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Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation "State of the art and prospects of solar system research" (26 January 2005)

A joint session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on January 26, 2005 in the conference hall of the P N Lebedev Physics Institute, RAS under the name "State of the art and prospects of solar system research". The following reports were presented at the session:

(1) **Boyarchuk A A** (Institute of Astronomy, RAS) "Opening address";

(2) **Zelenyi L M, Verigin M I, Zakharov A V** (Institute for Space Research, RAS, Moscow), **Izmodenov V V** (Mechanical-Mathematical Faculty, Moscow State University; Institute for Space Research, RAS, Moscow; Institute for Problems of Mechanics, RAS, Moscow), **Skalsky A A** (Institute for Space Research, RAS, Moscow) "The heliosphere and the interaction of the terrestrial planets with the solar wind";

(3) **Korablev O I** (Institute for Space Research, RAS, Moscow) "Study of the atmospheres of the terrestrial planets";

(4) **Owen T** (University of Hawaii, Institute for Astronomy, Honolulu), **Atreya S** (University of Michigan, Department of Atmospheric, Oceanic and Space Sciences), **Niemann H** (NASA/Goddard Space Flight Center, Greenbelt, MD) "A 'wild surmise': first results from the Huygens probe into Titan's atmosphere";

(5) **Marov M Ya** (Keldysh Institute of Applied Mathematics, RAS, Moscow) "Small bodies in the solar system and some problems in cosmogony".

An abridged version of reports 2, 3, 4 and 5 is given below.

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The heliosphere and the interaction of the terrestrial planets with the solar wind

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1. Outer heliosphere and interaction with the interstellar medium

The heliosphere as circumsolar space where the properties of the medium are primarily controlled by the Sun was conceptualized by Davis [1] prior to both Parker's theoretical prediction of the existence of solar wind [2] and the discovery of solar wind by Gringauz's team in 1959–1961 based on the data gathered by the 'Luna 2', 'Luna 3', and 'Venera 1' Soviet space probes [3]. According to current views, the boundary of the heliosphere is located at a distance of $\sim 120-150$ a.u. (where a.u. is the astronomical unit, or the distance from the Sun to the Earth, equal to 149.6 million kilometers). The nature and position of this boundary, as well as the structure and properties of the outer heliosphere, are governed by the interaction between solar wind and the interstellar environment of the Sun — the local interstellar cloud (LIC). It is currently beyond doubt that the LIC constitutes a partially ionized, gas – plasma parcel with a characteristic size of several parsecs. The local interstellar cloud is among a small group of clouds with temperatures of $\sim 5-10 \times 10^3$ K and particle concentrations on the order of 0.1 cm^{-3}. This group of clouds is located completely inside the hot 'Local Bubble' — an interstellar region (with a characteristic size on the order of 100 pc) filled with ionized plasma (with a temperature of 10^6 K and a particle number density of about 0.002 cm^{-3}).

The nature of the Local Bubble is the subject of numerous scientific discussions. There is a hypothesis that attributes the formation of the Local Bubble to the outburst of a supernova (or several supernovae) about one billion years ago. The temperature of the local interstellar cloud (~ 6700 K) and its velocity relative to the Sun (~ 24.6 km s^{-1}) are known to a good accuracy due to direct measurements (with the Ulysses space vehicle) of the characteristics of interstellar helium atoms freely penetrating into the heliosphere [4, 5]. The velocity and temperature of the stream of helium atoms inside the heliosphere coincide with the gas velocity and temperature in the unperturbed local interstellar medium.

Other LIC parameters, such as the densities of interstellar hydrogen atoms and protons, and the strength and direction of the interstellar magnetic field have not yet been determined to a satisfactory accuracy. Since no direct measurements are available for the region of interstellar medium – heliosphere interaction, the structure of the LIC is studied remotely, using space vehicles located at a distance of one or several astronomical units. Such indirect measurements can be correctly interpreted only based on theoretical models, the development of which was pioneered by Parker [6] and Baranov with coworkers (1970) [7]. The two-shock structure suggested in Ref. [7] formed the basis of the modern concept of the heliospheric interface (Fig. 1). The heliopause represents a tangential discontinuity that separates the charged component of the interstellar medium from the solar-wind plasma. Since the solar wind and interstellar medium move at supersonic speeds, the flow around the heliopause gives rise to two shock waves. The inner shock, in which the solar wind is decelerated to subsonic speeds, is referred to as the termination shock. The deceleration of the supersonic flow of the interstellar gas occurs in the outer bow shock. The long mean free paths enable the interstellar atoms to freely penetrate to the interior of the heliosphere through the discontinuity surfaces.

Even 40 years after the publication of the results of pioneering studies, the development of a comprehensive model of the heliospheric interface has not yet been completed. The principal difficulty stems from the multicomponent nature of both the local interstellar medium and solar wind. The local interstellar medium comprises at least five ingredients: plasma (electrons, protons, helium ions), hydrogen atoms, the interstellar magnetic field, galactic cosmic rays, and interstellar dust. In the heliosphere, the plasma component consists of solar-wind particles (protons, electrons, alpha particles, etc.), trapped ions, and the anomalous component of cosmic rays (ACR). To construct an adequate multicomponent model of the heliospheric interface, a true theoretical description must be found for each component of the interstellar medium and solar wind. The charged component of both the interstellar medium (electrons, protons, helium ions) and the solar wind (electrons, protons, alpha particles) can be adequately described in the framework of a hydrodynamic approximation. However, the mean free path of the interstellar hydrogen atoms measures the same order of magnitude as the characteristic size of the heliospheric interface. Therefore, a kinetic approach must be applied to describing hydrogen atoms in the heliospheric interface. Kinetic models are also needed for a correct description of the trapped ions and ACR.

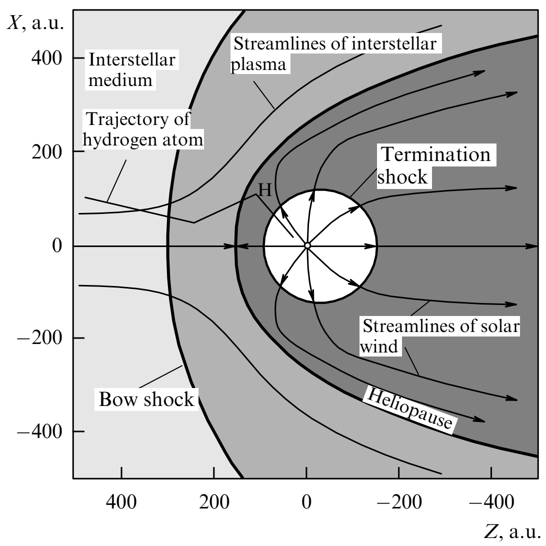


Figure 1. Schematic of the heliospheric interface — the region of interaction between the solar wind and local interstellar medium. The heliopause, the termination shock, and the bow shock divide the heliospheric interface into four regions: (1) the region of supersonic solar wind before the shock; (2) and (3) the heliosheath, or the shock layer between the heliopause and the two (termination and bow) shocks, and (4) the supersonic flow of the interstellar plasma. The positions of the shocks and heliopause were derived from the Baranov – Malama model.

Baranov and Malama [8] suggested a self-consistent kinetic – continual model for the interaction between the solar wind and a two-component interstellar medium that involves neutral hydrogen atoms and charged particles; this model was progressing rapidly in recent years. In particular, advanced models took into account the influence of the galactic and anomalous components of cosmic rays, the interstellar magnetic field, interstellar helium ions, and alpha particles of the solar wind, as well as the effects of solar-wind anisotropy and solar activity. Contemporary models of the heliospheric interface are reviewed in Ref. [9]. The basic advantage of these models over alternative models developed by other research teams is a kinetic approach to the description of the motion of interstellar neutrals. Izmodenov et al. [10] employed a weighting Monte Carlo technique with the splitting of trajectories [11] to calculate the distribution function of hydrogen atoms in the heliospheric-interface region. It was shown that this function is not Maxwellian. Therefore, a hydrodynamic approach is not correct if it is applied to the motion of interstellar atoms.

Several predictions that were verified experimentally had been made based on the kinetic – continual model [8, 12]. Among them was the prediction of the existence of a so-called hydrogen wall in the outer-heliosheath region between the heliopause and the bow shock (Fig. 2). By hydrogen wall is meant a region in which the atomic number density is substantially higher than the number densities typical of the interstellar medium. Such a density increase is due to the production of secondary interstellar atoms through the charge exchange process. The motion of the secondary hydrogen atoms preserves the parameters of the motion of the protons from which these atoms were formed. Since the velocities of the interstellar-medium protons in the outer heliosheath are smaller than their velocities in the unperturbed interstellar medium, the velocities of the newly born secondary hydrogen atoms are also lower than the velocities of the primary atoms. The deceleration of the secondary atoms increases the total atomic concentration or results in the formation of a hydrogen wall in the region of outer heliosheath. The interpretation of the high-resolution absorption spectra obtained using the Hubble Space Telescope [13, 14] gave an experimental confirmation of the existence of the hydrogen wall. It was shown that the absorption spectra cannot be accounted for without considering an additional absorbing medium with parameters corresponding to those of the secondary component of interstellar hydrogen atoms. The discovery of the heliospheric hydrogen wall gave an impetus to better comprehend the absorption spectra observed. In particular, it was shown in Refs [13, 14] (see also review [15])

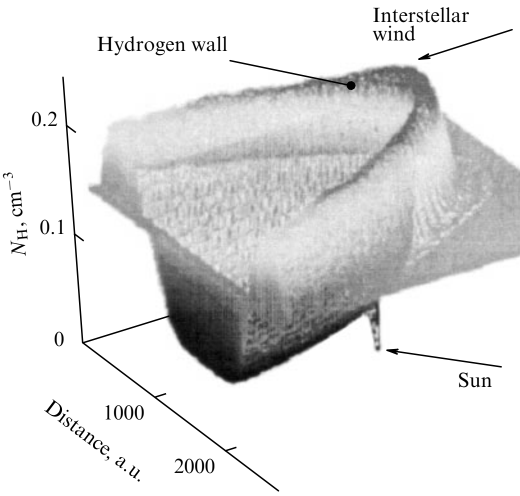


Figure 2. The hydrogen wall, or enhanced number density of hydrogen atoms (compared to the interstellar medium) in the region between the bow shock and heliopause. The concentration $N_{\rm H}$ of interstellar hydrogen atoms in the neighborhood of the Sun is marked. The upper arrow indicates the direction of motion of the interstellar medium relative to the Sun; the lower arrow, the position of the Sun. The decrease in the atomic number density corresponds to the region of strong ionization around the Sun [14].

that certain absorption spectra can be accounted for only if we assume the existence of an astrospheric hydrogen wall around the stars observed, in addition to the heliospheric hydrogen wall. It proved that the observed absorption spectrum can be used for estimating the parameters of the hydrogen wall near the given star and, thereupon, the parameters of the stellar wind. Thus, a new technique of diagnozing stellar winds was revealed. It proved to be the only applicable one for some types of stars. Another important verification of merits inherent in the Baranov–Malama model [8] was the prediction of the solar-wind deceleration at large heliocentric distances due to the charge exchange process. Because of this process, the solar wind loses protons that possess velocities of about 400 km s^{-1} and acquires protons with velocities on the order of the velocities of interstellar atoms, 20–25 km s^{-1}. As a result, the solar wind slowly decelerates, which was recorded by Voyager 1 and Voyager 2 space probes. The number density of hydrogen atoms in the outer heliosphere can be estimated from the deceleration of the solar wind; in the neighborhood of the shock wave, this number density comprises 0.09–0.1 cm^{-3}. In the region of the heliospheric interface, the interstellar hydrogen atoms are filtered, i.e., their density decreases compared to the density of the interstellar medium. According to the model [8], such a filtration amounts to about 50%. Therefore, the atomic number density in the local interstellar medium reaches 0.18–0.2 cm^{-3}. Other techniques for determining the atomic concentration are based on indirect measurements of the parameters of interstellar atoms by recording the scattered solar L_α onboard the SOHO, Voyager 1, Voyager 2, and Pioneer 10 spacecraft, as well as on observations of the ions produced from interstellar atoms by charge exchange and photoionization. Such ions are trapped by the heliospheric magnetic field and are thus termed trapped ions. They were recorded by Ulysses and ACE.

In mid-2003, Krimigis et al. claimed in their paper [16] that the Voyager 1 space probe intersected the termination shock in the second half of 2002. That study prompted a lively discussion in the heliospheric-science community. Simple and most direct confirmations of the intersection of the termination shock by a space vehicle would be an observed sharp deceleration of the solar wind and an increase in its density. Unfortunately, the detector measuring the parameters of the solar wind on Voyager 1 failed several years ago. However, over about 200 days after August 2002, Voyager 1 recorded substantial increases in the flux of energetic (0.57–1.78 MeV) charged particles (the particles are called energetic if their energies exceed the characteristic thermal energy). Krimigis et al. [16] used the degree of flux anisotropy to estimate the speed of solar wind, which proved to be ~ 100 km s^{-1}. Precisely on this basis, it was concluded that the space vehicle had intersected the termination shock in mid-2003. At the same time, analyses of the cosmic-ray fluxes measured on Voyager 1 in 2002 suggest that these fluxes were strongly modulated [17]. It can therefore be concluded that the space vehicle was then in the region of supersonic solar wind, i.e., it had not yet reached the termination shock. Theoretical computations based on a nonstationary model of the heliospheric interface [18] confirm this inference (Fig. 3), while the enhanced fluxes of energetic particles only imply that in 2002 the space vehicle entered the so-called prefrontal zone that forms before the termination shock due to the influence of the anomalous component of cosmic rays on solar-wind plasma (see, e.g., Ref. [19]). The spatial position of the shock wave varies with the phase of the solar cycle (see Fig. 3). According to model calculations, the shock wave in 2002 was at a minimum distance from the Sun, after which it began to recede by 3–4 a.u. per year. Voyager 1 moves away from the Sun at a similar velocity. The termination shock will recede from the Sun over 3–4 years, after which it will start approaching it. We note that, during its movement, the shock front can experience small-scale oscillations due to fluctuations in the medium, which are naturally ignored by the model under discussion. For this reason, Voyager 1 can intersect the termination shock several times already in the near future. Voyager 1 and Voyager 2, reaching the termination shock, will open a new chapter in space exploration.

Undoubtedly, the measurements that will be done beyond the termination shock will substantially change our understanding of the nature of the medium at the frontier of the solar system. NASA is developing an ambitious program of investigating the region of interaction between the solar wind and interstellar medium and measuring the parameters of the unperturbed interstellar medium. According to this project,

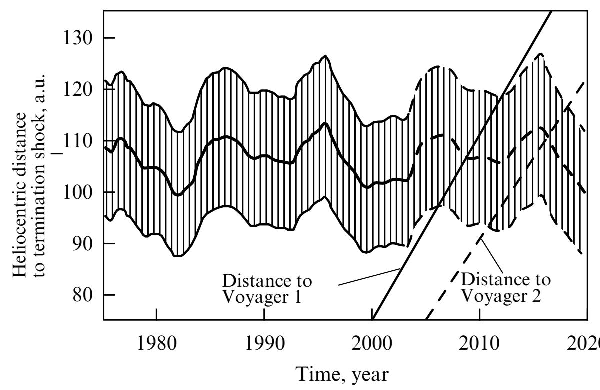


Figure 3. Position of the termination shock depending on the solar-activity cycle, computed based on a nonstationary model of the heliospheric interface [18, 21].

the local interstellar medium unperturbed by heliospheric influence should be reached within 10–15 years. It is noteworthy that NASA considers this project (called Interstellar Probe) to be a trial preceding the launch of the first interstellar space vehicle toward the closest α-Centauri star. This will require developing novel types of space vehicles and scientific instrumentation. In our opinion, a parallel Russian project of investigation of the interstellar medium could become an important ingredient of the future Federal Space Program.

2. Inner heliosphere

The inner heliospheric regions are filled with solar-wind plasma. The solar wind constitutes a persistent radial outflow of the solar coronal plasma to interplanetary space. This plasma motion entrains solar-born magnetic field lines [2, 3]. The solar-wind plasma mainly consists of protons, alpha particles, and electrons (with a minor fraction of heavier ions); it is accelerated to supersonic speeds already in the close neighborhood of the Sun and interacts with all planets of the solar system. The character of this interaction and the structure peculiarities of the region of the solar-wind-plasma flow around one planet or another depend on the presence of a planetary magnetic field and on the properties of the gaseous envelope of the planet.

The outer planets of the solar system (Uranus, Neptune, Saturn, Jupiter), Earth, and presumably Mercury have their own magnetic fields and, therefore, their own magnetospheres; the hierarchy of their scales is shown in Fig. 4. As can be seen from the figure, the magnetospheres of the outer planets are comparable in size to the heliosphere; therefore, they can affect the dynamics of the entire circumsolar space. Another type of interaction with the solar wind is exemplified by Venus which has no proper magnetic field; for this reason, the flow of interplanetary plasma directly interacts with the outer layers of the Venusian gaseous envelope (ionosphere). The resulting structure of the plasma flow and magnetic field around this planet came to be known as an induced magnetosphere.

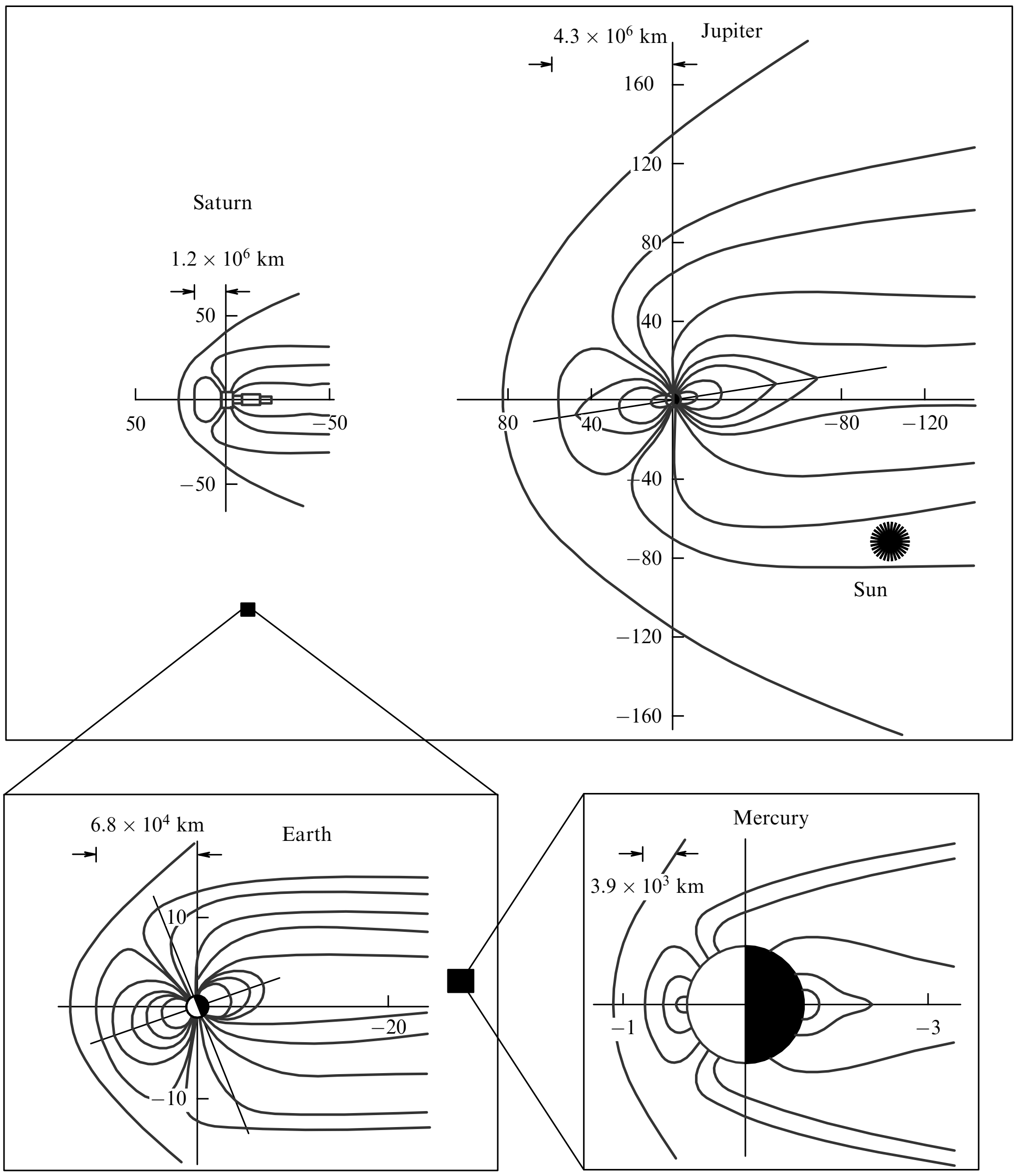


Figure 4. Comparative sizes of the planetary magnetospheres in the solar system.

Below, we will give our principal attention to the inner (terrestrial) planets of the solar system and to particular features of their interaction with the solar wind.

3. Terrestrial planets

The terrestrial group of planets includes Mercury, Venus, Earth, and Mars. They are located near the Sun at distances of 0.39 to 1.52 a.u. The terrestrial planets are relatively small in size and mass but have a high mean density of 5.5 g cm^{-3}. The basic parameters of these planets are listed in Table 1.

3.1 Magnetic fields of terrestrial planets

An intrinsic magnetic field of a planet is produced by the process known as the planetary dynamo [22]. It is underlain by the phenomenon of electromagnetic induction, i.e., the generation of a magnetic field and the related current system due to the turbulent motion or convection of a conductive medium across magnetic field lines. The theory of planetary dynamos assumes that a liquid conductive core resides in the interior of the planet and an available energy source (along with the axial rotation of the planet) maintains convective fluid motion in the core. The radioactive decay occurring deep in the planet is considered as the internal source of energy for terrestrial planets. If a solid inner core is formed at the center of the planet (as in the case of Earth), the crystallization of the matter at the surface of the core from the melt constituting the outer liquid core provides an additional heat source that contributes to the maintenance of convection.

Among all the terrestrial planets, only Earth has a fairly strong proper magnetic field. This geomagnetic field is basically dipole; at present, its dipolar magnetic moment equals 8×10^{25} G cm^{-3}, and the quadrupolar-to-dipolar component ratio is 0.14. Paleomagnetic studies testify that the magnetic dipole of Earth has changed its orientation (from south to north and vice versa) several hundreds times over 160 Myr, whereas an inversion took a relatively short time of about 1000 – 6000 yr; the strength of the magnetic field substantially decreased during the inversions.

The revelation of a proper magnetic field for Mercury in 1972 was a completely unexpected discovery. The magnetic field of the planet was approximated by a dipole field with a magnetic moment of $\sim 1\%$ of Earth's magnetic moment and with a dipole axis inclined by 7° to the rotational axis of the planet. According to then adopted views, the interior of Mercury had become cool 1.5 – 2 Gyr ago, so that the core should be solid and the action of the planetary dynamo should not be possible. However, if we assume that a sulfur addition to the iron – nickel alloy is present in the interior of the planet and the freezing temperature of the core is therefore reduced, we can expect the core to remain liquid over a longer time, so that the planetary dynamo and the magnetic field generated by dynamo mechanism could survive to the present time. Another explanation assumes that, because of the large eccentricity of Mercury's orbit, the outer layers of the solid core are molten due to the tidal scattering of energy at certain segments of the orbit. As an alternative to the classic hydromagnetic dynamo, a generation mechanism based on the thermoelectric effect has been considered in recent years for the magnetic field of Mercury [23, 24].

The magnetic-field and plasma measurements carried out by Soviet and American spacecraft in flyby trajectories and elliptical orbits during the 1960 – 1980s yielded some indirect evidence for the existence of an intrinsic magnetic field on Mars. Estimates of the dipole magnetic moment of this planet, obtained by some investigators, are presented in Fig. 5.

However, measurements of the magnetic field done later by the American spacecraft Mars Global Surveyor (MGS) in relatively low orbits [24] have shown that, instead of a global magnetic field, isolated areas of fairly strong magnetization are present on the Martian surface, mainly in the southern hemisphere (Fig. 6). The MGS spacecraft has revealed many areas, extending over up to several hundred kilometers, where

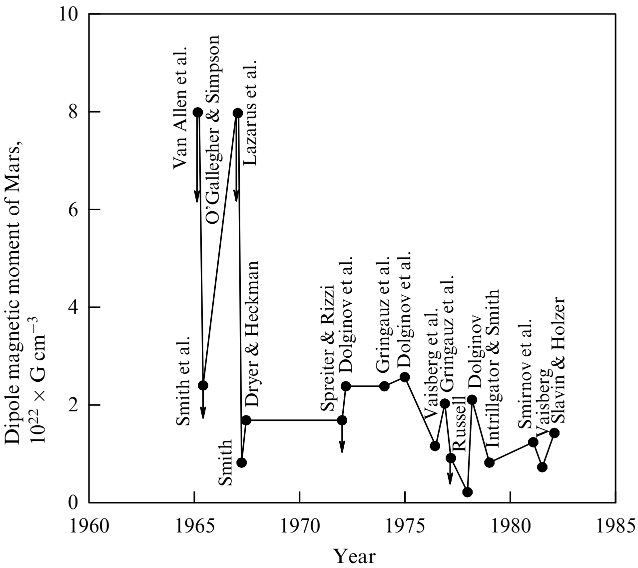


Figure 5. Estimates of the dipole magnetic moment of Mars, given by different investigators.

Table 1. Basic parameters of terrestrial planets.

Planet	Heliocentric distance, a.u.	Mass (relative to the Earth's mass)	Rotational period, terrestrial day	Surface temperature, K	Surface pressure P_{atm}, bar	Atmosphere composition	Proper magnetic field	Ionosphere
Mercury	0.39	0.052	58.8	440	10^{-16}	Na, He	+	–
Venus	0.72	0.81	243	735	92	CO_2, N_2	–	+
Earth	1	1	1	289	1	N_2, O_2 (CO_2, H_2O)	+	+
Mars	1.52	0.11	1.03	214	0.006	CO_2, N_2 (H_2O)	±*	+

* Strong remanent magnetization of isolated surface areas.

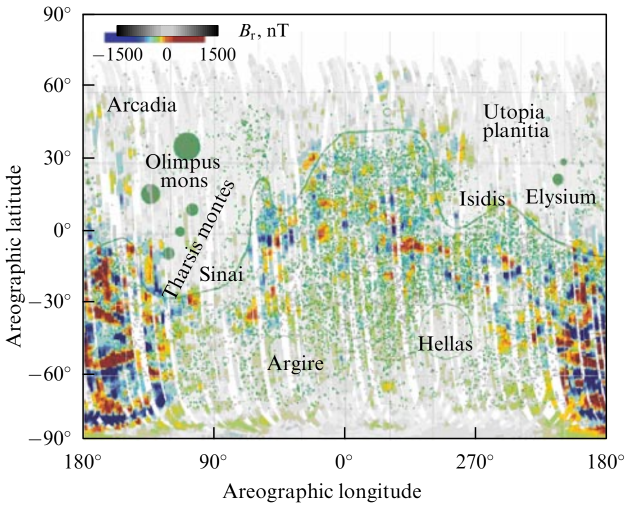


Figure 6. Magnetic anomalies on the Martian surface. The positions and intensities of the radial component B_r of the magnetic field measured by the MGS during flights over 916 elliptic orbits at heights of 100 – 200 km are superposed on structural features of the Martian surface [42].

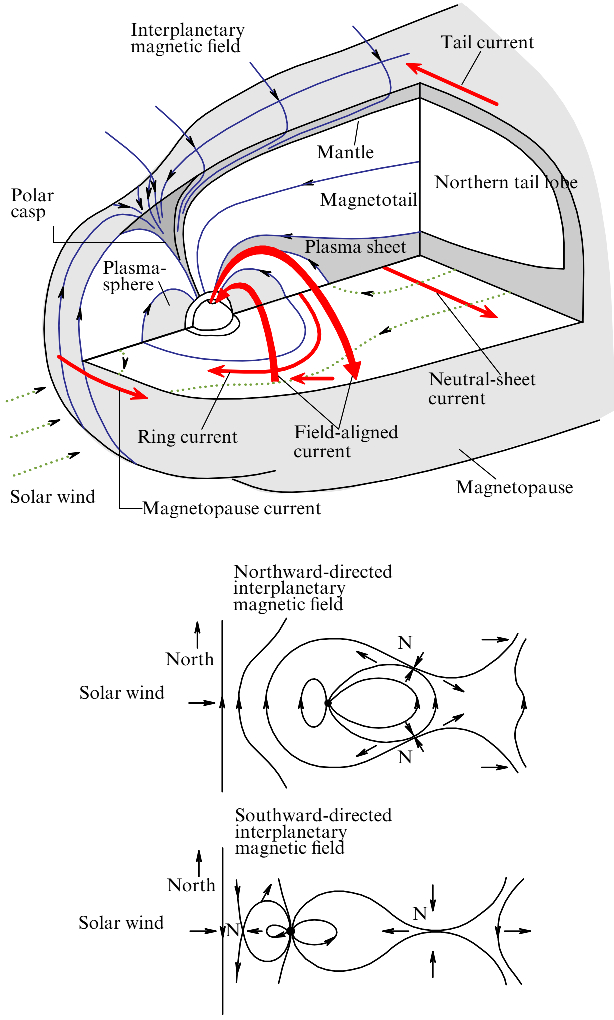


Figure 7. Structure of the Earth magnetosphere and the interaction of terrestrial and interplanetary magnetic field lines (their reconnection in the presence of a southward-directed component of the interplanetary magnetic field 'opens' the magnetosphere) [26].

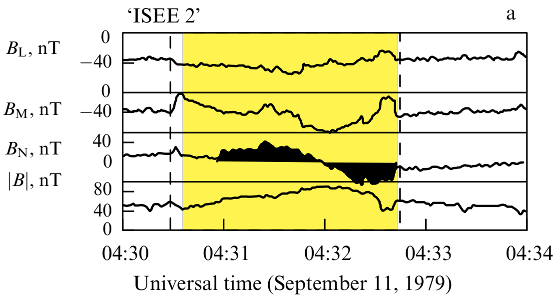
variously oriented magnetic fields are present. The strong magnetization of isolated surface areas suggests that the planet had a proper global magnetic field in the remote past and, accordingly, a planetary dynamo was then active. Mutually opposite orientations of the magnetic field over some surface areas seem to be due to reorientations of the Martian magnetic dipole in the past. It is not unlikely that the Martian magnetic field is now in the process of inversion, similar to the paleomagnetic phenomena known on Earth, and it may therefore be substantially reduced.

Spacecraft measurements carried out near Venus failed to detect an intrinsic Venusian magnetic field. Venus has much in common with Earth, so that the absence of a proper magnetic field on this planet was largely surprising. As possible reasons for it, investigators regard the slow rotation of Venus and the deficiency of heat flux in its interior, due to which the intensity of convection in the liquid core of the planet is low and insufficient for an active hydromagnetic dynamo [23].

3.2 Planetary magnetospheres and reconnection processes

The magnetosphere of the Earth is the best studied magnetosphere in the solar system. Its structure and dynamics depending on the direction of the interplanetary magnetic field are sketched in Fig. 7. In the early 1960s, the concepts of open and closed magnetospheres were formulated [26]. If the interplanetary magnetic field has a southward-directed component, its field lines can reconnect with terrestrial-field lines at the dayside of magnetosphere, which results in the penetration of solar-wind-plasma particles into the geomagnetic cavity (open magnetosphere). Such a process is impossible if the interplanetary magnetic field has a northward-directed component, so that the magnetosphere remains closed for the penetration of plasmas from outside. According to subsequent cosmic experiments, the interaction of the Earth magnetosphere with the incident solar-wind flux proved to be somewhat more complex, but the hypothesis for the effect of the direction of the interplanetary magnetic field on this interaction was largely confirmed.

The reconnection of oppositely directed magnetic field lines still remains among the main subjects of theoretical and numerical analyses and experimental investigations carried out in circumterrestrial space and ground-based laboratories [27]. The reconnection process has been studied in detail and understood fairly well in magnetohydrodynamics which predicts that the finite conductivity should 'break' the field lines at singular points of the magnetic field. This process is much more complex in the hot plasmas of planetary magnetospheres, where virtually no collisions occur, nor is there any obviously irreversible dissipation mechanism. As can be seen from calculations made in the framework of kinetic theory, the role of such dissipation can be played by skin effects (well known for the superconductivity phenomenon) due to the fact that the elementary carrier of current, the electron, has a finite (although very small) mass. Among the observable outcomes of reconnection at the dayside of magnetosphere are 'common' magnetic flux tubes that pass from the solar wind into the magnetosphere (flux transfer events) and are convected along the magnetosphere — magnetopause boundary. An observation of a reconnected magnetic flux tube is shown in Fig. 8, where a sketch illustrating the nature of the phenomenon is also given.



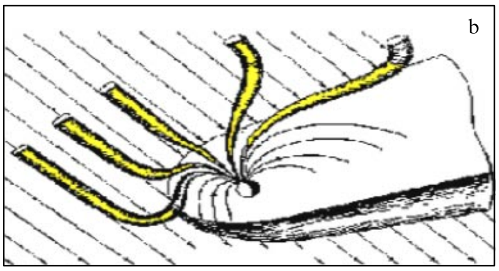


Figure 8. (a) Flux transfer event according to 'ISEE 2' data. The measured magnetic field is given in a terrestrial magnetopause frame of reference (B_N is the field component directed along the normal to the magnetopause surface; the components B_M and B_L are mutually orthogonal and lie in the magnetopause plane). The lowermost graph represents the absolute magnitude of the magnetic field. (b) Magnetic flux tube that has undergone reconnection is convected into the terrestrial magnetospheric tail along the magnetopause; the draping of external magnetic field around the tube produces a specific bipolar signal from the magnetic-field component normal to the magnetopause surface [29].

The reconnection of field lines in the dayside magnetosphere in the presence of a southward-directed component of the interplanetary magnetic field 'pumps' magnetic flux to the tail of the Earth magnetosphere. The release of the magnetic energy thus accumulated in the tail lobes occurs during magnetic substorms. A magnetic substorm is accompanied by the appearance of high-energy particles in the magnetosphere and the development of a system of field-aligned currents in the tail of the Earth magnetosphere. Field-aligned currents couple the outer magnetosphere with the ionosphere into a single electrodynamic system. The transverse current in the plasma sheet of the magnetospheric tail supports the tail configuration that consists of two lobes with antiparallel magnetic fields; one part of this current is closed by a current flowing over the magnetospheric boundary, while another part branches off to field-aligned currents.

The proper magnetic field of Mercury was detected by the Mariner 10 spacecraft. Onboard measurements of the magnetic field in the neighborhood of the planet indicated that the maximum magnetic-field strength was reached at the minimum distance from the surface of the planet, wherefrom the presence of a proper magnetic field on Mercury was inferred [28]. Since Mercury possesses its own magnetic field, is also has a well-developed magnetosphere which is similar to the Earth magnetosphere in its topology. Moreover, although the statistics of observations were very limited (three or four flybys by Mariner 10 near the planet), physical phenomena well known from measurements in the Earth magnetosphere were revealed. Events were noted that closely resemble the convection of reconnected magnetic flux tubes along the magnetopause (flux transfer events) [29]. Some events observed in the tail of the Mercurian magnetosphere were similar to those occurring in the Earth magnetosphere during the development of a substorm, viz., accelerated-particle fluxes and field-aligned currents in the tail occurred simultaneously with sharp changes in the magnetic-field strength and topology in the tail lobes [30].

Observations of such phenomena raised some questions in the magnetospheric physics of those planets that possess their own magnetic fields. In particular, the small lateral dimensions of the Mercurian magnetosphere poses the problem of finding the mechanisms of plasma acceleration in its tail. In turn, the absence of its own dense gaseous envelope made Mercury a unique object whose interaction with the solar wind is only controlled by the magnetosphere itself, without any influence of a dense, conducting ionosphere. Comparisons between the physical phenomena in the magnetospheres of Earth and Mercury make it possible to comprehend the role played by the ionosphere of a planet in the dynamics of the magnetosphere and its current system. It cannot be ruled out that the current systems that govern the dynamics of the Mercurian magnetosphere are connected to the conducting surface of the planet, the photoelectron cloud over it, and the rarefied exosphere which consists of neutral and ionized Na and K atoms.

Reconnection processes can also be important for the magnetospheric dynamics of Mars which has regions of strong magnetization on its surface. The reconnection of magnetic field lines anchored at magnetic anomalies and interplanetary-magnetic-field lines in the dayside region of the planet — with their subsequent convection to the tail of the planet — result in the formation of a fairly complex magnetic-field topology on the nightside and in the development of a layer of sheared magnetic field near the boundary of the Mars plasma environment [31]. Such magnetic field configurations are unstable towards the excitation of the tearing mode; at the nonlinear stage of its development, this instability stochastizes the magnetic field in the layer (and

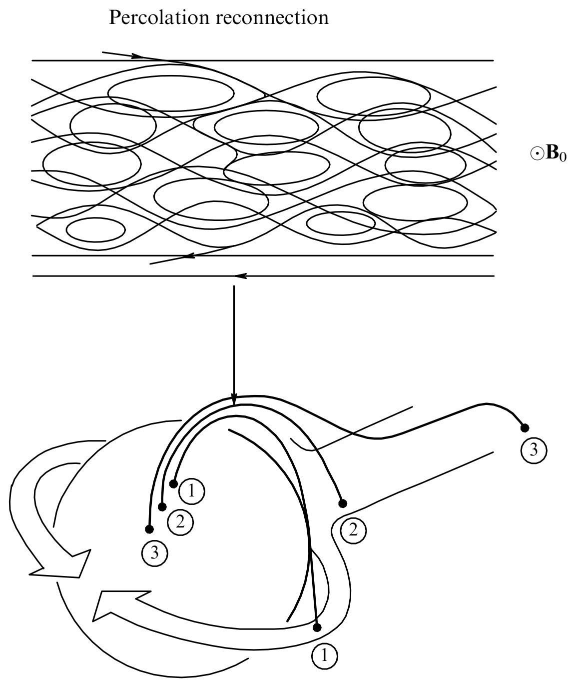


Figure 9. Percolation reconnection at the boundary of the Mars plasma environment [31].

forms magnetic islands) [32]. As this takes place, the penetration (diffusion) of magnetic field lines gives rise to percolating reconnection (Fig. 9). This mechanism of magnetic-field reconfiguration may be among the basic processes that control the convection of magnetic field lines in the Martian magnetosphere in the presence of a strongly conducting ionosphere.

3.3 Interaction of the solar wind with Venus

The interaction of Venus with the solar-wind flux is a classic situation in which a supersonic plasma stream interacts with a planet that has no proper magnetic field (Fig. 10). The pressure in the ionosphere and upper atmosphere of the planet is sufficient to stop the solar wind almost completely. In these conditions, a standing bow shock forms on the subsolar side of the planet. It deflects the incident stream, making it flow around the obstacle. The solar-wind-plasma stream, decelerated and heated by the shock, interacts with freshly ionized atoms of planetary origin, which leads to the changes in the parameters of the plasma stream near the planet and formation of a Venusian magnetic wake.

Data on the interaction of the solar wind with Venus were mainly obtained by the Venera 9 and Venera 10 Soviet spacecraft in 1975 – 1976 and also by the American Pioneer – Venus Orbiter (PVO) spacecraft from 1978 to 1992 [33]. The measurements showed that Venus possesses a so-called induced magnetosphere whose specific features are a relatively sharp boundary (ionopause) between the incident stream of the solar wind and the ionosphere of the planet, as well as a magnetic tail due to the interaction between the interplanetary magnetic field frozen into the solar-wind plasma and the Venusian ionosphere. The outer boundary that separates the ionopause from the incident solar-wind plasma represents a magnetic barrier in which the magnetic-field pressure exceeds the plasma pressure and the substitution of the ions of planetary origin for solar-wind protons begins. This structure forms due to the deceleration of the solar-wind-plasma stream near the obstacle, which is accompanied by the compression of magnetic flux tubes.

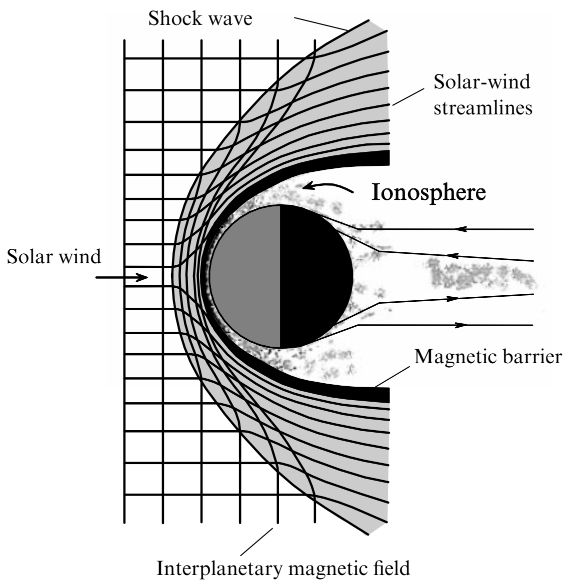


Figure 10. Venus: characteristic boundaries and the structure of the Venus – solar wind interaction region [44].

A characteristic feature of the planetary tail is the presence of two lobes in which the magnetic field is aligned with the Sun – Venus direction and has opposite orientations. As the boundary of the tail is intersected, a sharp change in the plasma parameters — the velocity, density, and ion and electron temperatures — is observed. The ions of planetary origin dominate as the main ion component in the tail.

The formation of the Venusian tail and the origin of ion fluxes in it were considered by Vaisberg and Zeleny [34]. It was shown that the interplanetary magnetic field penetrates into the upper layers of the planetary ionosphere on the dayside of the planet and is mass-loaded with planetary photoions — the products of ionization by solar radiation (Fig. 11). Magnetic flux tubes filled with plasma of planetary origin are convected to the nightside. This results in the formation of a magnetic tail (wake) from Venus and a plasma mantle (the ion flux in the tail). The magnetic-field configuration in the tail of the planet (the orientation of the transverse component of the magnetic field) depends on the direction of the interplanetary magnetic field and changes with time [35]. Another interesting feature of the Venusian tail is its 'twist', which is clockwise irrespective of the direction of the interplanetary magnetic field [36]. There is also indirect evidence of possible reconnection processes in the Venusian tail [37].

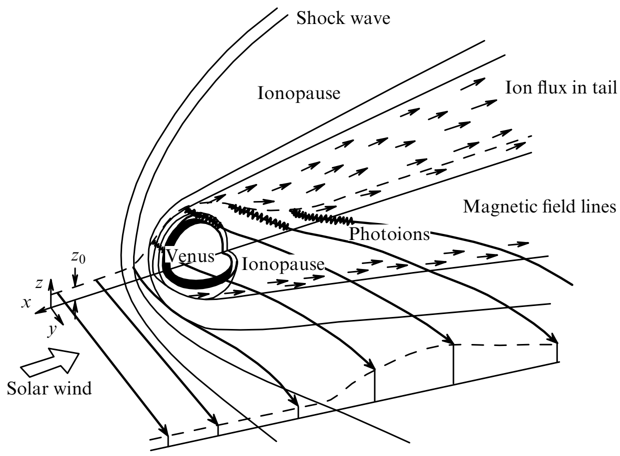


Figure 11. Venus: the interaction of the solar wind with the ionosphere of the planet (accretion tail) [34].

On the dayside of the planet, the penetration of flux tubes of the interplanetary magnetic field results in the formation of so-called magnetic 'ropes' (Fig. 12), which were revealed by observing the highly specific behavior of the components of the magnetic field (by its hodograph). The mass-loading of the magnetic flux tubes with ions of planetary origin — photoionization products — near the subsolar region of the ionopause results in their sinking into the ionosphere, which is accompanied by their compression (increase in the magnetic-field amplitude inside them) and the twisting of the magnetic field lines [38]. Another mechanism producing magnetic ropes can be related to the nonlinear stage of development of the Kelvin – Helmholtz instability at the ionospheric boundary [39].

3.4 Interaction of the solar wind with Mars

The atmosphere and ionosphere of Mars are fairly rarefied, and strong magnetic anomalies are present in its southern hemisphere, so that this planet is unique in terms of the type of

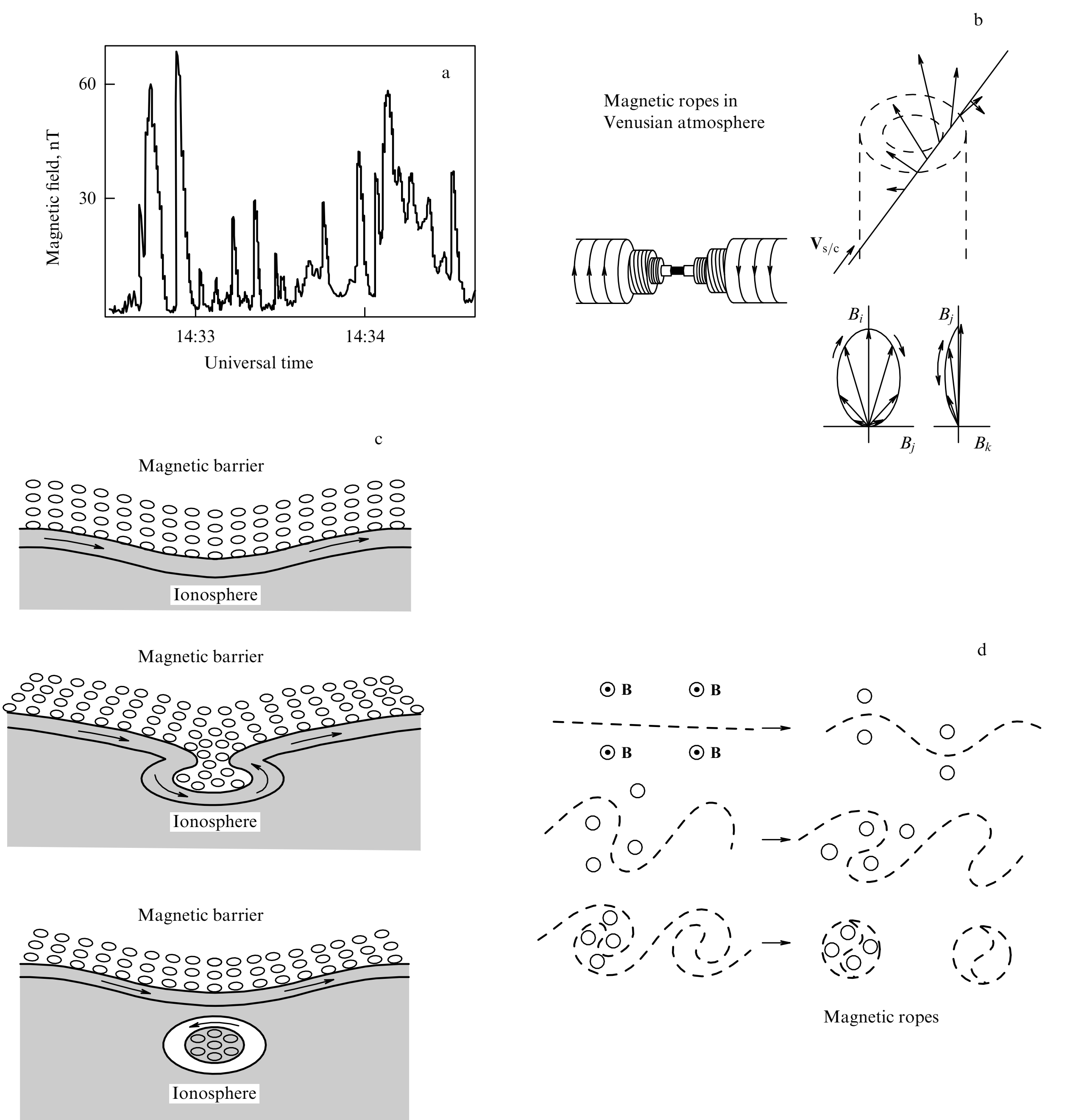


Figure 12. Magnetic ropes in the Venusian ionosphere and their possible formation mechanisms. (a) An example of observation of magnetic ropes in the Venusian ionosphere by the PVO spacecraft. (b) Magnetic-field topology and its hodograph associated with the intersection of a rope by a spacecraft (the satellite moves in the direction shown by the arrow $\mathbf{V}_{s/c}$). Possible formation mechanisms of magnetic ropes are due to (c) the mass-loading of interplanetary-magnetic-field lines with photoions of planetary origin (the arrows show the direction of the current along the ionospheric boundary), and (d) the development of the Kelvin – Helmholtz instability at the ionospheric boundary [43].

interaction with the solar wind. On the one hand, since Mars has no global magnetic field, its interaction with the solar wind is largely similar to the interaction of Venus with the interplanetary plasma. On the other hand, the magnetic fields of the anomalies form an additional obstacle (resistance) to the solar-wind stream; their reconnection with the interplanetary-field lines complicates the shape of the obstacle, the structure of the interaction region, and the dynamics of its characteristic boundaries.

Space-based explorations have shown that both Mars and Venus possess a bow shock — the region where the interplanetary magnetic field is compressed and squeezed (magnetic barrier). In this region, the flux of solar-wind protons drops abruptly, and they are substituted with ions of planetary origin. The interplanetary-magnetic-field lines carried to the nightside of the planet are stretched along the Sun – planet direction and form a magnetic wake (tail) of Mars. As in the case of Venus, a plasma sheet is located at the center of the tail, and intense fluxes of accelerated planetary ions are observed there [40]. The magnetic configuration of the wake and the location of a plasma sheet depend on the orientation of the interplanetary magnetic field.

In the ionosphere of the northern hemisphere, where no strong magnetic anomalies are present, magnetic ropes similar to those discovered in the Venusian ionosphere are observed.

The magnetic anomalies present in the southern hemisphere are intense enough to affect the size and dynamics of the Martian obstacle to the solar wind, as well as the position and structure of the magnetic-barrier boundary. It has been shown that the height of the magnetic barrier is increased by several hundred kilometers over the regions of magnetic anomalies.

The outer magnetic field lines of the anomalies can reconnect with the interplanetary-magnetic-field lines. This enables a fraction of energetic protons and electrons from the solar wind to penetrate to the in-depth layers of the Martian atmosphere (through the reconnection regions) along the open field lines. These particles ionize and heat the atmosphere. The number of such regions may be fairly large, and they can substantially affect the thermal balance and global dynamics of the Martian ionosphere and atmosphere.

The solar wind interacting with the Martian atmosphere gradually erodes it. The basic processes responsible for the losses in atmospheric constituents are (see Fig. 13): the dissociative recombination ($O_2^+ + e^- \to O^* + O^* + dE$); the collisions of planetary ions with solar-wind ions and picked up particles (sputtering); the pick-up of planetary ions by the solar wind on the dayside, and the planetary wind on the nightside, in the tail of the planet — the capture of ions by the solar-wind magnetic field that penetrates into the ionosphere. Table 2 presents estimates for the loss rates of the ionized atmospheric constituents due to the above-listed mechanisms. It can be seen from Table 2 that the losses of atmospheric constituents mainly result from the pick-up of ions by the solar-wind flux; it is these ions that play a key role in the general balance of losses of 'heavy' constituents (in particular, oxygen) by the gaseous envelope of the planet.

The structure of the planetary wind (fluxes of atmospheric ions in the tail of Mars), which is among the principal factors responsible for the losses of the gaseous envelope of the planet, is being investigated by the Mars Express space vehicle (Fig. 14). It has been shown that the planetary wind

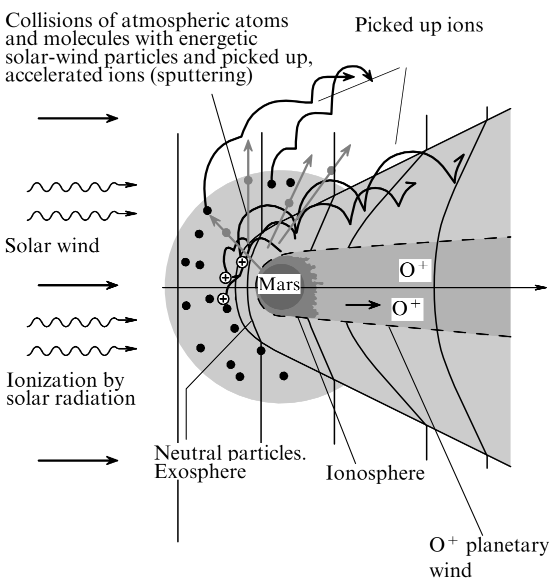


Figure 13. Basic mechanisms of nonthermal losses of atmospheric particles by a planet with a weak magnetic field.

Table 2. Ion-loss rates in the Martian atmosphere [s^{-1}].

Loss mechanism of ion constituent	O^+	O_2^+	CO_2^+	N^+
Dissociative recombination	6×10^6			5×10^5
Dissipation due to collisions (sputtering)	1×10^{24}		8×10^{23}	
Pick-up by solar wind	3×10^{26}			
Planetary wind	2×10^{25}	$\sim 10^{24}$	5×10^{22}	

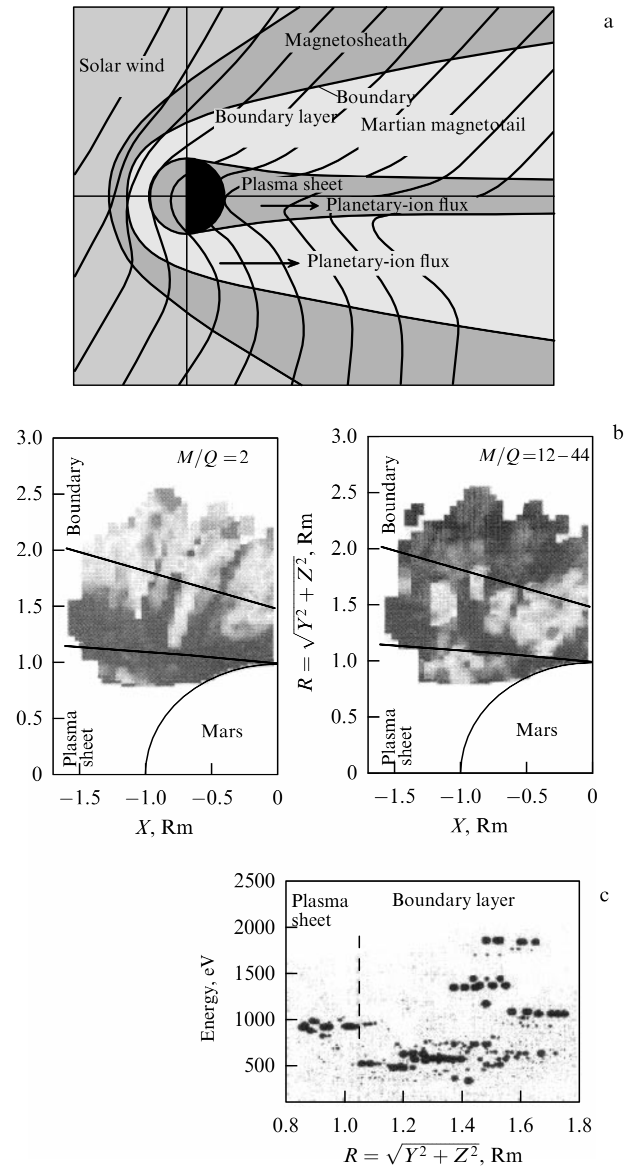


Figure 14. Planetary wind (according to the data from Mars Express spacecraft, 2004). (a) Characteristic regions and boundaries in near-Mars space. (b) Spatial flux distributions of ions with various mass-to-charge ratios M/Q on the nightside of Mars, which are represented in an areocentric cylindrical coordinate system. The Mars radius Rm = 3393 km is used as the unit length. Left: fluxes of ions with $M/Q = 2$ (solar-wind alpha particles); right: fluxes of planetary ions with $M/Q > 12$. (c) Characteristic values of the planetary-ion energy in the boundary layer and plasma sheet of Mars.

has two components. Oxygen-ion streams varying in intensity and energy were recorded near the boundary of the magnetic tail in the boundary-layer region. The energy of these ions, which is maximal at the boundary, decreases as the center of the magnetic tail of Mars is approached. At the center of the tail, in the plasma-sheet region, an ion flux with a relatively invariable energy and intensity is constantly observed.

A detailed survey of data on the interaction of the solar wind with Mars is given in the collected volume [41].

4. Prospects for exploring the inner planets of the solar system

4.1 Mercury

The European Space Agency (ESA), in cooperation with the Japanese Space Agency (JAXA), has started implementing the Bepi Colombo project aimed at investigating Mercury as completely as possible: its structure and chemical composition, its interaction with the solar wind, and the structure of the magnetosphere and exosphere should be studied. A mission to the planet, which is planned to be launched in 2012, involves two spacecraft — a magnetospheric satellite and a planetary satellite. The space vehicles should be put into polar orbits with a maximum (minimum) separation from the planetary surface of 11,800 (400) km for the magnetospheric satellite, and 1500 (400) km for the planetary satellite.

Both spacecraft will be equipped with instruments for measuring the parameters of charged particles and electromagnetic fields; Russian scientists are participating in the development of some of them.

4.2 Venus

In October 2005, the Russian Soyuz – Fregat rocket carrier will launch the Venus Express space vehicle developed under the aegis of the ESA. The spacecraft is planned to be injected onto an elliptic polar orbit around the planet with minimum and maximum distances from the surface of 450 and 66,000 km, respectively. The scientific equipment of the interplanetary probe will include instruments for measuring magnetic fields (MAG) as well as neutral and charged particles (ASPERA 4).

Russian scientists are participating in the experiments aimed at the investigation of the Venusian atmosphere (see the report by O I Korablev presented at this session).

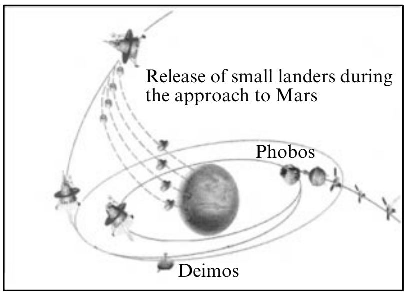
4.3 Mars

The Mars Express spacecraft of the European Space Agency, launched from Earth and put into a near-Mars orbit in 2003, has already successfully operated for more than a year. Its polar orbit has a pericenter and an apocenter height of 258 and 11,560 km, respectively.

The onboard instrumentation of the spacecraft is mainly intended for remote sensing of the Martian surface and atmosphere. Direct plasma and accelerated-neutral-particle measurements are only done aboard Mars Express with the ASPERA instrument; magnetometers were not included in the scientific payload.

4.4 The Phobos Soil project

The Phobos Soil spacecraft is planned to be launched in Russia in 2009. Its main goals are the landing on Phobos, a natural satellite of Mars, and the delivery of soil samples from the surface of Phobos to Earth (Fig. 15). In addition, the spacecraft will have on board a complex of scientific instrumentation for studying the Martian magnetosphere, ionosphere, and atmosphere using both the direct measurements and remote sensing.



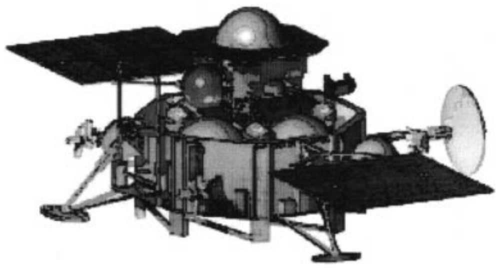


Figure 15. The Phobos Soil space misstion. Top: the mission scenario that includes the approach to Mars, a base orbit close to the orbit of the Martian natural satellite Phobos, and the start of the return vehicle; bottom: general view of the AIS — the orbital and return modules.

To study the interaction of the solar wind with the planet, the Phobos Soil spacecraft will be equipped with several charged-particle and magnetic-field sensors integrated into a single instrument named "Phobos: Plasma Magnetic System" (PhPMS). It is aimed on measuring the magnetic field and plasma parameters in a near-Mars space (Table 3).

Table 3. Components of the PhPMS* instrument

PPMS component	Measured parameters	Measurement range
Unit of magnetic-field sensors	Quasi-DC and varying magnetic fields	$-2000 - +2000$ nT
Planetary-ion sensor	Fluxes of ions of varying energies and masses in the Martian magnetosphere	Energies of 10 eV–10 keV; mass resolution of $M/\mathrm{d}M \sim 100$
Pick-up ion sensor	Planetary-ion fluxes in the solar wind around Mars	Energies of 10 eV – 50 KeV
Electron sensor	Energy distribution of electrons in the Martian magnetosphere	Energies of 1 eV – 5 KeV
Processing and control unit	Acquisition, preprocessing, and storage of information obtained by individual units of the instrument	

* The instrument has a total weight of 3 kg and consumes a power of 3.3 W.

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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References

1. Davis L (Jr) *Phys. Rev.* **100** 1440 (1955)
2. Parker E N *Astrophys. J.* **128** 664 (1958)
3. Gringauz K I et al. *Dokl. Akad. Nauk SSSR* **131** 1301 (1960) [*Sov. Phys. Dokl.* **5** 361 (1960)]
4. Witte M *Astron. Astrophys.* **426** 835 (2004)
5. Möbius E et al. *Astron. Astrophys.* **426** 897 (2004)
6. Parker E N *Astrophys. J.* **134** 20 (1961)
7. Baranov V B, Krasnobaev K V, Kulikovskii A G *Dokl. Akad. Nauk SSSR* **194** 41 (1970) [*Sov. Phys. Dokl.* **15** 745 (1971)]
8. Baranov V B, Malama Yu G *J. Geophys. Res.* **98** (A9) 15157 (1993)
9. Izmodenov V V, in *The Sun and the Heliosphere as an Integrated System* (Astrophys. and Space Sci. Library, Vol. 317, Eds G Poletto, S Suess) (Dordrecht: Kluwer Acad. Publ., 2004)
10. Izmodenov V V, Gruntman M, Malama Yu G *J. Geophys. Res.* **106** (A6) 10681 (2001)
11. Malama Yu G *Astrophys. Space Sci.* **176** 21 (1991)
12. Baranov V B, Lebedev M G, Malama Yu G *Asrophys. J.* **375** 347 (1991)
13. Linsky J L, Wood B E *Astrophys. J.* **463** 254 (1996)
14. Izmodenov V V, Lallement R, Malama Y G *Astron. Astrophys.* **342** L13 (1999)
15. Wood B E *Living Rev. Solar Phys.* **1** (2) (2004); http://www.livingreviews.org/lrsp-2004-2
16. Krimigis S M et al. *Nature* **426** 45 (2003)
17. McDonald F B et al. *Nature* **426** 48 (2003)
18. Izmodenov V, Gloeckler G, Malama Yu *Geophys. Res. Lett.* **30** (7) 3 (2003)
19. Alexashov D B et al. *Astron. Astrophys.* **420** 729 (2004)
20. McComas D et al. *AIP Conf. Proc.* **719** 162 (2004)
21. Izmodenov V, Malama Yu, Ruderman M S *Astron. Astrophys.* **429** 1069 (2005)
22. Stevenson D J *Earth Planet. Sci. Lett.* **208** (1) 1 (2003)
23. Stevenson D J *Earth Planet. Sci. Lett.* **82** (1–2) 114 (1987)
24. Giampieri G, Balogh A *Planet. Space Sci.* **50** 757 (2002)
25. Acuna M H et al. *Science* **279** 1676 (1998)
26. Dungey J W *Phys. Rev. Lett.* **6** 47 (1961)
27. Frank A G et al. *AIP Conf. Proc.* **703** 431 (2004)
28. Ness N F et al. *Icarus* **28** 479 (1976)
29. Russell C T *Adv. Space Res.* **26** 393 (2000)
30. Slavin J A et al. *Planet. Space Sci.* **45** 133 (1997)
31. Kennel C F et al. *Geophys. Res. Lett.* **16** 915 (1989)
32. Galeev A A, Kuznetsova M M, Zelenyi L M *Space Sci. Rev.* **44** (6) 1 (1986)
33. Vaisberg O L et al., in *Solar System Plasmas in Space and Time* (Geophysical Monograph, No. 84, Eds J Burch, J H Waite (Jr)) (Washington, DC: Am. Geophys. Union, 1994) p. 207
34. Vaisberg O L, Zelenyi L M *Icarus* **58** 412 (1984)
35. Eroshenko E G *Kosmich. Issled.* **17** 93 (1979) [*Cosmic Res.* **17** 77 (1979)]
36. Verigin M, Luhmann J G, Russell C T, in *Plasma Environments of Non-Magnetic Planets* (COSPAR Colloquia Ser., Vol. 4, Ed. T I Gombosi) (Oxford: Pergamon Press, 1993) p. 259
37. Verigin M I, Gringauz K I, Ness N F *J. Geophys. Res.* **89** (A7) 5461 (1984)
38. Russell C T, Elphic R C *Nature* **279** 616 (1979)
39. Wolff R S, Goldstein B E, Yeates C M *J. Geophys. Res.* **85** (A12) 7697 (1980)
40. Kotova G A et al. *Kosmich. Issled.* **37** (1) 31 (1999) [*Cosmic Res.* **37** 27 (1999)]
41. Winterhalter D, Acuńa M, Zakharov A (Eds) *Mars' Magnetism and its Interaction with the Solar Wind* (Space Science Series of ISSI, Vol. 18) (Dordrecht: Kluwer Acad. Publ., 2004)
42. Ness N F et al. *J. Geophys. Res.* **105** (A7) 15991 (2000)
43. Russell C T, in *Physics of Magnetic Flux Ropes* (Geophysical Monograph, 58, Eds C T Russell, E R Priest, L C Lee) (Washington, DC: Am. Geophys. Union, 1990) p. 413
44. Luhmann J G, in *Physics of Magnetic Flux Ropes* (Geophysical Monograph, No. 58, Eds C T Russell, E R Priest, L C Lee) (Washington, DC: Am. Geophys. Union, 1990) p. 425

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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.