (V. Moroz supervised this experiment.) From the bands' intensity, scientists could determine water content in the Venusian atmosphere at different altitudes. This quantity proved very small (2×10^{-3}% near the surface and 2×10^{-2}% at 50 km, or

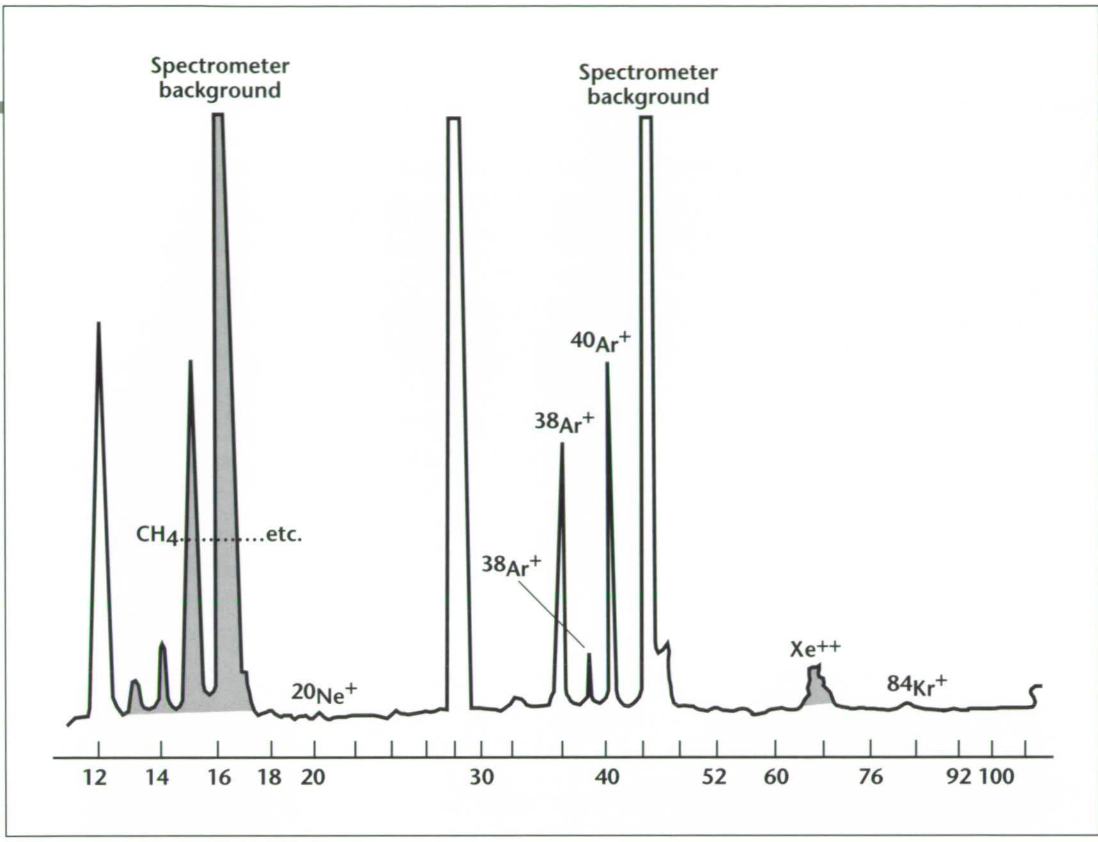


Figure 7-5. Averaged mass spectrum (the sum of seven separate spectra) obtained in the regime of noble gas analysis.

31 miles). Oyama's experiments had yielded a quantity several orders of magnitude greater.

Parallel measurements with a chromatograph and a mass spectrometer provided independent control of the results. The Venera 12 chromatograph did not detect water vapor. From this fact, it follows that, at an altitude below 24 km (15 miles), water vapor content is below 0.01%. The Veneras 11 and 12 mass spectrometers registered a slight excess in the oxygen-16 mass peak as compared with oxygen-18 (if the oxygen-18/oxygen-16 ratio is assumed to be exactly equal to Earth's). Note that oxygen-18 and oxygen-16 are formed in the instrument from carbon dioxide. If this excess is due to the water contribution (the molecular weight of water also is 18), the water vapor abundance correlates reasonably well with the optical measurements.

There is a simple way to verify whether the quantity of water vapor varies from site to site. The height dependence of temperature that Pioneer Venus' Large Probe obtained can be compared with infrared radiation fluxes measured by the same vehicle. This comparison makes it possible to calculate the mean absorption coefficient for thermal planetary radiation (into which the diffuse solar light penetrating deep in the atmosphere is

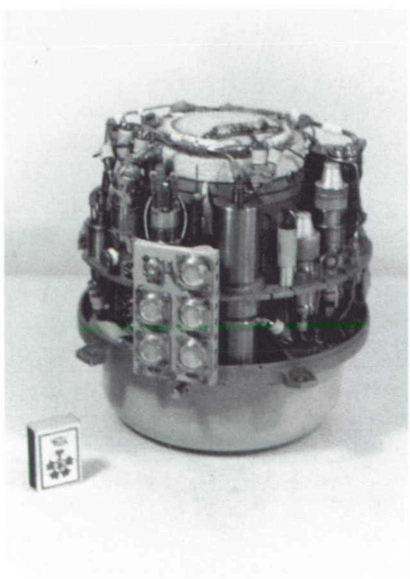


Figure 7-6. Gas chromatograph carried by the Veneras 11 and 12 spacecraft.

Table 7-2. Chemical Composition of the Atmospheres of Venus and Earth

Gas	Content by volume, %	
	Venus	Earth
Carbon dioxide	96.5	3.2×10^{-2}
Nitrogen	3.5	78.1
Water vapor	2×10^{-3}[a]	0.1
Oxygen	10^{-3}	21.0
Carbon monoxide	3×10^{-3}	10^{-4}
Sulfur dioxide	1.5×10^{-2}[b]	10^{-4}
Hydrogen chloride	4×10^{-5}[c]	—
Hydrogen fluoride	5×10^{-7}[c]	—
Methane	10^{-4}	1.8×10^{-4}
Ammonia	2×10^{-4}	—
Sulfur	2×10^{-6}[d]	—
Noble gases:		
Helium	2×10^{-3}	5×10^{-4}
Neon	1.3×10	1.8×10^{-3}
Argon	1.5×10^{-2}	0.9
Krypton	6.5×10^{-5}	1.1×10^{-4}
Mean molecular weight	43.5	28.97

[a]Mixing ratio near surface. At an altitude of 50 km, it is an order of magnitude higher; at 70 km, an order of magnitude less.

[b]Mixing ratio below 20 km; at 70 km, it is four orders of magnitude less.

[c]Mixing ratio above 60 km (only the data for ground-based spectroscopy available).

[d]Gaseous sulfur is meant (molecules S_2, S_3, S_4, S_5, S_6, S_7, and S_8); estimate refers to altitudes below 40 km.

transformed). This coefficient depends strongly on atmospheric water vapor concentration. The calculated water vapor concentration was found to correspond closely with optical measurements.

The total amount of water vapor in Venus' atmosphere appears to be disastrously small. If the planet's entire water vapor (2×10^{-3}%) condensed, it would form a liquid layer no more than 1 cm thick. Obviously, there can be no seas, oceans, and liquid water on Venus' surface—the temperature is too great for that. All of Venus' water is either in its crust or in its atmosphere. This is yet another anomaly, no less odd than the argon-36/argon-40 ratio.

There is nothing extraordinary about the atmosphere's high carbon dioxide concentration. Almost all of Earth's carbon dioxide is bound up in carbonates. On Venus, all carbon dioxide—because of the high temperature and absence of liquid water—is in the atmosphere. Total amounts of carbon dioxide on both planets are roughly equal. But the concentration of water on Venus presents a problem. Three explanations are possible: (1) Venus formed with less water; (2) at the early stages of evolution, water vapor dissociated, hydrogen escaped into the interplanetary space, and oxygen vanished through chemical reactions; and (3) water is bound up in minerals (where there are rocks that retain water very well at high temperatures).

Solar Radiation and Clouds in Venus' Atmosphere

Both the Veneras 11 and 12 landers carried spectrophotometers. From an altitude of 65 km (40 miles) until touchdown on Venus, they registered, for the first time, the daylight sky spectrum and the angular distribution of brightness at 10-second intervals. These measurements showed that a large amount of solar radiation reaches the planet's surface. Significantly, this is scattered rather than direct sunlight. Since the cloud cover at 60 to 70 km (37 to 43 miles) scatters solar radiation, an observer could not see the Sun from Venus' surface nor from an altitude of 55 km (34 miles). In terms of energy, it is unimportant what sort of radiation penetrates Venus' atmosphere—direct or scattered. An evaluation of solar energy reaching the surface (3%) and Venus' thermal radiation confirmed a pronounced greenhouse effect. This effect results in high temperatures in the atmosphere's deep layers and at the Venusian surface. The observation confirms the hypothesis that Carl Sagan put forward as far back as 1962.

According to Veneras 11 and 12 data, the energy distribution in the scattered sunlight spectrum changes as the probe penetrates deeper into the atmosphere. Just as on Earth, the effect results from two types of scattering. The first is aerosol scattering of light by cloud particles. The second is Rayleigh scattering by carbon dioxide and nitrogen molecules. The probes also detected light absorption in ultraviolet, which probably belongs to gaseous sulfur molecules.

There are several layers of clouds in Venus' atmosphere at altitudes from 50 to 70 km (31 to 43 miles). Their boundaries are distinct in the curves showing the decrease in scattered sunlight intensity with the probe's descent (Figure 7-8).

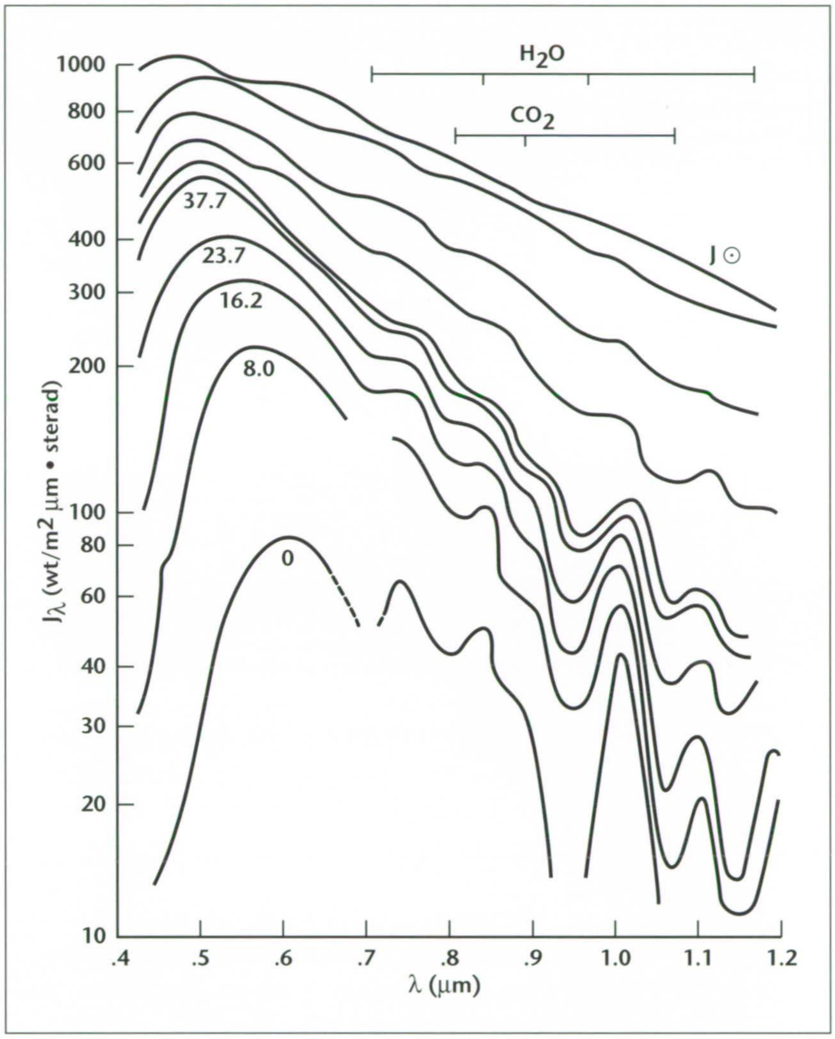


Figure 7-7. Scattered solar radiation spectrum in deep layers of Venus' atmosphere. Venera 11's descent module obtained the data. Numbers along the curves indicate altitudes in kilometers. Note how the lines for water (H_2O) and carbon dioxide (CO_2) became more dense as the probe descended. These spectra proved to be a very good source of data on the water vapor content in Venus' atmosphere.

Ground-based observations fixed the approximate position of the cloud cover's upper boundary. Veneras 9 and 10 nephelometers and photometers, however, first observed the lower boundary.

Veneras 9 and 10 nephelometer experiments (M. Marov, Institute of Applied Mathematics, U.S.S.R. Academy of Sciences) made it possible not only to determine the cloud cover's lower boundary, but also to estimate cloud particle concentration, size, and the atmosphere's refractive index. To a limited extent, the

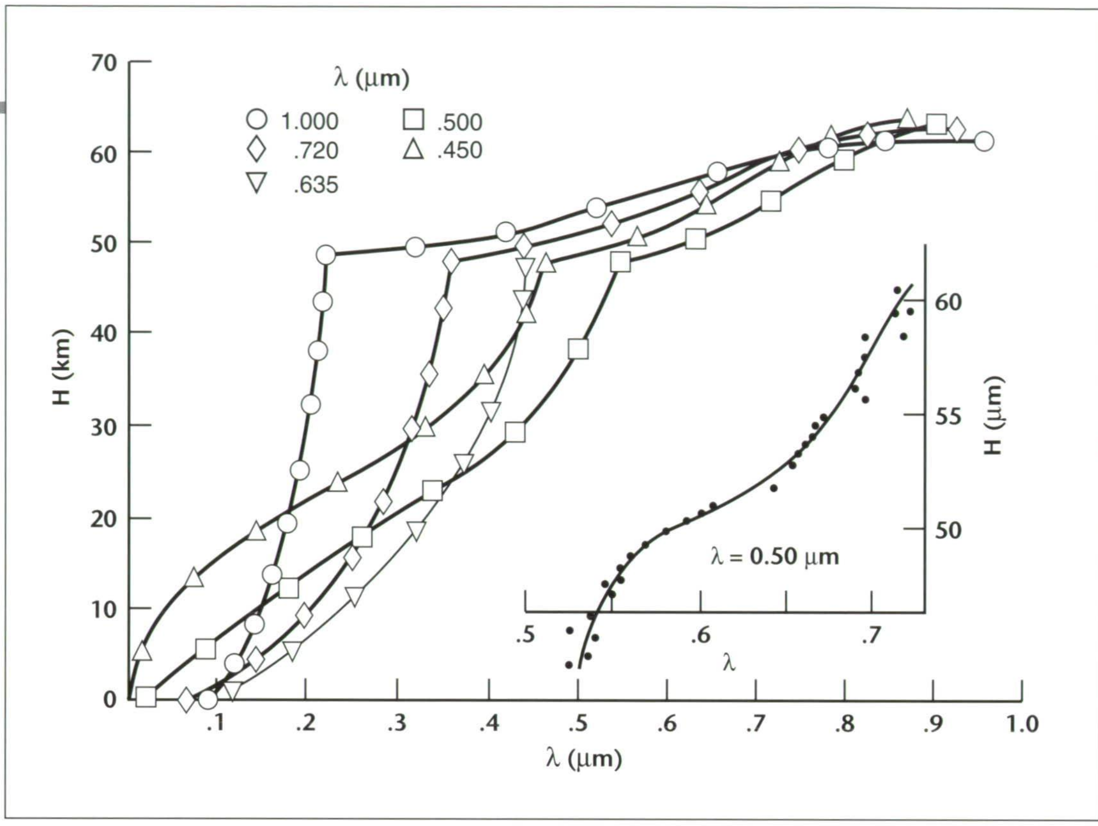


Figure 7-8. Radiation intensity from the zenith as a function of altitude for some wavelengths. Venera 11's descent module obtained the data. Symbols along the curves indicate wavelengths. The sharp change in the steepness of the curves at an altitude slightly less than 50 km (30 miles) is a result of crossing the lower cloud layer boundary.

Venera 11 mission repeated these observations. The Pioneer Venus Large Probe enabled R. Knollenberg and D. Hunten to study in great detail the particle-size distribution.

Venusian clouds are relatively transparent. The meteorological visibility inside the clouds is several kilometers. There are three layers. The upper layer is at 57 to 70 km (35 to 43 miles), the middle at 52 to 57 km (32 to 35 miles), and lower at 49 to 52 km (30 to 32 miles). Particles are of three types: large (7 microns in diameter), medium-sized (2 to 2.5 micron), and small (average diameter 0.4 micron). Only small and medium-sized particles are present in the upper layer. The other two layers have all three particle types. Large particles account for no less than 90% (in terms of mass) of the entire cloud cover.

The composition of Venusian clouds has long baffled scientists. The simpler hypotheses, based on Earth analogies (liquid or frozen water, mineral dust), were discarded when ground-based observations yielded data on the optical properties of the cloud particles. Since there is hydrochloric acid in Venus' atmosphere, scientists put forward yet another hypothesis. They speculated clouds consisted of hydrochloric acid droplets. But a number of considerations made it necessary to abandon this assumption, too. In terms of optical properties, a suitable candidate is sulfuric acid (H_2SO_4) which is present as tiny droplets in Earth's stratospheric clouds. Sulfur compounds reach the atmosphere all the time from Earths' interior, and chemical reactions produce particles that are in Earth's stratospheric clouds. An analogy appears quite reasonable here, since a sulfur compound (SO_2) and pure sulfur in the gaseous state occur on Venus.

Also in terms of refractive index and the infrared absorption coefficient, sulfuric acid is a suitable candidate for the main component of Venusian cloud particles. This, however, does not account for the planet's yellowish color. Scientists have suggested that the clouds contain larger particles of solid sulfur, in addition to particles of concentrated sulfuric acid. Nephelometric experiments revealed that only small and medium-sized particles could consist of sulfuric acid. The large particles must have a different composition. It was originally assumed they did consist of sulfur.

The Venera 12 mission included, for the first time, an experiment on the direct chemical analysis of cloud particles. (Y. Surkov, Institute of Analytical Chemistry and Geochemistry, U.S.S.R. Academy of Sciences, conducted the experiment.) Cloud layer particles were collected on special filters and analyzed with an x-ray fluorescent spectrometer. The instrument subjected a sample to hard radiation from a radioactive source. As a result, the inner electron shells of atoms (K-shells) were excited, which generated characteristic x-rays whose spectrum was recorded and used to identify the sample's composition. In fact, the composition was determined only at the element level since molecules or any types of bonds could not be determined. At altitudes from about 61 km (38 miles) down to 49 km (30 miles), the most abundant element among cloud-cover particles is chlorine. Either sulfur is not present at all or there is only about 1/20 as much sulfur as chlorine. Thus, it appears that the cloud cover's large particles consist of chlorine compounds, although it is not apparent which specific compounds these are.

Winds, Storms, and Night-Sky Glow

Ground-based observations had already established that Venusian winds are unusual. Near the upper boundary of clouds, the speed of fairly regular atmospheric streams is nearly 100 m/sec (328 ft/sec). These swiftly flowing atmospheric masses form a single stream as they sweep above the slower atmospheric layers and solid body of the planet. The rotation period of the planet's body is very long—243 Earth days. Venus' rotation is retrograde, opposite to the rotation of Earth and the other planets in the Solar System. The clouds move, together with the upper part of the atmosphere, in the same retrograde direction, completing one rotation in 4 days at an altitude of 65 to 70 km (40 to 43 miles).

Measurements of the lander's descent velocity made it possible to determine the wind profile down to the surface. As the lander approached the planet's surface, the wind gradually subsided. Within the last 10-km (6-miles) thick layer of atmosphere, the wind speed was only about 1 m/sec (3 ft/sec). To measure wind velocity on the surface, the Veneras 9 and 10 landers carried conventional wind vanes.

The existence of clouds in the atmosphere and the highly intensive dynamic processes that occur there made it quite probable that storm phenomena might be present. The objective of experiments that L. Ksanfomaliti (Institute of Space Research) supervised was to find effects in Venus' atmosphere similar to terrestrial thunderstorms. Storm discharges generate low-frequency electromagnetic pulses. Ksanfomaliti used a low-frequency (8 to 100 kHz) spectrum analyzer with an external antenna in the experiment and did, in fact, observe pulse radiation similar to that typical in Earth's thunderstorms (Figure 7-9). After receiving Veneras 11 and 12 mission results, scientists analyzed the night-side observation data that Veneras 9 and 10 had earlier obtained. It turned out that Venera 9 had, indeed, registered a short-lived glow on Venus' nightside. The glow was possibly storm-generated. Estimates suggest that the number of storms on Venus could be even greater than on Earth.

For a long time, many ground-based observers have noted a weak nightglow (the ashen light of Venus). It seems possible that this effect arises during periods of particularly high storm activity. Besides, another effect—a constant night airglow undetectable from Earth—results from chemical reactions in the upper atmosphere. In the visible spectrum, this airglow only occurs when molecular oxygen bands are excited in a carbon dioxide rich atmosphere such as Venus'. Veneras 9 and 10 orbiters were the first to register the bands. (V. Krasnopolsky, Institute of Space Research, supervised the experiment.)

The Sun's ultraviolet radiation (in the hydrogen and helium lines) is scattered by corresponding atoms in the planets' upper atmosphere. The excited atoms re-emit ultraviolet quanta and produce line-scattered radiation. Measurements of its intensity can be converted to hydrogen and helium concentrations. These lightest of elements make up the outermost portions of the atmospheres of Earth, Mars, and Venus. Veneras 11 and 12 flyby probes each carried an instrument to measure radiation intensity in the upper atmosphere in 10 different ultraviolet intervals of the spectrum, which included hydrogen and helium lines and lines of several other elements. V. Kurt (Institute of Space Research) supervised the experiment, which also involved French physicists J. Blamont and J. L. Bertaux. An analysis of the high-quality spectra provided some estimates of the composition and structure of Venus' upper atmosphere.

Experiments conducted during the descent of Veneras 11 and 12 into Venus' atmosphere studied three basic problems: fine chemical analysis of atmospheric gases, nature of clouds, and thermal balance of the atmosphere. Of these, the chemical composition studies were considered the most essential. All the experiments were successful. The scientific instruments on the Pioneer Venus probe were similar to those on the Venera probes—a gas chromatograph, a mass spectrometer, and some optical instruments. A comparison of the results is of great interest.

In April 1979, Soviet and American scientists who had participated in both missions met at the Institute of Space Research, U.S.S.R. Academy of Sciences, Moscow. During that meeting, they compared data from the different probes and discussed the implications. The meeting's published results made it clear that the space science community had succeeded in studying the fine chemical composition of Venus' atmosphere. The investigations of both the Soviet and American probes had cleared a way for solving the mysteries about Venus.

Solar-Wind Interaction with Venus—Bow Shock and Intrinsic Field

The first experimental observations of Venus' bow shock were obtained from descending and flyby trajectories of Venera 4, Venera 6, Mariner 5, and Mariner 10. The properties of the plasma were measured by Venera 4 with charged-particle traps. K. Gringauz, Institute of Space Research, U.S.S.R. Academy of Sciences, headed the experiments. S. Dolginov and his colleagues (Institute of Earth Magnetism and Radiowave Propagation, U.S.S.R. Academy of Sciences) measured the magnetic field.

The various types of charged-particle traps, or wide-angle detectors, are actually a system of electrodes—a collector and several grids. Various voltages—direct current, gradually changing direct current, and alternating current—are usually applied to these grids, which makes it possible to analyze the trapped particles by their energies and charge signs. Scientists observed the shock wave as a sharp, simultaneous increase in the interplanetary plasma and amplitude of magnetic field fluctuations that occurred some distance from Venus.

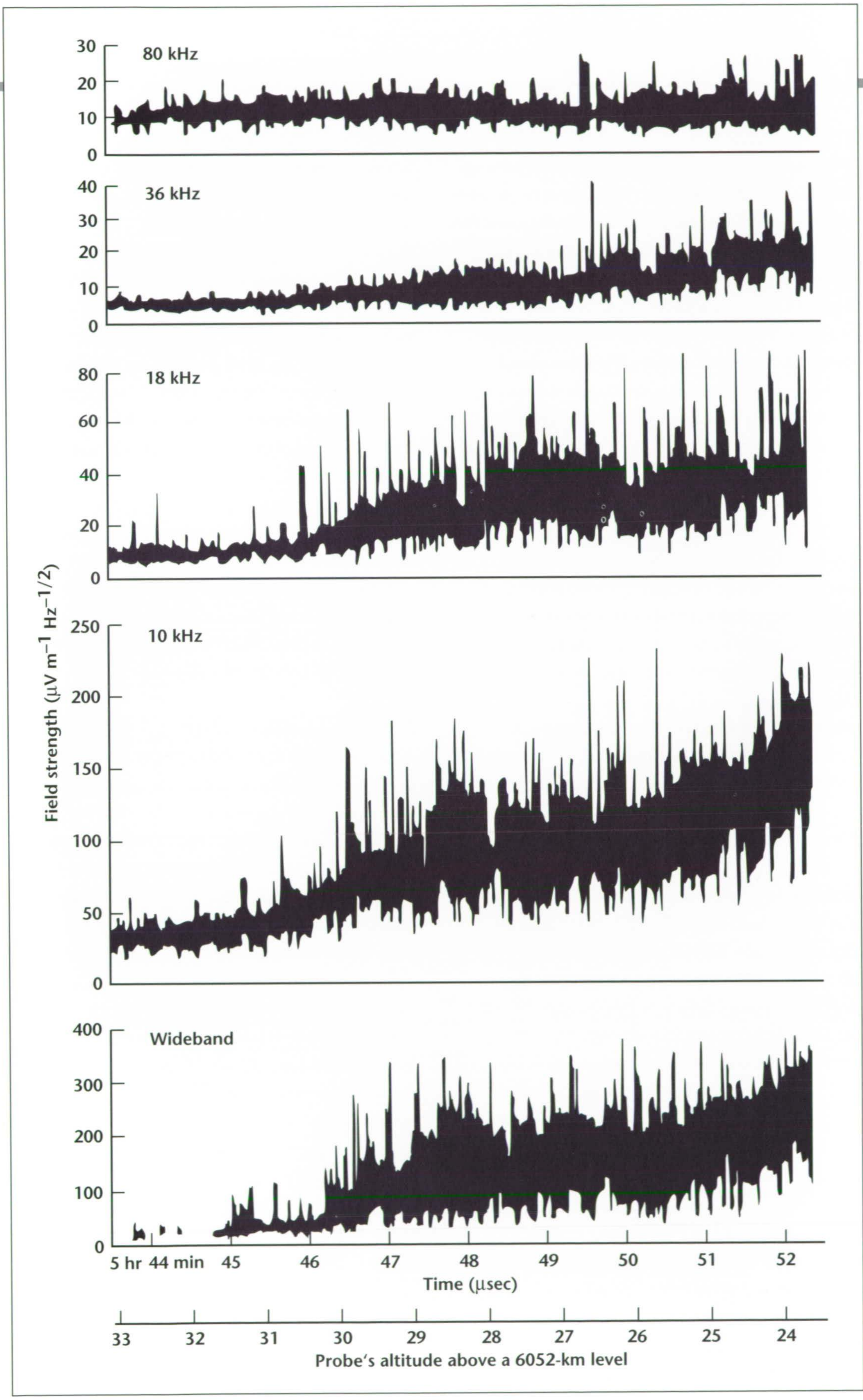


Figure 7-9. The "GROZA" experiment of the Venera 11 descent module recorded these radio noise bursts. The bursts are plotted against altitude for various frequencies. Lightning strikes in the planet's atmosphere evidently caused the noise.

Systematic observations of the interactions of the solar wind with Venus were performed with plasma and magnetic instruments onboard the first Venus orbiters, Veneras 9 and 10. The plasma properties were measured with wide-angle analyzers, Faraday cups, and retarding potential analyzers (RPA) (K. Gringuaz, Space Research Institute) and with narrow-angle detectors and electrostatic analyzers (O. Vaisberg, Space Research Institute). The magnetic measurements were made by S. Dolginov, Institute of Earth Magnetism and Radiowave Propagation.

An electrostatic analyzer is, in its simplest form, two curved concentric plates separated by a small gap. A potential difference is applied to the plates. Particles entering the gap pass through it only if they have a certain energy/charge unit ratio. This energy corresponds to the applied potential difference. By applying different potentials to the plates, an energy spectrum of particles can be obtained.

Figure 7-10 shows 32 bow shock crossings by Veneras 9 and 10. These data are from the wide-angle analyzers and show the mean front position, based on data of 86 crossings by Pioneer Venus (Slavin *et al.*). The shock front position near Venus is close to the surface—about 0.3 Venus radius in the frontal subsolar area. Two circumstances explain the differences in the mean front positions of Soviet and American vehicles. These spacecraft crossed the front at different latitudes, and the measurements occurred during different phases of the solar activity cycle.

Veneras 9 and 10 also took measurements with electrostatic analyzers, which showed that the asymmetry of Venus' bow shock was linked to the solar wind's anisotropic nature. The bow shock's radial distance in the polar direction is approximately 2000 to 3000 km (1243 to 1864 miles) greater than in the equatorial direction.

After the experiments on Venera 4 by S. Dolginov and his colleagues, Venus' magnetic moment was initially estimated as 5 to 8×10^{-21} gauss cm^3 (10 gamma on the surface). After reviewing Veneras 9 and 10 data, this estimate was lowered and the intrinsic field on the planet's surface was assumed not to exceed 5 gamma.

Magnetic field measurements at altitudes from 140 to 200 km (87 to 124 miles) showed that most field values did not exceed the threshold sensitivity of the instrument, or 2 gamma. Thus, it was confirmed that Venus' intrinsic magnetic field is all but absent.

Plasma Magnetic Tail

All trajectories of Soviet vehicles that have landed on planets or put artificial satellites into orbit have approached planets from their nightside and have allowed observations of the planets' wake at altitudes greater than 1500 km (932 miles). Veneras 9 and 10 entered the dayside only to latitudes above 32°. These vehicles penetrated deep into the planet's optical umbra and allowed detailed measurements of the distribution of the plasma and magnetic field. Their measurements showed that a plasma-magnetic tail with typical features exists near Venus, some of the features being similar to the tail of Earth's magnetosphere. In particular, the oppositely directed bundles of magnetic field lines along the Sun-planet direction were present on Venus. In other words, the magnetic field component along the Sun-planet direction was essentially higher than the others.

These field line bundles in the tails were separated in the layer where the magnetic energy density had a deep minimum. This layer is similar to the "neutral-sheet" of Earth's magnetosphere. The data from wide-angle analyzers showed that plasma properties and distribution in the tail also resemble Earth's magnetotail. At the tail boundary and in the transition region, a characteristic change in differential ion spectra was observed similar to that in Earth's boundary layer, or plasma mantle. The plasma features deep in the tail resemble those in Earth's plasma sheath.

Figure 7-11 shows regions of solar-wind interaction with Venus. These regions include the shock wave, the transition region (A) behind the shock front, and the plasma-magnetic tail. The B-region corresponds to the corpuscular penumbra, or boundary layer. Data from electrostatic analyzers also indicated a tail boundary that separated plasmas with different

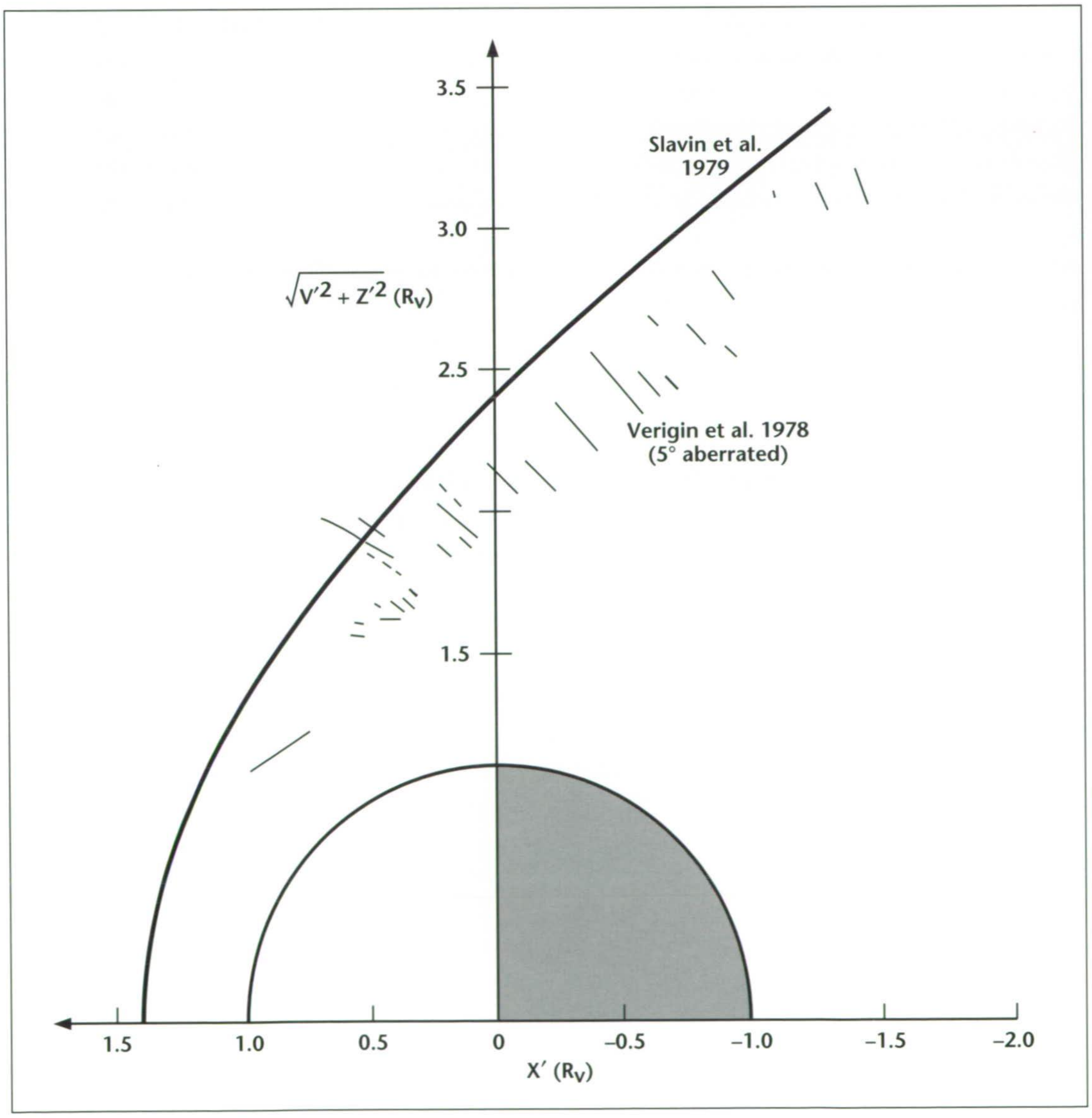


Figure 7-10. Position of the shock front near Venus (measured by Veneras 9 and 10). The lengths of the short curves and the points show the parts of the orbit where the spacecraft crossed the front. The solid curve shows the average position of the front (determined from Pioneer Venus data). The cylindrical system of coordinates is used where the X′-axis is oriented to the solar-wind direction.

properties. Outside this boundary, plasma was evidently of solar-wind origin but disturbed by its interaction with the obstacle. Inside the boundary, plasma was cooler and had a smaller bulk velocity, probably an accelerated or heated plasma of planetary origin. Such a boundary layer could appear, and its properties would resemble the boundary of two liquids. One boundary moves and, because of viscous interaction with the lower liquid, accelerates and heats it. When the solar-wind plasma with the frozen-in magnetic field moves relative to the ionospheric plasma, the boundary separating these liquids can be unstable. For instance, the boundary begins to move or fluctuate because of increasing solar-wind pressure. The bubbles of the solar-wind plasma flow are then pressed into the ionosphere, tearing away from the flow. This condition also could occur with ionospheric plasma rising up in the transition region. A variety of processes cause plasma instabilities, smear the boundary, and dissipate solar-wind energy and its subsequent transfer into the ionosphere.

In Figure 7-11, the region extending to 5 Venus radii (C-region), where the regular ion fluxes are absent, is positioned under the corpuscular penumbra, which is the corpuscular umbra region that does not coincide with the optical shadow of Venus. The behavior of the electron fluxes was quite different from the measured ion fluxes. The fluxes were everywhere, including the corpuscular umbra. Only their intensity decreased (Figure 7-12), and the character of the spectrum changed; that is, high-energy tails appeared in the spectrum. Apparently, electrons and ions inside the tail were subjected to some acceleration processes.

It was likely that in the far tail regions of Venus, the boundary layer gradually thickened and merged with the plasma sheath as it does for Earth. As in the plasma sheath of Earth's magnetosphere, accelerated ion fluxes with energy greater than 2 keV (C-region in Figure 7-11) were observed near the neutral-sheet plane. These fluxes occurred when the B_x component of the magnetic field reversed its sign (x-axis was along the Venus-Sun line—Figure 7-13). Thus, the large-scale pattern, magnetic field topology, and plasma distribution in the Venusian tail showed a striking resemblance to Earth's magnetosphere.

Nature of the Obstacle Forming a Shock Wave

An extended tail near Venus with properties similar to those in Earth's magnetosphere seems rather striking. Before the Pioneer Venus experiments, this tail led the American specialist C. T. Russell to revise the magnetic field estimates that Soviet specialists previously made. He increased the estimated value of Venus' intrinsic magnetic field.

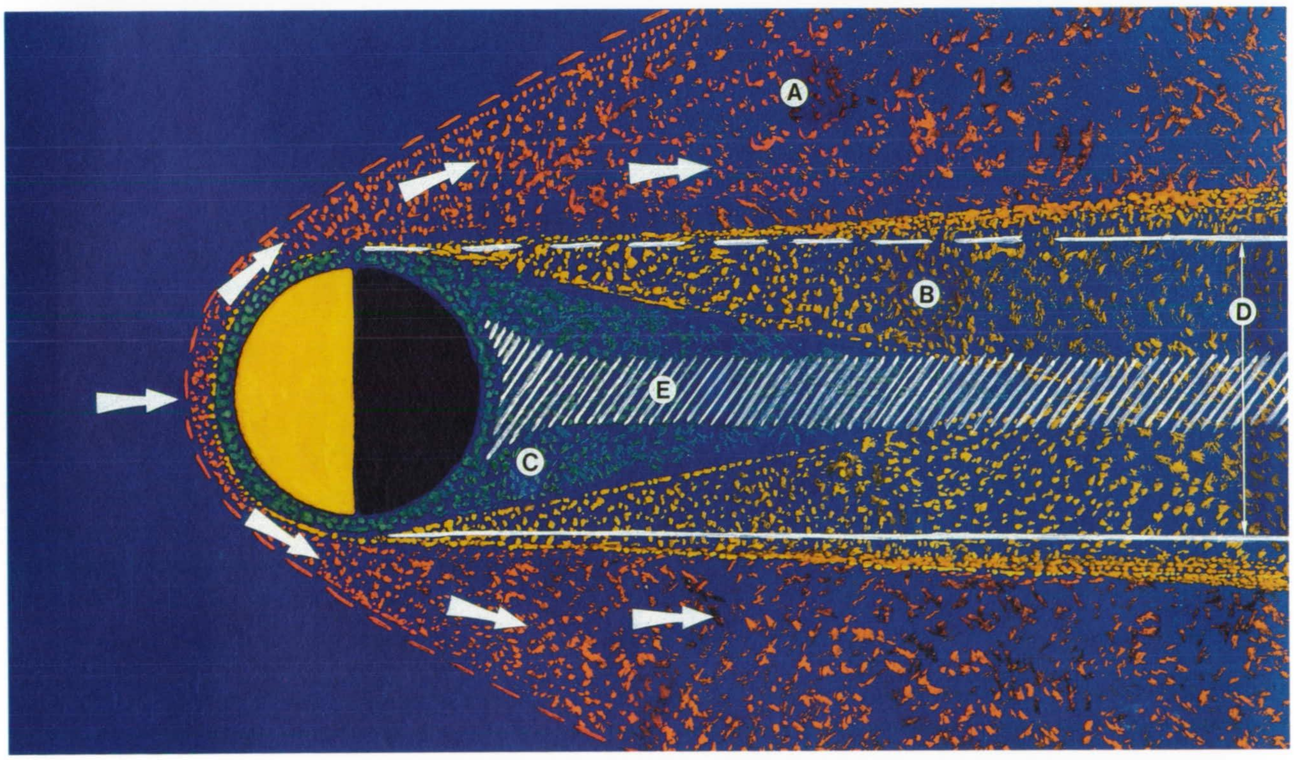
More careful study and detailed revisions of the data for magnetic and plasma measurements near Venus have begun. An analysis of magnetic measurement data on Veneras 9 and 10 showed that the tail's magnetic field properties had one essential difference. This difference became apparent after comparing data the two spacecraft obtained simultaneously. One spacecraft was in undisturbed solar wind and the other in the planet's tail region.

During each measurement, the magnetic field topology—two field line bundles stretched along the tail—was preserved. However, in several instances, the plane of the neutral sheet separating these bundles changed its orientation. Sometimes this plane was located vertically, almost parallel to the meridian plane, but this is not typical, for example, of Earth's magnetotail. By comparing the magnetic data two spacecraft obtained at the same time, E. Eroshenko (Institute of Earth

Magnetism and Radiowave Propagation) showed that the neutral-sheet plane in the tail always remained perpendicular to the transverse component of the interplanetary magnetic field. It rotated with the rotation of this transverse component.

The conclusion is that the measured magnetic field is not the planet's intrinsic field. Rather, it is the field of the "magnetic barrier" that currents flowing in Venus' conductive ionosphere induce. In other words, magnetic field tubes of the solar plasma flowing around the planet encounter an almost ideal conductor: the ionosphere. They cannot penetrate it and they deform, retarding especially strongly near the stagnation subsolar point of the ionosphere. The magnetic field accumulates at the subsolar region and forms a magnetic barrier. Still flowing around the planet, the solar wind carries the ends of the field tubes retarded at the frontal part of the planet. The tubes drape the planet and stretch tail-like on the nightside. Thus, the field line bundles elongate in opposite directions on the two sides of the planet. The orientation of the plane separating these bundles depends on the orientation of the magnetic field in the undisturbed solar wind. In the simplest case, if the interplanetary magnetic field vector lies in the ecliptic-horizontal plane, field lines of the tubes draping the planet are in opposite directions on the dawn and dusk sides. In this case the neutral-sheet plane is parallel to the meridian plane. If, however, the interplanetary-field vector is in the meridian plane or near it, the neutral-sheet plane will either partially or completely coincide with the ecliptic plane. It is very difficult to distinguish this case from

Figure 7-11. Schematic representation of the near-planet shock wave (dotted line) and Venus' magnetosphere from Veneras 9 and 10 data. Arrows show the direction of the solar-wind plasma flow. The A-region is the transition layer behind the shock front. The B-region is the boundary layer. The C-region is the corpuscular shadow. The D-region (solid line) is the magnetosphere boundary. The E-region is the plasma sheath which contains a neutral sheet separating magnetic field lines directed toward each other.



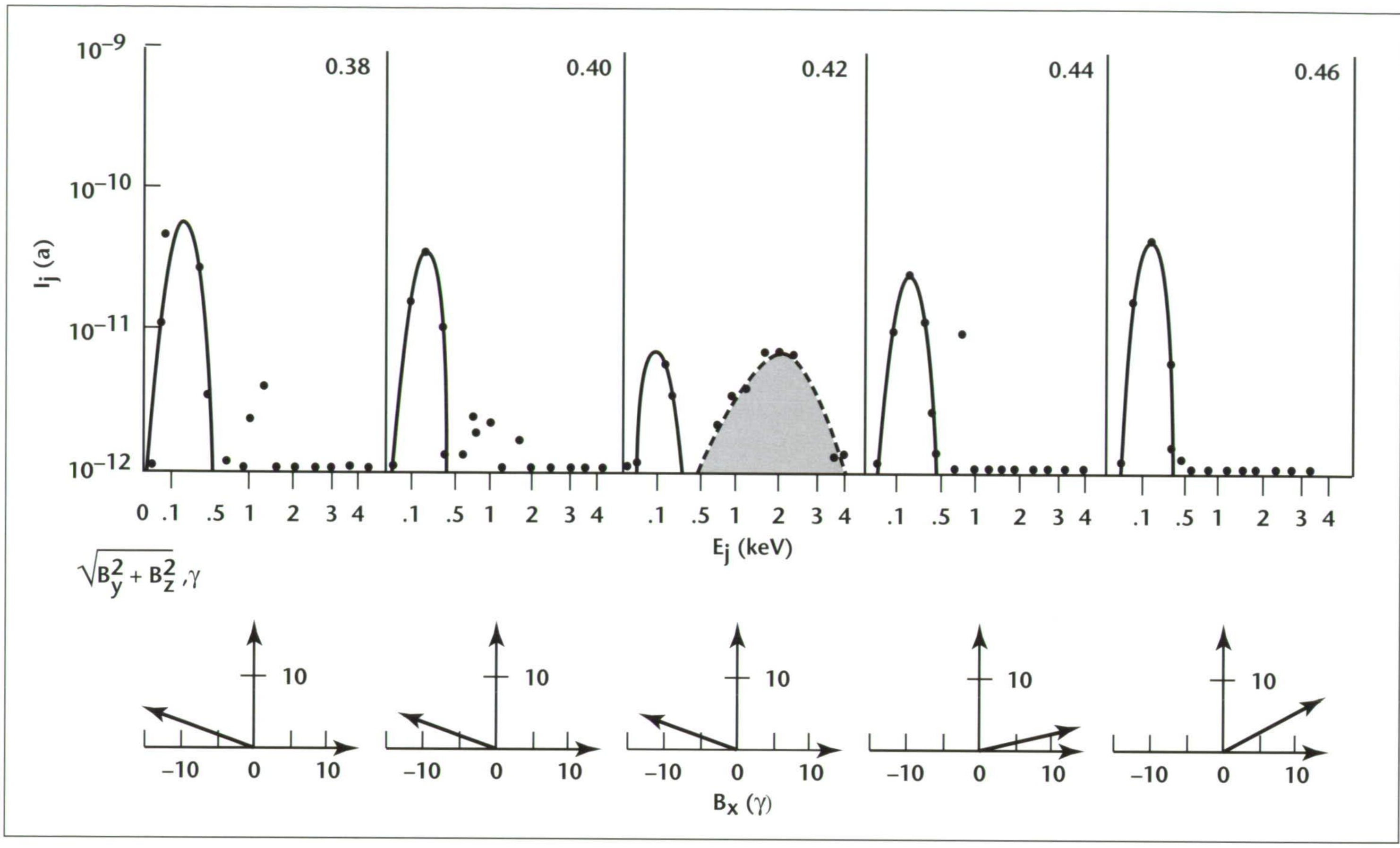


Figure 7-12. Ion energy spectra that Venera 10 obtained on April 19,1976. The spacecraft measured the intense flows of energetic ions (shaded part of the 0.42 spectrum) in the region of the planet tail where the magnetic field B_x-component changed its sign (B_x-component turn is shown underneath the spectra between 0.42 and 0.44). These flows are part of the plasma sheath of the Venusian tail.

the intrinsic magnetosphere tail, with the dipole axis near the polar axis, as for Earth.

The problem remained unsolved for currents that form the induced magnetosphere flow. Another unsolved problem was how an extended induced magnetic tail can form.

After Veneras 9 and 10 experiments and on the basis of research by American investigators (P. Cloutier and R. Danniel), E. Eroshenko assumed that currents are induced in the ionosphere itself and are mainly in its maximum. The region from the ionosphere maximum to its upper boundary is 200 to 300 km (124 to 186 miles) on the dayside.

Soviet laboratory simulation experiments (at the Space Research Institute, headed by I. Podgorny) were very important in understanding tail formation in the "induced" magnetosphere. In these experiments a Venusian artificial ionosphere was formed from vaporization products of a wax sphere placed in a hydrogen plasma flow with a frozen-in magnetic field. On the artificial ionosphere's dayside, a sharp boundary formed, over which the magnetic field increased with the "magnetic barrier." Field lines were parallel to the ionospheric boundary. Measurements on the wax sphere's nightside showed that a long tail forms (up to 10 radii of the sphere) with the field orientation in the tail being typical of the observed Venusian magnetosphere (Figure 7-14).

The experiments on Pioneer Venus finally confirmed that Venus has practically no intrinsic magnetic field and that a magnetic barrier forms on its dayside.

If the assumption that the induced current flow inside the ionosphere is correct, the upper ionosphere boundary should coincide with the magnetic barrier's upper boundary. However, it does not. From Pioneer Venus data, the

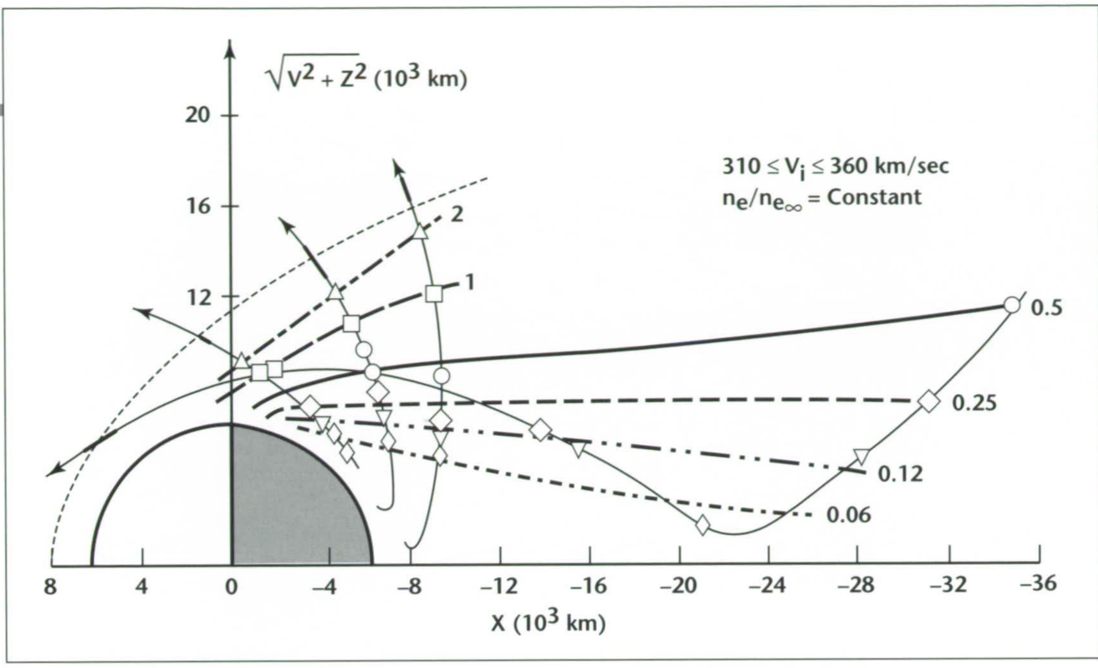


Figure 7-13. Distribution lines for constant number densities of the plasma's electron component near the region where the solar wind interacts with Venus (from Veneras 9 and 10 data). Electron measurements corresponding to velocities of solar wind, v_i, in the narrow interval 310 to 360 km/sec (193 to 224 miles/sec) were chosen for the analysis. Numbers along the lines designate the values of electron number density, h_e, relative to their values in the solar wind.

barrier's magnetic field usually decreases sharply on the upper ionosphere boundary, or ionopause, simultaneously with the growth of the thermal ionospheric plasma's concentration and temperature. That is, the field behaves as if there is a conductor carrying a current in the ionopause region at 50 to 100 km (31 to 62 miles). Sometimes Pioneer Venus detected high values of the magnetic field inside the ionosphere in the region of the main maximum.

It is evident that, in the ionosphere itself, strong currents could flow. C. T. Russell associated that phenomenon with the discovery of magnetic "flux ropes" in Venus' dayside ionosphere. American specialists (F. Johnson and W. Hansen) and Soviet specialists (T. Breus, E. Dubinin *et al.*, Space Research Institute) gave qualitative explanations and estimated flux-rope characteristics.

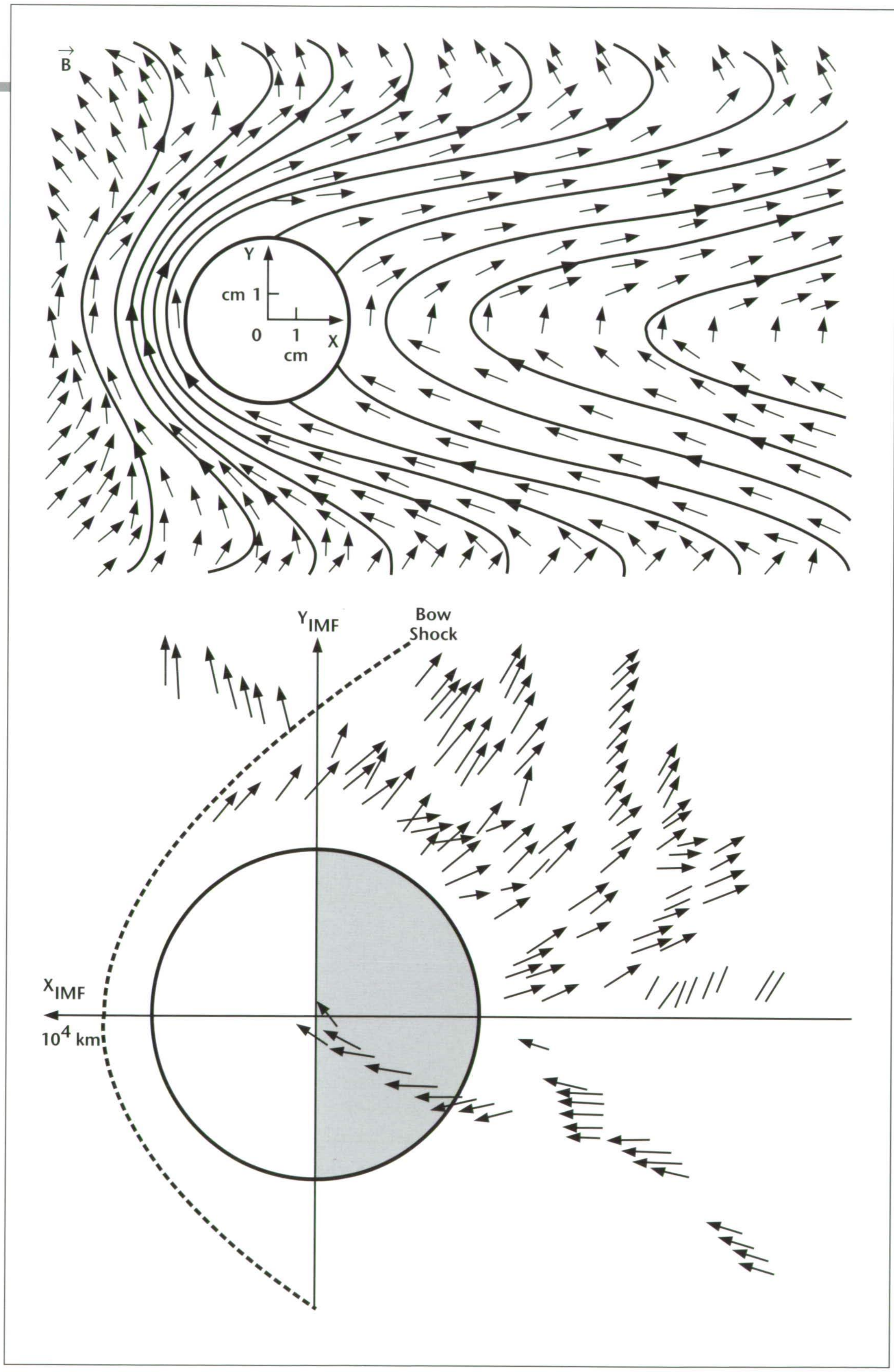
In the dayside ionosphere, a special set of magnetic field tubes from the magnetic barrier, which results from the instability of the ionopause as it fluctuates due to varying solar-wind pressure, apparently can press in the ionosphere, tear off the solar-wind flow, and submerge into the ionosphere. With these tubes moving in such a manner, the field-aligned current can twist them into spirals and make their cross sections more compressed as they submerge deeper into the ionosphere. Pioneer Venus data showed that the entire dayside ionosphere was often filled with these flux ropes or their pieces.

Dayside and Nightside Ionospheres of Venus

Scientists investigated properties of Venus' dayside and nightside ionospheres by observing radio occultations. This was during the flybys of Mariners 5 and 10, Veneras 9 and 10, and the long mission of Pioneer Venus Orbiter.

In 1967, ion traps on Venera 4 made the first direct measurements of the ion number density's upper limit in Venus' nightside ionosphere. In 1978-1979, Pioneer Venus, using various mass spectrometers and plasma analyzers, measured ion and electron number densities, temperatures, and ionosphere composition. The spacecraft made these direct measurements down to 140 km (87 miles) on both the dayside and nightside of Venus.

Figure 7-14. Comparison of laboratory model of induced magnetosphere (top of figure) with the field topology in the tail of Venus' magnetosphere measured during the Veneras 9 and 10 experiments. Projection of magnetic field vectors appears in the system of coordinates rotating together with the interplanetary magnetic field vector.



Venus' Dayside Ionosphere

Early experiments and radio-occultation observations during Mariner 5 and 10 flybys of Venus indicated that a sharp upper boundary—an ionopause—exists on electron number density profiles in the dayside ionosphere.

The ionopause heights of these profiles were very different: 500 km (310 miles) on Mariner 5 and 350 km (217 miles) on Mariner 10. The dynamic pressure of the undisturbed solar wind during Mariner 10's flyby was higher than during Mariner 5's. Based on this difference, American investigators suggested that the solar wind could compress the Venusian ionosphere (S. T. Bauer). As a result, the electron number density profile should be distorted, and the significant flow of the solar wind could then penetrate to the ionosphere. According to some estimates (C. T. Russell), the value of the incoming solar-wind flow could be 30% of the total solar flux. As a result, the shock wave might "settle down" on Venus' surface and become attached rather than detached (C. T. Russell). As the data from Veneras 9 and 10 showed (N. Savich, Radio-electronics Institute), the ionopause has a distinct dependence on solar zenith angle. Near the subsolar region, the ionopause was at 250 to 280 km (155 to 174 miles). With an increase in the Sun zenith angle x, the ionopause height increased. This dependence had the following form: $1/\cos^2 x$. In other words, it corresponded to variations with zenith angle of the solar wind's dynamic pressure $pv^2 \cos^2 x$ (p is density and v velocity of the solar wind).

In the stagnation region, where $\cos^2 x = 1$ and the dynamic pressure is maximum, the ionopause is much nearer the surface. At the flanks, with an increase in x, it moves farther away from the surface and experiences greater variations in height. Beginning with a zenith angle of approximately 58° to 60°, a region appeared above the main ionization maximum. This region had an almost constant electron number density on the order of 10^3 cm^{-3}. It also displayed an extension of roughly 300 km (186 miles) or more, the so-called "ionosheath." The Pioneer Venus data showed that heights of the upper ionospheric boundary vary considerably. The amplitude of its variations increased with zenith angle, but the character of the boundary behavior was generally the same as that shown by Veneras 9 and 10 data. The large range in ionopause heights that Pioneer Venus measured was due to differences in measurement techniques. Data that gave the positions were from various sensors that were subjected to the effect of the vehicle potential, especially near the terminator. During transfer from the illuminated to nonilluminated portion of an orbit, the photocurrent from the vehicle decreases in the shadow. Consequently, the potential of the free body in the plasma decreases, which affects the zero reference in measurements with traps.

Another reason might be that the very low position of its periapsis may have caused the Pioneer Venus trajectory in the ionosphere to give a horizontal rather than vertical cross section. The results then would depend on horizontal plasma variations, which perhaps were even greater than usually appear in radio-occultation data.

In any case, according to radio-occultation observations on Pioneer Venus and Veneras 9 and 10, these ionopause variations were less striking. However, this problem required further analysis and correlation.

With increasing distance from the subsolar point, the boundary between the solar wind and the ionosphere becomes unstable. The magnetohydrodynamic boundary layer develops because of viscous interaction of two plasmas, instabilities, and dissipation of energy. Its thickness grows to the flanks. Possibly the ionosheath formation on the electron number density profile is associated, in a yet unknown way, with the formation of this boundary layer.

How much solar wind penetrates to Venus' ionosphere? Is it 30% of the flux coming toward the planet, or is it less?

Based on indirect data (T. Breus, Space Research Institute) and theoretical estimates (P. Cloutier and R. Danniel), the absorption should be negligibly small. Actually, it should not exceed 1% because the shock front position near Venus is sufficient to follow the law of magnetohydrodynamic flow around an impenetrable obstacle. Pioneer Venus results later confirmed this value.

Venus' Nightside Ionosphere

It became evident after radio-occultation experiments onboard Mariners 5 and 10 and Veneras 9 and 10 that Venus' nightside ionosphere was irregular. Electron density profiles in the nightside ionosphere sometimes had two narrow maxima of roughly the same order of magnitude. These maxima were 5 to 10 km (3 to 6 miles) apart. Sometimes the number density in the upper maximum exceeded that in the lower one. It was natural to associate irregular electron density variations in the nightside ionosphere with the influence of solar-wind flows. It was just such an assumption that Soviet and American specialists made after their respective Venera 4 (1967) and Mariner 5 experiments. But it was still obscure how the solar wind penetrated to such low heights in regions far from the terminator. (This was before Veneras 9 and 10 experiments and before discovery of the plasma magnetic tail near Venus.) The assumptions and estimates on how solar-wind electron fluxes ionized Venus' nightside atmosphere seemed inconclusive.

American researchers suggested another hypothesis. They assumed that hydrogen and oxygen ions forming in the dayside ionosphere were transported with the solar-wind flux to Venus' nightside. The ions then diffused down to the heights of the main maximum of the night ionosphere and exchanged charge with neutral molecules of CO_2 and O_2. As a result, ions O_2^+, O^+, and CO_2^+ formed, and the nightside ionosphere consisted of these ions.

Veneras 9 and 10 measured electron fluxes at an altitude of 1500 km (932 miles) in the region of Venus' optical umbra (see Figure 7-12). K. Gringauz and his colleagues Verigin, Breus, and Gomboshi suggested that these fluxes can ionize the atmosphere and form the upper maximum of the night ionization.

Calculations showed that, because of these electron fluxes, the maximum of the electron number density could really form, which corresponded to the radio-occultation measurements of Veneras 9 and 10 (Figure 7-15). The fact that electron density variations in the flux at altitudes of 1500 km (932 miles) correlated well with those in the ionosphere's upper maximum also argued in favor of the assumption. The calculated and experimental profiles, however, coincided only when the neutral atmosphere density in the calculations (that is, an initial ionizable material) was more than an order of magnitude less than in available models. The neutral temperature also might be lower than in these models. Veneras 9 and 10 radio-occultation measurements (N. Savich) also showed the neutral temperature to be much lower (about 100 K) than had been suggested before. Other observations need explanations, too. For example, scientists knew that electron fluxes coming into the atmosphere caused nighttime glows. Experiments, however, did not show these glows. Another question puzzled scientists: How were electrons at 1500 km (932 miles) able to reach 140 km (87 miles)?

An explanation is also needed for the ionization source that produces the second maximum in the nightside ionosphere, which frequently has the same order of magnitude as the upper one. Ionization sources such as ion transport from the dayside ionosphere and diffusion and charge-exchange of ions with atmospheric molecules can hardly account for one or two very narrow maxima that have been observed in experiments. Electrons with energies greater than 70 eV, which Soviet scientists had used in the calculations described earlier, could not reach the lower maximum because they "died" at higher altitudes.

American specialists (D. Butler and J. Chamberlain) and a Soviet specialist (V. Krasnopolsky) hypothesized that the lower maximum formed as a result of meteor ionization at an altitude level where the number density of neutrals was 10^{12} to 10^{13} cm^{-3}. This level was actually lower by about 20 km (12.5 miles) than that for 2×10^9 cm^{-3}, at which the upper ionization maximum that K. Gringauz and his colleagues had estimated is formed. Meteor ionization could produce a rather narrow maximum. Despite criticism and correction of the available neutral atmosphere models, Soviet investigators followed this hypothesis based on their own data.

Eventually, Pioneer Venus data verified the results of calculations that, in turn, confirmed this hypothesis. These data indicated that the number density of neutral components and plasma temperature at the height of the ionization upper maximum was several orders of magnitude less than in available models (Figure 7-16). The neutral temperature in Venus' nightside atmosphere was about 100 to 140 K.

Pioneer Venus detected fluxes of electrons with energies less than or equal to 250 eV (the upper threshold of the instruments) at an altitude of 140 km (87 miles). The intensity of the flux was sufficient to produce ionization equal to that measured experimentally. This information was conclusive evidence that the Soviet hypothesis for an electron source of ionization in Venus' upper ionosphere was correct.

Pioneer Venus measured velocities of the O^+ ion transport from the dayside to the nightside ionosphere. These velocities were sufficient to sustain the nightside ionosphere. However, the maximum of the ionization so formed gradually decreased with increasing height in the region above the maximum. Soviet data showed that the thickness of the ionization layer at the maximum half-width level exceeded by about two times the thickness of the experimental profile layer.

From these observations, it became clear that electron fluxes help form the narrow upper maximum of ionization in the planet's nightside ionosphere. It is even possible that double-component electron flux (consisting of electrons with energy less than 70 eV and greater than 350 eV) forms double maxima of very irregular ionization. It also is possible that accelerated fluxes of ions that Veneras 9 and 10 detected in the tail form the lower maximum (T. Breus, A. Volacitin, and H. Mishin). The transport of O^+ ions from the dayside ionosphere contributes mainly to the formation of the ionosphere's upper region.

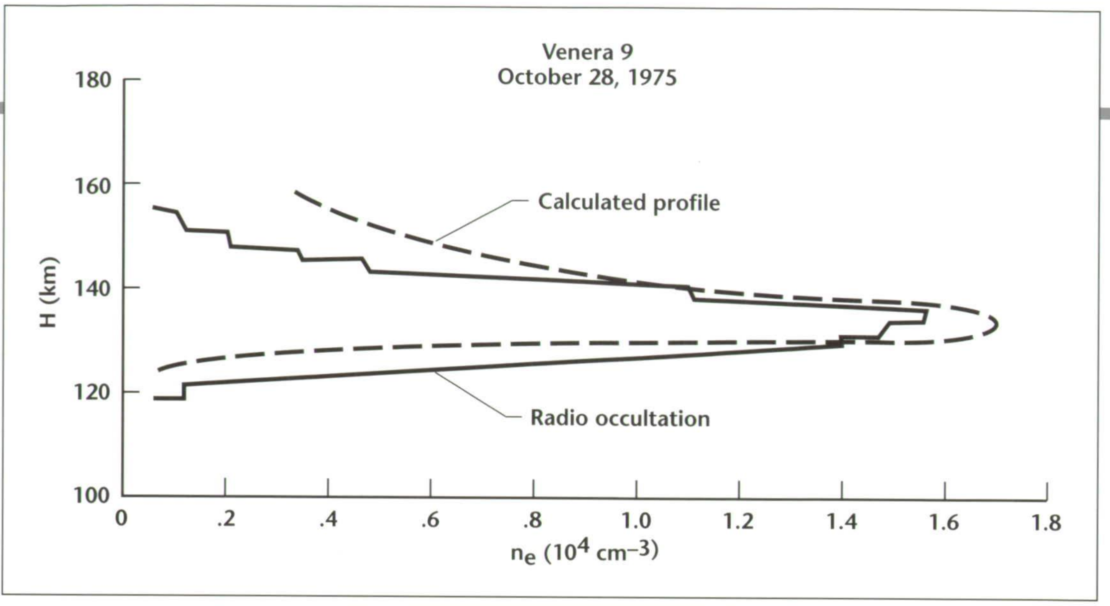


Figure 7-15. Comparison of the electron-number density profile in Venus' nightside ionosphere (from Venera 10 data that measured electrons ionizing the atmosphere) with the profile obtained by radio-occultation measurements.

Where do electron fluxes appearing in the planet's optical umbra form? How do they enter the atmosphere at altitudes of 100 to 140 km (62 to 87 miles)?

Veneras 9 and 10 detected a plasma-magnetic tail near Venus. This discovery provides at least a partial answer to these questions. For the present, it allows appropriate assumptions to be made.

Indeed, in the plasma sheath, acceleration of solar-wind particles was observed, the latter flowing into the tail from its flanks. Also, acceleration of ions and electrons in the day-side ionosphere could occur and these could be transported to the tail and picked up by the solar-wind flux.

Different mechanisms in the tail can accelerate electron fluxes. These fluxes can precipitate and then be injected into the atmosphere at low altitudes to produce an irregular source of ionization. Such a source essentially depends on the properties of the solar-wind and the situation in interplanetary space.

The plasma and magnetic experiments the Soviets conducted near Venus for over a decade were very useful. At the XVII General Assembly of the International Association of Geomagnetism and Aeronomy in Canberra, Australia (December 1979), results of magnetic and plasma measurements near Venus were summarized. Here is a list of basic results obtained by Soviet (Veneras 9 and 10) and American (Pioneer Venus) investigators. The list also includes theoretical work and models that contributed much to the interpretation of the results:

- Discovery of the plasma-magnetic tail (Venera vehicles)
- Identification of the induced nature of the magnetic field measured near Venus (Venera vehicles and Pioneer Venus)
- Determination of the shock front position (Venera vehicles)
- Detection of the shock front asymmetry (Venera vehicles)
- Hypothesis of an electron source of night-side ionosphere ionization (Venera results and calculations)
- Confirmation of the Venus "induced" tail in laboratory simulation experiments (Soviet data)
- Evidence for the pressure balance at the iono-pause, sustained by the "magnetic barrier" and the ionosphere thermal plasma pressure

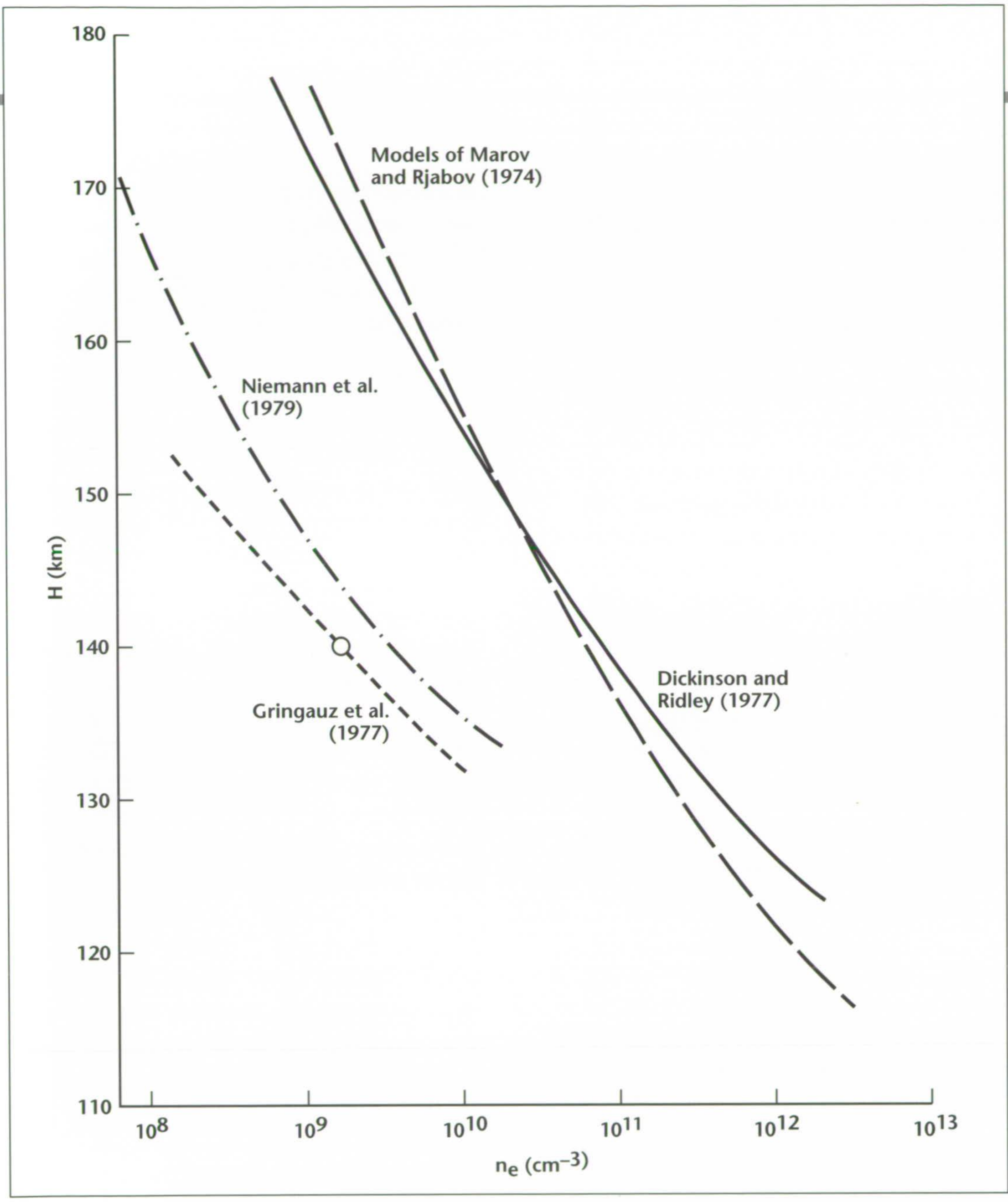


Figure 7-16. Dependence on a height, h, of number density of neutral particles, n_n, according to the models by M. Marov and O. Rjabov (Institute of Applied Mathematics, U.S.S.R. Academy of Sciences), R. Dickinson, and E. Ridley. The dependence $n_n(h)$, suggested by the group headed by K. Gringauz (Space Research Institute, U.S.S.R. Academy of Sciences), agrees with the results of H. Niemann et al. *obtained from Pioneer Venus.*

on the one hand and by solar-wind streaming pressure on the other (Pioneer Venus)

- Discovery of magnetic "flux ropes" in the ionosphere (Pioneer Venus)
- Explanation of the nature of the magnetic flux ropes (Soviet and American interpretation of results)
- Detection of the magnetic field increase before the ionopause in laboratory and numerical experiments, confirming the existence of the magnetic barrier (Soviet results).

Prospects for Further Research

Not everything we have learned about Venus appears here. Our knowledge of the planet has been enriched considerably. But has Venus ceased to be a mystery planet? Unfortunately (or fortunately), the answer is no. Venus still has many mysteries. While earlier puzzles were unraveled and many problems were solved, new mysteries arose which are much more difficult to understand.

Some of the problems yet to be solved are:

- We still have no true explanation for the higher content of primordial inert gases on Venus.
- It is entirely unclear why there is so little water in the Venusian atmosphere. Has Venus formed without water? Is water hidden in the crust, or was it lost during the planet's evolution? Why is the vertical profile of water vapor concentration so extraordinary?
- We have not yet determined the chemical composition of the cloud cover particles.
- We do not understand the mechanism responsible for the motion of the atmosphere at altitudes of 40 to 70 km (25 to 43 miles), the four-day rotation.
- How active is the planet's interior? Is there volcanic or seismic activity?
- Finally, we do not know when the present temperature conditions of Venus' atmosphere and surface set in. Did these conditions exist when Venus formed? Or was Venus' climate more moderate during a sufficiently long initial epoch?

How should the exploration of Venus continue? Evidently, only spacecraft of different types can solve such diverse problems. To study atmosphere dynamics, balloons are indispensable. We also could use them to investigate the cloud cover's physical and chemical properties.

Descenders, or probes, are needed to study the chemistry of the minor constituents of Venus' atmosphere and its thermal budget. These spacecraft would operate along the usual descent trajectory from parachute deployment to touchdown. For best results, they should begin to function at the highest altitude possible, at no less than 70 km (43 miles). Finally, seismic observations require that instruments remain on the planet's surface for many months. Engineers must design this special equipment to operate at high temperatures. The technical problems are numerous, but we are hopeful that we can solve them. We also expect that new and more sophisticated instruments will appear.

Another interesting program was the Soviet-French Vega project. This program included two new spacecraft that were improvements on Veneras 11 and 12. These spacecraft would fly by the planet and jettison two landers for a soft landing on the planet. Each flyby also would inject two balloons to study atmospheric dynamics.

The remaining Russian contribution to this book (below) refers to the Vega mission. The new spacecraft's mission to Venus and to Halley's comet was highly successful. Its results appear in the next section of this chapter.

The Vega landers are designed to study chemical composition of inert gases, aerosol particles, thunderstorms, and other properties during their descent. These landers are equipped to measure pressure, temperature, chemical composition of Venus' soil, and possibly seismic activity.

A particularly fascinating Vega mission involved one of the brightest and most interesting comets in the Solar System. The comet Halley approaches the Sun once every 76 years. Such an event occurred in 1986, and Soviet scientists prepared a Vega mission to record the event.

Comets can help us understand the Universe's origin and evolution. There is an assumption that comet nuclei are the material from which the planetary system formed. Until the Vega mission, astronomers could only study comets with ground-based instruments. We knew practically nothing about the structure of comets' nuclei, ionization sources, mechanisms for formation of plasma structures in comets' tails, and the reasons for the comets' various shapes.

Conditions for observing the comet from Earth were relatively unfavorable in 1986. So studying Halley's comet from space was particularly important. To investigate Halley's comet, the European Space Agency launched the comet flyby spacecraft Giotto. Japan launched two spacecraft, Sakigake and Suisei.

The Soviets had not planned a special mission to the comet. However, Vega flyby vehicles to Venus were able to use a gravitational maneuver near the planet to travel on to the comet (Figure 7-17). These vehicles approached within several thousand kilometers of the comet and were able to photograph its nucleus. Among many other phenomena, they studied components of the dust and gas that evaporated from the nucleus, and ion concentrations. These three projects—European, Japanese, and Soviet—complemented each other, in terms of both scientific goals and equipment.

THE FINAL VENERAS AND THE NEW VEGA SPACECRAFT

R. O. Fimmel, L. Colin, E. Burgess

We have added the following material to this chapter to give you information that goes beyond the period covered by the Soviet authors. This material documents other events in the exploration of Venus. It covers the period from the extended Pioneer Venus mission to the beginning of NASA's Magellan mission to Venus.

After missing the 1976-1978 launch opportunity, the Soviets sent their next mission to Venus in September 1978. Veneras 11 and 12 were each a combination flyby and lander spacecraft. They arrived in December 1978. The flyby spacecraft gathered data on the ultraviolet spectrum of the upper atmosphere as they sped by Venus. They successfully telemetered these data back to Earth.

Both landers provided atmospheric data as they penetrated the atmosphere before landing safely on the surface. During the descent through the atmosphere, an instrument designed to search for "thunderstorm" activity recorded radio bursts that might be attributed to lightning. These data reached Earth about five days before Fred Scarf detected "whistlers" with the Pioneer Venus instruments (see Chapter 6). Pioneer's orbital configuration did not allow an earlier search for such whistlers.

The Venera landers found the ratio of argon-40 to argon-36 was several hundred times less than in Earth's atmosphere. Why did Venus have so little argon-40, a decay product of potassium-40? The amount of this potassium isotope in Venusian rocks is about the same as in terrestrial rocks. One possibility is that Venus may not have experienced as much volcanic activity as Earth. Arguing against this, however, are the images returned by Magellan showing that Venus has experienced a great deal of volcanic activity.

The issue might be resolved if atmospheres were the result of comet impacts rather than mainly the result of internal activity and evolution of volatiles from within the planets. In such a scenario, incoming material, not planetary material, would govern isotopic ratios. The atmospheric ratios would bear no relationship to ratios in the material of the planet itself.

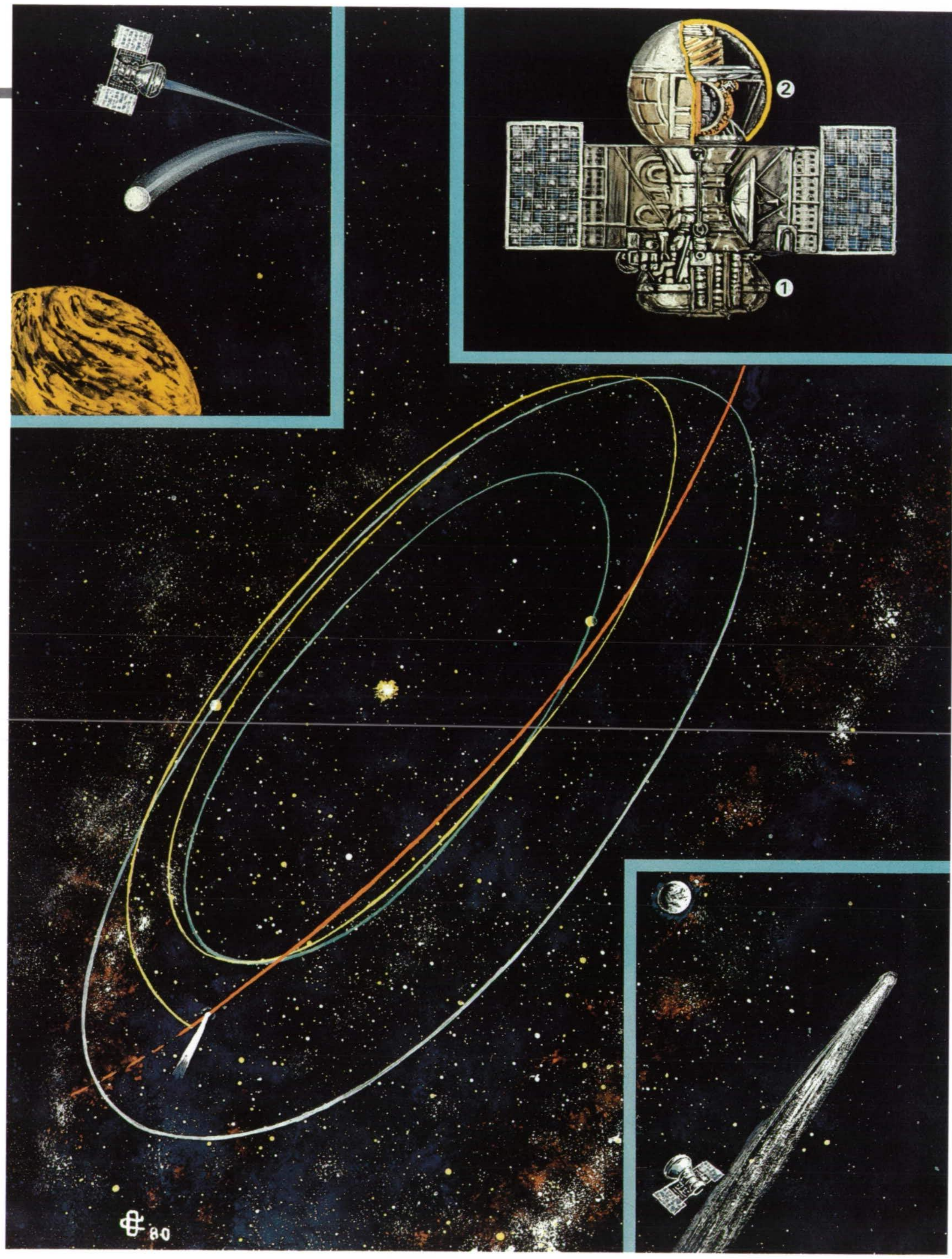


Figure 7-17. Vega-Halley mission—the red line shows the flight trajectory of Halley's comet; the yellow line shows the trajectory of the flyby vehicles. The green and blue lines show the orbit of Venus and Earth, respectively. Top left shows the descent module separating from the flyby spacecraft at Venus. At the top right is a general view of a prototype of the Vega spacecraft: 1) the flyby spacecraft, and 2) the descent module. The final version carried a balloon probe and a lander in the descent module. In bottom right, the flyby spacecraft is passing by Comet Halley, almost nine months after its encounter with Venus.

Venera 12's lander settled on the surface near Phoebe Regio, where it measured a surface temperature of 480°C (896°F). It also recorded an atmospheric pressure 88 times greater than Earth's sea level pressure. The flyby spacecraft relayed telemetry from the lander. After roughly 110 minutes of data relaying, the flyby spacecraft went below the horizon as viewed from the landing site. Communication ended. The other lander, Venera 11, measured close to the same atmospheric pressure, but it recorded a temperature some 34°C (93°F) less than at the Venera 12 site about 725 km (450 miles) farther north in Phoebe Regio. This lander lost contact with the flyby spacecraft 95 minutes after landing.

No Russian spacecraft were sent to Venus at the 1980 opportunity. The next missions were Veneras 13 and 14, two spacecraft launched on October 30 and November 4, 1981 (see Table 7-3). Again the buses that transported the landers to Venus were flybys. This arrangement allowed more weight to be allocated to the landers for a given launch weight. Soviet scientists again targeted the landers for the Phoebe Regio area, where they landed on March 1 and March 5, 1982, respectively.

These landers accomplished the high technology task of gathering small soil samples from the planet's hot surface and examining them without exposing the interior of the landers to the high surface pressure and temperature. The samples were analyzed within closed chambers. A series of airlocks moved the samples by airstream to chambers of decreasing pressures. The last chamber had a temperature of only 30°C (86°F) and a pressure one-tenth of Earth's at sea level. Basaltic sand and dust was identified in the samples at both landing sites. Of the two varieties in the samples, one is scarce on Earth. No granite was found in the sample material. The landers had improved photo-imaging systems and returned excellent images to Earth for color reproduction. These showed the typical flat Venusian landscape strewn with flattened rocks and weathered lava flows. Fine rubble covered much of the surface at the Venera 13 site, but there was much less of this material at the Venera 14 site, which was 725 km (450 miles) farther south and 740 km (460 miles) to the west in a lower area. Fluid lavas from the Phoebe volcanoes may have covered this area. Plate-like rocks visible in the Venera 14 and other surface images so resemble sedimentary rocks that some Russian experimenters have suggested that Venus' high atmospheric pressures may have led to a sedimentation process in the atmosphere similar to that in bodies of water on Earth.

Dust suspended in the atmosphere colored the sky orange, somewhat like the skies of Mars. The light yellowish-orange color of soil and rocks suggests that the surface is heavily oxidized, again like Mars. This oxidation might imply that the planet once possessed large bodies of water, the oxygen from which became trapped in surface rocks while hydrogen escaped into space.

Venera 14's instruments also detected what scientists believed were slight seismic disturbances. However, the other lander did not detect any such disturbances.

Veneras 13 and 14 temperature and atmospheric pressure readings were very similar to earlier lander measurements. These landers operated successfully for much longer than their design lifetimes. Venera 13 survived for 127 minutes. Venera 14 lasted for 63 minutes at a lower elevation and at a pressure of nearly 100 atmospheres.

Soviet scientists launched Veneras 15 and 16 on June 2 and June 6, 1982. These spacecraft went into near polar orbit around Venus in October 1982. Like Pioneer Venus Orbiter, they had an orbit with a period of 24 hours. Periapsis was a few thousand kilometers over the northern hemisphere and apoapsis about 65,000 km (40,391 miles) above the southern hemisphere. Science data began flowing to Earth in late October. The spacecraft carried advanced side-looking radar, which produced surface radar maps at higher resolution than those from Pioneer Venus Orbiter. The spacecraft also were able to map the surface into higher northern and southern latitudes, supplementing the Pioneer data. A radar map

Table 7-3. Soviet Space Vehicles That Studied Venus 1979 to 1986

Space vehicle		Date	Arrival	Activity
Name	Type	Launch		
Venera 13	Lander Flyby	10/10/81	3/1/82	Landed in region of Phoebe Regio; analyzed soil samples; returned colored photo images from surface
Venera 14	Lander Flyby	11/4/81	3/5/82	Same as Venera 14 but from another site
Venera 15	Orbiter	6/2/82	10/10/82	Radar maps of the planet to high northern and southern latitudes
Venera 16	Orbiter	6/6/82	10/14/82	Same as Venera 14
Vega 1	Lander Probe Flyby	12/15/84	6/11/85	Lander continued work of earlier landers, but in Aphrodite Terra region. Probe carried by balloon around planet sampling atmosphere. Flyby spacecraft continued to a flyby of Halley's comet on 3/6/86
Vega 2	Lander Probe Flyby Halley	12/21/84	1/15/85	Same as for Vega 1 Encounter 3/9/86

atlas was published confirming the earlier Pioneer Venus Orbiter maps, which showed Venus as a very complex planet. The Soviet maps revealed many shield volcanoes, volcanic domes, lava flows, chaotic terrain, long ridges, great depressions, parallel mountains and valleys, regions of intersecting ridges and valleys, and many impact craters. Later, all these features appeared with greater detail in NASA Magellan images. Planetologists interpreted some features as evidence of plate tectonics and earthquake-type displacements. A major surprise was that erosion has degraded many craters. The spacecraft also used infrared spectrometers to map Venus. These images showed warmer temperatures at the poles than at the equator and confirmed that there is little difference between day and night temperatures.

The New Vega Spacecraft

After the Venera series, the Soviet Union continued Venus exploration with a new type of spacecraft, Vega. These advanced spacecraft consisted of a flyby bus, an atmospheric balloon probe, and a soft lander. The balloon probes each carried four scientific experiments, the landers carried nine. The multipurpose bus carried the probe and lander to Venus and then continued to a rendezvous flyby with Comet Halley.

The mission started in December 1984 with launches of two identical spacecraft, Vega 1 and Vega 2. Both arrived at Venus in June 1985. Explosive bolts fired, and the descent capsules separated from the flyby bus. The Vega 1 descent capsule entered the atmosphere on June 11, 1985; Vega 2 entered on June 15.

At about 125 km (78 miles) above the surface, each descender separated into a lander and a balloon-sonde. The landers were targeted for the area north of Aphrodite Terra, where they soft-landed successfully. The balloon-sondes used a French-designed balloon and drifted through the atmosphere for about two Earth days at an altitude of about 50 km (31 miles). Venusian winds carried them along at an average speed of about 65 m/sec (about

146 mph). As each balloon traveled some 10,000 km (6214 miles) around Venus, an international team of scientists evaluated their paths. Instruments recorded changes in light intensity but produced no conclusive evidence of lightning flashes.

The landers continued the Veneras' earlier work with more advanced instrumentation. Soil analysis by the Vegas discovered anorthosite-troctolite, a rock that is quite rare on Earth but common on the primitive crusts of the Moon and Mars. As they descended through the atmosphere, the landers also used instruments to sample the clouds to determine their sulfuric acid content. Both landers provided gas chromatograph and chemical reactor data that showed that clouds between 48 and 63 km (30 and 39 miles) contained one milligram of sulfuric acid per cubic meter. A mass spectrometer and an aerosol collector confirmed these concentrations.

Small samples of clouds were excited by x-ray to reveal the presence of other components. These included elemental sulfur, chlorine, and phosphorous. Other instruments determined the way in which light is diffused by the clouds and discovered that the particles have a size of about a tenth of a micron. (One micron is one thousandth of a millimeter.) The particle size determinations differed from the trimodal distribution that Pioneer Venus probes (1978) and Venera probes measured. The spacecraft identified two cloud layers at 50 and 58 km (31 and 36 miles) above the mean surface and each was about 5 km (3 miles) thick. The cloud layer results differed from earlier Soviet probes, suggesting that major changes occur in the clouds over large regions, since the two Vega probes entered the atmosphere some 1500 km (932 miles) from each other.

Comet Halley

In 1986, the flyby Vega spacecraft hurtled past Comet Halley on March 6 and March 9. Each spacecraft carried 15 scientific instruments for an international group of experimenters from nine countries. The first objective was to obtain a good look at the nucleus, which appears only as a star-like body from Earth.

The spacecraft observed the nucleus from distances of 8000 to 9000 km (4971 to 5593 miles). It was an elongated body some 14 km (8.7 miles) long and 7.5 km (4.7 miles) across, somewhat curved and irregular but definitely not two bodies. Images from the two spacecraft suggested a 53-hour rotation period for the nucleus. Even though dust clouds obscured the surface, the spacecraft were able to measure its reflectivity as being somewhat like that of the lunar surface.

Infrared measurements of the region near the nucleus suggested a surface temperature higher than predicted by the icy nucleus hypothesis. Scientists thought this high temperature might result from dust clouds close to the surface rather than from the surface itself. Ices must be present in the nucleus to give rise to the gas in the comet's coma, and evaporation of these ices would be expected to cool the nucleus. One explanation Russian experimenters suggested is that the nucleus' surface is covered with a thin refractory porous material. Solar radiation heats the top surface while the bottom is insulated and in contact with the icy material. Heat can be conducted internally to evaporate the ice while the resulting gases can escape through the porous material.

The spacecraft also made major contributions to studies of the comet's dust cloud. Scientists obtained hundreds of spectra from which they determined the dust's composition. Interaction of the comet with the solar wind was investigated using another group of instruments, which also recorded crossings of the comet's bow shock. The information these instruments gathered is important to continuing studies of how Venus and other planetary bodies interact with the solar wind.

Studies of Venus, the other planets, and the comets in our Solar System will provide the key to a better understanding of Earth's evolution. Answering these questions is vitally important to our future, and efforts invested in such projects are certain to bear fruit.