

PHYSICS OF OUR DAYS

PACS numbers: **96.25.–f**, 96.30.Cw, 96.30.Ys

Disintegration of comet nuclei

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DOI: 10.3367/UFNe.0182.201202c.0147

Contents

Abstract. **The breaking up of comets into separate pieces, each with its own tail, was seen many times by astronomers of the past. The phenomenon was in sharp contrast to the idea of the eternal and unchangeable celestial firmament and was commonly believed to be an omen of impending disaster, especially for comets with tails stretching across half the sky. It is only now that we have efficient enough space exploration tools to see comet nuclei and even — in the particular case of small comet Hartley-2 in 2010 — to watch their disintegration stage. There are also other suspected candidates for disintegration in the vast family of comet nuclei and other Solar System bodies.**

1. Introduction

Comets, whose tails decorate Earth's sky and sometimes stretch in space to interplanetary distances, lost their former glory of celestial forerunners of terrestrial troubles with the advent of space vehicles. These spacecraft enter the ephemeral atmospheres (comas) of comets and explore their nuclei, which vary in size from a fraction of a kilometer to several dozen kilometers. The shapes of the nuclei of comets are very similar to those of small asteroids, although it is commonly believed that their origins are different. However, some asteroids, about 6% of the total, are so-called extinct comets, and the boundary between the two types is becoming more and more blurred, although only cometary nuclei can contain as much as 80% of water ice.

The principal optically observable distinctive features of comets are the highly elongated orbits and, of course, very long tails. At the perihelion, as the comet approaches the Sun, cometary nuclei are heated, become active, and emit enormous masses of volatile components: water vapor, carbon dioxide, and other gases, as well as dust particles ranging in size from tiny to large. As comets approach the Sun, they often penetrate within the orbit of Earth, and some of them move so close to the Sun that they never return from the perihelion. At their farthest distance from the Sun (at the aphelion), the orbits of short-period comets stretch beyond the orbits of Jupiter and Neptune.

A comet is characterized as short-period if the period of its repeated emergences is less than 200 years. This is indicated by adding a letter P after the number in a comet name. A large group of comets is linked with Jupiter, whose gravitational pull sometimes changes their orbits quite significantly. Jupiter's influence led to the catastrophic events of 1994, in which a huge amount of energy (2.5×10^{22} J) was released in collisions of fragments of Comet SL-9 with Jupiter.

In November 2010, the spacecraft *Deep Impact* of the project EPOXI (Extrasolar Planet Observation and deep impact eXtended Investigation) of the US National Aerospace Agency (NASA) maneuvered itself close to the nucleus of comet 103P/Hartley-2 and transmitted images of this small dumbbell-shaped celestial body with a smooth waist. Because rotation of the nucleus creates centrifugal forces, it was conjectured that the dumbbell waist resulted from the action of these forces, and that the waist undergoes slow but continuous elongation, which should end in breaking the nucleus into fragments.

This article focuses on the destruction of cometary nuclei, and specifically on the dynamic evolution of the nucleus of comet Hartley-2. The results of the calculation show that the centrifugal force increases stronger than gravity in a narrower part of the nucleus, and the nucleus is indeed in a state of approaching disintegration into two parts. The nucleus of comet Hartley-2 is a spectacular example of a celestial body in the process of observable destruction. In the case of no external disturbances, the two components of the celestial body will separate to a distance of less than 1 km.

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Received 9 February 2011, revised 10 May 2011
Uspekhi Fizicheskikh Nauk **182** (2) 147 – 156 (2012)
DOI: 10.3367/UFNr.0182.201202c.0147
Translated by V I Kisin; edited by A M Semikhatov

2. Early days of exploration of cometary nuclei

The coma (comet's 'head') is seen as a small hazy blob, even in the best photographs taken from Earth, and therefore the nucleus of the comet cannot be resolved. Exploration of cometary nuclei using space vehicles was begun by the Soviet space mission Vega and the Giotto mission of the European Space Agency (ESA). On March 6 and 9, 1986, the spacecraft *Vega-1* and *Vega-2*, and on March 14, the space probe *Giotto* approached the nucleus of comet Halley, one of the largest short-period comets [1–4]. Also, *Planet-A* of the Japanese space agency [5] flew at a greater distance from Halley on March 8.

Usually, the orbital planes of such comets lie close to the ecliptic plane (plane of Earth's orbit), although some comets orbit on a plane tilted at a very considerable angle to the ecliptic. Such are comet Swift–Tuttle, whose debris of destruction are familiar as the 'star shower' occurring every August, and comet Halley, one of the most interesting comets. Halley moves along a very elongated elliptical orbit and returns to the Sun once every 76 years (it is assumed, therefore, that only a Methuselah can see it twice).

The spacecraft converged on comet Halley on a head-on course, at a huge approach velocity of about 75 km s^{-1}. Any speck of dust constituted great danger for the craft. Each unit of mass carried a kinetic energy 5600 times greater than that of a unit mass body moving at a velocity of 1000 m s^{-1} (typical for anti-aircraft artillery shells). However, the built-in protection systems allowed the missions to cross the dust shell, enter the head of the comet, and come close to its nucleus. The probes photographed the nucleus and studied in detail the composition of both the dust and the gas ejected by the comet, and also of the plasma surrounding the comet. The physical characteristics of the nucleus were also studied. This nucleus, composed of frozen water with an admixture of other substances, was found to be considerably larger in size than expected.

The *Vega* probes transmitted images from a distance of about 8000 km from the nucleus; the images showed gas jets streaming into space from the surface of the nucleus illuminated and heated by the Sun (Fig. 1a). *Giotto* came even closer to the nucleus, to within 610 km, but this caused some disruption in the functionality of its systems. One of *Giotto's* photographs taken from a large distance 5 days after Vega had produced its photos is shown in Fig. 1b.

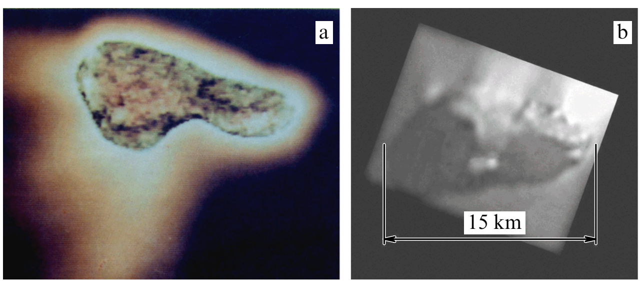

Figure 1. (a) Processed image of the nucleus of comet Halley, with enhanced definition of the hazy nucleus superposed on the primary image of gas jets streaming from the nucleus (photo from the probe *Vega*). (b) View of the other side of the nucleus of comet Halley (photo from the probe *Giotto*). Insufficient clarity of the images is a consequence of the conditions under which the probes operated and the compromise between the definition of photographs and probable loss of the spacecraft if it approaches too close to the nucleus.

The nucleus of the comet is mostly a big lump of ice of irregular shape, covered with a hard black crust. The length of the larger axis of the nucleus is about 15 km, while the smaller axes are about 7–8 km long. The mass of the nucleus is close to 6×10^{14} kg. The nucleus slowly rotates around the axis, passing approximately through the greater segment in Fig. 1a, making one rotation in 53 hours.

The surface of the nucleus is very dark, about 4% at albedo: darker than asphalt. The surface temperature at a distance of 0.8 a.u. from the Sun is close to 360 K. At first glance, the dark surface and high temperature are incompatible with the icy nature of the nucleus. It was discovered, however, that the dark layer on the surface is a crust forming some sort of thermal insulation coating the solid or grainy ice. Photographs show that in places where the crust has been broken, ice melts and gas jets are ejected from under the crust. In addition to water vapor, jets of other gases are emitted, carbon dioxide most of all, and also dust. At the stage of maximum evaporation, the comet loses about 45 tons of gaseous ingredients and 5–8 tons of dust every second [6, 7]. However, this only occurs in the vicinity of the perihelion. Comet Halley probably has enough material to survive another 100,000 years, after which it will slip into the grave of extinct comets. It is possible that its nucleus will break into fragments much earlier.

3. Catastrophic cometary events

Space probes became a powerful tool for exploring comets. Along with the use of space vehicles, improvements in ground-based astronomical equipment made it possible to monitor objects of this type — a feat that seemed highly improbable, even quite recently.

One of the main tasks of science is the classification of phenomena and events. Alas, definitions sometimes cease to be very precise once their subject is more closely inspected. This is what is now happening to such seemingly stable astronomical concepts as satellites, asteroids, comets, and even planetary rings. Boundaries that separate them are growing blurred. It appears that Mars's satellite Phobos is hardly different from a certain class of asteroids. Some asteroids, in turn, may be 'extinct' comets, i.e., bodies that lost their store of volatile components. Jupiter's satellites, in fact, include so-called Trojans, a group of asteroids whose orbits are locked on Jupiter. A new hypothesis has been suggested about the relatively short longevity of rings born (or refreshed) in destructive collisions of satellites. The initial processes of the formation of the Solar System were common for all its bodies [8]. Critics of the 'unifying' hypothesis advance roughly the following objection: why do we not observe the impacts, collisions, or other catastrophes themselves? Well, astronomers have at last been able to observe them.

A strange comet was discovered at the beginning of 1993 and given the name of the astronomers who discovered it (spouses E and C Shoemaker and D Levy): comet Shoemaker–Levy 9 or SL-9; to use the expression chosen by the discoverers, the comet looked 'squashed': more than 20 large individual cometary bodies were strung out in a line not far from Jupiter's orbit (Fig. 2).

Analysis showed that the orbit of comet SL-9 traces back to a group of Trojan satellites; this could be a small satellite rich in condensates of volatile ingredients that escaped from a remote orbit, or a comet captured by Jupiter. The disintegra-

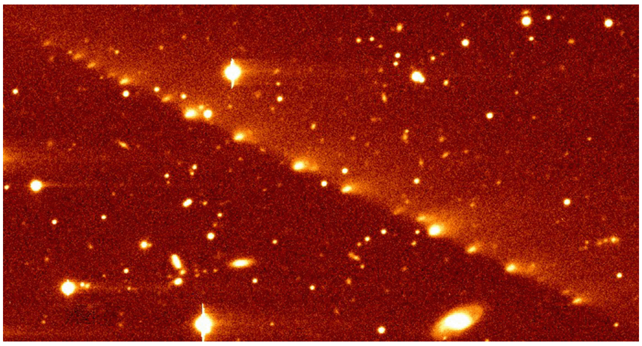

Figure 2. Comet SL-9, which disintegrated in 1992 into 21 fragments after passing through Jupiter's Roche lobe in the vicinity of the planet. Large cometary bodies stretched in a chain 200,000 km long near the orbit of Jupiter, and in July 1994 they collided with the planet one after another. Other objects in the picture are stars and distant galaxies. (Image taken by the Hubble Space Telescope)

tion of the comet into fragments was triggered in 1992 (a year before this comet was discovered) by its passing at a close distance to Jupiter within Jupiter's Roche lobe. The Roche limit is the distance at which tidal forces break up the approaching celestial object; if the body cannot withstand mechanical tension or its parts are weakly bound, it disintegrates. Such effects are very strong in the vicinity of Jupiter owing to its immense mass. However, the body may also be destroyed owing to the frictional resistance of the topmost layers of Jupiter's atmosphere through which it would be moving on its orbital motion, even if the Roche effect was irrelevant.

The subsequent fate of comet SL-9 was predicted immediately (although there were sceptical voices too [9]): astronomers were soon to witness a celestial cataclysm on a scale much bigger than the one that Earth suffered 65 million years ago when almost 80% of all living species were killed. Before the SL-9 event, the probability of an event of such a scale appeared to be so infinitesimally low that it was treated as a mere fact of remote history. Nevertheless, the results of calculations [10] confidently predicted that between July 15 and 22, 1994, pieces of the comet 1 to 10 km in size would smash into Jupiter at a velocity of 64 km s^{-1}. The collision was to occur in the southern hemisphere of the planet and would release enormous amounts of energy.

If a body moving at cosmic velocities suddenly stops, its vast kinetic energy is released in the form of heat. The products of instantaneous evaporation of the body itself and of the obstacle create enormous explosive pressure. It was suggested that a new Great Red Spot or something similar may be created on Jupiter. Special astronomical observation services were set up to be ready on the days of the collisions. Great expectations were connected with the orbital observatory — the Hubble Space Telescope — capable of obtaining detailed photographs of Jupiter from Earth's orbit. The situation presented additional problems because the collisions were to occur on the side of Jupiter not visible from Earth. The night side of Jupiter was observable from the space vehicle *Galileo*, which was then traveling towards Jupiter but was still too far, 238 million km from it. On the other hand, there was hope that owing to the rapid rotation of Jupiter, some traces of collisions on the regions emerging from Jupiter's limb would nevertheless be seen.

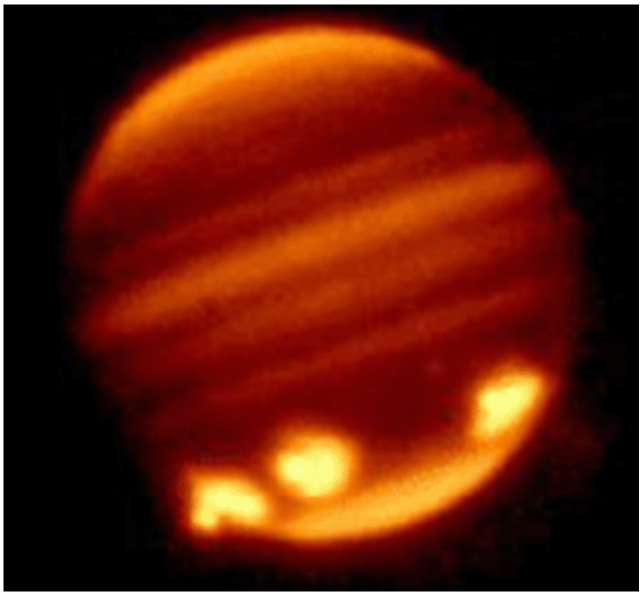

Figure 3. View of Jupiter on July 22, 1994 in infrared light. Traces of collision spots of comet SL-9 in the southern hemisphere of the planet (fragments G, D, S, R, and some smaller ones).

Fragments of the comet exploded between July 16 and 22, 1994. In snapshots in infrared light (Fig. 3), flares with temperature up to 24,000 K looked brighter than the entire planet. The energy released by the explosion of the largest fragment (G) was evaluated as 2.5×10^{22} J (6 million hydrogen bombs of 1 megaton TNT equivalent each). We can recognize traces of these explosions in Figs 3 and 4. The photos were obtained using the cameras of the Hubble Space Telescope. Explosion traces are darker than the surrounding background color of clouds.

The diameter of the thin ring around the center of the explosion of fragment G (the third photo from top in Fig. 4) is equal to Earth's diameter. Fragment G entered the atmosphere from the south at an angle of 45°. The wide dark arc to the right appears to be formed by the ejecta thrown in the direction of the impact. The figures also show the trace left by fragment D — the dark dot to the left of the ring. Other fragments of the comet also left a chain of similar but smaller traces in the top layer of clouds in Jupiter's atmosphere. Evaluations indicated that the explosions occurred fairly deep inside the atmosphere. The products of the explosion formed a semisphere above Jupiter's limb stretching to 3000 km above the planet; in approximately 20 minutes, they became a stripe above the horizon.

Spectroscopic measurements established that the products of the explosion included a large amount of sulfur-containing compounds (such as carbon disulphide, an allotrope of S_2), even though routine observations of Jupiter do not detect any sulphur on the planet.

Papers analyzing the collision of comet SL-9 with Jupiter [11–13] will remain a unique data resource for a long time, perhaps for centuries to come.

There is, however, another aspect to events of this sort: their very real danger to Earth (even though the problem of the danger constituted by comets for Earth is not the subject of this paper). It was indeed the collision of a rather small comet with Earth that caused the widely known Tunguska event (1908) which released about 1.5×10^{16} J of energy [14].

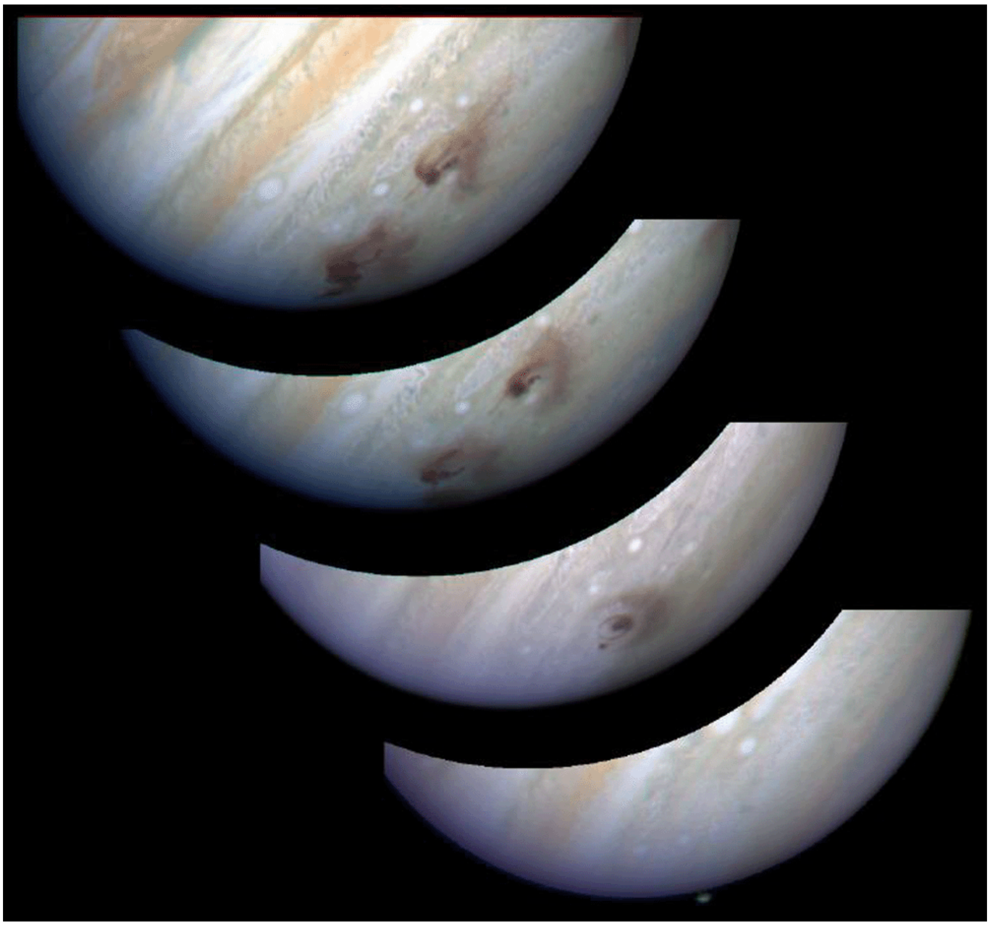

Figure 4. Dark traces of explosions of the fragments of comet SL-9 left on the top cloud layer of Jupiter's atmosphere. (Photographs are courtesy of the Space Telescope Institute and NASA.)

One hypothesis [15] suggests that this body could be a fragment that broke off the large comet Encke.

4. Comet Hartley-2

In the 17 years that followed the collision of comet SL-9 with Jupiter, spacecraft visited five nuclei of different comets (Fig. 5), which allowed exploration of many comet-specific phenomena. Several more probes are now on course to target comets, such as the Rosetta probe [16] of the European Space Agency, with a very complex program for the forthcoming visit to the large comet Churyumov–Gerasimenko in 2014.

All comets studied so far have irregularly shaped nuclei. A celestial body can be spherical only if its mass is quite high, but the mass of all known cometary nuclei is insignificant. Their shapes are illustrated in Fig. 5, which displays all nuclei explored so far. The visiting instruments found them at different phases of activity (at different distances from the Sun). Despite significant differences in parameters, the nuclei of Borelli and Hartley-2 have very similar elongated shapes. The nuclei are usually covered with a very dark crust left after evaporation of volatile matter. For example, the surface of comet Hartley-2 reflects less than 3% of the sunlight incident on it [17], and hence its surface is strongly heated and heat penetrates inside the nucleus, enhancing release of volatile matter where the crust is disturbed. The nucleus of this comet is considerably smaller than those of the cometary bodies studied earlier, its maximum size is only 2.2 km [18].

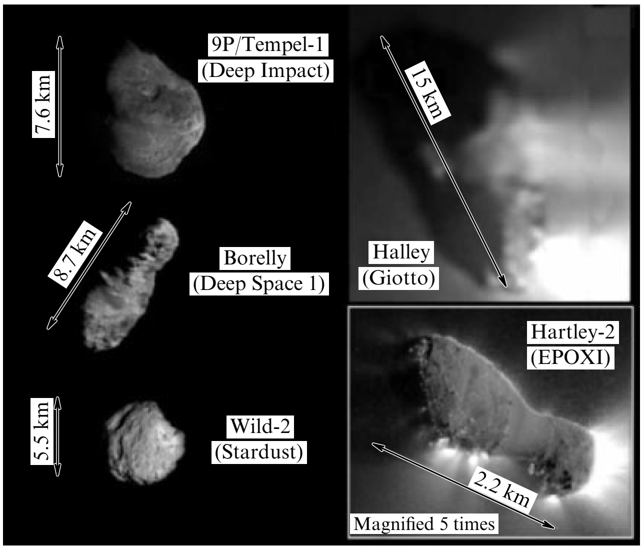

Figure 5. Nuclei of already explored comets 9P/Tempel-1, Borrelly, Wild-2, Halley, and Hartley-2 shown on the same scale (with the exception of Hartley-2). Given in brackets in the photos are the names of the space missions that studied these comets. (Photographs are courtesy of NASA and ESA.)

Hartley-2 is the second comet encountered by the space mission Deep Impact. Six years ago, in July 2005, Deep Impact explored the nucleus of comet Tempel-1, which is another comet of Jupiter's group and is much bigger than Hartley-2. The technique chosen for the exploration was high-speed impact [19]. A massive copper impactor (372 kg) was guided onto the nucleus at a speed of 10.2 km s^{-1}. The energy released by the impact was 2×10^{10} J. The collision formed a crater 100 m in diameter and 20–30 m deep. Products of the impact were analyzed remotely [20, 21]. It was found that they included micrometer-size dust particles: smectites, silicates, carbonates (including aromatic polycyclic hydrocarbons), metal sulphides, and amorphous carbon. The average density of the nucleus of comet Tempel-1 proved to be unusually low, below that of water. Evaluations gave the following results: from 0.2 to 1 g cm^{-3} [22] and (0.45±0.25) g cm^{-3} [23]. Paper [24] gives the estimate 0.62 g cm^{-3}.

Space missions have studied comet nuclei twice. Six years after the Deep Impact mission, on February 15, 2011, the Stardust mission (the probe was renamed NeXT for New eXploration of Tempel) undertook new studies of the nucleus of comet Tempel-1. Detailed images of the crater produced by the impactor were obtained; an improved value for the diameter of the crater was evaluated as 150 m.

The spacecraft *Deep Impact* remained functional on completing the Tempel-1 mission in 2005. A decision was taken to use it in the framework of the program Search for Exoplanets, and it was renamed EPOCh (Extrasolar Planet Observation and Characterization). The mission to comet Hartley-2 was an extension of the mission DIXI (Deep Impact eXtended Investigation) [25], which was reflected in another redesignation of the probe to EPOXI.

The encounter was successful, providing important scientific results. Figure 6 shows the nuclei of comets Tempel-1 and Hartley-2 on the same scale. The nucleus of comet Hartley-2 is considerably smaller but its activity is much greater. In November 2010, *Deep Impact*/EPOXI approached the nucleus of comet Hartley-2 and transmitted photographs of this small celestial body shaped like dumbbells with a smooth waist (Fig. 7). The minimum distance between the Deep Impact probe and the nucleus of the comet on encounter was 640 km.

The unusual shape of the nucleus has attracted the attention of many researchers. The author of this article offered a conjecture that the smooth waist was formed as a result of centrifugal forces produced by rotation of the nucleus. Calculations were performed that were expected to demonstrate whether slow elongation of the waist of the dumbbells does occur and whether splitting of the nucleus of the comet into fragments is possible.

The nucleus of comet Hartley-2 is much smaller than in other explored cometary bodies, its the maximum size is only 2.2 km. Jupiter affects its orbital period: changes in this period were recorded several times in the past; presently, it is 6.46 years. In contrast to the nuclei of other comets, the nucleus of Hartley-2 has a relatively regular shape, resembling dumbbells with two heads of different sizes. Details of the shadowed surface of the part seen in the upper half of Fig. 7 are shown in the upper right-hand part of Fig. 8. In a narrow part of the elongated shape, we can see a relatively smooth area, kind of a narrow belt, appearing sharply different from other parts of this celestial body in the fine structure of the covering material (see Figs 7, 8). The narrow part — the waist — reveals hardly any traces of meteoritic impacts on its surface, which can be regarded as evidence that it is relatively 'young'.

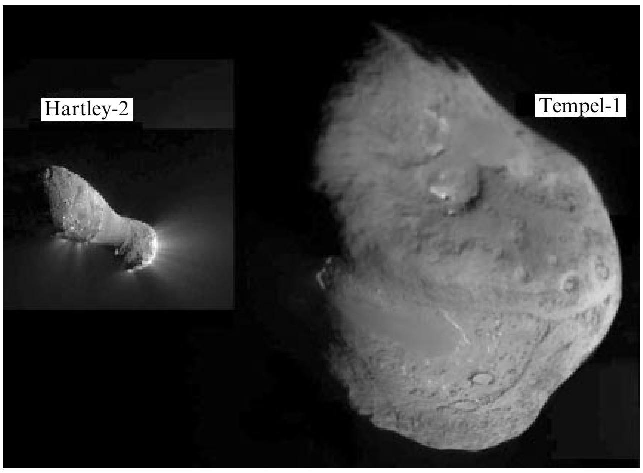

Figure 6. Comparison of the sizes of the nuclei of comets Hartley-2 and Tempel-1, which were investigated by the *Deep Impact* probe respectively in 2010 and 2005. (Photographs are courtesy of NASA.)

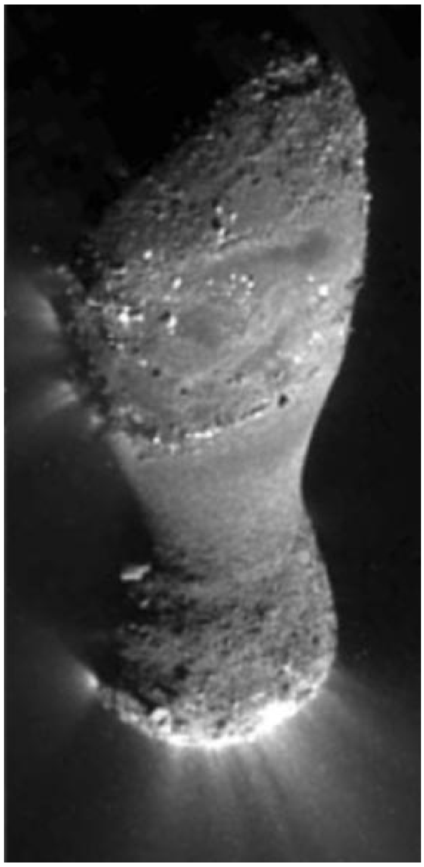

Figure 7. Comet 103P/Hartley-2, Jupiter's family. Size 2.2 km. Orbit: perihelion 1.08 a.u., aphelion 5.6 a.u., orbital period 6.4 years. Rotation period 18.1 h. Mass estimation: 3×10^{11} kg. On October 20, 2010, the comet was at a distance of 18 million km from Earth. The comet nucleus ejects jets of water vapor and other volatile matter, dust, snowflakes, and icicles that form the comet tail. The rotation axis, pointing approximately toward the reader, passes through the upper part, slightly below its center. Rotation produces centrifugal forces, which are assumed to shape the elongated waist and tend to tear the nucleus apart. Centrifugal forces are counteracted by forces of friction and gravitation (mutual attraction of the larger parts of the nucleus). The forces are weak but can act for an infinitely long time. (Photographs are courtesy of NASA.)

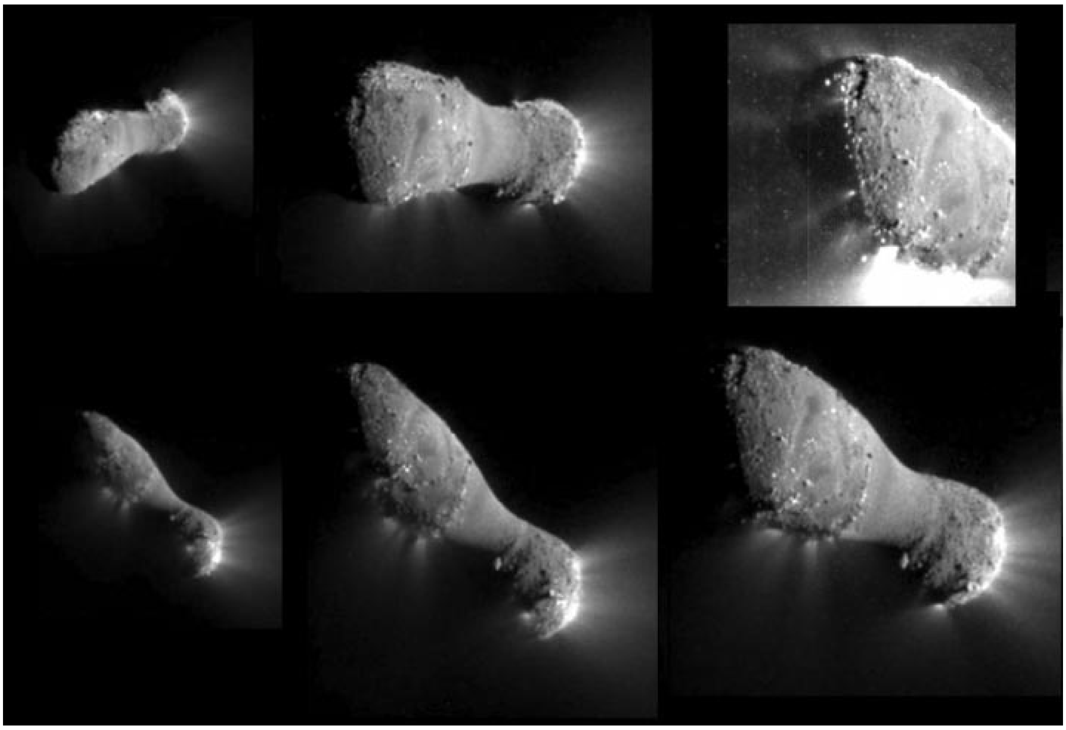

Figure 8. Images of the nucleus of comet Hartley-2 oriented differently with respect to the spacecraft show its rather symmetric shape, which facilitates calculations. The part of the surface in the shadow in the upper-right photo stands out against the background of gaseous ejecta. (Photographs are courtesy of NASA.)

As the EPOXI mission was closing in on Hartley-2 on November 4, 2010, its cameras succeeded in obtaining 199 photographs of varying quality; in these, we see the nucleus of this comet variously oriented relative to the camera (see Fig. 8). The length of the waist is around 400 m. Of course, the notions of the young age or regeneration of the surface of cometary nuclei are somewhat conventional. In fact, the surface of the waist shows no traces of impact craters, although they inevitably appear over a long time of exposure and are always found on celestial bodies of this type. Practically none are detected in this case. Furthermore, craters with diameters up to 100–200 m and other irregularities are seen quite well on the spherical parts of the dumbbells. On the other hand, the high activity of comet Hartley-2 results in a loss through evaporation of a surface layer several decimeters thick over each orbit (perihelion assumed to be at the level of Earth's orbit); this process is likely to level the surface to some extent.

Indications of a considerable loss of material by the small nucleus were obtained in November 2010, when EPOXI was approaching the nucleus: it ejects as much water (in the form of water vapor) as the 10-times-bigger surface of the nucleus of comet Tempel-1, and several times greater amounts of gas and dust. High-resolution photographs display numerous snowflakes and icicles leaving the nucleus of the comet, while ground-based observations have recorded sharp increases in the ejection of cyanides (derivatives of hydrocyanic acid). The already mentioned extremely low reflectivity of the surface (its albedo) is an indirect indication of an intense loss of volatile components in the history of the comet.

It is important to see how the geometry and shape of the nucleus are related to its dynamic evolution. As noted above, the specifics of the surface of the relatively smooth waist compared with the surfaces of the other parts of the nucleus allows making a hypothesis that the shape of the nucleus of comet Hartley-2 is evidence that we are witnessing the destruction of this celestial body. The nucleus revolves around the axis passing through the center of mass, generating centrifugal forces. It can be assumed that centrifugal forces cause slow but continuous elongation of the waist, and this will lead to the destruction of the nucleus. The factors resisting it are the gravitational attraction between the parts of the nucleus and a gradual deceleration of the rotation of the body due to waist elongation and frictional losses in the material of the waist.

With the size of the nucleus and some of its other characteristics having been measured, it is possible to perform the necessary calculations to confirm or disprove this hypothesis. Using the obtained results and the calculations of the moment of inertia of the irregularly shaped nucleus, we have even been able to predict its possible further evolution.

5. What we were able to calculate

Even a body as small as the nucleus of comet Hartley-2 has enormous kinetic energy of its orbital motion. However, its rotation around the axis is a very different matter. The stored energy of a rotating body is determined by its moment of inertia (which is small in this small celestial body) and by the square of the rotational velocity. The nucleus is revolving slowly, with a period of 18.1 h. The rotational energy of the nucleus is small: 4.8×10^8 J (this is equivalent to only 25 liters of automobile fuel). However, as we show below, it is the energy of rotation that determines the future evolution of the nucleus.

The calculations also determined the centrifugal and gravitational forces in the waist and the corresponding tensile and compressive stresses, the volume of the nucleus

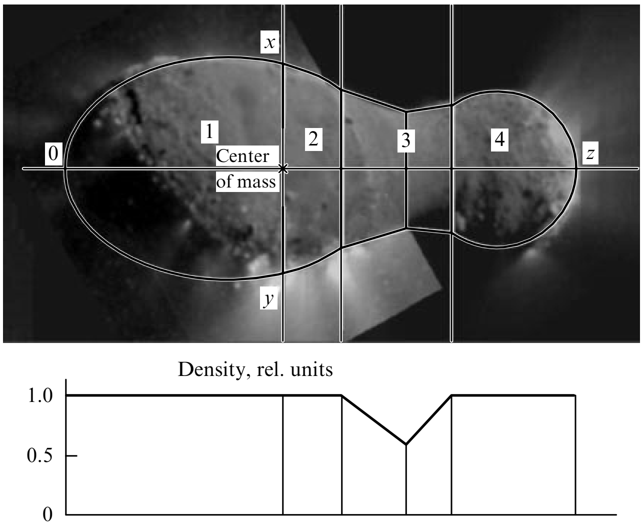

Figure 9. To perform calculations, the relatively symmetric shape of the nucleus of comet Hartley-2 was split into fragments 1–4, which made the results visually clearer.

and its average density, and the position of the barycenter and of the center of rotation. The shape of the cometary nucleus is not very different from a body of revolution with its axis z pointing along its major axis. This is obviously the geometric axis, not the axis of rotation.

Calculations of the volume of the nucleus and of its other features become more transparent if we divide the nucleus into several interconnected fragments (Fig. 9). Fragment 1 is a truncated ellipsoid of revolution and fragment 2 is the part of the ellipsoid bounded by the plane containing the center of mass of the entire nucleus and the axis of rotation of the nucleus passing through this center. As far as we can judge from the sequence of published photographs, the axis of rotation is almost perpendicular to the z axis, which passes through the center of mass but does not necessarily coincide with the xy direction (see Fig. 9). Fragment 3 is formed of two continuous truncated cones of variable density, and fragment 4 is a truncated sphere. We assumed that each fragment is formed as a body of revolution around the z axis, which facilitates integration. As we see in Fig. 9, this structure is not a bad fit to the image of the nucleus.

No data on the distribution of material density was available. We have assumed arbitrarily that the density is the same in all fragments except in the waist, while the density of the waist decreases linearly to 0.6 of the selected value. The dimensions determined using the photographs were as follows: the size of the ellipsoid of revolution 1360×990 m; the diameter of the truncated sphere 720 m; the radius at the point of transition to a truncated cone 305 m; the diameter at the narrowest part 3 of the waist 450 m; the diameter of the cross section passing through the position of the calculated common center of mass (see below) 880 m.

The following results were obtained. The total volume of the nucleus is about 1 billion m^3, or 0.94×10^9 m^3 to be precise. The mass of the nucleus of comet Hartley-2 was evaluated in [17] as 3×10^{11} kg. The average density of the material of the nucleus, assuming the volume as calculated (0.94×10^9 m^3), is merely 320 kg m^{-3} (0.32 g cm^{-3}).

There is a very wide spread of estimates on the average density of cometary nuclei (and asteroids). To a certain extent, the density of asteroids (including extinct comets) may serve as a basis for comparison. A rather typical density for the explored bodies is 1.8–2 g cm^{-3}, as was found for Phobos, Mars' satellite, or asteroid Itokawa. Both much larger and smaller densities of cometary nuclei and asteroids are known. For instance, the spacecraft *Rosetta* had an encounter with the 100-km asteroid Lutetia on July 10, 2010, and it was found [26] that the average density of this asteroid is 3.2 g cm^{-3} (which is higher than the density of granite, 2.5–2.8 g cm^{-3}). At the same time, the density of the nucleus of comet Tempel-1 is only 0.62 g cm^{-3}. Nevertheless, 0.32 g cm^{-3} for the density of the nucleus of comet Hartley-2 appears to be exceptionally low. There is a suspicion that this estimate is erroneous (this proposition is discussed below). The calculated position of the common center of mass (see Fig. 9) is, as expected, displaced relative to the center of the ellipsoid and removed by 955 m from point 0.

Calculations were carried out so as to make their results independent of the value of the density. However, the density becomes a dominant factor if we wish to find the forces and stresses in the material of different parts of the nucleus. Centrifugal forces stretch the nucleus. For the average density 320 kg m^{-3} and the rotation period of the nucleus 18.1 h, the net centrifugal tensile forces in the section passing through the common center of mass are 1.23×10^6 N and the corresponding stress is 2.0 N m^{-2}. The centrifugal forces are much the same in the most narrow section of the waist, 1.15×10^6 N, but the tension in the narrow section is much higher, 7.2 N m^{-2}. Centrifugal forces increase as the density of the material increases, and depend on the squared velocity of revolution (about 10^5 s^{-1}).

Tension is counteracted by forces of compression, which are determined by the total attraction of fragments. Compression forces are 3.0×10^6 N in the cross section passing through the common center of mass, and 1.0×10^6 N in the narrowest cross section of the waist. In the former case, the forces are greater by a factor of three as a result of closeness of the surrounding masses. The corresponding compression stresses in the cross section passing through the common center of mass are approximately 5 N m^{-2}, and in the narrowest cross section, about 6 N m^{-2}. Unlike tensile forces, compression forces scale as the squared density of material. (For more detailed results of analyzing the state of the nucleus of comet Hartley-2, see [27].)

In low-density media, even such low tension can cause gradual lengthening of the waist over very long time, eventually leading to rupture. The material of which the waist consists is not known with any certainty, but because its density is small and it has been established that the nucleus ejects water vapor in great amounts, it is logical to assume that water vapor partially condenses onto the waist surface in the form of hoarfrost or loose snow.

6. Further evolution of the nucleus of comet Hartley-2

Comparisons of the characteristics of the nucleus of comet Hartley-2 obtained for a number of scenarios led to a paradoxical result: if tensile stresses dominate in the waist, then compression stress dominates in the cross section passing through the common center of mass; we note that the increase in the intensity of tensile stress in the former case is only 10%, while in the latter case, the intensity of compression stress increases by a factor of 2.4. The elongated shape of the waist is therefore not an accidental feature. The right-hand side of the waist and fragment 4 (see Fig. 8) are held together only by small friction forces in the waist. Were it not for friction, fragment 4 should have split off and drifted away. It is even possible to calculate how far it would have traveled. Its receding in the gravitational field of the nucleus would consume the main part of the energy of rotation of the nucleus (see above), 4.8×10^8 J. Some fraction of it would be spent on overcoming friction forces in the material of the waist. This is an unknown quantity; however, if losses to friction amounted to 10%, the rotational energy of the nucleus would be completely spent by the time fragment 4 recedes to a distance of 760 m; if the losses were 50%, then the distance would be 316 m. With no loss to friction, it could recede to 920 m.

It is difficult to predict when rupture will occur, because the mechanical properties of the waist of the nucleus are unknown. It was noted that the process of destruction is accompanied by deceleration of the rotation of the nucleus. Consequently, precise measurements of this slowdown would allow calculating a probabilistic prediction of the time frame of events to come. However, this task is unfeasible, and not only because the small size of the nucleus of comet Hartley-2 does not allow remote measurements of this sort. (Indeed, in 2010, the maximum angle at which the nucleus was visible from Earth was only 0.02 arcseconds. This is, in fact, the limit even for a space observatory. In the next perihelion passage (which will occur on April 20, 2017), the comet will again pass far from Earth.) The main factor is the random effect of many gas and dust jets on the orbital period, which decreases or increases as a result. We also mention that the orbital period of comet Hartley-2 is affected each time the comet passes near Jupiter. In 1971, the comet passed at a distance of 0.085 a.u. from Jupiter, and its orbital period shortened as a result from 7.92 to 6.12 years. Measurements of the ongoing elongation of the nucleus of Hartley-2 could be a more promising approach.

We have mentioned above that the very low density of the nucleus of comet Hartley-2 (320 kg m^{-3}) supports the suspicion that the density was determined incorrectly and is in fact higher. To check this hypothesis, we assume, for example, that the average density is 10^3 kg m^{-3}. Then the mass of the nucleus increases to 9.4×10^{11} kg, but the main effect is the inverse ratio of the tensile and compressional forces. The stresses increase considerably, and compression now exceeds tension by a factor of seven. In order to restore their approximate equality and have a waist formed, the hypothetical angular velocity of rotation of the nucleus must be increased by a factor of 2.6 and the period of revolution of the nucleus must be reduced to less than 7 h. This conclusion is alarming, because a short period corresponds to the early epoch, the so-called isochronism of the bodies of the Solar System [28]. The cause cannot be a past catastrophic event either; rotational energy lost during the time of the comet existence is negligibly small in comparison with the losses suffered in collisions of bodies with masses of this type. As regards isochronism, that epoch belongs in the early stages of the evolution of the Solar System. However, the waist is special in being relatively 'young' — indeed, it shows virtually no meteoritic craters. It is hardly possible for this surface to stay smooth for so long, with no traces of the meteoritic impacts, which are so prominent on the rest of the nucleus.

The key to resolving this paradox lies precisely in the density of the material. Indeed, tensile forces are proportional to density, while compressional forces, dictated by gravitation, are proportional to the density squared, because density enters the product of masses in the law of gravitation twice. As a result, the hypothesis of the density value 10^3 kg m^{-3} leads to the domination of compression, which is in contradiction with the observed formation of the waist. The average density of the nucleus of comet Hartley-2 must indeed be close to 300–320 kg m^{-3}, and the nucleus of the comet is currently going through a disintegration stage; it appears to be held together only by friction forces in the narrow part of the waist.

7. Waist of asteroid Itokawa

The nucleus of comet Borelli (see Fig. 5) is similar to the nucleus of Hartley-2 in its elongated form, but it is four times longer. Unfortunately, the photo was taken from a great distance, and it is therefore impossible to resolve any details and then carry out calculations. However, it is possible to identify an area resembling the waist of comet Hartley-2 on asteroid Itokawa — a celestial body of a different class. Should we expect that this asteroid will rupture?

The orbits of asteroids concentrate in the Solar System in a belt at a distance from the Sun two to four times greater than the radius of the orbit of Earth. There are hundreds of thousands of small asteroids. On November 10, 2005, the spacecraft *Hayabusa*, the 'firstborn' of Japanese space missions to asteroids, approached the small asteroid Itokawa (designation in honor of Hideo Itokawa, one of the founders of Japanese space studies) and even touched its surface [29, 30]. Unfortunately, it failed to fulfill one of the main objectives of the mission — to take a sample of the soil and deliver it to Earth. When the sample capturing device returned to Earth on July 13, 2010, it was found empty. However, this was the very first mission of this type, and not only for Japan. A large amount of very interesting scientific material was obtained.

Asteroid Itokawa has an irregular shape (Fig. 10), which makes it very difficult to approximate it with simple geometric shapes, and its size is $535 \times 294 \times 209$ m. The length is so small that this asteroid could be displayed, for example, in Red Square in Moscow (the distance between the History Museum and St. Basil's Cathedral is 695 m). Unlike the density of Hartley-2, the average density of Itokawa is almost 2×10^3 kg m^{-3} and its surface is 20 times lighter. At perihelion, this asteroid is inside the orbit of Earth and in aphelion, it recedes to 100 million km beyond Mars's orbit.

The waist area resembles the waist of comet Hartley-2; we see it in the middle of the asteroid (Fig. 11). It was of interest to calculate stresses as in the case of cometary nuclei and to check to what extent the asteroid is stable with respect to centrifugal forces, especially because its rotation period is less by a factor of 1.5, while centrifugal forces under the same conditions are greater by a factor of 2.2. However, the gravitational forces must be much stronger because the asteroid density is 6 times higher.

The simplified geometry of parts of the asteroid (with equal volumes, mass, and orientation) was ultimately worked out. The algorithm of computations is fairly complicated and involves a small middle fragment (3) and two triaxial ellipsoids (1, 2) (Fig. 12). The main axes of the ellipsoids are at an angle of 62°.

The total mass of the asteroid is fairly large, despite its small size, 3.51×10^{10} kg (1/3 of the mass of the nucleus of Hartley-2), and it is distributed between its larger fragments as 3 : 1. The results of the computation showed that the

Figure 10. Asteroid Itokawa explored in 2005 by the Japanese spacecraft *Hayabusa*. The widest part of the asteroid in this photo is approximately 300 m. (Photograph is courtesy of the JApan eXploration Agency (JAXA)).

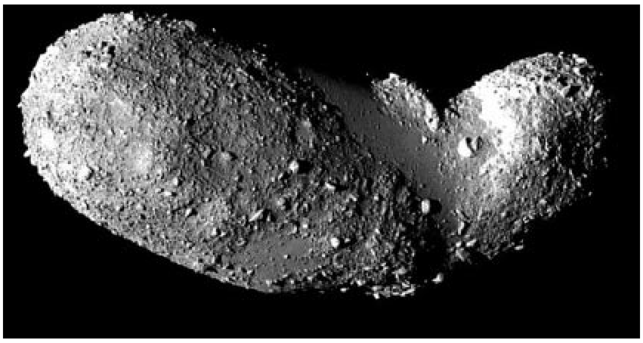

Figure 11. View of the other side of the asteroid (courtesy of JAXA). The central part of the asteroid shows a smooth area resembling the waist of the nucleus of comet Hartley-2.

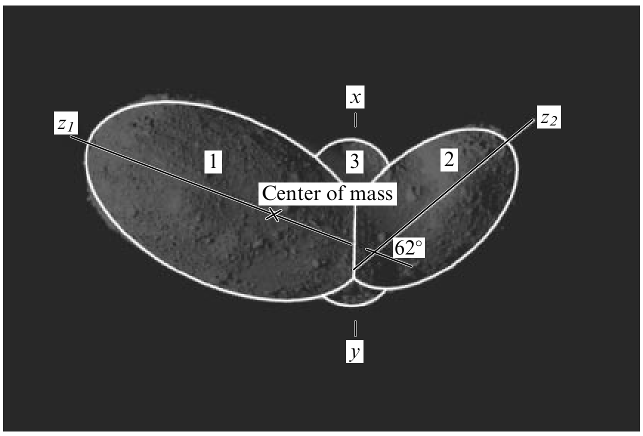

Figure 12. The complex form of asteroid Itokawa makes computations difficult but still feasible if a simplified description of the shape is used. Stresses caused by centrifugal forces in the cross section are only one fifth of compressional stresses. Itokawa is not breaking into pieces.

asteroid is mechanically stable. The compression forces due to gravitational interaction between all fragments relative to cross section xy are 3.4×10^5 N and the stresses are 20 N m^{-2}. Tensile centrifugal forces in the cross section xy are 6×1^5 N and the stresses are 3.5 N m^{-2}, i.e., roughly one fifth of compression. Owing to the angle at which the axes are tilted, the maximum tensile stresses in the cross section xy are somewhat higher, although not much higher.

In other words, the evolution of asteroid Itokawa will not involve catastrophic consequences, unless unpredictable collisions occur. It is worth mentioning that in view of the small size of Itokawa, its total moment of inertia is approximately a thousand times less than that of comet Hartley-2. The energy stored in the form of rotation of the asteroid is even less than 10×10^6 J.

8. Conclusion

Comets and asteroids constitute extremely important objects of research because they retain the characteristics acquired at the time of formation of the Solar System, and then continued aggregation of dust and gas from the interplanetary space. Mechanisms of the formation of the Solar System from gas-and-dust objects and the evolution of solar bodies are extremely complicated. Cometary nuclei retain traces of primary processes of formation of the Solar System, and are composed to a great extent of the original ingredients, which were later incorporated into all planets and smaller bodies of the Solar System.

The physical properties of cometary nuclei as objects of exploration [31] became accessible to astronomers only recently. Nuclei evolve in a very special manner, and they continue to evolve here and now, and everywhere in our planetary system. As regards the stability of their shapes and their integrity, the lower their mean density is, the more easily cometary nuclei and asteroids disintegrate; this plays a greater role than does their size. Such are the direct results of exploration of celestial bodies, of the progress in the theoretical understanding of their formation, and of the analysis of the new and constantly growing array of data on cometary observations.

The peculiar shapes of small celestial bodies (Fig. 13) — asteroids and cometary nuclei — are a consequence of the exceptionally complicated history of their formation and

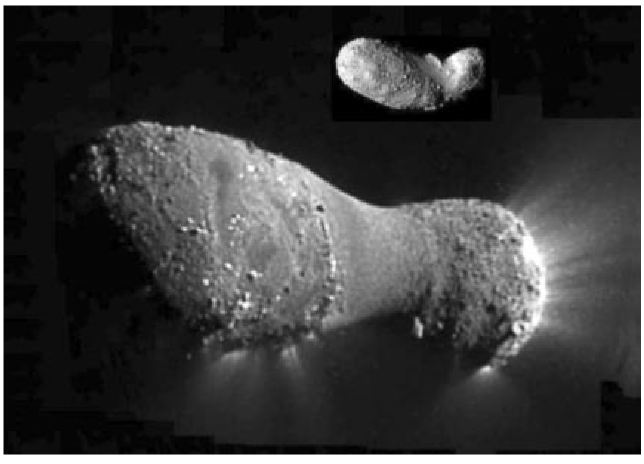

Figure 13. The nucleus of comet Hartley-2 and asteroid Itokawa on an identical scale. (Photos are courtesy of NASA and JAXA.)

evolution. The twisted story of the formation of the Solar System is currently revealing fascinating new details [8].

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