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30 years of the Vega mission: Comparison of some properties of the 1P/Halley and 67P/Churyumov–Gerasimenko comets

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Contents

Abstract. On March 6 and 9, 1986, for the first time in the history of science, the Russian spacecraft Vega-1 and Vega-2 approached and closely passed by the nucleus of Halley's comet (1P/Halley). A few days later, on March 14, 1986, the same was done by the European Space Agency's (ESA) Giotto spacecraft. These missions, together with the Japanese Suisei (JAXA), marked a successful start to spacecraft exploration of cometary nuclei. Subsequent missions to other comets have been aimed at directly studying cometary bodies carrying signs of the formation of the Solar System. The Rosetta spacecraft, inserted into a low orbit around the nucleus of the 67P/Churyumov–Gerasimenko comet, performed its complex measurements from 2014 to September 2016. In this review, some of the data from these missions are compared. The review draws on the proceedings of the Vega 30th anniversary conference held at the Space Research Institute (IKI) of the Russian Academy of Sciences in March 2016 and is not meant to be exhaustive in describing mission results and problems in the physics of comets.

Keywords: comets, cometary physics, space investigations, comparison of comets

1. Introduction

In historical documents, the appearance of comets has always been attributed to major events. Halley's comet was mentioned for the first time in ancient Greek chronicles in 468–466 BC and at the same time was noted in Chinese records. Only in 1531 and 1607 did the appearance of Halley's comet start to be recorded in the Julian and Gregorian calendars, respectively. However, before Edmond Halley (1656–1742), comets were hardly regarded as objects related to the Solar System. According to Aristotle (384–322 BC), a comet was not an astronomical but an atmospheric phenomenon. Unlike the planets, their appearance was unpredictable, as was their movement, which is not related to the Zodiac constellations, where all the planets move. Comets appeared from 'nowhere' and disappeared to 'nowhere'. All this led Aristotle to assert that comets were a vapor rising from the Earth and accumulating in the upper 'flamy' part of the atmosphere, where they slowly burn out. Centuries passed. Lucius Seneca (4 BC–65 AD) was the first to claim that the movement of comets outside the Zodiac belt is not a reason to exclude them from being astronomical objects and that the comet is an eternal product of Nature.

Then came another time. In 1578, Andreas Celichius criticized Aristotle's ideas by viewing a comet as "the thick smoke of human sins, rising every day, every hour, every moment, full of stench and horror before the face of God, and becoming gradually so thick as to form a comet, with curled and plated tresses, which at last is kindled by the hot and fiery anger of the Supreme Heavenly Judge" (cited from reviews [1, 2]).

Around 1740, Halley's comet became one of the dominant catalysts in the development of astronomy and is still the subject of profound research. The appearance of Halley's comet in 1758–1759 was predicted by the calculations of Edmond Halley and the subsequent work of Newton. Besides scientific interest, there are also two more reasons for public interest in the comet. First, Halley's comet returns about every 76 years. The interval between returns is not too long for the interest in the event to be lost, but not too short for the appearance of a large comet to become a trivial phenomenon. Second, although most comets are not so bright to attract the attention of common people, they are bright enough to be seen by the naked eye of an inquisitive amateur astronomer. Halley's comet belongs to the brightest

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short-period comets (those with orbital periods less than 200 years). In the 17th century, it was called the comet de la Caille, in honor of the French astronomer Abbe Nicholas-Luis De la Caille. However, already by its next return in 1835, the name 'Halley's comet' had become generally accepted [2].

Halley's comet (1P/Halley), one of the largest short-period comets, was destined twice to play a major role in comet research. First, it was the work of Edmond Halley, who observed a comet in 1682 in London and subsequently devoted all his life to comets. Halley was the first to establish the periodicity of the appearance of 1P/Halley and other comets and to create analytic tools for their research. He succeeded in attracting Newton to this work. The history of the problem is described in detail in [2] (1986). It is interesting to note Newton's conclusion, cited in his *Principia*: "the bodies of comets are solid, compact, fixed, and durable, like the bodies of the planets." Newton probably came to this conclusion mainly because the comet 1680/1 was preserved after passing its perihelion located very close to the Sun. At the same time, he also wrote that, in approaching the Sun, the comet's head starts evaporating into the aether medium, "and those reflecting particles heated by this action, heat the matter of the aether which is involved with them. That matter is rarefied by the heat which it acquires, and because, by this rarefaction, the specific gravity with which it tended towards the sun before is diminished, it will ascend therefrom, and carry along with it the reflecting particles of which the tail of the comet is composed...." Two years after the death of Halley, in 1744, M V Lomonosov observed a large comet and came to the following conclusion: "On the shady side it is cold, on the sunny side it is hot. Near the shadow, a strong atmosphere movement takes place, and this is the reason why a great electrical force is excited and arises" [3].

The second time Halley's comet appeared on the front pages of scientific publications was 300 years later, in 1986, when it became the first comet whose nucleus was explored by a spacecraft. Historical studies of 1P/Halley (1986) by the Vega, Giotto, and Suisei missions were made 30 years ago. Since then, spacecraft have explored five other comets. More than two years have passed since the beginning of direct studies of the comet 67P/Churyumov–Gerasimenko (referred to as 67P/CG below). Numerous papers on this research have been published, and some of the results are partially discussed below. A Russian overview of preliminary results is published in *Solar System Research* [4]. One of the most significant conclusions is the ever complicated physics of comets, indicating a large diversity of these objects. Differences in the physical properties of comets suggest the extreme complexity of the physical-chemical properties of the environment where they originated.

Many cometary nuclei keep traces of processes that occurred during the first stages of the Solar System's formation. At present, improvement in the spectroscopic equipment of ground-based and space observatories makes it possible to investigate cometary emissions with a very high resolution. It might appear that the chemical composition of cometary nuclei should be known with sufficient accuracy. However, this is not the case. The spectrum of the photometric 'nucleus' can simply be the reflected solar continuum or molecular emission spectrum, which does not carry any information about the nature of the reflecting area. The emission gas spectrum itself provides information on the chemical composition of the atmosphere surrounding the nucleus, but not on its surface. The molecules in the investigated range (C_2, CN, CH, NH, and others) are secondary, subsidiary molecules of more complex molecules or molecular complexes of which the nucleus consists. These complex parental molecules are sublimated into a supra-nuclear gas–dust envelope and are immediately destroyed under the action of solar radiation and due to interaction with the environment. They decay or dissociate into simpler molecules whose emission spectra are 'seen' by spectrometers, and the parent molecules themselves mainly produce a continuous spectrum. As regards the dust, most often it represents a mix of carbon–hydrogen–oxygen–nitrogen infusible organic compounds (CHON) and a rock substance composed of chondrite.

Finally, another obvious problem that cannot be solved without the use of a spacecraft is the exploration of the relief, morphology, and detailed composition of different parts of the nuclei themselves. In this regard, the results of studies of the comet 67P/Churyumov–Gerasimenko by the Rosetta mission exceeded all expectations, as shown below. It was also expected to conduct such studies directly on the surface of the nucleus, but the unsuccessful landing of the Philae spacecraft in 2014 became a great failure of the Rosetta mission. Therefore, further development of this type of research is necessary.

Figuratively, cometary nuclei studies can be thought of as investigations of rather small-mass cosmic bodies with huge scientific baggage. When preparing the Vega mission, one of the French participants compared the interest in comet explorations with the effects created by perfume products: "Small amounts of substance that give rise to strong emotions."

Spacecraft studies of the cometary nuclei are topical largely due to the heterogeneity of the obtained results. It is well known that cometary tails contain plasma and dust, and there is an invariable presence of water vapor, carbon dioxide, carbon monoxide, and many dozens of various ions, atoms, and molecules in the coma and tails. However, most frequently each comet has its own composition. The relative abundance of deuterium (the D-to-H ratio) appears to be heterogeneous, which is commonly believed to characterize not only the physical conditions at the time the body formed but also the role of comets in the creation of the terrestrial hydrosphere. A comparison of the morphological properties of the surface of cometary nuclei, for example, the surfaces of the nuclei of 67P/CG, 1P/Halley, 19P/Borrelly, and 103P/Hartley-2, suggest the complexity and extreme heterogeneity of their formation processes, which can possibly be studied only from a closely located space laboratory or probe descending to the surface of the nucleus.

An important role is played by the possibility of long-term observations of the object and its emissions conducted from landing or low-orbit spacecraft. Sometimes, the obtained results put the researchers at a deadlock, as, for example, was the case with local oxygen emissions by the 67P/CG nucleus (presumably relic origin oxygen) or the presence of different components, differently enriched with various sulfur isotopes. Although comet nuclei are usually divided into types by the ejected material (mainly gas or dust components), a detailed classification of cometary nuclei is far from complete to date.

This paper is based on reports at the memorial conference at the Space Research Institute (IKI) of the Russian Academy of Sciences (RAS) in March 2016 dedicated to the 30th anniversary of the Vega mission and does not attempt to

Figure 1. Ground-based image of comet 1P/Halley, one of the largest short-period comets, obtained during the operation of the Vega mission near the comet on March 6 and 9, 1986. (Source: IKI RAS archive.)

exhaustively cover the problems of cometary physics. The meteor hazard associated with comets was considered, in particular, in [5]. The probability of such events is not high, although the recent event in the Chelyabinsk region (near Lake Chebarkul, 2013) rather loudly reminds us about its existence [6].

Figure 1 shows a detailed ground-based snapshot of Halley's comet (1P/Halley) obtained on March 6–9, 1986, when the Vega-1 and Vega-2 spacecraft were approaching the comet with a speed of up to 79 km s^{-1}. The image clearly shows the numerous strips, jets, and 'rays' formed by gas and dust flows associated with separate sources on the surface of the nucleus. The relatively slow rotation of the nucleus causes the appearance of recurring material clusters (outside the image frame).

Published materials from the 67P/CG and 1P/Halley missions allow us to compare some of the results. The conditions of the experiments were different, however. For example, the Rosetta mission was in a quasisatellite orbit around the comet. The dust component emitted by the comet fell on the device at low speeds, which did not pose a serious threat to the Rosetta spacecraft, although near the perihelion (in August 2015) it was kept at a distance of at least 350 km from the nucleus for safety. In contrast, the Vega-1 and Vega-2 spacecraft approached the cometary nucleus at colliding courses with a tremendous relative velocity, up to 79 km s^{-1}. The transmission of images of nuclei and a detailed study of the composition of the dust and gas emitted by the nucleus, of the magnetic field, and of the plasma surrounding the comet were performed under unprecedented conditions of an enormous meteor hazard. For the first time, at a distance of about 1 million km, the spacecraft crossed a shock wave (Fig. 2), and at a distance of about 160,000 km they crossed the theoretically predicted 'cometopause', where a sharp change in the proton distribution function occurred.

The energy carried by dust grains and fragments of the cometary crust exceeded the energy of the artillery projectile (per unit mass) 7000-fold. Therefore, the Vega-1 and Vega-2 spacecraft, designed and built at the Lavochkin Science and Production Association (SPA), were equipped with unprecedented means of protection, which to a large extent ensured the missions success [8].

On March 6 and 9, 1986, the Russian Vega-1 and Vega-2 spacecraft [9], and after them, on March 14, 1986, the Giotto space probe [10] of the European Space Agency (ESA),

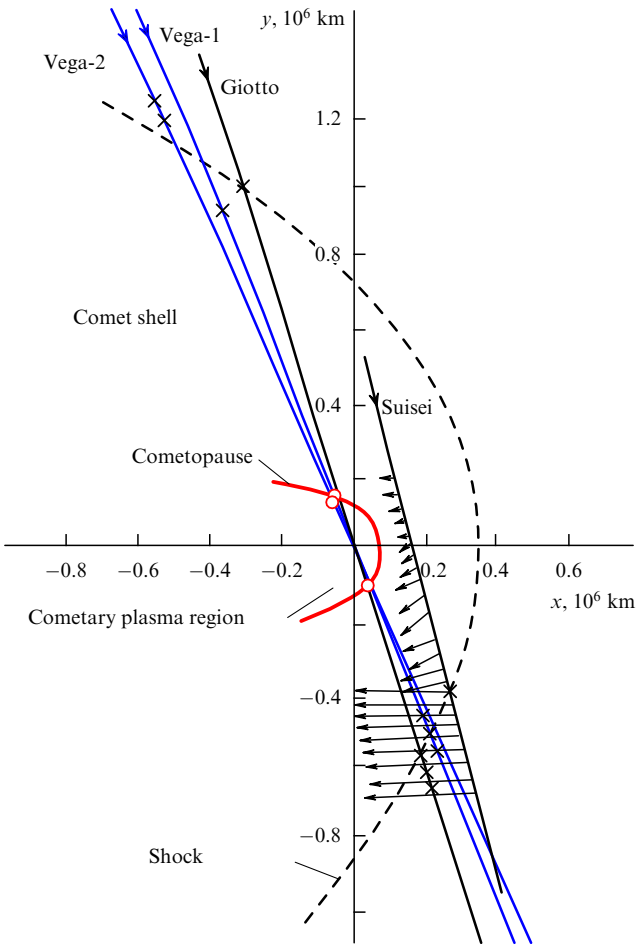

Figure 2. Trajectories of Vega-1 and Vega-2, Giotto, and Suisei spacecraft approaching the nucleus of Halley's comet. The arrows on the Suisei trajectory show the changes in the magnetic field. (From [7].)

initiated historic research on cometary nuclei using space missions. At the same time, on March 8, 1986, the Suisei ('Planet') spacecraft of the Japanese Space Agency (JAXA) passed at a greater distance from Halley's comet [11].

Comet 67P was discovered on October 23, 1969 by astronomers K I Churyumov and S I Gerasimenko at the Astronomical Observatory of Shevchenko Kiev State University during an analysis of five photographic plates that had been obtained on September 9, 11, and 21, 1969 during the comet patrol program. The program was carried out by an expedition from Kiev State University at the Almaty Observatory. Comet 67P was named the Churyumov–Gerasimenko comet (67P/CG). The discoverers were awarded the Medal of the Astronomical Council of the USSR Academy of Sciences "For the discovery of new astronomical objects." Comet research was a matter dear to Churyumov. Comet 67P/CG has been regularly observed by astronomers. Since the discovery of the comet, the perihelion has been passed seven times: in 1976, 1982, 1989, 1996, 2002, 2009, and 2015. In 2014–2016 the comet was the focus of the Rosetta mission of the European Space Agency.

In this paper, we present some results of both missions: to the Halley comet and to the Churyumov–Gerasimenko comet. A comparison of the main numerical data for both comets is given in the summary table compiled by Churyumov and published in [12]. Some refinements are noted in the text and in comments to the table.

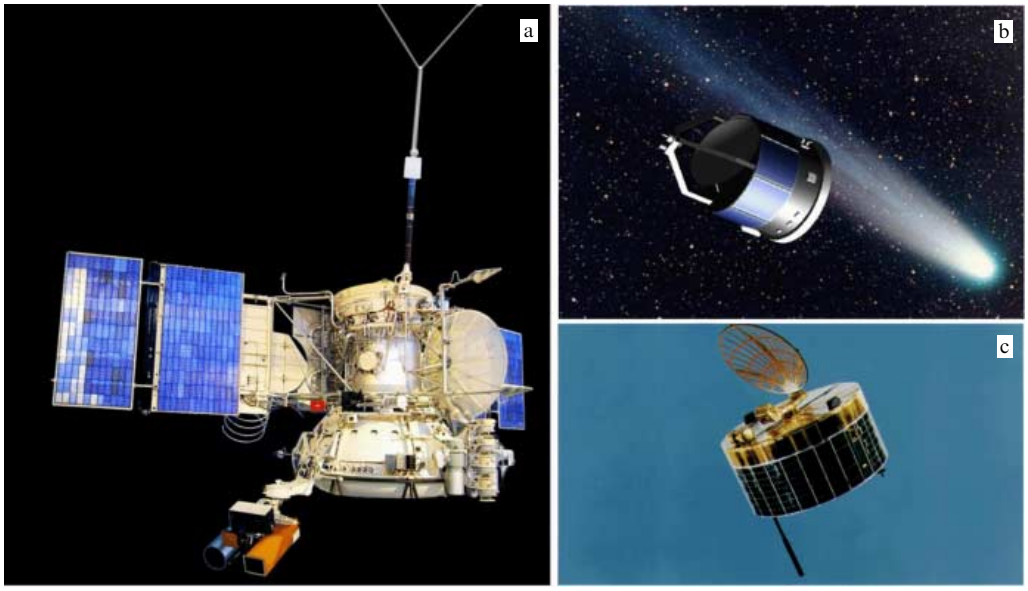

Figure 3. (a) Vega, (b) Giotto, and (c) Suisei spacecraft. The scale of the images is different. The spacecraft are shown without the heat insulating cover. (Source: IKI RAS archive.)

2. Morphological properties of the surface, limited possibilities of comparison, and landing of the Philae probe

The spacecraft mentioned above are shown in Fig. 3; the Rosetta spacecraft in preflight preparation is shown in Fig. 4. Starting with Halley's Comet, six cometary nuclei were explored by spacecrafts by 2016, and taking snapshots of the nuclei was one of the main and most important mission tasks. For example, the cost of carrying out a television experiment is incomparable with the remaining experiment costs. The same applies to the scientific payload of the Rosetta spacecraft, in which (along with an NAC narrow-field camera and wide-field cameras [13]) images in different bands were also taken by other devices (http://sci.esa.int./rosetta/35061-instruments). The OSIRIS system (Optical, Spectroscopic, and Infrared Remote Imaging System) can also provide an example. A significant number of detailed images have been obtained. However, comparing the morphology of the surface of 67P/CG and 1P/Halley is the most difficult. For 67P/CG, there are numerous detailed images with a resolution of up to a few dozen centimeters, but the resolution in the images of the surface of the nucleus of Halley's Comet is about 1 km. The nucleus was observed through a rather dense matter of gas and dust, which are intensively ejected by the nucleus (fuzzy images on the left in Fig. 5a).

In addition, all the spacecraft that participated in the Halley's comet studies imaged reliably only about 25% of its surface, and the Rosetta mission obtained images of almost the entire surface of the nucleus.

The original images of the nucleus of Halley's comet [14] taken by the CCD camera of the Vega spacecraft are shown in Fig. 5a, b. Further processing of the images [15] enabled an improved snapshot of the nucleus and a refining of its shape (Fig. 5c). Figure 5d shows the nucleus of comet 67P/CG. The scale of the images is shown in the figure. The size of the respective bodies is $15.3 \times 7.2 \times 7.2$ km and about $4.1 \times 3.1 \times 2.2$ km. The scale in the figure allows estimating the size of individual elements of the nucleus. It has been noted that the nucleus of Halley's Comet has a

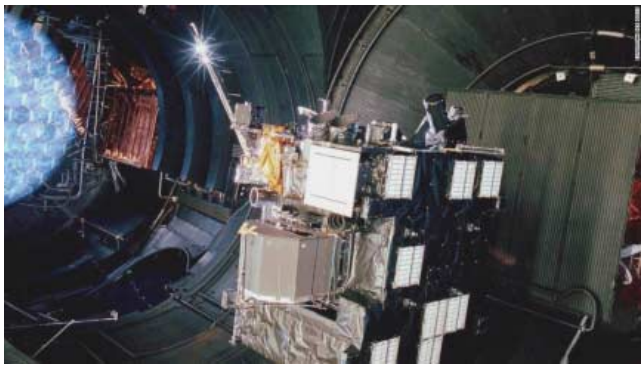

Figure 4. Rosetta spacecraft assembled for tests. The gray protruding block is the Philae probe. (ESA, 140109134929-rosetta-spacecraft-horizontal-large-gallery.)

topographically diverse surface with hills, mountains, ridges, dips, and at least one large crater. In the lower part of the orbit, near the perihelion, when the temperature on the surface of the nucleus increased, active processes destroyed some forms and created other ones. At the perihelion of Halley's comet at 0.5712 a.u., the registered temperature of the dark crust of the nucleus was about 300 K, and at the hottest points it reached 400 K [16].

Near the perihelion, heated pieces of crust were destroyed, separated, and carried away by dust and gas. Nevertheless, the temperature deep inside the nucleus was found to remain very low, which was also noted in the case of comet 67P/CG. Thus, according to the data of the VIRTIS experiment (Visible and Infrared Thermal Imaging Spectrometer), the daytime surface temperature was about 200 K at a depth of 5–6 cm, and the temperature in the investigated parts remained constant at about 130 K [17]. An analysis of the formation conditions of some of the emitted gas components suggests a temperature of 35 K deep inside the nucleus.

More detailed images of Halley's comet (Fig. 6) were obtained by a camera aboard the Giotto spacecraft [10, 18], which operated on a closer trajectory near the nucleus, but was damaged at a distance of 1200 km. The opposite side of

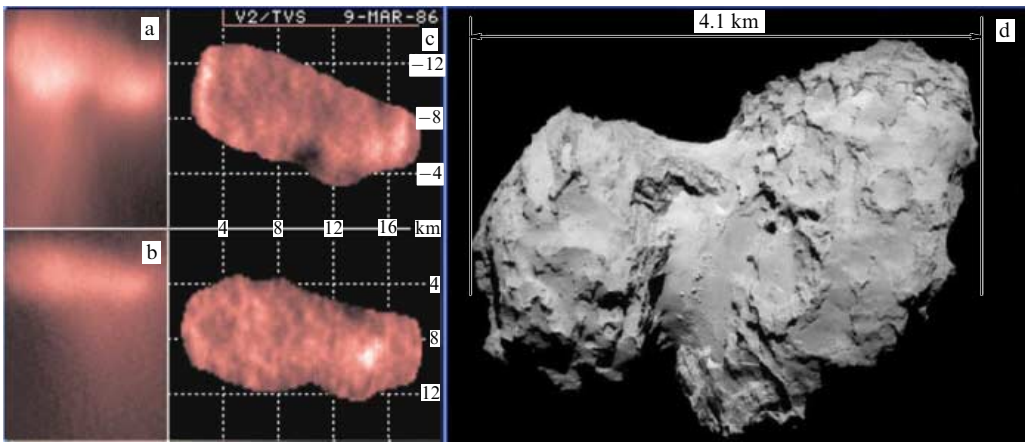

Figure 5. (a, b) First images of Halley's comet (1P/Halley). The image taken by the Vega spacecraft, TVS camera (1986), before processing. (c) The nucleus of Halley's comet after image processing [15]. The sharpness of the images is limited by intensive emission of gas and dust from the nucleus of the comet, through which the nucleus was observed. (d) One of the first images of the nucleus of comet 67P/CG taken by the Rosetta mission in 2014.

the nucleus was observed in comparison with the upper image taken by Vega in Fig. 5. Due to the favorable location of the spacecraft, gas emissions occulted the nucleus less. Its image reconstructed from the Giotto observations is shown in Fig. 7b in comparison with 67P/CG.

New processing methods in [19] allowed obtaining a more detailed image shown in Fig. 8, in which the nuclei of Halley's comet and of 67P/CG can already be compared to some extent. First of all, the general similarity of the shapes of two bodies is clearly seen, despite a fourfold difference in their sizes. Generally, the surfaces of both comets are similar in large details. The 'head' (most of the 67P/CG core) ends in the Imhotep area and has a flatter shape than the head of the nucleus of Halley's comet (Fig. 8). Landing the Philae probe was planned to be near the Imhotep area, in the Agilkia region. The spectrophotometric properties of these areas are considered in [20]. The average geometric albedo of the surface is very low and for Halley's comet is close to 0.04, while for the comet 67P/CG it is about 0.065 at a wavelength of 649 nm.

The nuclei of both comets also have a similar narrow region, a 'neck', light in 67P/CG and dark in 1P/Halley (see Figs 7 and 8). The neck of the nucleus of Halley's comet is less prominent and relates to the darkest areas of the surface.

We note that the physical conditions for the neck are somewhat different from those at the peripheral parts. Such are, for example, the radiation conditions. The solid angle at which the platform on a flat surface near the neck 'sees' free space is 2π, and a pad at the neck sees less than 2π. As shown below, the density of the neck material can be significantly different from that of the adjacent parts. The dark cavity at the neck of the nucleus of Halley's comet has a complex form and can be a developing process of the destruction of the body. At the same time, the origin of the neck in 67P/CG can be a consequence of other processes [21]. In [22], the stress of the comet neck was calculated using the example of 103P/Hartley-2, which is close to destruction. Extended dumbbell cometary nuclei (as in comet 103P/Hartley) are most convenient for analysis of the physical state and possible evolution of the comet nucleus. A detailed calculation has not been carried out for Halley's comet. The comet is much larger in size R and mass M, but its rotation velocity ω is three times lower (the spin period of the nucleus of Halley's comet is 52 hours, and that of the comet 67P/CG is 12.40 hours). Stresses F caused by centrifugal forces in the equilibrium cross section of all mass elements M_i is

$$F = \sum_{i=1}^{N} M_i R \omega^2$$

and turn out to be close to destructive, but smaller than in the case of 103P/Hartley-2. However, such calculations require

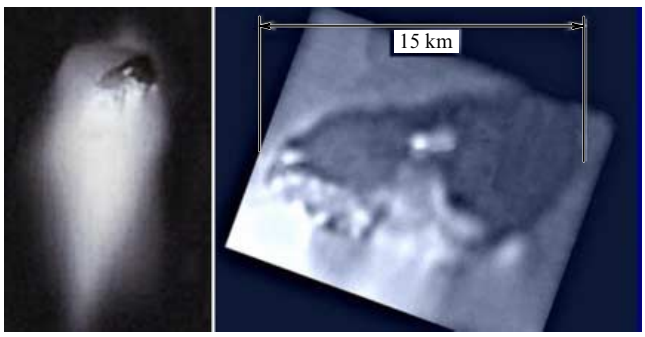

Figure 6. Snapshot of Halley's comet taken by the Giotto spacecraft camera on March 14, 1986. (Source: IKI RAS archive.)

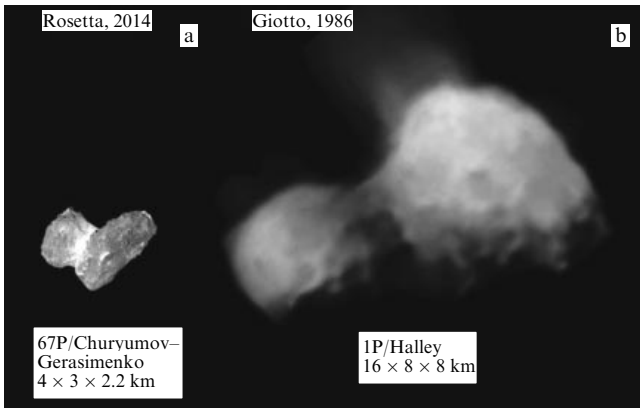

Figure 7. (a) Image of the nucleus of comet 67P/CG (http://rosetta.esa.int/). (b) Snapshot of the nucleus of Halley's comet taken by the Giotto spacecraft in 1986. The objects are on the same scale.

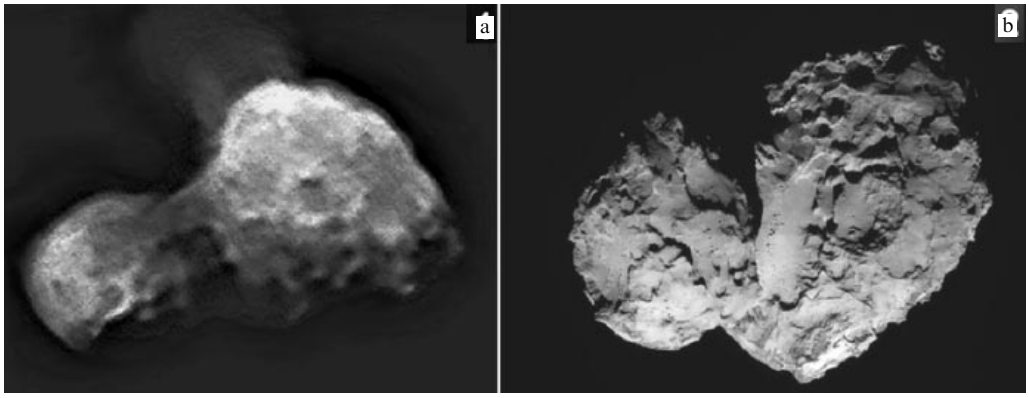

Figure 8. (a) Image of Halley's comet taken by the Giotto spacecraft and processed by the author (published for the first time); scale 1:4. (b) One of the first images of the nucleus of the comet 67P/CG (http://rosetta.esa.int/); scale 1:1.

that the shape of the 1P/Halley comet nucleus be known with a higher precision. In Fig. 8, on the surface of most of the nucleus of Halley's comet (at the center and on the right), we can see three large annular formations (apparently craters) and a more complex structure on the left side of the nucleus, where two closely related objects with a bright boundary are visible. In both parts, they are joined by long plains. The contours of the annular formations are fuzzy; perhaps they are dilapidated craters. Hills, mountains, and hollows are also noticeable. We note that some of the smallest details in Fig. 8 may be an artifact — features of the processing codes. The mechanical model for 67P/CG is much more complicated and includes protruding parts and a complex diagram of the distribution of mechanical stresses. The estimated stresses are approximately the same, but the results need improvement.

The surface of the 67P/CG nucleus, which was studied in much more detail, turned out to be very heterogeneous in comparison with Halley's comet. Detailed pictures given below show the peculiar properties of this nucleus, which sharply distinguish it from the already familiar 1P/Halley or 103P/Hartley-2. Typical 67P/CG and 103P/Hartley nuclei are presented in Fig. 9 and compared with 67P/CG. On the left in Fig. 9, shown is a deep saddle between the larger and smaller parts of the nucleus. Apparently, the surfaces are so different that their properties are difficult to compare. Unlike the relatively smooth dust cover of 103P/Hartley-2, the nucleus of 67P/CG is covered with coarse faults, dips, and lumps.

Images taken at different positions of the nucleus are demonstrative of the nature of the nucleus and its surface. One of the most detailed pictures is shown in Fig. 10. Both halves and the neck are visible. Large blocks are scattered over the smooth (as if powdered) part of the neck of Hapi. The spatial resolution of the image is about 30 cm. On the adjacent Hathor slope (less than half the nucleus), there is a distinct layered structure with a sharp boundary on a smoother surface at the top. Apparently, the nature of the latter surface is a more recent destruction and is identical to the nature of the lower half of the comet facing the observer. In both parts, there are numerous traces of impact craters of different depths and different degradations, as well as coarse fractures of the surface. The light shades in the figure are deceptive; the surface is very dark: the albedo is about 3% (darker than soot). It can be considered light only in comparison to the adjacent dark cosmic background. Deep shadows do not necessarily indicate troughs: the surface is illuminated by direct sunlight, and diffuse light is reflected by

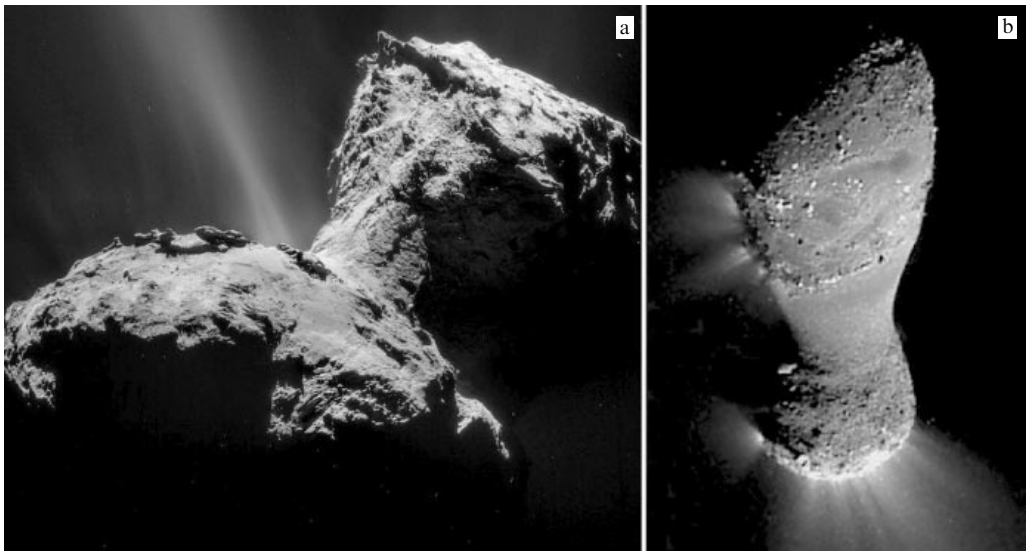

Figure 9. Variety of forms and relief of cometary nuclei. (a) The surface of the 67P/CG nucleus (image ESA/ Rosetta/Navcam — CC BY-SA IGO 3.0 obtained on January 31, 2015), (b) the surface of the 103P/Hartley-2 nucleus (image by JASA, 2005). The characteristic size of the 67P/CG nucleus is twice as large (4.1 and 2.2 km, respectively).

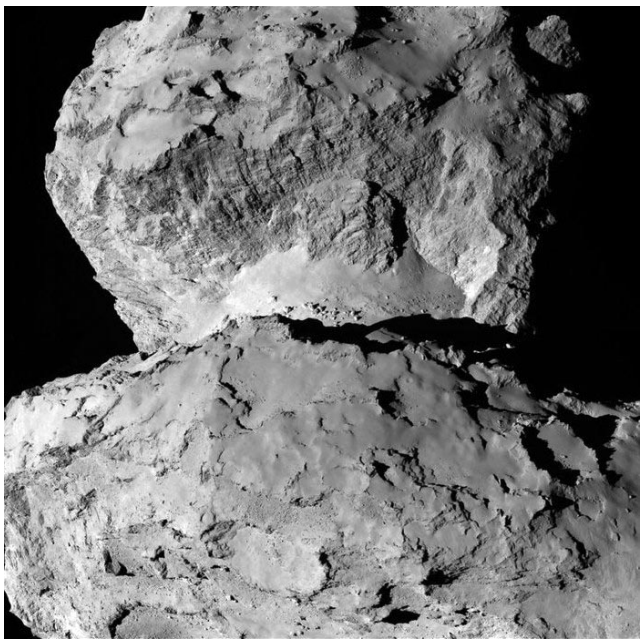

Figure 10. One of the most detailed images showing both halves and the neck of the nucleus. The image was taken by a narrow-angle camera of the Rosetta mission on August 7, 2015, from a distance of 104 km. (Image: MPS/MPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.)

other areas of the relief. This is the surface of a body that has hardly changed over 4.5 billion years, since the origin of the Solar system.

The steep, layered slope of Hathor in Fig. 10 has a height of about 1 km. The barycenter of the body is located at the Hapi saddle near the greater half of the body. The fragments and dust deposits are apparently formed by screes from the slopes of Hathor. However, as became clear after the Philae landing, a thin dust layer covering the surface can conceal very hard rocks, which cannot be drilled. Presumably, its composition is a low-temperature ice environment with inclusions of dust and debris of silicate rocks. The shedding itself occurs very slowly, and the free fall acceleration $g_c = GM/r^2$ at the top and bottom of the wall is not the same. With the body weight $M = 10^{13}$ kg and the gravity constant G, the acceleration g_c is 0.167×10^{-3} m s^{-2} at the peak ($r = 2$ km to the gravity center) and 0.667×10^{-3} m s^{-2} on the surface of the saddle ($r = 1$ km). In these conditions, it would take more than an hour for debris to fall from the top.

On the basis of morphological and structural features, the authors of [23] identified 19 characteristic surface types, each given a name borrowed from ancient Egyptian mythology. The zoning, marked according to geomorphological principles, with the marked names of the objects, is shown in Fig. 11.

The nucleus rotates with a period of 12.4043 h about the axis passing through the mass center. Rotation leads to the appearance of centrifugal forces. It can be assumed that under their action, a slow but continuous elongation of the neck occurs, which should result in the nucleus fragments separating. This is impeded by the strength of the neck material, the attraction between the parts of the nucleus, and the gradual deceleration of its rotation due to friction losses in the neck material and the gradual elongation of the body.

The diversity of relief of the 67P/CG nucleus is also illustrated in Fig. 12, where the processed image of the complex Atum–Anubis region is shown (in Fig. 11, it is on projections 1 and 2), the length is 1.6 km. Among the types of surface, the most common is what the authors called consolidated and destroyed surface. In some cases, regions with a smooth surface (formed by fine-grained dust material with block inclusions) adjoin it. Such areas are also numerous. The authors of [23] note that their formation is probably related to the ongoing sublimation of the volatiles that make up the comet nucleus. The inhomogeneity of the propagation of subliming inclusions is evident, which results in the formation of huge gaps. In many places, a layered surface structure is observed. The structure of the wide (up to 1 km) steep slope of the nucleus 'head' (Fig. 12) with screes of collapsing material and signs of stratification is interesting, in sharp contrast to the adjacent neck region. The variety of areas includes small hills, annular formations (some of which can be destroyed craters), plains, and deep faults. The surface is extremely heterogeneous: the left part of the region is composed of elements resembling layered structures, and the Anubis area (on the right) is covered with smoother sediments. On the bottom right, a part of the 'shaded' neck can be seen.

Partial sublimation of the nucleus material leaves fragile formations with a bizarre shape. The origin of some objects, features, heterogeneity, and the 'variegation' of the surface structure of 67P/CG were considered in detail in [13, 23–27], among others. It was expected that important data would be obtained by the Philae probe.

For the first time, the Rosetta mission was equipped with a landing module to explore the surface of the comet nucleus. Philae was the first probe designed for a soft landing on the nucleus of a comet. It was equipped with different instruments for scientific research. The mass of Philae is 100 kg. Prior to the Rosetta mission, two spacecraft, NEAR Shoemaker (Near Earth Asteroid Rendez-vous Shoemaker) (2000) and Hayabusa ('Peregrin') (2005), had made experimental (unplanned beforehand) soft landings on the Eros and Itokawa (2005) asteroids, respectively, and then the Hayabusa apparatus took off and returned to Earth. The ballistic (uncontrolled) descent of the Philae probe took place on November 12, 2014. The choice of the landing site was very important. On the one hand, the possibility of easily watching the adjacent relief and studying the surface was assumed; on the other hand, the safety of the landing surface was important, and the lighting conditions had to ensure the operation of solar cells. Due to low gravity, the descent time (in fact, falling on a comet from a height of 20 km) reached 7 hours. The spacecraft descended along a ballistic (uncontrolled) trajectory and landed on the surface. A system of three pillars was equipped with devices to weaken the impact when landing. Three devices — a clamping rocket motor on the upper side of the Philae probe, ice screws on the supports, and a harpoon to pierce the surface — were supposed to prevent a bounce. The ice screws were driven by the impact energy when landing and were supposed to crash into the surface. Then harpoons, fired off by special pyrocartridges, were to be pushed into the surface at a speed of 70 m s^{-1}. The clamping motor was a kind of thruster, but working on a cold gas in order not to pollute the surface under investigation. This should have reduced the bounce of the spacecraft and reduced the impact of shooting with the harpoons. Unfortunately, none of the three devices fulfilled their task [4]. The only thing that could keep Philae from leaping was the insignificant weight of the spacecraft on the surface of the comet. If we assume that the surface is at a distance $r = 1$ km from the gravity center of the body, then the free fall

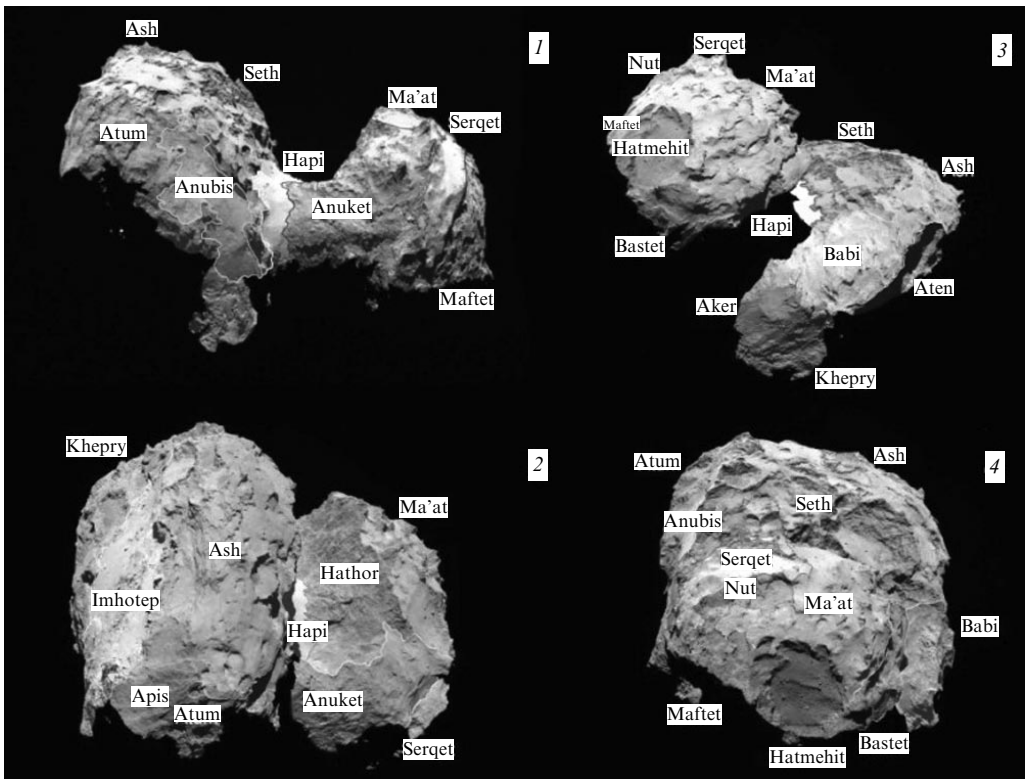

Figure 11. Nucleus of comet 67P/CG in four positions with the boundaries and names of the designated areas (from [23]). In projection *1*, the spin axis is directed vertically and lies in the figure plane; in projection *2* it is directed to the observer.

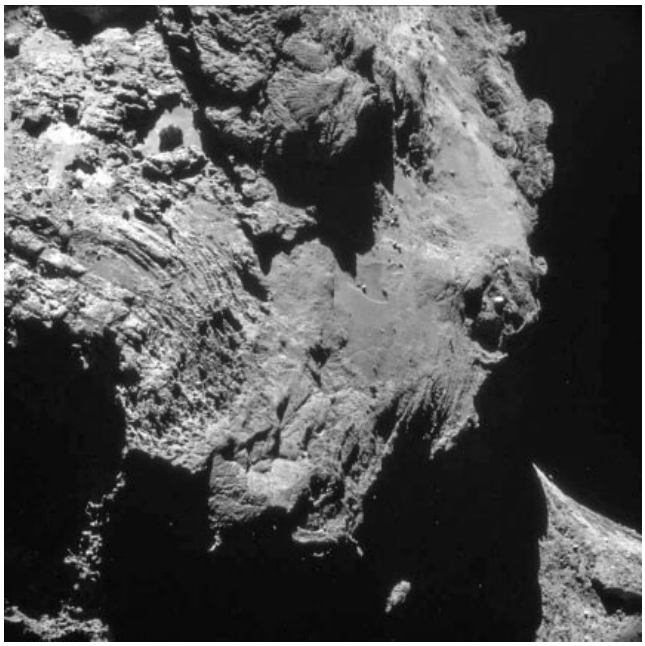

Figure 12. Heterogeneous region Atum-Anubis; the length of the site is 1.6 km, the resolution is 1.6 m/pixel. The image was taken on 1.05.2016 from a distance of 18.8 km. (Image © ESA/Rosetta/NAVCAM — CC BY-SA IGO 3.0.)

acceleration on the comet g_c is only 6.8×10^{-4} m s^{-2}, and the weight of the spacecraft is only 0.068 N for its mass of 100 kg. The supports sprang off and threw the probe upwards at a speed of about 0.4 m s^{-1}. With the low gravity of the comet, the kinetic energy of the probe at the time of landing (about 50 J) was enough to bring Philae to a height of about 1 km and to descend back almost two hours later. The probe then sprang off and ascended again, but not high, and finally stopped two hours after the first contact. While the Philae probe rose and fell, the comet continued spinning. Instead of a flat, open area, fully illuminated by the sun, there were rough stone slopes and dips under the probe. The descent module finally stopped, but in extremely difficult conditions. The probe was in a hollow among the high jagged rocks, near a dead wall, and the probe itself was in a deep shadow, where the solar batteries were useless. Before the energy of the batteries was exhausted, the device had managed to transmit only the data accumulated during the landing. The failure with the Philae landing is very disappointing, but it was partially compensated by subsequent approaches of the Rosetta spacecraft to the nucleus at a distance of several kilometers.

3. Mass loss of comets in the perihelion passage

The activity of nuclei of both comets increased when approaching the perihelion. Halley's comet at the perihelion (0.5712 a.u.) ejected the most intense gas–dust jets (Fig. 13a), propagating a hundred thousand kilometers. The nucleus was observed from a spacecraft in a fly-by mode on March 14, 1986. The perihelion of comet 67P/CG was located much further. The daily surface temperature on the comet was in the range 140–200 K [17, 28] and only at some points rose to 230 K. Mass loss from the nucleus of comet 67P/CG was found to be much smaller because of both the higher perihelion (1.2432 a.u.) and the smaller size of the nucleus. The mass of the 67P/CG nucleus is 1/22 that of Halley's comet. Measurements of the gas–dust activity of the 67P/CG nucleus are presented in Fig. 13, frames b–e. The areas of the 67P/CG neck were markedly active (Fig. 13b, c), but not only.

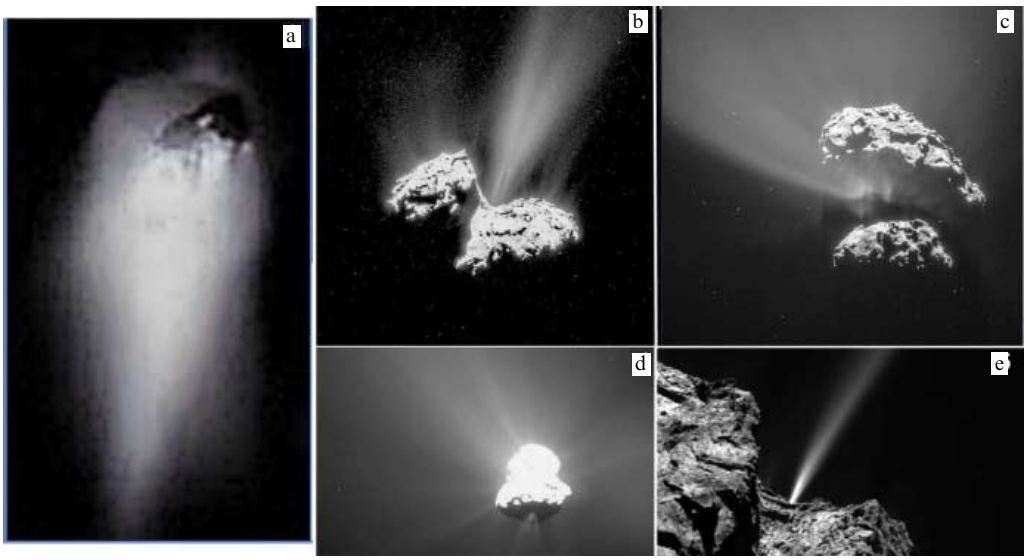

Figure 13. (a) Activity of the nucleus of Halley's comet (1986). The activity development of the comet 67P/CG in February–June 2015. (b) Emissions from the neck, February 6, 2015. Image ESA/Rosetta/NAVCAM — CC BY-SA IGO 3.0. (c) Development of gas–dust emissions from the neck (Hapi region), February 9, 2015. Image ESA/Rosetta/NAVCAM — CC BY-SA IGO 3.0. (d) High activity of gas–dust emissions, March 12, 2015. A gushing outflow from the lower, unilluminated part of the nucleus is seen. Image: ESA/Rosetta/MPS/MPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA. (e) Irregular narrow jet, July 29, 2015 (camera OSIRIS. Image © ESA/rosetta/MPS for OSIRIS team).

In frame d, emissions cover a significant part of the nucleus and are visible in the center of the lower, unilluminated part of it, where a gushing ejection is visible. As can be seen from Fig. 13, unlike with Halley's comet, the mass outflow from the 67P/CG nucleus was limited to local sources. However, it should be recalled that the total area of the sources of the ejected gas–dust medium of Halley's comet at perihelion was also estimated to be 10% [29], although the ejecta were incomparably larger in mass and length than from 67P/CG. A narrow jet (Fig. 13e) appeared irregularly on July 29, 2015. Similar jets were observed in other regions.

The dust particles of Halley's comet comprise mostly a mix of carbon–hydrogen–oxygen–nitrogen (CHON) refractory organic compounds and rocky chondrite material.

In the experiments GIADA (Grain Impact Analyzer and Dust Accumulator) and OSIRIS on the Rosetta spacecraft, a dust component was detected near the nucleus of the comet along the route of flight in the interval 3.6–3.4 a.u. [30]. In total, 35 particles or fragments with masses from 10^{-7} to 10^{-4} g and 48 pieces with masses from 10^{-2} to 10 g were detected in the experiments. The mean dust/gas ratio over the daylight part of the nucleus was found to be 4 ± 2 [with account for data obtained in the MIRO (Microwave Instrument for the Rosetta Orbiter) experiment] [29].

The average dust/gas ratio turns out to be 3. Up to 100×10^3 particles and debris up to one meter in size rotate above the nucleus, and the density of the particles themselves is close to $(1.9 \pm 1.1) \times 10^3$ kg m^{-3}. The loss of water for 3 months in June–August 2014 increased from 0.3 to 1.2 liters per second. The total mass loss from the nucleus of 67P/CG per one perihelion passage was $(3-5) \times 10^9$ kg [32]. The activity of the nucleus near the perihelion increased significantly (Fig. 14), but the absolute values of the losses remained small.

The boundaries of the cross section of the Halley's comet coma exceeded 10^5 km, which is typical for large comets. Due to photolysis, the main component, water vapor, dissociated, and the extent of the gas and ionic components (hydrogen and other volatiles) is estimated to reach 20×10^6 km. The mass loss from Halley's comet at the perihelion has been considered in many papers (see review [29]).

According to the data obtained by Churyumov (see the Table), the gas production of water Q_{H_2O} in Halley's comet after the perihelion passage at a distance of 0.9 a.u. from the Sun was 4×10^{29} s^{-1}, or $4 \times 10^{29} \times 18 \times 1.66 \times 10^{-27} = 1.20 \times 10^4$ kg s^{-1}. The 67P/CG atmosphere consists of about 80% water vapor, and from June to August 2014 the loss of water increased from 0.3 to 1.2 l s^{-1} with variations by a factor of five [31]. In August 2015, H_2O gas production, according to [33], ranged from 10^{24} to 3×10^{25} (s sr)$^{-1}$, and within a month the maximum variations in H_2O productivity were by a factor of 30 (the MIRO experiment [33]): the maximum H_2O production rate was $4\pi \times 3 \times 10^{25} \times 18 \times 1.66 \times 10^{-27} = 112.6$ kg s^{-1}, and the minimum was about 3.75 kg s^{-1}. The data are somewhat inconsistent

Figure 14. Comet 67P/CG passing the perihelion. Emission activity increased significantly. Image © ESA/Rosetta/NAVCAM — CC BY-SA IGO 3.0, August 22, 2015.

as regards the dimensionality: the authors of [31] indicate 2×10^{25} molecules s^{-1} (in June 2014), while the authors of [33] estimates up to 3×10^{25} molecules $(s\ sr)^{-1}$ in August 2014.

The atmosphere of comet 67P/CG includes 17% carbon monoxide and about 3% carbon dioxide. Small amounts of methane and ammonia were also found [34]. Measurements of the dust component were more complicated. At the-gas-to dust mass ratio of 7:1 (short-term), the total losses reached 1.60×10^4 kg s^{-1}. There are significant discrepancies in estimates of the mass loss of Halley's comet near the perihelion. Estimates of losses Δm per orbital period ($\sim$ 76 years) range from 2.2×10^{11} to 5×10^{11} kg, i.e., from 10^{-3} to 2×10^{-3} of the total mass of the nucleus. Three dust experiments, DUCMA (Dust Counter and Mass Analyzer), SP-1, and SP-2 were performed on board the Vega-1 spacecraft [35–37]. The data of the Vega-1 and Vega-2 DUCMA experiment on the registration of particles with masses from 1.5×10^{-13} to 10^{-8} g were reported in [35, 38, 39]. Figure 15 illustrates the increase and subsequent decrease in the count rate in the DUCMA experiment [38] when approaching the nucleus at a distance of 8045 km. The integration of data obtained by dust instruments with the assumed mass distribution functions of particles increased the maximum mass loss rate at the perihelion to 2.9×10^4 kg s^{-1}.

We note that the total mass of Halley's comet nucleus (2.2×10^{14} kg) (see the Table) is calculated using its exactly unknown density [40], estimated from 100 to 700 (and even up to 1500) kg m^{-3}, and the poorly known density of dust particles. Usually, 600 kg m^{-3} is assumed, which indicates a high porosity of the nucleus formed by a large number of small, loosely bound elements.

Halley's comet is assumed to have already passed the perihelion approximately 2300 times [29], which leads to a very large initial mass by assuming mass losses Δm from 10^{-3} to 2×10^{-3} of the total mass of the nucleus discussed above. The initial mass is $M_0 = M_{\text{Halley}}/(1 - \Delta m)^n$, where n is the number of passages, which yields $M_{\text{Halley}} = 2.2 \times 10^{14}$ kg and $M_0 = 2.2 \times 10^{15}$ kg for $\Delta m = 10^{-3}$ and 2.2×10^{16} kg for $\Delta m = 2 \times 10^{-3}$, respectively. Comets with such large masses are unknown. However, on large time scales, for example, beyond 40–50 orbits, calculations of the dynamics of a comet become unreliable. With a mass loss rate of 2.9×10^4 kg s^{-1} at the perihelion and 1.20×10^4 kg s^{-1} at a distance of 0.9 a.u., the mass fraction 10^{-3} actually rapidly accumulates near the perihelion in less than 220 days. The speed of the nucleus V_{Halley} at the perihelion is

$$V_{\text{Halley}} = \left(\frac{GM_{\odot}(1 + \varepsilon_{\text{Halley}})}{q_{\text{Halley}}} \right)^{1/2} = 55.2 \text{ km s}^{-1},$$

where $q_{\text{Halley}} = 0.5712$ a.u. is the perihelion distance, the eccentricity is $\varepsilon_{\text{Halley}} = 0.9671$, and the solar mass is $M_{\odot} = 1.989 \times 10^{30}$ kg. The orbit is inclined to the ecliptic by 162° (retrograde rotation).

According to measurements in early 2015, the gas composition of the 67P/CG coma included water, carbon monoxide, carbon dioxide, ammonia, methane, methanol, formaldehyde, hydrogen sulphide, hydrogen cyanide, sulfur dioxide, carbon disulphide, sulfur, and carbonyl sulphide, as well as sodium and magnesium in the composition of dust grains [28, 32, 34]. Earlier reports indicated that hydrogen sulphide contained the sulfur isotope ^{32}S, and the ^{34}S isotope could have a different origin. Among other gas components, the ROSINA experiment discovered inert argon gas in the nucleus of the comet (Fig. 16) [41], and the $^{36}Ar/^{38}Ar$ ratio of isotopes is 5.4 ± 1.4, which is close to the terrestrial value 5.3. Argon in comets was detected not for the first time: earlier, argon emissions were reported in the "Big comet of 1997," Hale–Bopp [42], in which a synthesis of organic substances was also presumably found [43].

An important discovery was molecular oxygen O_2 in the atmosphere of the comet by the ROSINA mass spectrometer aboard the Rosetta mission [44], and oxygen was among the four most abundant constituents of the comet atmosphere (Fig. 17). Its concentration (from 1 to 10% of water vapor, 3.8% on average) changed little during the six months when the measurements were carried out, which suggests that the nucleus is its steady source.

Oxygen diffuses from the nucleus interior and is not supposed to be a product of water dissociation, but is preserved in the nucleus after its formation. However, it remains unclear which initial medium could be significantly enriched with relic oxygen and why oxygen, a highly reactive element, is not bound in reactions with nuclear materials. We

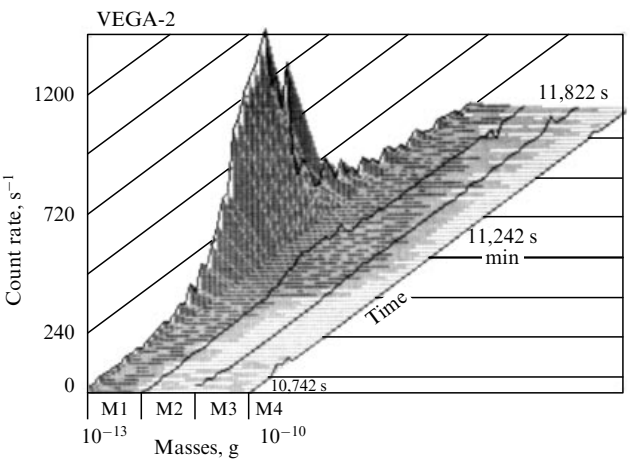

Figure 15. Measurements of the dust particle count rate in the DUCMA experiment on March 9, 1986 [38] during the Vega-2 maximum approach to the nucleus (8045 km).

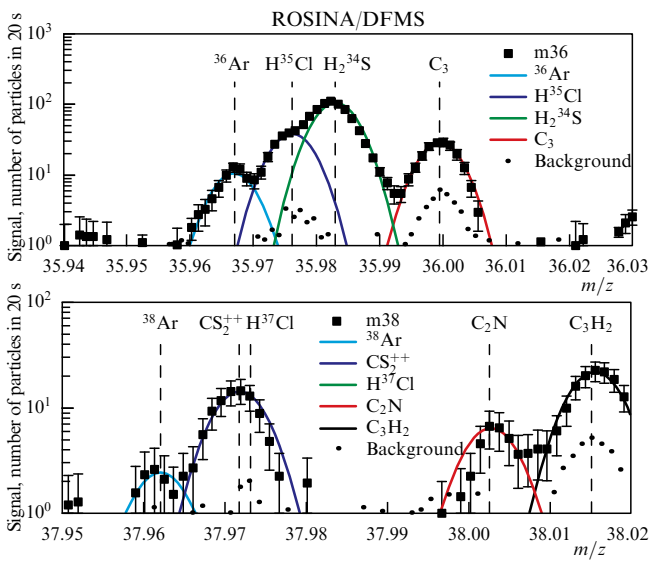

Figure 16. Isotopes ^{36}Ar and ^{38}Ar and other gaseous components of comet 67P/CG, registered in the ROSINA experiment (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) [39].

Table.

	Comet 1P/Halley	Comet 67P/Churyumov–Gerasimenko
Date of discovery	1758 (first predicted perihelion)	October 22, 1969
Orbit characteristic	Epoch February 17, 1994 (JD 2449499,5)	Epoch December 9, 2014 (JD 2457000,5)
Eccentricity e	0.9671	0.641
Semimajor axis a	17.8584 a.u.	3.4628 a.u.
Perihelion q	0.5712 a.u.	1.2432 a.u.
Aphelion Q	35.082 a.u.	5.722 a.u.
Orbital period P	75.5 yrs	6.44 yrs
Orbital inclination	162.2366°	7.0401°
Last perihelion	9 February 1986	August 13, 2015
Next perihelion	July 28, 2061	January 21, 2021
Ascending node longitude	58.9407°	50.1409°
Perihelion argument	111.33249°	12.7868°
Size	$15.3 \times 7.2 \times 7.2$ km	'Head' (smaller part) $2.6 \times 2.3 \times 1.8$ km, 'body' (greater part) $4.1 \times 3.3 \times 1.8$ km
Mass	2.2×10^{14} kg	10^{13} kg
Average density	550 ± 250 kg m^{-3} (estimates vary from 200 to 1500 kg m^{-3})	470 kg m^{-3}, porosity 70–80%*
Albedo	0.04	0.065
Imaged nucleus surface	25%	> 95%
Spin rotation period	52 h	12.4 h
Chemical composition of the nucleus	H_2O — about 80%, CO_2 — from 3 to 4%, CO — about 27%	H_2O, CO_2, CO (no accurate data)
Nucleus surface temperature	300–400 K (27–127 °C) at 0.9 a.u. from Sun (after perihelion passage)	200 K (−70 °C) at 3.7 a.u. from Sun ('hot' spots up to −40 °C)
Gas productivity of water (after perihelion passage)	$Q_{H_2O} \approx 4 \times 10^{29}$ s^{-1} at 0.9 a.u. from Sun	$Q_{H_2O} \approx 10^{27}$ s^{-1} at 1.35 a.u. from Sun**
Atoms and ions	H, O, C, S, Na, K, Ca, V, Mn, Fe, Co, Ni, Cu, H^+, C^+, CO_2^+, Fe^+, Ca^+, CH^+, CN^+, N_2^+, H_2O^+, H_2^+	S Na^+, Mg^+
Molecules	C_2, CH, CN, CO, CS, NH, OH, C_3, NH_2, H_2O, HCN, CH_3CN, S_2, HCO, NH_3, NH_4	H_2O, CO, CO_2, NH_3, CH_4, CH_3OH, CH_2O, H_2S, HCN, SO_2, CS_2
Magnetic field in the coma (gradual increase)	Up to 75–80 nT at 0.9 a.u. from Sun	Up to 100–110 nT at 3.4 a.u. from Su
Isotopic composition D/H	$(3.06 \pm 0.34) \times 10^{-4}$	$(5.3 \pm 0.7) \times 10^{-4}$
Dust/gas ratio	1 : 7 – 1 : 8	2 : 1 – 4 : 1

* According to [27], the nucleus of comet 67P/CG has the density 533 ± 6 kg m^{-3} and a high porosity, 72–74%.

** Gas production of water vapor at an orbital distance of about 3.4 a.u. is $Q_{H_2O} \approx 2 \times 10^{25}$ s^{-1} sr^{-1} [33].

note that the connection between the abundance of the observed components and the original composition of the comet nucleus is among the topical problems of the physics of comets [45].

The main feature of the Rosetta mission, in contrast to Vega, is that due to the quasi-satellite position of the spacecraft relative to the nucleus of 67P/CG, systematic and long-term observations are possible, as in the case of the detection of oxygen. Nevertheless, the Vega mission also gave many surprises during the short-time approach of the spacecraft to the comet. Immediate direct measurements of the composition of cometary plasma indicated the presence of ions with the mass 56 (Fig. 18), which were hypothetically identified with iron ions Fe^+ and had not previously been observed in the plasma of Halley's comet.

As noted above, comet 67P/CG, in contrast to Halley's comet, is classified as a dust–gas comet. In Churyumov's table, the dust-to-gas ratio is estimated to be 4:1, but is apparently closer to 3:1. The peak dust productivity near the perihelion of 2002–2003 was 60 kg s^{-1}, and in 1982–1983 it reached 220 kg s^{-1}. In terms of the H_2O productivity, ranging from 3.75 kg s^{-1} to 112 kg s^{-1} according to [33], these values are consistent with the above bounds. The productivity of water vapor, $Q_{H_2O} \approx 4 \times 10^{25}$ s^{-1}, is 10^{-4} of that in Halley's comet. Therefore, these dust/gas ratios result in a minimum dust loss estimate of about 15 kg s^{-1}. In general, the scatter in

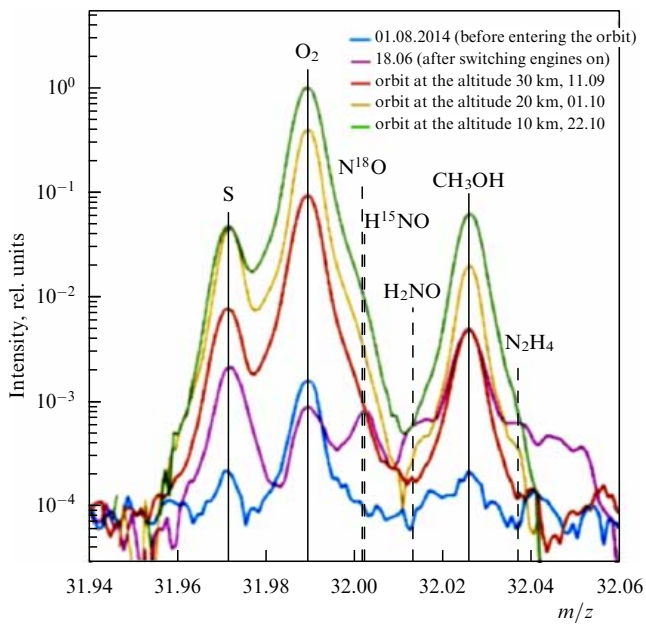

Figure 17. (Color online.) The abundance of oxygen and other gaseous constituents in the atmosphere of comet 67P/CG measured by the ROSINA mass spectrometer at different distances from the nucleus [44]. The peak to the right is methanol (CH_3OH).

the estimates makes it difficult to determine the total losses, but they are negligibly small in comparison with the nucleus mass (10^{13} kg). Dynamic impacts of micrometeorites, gas, and plasma with the surface of the nucleus and coma are in general (if we take only the orbital motion of the comet into account) much lower than that for Halley's comet. The orbital speed V_{67P} at the perihelion ($q_{67P} = 1.2432$ a.u., $\varepsilon_{67P} = 0.6410$) is

$$V_{67P} = \left(\frac{GM_{\odot}(1+\varepsilon_{67P})}{q_{67P}}\right)^{1/2} = 34.2 \text{ km s}^{-1}.$$

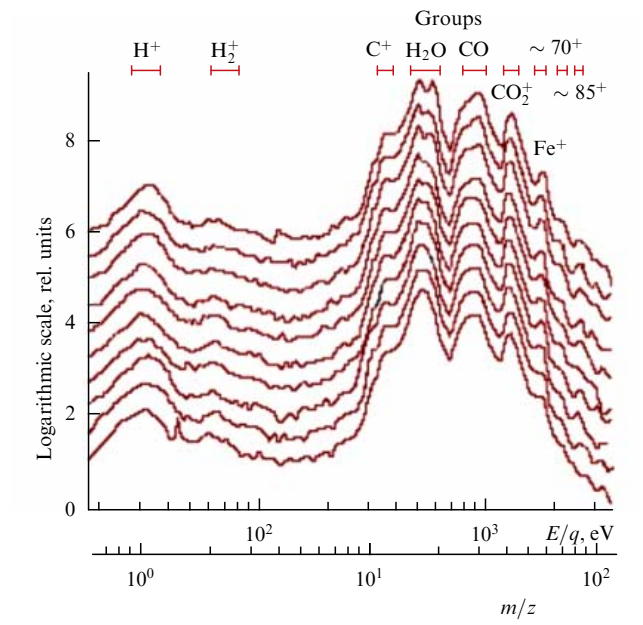

Figure 18. Iron ions Fe^+ were first detected in the plasma of Halley's comet in the Vega mission experiments. The curves were obtained during the spacecraft's approach to the nucleus [7].

An interesting phenomenon was discovered thanks to the rapid motion of the Vega spacecraft itself relative to the Halley's comet nucleus. The spatial distribution of the dust grains in the vicinity of the nucleus was inhomogeneous and indicated a certain periodicity in the dust medium structure. The phenomenon was interpreted by Waisberg in terms of a spatial spiral form of the most intense dust jets, which is due to the rotation of the nucleus [37, 46]. Thanks to the rapid motion, the Vega spacecraft consecutively crossed them several times [39].

4. Origin and deuterium abundance of comets 1P/Halley and 67P/CG

The comparison of the cometary atmosphere compositions given in the Table suggests a significant difference between comets 1P and 67P, which is due to differences in their origins. The Kuiper Belt is thought to be the Solar System region where bodies similar to comet 67P [47] can be located. Features of the orbit of Halley's comet suggest its ancient origin from a more distant region, the Oort cloud, the bodies in which are unrelated to the ecliptic plane and have D-to-H ratios that can be different from other bodies of the Solar System. Halley's comet belongs to the short-period group (with the period less than 200 years), but its orbital features suggest that it originated in the Oort cloud and (due to perturbations by the giant planets in the lower part of its orbit) turned out to be in a short-period orbit. At the same time, the available historical data show that 1P/Halley has been in a modern, relatively stable orbit for a long time [29]). Ancient Greek and Chinese records first mention it in 468–466 BC, and its description can be found in Chinese chronicles dated 240 BC. In the Middle Ages, the Julian and Gregorian calendars marked the dates of the appearance of 1P beginning in 1531 and 1607, respectively. The evolution of the 67P/CG orbit is not traced that far. Calculations of the evolution before the 20th century give unreliable results. Until 1840, its distance at the perihelion (as the backward integration of the orbit shows) was three times larger than the modern 4.0 a.u. Later, a series of rapprochements with Jupiter reduced the distance at the perihelion to 3.0 a.u., and then to 2.77 a.u. More recently, in 1959, there was a further decrease in the perihelion of the comet to 1.29 a.u.. The orbital period of 67P is now 6.45 years.

It was extremely important to measure the D-to-H ratio (deuterium–protium). Express review [4] noted that an analysis of the isotopic composition of the significant masses of water vapor emitted by the 67P/CG nucleus indicated an unusually high D-to-H ratio. Because new papers have already been published, it is appropriate to consider both the results of new measurements [47] and their interpretation. The topic of the deuterium–protium ratio in connection with the origin of terrestrial oceans was considered by many authors, among which we mention the authors of [47–49], Tobias C Owen and Akiva Bar-Nun, whose work covers the period from the 1980s until the present time. It was assumed that the volatiles fell on the inner planets in the form of planetesimals and ice nuclei of comets [48], and comets brought up to 40% of the water in Earth's oceans, with planetesimals and asteroids accounting for about 60% of the water. However, experimental facts about the deuterium–protium ratio, which have been gradually accumulated, shifted the origin of terrestrial water to favor of planetesimals and asteroids. It is noted in [50] that comets alone could

not form oceans on Earth; other sources with a low D-to-H ratio were needed for this. This problem was considered in detail in [51]. The measured D-to-H ratio in Rosetta mission experiments is $(5.3 \pm 0.7) \times 10^{-4}$ [52]. The authors note that the earlier cometary measurements and new results suggest that the broad limits of D-to-H in the water of the family of Jupiter's comets rule out the possibility that this reservoir was the only source of water for terrestrial oceans. Although this conclusion is cautious, numerous comments have nevertheless suggested that the Rosetta results finally close the issue with comets, which is not the case. It cannot be ruled out that the terrestrial value of D-to-H itself could evolve [53]. Although there is not much water in various phases on the surface of the cometary nucleus [17], daily diurnal cycles are observed, but water ice enters in the main components of the cometary nuclei, which have brought a significant proportion of matter to Earth. If there are 156 molecules of heavy water (HDO) for every 10^6 ordinary Earth water molecules (H_2O), i.e., 156 ppm, the Rosetta measurements yield 530 ppm (parts per million), i.e., 530 molecules of HDO for every 10^6 molecules of ordinary water.

Figure 19 is based on data from [47] and other publications. In Halley's comet, D-to-H was 310 ppm [54], which is twice the terrestrial value (156 ppm). The ratio in the Hale–Bopp comet was almost the same (330 ppm) [55]. Thus, these respective celestial bodies are enriched with deuterium 2 and 3.4 times as much as Earth is, and more than 15 times than the protostellar nebula is. The horizontal line in Fig. 19 shows terrestrial water (156 ppm), and the lower part of the figure shows the initial D-to-H ratio in the protostellar nebula (20–23 ppm [56]). Recent measurements for 103P/Hartley-2 yielded D-to-H equal to $(1.61 \pm 0.24) \times 10^{-4}$ [57]. Although both comets, 103P/Hartley-2 and 67P/CG, appear to have come from the Kuiper belt [45], their D-to-H ratios differ by a factor of 3.

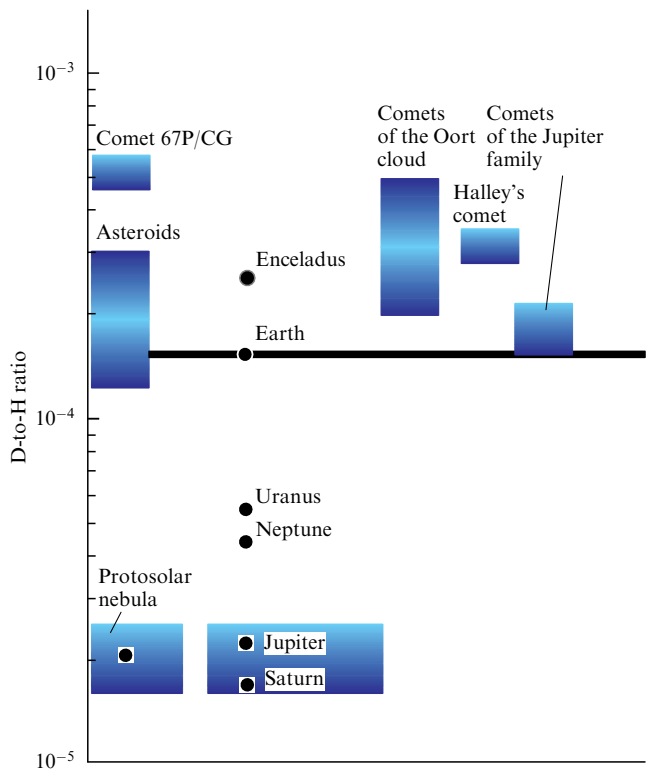

Figure 19. Generalized diagram of the D to H ratio in Solar System bodies. Enceladus is a satellite of Saturn. The height of the rectangles shows differences in the values in the group or dispersion of the measurements. The horizontal line is the water on Earth. The upper value, 530 ppm, is for 67P. The initial D to H ratio in the protostellar nebula is about 20 ppm. Jupiter and Saturn have similar D-to-H values. The twofold (on average) terrestrial D-to-H values are typical for Oort cloud comets (such as Halley's comet).

It is naive to believe that the issue of the origin of water in terrestrial oceans can be solved based on the results of the 103P/Hartley studies. Figure 19 also indicates the complexity of the problem, and the concentration of D-to-H values near the terrestrial value rather supports planetesimals and asteroids, although there were other sources of water. Undoubtedly, comets [41] also brought part of the oceanic water, and the water of the oceans is a mixture of different sources. Nevertheless, Fig. 19 once again points to the complexity of the problem.

5. Formation of complex cometary nuclei in low-speed collisions

A significant portion of cometary nuclei has the form of a dumbbell with a narrow 'neck' separating more massive parts. These are the nuclei of comets 67P/CG, 1P/Halley, 103P/Hartley-2, 19P/Borrelly, and others. As in the case of 67P/CG, the most intensive material outbursts are often observed from the narrow neck, which suggests that the gradual destruction of nuclei occurs precisely in the narrow section. The decrease in the neck is accompanied by an increase in the mechanical stresses arising under the action of centrifugal forces from the rotation of the body, and by a number of other physical factors. An example of analysis of mechanical stresses was given in [5] for comet 103P/Hartley-2, where the body is kept from disruption only by friction forces. Probably, in a number of cases, the rupture occurs if the regolith of the neck is sufficiently crumbly. The nucleus of Halley's comet has an average density of about 550 kg m^{-3} (see above) and a porosity of about 50%. This indicates that it consists of a large number of weakly coupled small elements.

The nucleus of comet 67P/Churyumov–Gerasimenko also has a low density, 533 ± 6 kg m^{-3} according to improved data, and a high porosity, 72–74% [27]. The authors note that in general the dust composition and porosity of the 67P/CG body are similar to those of comet 9P/Tempel 1. The probable dust-to-ice ratio is about 4 by weight and 2 by volume. Similar results of the Rosetta mission have already been cited above [31]. The nucleus material is sufficiently homogeneous, and the presence of voids is unlikely.

At the same time, experiments performed during the Philae probe landing showed that although the mean porosity of the core is high, the material at the final landing point in the Abydos region had the rigidity of frozen ice mixed with dust grains. However, at the point of the first contact (Agilkia), the surface was weak, but hard enough to rebound the probe. The surface material is nonhomogeneous.

As a result of these observations, the known assumptions that the dumbbell shape of cometary nuclei results from a previous merger of independent bodies rather than signals their future destruction are becoming more popular. It is the nucleus of comet 67P/CG that presents such evidence (see, e.g., [21, 25, 58]). The authors of [21] also discuss the hypothesis of deposition of material layers on the already

formed body. The shape of the nucleus and its properties raise the question of whether the body formed from contact between two large planetesimals 4.5 billion years ago or is a single slowly destructing body [24]. The idea of the formation of a nucleus from colliding pieces is not new but meets with difficulty in that the energy released in collisions destructs the impactors rather than uniting them.

Of course, in most cases, exactly such destructive collisions have occurred. However, there have been many colliding bodies, including those whose collision speeds were small, 1–10 m s^{-1}, such that the impactors could collide without significant damage, and the neck material could be compressed. Such conditions could lead to the formation of dumbbell-shaped comets (67P/CG, 103P/Hartley-2, 1P/Halley), which, of course, does not contradict their continuing destruction in the narrow cross section.

A convincing example of the heterogeneity of the 67P/CG nucleus is shown in Fig. 20. The Hathor ledge shows signs of continuing destruction, and the exposed surface has a structure resembling layering. At the base of the ledge, a crumbling material and detached blocks overlapping the neck Hapi can be seen. Apparently, the surface is heterogeneous and carries traces of fractures and cracks [24]. The structure of the opposite side, Seth, is completely different [24]. Thus, the two parts of the 67P/CG nucleus have different natures [21], which favors the hypothesis of fusion of proto-comet bodies. In this case, we can expect that the regolith should have an increased density in the contact area of colliding bodies. Perhaps such a heterogeneity of the regolith on the surface of the 67P/CG nucleus was met on the Philae probe landing site.

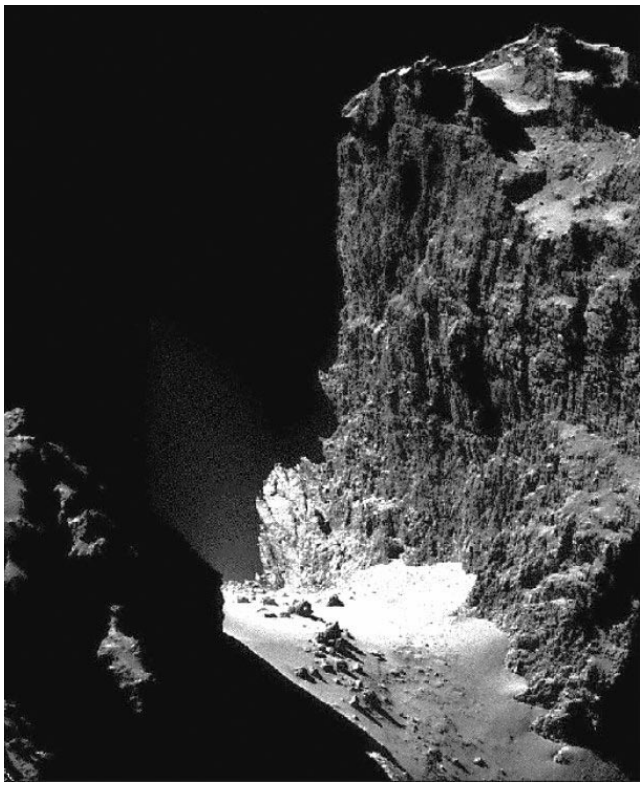

Figure 20. Slope of the smaller half of the 67P/CG nucleus (Hathor ledge) has a height of about 1 km. The image shows a crumbling slope and regolith and clods falling on the neck Hapi. The opposite side, the Seth region, has a different nature. (Image © OSIRIS, ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, with changes.)

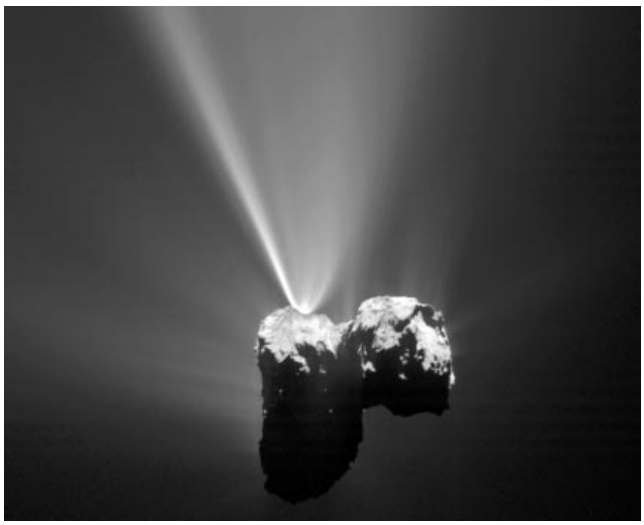

Figure 21. Probability of collisional destruction of bodies during the Solar System formation was much higher than that of merger, but low-speed collisions of the countless primary bodies did occur. It cannot be ruled out that the core of 67P/CG was once created in such a merger. (Image © OSIRIS, ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, August 12, 2015.)

The hypothesis of cometary nuclei fusion in low-speed collisions is supported by many researchers. In collisions, the probability of destruction is much higher than the probability of merger, but during the Solar System's formation, low-speed collisions also occurred among the countless primary bodies. The coalescence of primary bodies should occur in different ways in bodies of small and large mass. In the latter case, even at low collision velocities, the energy dissipated so much that the contact area must be completely compressed. If we assume that the nucleus of Halley's comet experienced a similar process, its image (Fig. 8) may confirm this idea. However, the statistics are still too few. Thus, the 'necks' in cometary bodies (and asteroids) should be encountered more often for smaller masses, as in the nucleus of 67P/CG (Fig. 21). Of course, the image in Fig. 21 cannot be direct proof of a previous merger of independent nuclei, but the impression is that their unification occurred precisely along the plane of the narrow section in the figure. The development of the hypothesis of a merger of proto-comet bodies as a major new step in the study of comets was presented in 2015 in the Memorial Gruber Lecture [58] at the XXIX IAU Assembly devoted to new ideas about the Solar System formation.

6. Conclusion

The above comparison of certain properties of cometary nuclei, of course, is far from complete. Direct studies of cometary nuclei launched 30 years ago by the Vega mission suggest the diverse nature of cometary bodies, their atmospheres, and their formation regions. Comparisons of the most thoroughly studied comets, such as 1P/Halley and 67P/Churyumov–Gerasimenko, indicate significant differences in their physico-chemical properties, origin, dynamics, and evolution. It can even be noted that the widespread assertion that the study of the physics and the evolution of comets will speed up resolving cardinal issues on the origin of our Solar

System is somewhat naive. On the contrary, new processes are being revealed, complicating hypotheses on the Solar System formation.

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