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PHOBOS AND DEIMOS -- SATELLITES OF MARS

V. M. Zharkov, A. V. Kozenko

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16. Abstract
The brochure talks about Mars' satellites, the study of which has recently made considerable progress due to use of spacecraft. Interest in Phobos and Deimos results particularly from the fact that they are representatives of a class of small objects quite common in the Solar System.

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INTRODUCTION

Nine large planets revolve around the Sun. In order of their distance from the Sun, they are Mercury (0.39 a.u.), Venus (0.72), Earth (1.00), Mars (1.52), Jupiter (5.20), Saturn (9.54), Uranus (19.19), Neptune (30.07), and Pluto (39.52). The planets' distance from the Sun is given in parentheses in astronomical units (1 a.u. = 149.6 million km). /3*

In terms of physical characteristics, the planets are divided into two groups (planet masses and average densities are given in parentheses): a) Terrestrial planets -- Mercury ($0.3302 \cdot 10^{27}$ g; 5.44 g/cm^3), Venus ($4.869 \cdot 10^{27}$; 5.25), Earth ($5.974 \cdot 10^{27}$; 5.514), and Mars ($0.6422 \cdot 10^{27}$; 3.94) -- and b) Giant planets -- Jupiter ($1.902 \cdot 10^{30}$; 1.334), Saturn ($0.569 \cdot 10^{30}$; 0.69), Uranus ($0.0872 \cdot 10^{30}$; 1.26), and Neptune ($0.103 \cdot 10^{30}$; 1.67).

The least studied and most distant planet, Pluto, along with its satellites, has a mass 393 times lower than that of Earth. In terms of its characteristics it more resembles Jupiter's satellites Ganymede and Callisto than any of the planets.**

The planet groups are separated by a belt of asteroids -- many thousands of small planets with cross sections from about 1 to 1,000 km revolving around the Sun in elliptical orbits. This asteroid belt (more precisely asteroid ring) lies 2-4 a.u. from the Sun. The total mass of all asteroids is surprisingly small; it constitutes 1/20th the mass of the Moon. This indicates that asteroids are in no way the result of the catastrophic breakup of a large planet (this total mass is very small). It is now /4
clear that formation of the last planet in the terrestrial group did not occur in the asteroid belt because of the disturbing action of Jupiter's gravitational field. Mars' small size is apparently attributable to this effect.

Generally speaking, one can hypothetically identify three pairs of objects related to terrestrial group planets. The first pair are Mercury and the Moon, whose surfaces are extensively covered with craters -- traces of the age of planet

*Numbers in the margin indicate pagination in the foreign text.
**Then in terms of physical properties the Moon, whose mass is 81 times lower than that of Earth and whose density is 3.344 g/cm^3, must be classified as a terrestrial planet.

formation. The second pair is Venus and Earth, which are "twin" planets. Finally, the third pair is Mars and the asteroid belt, which suffered most from their neighbor Jupiter during the age of formation.

Major upheavals have recently occurred in the study of asteroids. Evidence has been obtained that the asteroid belt is differentiated in its composition. Asteroids consisting of a substance resembling ordinary chondrites -- the most common type of silicate meteorites (the Earth and Moon are made of this type of matter) predominate in its interior zone, i.e. closest to us. These are relatively bright rocks called S-asteroids. Toward the outer edge of the asteroid ring, a concentration of dark objects, called C-asteroids, is growing. Their matter resembles type 1 and 2 carbonaceous chondrites (or, as they say, type C1 and C2 chondrites) -- the simplest meteorites, made up of silicates and volatile compounds.

Thus, differentiation of the asteroid belt in terms of its makeup confirms the idea that high-temperature compounds condensed closest to the Sun in a primary gas-dust cloud, while low-temperature compounds condensed in more remote regions.

Let us turn now to the basic topic of our brochure: Mars' satellites. The main physical characteristics of these objects appear in table 1, which illustrates the striking similarity of Phobos' and Deimos' size, mass, and density to those of asteroids (more accurately, C-asteroids, since in terms of density Mars' satellites -- particularly Phobos -- are closer to C1 and C2 meteorites). And, by all appearances, Phobos and /5
Deimos are actually two small C-asteroids which in some still unknown way entered into orbit around Mars.

TABLE 1
PHYSICAL CHARACTERISTICS OF MARS' SATELLITES

Characteristic	Phobos	Deimos
Mass, 10^{18} g	9.9 ± 1.1	2.0 ± 0.7
Dimensions, km		
Maximum	27 ± 1	16 ± 2
Minimum	19 ± 1	11 ± 1
Density, g/cm^2	2.2 ± 0.2	1.7 ± 0.2

Phobos and Deimos are in synchronous rotation with the planet, i.e. revolving around it in an orbit with the same side always turned toward Mars. The orbits of the Martian satellites are almost circular; their eccentricity equals 0.015 ± 0.001 for Phobos and 0.0005 ± 0.0003 for Deimos. They lie almost on the plane of Mars' equator: the inclination of Phobos' orbit is 1.02°; that of Deimos, 1.82°. The major semi-axes of Phobos' and Deimos' orbits equal 9,378.5 and 23,459 km respectively; their periods of rotation, 7 hr 39 min and 30 hr 21 min. Thus, Phobos in its orbit overtakes the planet's daily rotation and, for an observer on Mars, sets in the west and rises in the east.

It is interesting to note that Phobos and Deimos are respectively below and above stationary, or synchronous, orbit, in which the revolutional velocity of the satellite matches the angular velocity of the planet's rotation around its axis. Due to tidal friction, Phobos is gradually approaching the planet, while Deimos is very slowly moving away from it. According to specialists' estimates, Phobos should collide with Mars in 30-70 million years. Since the bodies in the Solar System are very old -- about 4.6 billion years -- the possibility of observing Phobos now can be generally considered pure chance.

Hence the question arises whether Mars had other satellites in the past.

We will discuss this interesting problem at the end of this brochure, but first we will consider the question of the /6
evolution of Phobos' and Deimos' orbits, which is an exceptionally complex problem, quite important from the standpoint of the origin of the Martian satellites. As we know, they are very likely C-asteroids trapped by Mars. Thus, detailed studies of Phobos and Deimos via spacecraft near Mars can be considered initial observations of a broad class of celestial objects extensively represented in the asteroid belt (and also among small satellites of giant planets).

The brochure will use Phobos and Deimos as as example to discuss the probable internal structure of objects of this type and the structural formations on their surfaces. All this puts into the hands of scientists rich and unique information both on the origin of such bodies and on the formation of the entire Solar System. This in brief is the set of questions with which we wish to acquaint the reader.

PREHISTORY OF THE DISCOVERY OF THE SATELLITES

The discovery of Mars' satellites was not accidental or unexpected, as are many astronomical discoveries. But that is what makes it surprising.

J. Kepler apparently first hypothesized the existence of Mars' satellites. In his "Conversation with a Celestial Messenger," issued in 1610 as a detailed review of Galileo's "Celestial Messenger," he wrote, "I am far from the thought of questioning your correctness in the rest of the book and where you discuss Jupiter's four moons. But I would prefer instead to have a telescope with which I could outdo you by discovering the two (as, in my opinion, proportion demands) moons of Mars... For this search, if one speaks of Mars, the most appropriate time should be next October, when Mars will be opposite the Sun, and the Earth (except for 1608) will be right next to it, with a calculation error of less than 3°."*

We see that Kepler not only correctly predicted the number of Mars' satellites, but also gave reasonable recommendations on the most favorable time to search for them on the basis of the Copernican system which he himself refined. However, more than 250 years passed before Mars' satellites were observed. /7

Authors of popular books often intrigue readers with a surprising prediction of Mars' satellites made in 1726 by Jonathan Swift, the author of "Gulliver's Travels." In fact, 150 years before the discovery of Phobos and Deimos, Swift rather accurately gave the periods of their rotation around the planet, and this cannot be explained by simple coincidence.

At the beginning of this century, the German astronomer and historian of science F. Ludendorf hypothesized that Swift took as a prototype for the spatial distribution of Mars' satellites the distribution of the two Galilean satellites closest to Jupiter. However, rotation periods cannot be transferred by analogy. As the English researcher N. Rosewier stresses, Newton's "Origins" asserts that "all things being equal, the smallest planets have much higher density." If one assumes that Mars' density is 22 times that of Jupiter (since Jupiter's diameter is about that many times the diameter of Mars) and applies Kepler's third law, then one can obtain Swift's result.

Generally speaking, the assumption that Mars might have two satellites was rather common during Swift's time. As early as 1702, in an English translation of "Conversation on the Multiplicity of Worlds" by B. Fontanel, it was said that "Mars cannot experience a lack of moons." And in 1752 in "Micromegas," Voltaire said that "the very best philosophers know how difficult it would be for Mars to have less than two moons, since it is next after Earth from the Sun.

Therefore, one should not be surprised that even Herschel's notes of 1783 contain evidence of an attempt to find Mars' satellites. In the middle of the last century, G. D'Arre conducted an intense search for them with a 25-centimeter refractor at Copenhagen Observatory. However, all attempts to detect Mars' satellites ended in failure.

*In opposition, Earth is on the straight line connecting Mars and the Sun.

Success came to A. Hall, who first saw a Martian satellite on 12 August 1877 during observations with a 66-cm refractor at the U.S. Marine Observatory. On 17 August, exactly 5 days later, he discovered the second (inner) satellite. The satellite closest to Mars was named Phobos; the outer, Deimos, after the Ancient Greek names of the followers of Ares (Mars) -- Fear and Horror.

Astronomical observations of Mars are now usually done during opposition. Most convenient are the major oppositions (when Earth and Mars are closest), which occur every 15-17 years. A great number of observations are attributable to Russian astronomers who worked with the 76-cm reflector at the Pulkovskiy Observatory. For example, S. K. Kostinskiy obtained the first photographic images of Deimos at Pulkova (as early as 1896), and in the 1909 opposition, he took clear photos of both satellites.

However, from the astronomical standpoint, these observations had no advantages over visual observation.

The first indications that the surfaces of Mars' satellites consist of carbonaceous chondrites was obtained by J. Coiper at the end of the 50s from photometric measurements. Specifically, his evidence was the low reflectance of the surfaces of both bodies. The percentage of reflected sunlight (albedo) was only 0.06-0.07.

In the 1971 opposition, B. Zelner took precise polarization measurements of Deimos and determined that they correspond to the polarization of light reflected from a layer of lunar regolith.* It was also determined that Deimos' surface is covered with a layer of regolith.

The first theory of the motion of Martian satellites was put forth in 1911 by G. V. Struve, the son of V. Ya. Struve, founder of the Pulkovskiy Observatory. On the basis of analysis /9
of satellite observations performed from 1877 to 1909, he calculated elements of the orbits, which still today make it possible to successfully predict the positions of the satellites in orbits in terrestrial observations.

In 1945 B. Sharpless concluded that Phobos is in permanent acceleration, i.e. in his opinion, the satellite's motion in orbit is acclerating over time, and the orbit itself is constantly diminishing, so that Phobos is spiraling closer to the planet. According to his estimates, in about 15 million

*The lunar surface is covered by weakly bound crushed rubble called regolith. As it turned out, both the asteroids and Mars satellites are also covered with this material.

years this satellite should collide with Mars and cease to exist.

During study of Phobos and Deimos via spacecraft near Mars, characteristics obtained during terrestrial observation of the Martian satellites, as well as elements of their orbits, were greatly refined. Later in this booklet we will detail the results of these studies, but one must not think that terrestrial observations are now of no importance. Quite the contrary, the space studies were performed over very brief time periods, and continuous measurements are necessary to obtain information about, let us say, the evolution of Martian satellite orbits. This can be done only during terrestrial observations.

SPACE AGE OF MARS' SATELLITES

Research Methods. A qualitatively new stage in the study of Mars' satellites began in 1969, when they were first studied with spacecraft. The bulk of the information was obtained from analysis of photos transmitted to Earth. Thus, television transmission from Mariner-9 in 1971-1972 made it possible to obtain an extremely high-resolution image of the Martian satellites at various phase angles (angles of solar illumination).

Measurements were taken in other parts of the spectrum. For example, aboard Mariner-9 were an infrared radiometer and an ultraviolet spectrometer. Photometric and polarimetric measurements were taken. Specifically, photometric analysis /10
indicated the possibility that regolith existed on the satellites' surfaces. Polarimetric measurements at high phase angles revealed high positive polarization of satellite radiation (20-25%), which is also typical for a regolith covering.

Phobos was also studied with a 10-20-micron infrared radiometer when the satellite crossed Mars' shadow. It turned out that Phobos cools and heats very quickly, and that its level of radiation flow during eclipse is quite low. The figure obtained for thermal inertia* corresponds to a looser layer of dust than on the Moon. This is not surprising, since gravity on Phobos' surface is much weaker.

Photos of Mars' satellites obtained from spacecraft -- particularly beginning in July 1976 (Viking) -- were used to increase the precision of astronomical observations. On these

*The amount of thermal inertia governs the surface's thermal regime: the higher this parameter, the fewer fluctuations in temperature at sunset and sunrise. This parameter is about 20 for solid rock; for pumice, gravel, and sand, 100-200; for various powders in a vacuum, about 1,000 (the latter is typical also for the Moon's surface).

photos satellites usually lie on a background of stars whose coordinates are known with high accuracy. This makes it possible to obtain the satellites' coordinates also with high accuracy. The application of space methods reduces error in determining the position of Mars' satellites more than tenfold.

Photos with the best spatial resolution were obtained on close flights. One could distinguish details measuring about 1 m on them. Stereoscopic images which were produced made it possible to determine the height of surface details and to study in detail fractures, crater chains, the structure of the craters themselves, etc. Let us now discuss the morphological features of Phobos' and Deimos' surface in greater detail. /11

Surface Morphology. Study of the surface morphology of both Phobos and Deimos permitted identification of four main groups of surface formations: 1) craters* and features directly related to them (regions covered with ejecta, regoliths); 2) elongated depressions or furrows, as well as systems of parallel furrows (this type of relief is typical for Phobos); 3) structures varying in albedo (dark matter in craters, lighter crater walls on Deimos, and light ribbon-like formations); 4) ridge-like forms.

All these features appear on the maps of Phobos and Deimos shown in fig. 1-3. The abundant coverage of the surfaces of both planets by craters is immediately apparent. In the case of Phobos, P. Thomas proposed a morphological classification of craters similar to that for those on the Moon: 1) clearly pronounced or "young" craters with extended, obvious walls; 2) smoothed craters with no clear wall over their entire perimeter; 3) degraded craters with blurred walls (much deeper than craters of the previous classes and quite covered with craters and scored by furrows; 4) ghost-craters whose traces are barely discernible as various round depressions (they are quite often difficult or impossible to see during direct solar illumination).

Studies of the morphology of Phobos' and Deimos' craters is just beginning, but important results have already been obtained. For example, measurements of the length of the shadows cast by craters make it possible to calculate the depth of "young" and smooth craters and to define the relationship between crater depth d and its diameter D as D:d=0.2D. This relationship is similar to that for "young" craters on the Moon. The shape of craters in all classes is successfully approximated by a segment of a sphere. /12

In their proposed detailed classification of the state of

*Of course, all these craters are attributable to impacts, since Phobos and Deimos are too small for volcanic activity to occur in their cores.

preservation of craters, Soviet planetologists A. T. Bazilevskiy and I. M. Chernaya presented the distribution of Phobos' craters (in percents) as a function of their depth-to-diameter ratio.

Interesting results come from calculation of Phobos' craters in which those with a diameter on the order of several meters were considered. The craters' surface density (i.e. the number of craters per unit area) turned out to be close to the corresponding figure on the continental part of the Moon most speckled with craters. As the lunar continents, Phobos' surface is in a state of crater "saturation", i.e. formation of more craters on the surface is impossible, since those formed would destroy or overlap old craters.

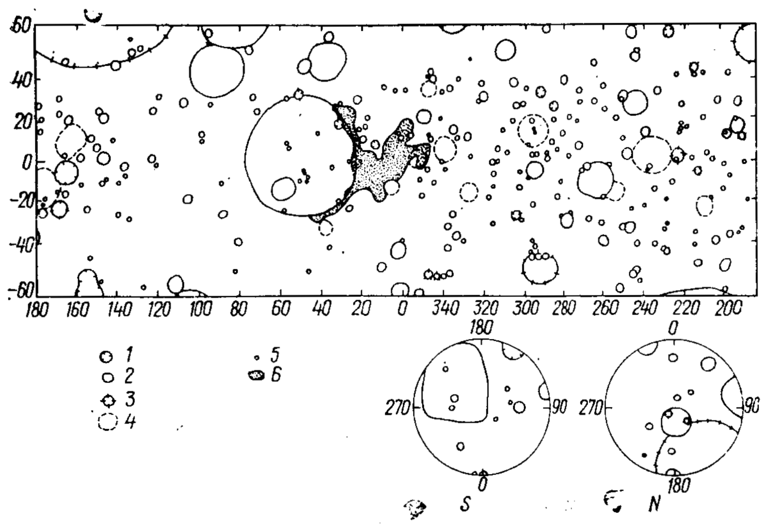


Fig. 1. Map of craters and ejects on Phobos' surface (equation length 77 m):
1 - Distinct craters;
2 - Leveled craters;
3 - Degraded craters;
4 - Crater traces;
5 - Boulders;
6 - Surface covered by ejecta from the crater Stickney.

This makes it possible to estimate the minimum age of the satellite's surface at more than 1 billion years, if we assume that the flow of falling bodies causing the craters was similar to that on the Moon. Phobos' surface has no segments of different ages, and thus there is no basis for assuming that large-scale segmentation of the satellite took place in the past, at least in the last 1 billion years. /14

The largest craters on Phobos, measuring 6-10 km, were named Hall (in honor of their discoverer, A. Hall) and Stickney (the maiden name of Hall's wife). Certain other craters also have names (e.g. Roche). The cross sections of Stickney and Hall appear in fig. 4. Stickney is associatedd also with typical details of Phobos' surface, such as ejects from craters and furrows.

The latter are long, linear depressions formed in the regolith. They are 100-200 m wide, 10-20 m deep. They extend for distances up to 30 km, which exceeds the length of Phobos' longest cross section. The furrow distribution map (fig. 2) shows that furrows are pronounced at Stickney and virtually disappear near the antipodal point. Calculation of the number /15

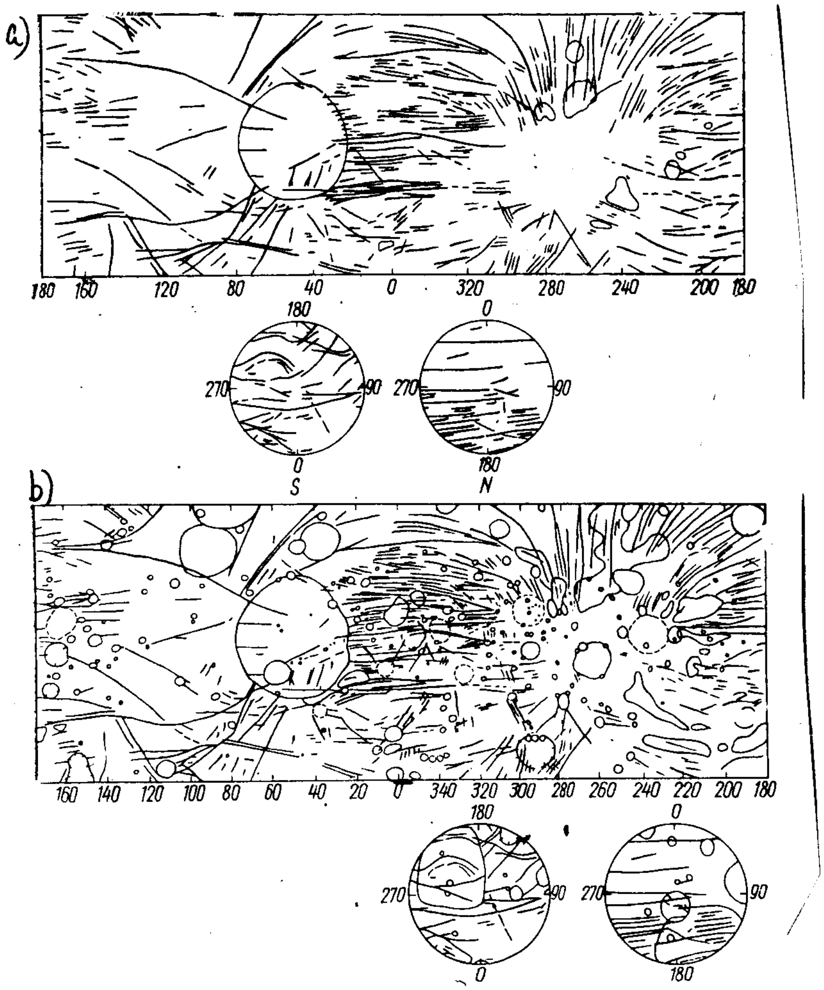


Fig. 2. Map of furrows and related features on Phobos. /13

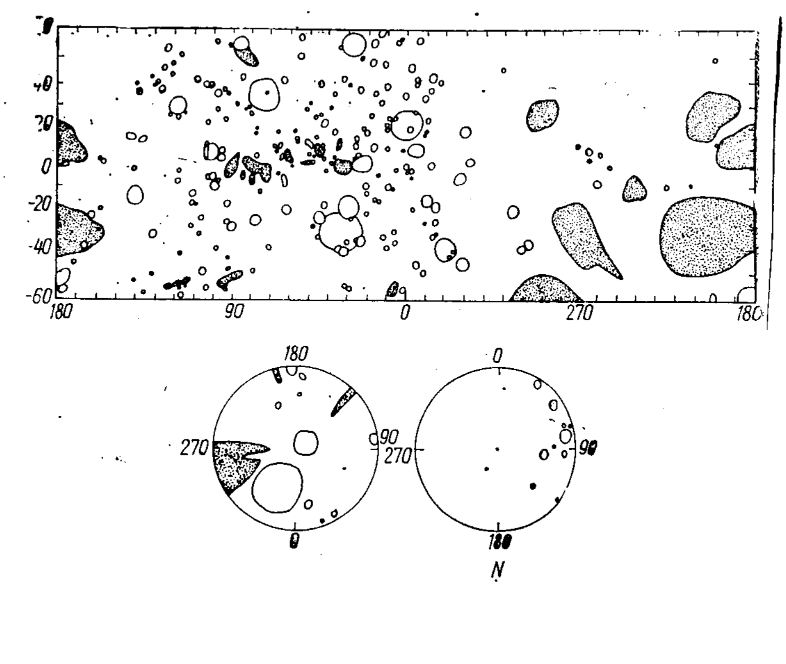


Fig. 3. Map of Deimos' surface features (equation length 43 km). /14

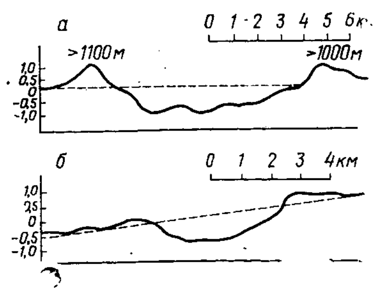


Fig. 4. Relief of a) Stickney and b) Hall craters in cross section. The zero-level is the surface of the hypothetical triaxial ellipsoid. The true depth of the first crater is estimated at 1.3 km; that of the second, 4.8 km. /15

of craters on furrows makes it possible to conclude that the formations are no younger than the rest of the satellite's surface.

The entire set of furrows on Phobos can be divided into four groups: parallel to the equatorial plane; one perpendicular to the satellite's longest axis; and two more, symmetrically intersecting the equatorial plane at about a 25° angle. Because of the uniform distribution of furrows on Phobos' surface, certain regions crossed by two or more groups of parallel furrows make the relief look quite carved. The cross section of the furrows is smooth and arc-shaped. Furrow slopes are usually rather slight, their inclination less than 10°, but a slope of 30° does occur.

Only the largest furrows near Stickney are 400-600 m wide and 60-90 m deep and have a complex floor topography. Sometimes the floors have thin linear formations which are now interpreted as younger furrows.

In certain areas of Phobos' surface, craters are intersected by furrows which cause considerable deformation. For example, the crater Roche crosses 21 furrows, each 200 m wide, and it is apparently somewhat compressed in the direction perpendicular to the furrows and somewhat extended in the direction parallel to them. Since the difference in crater diameters is about 400 m, each furrow is widened by at least 20 /16
m, which amounts to one-tenth their width.

Let us turn now to Deimos. It has no furrows. Crater dimensions on Deimos are smaller than on Phobos, but the largest crater is 2 km in diameter. The primary feature of Deimos' surface is a substantial layer of dust covering craters less than 50 m in diameter. This dust layer makes the surface look rather smooth. For this reason craters on Deimos' surface cannot be classified in such detail as those on Phobos. Even rather large craters are partially filled with ejecta (to a depth of approximately 5 m), which is not the case on Phobos.

All this considerably complicates study of the variation in surface density of small craters on Deimos. Nonetheless, crater statistics indicate that this density on Deimos -- within the limits of measuring error -- matches the same parameter for Phobos and, consequently, for the Moon's continental areas. Apparently, the lower limit for the age of Deimos' surface is also equal to or greater than 1-1.5 billion years.

Areas with high albedo (i.e. of lighter material) associated with small craters are narrow belts extending from one or both sides of a crater. They may extend 150 m from a crater measuring only 30 m. These surface elements are probably formed by a very thin layer of matter which has rolled from crater walls and blocks. The roll-off of matter and its accumulation in lowlands are important processes occurring on Deimos. Both light and dark matter are subject to this form of movement on Deimos.

Light material on Deimos is 30% lighter than the surrounding surface. It is precisely this fact which defines /17
Deimos' higher integral luminance as compared to Phobos.

Origin of Structural Forms. The satellites' surfaces formed due to intense bombardment by meteoroid bodies. During impacts, a mass of soil several orders of magnitude greater than the mass of falling particles became involved in the crater-formation process. Consequently, impact conversion of the surface became the dominant process which formed its structure on the Martian satellites.

Satellite rock was also crushed due to surface heating and cooling. The surfaces of Phobos and Deimos are exposed to ultraviolet radiation, solar wind, and cosmic rays. These radiation flows, which strongly activate surface substances, form in them free valent bonds and electrical charges which -- given the considerable vacuum -- may exist for a long time and promote cementation of fine-grain surface matter. The cosmic vacuum also promotes sticking (adhesion) of soil particles due to intermolecular forces.

However, low gravitational force causes the rock matter to lie very loosely on the surface of Martian satellites. This soil layer on Phobos and Deimos, subject to impact conversion under a high vacuum (just as on the Moon) is called the regolith.

As we know, photometric, polarimetric, and temperature measurements point to the existence of regolith on Phobos and Deimos, and the results of measurements in the infrared range make it possible to assert that Phobos has a layer of regolith at least 1 mm thick. The thickness of Phobos' regolith layer can be estimated also from the amount of ejecta from craters.

According to J. Pollak's estimates, the average depth of Phobos' regolith probably amounts to several hundreds of meters, while on the Moon it averages no more than several tens of meters. This is due to a gravitationsl force on Phobos which is substantially lower than on the Moon. Consequently, the regolith on Phobos must be much less dense than that on the Moon. In Bazilevskiy's opinion, it is not impossible that there /18 may be outcroppings of hard rock on Phobos.

The regolith becomes denser because of its own weight and micrometeorite bombardment. Its density should exponentially increase with depth, as has been soundly proven in studies on the Moon's surface and in terrestrial laboratories. Obviously, this density distribution is also typical for the regolith on Phobos.

Nevertheless, the presence of a thick regolith layer on Martian satellites may arouse some skepticism. The satellites' low mass may result in a significant runaway speed (second cosmic speed); the greatest, about 13 m/sec, is on Phobos. Chips and dust formed upon meteorite impact should therefore easily escape Phobos and Deimos. However, the fact is that the rate at which rubbly material is ejected is still insufficient to overcome the gravitational attraction of Mars. Therefore, all these particles would rotate around the planet in orbits close to those of the satellites, and in a relatively short time (1,000-10,000 yr) would again be trapped by Mars' satellites.

The efficiency with which rubbly material is ejected is high only if meteorite impacts are strong, when the hard rock beneath the regolith is destroyed. As studies show, during impacts at high meteorite speeds, but with porous targets, the speed at which particles scatter from the crater must be two orders of magnitude lower than upon impact with solid material, amounting to only a few meters per second. During an impact originating in the regolith, more than 99% of the ejected matter should remain on the Martian satellites. The stationary regolith layer thus established (with negligible surface transformation) represents a case when the depth of the primary regolith layer is greater than the average depth of ejecta. This is achieved at a regolith depth of several hundred meters.

When the Martian satellites formed, the regolith's depth was insignificant, but subsequent bombardment caused it to thicken. Matter ejected into orbit around Mars accumulated /19 according to the mechanism of cyclic transformation.

The thick regolith layer and weak gravitational force explain the morphological characteristics of Phobos' craters. Bright rings noticeable at small phase angles around many craters (they are 5-10% brighter than the surrounding matter) indicate coarsely crushed ejecta near crater walls. Certain craters have a darker floor, which is interpreted as the presence of a hardened impact melt.

Chains and irregular groups on Phobos' surface usually consist of extended craters measuring 50-200 m. Sometimes there are groups in the shape of "Christmas trees," typical for secondary craters on the lunar surface. They seem to have appeared as a result of secondary collision of the satellite with particles ejected into orbit around Mars.

Analysis of the so-called limited problem of three bodies as applied to the Mars-Phobos-particle system has shown that the motion of a small particle in this system is quite complex. It has been determined that Hill's space (the maximum area in which satellites can still exist near a celestial body) for Phobos does not even interfere with Phobos itself: the limit closed surface of zero velocity (including the so-called LaGrange point L_1) passes outside Phobos' body only close to its sub-Martian and anti-Martian points; in all other places it is inside Phobos (fig. 5). This unique feature means that there are no stable satellite orbits around Phobos.

However, as a result, a significant part of its surface is not bound by energy, and in the past, when Phobos was bombarded by meteorites, when its surface was slightly covered by regolith, rubble easily escaped the satellite. The structure and location of surface details on Phobos greatly depend on the behavior of such ejecta during crater formation on its surface. The study of ejecta movement can be based on analysis of the motion of particles leaving the surface of the synchronously rotating satellite.

It is been determined that the trajectories of ejecta are highly dependent on the longitude of the primary impact site /20
and on the velocity and direction of the discharge. Sedimentary rocks on Phobos primarily extend westward due to the high velocities of discharges in this direction. Typical particle trajectories explain the presence of loops, projections, points of intersection, accumulations, and other features on the satellite's surface. This also results in the arrangement of secondary craters and the anisotropy of discharges around primary craters (chains of secondary craters are always curved).

It is true that furrows discernible on Phobos are usually straight, which is evidence against their genetic link to secondary crater chains. Three mechanisms have been proposed to explain these structures: impact destruction, tidal action, and forces of atmospheric resistance acting during the hypothetical entrapment of the satellite by Protomars. Attempts have been made to explain the existence of furrows, but not their morphology. Moreover, the last mechanism itself is based on the action of an insufficiently understood phenomenon. /21

The mechanism of the tidal origin of furrows should be discussed separately. In 1980 J. Berns and A. Dobrovolskis, using new calculations of Phobos' mass and density, observed that it is much closer to its own Roche limit. This parameter is defined as the limit distance of a satellite from a

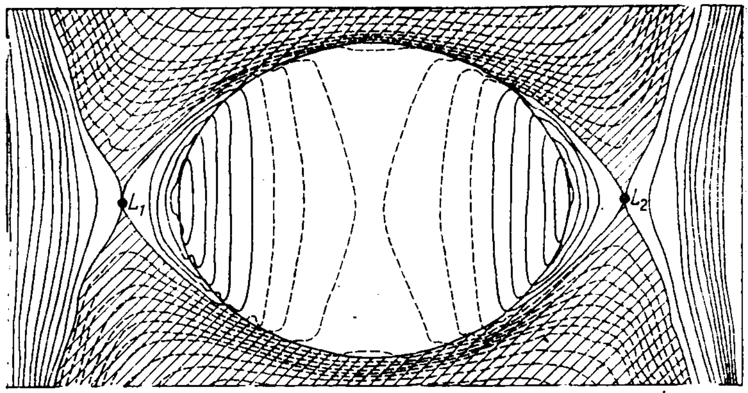


Fig. 5. Zero velocity curves shown in Phobos' equatorial plane at its current distance from Mars, 2.75 times its radius, are denoted by dotted lines. Curves inside Phobos are projections on the equatorial plane of the intersections of zero velocity curves and Phobos' surface. All curves are plotted at a 1-m/sec interval. Shaded curves indicate higher potential energy than that of internal point L_1. Thus, Phobos exceeds the boundaries of its own Roche space, and most of its surface is not bound by energy. The scale here is set by the distance from L_1 and the satellite's center.

planet, at which the satellite can come no closer without being torn apart by tidal forces. Phobos, revolving around Mars below its Roche limit, should experience tensile stresses due to the planet's tidal action.

However, as we will learn later, Phobos is not always so close to the planet. Over its entire history, it has been slowly spiraling toward Mars. At least some of the furrows should be very young, but none are younger than the rest of Phobos' surface, which casts doubt on the hypothesis of tidal origin.

Nor does the mechanism of impact destruction explain the general location of furrows on Phobos; in particular, the surface density of craters within furrows is the same as that of those on other parts of the satellite's surface. As we have already noted, there is no basis for considering furrow formation as related to secondary craters when Stickney developed. Nevertheless, the mechanism of impact destruction is apparently more acceptable if we consider furrow formation to be due to impact cracking of the entire satellite during the development of its largest and oldest crater, Stickney, whose dimensions are only a little smaller than those of Phobos itself.

This hypothesis is difficult to check experimentally, since the scale of the impact process is too large for it to be reproduced in an experiment. Indirect confirmation is the absence of furrows on Deimos, where there are no craters with relative dimensions resembling those of Stickney.

The energy of the impact which produced Stickney on Phobos is estimated to be $6.5 \cdot 10^{25}$ erg, which corresponds to an energy density of about $1.3 \cdot 10^{7}$ erg/cm^3. Total destruction of Phobos would require only an energy density about $3 \cdot 10^{7}$ erg/cm^3, i.e. at an impact energy only 2.5 times greater, Phobos would have been completely destroyed. /22
Naturally, with so powerful an impact, cracks could have formed which would in time become furrows (with their current profile) due to their gradual filling with regolith (fig. 6).

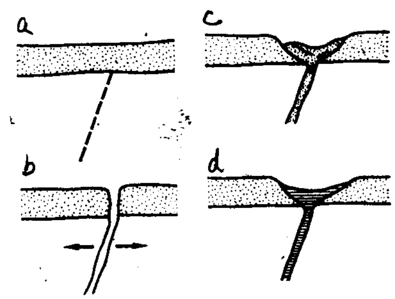


Fig. 6. Development of furrows due to matter filling cracks. The shaded layer denotes weakly bound regolith. Initial conditions are: a) loose regolith lying above a solid body possibly with concealed fractures; b) impact exposes a crack and divides the regolith layer; c) regolith breaks up and permeates the crack (this penetration may be slow and complicated by subsequent seismic phenomena during strong impacts). The final form (d) depends on the number of cracks and possibly on the mobility of the object.

The nature of Phobos' straight furrows may have an even more complicated explanation. Their formation may be related, for example, to the sudden release of volatile substances during the collision between Phobos and a body which created the crater Stickney. In fact, analysis of ultraviolet irradiation of Phobos indicates the existence of clayey materials found in Cl and C2 carbonaceous chondrites. The material of these meteorites contains about 10-20 wt. % bound water and is unstable above 400 K. Since Phobos' surface temperature is at least 250 K, during a strong impact which locally raises temperature 150 K, gases should begin to be released.

The release of volatile substances along cracks may also explain the chains of small craters observed on Phobos and the oreoles of darker matter around certain small craters. This can be interpreted both as depressions in certain furrows and as the appearance of their raised edges. In fact, it is difficult to explain deepenings in furrows by the subsurface penetration of regolith into fractures, since the low gravitational force on Phobos' surface makes the process of regolith deposition inefficient.

There is particular interest in the hypothesis of Soviet astronomer G. A. Leykin regarding the link between furrows and natural seismic oscillations aroused by the collision of the satellite and a large body. A system of standing waves which concentrated the weakly bound regolith into nodes, thus creating a regular structure of ridges and furrows, must have formed on Phobos' surface.

Other problems arise in explaining the morphology of Deimos' surface. It has no furrows, and this satellite is in a different dynamic situation than Phobos. In contrast to the latter, it is quite far from its Roche limit. Although Deimos' surface is heavily cratered, it appears smoother, as if in a haze, due to /23
the thick layer of dust which covers craters less than 50 m in diameter. Deimos' surface is characterized by craters smaller than Phobos'.

The regolith on Deimos is also thinner -- its average thickness is 10-50 m. Many craters on Deimos are filled to a depth of 5 m, and this defines the lower limit of the regolith's thickness. Deimos exhibits more ejecta on its surface than does Phobos -- both fine (whole areas and filled craters) and coarse (boulders and blocks). This difference in surface morphology is possibly due to the fact that Deimos more easily restricts discharge of matter during crater formation.

At first glance, this hypothesis seems paradoxic, since Deimos' mass is less than Phobos'. But we must not forget that Deimos is farther from Mars. In addition, it is quite possible that Deimos' surface is made up of more weakly bound material than that of Phobos. Then the speed of the ejected matter during crater formation will be slow, and most of the mass of this matter will again fall onto the satellite.

The distinguishing feature of Deimos' surface is rather extensive areas of lighter material. Its origin may be connected with the impact process by which matter solidifies (fuses), which plays an important role during impacts with /24
weakly bound surface material. In contrast, it is possible that the light material forms as a result of crushing due to micrometeorite bombardment, since very fine particles possess increased albedo. Finally, dark and light areas on Deimos may seem so only because surface details are observed at different angles of solar illuminance. This effect is familiar from lunar craters.

Light material on Deimos extends downward along crater walls in a thin layer as much as 10 cm thick; it forms restricted flows to 3 km long which are a morphological feature of the satellite's surface. Several mechanisms have been proposed to explain these flows. However, this problem is still not entirely clear.

We must state that surface structures to a great extent are a reflection of the satellite's internal structure and of their physical fields, which will be discussed in the next section.

GLOBAL CHARACTERISTICS AND INTERNAL STRUCTURE

Shape and Related Characteristics. Even the first photograph of Phobos showed that the satellite is spherical. As a result, from data obtained from the Viking spacecraft, R. Turner constructed a model of Phobos (in 1:60,000 scale), using 3,460 reference points. In it he approximated the satellite's surface as a polygon with triangular faces (a total of 288 faces). This model (fig. 7) permitted more precise calculation of Phobos volume -- 5,620 km^3 -- and the plotting of topographic maps.

However, when celestial bodies are studied, a simpler shape is usually used for the surface. Specifically, triaxial ellipsoids with parameters presented in table 2 were chosen for Mars' satellites. Note that accuracy is diminished (although calculations are somewhat simplified). For example, Phobos' volume when its shape is approximated by a triaxial ellipsoid is, according to J. Veverk's estimates, 5,810 km^3 (see previous estimate).

/25

TABLE 2
TRIAXIAL APPROXIMATION OF MARS' SATELLITES

Major half-axes	Phobos	Deimos
a, km	13.3±0.4	7.5±0.3
b, km	11.0±0.3	6.1±0.1
c, km	9.2±0.3	5.5±01

The most important characteristic of the Martian satellites is their mass. It was calculated most accurately on the basis of perturbations in spacecraft velocity during close-in flights around the satellites. Perturbation was recorded according to the Doppler shift in radiosignals received at that moment from the spacecraft. With regard for the estimates of satellite volume cited above, the results make it possible to derive average density, which differed for Phobos and Deimos (see table 1). However, any conclusions are problematic here: the accuracy of assessments of both mass and volume is still inadequate.

Of considerable importance is the study of Phobos' and Deimos' gravitational fields, since the properties of these fields are related both to the form of the surface and to the distribution of mass in the satellite interiors. Indeed, we still cannot make any sort of conclusion about how mass density changes within the Martian satellites. Of course, it would be useful to measure the force of gravity directly on Phobos' and Deimos' surfaces. However, this is naturally a matter for the distant future and, moreover, certain difficulties arise if we use ordinary gravimetric instruments.

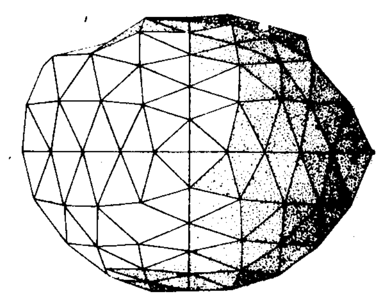


Fig. 7. The northern hemisphere according to M. Turner's model of Phobos.

For example, a pendulum which on Earth has a period of 0.5 sec would complete one oscillation in 22.5 sec on Phobos. Moreover, to use gravimeters on Phobos, one would have to alter the rigidity of their springs. Absolute measurements of gravitational force of the free fall of a body over time are also quite specific: the free fall of a body in a vacuum from an altitude of 1 m, which takes 0.451 sec on Earth, will last 20.3 sec on Phobos. In addition, in measuring gravitational force on Phobos, one must somehow eliminate the disturbing influence of Mars, to which this planet is extremely close. /26

Thus, at present one can obtain only global characteristics of the Martian satellites' gravitational fields. The first detailed model of Phobos' gravitational field was constructed by Moscow State University Professor M. U. Sagitov and his colleagues. R. Turner's model of Phobos' shape was used, and it was assumed that density in the satellite's depths was constant. In addition, Phobos' rotation was considered to cause corresponding centrifugal acceleration, which reduces gravitational force at the planet's equator.

However, after it was determined that Phobos is closer to Mars than its Roche limit, it was necessary to account for Mars' tidal action. That this is indeed significant for Phobos can be judged from table 3, where parameters of Phobos' and Deimos' gravitational fields are compared. The distribution of acceleration of free fall over Phobos' and Deimos' surfaces, derived by D. Davis, K. Hausen, and R. Greenberg with regard for Mars' disturbing force, proves this. Figure 8, a and b give free fall accelerations calculated by these authors (in cm/sec^2) at 10° longitudinal intervals and 5° latitudinal intervals.

Nonspherical form, complex gravitational field configuration, centrifugal acceleration, and Mars' tidal force create stresses within its satellites. These stresses are particularly important for Phobos because of its proximity to the planet. A. Dobrovolskis considered stresses in the Martian satellites when he approximated their shape with a triaxial ellipsoid, assuming that density distribution was uniform and that the matter of the satellites' interiors was identical in elastic properties to carbonaceous chondrites. This made it possible to derive a picture of Phobos' elastic deformation at its equator, as shown in fig. 9. /27

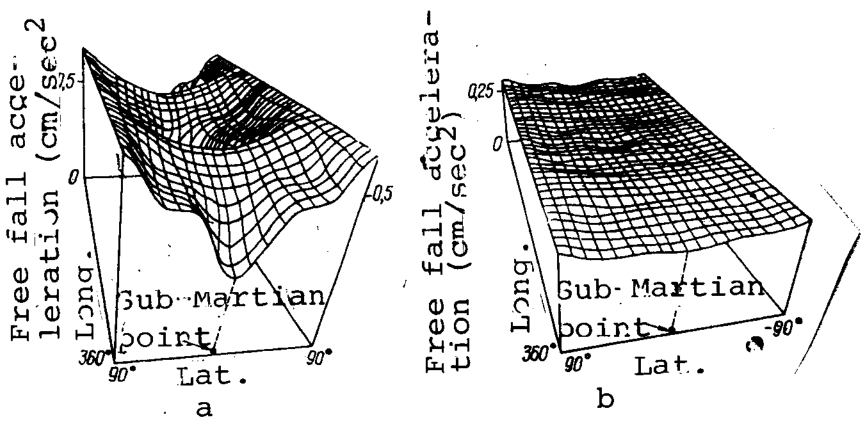


Fig. 8. Schematic distribution of free fall acceleration (with adjusted numerical values from table 2) on the surface of a) Phobos and b) Deimos at 10° longitudinal intervals and 5° latitudinal intervals.

Phobos is somewhat elongated along the axis which connects it to Mars, to which, as we know, it always has the same side turned. However, deformation along this axis is negligible, and stresses it creates are also very small. Maximum stress in Phobos' center is also small, and, overall, Phobos' matter withstands it entirely. This is not entirely obvious for the loose rocks on the satellite's surface, which, indeed, like lunar soil, withstand through cohesion the slight stresses to which it is exposed.

TABLE 3
CHARACTERISTICS OF PHOBOS' AND DEIMOS' PHYSICAL FIELDS

Acceleration, cm/sec^2	Submartian point		Pole	
	Phobos	Deimos	Phobos	Deimos
Free fall of body	0.54	0.31	0.68	0.36
Tidal interaction	0.14	0.005	0.05	0.002
Centrifgual forces	0.07	0.002	0.0	0.0

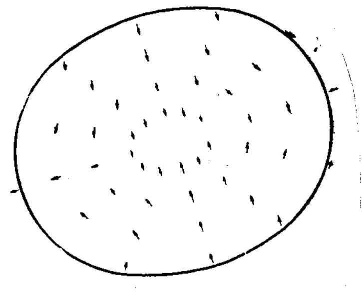


Fig. 9. Elastic shifts in Phobos' equatorial plane. /28

In any event, the observed orientation of furrows and linear features of Phobos' relief do not agree with the theory of their tidal origin. Most probably, as already discussed, all these features are attributable to the consequences of the satellite's collision with a large body, the culprit in the formation of Stickney. Moreover, in the past Phobos was subject to much lighter stresses, since it was far from Mars, and the planet's tidal action therefore had less impact.

In the future, as Phobos approaches Mars, stress in its interiors will increase. Calculations show that, when the satellite is 1.9 Martian radii from the planet's center, it will begin to lose loose material from its surface. At closer proximity to Mars, Phobos will be torn apart by tidal forces.

Tidal force has much less effect on Mars' outer satellite, Deimos. It is far beyond its Roche limit, its average density is somewhat lower, and its orbital evolution is extremely slow, although there are indications that it is moving still farther from the planet.

Distribution of Temperature and Thermal Flow. Observations of the Martian satellites provide information primarily on their surface matter. Their average density is an indirect indicator of the likely composition of their interiors. Certain data on /29
internal makeup could be obtained by measuring surface thermal flow. The latter depends on the content of radioactive elements in the interior and differs significantly, for example, for basalt and chondrite compositions.

If surface thermal flow of the Martian satellites corresponded to a basalt composition, this would prove the differentiation (separation of the core) of the satellites' internal makeup. However, because of their smallness, Phobos and Deimos have always remained cold, undifferentiated bodies. The lack of a significant heavy core in the central areas is evidenced by the comparatively low average density of both satellites.

Long-lived radioactive isotopes (uranium, potassium, etc.) are the most important, longest-acting sources of heat in the thermal history of planetary and satellite bodies. The distribution of these heat sources in the depths of the Martian satellites (as in the asteroids) is assumed to be uniform. However, in constructing a general thermal model for Mars' satellites, one must account for the role of the thick regolith layer. For example, in S. V. Mayeva's calculation of Phobos' thermal flow, it was necessary to consider both the differing contents of radioactive elements and thermal conductivity of matter in the interior and the different layer thicknesses and thermal conductivity of regolith.

The content of radioactive elements depends on the composition of the satellites' matter and is generally unknown. Therefore, Phobos' thermal model was constructed for varying radioactive element contents typical for a particular type of meteorite (ordinary and carbonaceous chondrites, as well as basalt achondrites). Data on lunar regolith served as the regolith's thermal characteristics.

Because of the Martian satellites' small dimensions, their brief period of heating as a result of buildup of radiogenic (due to radioactive decay) heat should quickly be suppplanted by cooling. In the modern age, both satellites are in a steady thermal state, when the release and loss of heat accurately compensate one another. The nature of Phobos' thermal regime presupposes that it took about 100 million years to cool, which is much less than its presumed age, 3-5 billion years.

Calculations show that thermal flow is weakly dependent on regolith layer thickness. Even if the thermal conductivity of Phobos' regolith were 10^{-6} cal$\cdot$(cm$\cdot$sec$\cdot$K)$^{-1}$, for a regolith layer thickness of 100 m or less, the surface temperature gradient relative to depth would correspond to the body's steady thermal state. At a regolith thickness less than 10 m, almost the entire satellite would be at its surface temperature -- about 220 K.

If the thermal conductivity of Phobos' regolith were an order of magnitude greater, 10^{-5} cal$\cdot$(cm$\cdot$sec$\cdot$K)$^{-1}$, temperature at its center would differ very little from surface temperature, even if maximum regolith thickness were 1 km and surface temperature gradient relative to depth would therefore be one order of magnitude lower. In fact, the thermal conductivity of Phobos' interior is believed to be about 10^{-3}-10^{-4} cal$\cdot$(cm$\cdot$sec$\cdot$K)$^{-1}$, and the temperature gradient on the surface relative to depth is entirely independent of regolith thickness.

Table 4 presents certain parameters for Phobos' and Deimos' thermal models. The model for Phobos was calculated as a function of the differing composition of their interiors (although, generally speaking, a basalt composition is highly unlikely), which results in a particular content of radioactive elements. The relationships between surface temperature gradient relative to depth and composition of the matter of the /31
Martian satellites are illustrated in fig. 10, where the

TABLE 4
THERMAL MODELS OF PHOBOS AND DEIMOS

Parameter	Phobos		Deimos	
	Ordinary chondrites	Carbon. chrondrites	Basaltic chondrites	Carbon. chrondrites
Content of radioactive elements today, g/g				
Uranium	$1 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$10 \cdot 10^{-8}$	$2 \cdot 10^{-8}$
Potassium	$8 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$8 \cdot 10^{-4}$
Surface temp. gradient relative to depth, K/m	0.08	0.11	0.36	0.07
Thermal flow, $erg \cdot (cm^2 \cdot sec)^{-1}$	0.034	0.048	0.150	0.031

following types of matter -- carbonaceous chrondrites, ordinary chondrites, basaltic achondrites, lunar material -- are indicated on the left.

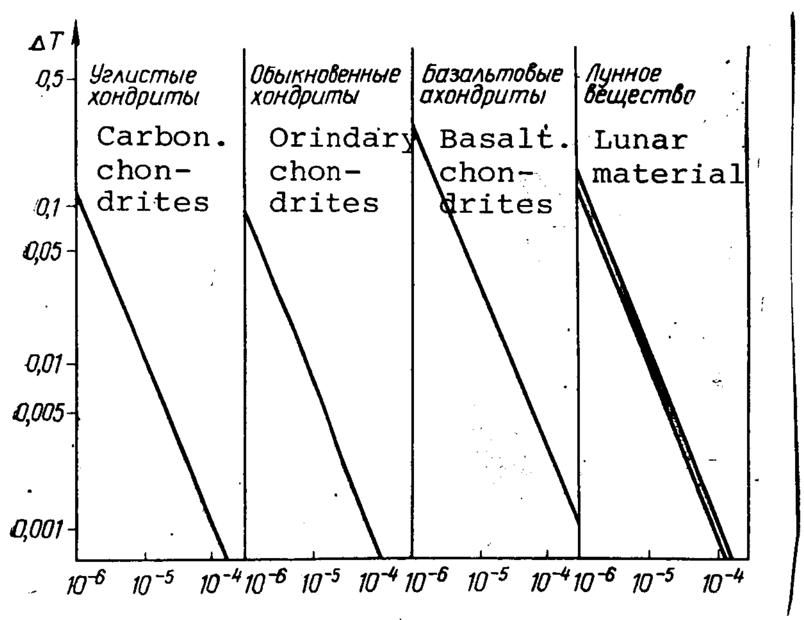


Fig. 10. Relationship of temperature drop relative to depth T and substance composition. The x-axis represents thermal conductivity $[(cal \cdot sec \cdot K)^{-1}]$. From left to right are carbonaceous chondrites, ordinary chondrites, basaltic achondrites, and lunar matter.

In conclusion, let us stress that, given Deimos' smaller size and mass, thermal flow from its surface is about 1.5 times lower than that of Phobos, which has the same makeup (see table 4).

Internal Structure Models. In considering complex objects, science often resorts to constructing their models in an attempt to account for everything that is known about the object, if only to identify its more essential characteristics. Planet and satellite models are defined as a sort of cross section of the given celestial body which shows how main parameters change with depth: density, pressure, gravitational acceleration, seismic /32 wave velocity, etc.

To better clarify the essence of the matter, let us begin the discussion with the simplest example. The simplest model of a planet is a homogeneous model in which density does not vary with depth, and shape is taken as spherical. An approximation of a so-called equidimensional sphere, whereby the volume of the latter equals the planet's actual volume, is used. For these simple models it is easy to calculate how pressure and gravitational acceleration are distributed in them relative to depth.

For Mars' satellites, just as for asteroids, the homogeneous model serves as a good approximation: because of their small size, pressure in the central regions of these objects is low and matter there is almost uncompressed. Indeed, for the Martian satellites, one can calculate even a two-layer model with regard for the regolith layer (1 km thick in Phobos' case).

As we know, analysis of photographs of Phobos obtained from spacecraft showed a lack of highly crushed material (fine fraction) constituting its surface. This indicates that the density of Phobos' surface layers is probably about 1 g/cm^3, slightly higher at a depth of several meters. Depending on the thickness of the regolith layer with a density of 1 g/cm^3, the density of Phobos' interior lies between 1.9 and 2.2 g/cm^3.

Figure 11 shows the distribution of pressure and gravitational acceleration for free fall for such a two-layer model of Phobos with a regolith layer 1 km thick with a density of 1 g/cm^3. The difference from the homogeneous model is slight: pressure at the center of the satellite in this model is 0.63 bar; in the two-layer model, 0.72 bar. If the regolith layer is thinner, perhaps on the order of hundreds of meters or less, the change in pressure and free fall acceleration distribution relative to depth will be even less than for the homogeneous model.

Constructing models of the Martian satellites makes it possible to compare the dominant pressures in their interiors with the hypothetical strength of their interiors. If satellite strength exceeds 10^6 dyne/cm^2, then their shape is most likely not related to the level surface of gravitational field potential.* /33

It is still early to make any kind of general conclusions about the internal structure and material composition of the Martian satellites. This requires further studies, especially with spacecraft landing on the satellite. Most information would come from direct investigations on Phobos and Deimos such as soil samples from the surface of the satellites and active seismic experiments.

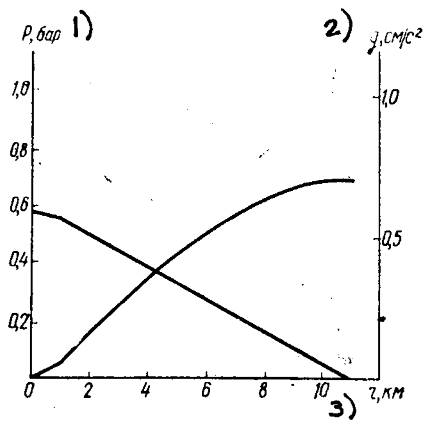


Fig. 11. Two-layer spherically symmetric model of Phobos.
KEY: 1) bar; 2) cm/sec^2; 3) km.

In the latter case, it will be possible to derive the relationship (in seismology it is called a travel time curve) of the travel time of a seismic wave and epicentral distance, i.e. the angular distance between the wave source and receiver. Let us remember that seismic waves are a type of three-dimensional wave propagating in an elastic medium. They may be longitudinal (elastic compression waves) and transverse (elastic shear waves).

Analysis of the travel time curve makes it possible to derive the distribution of seismic wave velocities in terms of depth and directly point out the structure of the satellite's interior. If seismic wave velocities were constant and not a function of depth, travel time curves reduced to the relationship between seismic wave travel time and depth would be straight line segments. However, the more complex the structure of the object studied, the more curved the experimental travel time curve. When there is a very rapid increase in seismic wave velocity, the curve may take the form of a loop if there is compression at the layer interface. /34

To illustrate this, figure 12 shows a theoretical travel time curve calculated on the basis of the two-layer model of

*One major characteristic of a gravitational field is its potential, whose value at a certain point depends only on its coordinates. The general configuration of a gravitational field is governed by the equipotential surface.

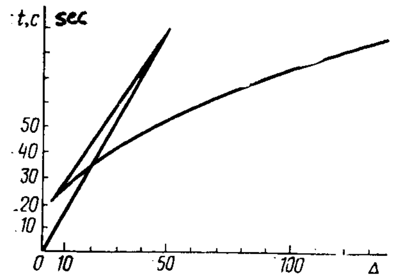


Fig. 12. Travel time curve for longitudinal waves in the two-layer model of Phobos. The x-axis is the epicentral distance Δ in degrees; the y-axis -- seismic wave travel time t.

Phobos discussed above. It is assumed that the speed at which longitudinal waves propagate in the regolith is the same as that in the lunar regolith (104 m/sec), while, in the interior of the satellite, it corresponds to propagation in a cracked basaltic material (300 m/sec).

The upper branch of the curve represents seismic waves reflected from the layer interface (at a depth of 1 km), at which wave velocity increases in steps. A branch of waves which do not penetrate deeper than the regolith layers emerges from the center of the system coordinates. There is one more branch -- refracted waves crossing the internal, high-velocity region. Of course, experimental travel time curves for the Martian satellites will have a more complex form, but it is precisely this complexity which will help us more accurately represent the actual structure of the satellites' interiors.

THE PROBLEM OF ORIGIN

Basic Concepts. The following scheme is accepted for the origin of the planets and their satellites. When the Sun was /35
forming as a result of the compression (collapse) of the protosolar cloud, a gas-dust nebula remained in its vicinity, later evolving into the planets and their satellites (fig. 13).

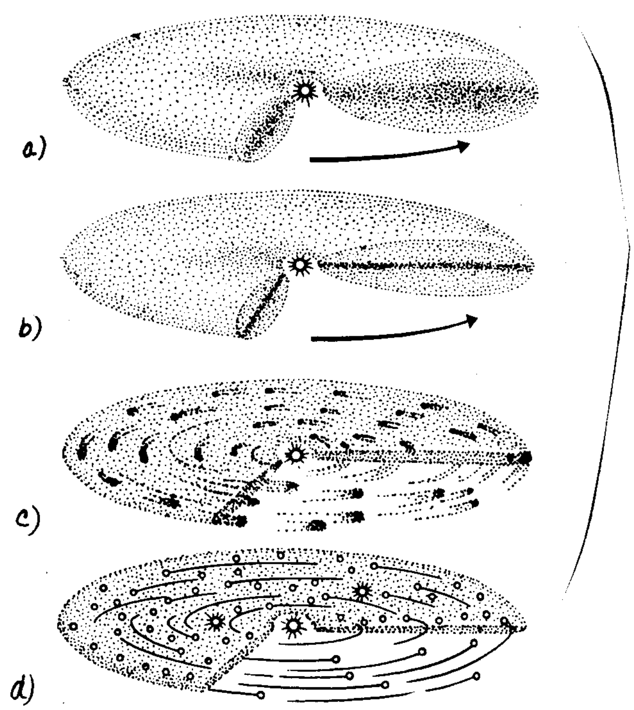
After the turbulent motions in this cloud attenuated, it still occupied an extensive flattened area of toroidal form (fig. 13, a). As dust particles collided with one another and decelerated in the gaseous medium, they lost their relative velocity and settled on the base (equatorial) plane, where a thin disk with increased material density formed (fig. 13, b).

As the concentration of the dust component in the central plane rose, the homogeneous thin dust disk became gravitationally unstable and decomposed into loose agglomerates (fig. 13, c) which later evolved due to gravitational interaction and combined during collisions into bodies similar in size to asteroids -- planetesimals (fig. 13, d). This process took roughly several million years.

This evolution of the primal cloud into planetesimals led to an increase in its transparency and temperature differentials between the area of future terrestrial group planets and that of the giant planets. This in turn played a decisive role in the chemical evolution of the protoplanetary cloud. At this stage in the development of the planetary system there arose zonal differences in the makeup of solid matter which then led to zonal differentiation in the planets' makeup.

In the next stage in the formation of the planetary system, asteroid protobodies (planetesimals) combined into planets. During this process some material was ejected into orbits around growing planets to form a sort of circumplanetary nebula. The combination of this material, which was moving in the nebula at Keplerian speeds, led to formation of satellites. This scheme is typical for the formation of Jupiter, Saturn, and their satellite systems. As hypothesized, these giant hydrogen-helium planets were created first by the formation of their cores from the substance of the dust component -- silicates and ices on /36
which the collapse of surrounding matter had already occurred. Modern analysis of models of the internal structure of the giant planets shows that, when Jupiter and Saturn formed from their feed zones, there was a colossal dissipation (dispersion) of gas, equal in mass to about 10-20 planetary masses.

Fig. 13. Formation of the Solar System.



Thus the growth of planets was associated with dissipation of a large amount of gas from the Solar System, and the influence of this process on the formation of planets and their satellites is still not entirely clear.

The composition of Phobos and Deimos is quite different from that of Mars and close to that of C-asteroids. This indicates possible gravitational entrapment of these Martian satellites in the past. Therefore, study of the dynamic evolution of their orbit is of particular importance. Tracing /37
the past evolution of the orbits, we try to find out how these bodies could have ended up orbiting Mars. Since the Martian satellites apparently formed far from the planet and gravitational entrapment alone is highly unlikely, the specific scheme is rather complex.

The original hypothesis was proposed by J. Berns, J. Pollak, and M. Tauber. According to this hypothesis, planetesimals revolving around the Sun in heliocentric orbits were trapped when they collided with the circumplanetary nebula mentioned above. Friction in the nebula could have led to a reduction in their energy and travel speed, and then the gravitational field of the forming planet could have shifted the planetesimals from heliocentric orbit to orbit around the planet. Stresses on the order of 10^7 dyne/cm^2 arising during planetesimal deceleration could have broken them into fragments.

If there was a collision with a circumplanetary nebula with a mass comparable to that of the planetesimal, the latter could have undergone gravitational entrapment by the planet. There was also a slight probability that bodies larger than 100 km could be trapped. On the other hand, rather rapid nebula dispersion was required if trapped planetesimals were not to fall to the planet in a short time.

A somewhat different mechanism for the entrapment of Phobos and Deimos was proposed by D. Hanten. In his opinion, satellites were trapped rather often by Mars' protoatmosphere (it was 10^4-10^5 times more massive than its present atmosphere). Phobos and Deimos are then the last of the trapped satellites which avoided falling to the planet, since the protoatmosphere almost instantaneously dispersed into space due to the loss of pressure in the Solar protonebula.

However, these models are naturally not the only possible ones. Entrapment of the Martian satellites could have occurred even in very irregular orbits (i.e. with high eccentricity and inclination), which invalidates previous entrapment scenarios. As we will see later, the evolution of Phobos' and Deimos' /38
orbits is rather complex and could ultimately have changed the irregular orbits of the Martian satellites into the regular orbits observed now -- which have slight eccentricity and

inclination.

Therefore, it is not impossible that asteroid bodies arrived in the vicinity of Mars, when it had virtually exhausted its feed zone. This could have happened because of a disturbance in the asteroid belt due to hypothetical pre-planetary bodies with mass about equal to that of the Earth, which crossed the asteroid belt from the area where Jupiter was forming. V. S. Safonov uses this asteroid belt disturbance to explain the existence of the asteroids' 5-km/sec velocity spread.

The probability that these asteroid bodies were trapped by Mars was analyzed in 1982 by E. L. Ruskol, who considered the possible expansion of the planet's feed zone due to collision of asteroids arriving in the vicinity of Mars because of a disturbance in the asteroid belt. For simplicity it was assumed that all these asteroids measured about 10 km, i.e. close to Phobos and Deimos. It turned out that thousands of collisions of asteroid bodies in the vicinity of Mars would have had to happen. Undoubtedly, the result indicates the theoretical possibility that Mars trapped its satellites in the past -- and even the high probability of this event.

However, in considering the origin of the Martian satellites, one must account for one important circumstance. As will be shown a little later, there is specific evidence that Mars once had a large number of small satellites. If this is indeed the case, we must explain the origin of this cluster of satellites. We must determine whether the cluster formed as a result of the decomposition and collision of asteroid bodies in the vicinity of Mars or if it was trapped as a whole all at once. In any case, consideration of the entrapment of the two Martian satellites may be related to the solution of the problem of the entrapment by the planet of a multitude of small bodies.

Consideration of the origin of the Martian satellites raises several questions which must be answered with a particular approach to solving the overall problem. For example, if Phobos and Deimos were trapped by the planet, then why have they turned out to be C-asteroids, which are found /39
farther from Mars in the asteroid belt than are S-asteroids? If the planet and satellites (especially a satellite cluster) formed simultaneously, then we must explain the planet's significant loss of volatile elements (Mars' composition differs from that of Phobos and Deimos).

At the same time, it is easy to explain why Mars has only two satellites while many more could have existed when the planet was being born. First, the very increase in mass of the developing planet had to have caused a reduction in the radius of the satellites' orbit, as a result of which they ultimately ended up at Mars. Second, the circumterrestrial nebula, which consisted of a large amount of dust and fragments from bodies which had collided, was a medium with high aerodynamic friction which reduced the satellites' velocity and also brought them to the planet.

As a result, the circumplanetary medium (the dense protoatmosphere or gas-dust nebula with fragments of collided bodies) gradually dispersed, and the satellite orbits continued to evolve without its influence. Apparently, Phobos and Deimos are Mars' last satellites, trapped by the planet in the remote past (Deimos somewhat later than Phobos). Analysis of the past evolution of their orbits makes it possible to clarify many problems related to the origin of these celestial bodies. However, such analysis is an exceptionally complicated task.

The Evolution of Phobos' and Deimos' Orbits. The problem of the origin of the Martian satellites cannot be solved if we disregard the past evolution of the orbits in which they now revolve around Mars. Naturally, their orbits have not remained constant, but have evolved faster or slower depending on several factors. They evolved under the influence of tidal interaction with the planet, as well as due to Mars' equatorial bulge (because of its rotation) which introduced a certain change in the planet's gravitational field, because of the disturbing effect of the Sun and, possibly, of other satellites, etc.

Obviously, a truer reconstruction of orbit evolution would /40 require determining the factors which had the most dominant effect on that evolution. However, the task is complicated by the fact that different dominant factors governed the satellites' evolution at different times.

In the second half of this century, one of the founders of geophysics, J. Darwin, showed by the example of the Moon's orbit that tidal action can radically alter the orbit of celestial bodies over an astronomically surveyable time period. The Moon causes a well-known tidal deformation in the part of the Earth which is at that time closest to the Moon. The resulting bulging (of the Earth's core and water surface) in turn introduces a distortion into the Earth's gravitational field which thus has an impact on the lunar orbit.

However, in and of itself, tidal bulging does not produce a major disturbance in the Moon's orbit as compared, let us say, to the equatorial bulge resulting from the rotation of the Earth as an elastic body. Because the Moon's orbital plane is inclined toward the Earth's equatorial plane, the centrality of the Earth's gravitational field is disrupted and, as a result, equatorial bulge produces a rather tangible, albeit periodic, disturbance in the lunar orbit (precession). The tidal bulge is much more complex, although it would seem to produce zero effect.

The tidal bulge is symmetric relative to the line passing through the centers of the Earth and Moon and through the common center of mass of the system formed by these two bodies. Nonetheless, tidal action has a significant and also irreversible impact on the Moon's orbit. The fact is that the planet's and satellite's non-ideal elasticity, the lunar orbit's inclination and eccentricity, and several other factors all cause a delay in the tidal bulge relative to the moment of the closest proximity of Moon and Earth.

This effect is particularly apparent if we consider tidal friction. Because of friction forces existing between the water envelope and solid terrestrial surface, marine tides are delayed (by so-called "tidal interval"). Tidal friction is also characteristic of the Earth's core during tidal bulging. /41
Unlike other factors discussed, tidal friction significantly alters the shape of the Moon's orbit over an astronomically surveyable time period.

In general, the delay as a tidal bulge forms causes dissipation (decrease) in the energy of the Moon's motion and therefore to an increase in the radius of its orbit. A similar effect also occurs with the formation of the tidal bulge on the Moon. Of course, this bulge has little effect on the rotation of the more massive Earth around the common center of mass in the system formed by the two bodies, but it still augments dissipation of the mechanical energy in this system.

Naturally, the picture of the lunar orbit's evolution is extremely complex. Considering it rigorously, one must take into account the Moon's so-called libration and the Sun's disturbing force (which causes tides on both Earth and Moon), as well as several other factors (such as the movement of the Earth's poles, the inelasticity of planet and satellite core matter, etc.). All this also causes the energy of the Earth-Moon system to dissipate and changes the total moment of revolution in this system.

Nevertheless, quite specific conclusions on the past evolution of the lunar orbit can be made on the basis of certain simplifications. G. MacDonald and P. Goldreich considered the evolution of the lunar orbit if it were circular (zero eccentricity) and equatorial (zero inclination). They posed the problem of tracing the change in lunar orbit radius due to energy dissipation in the Earth-Moon system because of tidal interaction.

A special parameter Q^{-1} may be introduced as a general characteristic of the lunar orbit's evolution. It defines the decisive degree of energy dissipation in the system. A lower Q represents greater orbit evolution. Specifically, MacDonald and Goldreich proposed that Q be constant over the entire history of the Earth-Moon system.

However, the result was rather unexpected. If, during its existence, the Moon had moved away from the Earth to its present radius because of tidal interaction, this would have required only 0.95-1.9 billion years. This is too little time for the tidal evolution of the lunar orbit, and a more acceptable result is obtained with a Q somewhat higher in the past. /42

Let us turn now to Mars' satellites. An important characteristic of their orbital motion is precessional fluctuation of the mean orbit plane (so-called LaPlace plane) due to the gravitational action of the Sun and Mars' equatorial bulge (the latter is much weaker than the Earth's because of the Martian satellites' smallness).

Figure 14 shows the location of this LaPlace plane relative to the orbit of Mars and its satellites. Angle I shows the inclination of the LaPlace plane to Mars' equatorial plane; angle , the inclination of the plane of orbit to the plane of the elliptic; angle i, the inclination of the satellite's orbit plane to the LaPlace plane. The diurnal movement of a point on the satellite's orbit plane (i.e. the point where this plane intersects the Martian equatorial plane) is labeled N.

Note that the precession of the planet's axis of rotation has no influence on the relative orientation of Phobos' and Deimos' orbits. However, the inclination of the satellites' orbits remains constant. Since the satellites' orbits are almost in Mars' equatorial plane (where, apparently, they formed), the planet's equator somehow "leads" the satellites' orbits, maintaining their position in the equatorial plane. However, it would be incorrect to assume that the satellites' orbits follow the precession of the planet's axis of rotation (then their location in Mars' equatorial plane would be accidental).

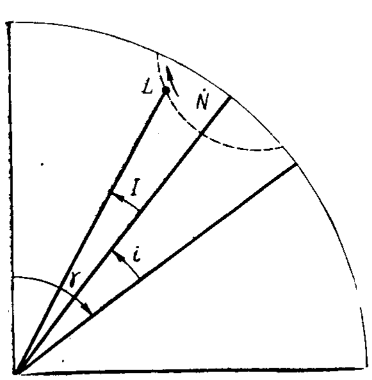


Fig. 14. Position of the instantaneous axis of the LaPlace plane.

Like the Moon, the Martian satellites possess synchronous rotation, i.e. only one of their sides is turned toward the planet as they orbit around it. This synchronicity is established by the tidal action of the planet over the rather long time during which the satellites have orbited Mars.

According to S. Piel's estimates, Phobos' synchronicity has lasted 0.1-1 million years; that of Deimos, 0.1-1 billion years. /43

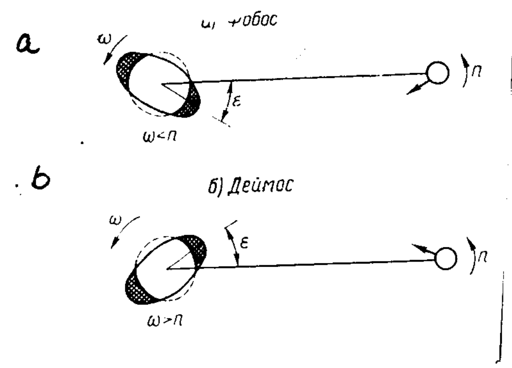


Fig. 15. Tidal disturbance of a) Phobos and b) Deimos by Mars. In the first case, the tidal bulge is delayed due to dissipation of energy in the planet's interior and lags behind the rapidly moving Phobos by angle ε. Tidal interaction takes Phobos' angular momentum and transfers it to the planet, accelerating its rotation (Phobos is approaching Mars). In the second case, the tidal bulge, rotating together with Mars, overtakes the disturbance which produces it. The planet's angular momentum and rotation energy are transferred to Deimos' orbital motion, causing it to move away from Mars.

The following notation is used: ω - angular velocity of Mars' rotation; n, angular velocity of satellite rotation.

As already stated, Phobos possesses a secular acceleration in orbit, which results from the planet's tidal action (fig. 15). According to estimates by Soviet geophysicist V. A. Shor, Phobos should fall onto the planet in 50 million years; according to other estimates, in 30-70 million years. On the basis of /44
this secular acceleration, Q was calculated to be 70-150.

Because of Deimos' very low mass and relative remoteness from the planet, its orbit is subject only to slight tidal disturbance. There have been no observations of Deimos' secular acceleration, and it cannot be measured, even with the current level of observation accuracy. Theoretical study of the history of Deimos' orbit indicates that the satellite previously was closer to stationary orbit.

In general, one might assume that both Martian satellites began their evolution close to one another. Phobos began to evolve inwardly; Deimos, outwardly from stationary orbit. However, this simple scheme no longer satisfies specialists. There are more detailed evolutionary scenarios for the orbit of the Martian satellites.

Tidal friction changes the energy of orbital motion and angular momentum. On the basis of this knowledge, in 1961 English geophysicist G. Jeffries arrived at a conclusion about the change in Phobos' and Deimos' eccentricity. He showed that the eccentricities of the orbits of both Martian satellites are now diminishing. From this, Goldreich concluded in 1963 that, in the remote past, Phobos' orbit eccentricity could have been much greater, while that of Deimos changed very little and, apparently, always remained negligible.

Since Phobos' orbit was apparently highly eccentric, it is quite likely that at some point in the past the satellite, moving in orbit, was in stationary orbit during one revolution around the planet and outside it during the next. As a result, its angular orbital velocity in one segment of its orbit would be greater than that of the planet's rotation; in another segment, just the opposite -- less.

Considering the evolution of the orbit with regard for this effect and assuming that Mars' dissipative factor Q is proportional to rotation speed, S. Singer derived the change in the major orbital semiaxis a as a function of orbital eccentricity e (fig. 16). The time scale here is entirely governed by Q for Mars. Using Singer's theory, G. Smith and P. Tolson determined the change in the position of Phobos' /45
apocenter over time (fig. 17) and discovered that, at Q less than 80, Phobos' orbit had to have intersected that of Deimos.

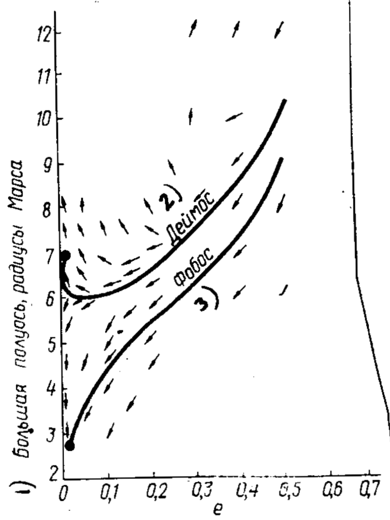


Fig. 16. Change in the Martian satellites' orbits.
KEY: 1) Major semiaxis, in Mars radii; 2) Phobos; 3) Deimos.

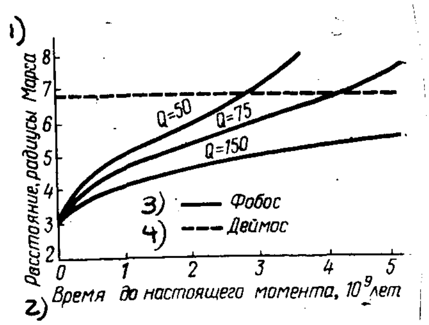


Fig. 17. Position of Phobos' apocenter according to L. Nesterenko's theory.
KEY: 1) Distance, in Mars' radii; 2) Time to present, 10^9 yr; 3) Phobos; 4) Deimos.

Smith and Tolson concluded that either Q averaged over time was greater than 80 or, in the case of gravitational entrapment, the satellites were acquired by Mars during a specific time period (whereby Phobos ended up in inner orbit). Averaging the dissipative factor over time is not a simple task. Specifically, change in Q over time is governed by the planet's thermal history, since a change in temperature distribution in the planet's interior can determine the speed at which differentiation (separation into core and mantle) takes place.

Because of the law of conservation of a planet's angular momentum, differentiation of its interior governs both the change in angular momentum of Mars' rotation and the position of stationary orbit. For example, according to Mars' thermal evolution proposed by V. Word, J. Berns, and O. Tunn, about 1 billion years after the planet formed, the angular velocity of its rotation increased about 10% due to the formation of Mars' core. Accordingly, during the first billion years of the planet's existence, stationary orbit lagged somewhat behind its current position. /46

This circumstance should be kept in view when one discusses the evolution of Phobos' and Deimos' orbits in their early stages.

K. Lambek made a significant contribution to this problem in 1979. He showed that one must take into account both tidal deformation on the planet caused by the satellites and tidal deformation on the satellites caused by the planet. It previously had been believed that the Qs of both the satellites and Mars were somewhere of the same order of magnitude.

For example, this was maintained by Goldreich, who assumed that the elastic properties of the matter of the satellites and planet were similar and that tides on the satellites caused by the planet make a minor contribution to the evolution of their orbits. However, since the satellites have a composition close to that of carbonaceous chondrites, their dissipative factor, Q^{-1}, should be much larger than that of Mars. Consequently, satellite energy dissipation will be greater than permitted by Goldreich.

In G. Lambek's work, Mars' Q was calculated with regard for the planet's two-layer model (with a molten core measuring 0.5 times Mars' radius). He found Q for Mars to be 50.

It was somewhat more complicated to calculate this parameter for Mars' satellites. Q could be only approximated on the basis of corresponding calculations for low-density, high-porosity lunar rock at low pressures. As a result, Q was estimated to be between 10 and 100.

However, Phobos' interior contains many cracks, since pressure in its central regions is very low and cracks will not disseminate under its action. Therefore, dissipation will probably depend more on the level of satellite interior cracking than on the composition of the matter. A high percentage of volatile elements may decrease Q even more. In any case, Lambek /47 and most other researchers after him assumed that Q equals 10 for Mars' satellites.

Despite Phobos' synchronous rotation, during which a radial tide on the satellite results only from the orbit's eccentricity, its low Q greatly accelerated the rate at which its orbit evolved. This is obvious from numerical calculations. Given the parameters chosen, energy dissipation exerted the dominant effect on orbit evolution, greatly accelerating the rate of evolution. During the satellite's life, the altitude of Phobos' orbit must have diminished from that typical of Deimos' orbit to its current level.

However, further study has only complicated the picture of satellite orbit evolution. In 1980, a landmark work by A. Cazenave, A. Dobrovolskis, and B. Lago appeared. It noted that Lambek's theory admits the existence of only small eccentricities in Phobos' orbit. However, even Lambek himself indicated the possibility that Phobos' previous orbit was highly eccentric. Thus Lambek's theory could not be used to study the distant past of the Martian satellites' orbits.

Earlier, in 1978, F. Mignard hypothesized that the libration of Mars' satellites could more than double their energy dissipation and that, hence, the choice of 10 for the satellites apparently somewhat underestimates the actual value and greatly reduces the actual time of orbit evolution. The problem of accounting for libration can be made even more complex if we consider orbit eccentricities greater than 0.3, when satellite rotation became asynchronous.

The article by Cazenave, Dobrovolskis, and Lago therefore used higher Qs. Increasing Q by about one order of magnitude also increased orbit evolution time. Calculations showed that, 3 billion years ago, the major axis of Phobos' orbit was greater than 20 times Mars' radius. At the same time, important evidence of the inconstancy of the location of the LaPlace plane was /48 obtained.

The fact is that the LaPlace plane, the natural plane of correlation for Phobos' and Deimos' orbits, can change its orientation in space if the distance between either satellite and the planet changes. It lies in a plane close to Mars' equatorial plane when the effect of the planet's compression prevails and close to the planet's orbital plane when the solar effect is predominant. For the Martian satellites, this critical distance equals 13.1 times the radius of Mars, and the theory indicates that, in the distant past, Phobos could have been much farther from the planet.

This leads to a key conclusion on the possibility that Phobos was taken from a parabolic orbit lying in the plane of orbit of the planets in the Solar System, i.e. the plane in which, specifically, the asteroid belt is found. It is interesting that the altitude of Phobos' pericenter remains nearly constant. However, it may correspond to the closest approximation to the planet during entrapment.

Since Deimos' orbit has evolved little, Phobos' orbit may have intersected it 1 billion years ago. The two satellites could have collided when their orbits intersected. This collision -- which, by the way, could have caused the crater Stickney -- should have changed the eccentricity of Phobos' orbit by 0.01. It would seem natural to use this fact to explain the current eccentricity of Phobos' orbit, which equals 0.015.

However, this explanation would arouse no objection if the evolution of an orbit with a low initial eccentricity -- about 0.001 -- were considered. The fact is that Stickney is more than 1 billion years old, while the eccentricity of Phobos' orbit is no more than 0.4-0.5. Therefore, the orbits of the Martian satellites, most probably after entrapment, gradually evolved from parabolic orbits to their current ones -- almost circular due to tidal interaction. Mignard reached these conclusions in a detailed study published in the beginning of 1981.

The magnitude of tidal energy dissipation in the satellite /49
is a key parameter in selecting between the two alternative scenarios for the origin of satellites: entrapment or formation from a gas-dust nebula around the planet. For weak dissipation, the inclination of the orbit to the equator has varied little in 4.5 billion years. Phobos has revolved around Mars at a distance no greater than 7-10 times the planet's radius since it appeared, and its orbital eccentricity has been about 0.6. In the case of strong dissipation, the major axis of the planet's orbit could have exceeded 20 times Mars' radius, and a highly eccentric orbit could have lain on the plane of the elliptic.

To consider the alternative scenarios which allow for strong or weak dissipation, we will introduce parameter A, which expresses the relationship of the tidal effect on the satellite and on the planet. Mignard calculated A=20 as the most likely value. In this case Phobos' eccentricity will diminish, the radius of its orbit will decrease, and the satellite will fall to Mars in about 36 million years or even earlier. Deimos' orbit will evolve very slowly.

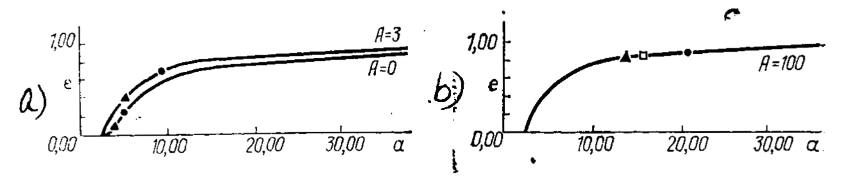


Fig. 18. Change in the eccentricity of Phobos' orbit as a function of the change in its major semi-axis (in Mars' radii): a - A=1, 3; b - A=100. Evolution took 0.5 billion years (triangles); 2 billion years (squares); 4.5 billion years (dots).

Calculations of the evolution of Phobos' orbit in the past appear in fig. 18, a and b, where eccentricity is expressed as a function of the major semi-axis of the orbit. Figure 19, a and b show the change in the inclination of Phobos' orbit toward the plane of the planet's orbit and its equator as the major semi-axis changes for different A values. Unlike the results obtained by Cazenave, Dobrovolskis, and Lago, consideration of the effect of the change in eccentriciy on the orientation of the LaPlace plane somewhat elongates the time scale of the evolution of the inclination of Phobos' orbit. /50

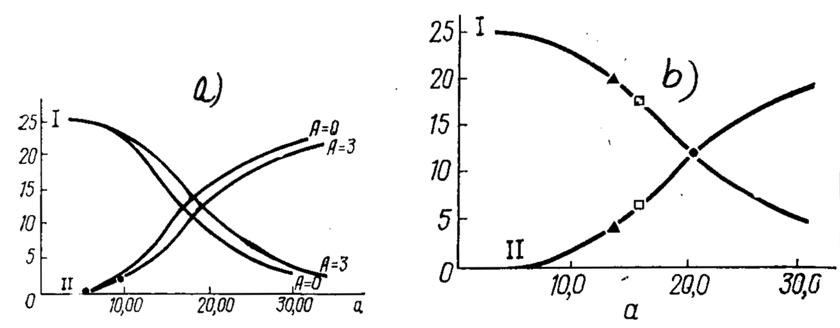


Fig. 19. Evolution of the inclination of Phobos' orbit as a function of change in the major semi-axis: a - A=1, 3; b - A=100. Evolution lasted 0.5 billion years (triangles); 2 billion years (squares); 4.5 billion years (dots); I - inclination to orbit; II - inclination to the equator.

However, for large A values, the evolutionary time scale is quite acceptable, and a major semi-axis 25 times the planet's radius is quite attainable (the satellite's initial orbital plane and that of the planet coincide). This evolution of Phobos' orbit makes it possible to consider the hypothesis of entrapment as the more likely. The major objection, made by J. Berns, that conditions permitting current small inclinations in the orbital planes of the Martian satellites are highly improbable, is eliminated.

Mars' "Forgotten" Satellites. Modern theories of the entrapment of the Martian satellites indicate that Phobos was trapped first, followed a little later by Deimos. But is it not possible that there were entrapments before Phobos? Could these satellites, trapped before Phobos have ceased to exist by now, having fallen to Mars as their orbits evolved? Can we now try to find any evidence of the past existence of these forgotten satellites of Mars?

P. Schultz and E. Lutz-Gerikhen proposed to find the answer to this last question by studying Mars' surface. If they fell /51 at low velocities, these previously existing satellites must have made impacts on Mars' surface in the form of craters -- with oblique angles of incidence for the crater-forming body. The systematic study performed by these researchers on these craters showed an anomalously large number of craters with clearly non-random orientation distribution.

It was assumed that these formations could have resulted from the past existence of Martian satellites similar to Phobos and Deimos with rapidly evolving orbits lying in a plane close to the planet's equatorial plane. If this interpretation is valid, then changes in the orientation of the satellite orbit's major semi-axis over time indicate that the planet's poles have wandered.

Identification of craters with oblique angles of incidence for the crater-forming body is based on four criteria: 1) ellipsoidal form, 2) saddle-shaped wall, 3) butterfly pattern of ejected material, and 4) central mountain range on the floor. These criteria were selected on the basis of laboratory experiments and during study of the morphology of ancient craters with oblique angles of incidence for their crater-forming bodies.

The craters studied were placed into 5 categories according to their state of preservation. The first class covered craters with all four properties, perfectly preserved and formed in recent geological ages. The second class retained all the criteria of the first class, but included lighter, deteriorated craters. The third class was made up of craters deteriorated to such an extent that ejecta were still identifiable, but they exhibited no microstructure. The fourth class comprised craters with barely distinguishable ejecta; the fifth, craters with indistinguishable ejecta.

A total of 175 craters were identified. The azimuth corresponding to the largest diameter of each crater indicated the direction of the impact and both the direction and position of the crater itself clearly defined the orbital plane of the descending body. The axis perpendicular to the satellite's orbit and crossing the center of the planet intersects Mars' surface 90° from the crater in the direction perpendicular to the azimuth of the impact. These points are called poles. /52

The distribution of these poles for various crater classes reveals specific sets of orbits for former Mars satellites. For example, the orbits of forgotten planets which formed the youngest craters when they fell (classes 1 and 2) yield a grouping within 40°, relatively symmetric, in the planet's polar regions (fig. 20). This region is only about 23% of Mars' surface area, but contains 56% of the poles; i.e., clearly, the orbits of a large number of forgotten satellites had a complex orientation.

Older craters have about 50% of the poles, grouped around the point 45°N, 180°W in a spherical segment constituting 36% of the planet's surface area. Figure 20 shows that there are two main regions where their poles are concentrated -- with coordinates 60°N, 90°W and 30°N, 190°W. The oldest craters have poles concentrated in three regions with centers at: 40°N, 50°W,; 0°N, 180°W; and 30°S, 80°W. In this group, 38% of the poles lie within 30° of the equator (fig. 20, c).

These results are difficult to explain in any other way except that Mars once had a large number of satellites, of which Phobos and Deimos are the only remaining representatives. In fact, as compared with Mars, neither Mercury nor the Moon has such a relative frequency of craters formed by collision with a crater-forming body at an oblique angle.

From this viewpoint, we derive a natural explanation for the fact that the longest-preserved satellites are concentrated in orbits close to the planet's equatorial plane. The forgotten satellites may have had other orbital orientations, and the planet's poles may also have migrated.

Indeed, it is not impossible that these are secondary craters from discharges when Mars collided with large bodies. However, the appearance of these craters during collision with bodies moving in heliocentric orbits with small inclinations is highly unlikely due to the sampling criteria and the statistical grouping used.

In conclusion, note that studies of Phobos and Deimos have /53
turned a new page in the study of the Solar System. Just recently, these two minute satellites were merely physical points to us. Now we know their dimensions, masses, average densities, and surface structure. We know that they are apparently C-asteroids -- a very important and interesting type of primary object in the Solar System. Nevertheless, fundamental questions of the origin of these satellites, their age, composition, and structure, remain unanswered.

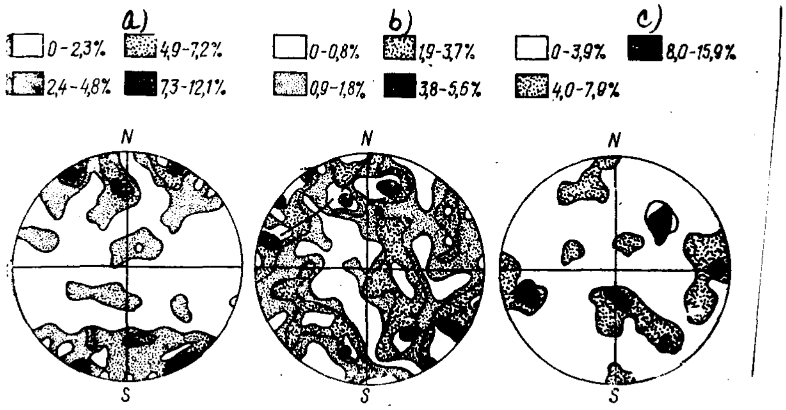


Fig. 20. Distribution of orbital "poles" for satellites which have fallen to Mars:
a - Youngest craters (classes 1 and 2); b - Older craters; c - Oldest craters.

Clarifying these questions is extremely important in reaching a general understanding of the origin and evolution of the Solar System. Therefore, it is not impossible that, in this century, study of Phobos and Deimos will continue via spacecraft landing on their surfaces. Until then, the Martian satellites will obviously be studied in detail during close flybys of spacecraft entering orbit around Mars.

Landing a spacecraft on a satellite's surface makes it possible to greatly expand research methods. Direct analysis of soil structure and composition is possible, and drilling can be done as part of a wide range of geophysical methods. This makes it possible to construct a model of their internal structure. To this end, seismic experiments on the satellites becomes /54 promising. Finally, important information can be acquired during direct measurements of the thermal flow from the satellites' interiors.

Close flybys by spacecraft also help greatly to broaden investigations of Phobos and Deimos. Creation of photographic atlases of Mars' satellites, maps of their surfaces, stereosurveys of their entire surfaces, and more detailed study of their structures will show more completely how they look. Equipping spacecraft with high-sensitivity gradient meters will make it possible both to obtain precise evaluations of satellite masses and to determine the structure of their gravitational fields. Remote probes of Phobos and Deimos using appropriate equipment are quite promising in this regard.

Similar spacecraft studies will probably be simultaneously conducted on asteroids. Naturally, comparison of the results of direct investigations of asteroids on the one hand and of Phobos and Deimos on the other will make it possible to answer many questions which, as this brochure has noted, now confront researchers.

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ARE QSO GALAXIES SPIRAL?

There are now few astronomers who doubt that quasars and other quasi-stellar objects (QSOs) are the nuclei of remote galaxies. Some are even certain that QSO galaxies, i.e. those which include QSOs are among the so-called type I Seyfert galaxies. QSOs are referred to by this name in several articles. But what are the grounds for assuming that QSO galaxies are similar to spiral galaxies with active nuclei, which is what Seyfert galaxies are? Of course, many characteristics of these objects are quite similar if we ignore the scales on which activity is manifest. However, complete clarity requires direct observation of QSO galaxies, and this is not simple. QSOs cannot be resolved even in the largest telescopes; i.e., they remain point-like formations, as demonstrated, for example, by the Palomar sky survey, where the fine structure of a great number of galaxies is seen, but not that of QSOs. Indeed, not even use of modern electronics on the largest telescopes makes it possible to identify many details of optical targets missing on the best photographs obtained by direct photography using the world's largest telescopes. Thanks to the use of electronics with much higher light sensitivity than ordinary photoemulsions, it has been possible for the first time to resolve QSOs, identifying in several an extended weak envelope: the QSO galaxy's wake. At first this was done for 3C 47 and 3C 273, the QSOs closest to us, which have red shifts z=0.37 and 0.158 respectively. In several of its characteristics the envelope of 3C 273 strongly resembles a gigantic elliptical galaxy, as does that of 3C 48, although the most recent spectroscopic analysis indicates that it may be a spiral galaxy. It was recently announced that /56 envelopes of another 85 QSOs have been observed, and conclusions about the type of QSO galaxies were completely different (Astrophys. J., 1984, vol. 280, No. 1). It is interesting that observations were performed with small telescopes equipped with modern electronic radiation receivers. J. Hutchins, D. Crampton, and B. Campbell used the 1-m telescope of the Franco-Canadian Observatory on Hawaii to obtain optical images of 78 QSOs, and only 8 exhibited no envelope. In the authors' opinion, 40% of the recorded envelopes had the properties of spiral galaxies. The others, although their morphological type has not been defined, exhibit no indications that they are elliptic galaxies. The sample is uniform, i.e. an equal number of QSOs identified in the radio-, optical, and X-ray spectra. Indeed, they all possess rather strong luminance in the optical range and are rather close to us (z less than 0.7). In contrast to these criteria, M. Melken, B. Margon, and J. Kenen, who used the 1.5-m telescope at Mt. Palomar, observed 24 QSOs with relatively low luminance in the optical range discovered during identification of X-ray sources recorded by the satellite Einstein. All 15 QSOs with z below 0.4 exhibited envelopes;

they were identified with less certainty in two QSOs with z=0.45. One of the authors' conclusions is quite categorical: "All 15 QSOs with z=0.4 or less...closest to us were classified as nuclei of type 1 Seyfert galaxies with high luminance." As regards the envelopes themselves, the authors usually relate them to normal spiral galaxies on the basis of several characteristics. There is a clear difference in the characteristics of the envelopes of these QSOs and those of 3C 48 and 3C 273. Here the authors come to an unexpected conclusion, hypothesizing that there may be two types of QSO galaxies -- elliptic QSOs, which are strong radio sources (similar to radiogalaxies), and spiral QSOs, identifiable especially in the x-ray spectrum. Generally speaking, this contradicts the findings of Hutchins, Crampton, and Campbell, who considered a uniform sample of QSOs including strong radio sources, although they concluded that all QSO envelopes detected /57
do not have the characteristics of elliptic galaxies. In addition, Melken, Margon, and Kenen believe that, given the high luminance of QSOs in the optical spectrum, it is difficult to separate light from the QSO itself from the weak emission of the envelope; therefore, they used a sampling of QSOs with relatively low optical luminance. Just the opposite was the case in the QSO sampling of Hutchins and his colleagues. Naturally, this is cautionary, and final conclusions can be made apparently only after careful spectroscopic analysis of envelopes detected near QSOs. However, detection of weak envelopes near almost 100 QSOs is an unquestionable achievement.

QSO COVERAGE BY A GALAXY

The "harvest" of discoveries made on the basis of results obtained by the x-ray satellite Einstein continues. Time after time a new identification of sources recorded by it yields something new. Several such discoveries were made in the field if extragalactic astronomy, and they are all related to QSOs. For example, identifying source 1E 0412.5-0803, astronomers observed that this QSO, which lies in the cluster of galaxies, is a rather rare case and quite interesting to scientists. To the joy of lovers of "gravitational lenses", a pair of QSOs with an identical red shift (1E 0849.0+2845/1E 0850) was detected during identification. This was the discovery of a unique coverage of QSOs by a galaxy, as clearly indicated by optical surveys on X-ray source 1E 0104.2+3153 (Sky and Telescope, 1984, vol. 68, No. 4). This source was detected on June 30, 1980, but observations after this on February 15, 1981 gave a negative result. Nevertheless, it was possible to localize the source in the sky with an accuracy to 30", and in February 1982 R. Shield made his preliminary identification. Then J. Stock and J. Liebert performed a spectroscopic survey of all optical objects in the range 1E 0104.2+3135. They used the 2.3-m telescope at the Steward Observatory and a composite (multi-mirror) 10-m telescope in Arizona. The latter is usually used to find /58
sparks of Cherenkov radiation in the atmosphere which arise

during the interaction of the atmosphere and cosmic gamma-rays of superhigh energy. However, it has recently come into use for several other astrophysical investigations. It turned out that there is a small cluster of galaxies near the X-ray source: one QSO and several Milky Way Galaxy stars. Apparently, x-rays come from the giant elliptical galaxy, which dominates the cluster. However, the QSO, which has a red shift z=2.03, may also be an x-ray source, since it is very close to the elliptic galaxy in the sky. Generally speaking, it is so close to it that it is actually observed through its peripheral portion. It is interesting that cases of galaxies neighboring QSOs were presented previously, as evidence of the possible non-Doppler nature of the QSO's red shift. The adjacency of a QSO to a galaxy with a much smaller red shift can be interpreted as the actual proximity of these objects in space. However, 1E 0104.2+3153, which is the closest proximity in the sky of a QSO and a galaxy, indicates otherwise. QSO spectra obtained by Stock and Liebert have a noteworthy pair of absorption lines near the 440-nm wavelength. It is easily identified with the well-known pair of lines for ionized calcium (H and K), shifted by z=0.11, although all other lines in the QSO spectrum were shifted, as noted, by z=2.03. The origin of the H and K lines in the QSO spectrum is apparently related to the absorption of light coming from the QSO and propagating on its path across the elliptic galaxy. This certainly evidences the reality of the considerable spatial separation between the QSO and the galaxy. Detection of the pair of H and K lines is important not just because of this circumstance. The fact is that, previously, the presence of this pair had been detected in the spectra of three remote galaxies, but one of them was not elliptic. More careful spectroscopic investigations will undoubtedly make it possible to obtain new and, possibly, unexpected information, since for the first time it is possible to study a galaxy "illuminated" /59
by QSO rays. Therefore, it is appropriate here to discuss again the effect of the "gravitational lens." There are now six known multiple (including double) QSOs with identical red shifts (including 1E 0849.0+2845/1E 0850), which can be interpreted as the manifestation of the gravitational focusing of light beams emitted by the QSO closest to us by a "galactic lens." The latter so bends QSO light beams that it produces several images of it in the sky. Many astronomers do not doubt the veracity of this interpretation, but others are wary of the negative result of the search for the "lens" galaxy. In the case of 1E 0104.2+3158, when the QSO image is covered by the image of the galaxy, we can for the first time observe such a "lens" galaxy. Einstein, predicting in 1936 the effect of gravitational lenses, grasped the idea of projected objects in the sky. Naturally, given the nearby location of objects in the line of sight, the possibility that such QSO images can arise is eliminated, although the lens galaxy can amplify the QSO's light and create several other effects. Only further observations will show how much this corresponds to reality.

NEWS ABOUT THE DEVA CLUSTER

The cluster of galaxies in the constellation Deva, or simply the Deva Cluster, has long attracted astronomers. First, it is the galaxy cluster closest to us, being 10-20 Mpk from our own group of galaxies. Second, it lies in the center of the so-called Local Supercluster of galaxies, which includes our own galaxy group, which includes the Galaxy itself and the Andromeda Nebula. However, study of this cluster, discovered in 1926 by H. Sheply and A. Aimson, is hindered by the extremely fragmented structure of the cluster, as well as the unknown amount of action from the Local Supercluster, to which our group of galaxies belongs. Finally, the proximity of the cluster Deva, although strange, complicates analysis of the distribution of galaxies in it. Hubble's law, used to determine the distance to galaxies, is quite indeterminate in the case of relatively close galaxies. It is sufficient to say that, if the average speed /60
of galaxies is 1,000 km/sec in the Deva cluster, the spread of velocities may be 100 km/sec, and it is precisely with this accuracy that the speeds of galaxies at the distance of the cluster Deva are determined if Hubble's law is used. Nevertheless, in recent years, quite important results have been obtained regarding the structure of this cluster. For example, it has been decisively proven that the cluster Deva is expanding. Average velocities of galaxies in the cluster increase relative to distance from the center of the cluster. This result contradicts the previously used spherical model of the cluster (with expanding envelope). If galaxies with velocities of 2,000-2,500 km/sec were previously included in the cluster Deva, in the light of new concepts, as well as with regard for the effect of the Local Supercluster, attribution of these high-velocity galaxies to the cluster is questionable. This is supported by J. Wakuler's observation in 1960 of "clouds" from 24 galaxies with an average velocity of 2,198 km/sec (W-clouds), which do not belong to the cluster Deva, but had formerly been included in it. Recently K. Phteklis, M. Fenelli, and M. Stramble announced discovery of two more galaxy groups formerly attributed to the cluster, but, indeed, far from it (Astrophys. J., 1984, vol. 282, No. 1.). The existence of one of the groups, called the M-cloud, was indicated in 1928 by Sheply and Ames. However, it was then decided that this was one of the cluster groupings. As it has now been established, 29 M-cloud galaxies, with an average velocity of 2,179 km/sec, lie outside the cluster Deva. One more group of 16 galaxies (N-cloud), unlike the two previous, has a low average velocity, but Phteklis and his colleagues present conclusive evidence that it does not belong to the cluster and is also far from it. The authors explain the fact that a low-velocity group of galaxies lies far from the cluster Deva by a unique manifestation of the Local Supercluster. One must say that the elimination of a substantial number of galaxies from the cluster Deva (from 9% for relatively bright galaxies and, according to estimates, to 20% for weaker members) changes certain ideas about this cluster

closest to us. First, it must be somewhat closer to us, and, second, the average velocity at which the cluster is moving away must be somewhat slower. It is interesting that the spread of galactic velocities remains unchanged after this group of galaxies has been subtracted, which in the authors' opinion indicated the actual "differentness" of these groups. One other change pertained to the structural type of the cluster Deva. There are two broad classes of galactic clusters: one with galaxies strongly concentrated toward the center, and one with more or less uniform distribution of galaxies in a fragmented structure (the latter includes Deva). Removal of galaxies from Deva has even more strongly reduced the concentration of galaxies toward the center of this cluster, making it an almost marginal representative of this cluster class. Of course, the results still require confirmation, specifically by corresponding observations of the most representative members of the clouds detected (e.g. NGC 4254 galaxy from the M-cloud and NGC 4321 galaxy from the N-cloud). /61

DOUBLE GALACTIC NUCLEI

A galaxy's nucleus comprises the most noteworthy galactic formations, which sharply differ from all other components of the galaxy in terms of their characteristics. The activity of the processes going on in them at any one time is so great that their stormy manifestations become comparable to the galaxy itself, and sometimes overshadow it (remember quasars). However, although they determine the power of a whole galaxy and often the structure of this stellar system, nuclei are almost inaccessible to observation in the optical range. Therefore, little is known about their composition, structure, and power source. The secret of galactic nuclei can be penetrated only by investigation in the radio, infrared, and ultraviolet spectra. Specifically, the nuclei of certain galaxies are extremely active in the UV range, which gave Soviet astronomer B. E. Markaryan the basis for compiling a catalog of galaxies with strong excess UV radiation. Detailed study of these objects has confirmed the considerable activity of Markaryan's galactic nuclei and led to the discovery of unexpected objects. /62 Specifically, A. R. Petrosyan, K. A. Saakyan, and E. Ye. Khachikyan, recently surveying Markaryan's galactic catalog with a 6-m telescope, made an important discovery: almost 10% of the galaxies studied have a multiple nuclei (most often two). The duality of the nuclei of certain galaxies was known previously. For example, 15 years ago, F. Zvicki observed that galaxy NGC 5256 has a double nucleus. Two nuclei are actually observable: one lies slightly to the northeast (a), the other to the southwest (b). Galaxy NGC 5256 has recently attracted the attention of many astronomers, partially because, with high excess UV radiation, it occupies a prominent place in Markaryan's catalog. Studies have naturally been related to its galactic nuclei. It has been determined that both nuclei rotate and the rotation of nucleus b is much stronger, as are other manifestations of its activity. According to estimates by Armenian scientists, the masses of nuclei a and b respectively equal $7 \cdot 10^9$ and $3 \cdot 10^{10}$ times the mass of the Sun, and in terms of their characteristics both formations resemble the nuclei of so-called type II Seyfert galaxies. Later, Stock and his colleagues detected a certain elongation of the nuclei from north to south. Then D. Osterbrok and O. Dakhari, after taking careful spectroscopic measurements, established that nucleus a is indeed somewhat weaker than the nuclei of type II Seyfert galaxies. Results were recently published from an almost 7-hour observation of NGC 5256 using the UV telescope on the satellite IUE (Astron. and Astrophys. 1984, vol. 135, No. 6). The spectrum of the galaxy obtained using the satellite-borne equipment confirms its similarity to nuclei of type II Seyfert galaxies. In contrast, the spectral characteristics of nucleus a indicate that this nucleus cannot be classified in this way. The total stream of UV radiation from this nucleus turned out to be half that of nucleus b, Of course, the presence in a Seyfert galaxy of two nuclei with identical activity at the same time would be quite effective. However, it is rather intriguing that, in addition to an ordinary nucleus, a Seyfert galaxy has one other rather active nucleus.

ON THE MAGNETIC FIELDS OF CELESTIAL BODIES /63

In recent years, the nature of the magnetic fields of stars and planets has been thought to be completely understood. The combination of a mechanism such as a dynamo and the process of mixing (convection) of matter in their interiors, which complicates magnetic force lines, correlates satisfactorily with observations. However, Soviet astronomers V. I. Grigor'yev and Ye. V. Grigor'yeva have turned their attention to one class of effects which can significantly influence magnetic fields of celestial bodies (Vestnik MGU, 1984, ser. 3, vol. 25, No. 2). As we know, magnetic fields arise during the movement of electrical charges. Although cosmic bodies on the whole are to a certain extent electrically neutral, the rotation of these bodies can lead to generation of a magnetic field if a process leads to redistribution of charges within the body. In other words, positive and negative charges within a body have a different average distance from the axis of rotation. This situation may occur in most celestial bodies. The fact is that any body in equilibrium due to gravitational forces and internal pressure must be, so to speak, electrically polarized: it must have an excess positive charge inside and negative on the surface. The nature of this gravitational polarization stems from quantomechanical processes which cause different pressures for different sorts of particles. The region of space in which gravitational polarization is manifest is very small, and its size depends on the density of the matter. At the density of matter typical for stars and planets (about 1 g/cm^3), electrons, for example, experience stronger quantomechanical pressure than do ions with higher mass. Therefore, electrons on the average are arranged somewhat farther from the planet's center, although the difference is slight -- less than the size of an atom. However, separation of the charges still takes place -- excess positive charge arises within the planet's or star's interior, a very thin negatively charged layer on its surface. If this star (or planet) rotates, then it must develop a magnetic field. Calculations conducted by Grigor'yev and Grigor'yeva show that, outside a rotating sphere, the developing field has an ordinary dipole structure just as do the magnetic fields of Earth and other planets. The intensity of the magnetic field within the framework of this theory depends only on the radius, mass, and velocity of rotation of the planet, not on the details of its internal structure (e.g. on the presence or absence of a metallized nucleus or convective movements in the interior). Of course, the proposed mechanism for generation of a magnetic field does not repudiate the role of the dynamo process, but is augmented by it if there are convective movements of matter in the planet's interior. How realistic is the Soviet scientists' hypothesis? On the one hand, the complex geometry and time-related changes in magnetic fields observed in stars and planets mostly probably indicate interaction of several physical mechanisms of field generation. On the other hand, there is apparently initial experimental confirmation of the action of this type of quantomechanical effect. B. V. Vasil'yev, member of the All-Union Institute for Nuclear Research (OIYaI) in Dubna recorded the appearance of a magnetic field in electrically neutral bodies (Pr. OIYaI, 1983, R14-83-406) in experiments with rotating metal cylinders. This quantomechanical effect, unlike gravitational polarization, is related to manifestation of centrifugal forces which, in the experiment, played virtually the same role as does gravitation in celestial bodies (although in the opposite direction).