The main scientific objectives of the PhPMS are pointed on investigating the Martian-atmosphere erosion due to the interaction of the planet with the solar wind, estimating the loss rate of planetary ions, and studying the relative contributions of various mechanisms to the erosion of the atmosphere (planetary wind, capture of planetary ions from the planetary oxygen/hydrogen corona by the solar wind flux). The PhPMS is also aimed at:

- investigating the mechanisms of charged-particle acceleration (heating) in the tail of the Martian magnetosphere;
- studying the physical processes in the neighborhood of the magnetopause — the outer boundary of the pill-up region of the interplanetary magnetic field;
- studying the movement of the plasma boundaries in near-Mars space and improving the physical models of their movement depending on the phase of planetary rotation and the parameters of the solar wind;
- investigating the kinetic processes at the near-Mars shock wave and estimating the role of solar-wind-trapped planetary ions in these processes,
- and searching for evidence for the interaction of solar wind and/or Martian magnetospheric plasma with Phobos and studying the chemical composition of the Martian surface using the mass analysis of the ions knocked out by the solar wind.

An extensive program of Martian research has also been prepared by NASA. It can be hoped that many enigmas of the Mars plasma environment will be resolved by mid-century, which will be a step toward a manned expedition to this planet.

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Study of the atmospheres of the terrestrial planets

O I Korablev

1. Introduction

Terrestrial planets Venus, Earth, and Mars have significant atmospheres. Mercury and the Moon are considered to be atmosphereless celestial bodies, although both show traces of rarefied atmospheres. Processes in the much denser atmospheres of Venus and Mars can be directly compared to similar processes in Earth's atmosphere, and their studies are directly related to important problems such as changes to habitable conditions on Earth and the origin of life. Studies of Mars have made the most significant progress over the last fifteen years. Volatiles, water in particular, and their history, as well as serious indications of the climate changes, have mostly been studied. This report is devoted to a comparative analysis of the terrestrial planet atmospheres, with special attention to new results of Mars explorations obtained by the Mars-Express mission by the European Space Agency (ESA) with the participation of Russian scientists.

2. The formation and primary composition hypotheses

The Sun, the planets, and their atmospheres are believed to have condensed about 4.6 billion years ago (4.6 Ga) from the primeval solar nebula with a composition close to the solar one (H, He, and a tiny mixture of heavy elements). Compounds of these elements (minerals and ices) condensed and accreted into planets [1]. Atmospheres and volatiles on the planets can be relics of the primordial atmospheres, results of the collisional or gradual degasation of planetesimals, or, possibly, they could have been brought later by comets. The giant planets, which formed far away from the Sun, were capable of retaining a large amount of gas — their satellites and ring systems show the presence of an appreciable fraction of ices. The terrestrial planets consist mostly of minerals and contain only a small fraction of ices and volatiles, found in their atmospheres, in the Earth's ocean, in the polar caps, etc.

There are several hypotheses related to accretion of the terrestrial planets. According to one hypothesis [1], terrestrial planets can be formed by planetesimals collected from any part of the inner Solar system due to gravitational perturbations. Therefore, the primordial composition of volatiles on the planets should be approximately the same. Differences appeared in the course of the evolution: Mercury and the Moon either lost their atmospheres due to big impacts or their small masses proved to be insufficient to retain atmospheres. According to this hypothesis, Mars and Venus formed with the same amount of water as Earth. Depending on the amount of energy obtained from the Sun, water on the planets subsequently either froze and partially dissipated (Mars) or was virtually totally lost because of a catastrophic green-house effect (Venus). The favorable location of the Earth helped to preserve most water (Fig. 1).

Another school (see, e.g., [4]) relates the differences in the primordial composition to the distance from the Sun. The increase in the mean density of planets from Mars to Mercury lends support to this idea. According to this hypothesis, Mercury was formed only from solid minerals, Venus acquired more carbon, and water was retained only on Earth and Mars.

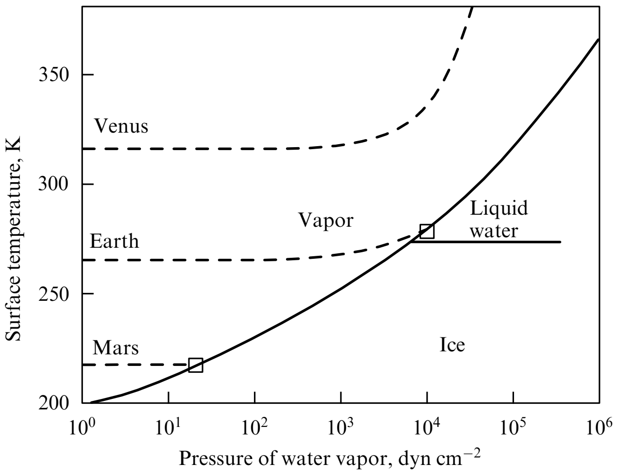

Figure 1. The simplest model of the early evolution of planetary atmospheres: gradual degasation; water accumulation and its phase transitions. The initial temperatures correspond to the effective ones (corresponding to the equilibrium between the planetary emission and incoming solar radiation). On Venus, all water remains in the atmosphere, the temperature drastically increasing due to the green-house effect. On Earth, oceans are formed; on Mars, ice and permafrost appear [3].

The primordial atmospheres could have been lost at early evolutionary stages during bombardment by progressively larger bodies (up to the size of Mars). Calculations for Earth show that almost the entire atmosphere is lost during such impacts [5]. In this case, water and volatiles had to have been brought later from outer, more quiet parts of the Solar system. The hypothesis on the cometary nature of atmospheres and the ocean was first suggested by Shmidt [6]. Modern calculations [7, 8] confirm that the amount of water sufficient to form the present ocean could indeed be accumulated due to random encounters with comets. However, Gerasimov and colleagues demonstrated [9, 10] that the mass of volatiles released during the collisional degasation can be two orders of magnitude higher than the mass of the present ocean. On the other hand, a new consideration of the mechanical aspects of the collisional interaction [11] have shown that not only the atmosphere of the Earth but also that of the impactor could be preserved during a violent encounter. This suggests that strong impacts lead not to the loss of the atmosphere but to its enrichment due to a rapid release of volatiles of the interacting bodies. Nevertheless, this does not exclude the possibility that comets could supply some volatiles at different stages of the evolution of planet atmospheres.

Thus, there is now no single explanation as to how atmospheres of terrestrial planets were formed and evolved. Most probably, different physical factors prevailed at different evolutionary stages. The abundances and isotope ratios of the 'heavy' noble gases (Ne, Ar, Xe, Kr) carefully measured under various conditions on the Earth form an experimental basis to check these hypotheses. Distant measurements of the amount of these gases are not possible and data obtained on the surfaces of Mars and Venus by mass-spectrometers have not been accurate enough. The measured abundances of noble gases on planets, which are very different from that on the Sun and in meteorites, formed the basis of many studies of their accumulation mechanisms, losses, and isotope fractioning (see, e.g., [12]). These abundances are virtually inconsistent with the total or partial lost of atmospheres during their formation [13] and are in better agreement with the dissipation hypothesis than with the idea of differentiation as a function of the distance from the Sun [14].

3. The present state, estimates of initial reserves, and dissipation mechanisms

The simplest model of the early evolution (see Fig. 1) ignores many factors. For example, to estimate the effective temperature, one should take the luminosity change of the Sun into account. The formation of planets occurred when the Sun settled on the main sequence of the Hertzsprung–Russell diagram. At that time, the solar luminosity should have been 30% smaller than its present value, but there are opposite estimates. As mentioned above, comets, which apparently replenished the resource of volatiles during evolution, served as external sources. Some volatiles are adsorbed by rocks or enter into their composition and participate in chemical reactions. Atmospheric circulation, clouds, and other gases also have an effect on the temperature of a planet. Finally, the dissipation of volatiles plays a decisive role.

Table 1. Some characteristics of the terrestrial planets.

Planet	Mean distance from the Sun, a.u.	Mass in units of the Earth	Surface pressure, bars	Surface temperature, K	Principal atmospheric gases	Green-house effect, K
Mercury	0.39	0.052	10^{-16}	440	Na, He	0
Venus	0.72	0.81	92	735	CO_2, N_2	500
Earth	1	1	1	289	N_2, O_2, (CO_2, H_2O)	39
Mars	1.52	0.11	0.006	214	CO_2, N_2, (H_2O)	4

Table 2. Principal atmospheric gases and reserves of volatiles on the terrestrial planets*.

Planet	Pressure, bar	CO_2	N_2	Ar	H_2O	D/H relative to the Earth
Mercury	10^{-16}	—	—	7 %	—	—
Venus	92	96.5 %	3.5 %	70×10^{-6}	$30-100 \times 10^{-6}$	146
Earth**	1.013	370×10^{-6}	78 %	0.934 %	< 3 %	1
Mars [11]***	0.0061	95.3 %	2.7 %	1.6 %	$< 100 \times 10^{-6}$	6

* Data from [10] with changes.

** The H_2O equivalent in the oceans and glaciers on Earth is 270 bar, the CO_2 and C equivalent in the crust is 53 bar.

*** In the polar caps on Mars, the CO_2 and C equivalent is 20 bar, the H_2O equivalent is 30 bar (upper limits).

The modern state of atmospheres is a result of their diverse development accounting for all the above factors. The principal data on atmospheres of the terrestrial planets are collected in Tables 1 and 2. The atmospheres of Mars and Venus mainly consist of CO_2, while on Earth this gas is totally bound in carbonates of the crust. The total amount of volatiles, which is quite accurately estimated for the Earth, is almost completely unknown for Mars. On Mars, water and carbonic acid ices are stable in the polar caps and in the soil (see below); one can also assume that there are deposits of carbonates, although no significant amount of them has been discovered. The initial ocean depth on Mars of 0.5 – 1 km ($\sim$ 30 bars) was inferred from indirect evidence for the existence of liquid water on Mars in the past, including geological facts (the size and number of channels, etc.) [16]. One may only assume that the amount of volatiles on Venus was initially about the same as on Earth.

Atmospheric evolution can be evaluated by considering the selective dissipation of isotopes with different masses. Masses of hydrogen isotopes are mostly different, and the ratio D/H, which in contrast to the noble gases can be measured by distant spectroscopy, is used as a convenient indicator. The D/H ratio on Earth is 10 times as large as the cosmic value. The assumption that such a fraction appeared at an early stage of planet formation implies that no selective dissipation occurred on Earth, Mars lost an appreciable amount of water ($D/H \approx 6(D/H)_{\mathrm{Terr}}$, see Table 2), and Venus lost almost all its water ($D/H \approx 150(D/H)_{\mathrm{Terr}}$). An extremely high D/H ratio on Venus has been very reliably measured by both a landing probe [17] and ground-based spectroscopy (see, e.g., [18]). The D/H ratio measured now on three comets is two times greater than Earth's value [19]. This does not exclude the cometary origin of water on planets because the measured values of D/H relate to comets from remote parts of the Solar system and volatiles were most probably brought at early stages by comets from the Jupiter zone.

Obtaining the simplest quantitative estimates (multiplying the modern water content by the factor D/H or greater, considering dissipation D) is not easy, because the present water content (for example, for the crust and polar caps on Mars), the balance between various dissipation mechanisms, and the factors affecting them are poorly known.

We consider the principal *dissipation mechanisms*. The classical *theory of thermal dissipation* is as follows: above a certain level, called exobase (500 – 600 km on Earth), atoms with the speed exceeding the second cosmic speed (11.2 km s^{-1} for Earth) leave the atmosphere. This theory explains the absence of atmospheres on Mercury and asteroids, the deficit of light elements (H, He) in atmospheres of terrestrial planets, and their abundance in atmospheres of giant planets. However, it encounters strong difficulties when a great amount of material needs to be 'expelled': the dissipation occurs only from the exobase level, where the atmospheric density is very small. The exponential dependence on the mass of the atmosphere (the effect is proportional to $\exp\{-GMm/kTr\}$) cannot explain the almost identical abundance of noble gases while their atomic masses increase by six times from Ne to Xe. Finally, the thermal dissipation predicts a stable nitrogen atmosphere on the Moon.

To bring theory into agreement with observations, one should assume that other mechanisms dominated at least at some periods during evolution. As discussed above, collisions of planetesimals and *bombardment* can both destroy and replenish atmospheres. Atmospheres of Earth and Venus have most probably sustained impacts, but the fate of Mars is not completely clear. For Mercury, any strong impact would be fatal, but water resources there could be replenished due to collisions with comets.

Therefore, to explain the ratio $D/H \approx 150(D/H)_{\mathrm{Terr}}$ on Venus, other mechanisms should be invoked. It is assumed that a *hydrodynamic removal* of volatiles prevailed at early stages [13]. In this mechanism, a strong outflow of a light gas

(H, H_2, and even CH_4) catches heavier atoms and molecules with an efficiency that depends linearly, not exponentially, on the mass of particles. This is consistent with the observed abundances of noble gases. However, to produce a sufficiently strong hydrogen outflow from Venus (or Earth), it is necessary to destroy the corresponding number of water molecules. Photodissociation is effective for an ultraviolet (UV) illumination with wavelengths shorter than 1000 Å, which corresponds to $\sim 10^{-5}$ fraction of the present spectral power of the Sun. One can assume that on the early Sun (before ~ 4 Ga), the UV radiation power was 100 times greater than now, for example, as in the case of a young T Tau star. However, whether such a powerful outflow of the gas-carrier actually took place in the history of planets remains an open issue.

The principal modern mechanism whereby planets lose their atmospheres is nonthermal dissipation. It occurs due to collisions of atoms and molecules in the atmosphere (mainly of ionized oxygen) with high-energy particles of the solar wind and with captured, accelerated ions. This mechanism is being investigated by one of the experiments on board the Mars-Express space mission [19].

Theoretical models of early atmospheres are speculative as yet. Possibly, a warm climate on Earth and Mars in combination with weak solar irradiation (the so-called dim early Sun paradox [21]) had been provided by the green-house effect in the atmospheres enriched by carbon dioxide with a small admixture of water vapor [22]. This model was first proposed by Mukhin and Moroz [23, 24], and only later was considered by western authors (see, e.g., [25]). The green-house effect plays an enormous role in the modern climate on Earth by maintaining the mean temperature 38 K above the effective one. A weak green-house effect is also present on Mars (≈ 4 K).

It is possible that a hypertrophic, *nonstationary green-house effect* formed the present view of Venus [26], which receives two times as much energy from the Sun as Earth. When H_2O evaporates in a CO_2 atmosphere, a positive feedback emerges, which leads to total evaporation (evaporation of Earth's oceans would produce 270 bars of water vapor). The temperature rises catastrophically, the dissociation of water vapor and loss of volatiles occur, and the hydrodynamic removal mechanism is possibly at work. As the UV-radiation from the Sun decreases, hydrodynamic removal stops, atmospheric cooling results in cloud condensation, and the formation of a liquid ocean becomes possible. Further dissipation of water is determined by thermal and nonthermal mechanisms; the depth of such a hypothetical 'ocean' can be estimated through the D/H ratio, which yields at least 30 m. Considering deuterium losses, this depth could be much larger (see above). The present temperature of 735 K on the Venusian surface is maintained by a stationary green-house effect. Furthermore, the cloudy layer is important, and the atmospheric circulation can contribute as well. Thermal radiation leaves the planet only through several 'transparency windows' between the main absorption bands of CO_2. Models indicate that the thermal balance is mainly determined by the abundance of water vapor and other minor components (for example, SO_2) filling the 'transparency windows' [27] (Fig. 2). A very young surface suggests that the surface temperature had reached the melting point at the age 0.6–1.1 Ga. A reason for this could be an impact with a comet or a massive ejection of volcanic gases. However, the models involve many assumptions and it is not possible to reliably decide whether the green-house effect is sufficient to maintain the surface temperature at the 735 K level.

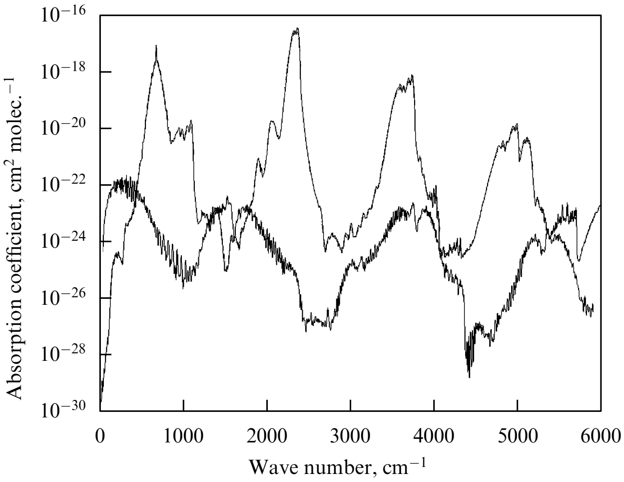

Figure 2. The model of radiation transfer in the Venus atmosphere. The spectrum of the absorption coefficient is shown. The upper curve is for CO_2, the bottom curve is for H_2O and other admixtures [28].

4. Studies of the atmosphere of Venus

The dense opaque atmosphere makes Venus an ideal object for cosmic research [30]. The first successful flight to Venus was performed by the US in 1962: the spacecraft Mariner-2 carried out a radar probing that confirmed a high surface temperature of the planet. Later on, Venus was most successfully studied by the USSR. In addition to 13 landing modules, four orbital satellites were launched. Atmospheric studies were most completely carried out by the Venera-9–Venera-13 landing spacecrafts (the complex of devices to study atmosphere and clouds), and by the satellites Venera-15 and Venera-16 (the Fourier-spectrometer, atmospheric circulation). The exploration of Venus by the USSR was completed by the very successful Vega mission (to Venus and Halley's comet, 1985), during which two landing modules and two aerostats were launched into the atmosphere; for the first time, they directly measured the temperature and pressure along the flight path in the cloudy layer at the altitudes 45–50 km. Vertical pulsations of the wind (convective motions) were also measured for the first time.

The Pioneer-Venus missions (1978; three landing modules and a satellite) and the radar-satellite Magellan (1989), which made the surface imaging of Venus with a greater accuracy than obtained earlier by Venera-15 and Venera-16, were the most important stages of the exploration of Venus by the US.

We list the principal data on the atmosphere of Venus [32–34]. The total mass of the carbonic acid (97% of CO_2) atmosphere is $\sim 10^{-4}$ of the planet's mass and about 100 times greater than Earth's. In addition to CO, O_2, SO_2, COS, HCl, and HF listed in Tables 1 and 2, noble gases Ar, Ne, Kr, and Xe are minor constituents of the Venusian atmosphere. The planet has anomalous (more than the relic on the Earth) isotope ratios of the noble gases. There is very little water, not more than 0.003 %; the D/H ratio is 150 times greater than on Earth.

The planet is covered by a thick cloud layer with a high albedo (0.76). The effective temperature of Venus is

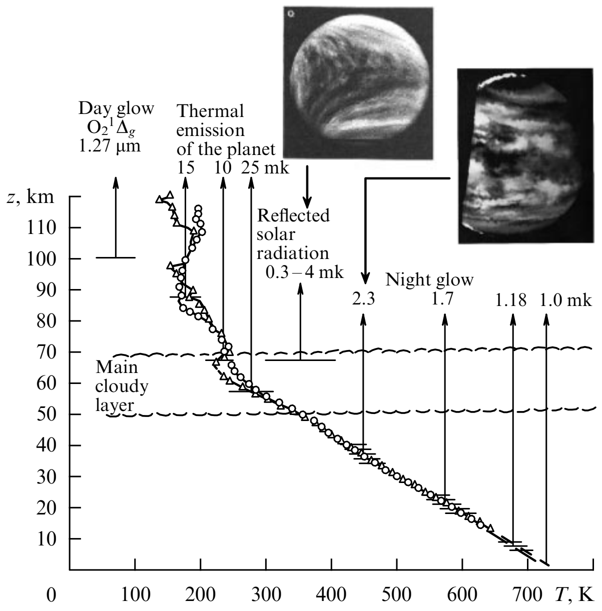

Figure 3. Vertical temperature profiles in the Venusian atmosphere measured by landing modules [32]. Shown is the location of the level $\tau \sim 1$ for radiation emitted by the planet at different wavelengths. The measurements at the latitudes 30° and 60° are shown by white circles and triangles, respectively. The profiles at different latitudes measured at different times of the day are very close. The UV (350 nm) image of Venus corresponding to altitudes of 70 km (the upper boundary of the cloud layer) and the near-IR image of the undercloud layer obtained by the Galileo probe [35] are also presented.

$T_e = 235$ K, but the surface temperature, determined by a huge green-house effect (see above), reaches 735 K. The temperature gradient is virtually independent of the altitude below 60 km and is close to the adiabatic value. In the bottom atmosphere, there are neither daily nor seasonal variations; temperature profiles at different latitudes are almost indistinguishable (Fig. 3). The reason for this is the big thermal inertia of the atmosphere. Near the poles, thermal radiation increases; at the altitude 60 – 65 km, a 'cold' collar is observed that separates a 'hot' polar dipole from low latitudes.

A superrotation is observed on Venus: the atmosphere (above the 50 – 60 km level) rotates with the period ≈ 4 days in the same direction as the solid body of the planet (the rotation period is 243 d). The superrotation was discovered by ground-based near-UV observations. The motion of clouds with the velocity 100 m s^{-1} and planet-sized waves are observed on shots taken by spacecraft in the UV range (see Fig. 3). Although the superrotation was predicted theoretically [36] and justified by numerical models of the atmospheres of Venus and Titan, the mechanism forcing the atmosphere to rotate is not completely known. The energy is supplied by dissipation of thermal tides, which consume $\sim 50\%$ of the Solar energy absorbed by Venus in the upper cloud layer at altitudes 60 – 70 km. The albedo of clouds in the UV-optical range is determined by an absorber of unknown composition; the nature of the observed UV contrasts is also unclear; possibly, these are sulfur allotropes.

It is also unclear how the angular momentum from the surface is transferred. Thermal probing by Venera-15 and Venera-16 confirmed that the meridional circulation is organized in the form of Headly cells. Air masses rise from the equator and move toward high latitudes against the pressure gradient near the upper boundary of clouds; here, the temperature increases with the latitude. They bring the angular momentum into middle latitudes. The reverse branch probably lies below the 60 km altitude, where the latitude thermal gradient changes sign. It is unknown how the circulation beneath the clouds is organized and whether Headly cells also exist there [32].

The thermal and reflected emissions of the planet are formed at the 60 – 70 km level. The thermal radiation of the under-cloud atmosphere passes through the cloudy layer in the 'transparency windows' (see above) between the CO_2 bands at wavelengths 1, 1.4, 1.7, 2.3, and 3.7 μm; it can only be observed on the nightside of the planet. Its spectrum bears information on the minor constituents at different levels. For the first time, the night radiation of the atmosphere in the near IR range was discovered by balloon experiments in the Vega project. Later on, this radiation was detected by ground-based observations [28] and during the Galileo flyby (see Fig. 3). The ESA space mission to Venus, Venus-Express (to be launched in October 2005), will study this glow from orbit for the first time, which will provide the global information on the deep atmospheric layers. The payload of the Venus-Express spacecraft includes devices designed and manufactured by European and Russian scientists from the Space Research Institute (IKI).

Venus, together with Mars, is one of the solar system's planets whose study is most important to understand the future of Earth. Key questions to answer include the origin of Venus and its atmosphere, the fate of water, and a possible period in the early history of Venus with a colder climate and liquid water on the surface. It is necessary to estimate the stability of the present green-house effect, the role of the cloud layer, and the possible contribution of dynamics. This planet now turns out to be almost forgotten: Venus-Express will fly to it after more than a 15-year hiatus. In the past, the exploration of Venus was the only field of fundamental cosmic research in which our country had an indisputable priority. Russian industry accumulated unique experience in constructing landing modules for the Venus explorations. A project stipulating a landing on Venus, to be launched in 2016, is included in the Federal space program. Modern mass-spectrometers and other devices on board the landing module will allow carrying out key measurements of isotopes of noble gases near the surface, to investigate the cloudy layer, to measure the distribution and composition of particles, and to elucidate the nature of the UV-absorber. Additional studies using several balloons will be performed. Each balloon can carry several mini-probes to study different places on the surface. The mission should include an orbital module for data transmission. We believe that Venus can and should become the aim of the long-term research program of Russia.

5. Studies of the atmosphere and volatiles on Mars

Much is known about Mars from ground-based observations. For example, water vapor in the atmosphere [37] and the bounded water in the soil and water ice of the north polar cap of the planet [38] were discovered from the Earth. Using high-resolution spectra, the first realistic estimates of the near-surface pressure were obtained, the presence of CO and O_2 was discovered. However, 'the canals' had been present on maps of Mars until the first cosmic images were obtained. The US leads in space explorations of Mars. The Mariner-9 spacecraft (1969) greatly contributed to the study of the atmospheric composition due to high-quality UV and IR spectral observations. About 80% of the planet's surface was mapped. The greatest breakthrough in the Mars explorations over the entire space epoch was made by the Viking project (1976; two satellites around Mars and two landing modules). The apparatus had a record-long lifetime. For example, the Viking Lander-1 operated on the Mars surface more than six years. Distant observations have been carried out for more than two Martian years. Based on the great amount of observational data, a picture of the modern climate on Mars, called 'the Viking climate', was constructed [22, 39].

In the USSR, the Phobos project was an important landmark in the Mars explorations. Although the landing on Phobos failed, for two months in 1989, the Phobos-2 orbiter did more than all previous Soviet missions. For example, pioneer data were obtained on the vertical distribution of H_2O and aerosols in the atmosphere [40, 41]. Then the period of big failures began. The NASA Mars Observer orbiter (1992) with various scientific payload perished when approaching Mars. A more ambitious Russian project, Mars-96 (550 kg scientific payload, two small stations, two penetrators) failed at the initial stage: the spacecraft was not launched in the interplanetary trajectory due to failure of the acceleration unit of the rocket. This accident hampered the Russian planetary program for many years. In the US, the various scientific devices on board the Mars Observer mission were switched on and operated alternately (despite the intensity of the American program, some experiments on board Mars Orbiter have not been performed). A significant step in the exploration of Mars was made due to the Mars Global Surveyor (MGS) mission (1996) with devices analogous to those on board Mars Observer: a Fourier-spectrometer TES, a television system, a laser altimeter, and a magnetometer. MGS is still working on orbit around Mars. Data obtained by TES allows monitoring the temperature, dust, condensation aerosols, and water vapor profiles over more than three Martian years [42]. The laser altimeter for the first time allowed high-precision measurements of the shape of the planet and its global asymmetry (the southern hemisphere is higher than the northern one) [43]. The data taken by the magnetometer enabled determining the residual magnetization of the Martian crust [44]. After the series of failures, the Mars Odyssey mission (2001) brought to Mars the gamma-spectrometer originally installed on board Mars Observer. Discoveries made using this device and the simultaneously operating neutron spectrometer HAND, including the discovery of water in the uppermost (1 – 3 m) layer, are widely recognized. The frozen water content amounts to 35 – 50% in the polar regions and to 5 – 10% in some regions near the equator [45, 46].

We list basic facts on the Mars atmosphere. In addition to the principal gases listed in Tables 1 and 2, CO, O_2, O_3, H_2O_2, He, Ne, Kr, and Xe were discovered in the atmosphere. The mean surface temperature is around 210 K; large daily, latitudinal, and seasonal temperature variations are observed: from 145 K (the polar night) to 290 K (on the equator in the afternoon). The mean atmospheric pressure is about 6 mbars (depending on the altitude of the place). Long-term observations by the Viking landing modules revealed big seasonal, latitudinal, and daily variations in parameters [47]. The seasons on Mars are similar to Earth's, but the seasonal cycle is complicated by a larger orbital eccentricity: the southern summer is much warmer than the northern one. During the winter time, CO_2 condenses in the polar caps; up to 25% of the atmosphere periodically transits to the condensed phase. This estimate follows from models of the general circulation based on seasonal pressure variations and is confirmed by the laser altimeter data. The high-energy neutron spectrometer HAND also enables evaluating the thickness of the solid CO_2 layer screening the hydrogen-rich layer [48]. The polar caps on Mars are strongly asymmetric: the North polar cap is significantly larger than the South one and consists mostly of ice. The seasonal water cycle is also asymmetric. Clancy [49] argued that this asymmetry is explained by the effect of condensation clouds, which are observed on the equator at the aphelion passage during evaporation of the North polar cap and prevent water transfer into the southern hemisphere; this hypothesis is confirmed by numerical simulations [50] (Fig. 4).

Sometimes at the perihelion passage, the whole planet can be covered by dust clouds. During this period, a positive feedback emerges between the advection of dust absorbing solar radiation and the circulation intensity of the Headly cells. The global dust storms on Mars have no analogs on Earth. The origin of the vertical transport of dust is unclear; it is possibly related to the sublimation of polar sediments.

Liquid water on Mars is unstable, although (and, most probably, not accidentally) the pressure and temperature are close to the triple point and the formation of short-lived water streams is possible [52]. Almost all water is found inside the soil in the form of ice. The dispute between geologists of whether the climate on Mars was warmer in the past and a terrestrial-like hydrosphere existed is cyclically renewed. After the frustration caused by the first pictures of Moon-like landscapes taken from spacecrafts flying by, Mariner-9 and Viking provided opposite clues: river-beds, valleys, and channels were clearly seen [16, 22, 53]. The measurements of the ratio $D/H = 5.5\,(D/H)_{\mathrm{Terr}}$ also confirmed this [54]. Later, river-beds and channels, in particular on the grounds of their form and cross profiles, have been more often interpreted as the result of glacial activity. Recent data taken by the laser altimeter [55] confirmed the hypothesis on the existence of an ancient ocean in the northern hemisphere. Traces of streaming water were found at the landing place of Pathfinder (1997), and the Spirit and Opportunity rovers discovered minerals for whose formation liquid water is prerequisite [56]. The last discoveries were made by the Moessbauer and alpha-X-ray spectrometers manufactured with the participation of Russian scientists. The prototypes of these devices were installed on small stations of the Mars-96 mission.

6. First results obtained by the Mars-Express mission

The ESA spacecraft Mars-Express has operated on orbit around Mars since January 2004. The realization of the Mars-Express project as a successor to the Russian Mars-96 spacecraft is the greatest success of European and Russian planetary science. The scientific payload on board the spacecraft includes seven devices: the TV-camera HRSC for stereometric imaging of the planet surface with a resolution of 10 m (from a distance of 250 km); the spectrometers OMEGA, PFS, and SPICAM; the neutral gas and plasma analyzer ASPERA [20]; the long-wavelength radar MARSIS; and the radio-sounding experiment MaRS. The experiments of Mars-Express repeat those planned to be performed by the

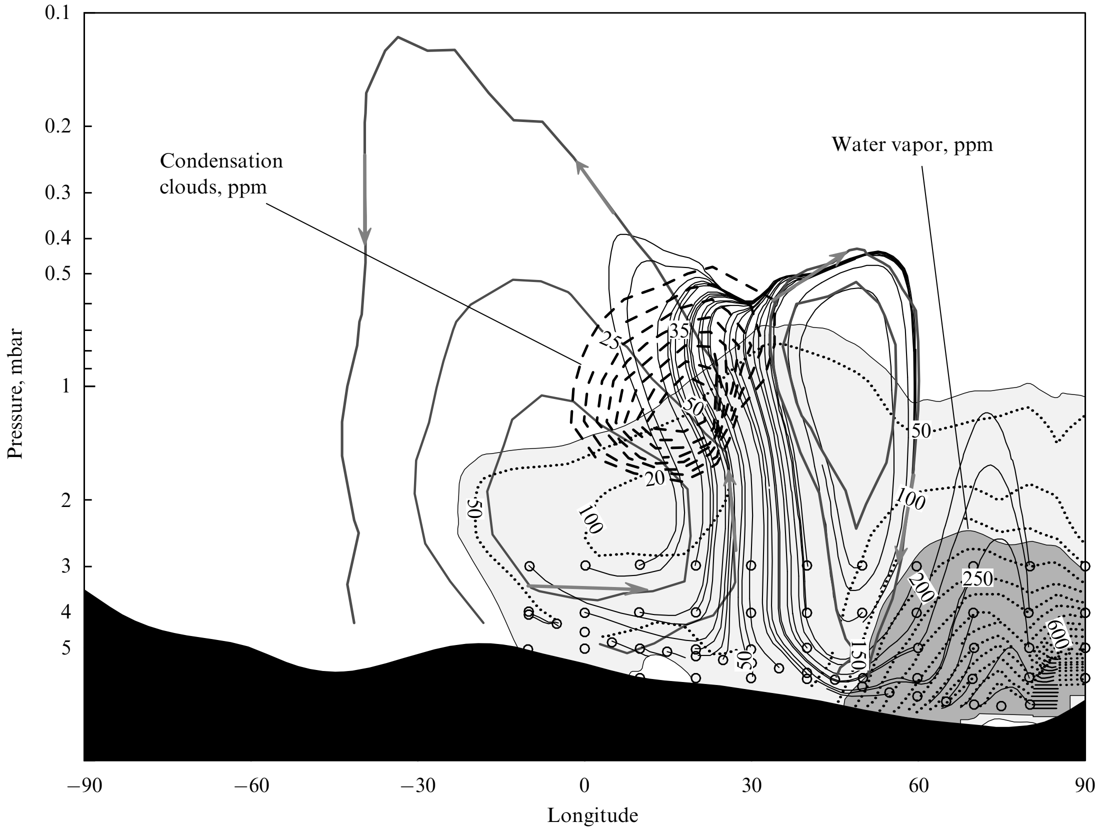

Figure 4. Modeling of water vapor in the Mars atmosphere [50]. Stream lines (transport) of water vapor (the solid curves) at the aphelion season (summer in the northern hemisphere) are shown. The relative content of water vapor is shown by grey scale, the condensation clouds are shown by the dashed contours (ppm — parts per million). Calculations are made using the general circulation model GFDL [51].

'Mars-96' project; the double device is even used in the OMEGA experiment. Despite all the preconditions, Mars-Express did not become a joint ESA – Roskosmos project. European scientists are the project leaders of all experiments; in six experiments, Russian scientists participate as co-investigators.

For three spectrometers, OMEGA (the mapping spectrometer operating in the wavelength range 0.5 – 5.2 μm with the spatial resolution 0.3 – 5 km), PSF (high-resolution IR Fourier-spectrometer in the wavelength range 1.2 – 40 μm with the resolution 1.4 cm^{-1}), and SPICAM (the universal UV-IR spectrometer to carry out measurements in the nadir and during eclipses of the Sun and stars), Russia supplied some important units: the OMEGA scanner, PSF detectors, and one of the two measurement channels of SPICAM — the near-IR spectrometer on the base of an acousto-optic filter (1.0 – 1.7 μm, spectral resolution 3.5 cm^{-1}) [57].

The mutually complementing measurements by the spectrometers manufactured with the participation of Russian scientists have already provided important results, many of which are being prepared for publication. The high-precision measurements of the atmospheric structure in an unprecedentedly broad range of altitudes, including the 100 – 150 km altitudes, where the braking of the spacecraft takes place, allowed studies of the distribution and properties of clouds and aerosols. The PSF device enables simultaneously restoring the temperature profile in the atmosphere up to 50 – 55 km, measuring the dust content, and detecting clouds. The atmosphere above the North polar region at the beginning of winter is being studied [58]. For the first time, the water vapor and ozone content in the atmosphere are being measured and mapped. Water vapor is measured by PFS and SPICAM in the IR, ozone is measured in the UV (SPICAM) and by the glow of $\mathrm{O}_2^1\Delta_g$ at 1.27 μm (Fig. 5). The glow emerges during the photodissociation of ozone above 15 – 20 km. It has been detected in spectra taken by all three experiments, with a high spectral resolution in the SPICAM and PFS experiments and with a high spatial resolution in the OMEGA experiment. The images taken by OMEGA at the 1.27 emission band exhibit a wave structure; similar waves are observed in the images of H_2O- and CO_2-ice clouds. These could be gravitational waves, so clearly observed for the first time. SPICAM detected a night glowing of NO, which is typical in the atmosphere of Venus but has not been observed earlier in the atmosphere of Mars [59]. There is no place here to comment in detail on these results. We comment only on two of the most exciting discoveries.

For the first time, ice has been detected in the permanent South polar cap at the end of the Martian summer. Polar caps on Mars consist of two parts — seasonal and permanent. The seasonal part, the CO_2 condensate, grows during autumn and winter and disappears during spring. The nature of permanent caps preserved near the poles even during summer is less clear. The permanent North polar cap is warmer and apparently consists of ordinary ice. The low temperature of the permanent part of the South polar cap has suggested CO_2 ice, but no direct confirmations have been made until recently. The direct proof was provided by the IR-spectrometers onboard Mars-Express. Spectra taken in all three experiments revealed the presence of absorption bands of

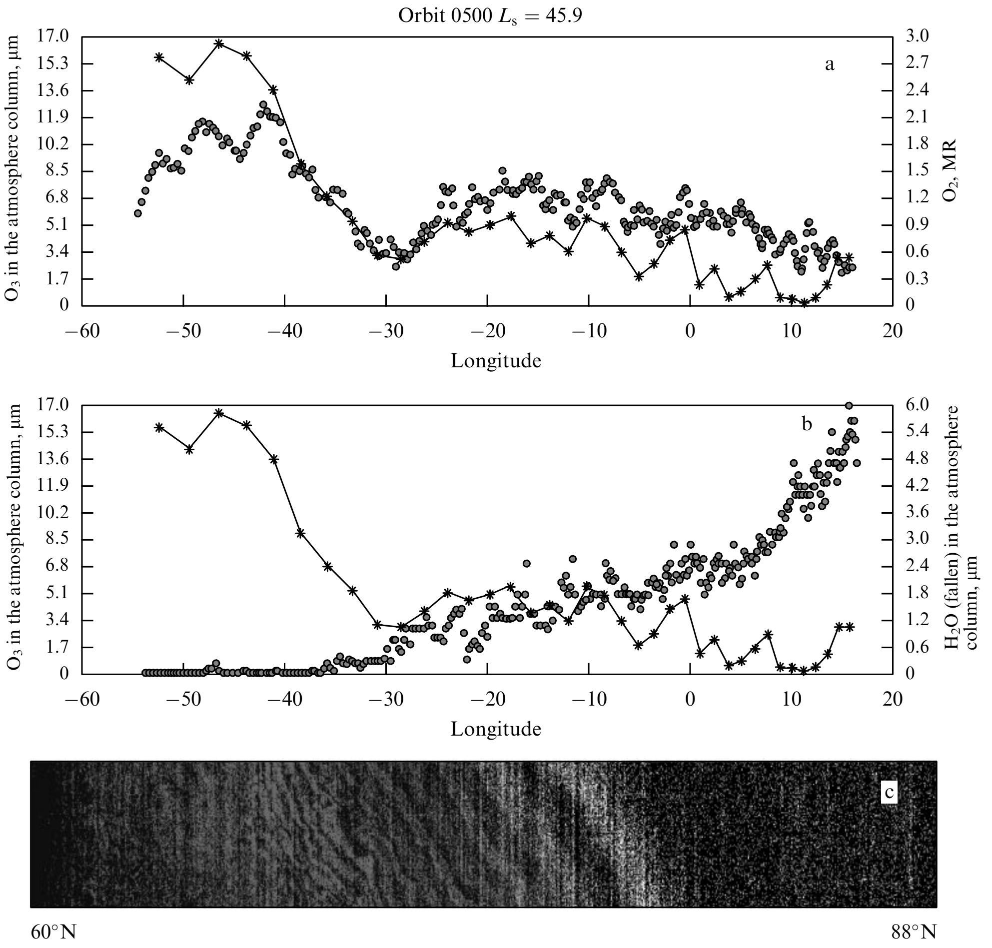

Figure 5. (a) Measurements of ozone along the orbit of the SPICAM experiment. The UV (200 – 300 nm) measurements are shown by the solid line, the $O_2^1\Delta_g$ band glowing at 1.27 μm is shown by dots. (b) The ozone – water vapor anticorrelation. The UV measurements of ozone are shown by the solid line, the content of water vapor measured by the 1.38-μm band (SPICAM-IR) is shown by dots. (c) The emission in the $O_2^1\Delta_g$-band in northern latitudes. Data from the OMEGA experiment.

the CO_2 ice. The CO_2 ice includes some admixtures of ice and dust grains (Fig. 6); the distributions of ice and dust are spatially inhomogeneous. The maps constructed by OMEGA with a resolution of 1 – 3 km indicate that the H_2O ice is located around the edge of large areas of the CO_2 ice [62]. In combination with the analysis of the MGS images [63], these data allow concluding that the thickness of the CO_2 ice does not exceed several meters [64]. Studies of the permanent North polar cap at the end of 2004 (after the summer solstice) confirmed that it consists of water ice and allowed tracking the ice grain growth with time. It is established that the dust contamination of the ice is insignificant ($\ll 1\%$) [65]. The OMEGA experiment performed the mineralogy mapping of a significant area of the planet and, despite the great variety of the mineral composition, no carbonates were detected. Thus, the data from Mars-Express do not confirm the presence of a significant storage of CO_2 on Mars.

After long fruitless attempts, *methane was detected in the Mars atmosphere* practically simultaneously by three independent groups. The planetary Fourier-spectrometer (PFS) has a high spectral resolution, which allows detection and measurements of the distribution of minor constituents in the Mars atmosphere. The mean methane content 10 ± 5 ppb (parts per billion) [66] was measured, which confirms astronomical data [67] that appeared somewhat earlier. The PFS measurements imply the various content of CH_4 in different regions of Mars from 0 to 330 ppb, and such a variability is confirmed by astronomical observations [68]. This content is small, but because methane is permanently destroyed in the atmosphere by photodissociation, a methane source providing ~ 300 t per year should be assumed [67]. It is difficult to explain the existence of such a source by abiogenic processes (residual volcanism, geothermal activity, etc.), because the IR-imaging spectrometer THEMIS (onboard the Mars Odyssey mission), specially designed to search for 'hot points', has detected none. The methane of cometary or meteorite origin can provide only from 2 to 4% of the necessary supply. Methanogenic bacteria like those found in deep underground ecosystems of Earth could be the source. Their existence on Mars is possible at the lower boundary of the cryosphere (> 2 km), where gas-hydrate deposits could be formed [69].

7. Conclusion

Did an 'epoch of warm Mars', single or multiple, actually take place in the history of Mars? With the measured water abundance in the sub-surface layers on Mars, apparently, carbonates should have been formed. Why have they not been detected so far? And if a warm and wet period indeed took place on Mars in the past, living organisms could have been formed there. The ESA program Mars-Express is aimed at

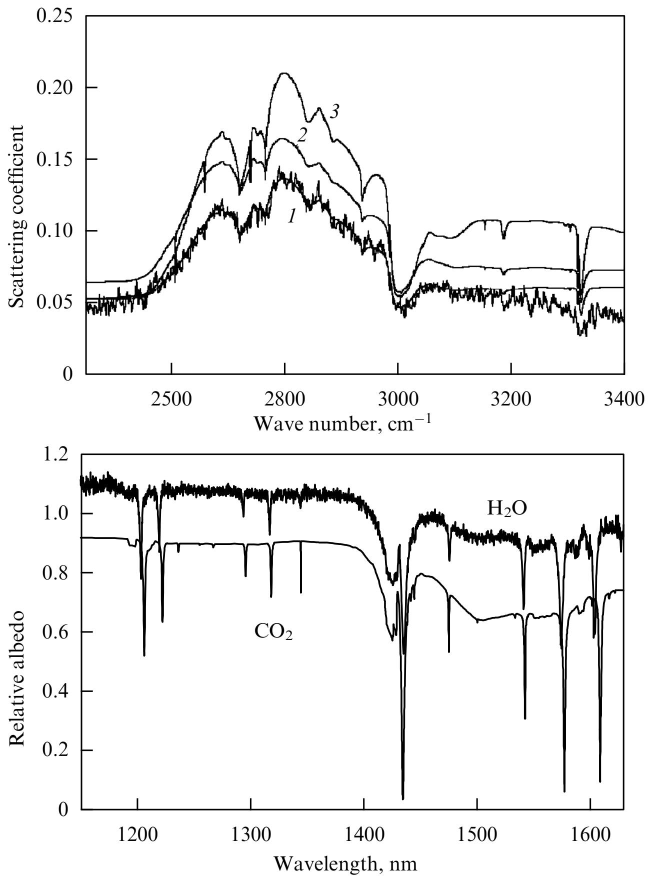

Figure 6. The spectra of the residual South polar cap obtained by PSF (Russian detectors) and the SPICAM IR-spectrometer (manufactured at IKI) revealing CO_2 ice with an admixture of dust and H_2O ice [60, 61]. Three synthetic spectra are shown corresponding to three different orbits; the measured spectrum is also presented for case 1. The fraction of the surface area not covered with ice changes from 0.14 to 0. The dust content is 0.005 – 0.05%, H_2O ice content is 0.0009 – 0.0025%. The size of CO_2 grains changes from 2 to 5 mm. The SPICAM spectrum is shown in comparison with that of CO_2 ice with an admixture of water and dust.

solving these problems. Mars-Express measurements do not confirm the presence of permanent lakes and oceans on the Mars surface later than 3 Ga. Carbonates that could absorb a dense CO_2-paleoatmosphere have not been detected either, and deposits of CO_2 in the polar caps are seemingly small. It appears that Mars lost its atmosphere at an early stage and the green-house effect could operate only for a short time. Instead, an appreciable amount of water has been preserved in the polar caps and in the soil. The Mars-Express radar, to be switched on in May 2005, will allow probing deep underground layers. The discovery of methane is sensational: it suggests the existence of living organisms or undiscovered volcanic activity.

The evolution of climate on Mars is significantly different from that on Earth. What is the fate of our planet in the future? Is there a possibility that it will become the second Venus or, like Mars, will lose its atmosphere? Finding answers to these questions is one of the tasks of future Venus and Mars explorations.

The participation of Russian scientists in the Mars-Express mission and the NASA projects has enabled Russia to preserve the school of planetary studies in the absence of national projects. The preparation of the Phobos-Ground mission is now renewed in Russia. This mission also envisages climatic monitoring and atmospheric measurements from orbit. The policy of using Russian devices in space projects of other countries remains a possibility as well.

The report is devoted to the memory of V I Moroz, who was the head of the department of Physics of Planets of the Space Research Institute (*IKI*) *of RAS for 30 years, and was the principal investigator of the Mars-96 project and Mars-Express mission* (*in Russia*). Materials by Moroz were used in preparing this report. The author thanks L V Zasova, L M Zeleny, A V Rodin, and A V Zakharov for assistance. The design and manufacture of Russian elements of the Mars-Express scientific payload were supported by Roskosmos. The participation of Russian co-investigators in the Mars-Express mission is supported by ESA, CNRS, CNR, and DLR; the work on data processing in IKI is supported by the RFBR grant 04-02-16856a.

The Mars-Express experiments with the participation of Russian scientists, project leaders, and members of the Russian teams:

ASPERA: G Lundin — project leader, S Barabash (Institute of Space Physics, Kiruna, Sweden), A O Fedorov, E Yu Budnik (IKI RAS);

HSRC: G Neukum — project leader (DLR, Berlin, Germany), A T Basilevsky (GEOCHI RAS), B A Ivanov (IDG RAS), R O Kuz'min (GEOCHI RAS);

MARSIS: G Picardi — project leaders (University La Sapienza, Rome, Italy), N A Armand, V M Smirnov (IRE RAS);

OMEGA: J-P Bibring — project leader (IAS/CNRS, Orsay, France), V I Moroz, V A Kotzov, L V Zasova, D V Titov, N I Igantiev (IKI RAS);

PFS: V Formisano — project leader (IFSI/CNR, Rome, Italy), V I Moroz, L V Zasova, N I Ignatiev, I V Khatuntsev, D V Titov, A P Ekonomov, B E Moshkin, A V Grigoriev, Yu V Nikolsky, V N Gnedykh, D V Patsaev, A V Kiselev (IKI RAS);

SPICAM: J-L Bertaux (Service d'Aeronomie/CNRS, Verrieres-le-Buisson, France), O I Korablev, V I Moroz, A A Fedorova, A.V. Rodin (IKI RAS).

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A ‘wild surmise’ [1]: first results from the Huygens probe into Titan’s atmosphere

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1. Introduction

On January 14, 2005, a dream that first captured our imaginations in 1982 was brilliantly realized: a European-built probe delivered by an American orbiter landed safely on the surface of Saturn's giant satellite Titan after a seven-year journey from Earth. Obviously, it is too soon to know everything that the extensive data set acquired by the probe will reveal. This brief and preliminary report summarizes the reasons Titan was chosen for such intensive study and gives some of the highlights that the various experiment teams have presented after the first weeks of analysis.

2. Why Titan?

Titan stood out as a goal for intense exploration because of its thick, intriguing atmosphere. The first hint that an atmosphere was present came from visual observations of limb darkening reported by the keen-eyed Catalonian observer Comas y Sola [1], and was established beyond doubt by G P Kuiper's [2] observations of absorption bands of methane in Titan's spectrum. However, it was the Voyager flyby in 1980 that did establish this satellite as a prime target for exploration by demonstrating that the atmosphere was mostly nitrogen, had a surface pressure of 1.5 bars, and harbored an active photochemistry that produced numerous organic molecules in the upper atmosphere, leading to dense layers of smog. Among the products of this photochemistry was HCN, an important compound in the reactions expected to precede the origin of life on Earth.

The photochemical smog prevented the Voyager cameras from seeing the satellite's surface. Titan, being bigger than Mercury, has the consequently largest unexplored surface in the solar system. This surface was expected to include drifts of precipitated aerosols and lakes, seas, and rivers of liquid hydrocarbons, participating in the equivalent of a hydrologic cycle. The photochemical destruction of methane meant that there must be an internal source to replace it, and therefore the surface might have fissures, geysers, or possibly even volcanoes to enable this degassing to occur. Unless, of course, we just happened to come on the scene when the last relic of an earlier much larger consignment of methane was about to disappear. At 1.9 gm cm^{-3}, the density of Titan indicated it was composed of 50% rock and 50% ice by mass, just like its similar-size cousins in the Jupiter system, Ganymede and Callisto. The rock should contain potassium, and the radioactive isotope of that element produces ^{40}Ar , as it does on

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[1] The title comes from the sonnet by John Keats: “On First Looking into Chapman's Homer”. Professor David Southwood, ESA Chief Scientist, read this passage with great feeling at the Press Conference celebrating the success of the Huygens mission. Southwood suggested that we were suddenly seeing a new world, like the European discoverers of the Pacific Ocean in Keats's poem.