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Comparison of Some Characteristics of Comets 1P/Halley and 67P/Churyumov–Gerasimenko from the *Vega* and *Rosetta* Mission Data

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Abstract—On March 6 and 9, 1986, for the first time in the history of science, the Russian spacecraft *Vega-1* and *-2* approached the nucleus of comet 1P/Halley and flew by at a small distance. A while later, on March 14, 1986, the *Giotto* spacecraft (European Space Agency (ESA)) followed them. Together with the Japanese spacecraft *Suisei* (Japan Aerospace Exploration Agency (JAXA)), they obtained spaceborne investigations of cometary nuclei. Direct studies of cometary bodies that bear traces of the Solar System formation were continued in the next missions to comets. Starting from 2014 and up to 2016 September, the *Rosetta* spacecraft (ESA), being in a low orbit around the nucleus of comet 67P/Churyumov–Gerasimenko, has performed extremely sophisticated investigations of this comet. Here, we compare some results of these missions. The paper is based on the reports presented at the memorial conference dedicated to the 30th anniversary of the *Vega* mission, which took place at the Space Research Institute of the Russian Academy of Sciences in March, 2016, and does not pretend to comprehensively cover the problems of cometary physics.

Keywords: Vega spacecraft, *Giotto* mission, comet 1P, comet 67P, cometary nuclei

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INTRODUCTION

Thirty years have passed since the *Vega* spacecraft started historical investigations of comet 1P/Halley (1986), one of the largest short-period comets. Two years passed since the beginning of the direct studies of the other comet, 67P/Churyumov–Gerasimenko (hereafter referred to as 67P/CG); their preliminary results were presented by Ksanfomality and Churyumov (2015) in the *Solar System Research* journal. The materials published to date allow us to compare some results of the missions to comets 67P/CG and 1P/Halley (1986). However, the conditions for carrying out the experiments were not comparable. For example, the *Rosetta* probe was on a quasi-satellite orbit around the comet. The dust component of the comet 67P/CG ejecta hit the spacecraft with low velocities that constituted no serious danger for the probe itself; though, near the perihelion (in August 2015), it was kept at a distance larger than 350 km from the nucleus for reasons of safety. In contrast to this, the *Vega-1* and *-2* probes approached the cometary nucleus on opposite courses with a very high relative velocity, 79 km/s. The transmission of images of the nucleus and a thorough analysis of the composition of dust and gas ejected by the nucleus and the magnetic field and plasma, enveloping the comet, were performed under conditions of a high huge meteorite hazard that had been never met before. For the first time, the probes crossed the shock wave at a distance of approximately 1 million kilometers (Fig. 1); and, at a distance of approximately 160000 kilometers, they crossed the theoretically predicted "cometary pause", where the distribution function of protons sharply changed.

The energy of dust particles and fragments of the cometary crust, surpassed per unit mass, that of an artillery shell by 7000 times. Because of this, the *Vega-1* and *-2* probes, which had been designed and created at the Lavochkin Association, were fitted out with unprecedented protective equipment, which largely assured the mission success (Sagdeev et al., 1986).

In 1986, on March 6 and 9, and, a while later, on March 14, the Russian spacecraft *Vega-1* and *-2* (Sagdeev et al., 1986) and the *Giotto* probe (European Space Agency (ESA)) (Reinhard, 1986), respectively, pioneered investigations of cometary nuclei with space probes. In the same period, on March 8, 1986, the Japanese spacecraft *Suisei* (*Planet-A*) (Japan Aerospace Exploration Agency (JAXA)) passed comet Halley at a larger distance (Hirao and Itoh, 1986). In this paper, we discuss some results of the missions to comet Halley and comet Churyumov–Gerasimenko. The main characteristics of the both comets are compared in the summary table composed by K.I. Churyumov and published in the paper by Zelenyi and Ksanfomality (2015). Several updated estimates are commented in the text and specified in the table note.

MORPHOLOGIC PROPERTIES OF THE SURFACE: LIMITED PROSPECTS FOR COMPARISON

Figures 2 and 3 show the spacecraft mentioned above and the *Rosetta* spacecraft during preflight tests, respectively. After the first observations of comet Halley, six cometary nuclei had been already investigated with space probes as of the beginning of 2016. Among the main and most important targets of the missions is to obtain images of these bodies. This is evidenced by the costs of the television experiment that are incomparable to those of the other experiments. The same is the case of the scientific payload of the *Rosetta* spacecraft, where the images in different spectral ranges were taken by several instruments, rather than only by the narrow-angle (NAC) (Auger et al., 2015) and wide-angle cameras (http://sci.esa.int/rosetta/35061-instruments). The Optical Spectroscopic and Infrared Remote Imaging System (OSIRIS) is one of such examples. Many detailed images were taken. However, to compare the surface morphology of 67P/CG and 1P/Halley is a challenging task. While a splendid album of detailed images with a resolution better than tens of centimeters is available for comet 67P/CG, the resolution in the images of the surface of the Halley nucleus is approximately 1 km. The nucleus was observed through a rather opaque medium of gas and dust intensively ejected by the nucleus (Fig. 4 (panel *1*), the blurred images on the left). Moreover, all the probes, participating in the investigations of comet Halley, took reliable images of only approximately 25% of the surface; at the same time, in the *Rosetta* mission, the acquired images cover almost the whole surface of the nucleus.

The unprocessed images of the comet Halley nucleus taken with the CCD camera of the *Vega* probe are shown in Fig. 4 (Sagdeev et al., 1987).

In the further processing of the images (Avanesov et al.,1989), an improved image of the nucleus was obtained and the nucleus shape was more accurately defined (Fig. 4, panel *1*). In Fig. 4 (panel *2*), the nucleus of comet 67P/CG is shown. The scale of the images is specified in the figure; the sizes of the bodies are 15.3 × 7.2 × 7.2 and 4.1 × 3.1 × 2.2.

The scale in the figure allows the sizes of individual elements of the nucleus to be estimated. It was noted that the surface of the Halley nucleus varies in topography, exhibiting hills, mountains, ridges, chasms, and at least one large crater. When the comet is in the lower section of the orbit, near the perihelion, the increase of the temperature induces active processes including the destruction of some forms and the initiation of the others. When comet Halley was at perihelion, at

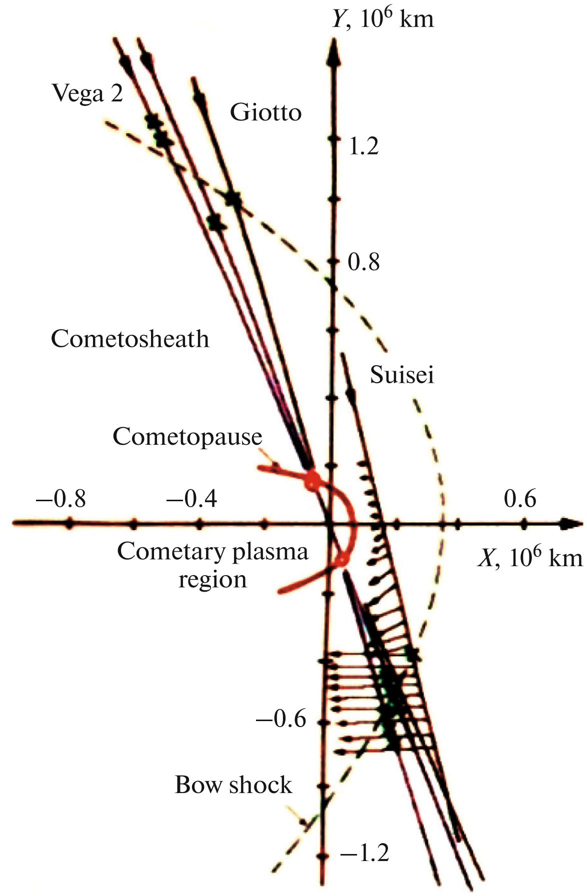

Fig. 1. Trajectories of the *Vega*, *Giotto*, and *Suisei* probes approaching comet Halley. Arrows on the *Suisei* trajectory indicate the magnetic field changes (by permission of M.I. Verigin, from his poster "*Vega-1* and *-2*: Rendezvous with comet Halley" at the Space Research Institute (2015)).

0.5712 AU from the Sun, the temperature of the dark crust of the nucleus was approximately 300 K and even reached 400 K at the hottest points (Combes et al., 1986). Near the perihelion, the heated fragments of the crust broke down, separated off, and were carried away by gas and dust flows. Nevertheless, it was found that, deep in the nucleus body, the temperature remains very low, which was also observed in comet 67P/CG. For example, from the data of the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) experiment onboard the *Rosetta* probe, when the daytime temperature of the surface was approximately 200 K, the temperature in the examined regions remained constant, approximately 130 K, even at a depth of 5–6 cm (De Sanctis et al., 2015). The analysis of the formation conditions of some ejected gaseous components suggests that deep in the nucleus the temperature is 35 K. The mean geometric albedo of the surface is very low for the both comets: approximately 0.04 and 0.065 (at a wavelength of 649 nm) for comet Halley and 67P/CG, respectively (Fornasier et al., 2015).

Comparison of the characteristics of comets 1P/Halley and 67P/Churyumov–Gerasimenko (the data by Churyumov)

Comet 1P/Halley	Comet 67P/Churyumov–Gerasimenko
Discovery date: 1758 (the first predicted perihelion)	Discovery date: October 22, 1969
Orbital characteristics: Epoch of February 17, 1994 (JD 2449400.5)	Orbital characteristics: Epoch of December 9, 2014 (JDT 2457000.5)
Eccentricity: 0.9671	Eccentricity: 0.6410
Major semiaxis $a = 17.8584$ AU	Major semiaxis $a = 3.4628$ AU
Perihelion $q = 0.5712$ AU	Perihelion $q = 1.2432$ AU
Aphelion $Q = 35.082$ AU	Aphelion $Q = 5.722$ AU
Rotation period $P = 75.5$ yr	Rotation period $P = 6.44$ yr
Orbit inclination: 162.2366°	Orbit inclination: 7.0401°
Last perihelion: February 9, 1986	Last perihelion: August 13, 2015
Next perihelion: July 28, 2061	Next perihelion: January 21, 2021
Ascending node longitude: 58.9407°	Ascending node longitude: 50.1409°
Ascending node-perihelion angle: 111.33249°	Ascending node-perihelion angle: 12.7868°
Sizes: 15.3 × 7.2 × 7.2 km	Sizes: 2.6 × 2.3 × 1.8 km for the head (smaller lobe) and 4.1 × 3.3 × 1.8 km for the body (larger lobe)
Mass: 2.2×10^{14} km	Mass: 10^{13} km
Mean density: 550 ± 250 kg/m^3 (the estimates vary from 200 to 1500 kg/m^3)	Mean density*: 470 kg/m^3 (with a porosity of 70–80%)
Albedo: 0.04	Albedo: 0.065
Imaged portion: 25% of the nucleus surface	Imaged portion: more than 95% of the nucleus surface
Rotation period around its own axis: 52 h	Rotation period around its own axis: 12.4 h
Chemical composition of the nucleus: 80% of water ice H_2O, 3–4% of carbon dioxide ice CO_2, around 27% of carbon oxide CO	Chemical composition of the nucleus: water ice H_2O, carbon dioxide CO_2, carbon oxide CO (?)
Temperature of the nucleus surface: approximately 300–400 K (27–127°C) at 0.9 AU from the Sun (after perihelion)	Temperature of the nucleus surface: approximately 200 K (–70°C) at 3.7 AU from the Sun (up to –40°C at “hot spots”)
Gas production rate of water: $Q_{H_2O} = 4 \times 10^{29}$ s^{-1} at 0.9 AU from the Sun (after perihelion)	Gas production rate of water: $Q_{H_2O} \approx 4 \times 10^{27}$ s^{-1} at 1.35 AU from the Sun (after perihelion), groundbased observations**
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_2S^+	Atoms and ions: ^{34}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	Molecules: 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 growth to 75–80 nT at 0.9 AU from the Sun	Magnetic field in the coma: gradual growth to 100–110 nT at 3.4 AU from the Sun
Isotope composition D/H = $(3.06 \pm 0.34) \times 10^{-4}$	Isotope composition D/H = $(5.3 \pm 0.7) \times 10^{-4}$
Dust-to-gas ratio: approximately from 1 : 7 to 1 : 8	Dust-to-gas ratio: approximately from 2 : 1 to 4 : 1

* From the data by Pätzold et al. (2016), the density of the 67P/CG nucleus is 533 ± 6 kg/m^3, and its porosity is high, 72–74%.

** The gas production rate of water vapor is $Q_{H_2O} \approx 2 \times 10^{25}$ molecules per second and steradian at a distance of approximately 3.4 AU (Lee et al., 2015).

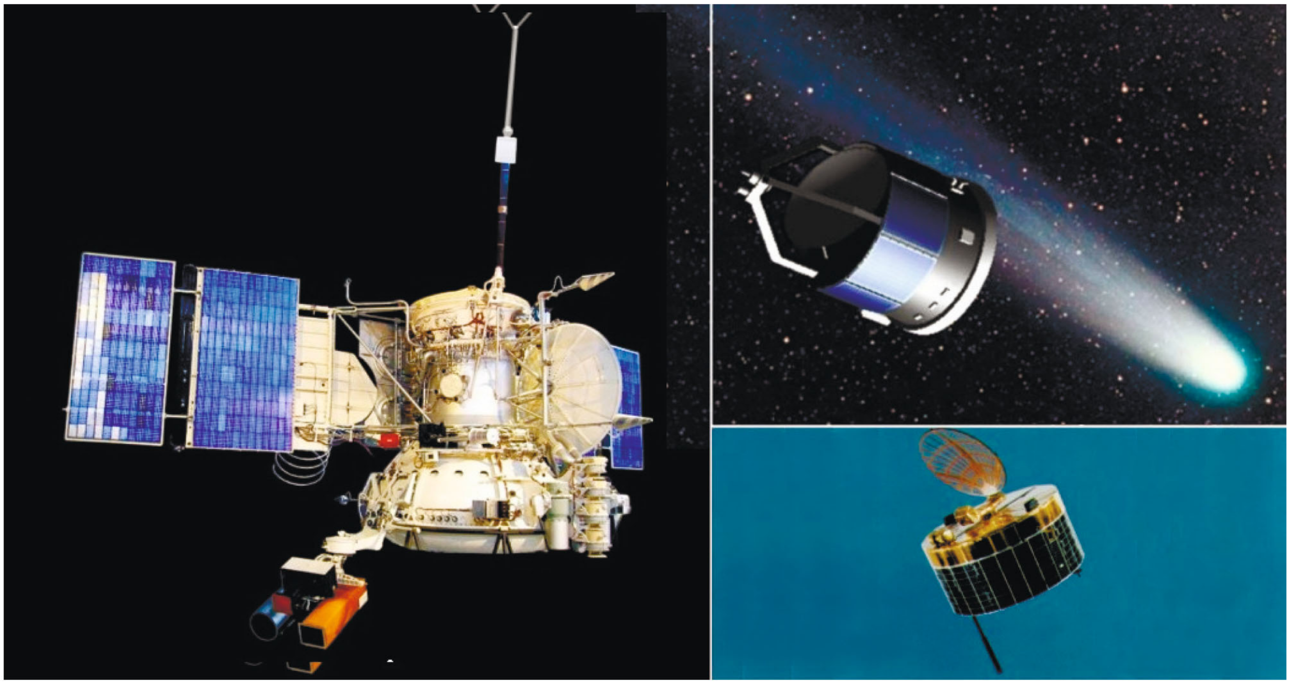

Fig. 2. The spacecraft *Vega* (left), *Giotto* (upper right), and *Suisei* (bottom right). The scale of the images is different (Avanesov et al., 1989; Keller et al., 1986; Hirao and Itoh, 1986).

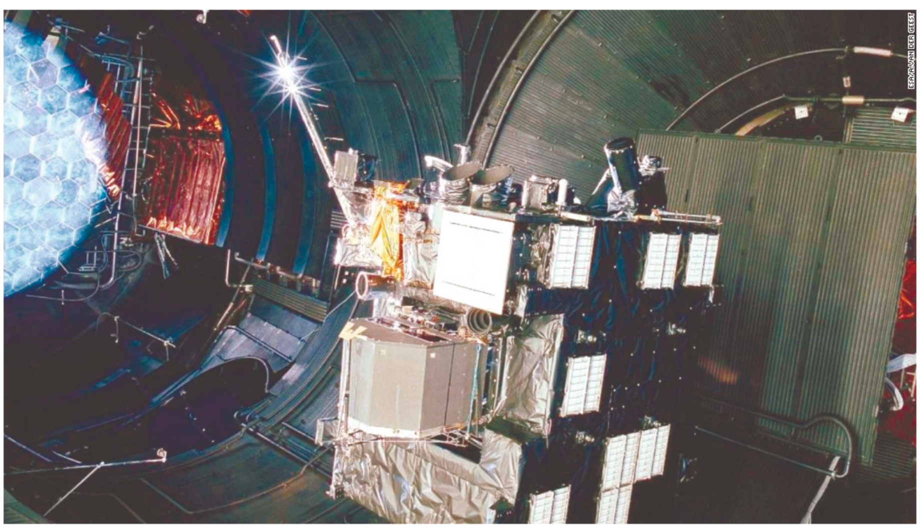

Fig. 3. The *Rosetta* spacecraft integrated at a testing bay. The grey outstanding unit is the *Philae* probe (ESA, 140109134929-rosetta-spacecraft-horizontal-large-gallery).

The images of comet Halley in more detail were acquired by the *Giotto* camera (Keller et al., 1986; Reinhard, 1986) that operated at a closer distance of the probe to the nucleus. However, at a distance of 1200 km, the camera was damaged and came out of action. As compared to the *Vega* image shown at the top of Fig. 4, an opposite side of the nucleus was observed. Due to a more favorable position of the spacecraft, the nucleus was not significantly obscured by gaseous ejecta (Fig. 5). In the further processing with the methods developed by the author (Ksanfomality et al., 2016), a more detailed image of the nucleus was obtained (see Fig. 6). To a certain extent, it can be even compared to the images of the nucleus of comet 67P/Churyumov–Gerasimenko. It is worth noting that, because of special features of the processing codes, some of the finest details in Fig. 6 may appear to be an artifact.

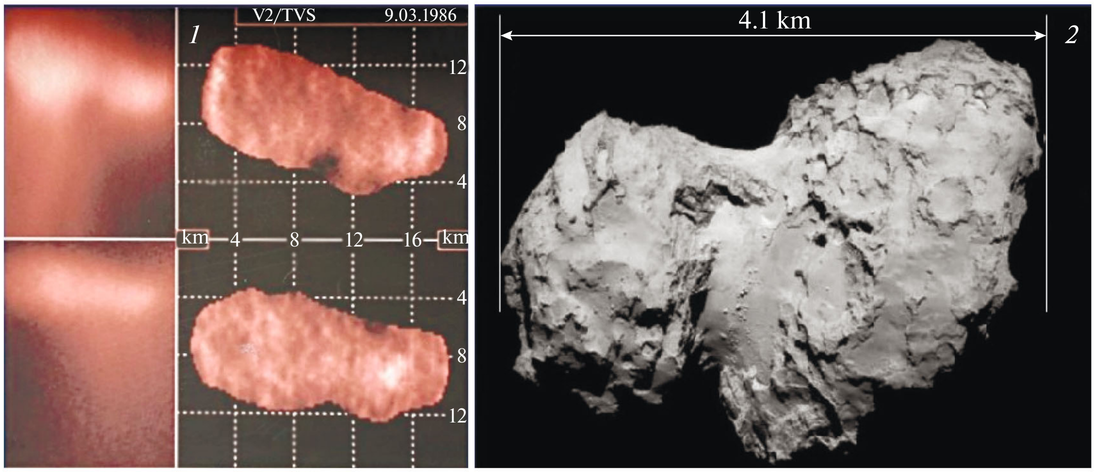

Fig. 4. Comet 1P/Halley is shown in the leftmost images. The unprocessed image taken with the TVS camera of the *Vega* probe (1986). Panel *1*: The nucleus of comet Halley seen in the processed images (Avanesov et al., 1989) is in; the image sharpness is restricted by the intense ejecta of gas and dust from the cometary nucleus, which obscured the nucleus itself. Panel 2: One of the first images of the nucleus of comet 67P/Churyumov–Gerasimenko acquired from the *Rosetta* probe in 2014 (http://rosetta.esa.int).

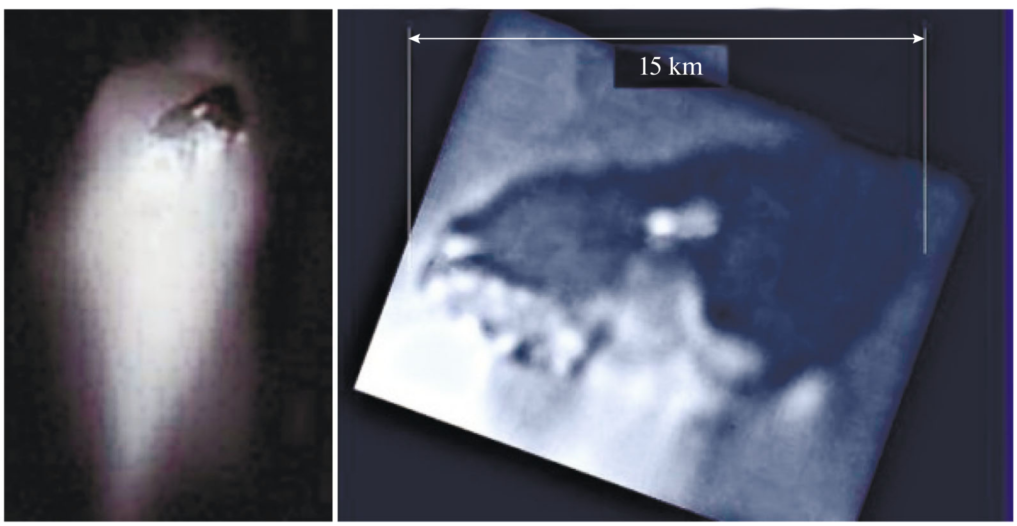

Fig. 5. An image of comet Halley acquired with the *Giotto* camera on March 14, 1986. (Image credit: ESA.)

Fig. 6. Left: An image of comet Halley acquired from the *Giotto* probe and processed by the author (published for the first time); the scale is 1/4 (panel *1*); an image of the nucleus of comet 67P/CG (http://rosetta.esa.int/) with a scale of 1 : 1 (panel *2*). Right: The considered objects are shown in the same scale.

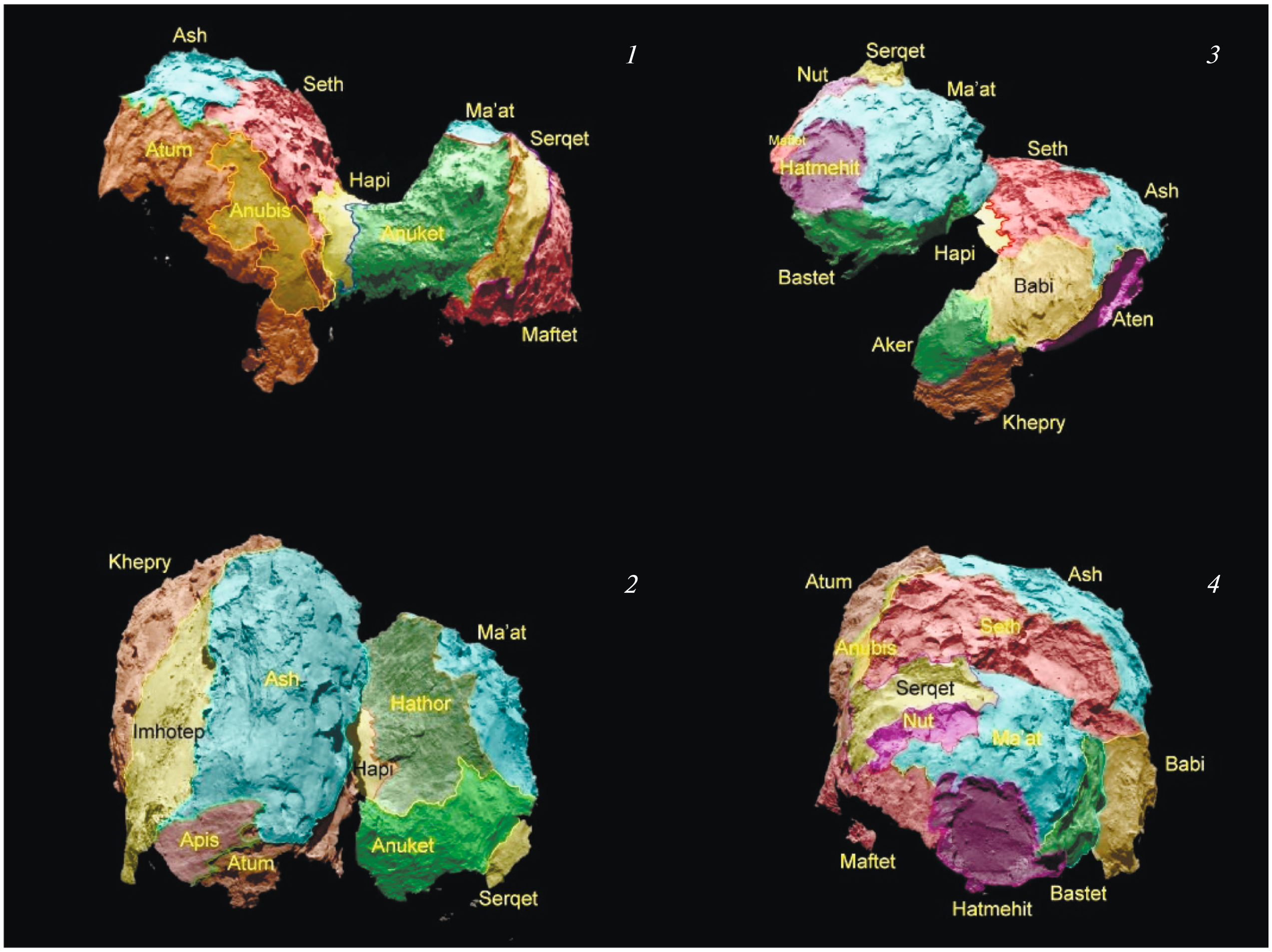

Fig. 7. The nucleus of comet 67P/CG in four positions; the borders and names of the distinguished regions are shown. In projection *1*, the rotation axis is vertical and lies in the figure plane; in projection *2*, the axis is directed to the observer. A fragment of the figure from the paper by El-Maarry et al. (2015) was adapted.

First of all, a general similarity of the shape of both bodies is conspicuous despite the four-fold difference in size. As a whole, the similarity of the surface of both comets is observed in many details. The shape of "a head", a larger lobe of the 67P/CG nucleus, which ends in the Imhotep region, resembles a head of the nucleus of comet Halley (Fig. 6). In the vicinity of Imhotep, in the Agilkia region, the *Philae* probe was to land. Spectrophotometric properties of these regions were considered by Fornasier et al. (2015). The nuclei of both comets also exhibit a similar narrow part, "a neck". However, in comet Halley, the neck is less pronounced, though also localized in the narrow part and presents the darkest region of the surface.

It is worth noting that the physical conditions near the neck somewhat differ from those in the peripheral regions. There are, for example, the radiation conditions. From the flat surface near the neck, free space is observed over a solid angle of 2π, while the angle is substantially smaller than 2π for the area at the neck. The dark cavity near the neck of the Halley nucleus is complex in shape, which may be caused by the developing process of the body destruction. At the same time, the origin of the neck in 67P/CG may be induced by other processes (Massironi et al., 2015). The stress condition for a cometary neck was calculated through the example of comet 103P/Hartley-2 that is supposed to be close to disintegration (Ksanfomality, 2011). The elongated dumbbell-shaped nuclei of comets (like that of comet 103P/Hartley-2) are mostly convenient for analyzing the physical state and probable evolution of a cometary nucleus. In regard to comet Halley, such calculations were not performed. The comet is much larger in both size R and mass M, and its rotation velocity is three times less (the rotation period of the Halley nucleus is 52 h versus 12.4 h for comet 67P/CG). In the equilibrium section from all of the mass elements M_i, the tensions from centrifugal forces are

$$F = \Sigma M_i R\omega^2,$$

and they turn out to be approximately the same as those for comet 103P/Hartley-2, i.e., close to the

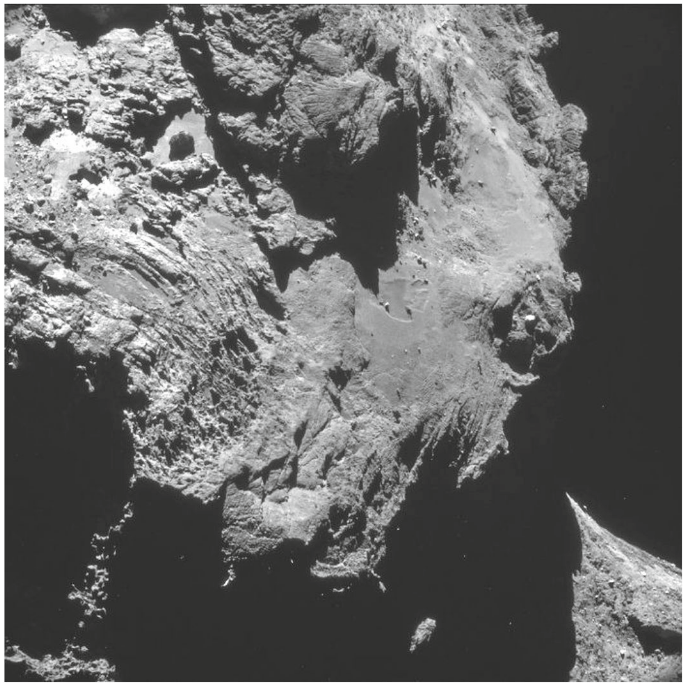

Fig. 8. The heterogeneous region of Atum-Anubis 1.6 km long; the resolution is 1.6 m/pixel. The image (ESA/Rosetta/NAVCAM–CC BY-SA IGO 3.0) was taken from the distance of 18.8 km on May 1, 2016.

breaking forces. However, for more accurate calculations, the shape of the nucleus of comet 1P/Halley should be known more precisely. The mechanical model for comet 67P/CG is more elaborate and includes the moment from the projecting fragments and a complex diagram of the mechanical stress distribution. The roughly estimated tensions are approximately the same, but require more accurate definitions.

In Fig. 6, on the surface of a larger lobe of the nucleus of comet Halley (in the center and on the right), three large circular formations (apparently, craters) can be observed; and a more complex structure is in the left part of the nucleus, where two closely connected objects outlined by a bright border are vaguely seen. Extended plains adjoin them in the both parts. The contours of the circular formations, which are, probably, half-buried craters, are ill-defined. Hills, mountains, and cavities are also noticeable.

As compared to comet Halley, the surface of the 67P/CG nucleus has been examined in much more detail. It turned out to be rather heterogeneous. From the morphologic and structural signs, El-Maarry et al. (2015) distinguished 19 characteristic types of the surface, each of which was given an unofficial name connected with ancient Egyptian mythology. The division into regions by geomorphologic principles is shown in Fig. 7, where the object names are also specified.

Among the surface types, the most common one is that called the consolidated and fractured surface. In some cases, smooth regions formed by the fine-grained dust material with block inclusions are adjacent to them. Such regions are also numerous. It is reported that some depositions of the dust material are active; this points to the recent processes of their formation and their connection with the sublimation of the volatiles composing the cometary nucleus. The large, up to 1 km, steep slope of the nucleus' head called Hathor is extremely interesting in structure: it exhibits the broken material taluses and the signs of layering, which sharply contrasts with the adjacent region of the neck. The crumbling itself occurs very slowly; moreover, the acceleration of gravity $g_c = GM/r^2$ is not the same at the top and the bottom of the wall. For the body mass $M = 10^{13}$ kg and the gravitation constant G, $g_c = 0.167 \times 10^{-3}$ and 0.667×10^{-3} m/s^2 at the top ($r = 2$ km to the gravity center) and the saddle ($r = 1$ km), respectively. Under these conditions, the integration yields the fall velocity of 0.82 m/s near the saddle; and it takes approximately an hour for a fragment to fall from the top.

The variety of regions is presented by small hills, circular formations, some of which are probably ruined craters, plains, and deep fractures. Figure 8 shows the processed image of the complex relief of the Atum–Anubis region, extending to 1.6 km (in Fig. 7, it is in projections *1* and *2*). The surface is strongly heterogeneous; in the left part of the region, it is complicated and contains the elements resembling layered structures, while the Anubis region, on the right, is covered by smoother deposits. At the bottom right, a fragment of the shadowed neck is seen.

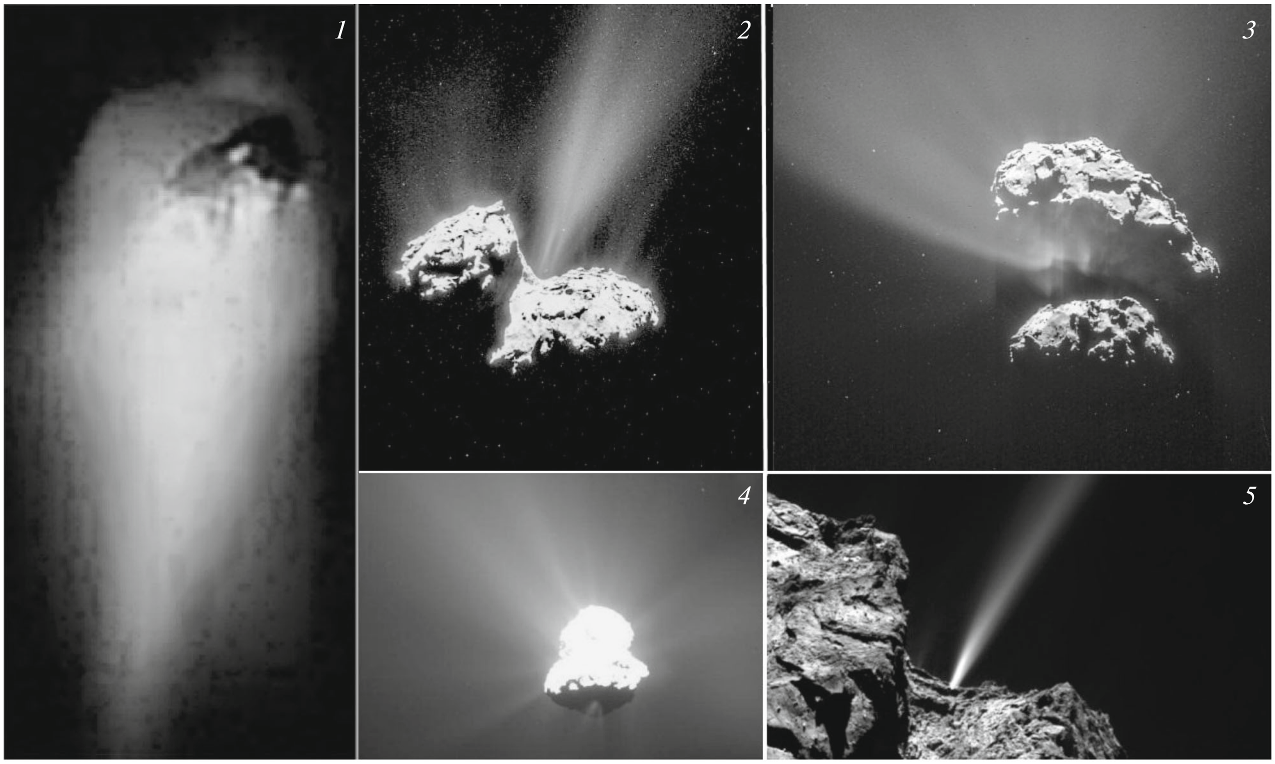

Fig. 9. Activity of the nucleus of comet Halley (1986) (image *1*). The activity development of the comet 67P/CG in the period from February to July 2015 (images *2–5*): the ejecta from the neck on February 6, 2015 (image *2*, ESA/Rosetta/NAVCAM-CC BY-SA IGO 3.0); the gas–dust ejecta developing from the neck (the Hapi region) on February 9, 2015 (image *3*, ESA/Rosetta/NAVCAM-CC BY-SA IGO 3.0); a gushing out jet from the lower unlit part of the nucleus during the high-activity period of the gas–dust ejecta on March 12, 2015; (image *4*, ESA/Rosetta/MPS/MPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA); the irregular narrow jet on July 29, 2015 (image *5*, ESA/rosetta/MPS for OSIRIS team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA taken by the OSIRIS camera).

The origin of some objects is undoubtedly connected with partial sublimation of the nucleus material, which results in brittle structures of fanciful shape. The peculiarities and heterogeneity, or diversity, of the surface structure of comet 67P/CG are considered in detail by Sierks et al. (2015), El-Maarry et al. (2015), Auger et al. (2015), Vincent et al. (2015), Oklay et al. (2016), and Pätzold et al. (2016).

The *Rosetta* mission was the first one that included a lander to investigate the surface of the nucleus. *Philae* is the first probe to land softly on a cometary nucleus. It was fitted out with a large complex of scientific instruments. The *Philae* mass is 100 kg. Before the *Rosetta* mission, two spacecraft, the Near Earth Asteroid Rendezvous Shoemaker (NEAR Shoemaker, 2000) and *Hayabusa* (2005), performed experimental (not planned beforehand) soft landings on asteroids Eros and Itokawa, respectively. Moreover, the *Hayabusa* spacecraft took off after that and returned to the Earth. The *Philae* probe performed the ballistic (uncontrolled) descent on November 12, 2014. Unfortunately, the landing was unsuccessful (Ksanfomality and Churyumov, 2015), and the tasks of the probe were not accomplished.

THE MASS LOSS AT THE PERIHELION PASSAGE

At the approach of perihelion, the activity of nuclei of the both comets was increasing. In its perihelion (0.5712 AU), comet Halley ejected the most intense gas–dust jets extending to hundreds of thousands of kilometers (Fig. 9 (*1*)). The perihelion of comet 67P/CG was significantly farther. The daytime temperature of the surface was in the range from 140 to 200 K (Capaccioni et al., 2015; De Sanctis et al., 2015) and increased to 230 K only at some points. The mass loss of the 67P/CG nucleus was substantially less than that of 1P due to both the higher perihelion (1.2432 AU) and the smaller size. The mass of the 67P/CG nucleus is 22 times less than that of 1P/Halley. Variations in the gas–dust activity of the nucleus of comet 67P/CG are shown in Fig. 9 (images *2–5*). The most active regions of 67P/CG were in the neck area (Fig. 9), but not only there. In image *4*, the ejecta, covering a substantial area of the nucleus, are seen in the center of its lower unlit part. As can be seen from the examples displayed in Fig. 9, the material outflow from the 67P/CG nucleus, contrary to comet Halley, was limited to local sources. However, it is worth recalling that

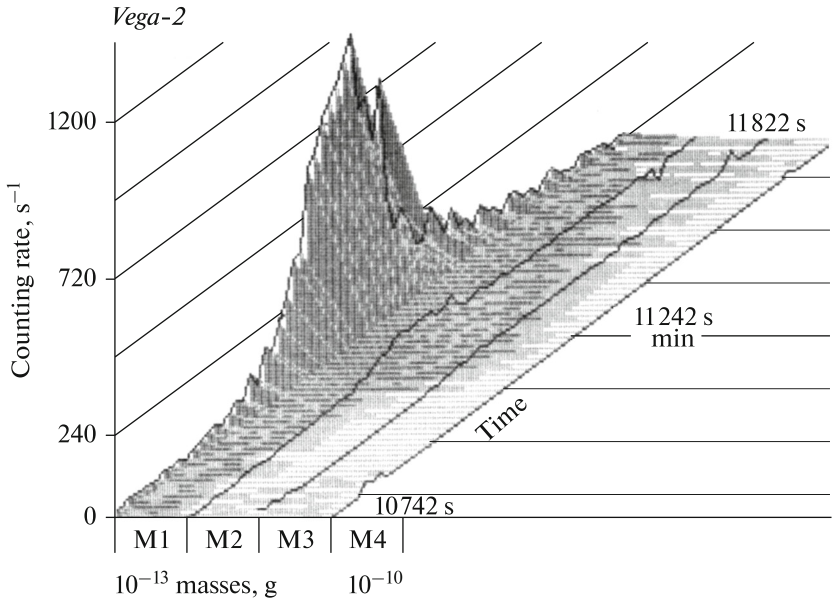

Fig. 10. Changes in the counting rate of dust particles in the DUCMA experiment on March 9, 1986, when the spacecraft most closely approached the nucleus (8045 km) (Simpson et al., 1993).

the total area of the sources of the ejected gas–dust material of comet Halley at perihelion was also estimated only at 10% (Cevolani and Bortolotti, 1987). At the same time, the ejecta were incomparably larger in mass and extension than those of comet 67P/CG.

Dust particles of comet Halley are mostly a mixture of carbon–hydrogen–oxygen–nitrogen refractory organic compounds (CHON) and a stony material of chondritic composition.

In the GIADA (Grain Impact Analyzer and Dust Accumulator) and OSIRIS experiments onboard the *Rosetta* probe, the dust component in the vicinity of the 67P/CG nucleus was registered along the flight trajectory in the interval of 3.6–3.4 AU (Rotundi et al., 2015). In total, the probe detected 35 particles or fragments with masses from 10^{-7} to 10^{-4} and 48 fragments from 10^{-2} to 10 g. Above the day side of the nucleus, the averaged dust-to-gas ratio was 4 ± 2 (with taking into account the data of the Microwave Instrument for the Rosetta Orbiter (MIRO) experiment (Gulkis et al., 2015)). It is noted that the dust-to-gas ratio is 3 on average. Approximately 100×10^3 particles and fragments with sizes up to one meter are orbiting above the nucleus, and the density of particles themselves is close to $(1.9 \pm 1.1) \times 10^3$ kg/m^3. For three months, from June to August 2014, the water loss increased from 0.3 to 1.2 L/s. For one perihelion passage, the total mass loss of the 67P/CG nucleus is $(3–5) \times 10^9$ kg (Taylor et al., 2015).

The boundaries of the cross-section of the coma of comet Halley exceeded 10^5 km, which is typical for large comets. Under the influence of photolysis, the main component, water vapor, dissociated; and the estimates of the extension of the gas and ion components (hydrogen and other volatiles) reached 20×10^6 km. The mass loss of comet Halley at perihelion was considered in many papers (see the review by Cevolani and Bortolotti, 1987). According to the data by Churyumov (see the table), for comet Halley at a distance of 0.9 AU from the Sun (after the perihelion passage), the gas production rate of water Q_{H_2O} was 4×10^{29} molecules per second or $4 \times 10^{29} \times 18 \times 1.66 \times 10^{-27} = 1.20 \times 10^4$ kg/s. The atmosphere of comet 67P/CG is composed of water vapor by approximately 80%; from June to August 2014, the water loss increased from 0.3 to 1.2 L/s, and changes up to five times that (Gulkis et al., 2015). In August 2015, according to Lee et al. (2015), the gas production rate of H_2O varied from 10^{24} to 3×10^{25} s^{-1} sterad^{-1}; during a month, the largest changes in the production rate of H_2O exceeded this by 30 times (the MIRO experiment (Lee et al., 2015)). Thus, the production rate of H_2O reached $4\pi \times 3 \times 10^{25} \times 18 \times 1.66 \times 10^{-27} = 112.6$ and 3.75 kg/s in maximum and minimum, respectively. There is some contradiction connected with the data dimension: Gulkis et al. (2015) report 2×10^{25} molecules per second (in June 2014), while Lee et al. (2015) give 3×10^{25} molecules per second and steradian (in August 2014).

The atmosphere of comet 67P/CG contains 17% carbon monoxide and approximately 3% carbon dioxide. Among the minor constituents, methane and ammonia were found (Biver et al., 2015). The measurements of the dust component were more complex. When the gas-to-dust ratio was 7 : 1 by mass (for a short time), the total loss reached 1.60×10^4 kg/s. The

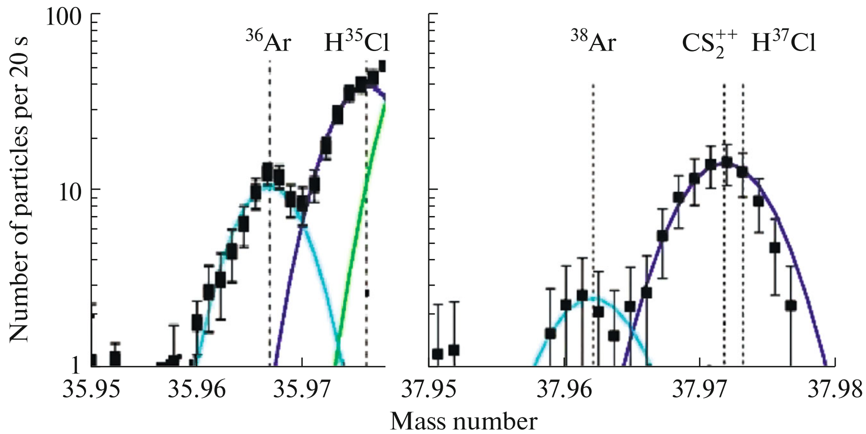

Fig. 11. Gaseous components of comet 67P/CG detected in the ROSINA experiment: ^{36}Ar and ^{38}Ar isotopes and hydrochloric acid. The atomic or molecular weight is along the horizontal axis. The plot is adapted from the paper by Balsiger et al. (2015).

estimates of the mass loss of comet Halley near the perihelion considerably diverge. The estimates for one orbital period (~76 years) vary from 2.2 to 5 × 10^{11} kg, i.e., from 10^{-3} to 2 ×10^{-3} of the total mass of the nucleus. Three dust experiments were carried out onboard the *Vega* probes: the Dust Counter and Mass Analyzer (DUCMA) and two plasma impact detectors (SP-1 and SP-2) (Simpson et al., 1990; Mazets et al., 1986; Vaisberg et al., 1987). In the papers by Simpson et al. (1993; 1989; 1990), it is reported that the particles with masses from 1.5 × 10^{-13} to 10^{-8} g were detected in the DUCMA experiment onboard the *Vega-1* and *-2* spacecraft.

Figure 10 illustrates the increase and the subsequent decrease in the counting rate in the DUCMA experiment, when the spacecraft approached the nucleus to 8045 km. Integration of the data of the dust instruments with the assumed functions of the mass distributions of particles yielded the increase of the largest mass loss (at perihelion) to 2.9 × 10^4 kg/s.

It is worth noting that the total mass of the Halley nucleus (2.2 × 10^{14} kg, see table) is calculated from the

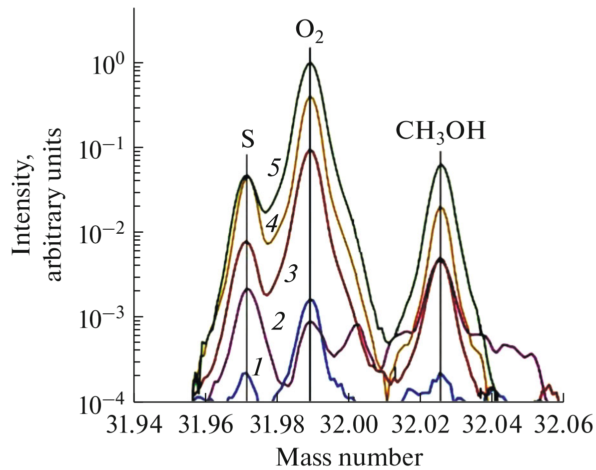

Fig. 12. Abundance of oxygen O_2, sulfur, and methanol in the atmosphere of comet 67P/CG detected in the ROSINA mass-spectrometer measurements at different distances from the nucleus: before the encounter, on August 1, 2014 (*1*); before injection to the quasi-satellite orbit, on June 18, 2014 (*2*); on the 30-km altitude orbit, on September 11, 2014 (*3*); on the 20-km altitude orbit, on October 1, 2014 (*4*); on the 10-km altitude orbit, on October 22, 2014 (*5*). The molecular weight is along the horizontal axis. The plot is adapted from the paper by Bieler et al. (2015).

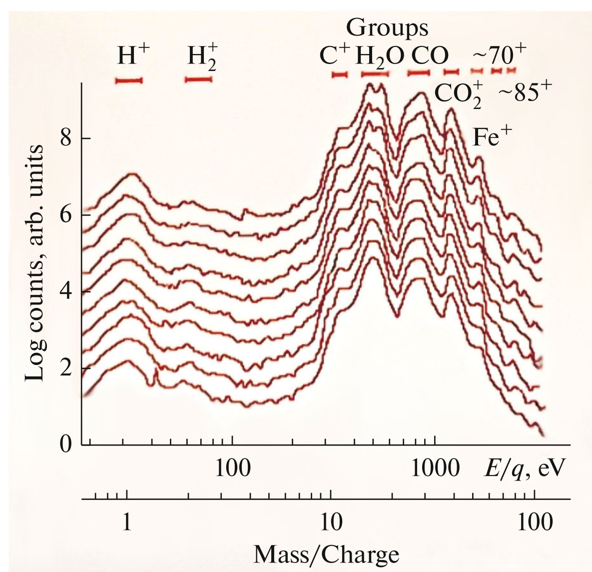

Fig. 13. Iron ions Fe^+ were for the first time detected in the comet Halley plasma in the *Vega* mission experiments. The curves were obtained, when the probe was approaching the nucleus (by permission of Verigin, from his poster "*Vega-1* and *-2*: Rendezvous with comet Halley" at the Space Research Institute (2015)).

roughly known density of the body, which is estimated at 100 to 700 (or even up to 1500) kg/m^3 (Sagdeev et al., 1988), and the poorly known density of dust particles. Usually, it is assumed at 600 kg/m^3, which points to a high porosity of the nucleus formed from a large number of small loosely coupled elements.

It is supposed that comet Halley already passed the perihelion approximately 2300 times (Cevolani and Bortolotti, 1987), which results in a very high value of the initial mass, if the above specified mass loss Δm is assumed at 10^{-3} to 2×10^{-3} of the total mass of the nucleus. The initial mass is $M_0 = M_{\mathrm{Hal}}/(1 - \Delta m)^n$, where n is the number of passages, $M_{\mathrm{Hal}} = 2.2 \times 10^{14}$, which yields $M_0 = 2.2 \times 10^{15}$ and 2.2×10^{16} kg for $\Delta m = 10^{-3}$ and 2×10^{-3}, respectively. Comets with such a large mass (2.2×10^{15} kg) are unknown. However, at larger time scales, beyond, for example, 40–50 orbits, the calculations of the dynamics of the comet become unreliable. If the loss rate is 2.9×10^4 kg/s at perihelion at a distance of 0.9 AU, the value of 10^{-3} of the mass quickly accumulates near the passed perihelion, for less than 220 days. The losses occur, when the velocity of the nucleus at perihelion is

$$V_{\mathrm{Hal}} = [GM_{\mathrm{S}}(1 + \varepsilon_{\mathrm{Hal}})/q_{\mathrm{Hal}}]^{1/2} = 55.2 \text{ km/s},$$

where $q_{\mathrm{Hal}} = 0.5712$ AU is the perihelion distance, $\varepsilon_{\mathrm{Hal}} = 0.9671$ is the eccentricity, and $M_{\mathrm{S}} = 1.989 \times 10^{30}$ kg is the solar mass. The orbit inclination relative to the ecliptic is 162° (the revolution of comet Halley is retrograde).

From the measurements performed at the beginning of 2015, the gaseous composition of the coma of comet 67P/CG included water, carbon monoxide, carbon dioxide, ammonia, methane, methanol, formaldehyde, hydrogen sulfide, hydrogen cyanide, sulfur dioxide, carbon disulfide, sulfur, and carbonyl sulfide; sodium and magnesium were also detected in the dust composition (Biver et al., 2015; Taylor et al., 2015; Capaccioni et al., 2015). In the earlier papers, it was reported that hydrogen sulfide contains sulfur isotope ^{32}S, while isotope ^{34}S may be of another origin.

In the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) experiment, it was found that the cometary nucleus contains, along with the other gaseous components, the noble gas argon with the isotope ratio $^{36}\mathrm{Ar}/^{38}\mathrm{Ar} = (5.4 \pm 1.4)$, which is close to the terrestrial ratio 5.3 (Fig. 11; Balsiger et al., 2015). Argon had been also detected in comets before. Earlier, Stern et al. (2000) reported argon emissions in the "Great Comet 1997"—comet Hale–Bopp—where the synthesis of organic compounds was presumably found (Rodgers and Charnley, 2002).

Detection of molecular oxygen O_2 in the atmosphere of comet 67P/CG with the ROSINA mass-spectrometer onboard the *Rosetta* probe has become an important event (Bieler et al., 2015); in addition, oxygen occurred among four most abundant components of the cometary atmosphere (Fig. 12). Its concentration (from 1 to 10% relative to water vapor and 3.8% on average) was weakly varying for six months of the measurements, which points to the nucleus as its stable source.

Oxygen diffuses from the nucleus interior and is supposed to have been kept in the nucleus since its origin rather than to be a product of water dissociation. However, it is still unclear what primary medium could be substantially enriched with oxygen and why oxygen, being a highly active element, was not coupled in reactions with the nucleus materials. It is worth noting that the problem of the relation between the abundance of the observed components and the initial composition of the cometary nucleus is among the urgent problems of cometary physics (Marboeuf and Schmit, 2014).

The main specific feature of the *Rosetta* mission, as compared to the *Vega* mission, is that the quasi-satellite position of the spacecraft relative to the 67P/CG nucleus allows systematic long-term observations; and the detection of oxygen was such a case. Nevertheless, in the *Vega* mission, during the short-term rendezvous of the probes with the comet, there were also many surprises. Direct measurements of the cometary plasma composition revealed the presence of ions with a mass of 56 (Fig. 13); they were hypothetically identified with iron ions Fe^+ that had not been detected in the plasma of comet Halley before.

As has been mentioned above, comet 67P/CG, as opposed to comet Halley, belongs to the dust–gaseous type of comets. In the table compiled by Churyumov, the dust-to-gas ratio is estimated at 4 : 1; however, it is apparently closer to 3 : 1.

The specified peak dust production rate of comet 67P/CG near the perihelion of 2002–2003 was 60 kg/s, while it reached 220 kg/s in 1982–1983. The recalculation to the H_2O production rate yields the values from 3.75 to 112 kg/s, which agree with the above specified ranges (Lee et al., 2015). The water vapor production rate is $Q_{H_2O} \approx 4 \times 10^{25}$ s^{-1}, i.e., 10^4 times less than that in comet Halley. Because of this, the specified dust-to-gas ratios are usually reduced to the minimum estimate of the dust loss at approximately 15 kg/s. As a whole, the scatter in the estimates makes it difficult to determine the total losses; however, relative to the nucleus mass (10^{13} kg), they are negligible. If only the orbital movement of the comet is taken into account, the dynamical effects of micrometeorites, gas, and plasma on the nucleus surface and the whole coma are substantially weaker than those in comet Halley. The orbital velocity at perihelion ($q_{67\mathrm{P}} =$ 1.2432 AU and $\varepsilon_{67\mathrm{P}} = 0.6410$) was

$$V_{67\mathrm{P}} = [GM_{\mathrm{S}}(1 + \varepsilon_{67\mathrm{P}})/q_{67\mathrm{P}}]^{1/2} = 34.2 \text{ km/s}.$$

Due to the rapid motion of the *Vega* spacecraft themselves relative to the Halley nucleus, an interesting phenomenon was found. The spatial distribution of dust particles in the vicinity of the nucleus was not uniform and pointed to some periodicity in the dust medium structure. O.L. Vaisberg interpreted this phenomenon as the spatial spiral shape of the most intense dust jets appeared due to the nucleus rotation (Vaisberg et al., 1987; 1986). Since the *Vega* spacecraft moved quickly, they successively crossed these jets several times (Simpson et al., 1989).

ORIGIN OF COMETS 1P/HALLEY AND 67P/CG AND THEIR ENRICHMENT WITH DEUTERIUM

Comparison of the data on the atmospheric composition of comets 1P and 67P (see the table) shows that they substantially differ, which is caused by the differences in their origin. The Kuiper belt is believed to be such a region of the Solar System, where the bodies like comet 67P may inhabit (Auger et al., 2015a). The orbital peculiarities of comet Halley suggest that it probably originates from the most distant zone, the Oort cloud (McDonnel, 1986), where the bodies are independent of the position of the ecliptic plain and may stand out against the other Solar System bodies by their D/H ratio. In projection on to the ecliptic plain, its revolution about the Sun is retrograde, as compared to that of the other Solar System bodies. Now comet Halley belongs to the group of short-period comets (the period is less than 200 years); however, exactly these orbital features allow us to suppose that it was formed in the Oort cloud and, due to perturbations in a lower part of its orbit caused by the giant planets, it appeared on a short-period orbit. At the same time, according to the historical data available, comet 1P/Halley has been on the current, more or less stable, orbit for quite a long time (Cevolani and Bortolotti, 1987). In the ancient Greek and Chinese sources, the first record about this comet dates from 468–466 B.C., while it was described in Chinese documents dated 240 B.C. In the medieval period, the Julian and Gregorian calendars marked the dates of the appearance of 1P starting from 1531 and 1607, respectively. The evolution of the 67P/CG orbit is not traced that far. The calculations of its evolution before the 19th century yield unreliable results. According to the inverse integration of the orbit, its perihelion distance was 4.0 AU before 1840, which is three times larger than the current one. The subsequent series of encounters with Jupiter decreased the perihelion distance to 3.0 AU and later to 2.77 AU. Quite recently, in 1959, the perihelion of the comet decreased to 1.29 AU. The orbital period of comet 67P is currently 6.45 years.

The measurement of the D/H ratio (deuterium to protium) turned out to be extremely important. The 67P/CG nucleus fumes a considerable amount of water vapor. According to the results of new measurements (Altwegg et al., 2015), the analysis of the isotope composition indicates an unusually high value of the D/H ratio (already mentioned in the express-review

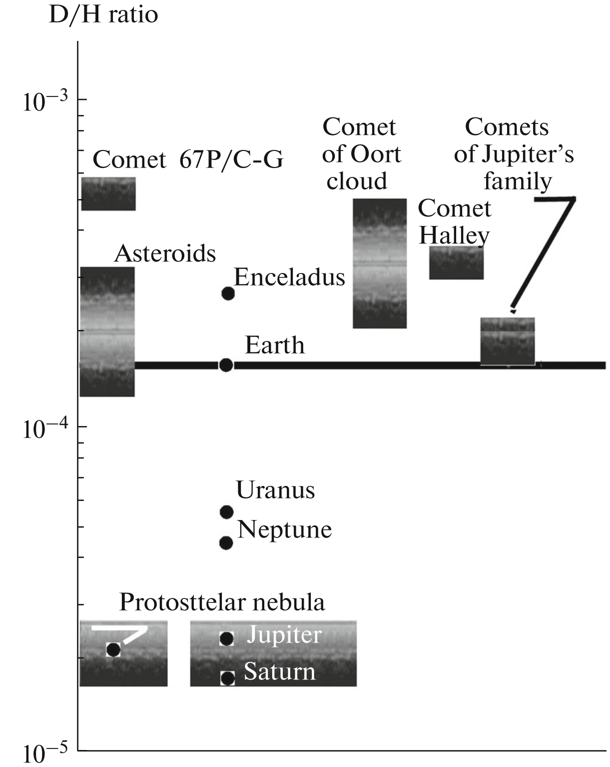

Fig. 14. Generalized diagram of the D/H ratio of the Solar System bodies. Enceladus is Saturn's satellite. The height of rectangles shows the differences in the values for the group or the scatter of measurements. The horizontal line at a level of 156 ppm corresponds to water on the Earth. The upper value, 530 ppm, is from the 67P data. The initial value of D/H in the protostellar nebula is approximately 20 ppm. Jupiter and Saturn exhibit similar D/H ratios. The two-fold (on average) values of D/H, as compared to the terrestrial ones, are typical of the comets from the Oort cloud (like comet Halley).

by Ksanfomality and Churyumov (2015)). A topic of the deuterium-to-protium ratio has been discussed by many authors in connection with the origin of terrestrial oceans; among them, we mention Tobias C. Owen and Akiva Bar-Nun, whose studies cover the period from the early 1980s to the present. It was supposed that volatiles got to the inner planets in planetesimals and ice nuclei of comets (Owen and Bar-Nun, 1995), and up to 40% of water in terrestrial oceans was brought by comets, while approximately 60% was released by planetesimals and asteroids.

While being gradually accumulated, the experimental facts about the deuterium-to-protium ratio moved the origin of the terrestrial water, however, in favor of planetesimals and asteroids (Owen, 1998). In the paper by Owen and Bar-Nun (2001), it is noted that comets could not be the only source of the Earth's oceans and other sources with a low value of D/H were required. The problem was considered in depth by Drake (2005). The D/H ratio measured in the experiments onboard the *Rosetta* probe is $(5.3 \pm 0.7) \times 10^{-4}$

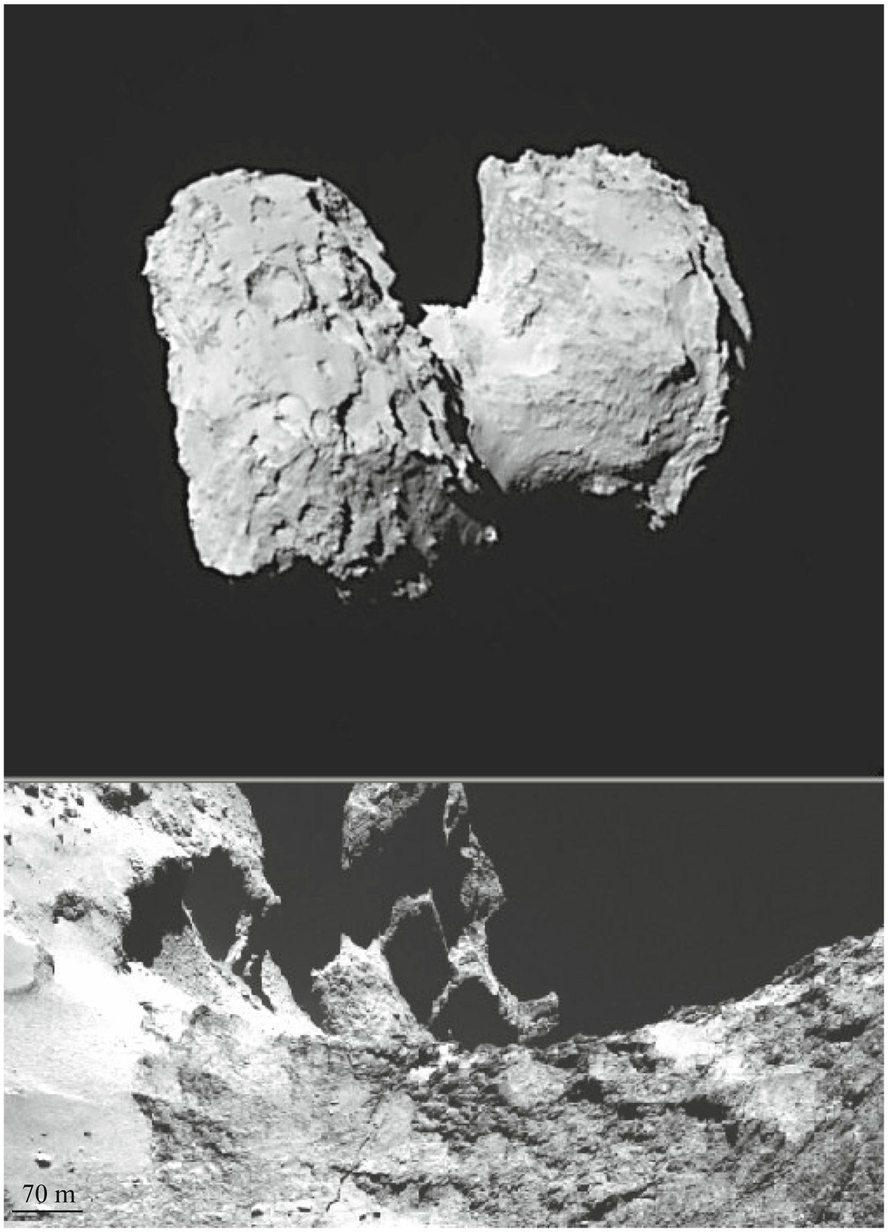

Fig. 15. The 67P/CG nucleus is composed of heterogeneous fragments. A steep slope above the neck on the right (the Hathor scarp) is approximately 1 km high. In the image, the crumbling slope is seen. The opposite side, the Seth region, is different in nature. In the bottom, the Hapi surface is zoomed in. The regolith and stones, crumbling onto the neck, are seen in the image. (The images were obtained with the NAVCAM (ESA/Rosetta/NAVCAM-CC BY-SA IGO 3.0) and OSIRIS (ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA) cameras.

(Altwegg et al., 2015). As the authors point out, the earlier measurements in comets and new results allow one to suppose that the wide ranges of the D/H ratio for water in the comets of Jupiter's family rule out the possibility that this reservoir was a single source of water for the Earth's oceans. The conclusion is cautious; nevertheless, a lot of comments have appeared that the results of the *Rosetta* mission decisively close the question about comets as sources of water for terrestrial oceans. However, this is not true. Though there is not much water, being in different phases, on the cometary surface itself (De Sanctis et al., 2015) and the diurnal phase cycles are observed, water ice is one of the main components of cometary nuclei, whose share in the material delivered to the Earth was substantial.

Moreover, the terrestrial D/H ratio itself could also evolve (Genda and Ikoma, 2008). While 10^6 molecules of normal terrestrial water (H_2O) are accounted for by 156 molecules of "heavy" water (HDO), i.e., 156 ppm, the *Rosetta* measurements yield 530 ppm in comet

67P/CG, i.e., 530 molecules of HDO for 10^6 molecules of normal water.

Figure 14 is composed from the data reported in many published papers. For comet Halley, the D/H ratio was 310 ppm (Eberhardt et al., 1987), which is twice as large as the terrestrial one (156 ppm). The ratio for comet Hale–Bopp turned out to be almost the same (330 ppm) (Meier et al., 1998). Consequently, these celestial bodies are enriched with deuterium by 2 and 3.4 times, respectively, as compared to the Earth, and by more than 15 times, as compared to the protostellar nebula. In Fig. 11 the horizontal line shows the terrestrial water level (156 ppm), and the interval of 20–23 ppm corresponds to the initial D/H ratio in the protostellar nebula (Geiss and Gloeckler, 1998). Recent measurements in comet 103P/Hartley-2 yielded the ratio D/H = $(1.61 \pm 0.24) \times 10^{-4}$ (Ceccarelli et al., 2014). Though the both comets, 103P/Hartley-2 and 67P/CG, apparently came from the Kuiper belt (Altwegg et al., 2015), they differ in the D/H ratio by three times.

It is naive to believe that the results of investigations of comet 67P/CG solved the problem on the origin of water in the Earth's oceans. Figure 14 also points to the complexity of the D/H ratio, and the clustering of the D/H values near the terrestrial values first favors planetesimals and asteroids, though the other sources of water also existed. At the same time, a portion of the oceanic water was also delivered by comets (Balsiger et al., 2015), and the water of oceans originates from a mixture of different sources. Nevertheless, Fig. 14 once again illustrates the complexity of the problem.

FORMATION OF COMETARY NUCLEI IN LOW-VELOCITY COLLISIONS

Many cometary nuclei exhibit a dumbbell-like shape with a narrow neck between more massive lobes. The nuclei of comets 67P/CG, 1P/Halley, 103P/Hartley-2, 19P/Borelli and many others are of such type (Ksanfomality, 2011). As in the case of comet 67P/CG, the narrow neck is a region that often demonstrates the most intense ejecta of the material. This allows us to suppose that the nuclei are gradually breaking down exactly at the narrow section (Fig. 15). The neck thinning is accompanied by the strengthening of mechanical stresses appearing under the action of centrifugal forces from the body's rotation and other physical factors. As has been already mentioned, the mechanical stresses were analyzed by an example of comet 103P/Hartley-2, where the body is kept from a rupture only by friction forces. Probably, in some cases, a rupture actually occurs, if the regolith in the neck is rather loose. The density of the nucleus of comet Halley is approximately 550 kg/m^3, and the porosity is approximately 50%, which suggests that its structure contains a lot of small loosely coupled elements. The density of the nucleus of comet 67P/Churyumov–Gerasimenko is also low, 533 ± 6 kg/m^3 according to the updated data, and its porosity is high, 72–74% (Pätzold et al., 2016). The authors note that, in general, the dust composition and porosity of the 67P/CG body are similar to the corresponding characteristics of comet 9P/Tempel-1. The probable dust-to-ice mixing ratio is approximately four by mass and two by volume. The analogous results of the *Rosetta* mission have been already cited above (Gulkis et al., 2015). The nucleus material is rather homogeneous, and cavities are unlikely present.

At the same time, as was shown in the experiments performed onboard the *Philae* probe in the course of its landing, though the mean porosity of the nucleus is high, the material in the final landing site near the Abydos region exhibited the rigidity of a rather firmly adfreezed mixture of ice and dust grains; while at the point of the first contact (the Agilkia region), the surface was weak (though sufficiently rigid for the probe to hop off). The results of these observations have initiated an increasingly greater interest in the other known hypotheses: it is supposed that the dumbbell-like shape of cometary nuclei is a consequence of the bygone merging of independent bodies rather than an indication of their impending fracture. It is the nucleus of comet 67P/CG that gives such evidence; it is considered by Benz (2015), Vincent et al. (2015), Massironi et al. (2015), etc. The latter authors also discuss the hypothesis about the depositions of layers onto the already-formed body. The shape of the nucleus and its properties raise the issue whether the body was formed in the contact of two large planetesimals 4.5 Gyr ago, or it is a single body, whose evolution travels the path of slow disintegration (Sierks et al., 2015). The concept of forming a nucleus from colliding bodies is not new; however, it meets the difficulty that the energy released in collisions disrupts the impactors rather than joins them. No doubt, in many cases, such disruption collisions actually took place. However, the number of colliding bodies was very high; and, among them, there were bodies with small collision velocities of 1–1.5 m/s. Consequently, the impactors could join almost nondestructively, and the neck material could be compressed. Precisely these conditions could result in formation of dumbbell-shaped nuclei of comets (67P/CG, 103P/Hartley-2, and 1P/Halley), which surely does not exclude their gradual disintegration at the narrow section.

A convincing example of the heterogeneity of the parts of the 67P/CG nucleus is shown in Fig. 15. The Hathor scarp exhibits the signs of the ongoing degradation, and the exposed surface resembles layers in structure. At the bottom of the scarp, the crumpled material and separated boulders covering the Hapi neck are seen. Its surface is enlarged in the bottom of the figure. It is seen that the surface is heterogeneous and bear the traces of disintegration and fractures (Sierks et al., 2015). The structure of the opposite side, the Seth region, is completely different (Vincent et al., 2015). Thus, two lobes of the 67P/CG nucleus are apparently different in nature (Massironi et al., 2015), which favors the hypothesis of merging of the protocometary bodies. In this case, we may expect that, in the region of the contact of two colliding bodies, the density of the regolith is higher. Probably, such heterogeneity of the regolith on the 67P/CG nucleus surface occurred at the landing site of the *Philae* probe.

The hypothesis on the cometary nuclei merging in low-velocity collisions has won many supporters. The probability of disintegration in collisions is much higher than that of merging; however, during the formation of the Solar System, low-velocity collisions also occurred among numerous primary bodies. For primary bodies of small and large masses, the merging process should go on in a different way. For the large bodies, even under low collision velocities, the scattered energy is so high that the contact region should be completely squashed. If we assume that the Halley nucleus has also passed such a process, its appearance (Fig. 6) seems to confirm this idea. However, for the present, there are too few statistics. Thus, the smaller the mass of cometary bodies (and asteroids), like that of the 67P/CG nucleus (Figs. 4 and 6), the more often necks should occur in them. No doubt, the images in Figs. 4 and 6 cannot be direct evidence of the merging of independent nuclei. However, probably, such a merging actually occurred and the contact was exactly in the plain of a narrow section shown in the figure.

The hypothesis on the merging of protocometary bodies, as a new stride in cometary studies, was presented at the 29th International Astronomical Union (IAU) Assembly, at the Peter Gruber Memorial Lecture focused on new understandings of the processes of the formation of the Solar System (Benz, 2015).

CONCLUSIONS

Needless to say, the above comparison of some properties of cometary nuclei does not completely settle the issue. Direct studies of cometary nuclei that were started by the *Vega* spacecraft 30 years ago show the variety of the nature of cometary nuclei, their atmospheres, and the regions of their origin. The comparison of the comets investigated in more detail, such as comets 1P/Halley and 67P/Churyumov–Gerasimenko, suggests that they are considerably different in physical and chemical properties, dynamics, and evolution. We may also note that the commonly encountered statement that the study of the physics and evolution of comets will prompt the solution of cardinal problems on the origin of the Solar System is rather naive. On the contrary, new processes come to light, which further complicates the concepts on its beginning.

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