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Pluto: Dwarf Planet 134340

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Abstract—In recent decades, investigations of Pluto with up-to-date astronomical instruments yielded results that have been generally confirmed by the *New Horizons* mission. In 2006, in Prague, the General Assembly of the International Astronomical Union (IAU) reclassified Pluto as a member of the dwarf planet category according to the criteria defined by the IAU for the term “planet”. At the same time, interest in studies of Pluto was increasing, while the space investigations of Pluto were delayed. In 2006, the *New Horizons Pluto* spacecraft started its journey to Pluto. On July 14, 2015, the spacecraft, being in fly-by mode, made its closest approach to Pluto. The heterogeneities and properties of the surface and rarified atmosphere were investigated thoroughly. Due to the extreme remoteness of the spacecraft and the energy limitations, it will take 18 months to transmit the whole data volume. Along with the preliminary results of the *New Horizons Pluto* mission, this paper reviews the basics on Pluto and its moons acquired from the ground-based observations and with the Hubble Space Telescope (HST). There are only a few meteorite craters on the surfaces of Pluto and Charon, which distinctly marks them apart from such satellites of the giant planets as Ganymede and Callisto. The explanation is that the surface of Pluto is young: its age is estimated at less than 100 Myr. Ice glaciers of apparently a nitrogen nature were found. Nitrogen is also the main component of the atmosphere of Pluto. The planet demonstrates the signs of strong geologic activity, though the energy sources of these processes are unknown.

Keywords: Pluto, planetary researches, *New Horizons* mission

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INTRODUCTION

In July, 2015, an important scientific event took place: the *New Horizons* spacecraft passed the encounter with Pluto. Currently, preliminary results have become available; and we think it is worth bringing them to the attention of readers of our journal. The paper also contains the key information on Pluto obtained before the *New Horizons Pluto* mission. It is worth noting that the results of the mission are slowly coming in. The capacities of a radio link between the *New Horizons* spacecraft and the Earth are severely limited. The power of the spacecraft’s transmitter is only 12 W, and the diameter of the narrow-beam parabolic antenna is 2.1 m. Even with the largest ground-based antennas, the data-transfer rate is to be only 768 bit/s, for the required signal-to-noise ratio is maintained. On Earth, the signal is received by several 70-m antennas of the deep space communication network. To transfer a 1-MB image of a moderate resolution requires approximately three hours. To transmit the whole data volume obtained will take 18 months. The electrical power for the spacecraft is provided by a radioisotope thermoelectric generator (that produces 200 W).

On January 19, 2006, after several postponements, the *New Horizons Pluto* spacecraft (NASA, United States) started its journey to Pluto. Up to 2006, dwarf planet 134340, Pluto, was considered as the ninth planet of the Solar System. However, also in 2006, at the IAU General Assembly in Prague, Pluto was reclassified as a member of the dwarf planet category according to the criteria defined by IAU for the term “planet”. At the same time, interest in studies of Pluto was increasing, while the space investigations of Pluto were delayed.

On July 14, 2015, the spacecraft, in fly-by mode, made its closest approach to Pluto. To place the spacecraft into a satellite’s orbit was impossible because of the limited propellant amount. The main operation period of the onboard instruments was scheduled for five months before and one month after the closest encounter with the planet. The heterogeneities and properties of the surface and rarified atmosphere were thoroughly investigated. Among the objectives, there were also the phase transitions of the surface and atmospheric components (leading to the changes in the albedo of the northern and southern hemispheres), the physics of the moons, and the other peculiar properties of Pluto’s system. Before the *New Horizons* mission, the accumulation of data that form the current conceptions of the planet (and that have been generally confirmed by the *New Horizons* mission), constantly met with contradictions and paradoxes, which ultimately resulted in the analysis of the most complex processes in the origin of the Solar System.

The preliminary data of the *New Horizons Pluto* mission and the main characteristics of Pluto are presented below.

According to the *New Horizons* data, the diameter of Pluto is 2370 km, while the diameter of Charon is one half that, 1208 km. As can be seen, the *New Horizons* data on the radii of Pluto and Charon differ quite little from those published earlier (given below in brackets). The total mass of the system is around 3 × 10^{-3} of the Earth's mass, which is close to the value obtained earlier. The total mass of the system is 1.47 × 10^{25} g, 10.4% of which, or 11.65% of Pluto's mass, is accounted for by Charon. The distance between the centers of the components is 19570 km.

MAIN CHARACTERISTICS OF THE PLUTO–CHARON SYSTEM

Semimajor axis (mean distance to the Sun)	39.4 AU = 5.874 billion kilometers
Sidereal rotation period ("year")	47.7 yr = 90470 days
Sidereal spin period ("sidereal day")	6.39 days = 6 days 9 h 17 min
Orbit inclination to ecliptic	17.2°
Orbit eccentricity	0.249
Equator obliquity to ecliptic (retrograde rotation)	57.5°
Mass	1.305×10^{22} kg = 0.002 $M_\oplus$
Mean density	1.87 g/cm^3 * g/cm^3 (1.88 ± 0.03 g/cm^3)
Equatorial radius	1185 km* (1184 ± 6 km ≈ 0.18 $R_\oplus$)
Acceleration of gravity	0.6 m/s^2
Dimensionless moment of inertia (MR^2 units)	0.39*
Geometrical albedo	changes between 0.49 and 0.66
Visual stellar magnitude	15^m (2015)
Solar radiation flux near the surface	0.88 W/m^2
Effective temperature	45 K
Atmosphere composition	N_2, CH_4, CO (probably, Ar and Ne)
Atmospheric pressure	0.6–1 Pa
Number of satellites	5
The main satellite Charon:	
Radius	604 km* (593 ± 13 km)
Mass	1.52×10^{21} kg
Mean density	1.65* g/cm^3
Center-to-center distance in the pair	19570 km
Orbital radius relative to barycenter	17536 km
Orbit inclination to ecliptic	64°
Orbit inclination to Pluto's orbit	57.5°
Period (orbital and spin)	6.39 days (retrograde rotation)
Visual stellar magnitude	17.5^m (2015)
Mass ratio of Pluto and Charon:	8.59/1

* The above values marked with stars are under updating.

In 2006, after several years of discussion, the XXVI IAU General Assembly in Prague created the criteria for the term "planet", according to which Pluto was reclassified as a member of the dwarf planet category and reckoned among minor bodies of the Solar System (Ksanfomality, 2007).

The discovery of Pluto dates from 1930, when Clyde W. Tombaugh, a young specialist of the Lowell Observatory (Flagstaff, Arizona, United States), found a slowly moving, extremely faint object (with the visual stellar magnitude of approximately 15th star magnitude). The photographic survey covered the sky sector that was suggested in 1909 by P. Lowell and W.H. Pickering as a probable location of "Planet X", presumably provoking weak deviations of the positions of Uranus and Neptune from the precalculated ones. However, Pluto was found not exactly at the expected location. In the following, more significant was the

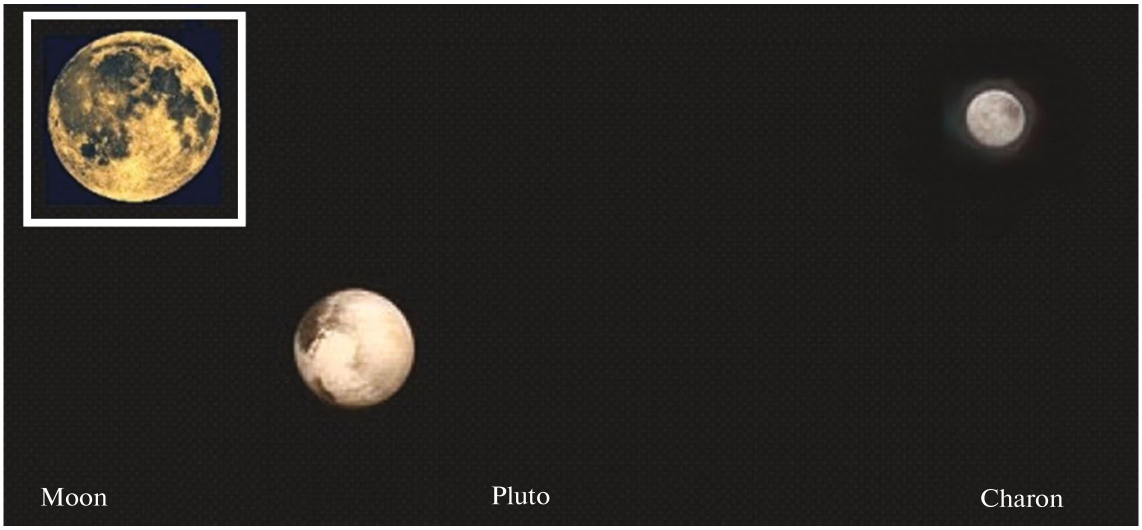

Fig. 1. Pluto and Charon are separated by 19570 km and rotate about a common barycenter. The Moon is shown in the inset. The celestial bodies and their distance are shown in the same scale.

fact that the mass of Pluto is too small to explain the disagreement with the perturbation theory and satisfy the expectations of theoreticians. It is now evident that, if Tombaugh had not considered his task as completed and had continued the surveying, he would have discovered a wide range of Pluto-like objects.

The history of the discovery of the planet and more precise determination of its parameters was described in detail in many publications (e.g., Tombaugh, 1946; Grebenikov and Ryabov, 1984; the Wikipedia web-site https://en.wikipedia.org/wiki/Pluto).

Even in 1930–1931, there were attempts to estimate the mass of Pluto from its brightness and orbital parameters (Nicholson and Mayall, 1930, 1931), which yielded 1 mass of the Earth. Up to 1978, the mass estimates were constantly under revision downward to 0.002 of the Earth's mass (Cruikshank et al., 2007, 2008). The discovery of the first moon of the planet, Charon, played a decisive role. Charon is comparable to Pluto in size; and the altitude of its circular orbit is 20 times less than the orbital distance of the Moon, which makes Pluto to be rightfully considered as a double planet. The same sides of Pluto and Charon always face each other. In Fig. 1 the sizes of Pluto and Charon are compared to that of the Moon, and their orbital distance is shown in the same scale.

ORIGIN OF PLUTO

Since Pluto differs so much from the giant planets, different hypotheses on its origin were repeatedly put forward starting from 1930, when it was discovered by Tombaugh (1906–1997) (Tombaugh, 1946).

The position of Pluto in the Solar System is known to contradict the Titius–Bode empirical law that predicts the semimajor axis of its orbit to be 77 AU (instead of the actual value of 39.4 AU). However, the position of planetary orbits is actually determined by the resonance theory, while the Titius–Bode rule is its special case. For Neptune, the agreement is also poor (30.1 versus 38.8 AU predicted). The position of the orbits of Neptune and Pluto relative to Uranus corresponds to the period ratios 1 : 2 and 1 : 3, respectively; this consequently corresponds to 2 : 3 for Pluto's orbit relative to Neptune's. For every three orbital periods of Neptune (around the Sun), there are two orbital periods of Pluto.

In 1988–1991, the position of the center of mass was successfully determined with the astrometric methods. The mean density of Pluto was estimated at 1.8–2.1 g/cm^3, which is typical for silicate–ice bodies, such as Triton, Titan, or Ganymede; and this value was confirmed in the *New Horizons* mission. It was expected that the density of Charon is 1.2–1.3 g/cm^3. According to the *New Horizons* data, the density of Charon is 1.65 g/cm^3. In general, one could expect that Pluto is composed of rocks and water ice, while Charon is an analogue of the minor ice satellites of Saturn. The *New Horizons* data suggest that water ice may amount to more than 50% of the composition of Pluto. Such a difference should point to the independent origin of these celestial bodies.

In 1936, when it was not known that Pluto is a double planet, it was hypothesized that some time ago Pluto had been one of the moons of Neptune, subsequently expelled from Neptune's system due to an encounter with an unknown celestial body, while the other moon—Triton—transferred to the unusual circular orbit, though with retrograde rotation. It was even supposed that the mass and the orbit of the unknown body, having caused the perturbations, can be retrieved from the current orbits of Pluto and Triton.

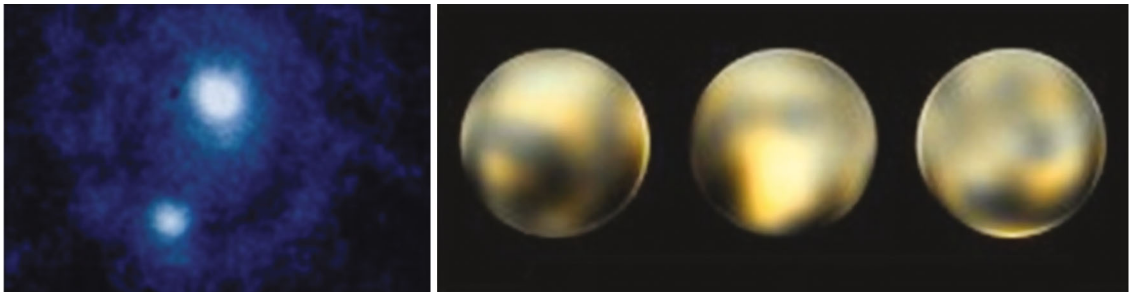

Fig. 2. The Hubble Space Telescope made it possible, first, to successfully distinguish Pluto and Charon (left) and, second, to acquire the sharper images of Pluto in different positions (right).

In some ways, Pluto is similar to Neptune's satellite Triton. In 1984, the hypothetical concurrent formation of Triton and Pluto was simulated by calculations estimating the probability of the event, where Neptune captures a massive protoplanetary body (planetesimal), having fragmented into Triton and Pluto. However, the calculations showed that Triton and Pluto are most likely of independent origin.

Nevertheless, similarity in the structure of these two bodies is quite possible, if similarity in the composition, mean density, size, atmospheric properties, and distance to the Sun is taken into account. Another issue is that the probability of the catastrophe of such a scale is low and its details can be hardly retrieved by calculations on the basis of the currently known orbits. Though such catastrophes are actually probable, the origin of Pluto is now considered in connection with the belt of trans-Neptunian objects (the Kuiper belt) (Cruikshank et al., 2007). Thus, the issue on the origin of Pluto and Charon remains open; and it is connected with the origin of trans-Neptunian objects (TNOs) themselves.

PLUTO AND CHARON

From 1979 to 1999, due to the large eccentricity of its orbit, Pluto was closer to the Sun than Neptune. Starting from 1930, when it was discovered, Pluto has been northward of the ecliptic; however, now (2015), it is close to the ecliptic plane.

Way back in the 1960s, it was found that the brightness of Pluto changes with a period of 6 days 9 h 17 min. This value was taken for the spin period of Pluto, and this is the case. However, it turned out that the same value of the period is also true for the other celestial body connected with Pluto. In 1978 it was shown that the weakly elongated shape of Pluto's image seen in the photos points to the presence of a satellite of this planet. Moreover, the sizes of both bodies are close.

With the Hubble Space Telescope (HST), whose capability is not restricted by the terrestrial atmosphere, the image of Pluto and Charon seen separately was obtained for the first time (Fig. 2). They are so close to each other (<1″) that they could be resolved from the Earth only with the speckle interferometry method. However, by 2000, new ground-based telescopes with adaptive optics allowed Pluto and Charon to be confidently distinguished. Later, sharper images of Pluto were acquired with the HST. From the comparison with the images taken from the *New Horizons* spacecraft, it can be seen that the large details in the HST images are real objects.

The period of 6.387 days turned out to be the period of mutual rotation of Pluto and Charon about a common barycenter. From the measured period and orbital radius, the total mass of the system of Pluto and Charon was estimated (1.47×10^{22} kg = 0.0025 $M_{\oplus}$). The mass ratio for Pluto and Charon (1/8.6) is higher than that for any other moon–planet pair.

The orbital plane of the components relative to the Earth is located in such a way that the systematic mutual eclipses lasting for several hours started in 1985. The full period of the eclipse phase began in 1988, and finished in 1991. From these observations, not only the sizes of the components were estimated more exactly, but also the distribution of the albedo over their surfaces was analyzed. The next period of eclipses will repeat in 124 years. In the eclipses, the brightness alternately decreased by 4 and 8%, which led to the conclusion that the surface of Charon is darker than that of Pluto by 30%. The *New Horizons* data point to the deeper differences.

At the distance of Pluto from the Sun, the solar disk is indistinguishable by a naked eye. Because of this, the Sun is as bright there as a dazzling star that dimly illuminates the surface. However, this light was enough for TV imaging; and it would be enough even for reading. While the illuminance of an area oriented normally to the solar constant on the Earth's orbit is approximately 127 klx, it is only 82 klx on the orbit of Pluto (this is approximately equivalent to the natural day illuminance at the back of a dwelling room).

PRELIMINARY RESULTS OF THE MISSION: THE SURFACE OF PLUTO

The main objective of the *New Horizons* mission is to study the dwarf planet Pluto and its moon Charon.

The scientific payload onboard the spacecraft was collecting the data about the surface structure and, partially, about the planetary interior and atmospheric composition. Whether Pluto has a magnetosphere was also investigated. A separate task was to investigate the interaction (not only gravitational) between Pluto and Charon. As has been already mentioned, the acquired results were accumulated in memory, and the data transmission rate is limited. It will take 18 months to transfer the whole data volume.

The trajectory of the *New Horizons* spacecraft was built in such a way that the spacecraft almost normally approached the main plane of the orbits of Pluto's moons. On July 14, 2015, at 06:30 a.m., the spacecraft, moving at a speed of 50000 km/h, was at a distance of 64000 km from Pluto. At 07:38 a.m., the spacecraft crossed the system's plane approximately at the distance of the orbit of Charon. It was supposed that such a trajectory should diminish the risk of collision with some unknown bodies. The closest approach of the spacecraft to Pluto, 12550 km, was at 07:49 a.m. At 08:51 a.m., the spacecraft entered into Pluto's shadow for a short time, so that the optical and radio occultations could be used for investigations of the properties of the planetary atmosphere with the scientific payload instruments. At 10:18 a.m., the spacecraft crossed the shadow of Charon, so that the effects of the hypothetical atmosphere of the moon could be observed. Since the signal from the spacecraft is too weak, the positions of a receiver and a transmitter were interchanged in the radio eclipse experiments: for the first time the continuous electromagnetic transmission probing was performed with a powerful monochromic radio signal sent by the ground-based transmitters and received onboard the *New Horizons* spacecraft (though, traditionally, the signal from the spacecraft itself is used).

As concerns the data already received and analyzed, this is mainly the images of Pluto and Charon, which actually turned out to be a scientific sensation. The images were taken with the Long-Range Reconnaissance Imager (LORRI) with a resolution of 1″. The information on the color and spectral properties of the surface was supplemented with the *Ralph* spectrometer data. In Fig. 4, the appearance of the planet seen from the approaching spacecraft is presented. The image was taken from a distance of 77000 km on July 14, 2015. This hemisphere of the planet is dull orange in color. The first thing that attracted the attention of researchers was the extremely small number of meteorite craters on the surfaces of both Pluto and Charon. This sets them far apart, for example, from the moons of Jupiter—Ganymede and Callisto. The only possible explanation is that the surfaces of Pluto and Charon are very young, and the earlier impact craters did not survive. For both bodies, the surface age is estimated at less than 100 Myr, i.e., the surface is very young. Rare impact craters occur in different regions of the planet. In Fig. 4 a deep crater is seen at the boundary of a dark terrain. It has a bright rim and a high central peak (in lunar terms). The inset in Fig. 4 shows the other part of the planet with a large impact crater that is more than 8 km deep, 320 km across, and surrounded by impact ejecta. In its central part, there is a high secondary 150-km rim with a chasm 80 km deep instead of a central peak. The strange structure of the crater suggests that the impact resulted in a cryovolcano that appeared in the crater center.

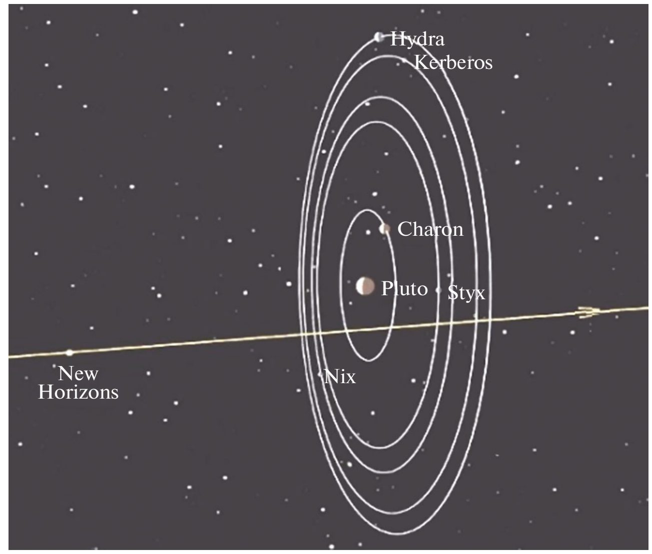

Fig. 3. The *New Horizons* trajectory.

It is clear that the most noticeable part of the hemisphere shown in Fig. 4 is a bright terrain extending to approximately 1600 km and resembling a bird or a butterfly by shape; though, the authors of the experiment called it "a heart". The bright terrain was officially named after Clyde Tombaugh (Tombaugh Regio). It is Tombaugh Regio that stands out as a bright spot in the image taken even by the HST and presented in the middle of the set of images in Fig. 2. Spectral observations of the bright terrain showed that the composition of the deposits on its surface is nonuniform: the concentration of solid carbon monoxide is higher in the central part than on the periphery.

The young age and color diversity of the surface and the vast bright and dark regions point to some powerful endogenous geologic processes. Their activity turned out to be one of the main surprises of the mission. What are the unknown sources of energy that induce their activity? Probably, some geologic activity of Pluto has still continued to this day. Its scale is illustrated, for example, by the extended very dark depression surrounding the southwestern part of Tombaugh Regio also seen in the bottom of the inset in Fig. 4. Due to its configuration, this depression was named "a whale" for convenience. The mottled ice surface demonstrates the expressed structure probably caused by internal convection in the interior of Pluto. The convection is induced by an unknown source of energy.

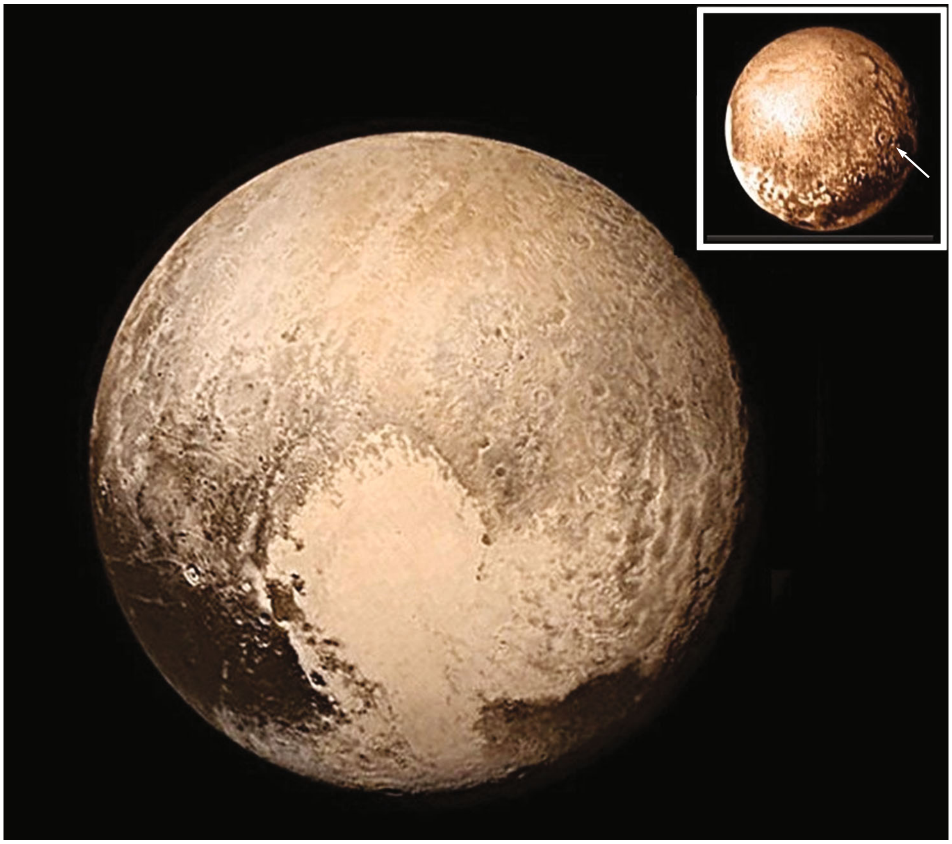

Fig. 4. Pluto as seen from the approaching *New Horizons* spacecraft from a distance of 766000 km. The diversity of colors and the bright and dark regions point to powerful geologic processes induced by unknown endogenous sources of energy.

The alternative explanation is that the surface structure was formed in the processes of compression of Pluto's lithosphere. Geo-planetology was hardly ready for such surprises from the cold Pluto, 6 billion kilometers from the Sun.

The central and southern parts of the bright terrain of Tombaugh Regio are shown in Fig. 5. Their substantial portion is a plain covered by shapeless ice plates, whose boundaries are backlined with corbelled solidified material. This terrain was named Sputnik Planum after the first (Soviet) artificial satellite of the Earth. Its meridional extension is around 1200 km.

The images of Sputnik Planum obtained with finer details brought one more sign of Pluto's activity: the fields, or huge plates, covering the plain, may be some icebergs apparently composed of nitrogen ice. Moreover, they move, forming glaciers similar to terrestrial ones. It can be seen in Fig. 6 that, near the Sputnik Planum "shores", the ice plates are deformed and cleft. They form separate fields, flow round the irregularities, and penetrate into the "shore" relief, as can be seen in the upper part of Fig. 6 by the example of the crater with a circular rim. Are there actually glaciers on Pluto? The physical conditions of the environment are worth mentioning: the temperature is around 45 K, the atmospheric pressure is around 1 Pa, and the atmosphere is mainly composed of nitrogen.

In the bottom of Fig. 6, a wide intermediate zone between the Sputnik Planum "shore" and the older continent, containing meteorite craters, can be seen. Here, the relief is almost completely mountainous 1–2 km high and evidently connected with the "shore" deformation. Now the question arises of whether the behavior of ice rafting is periodic or not.

The nature and mechanisms of these strange phenomena are still completely unclear. Who could expect that Pluto is a geologically active planet with strong sources of energy?

To some extent, by the surface diversity, Pluto resembles Jupiter's satellite Io that is permanently warmed up by tidal phenomena. However, Pluto and Charon, being under constant synchronous mutual orientation, do not have, at least nowadays, such a source of energy. If their orbits are strictly circular, the tidal scattering is excluded. However, was the eccentricity of their orbits always zero?

The subsequent studies of the acquired data showed that the other parts of the observed hemisphere of Pluto is no less unusual (Fig. 7). At the boundary between the dark and bright terrains there is a crater with an internal diameter of approximately 350 km

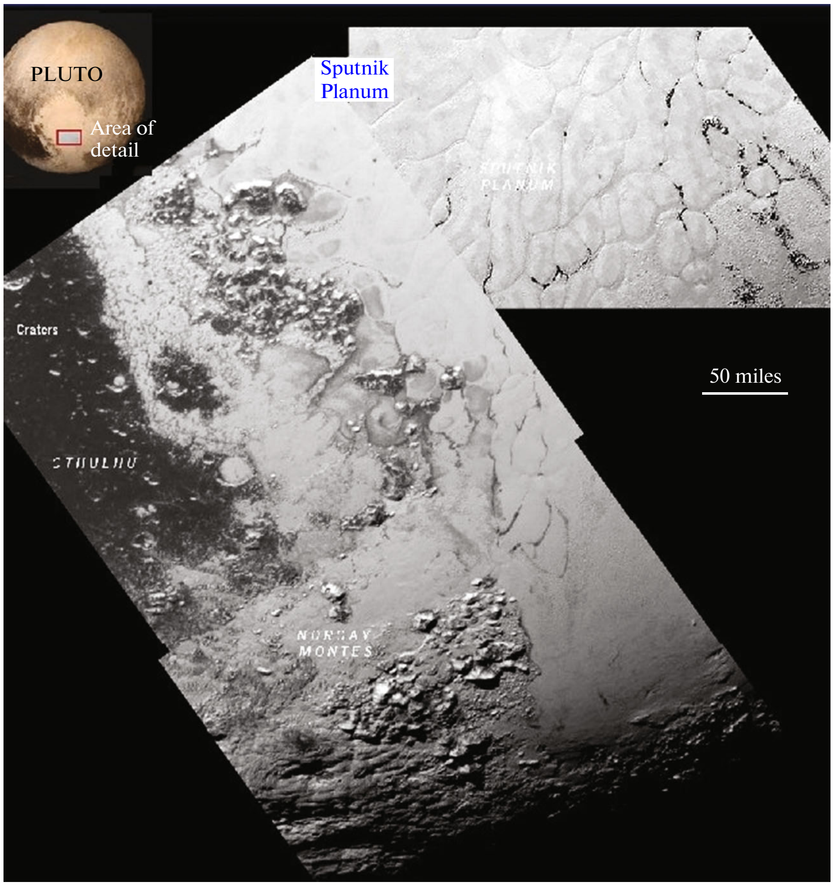

Fig. 5. A southern part of the bright terrain of Tombaugh Regio with Sputnik Planum and adjacent Norgay Montes. At the upper left, a rectangle sets off the region shown below.

and impact ejecta spreading to 700 km. No central peak is observed in this crater, though its bottom has some structure. In this image, the bright surface with small dark spots covers almost a half of the hemisphere. One may suggest that the nature of the bright terrain is similar to that shown in Fig. 5, since it is actually the extension of this region. In the dark part of the image, there are several small details such as, for example, impact craters. In the center of the bright field, the dark arc extending to 800 km and partially overlapped by a wide bright feature is seen.

The appearance of the planet in Fig. 7 can be also compared to that of Jupiter's satellite Ganymede, though the latter shows no vast bright fields. It can be hardly expected that the nature of these new unusual forms will find any explanation soon. The nature of Pluto's surface is apparently unique. It has been already suggested that the status of a dwarf planet should be probably repealed for Pluto and the latter should be reclassified as a member of the principal planet category. However, the question arises of whether the same or new surprises from the other TNOs await astronomers.

A vast highland is adjacent to the southern part of Sputnik Regio (Fig. 8); it was called Norgay Montes after one of the first conquerors of Mount Everest. The foothills skirt the Sputnik Planum border (the position of the region is indicated by a rectangle in the bottom right). On the left of the plain, the mountains reach 3.5 km in height. Their height was determined by the length of the shadows produced. On the right of the image, the mountain massifs pass into the vast folded terrain. The mountains are probably composed of water ice, whose properties, under low temperatures, correspond to those of strong rocks underlying the ices of other natures on the surface of the planet.

In Fig. 9, the color tints are amplified, which allowed the regions with different composition or texture to be distinguished by the comparison of the data from the LORRI camera (with a resolution of 1″) and the *Ralph* spectrometer. Sputnik Planum is probably a generator of the ice mass extending over the surface and forming the vast bluish terrains (the other parts of Tombaugh Regio) adjacent from the southwest. Here the composition of ices is specific and "exotic" (nitrogen and carbon monoxide?). The terrain at the northern polar latitudes is distinguished by the orange hue.

A general view of the surface of the planet containing Sputnik Planum is shown in Fig. 10. In its upper

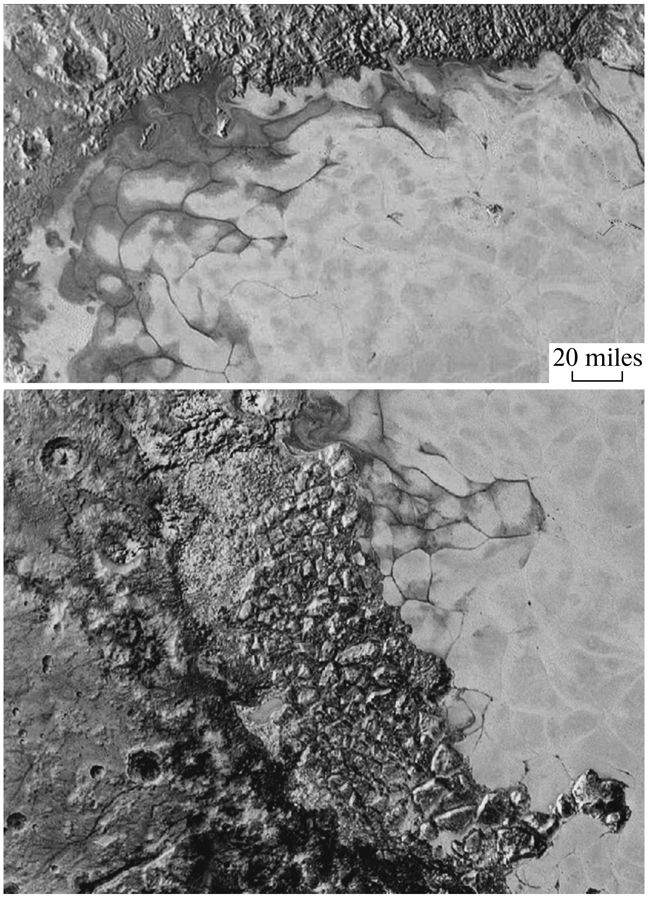

Fig. 6. “Glaciers” and “icebergs” of nitrogen ice are cleft and deformed, while their boundaries become clear-cut at the northern and western “shores” of Sputnik Planum.

part, the boundaries of the plain with growing glaciers are clearly seen.

It seems that the geologic activity of Pluto and, particularly, glacier drift, is proceeding in our times as well. One cannot exclude that there may be a liquid ocean under the surface. Such are the preliminary results of examination of the set of images of Pluto’s surface.

PRELIMINARY RESULTS OF THE *NEW HORIZONS PLUTO* MISSION: THE ATMOSPHERE OF PLUTO

The studies carried out in recent decades of the 20th century showed that nitrogen dominates the atmosphere of Pluto. At the same time, ground-based spectrometric measurements confidently pointed to the presence of methane in the atmosphere. However, it was unclear whether the observed methane bands are related to the atmosphere or to the hoarfrost on the surface. It was found that the methane frost exists, but the presence of the atmosphere was also proved. Moreover, it was even expected that the atmosphere is not very rarified. First, the researchers assumed that

Fig. 7. The observed side of Pluto, demonstrating the 700-km impact crater and the bright terrain spreading over half of the visible hemisphere.

Pluto’s atmosphere is composed of methane and concluded that it is thin, though can be detected at the potential limit of the state-of-the-art instruments. In the reflectance spectrum of Pluto obtained even in 1978, the bands at the wavelengths of 620, 790, and 840 nm were observed; they coincide with the calculated absorption spectrum of methane (Cruikshank et al., 2007, 2008). These bands are most likely related to the gaseous phase.

The deposits of condensed methane are nonuniformly distributed over the planet (Fig. 11). In the polar cap, methane is dissolved or absorbed in a thick layer of transparent nitrogen ice. Methane is detected by strong bands in the range at 2 μm (by the *Ralph* spectrometer). In the dark equatorial region, the methane bands are weaker, which points to the other surface texture with the other ratio of the components. In Pluto’s atmosphere, methane is on the brink of dissipation. The earlier published papers concluded the following. To preserve the methane atmosphere, the parameters of the planet should roughly take the following values: the mass of Pluto should be about 2.3×10^{22} kg, and the surface temperature should be less than 52 K on average and 62 K at maximum. Since the actual value of the mass is 1.305×10^{22} kg, methane slowly escapes from the atmosphere; though its amount on the planetary surface is substantial (Fig. 11). Minor seasonal changes of the pressure are connected with the global variations of the temperature of Pluto, which yields the accumulation of methane and nitrogen condensates in the polar caps in winter and the increase of the atmospheric mass in summer, when the polar caps are melting. According to calculations, the decrease of the temperature only by

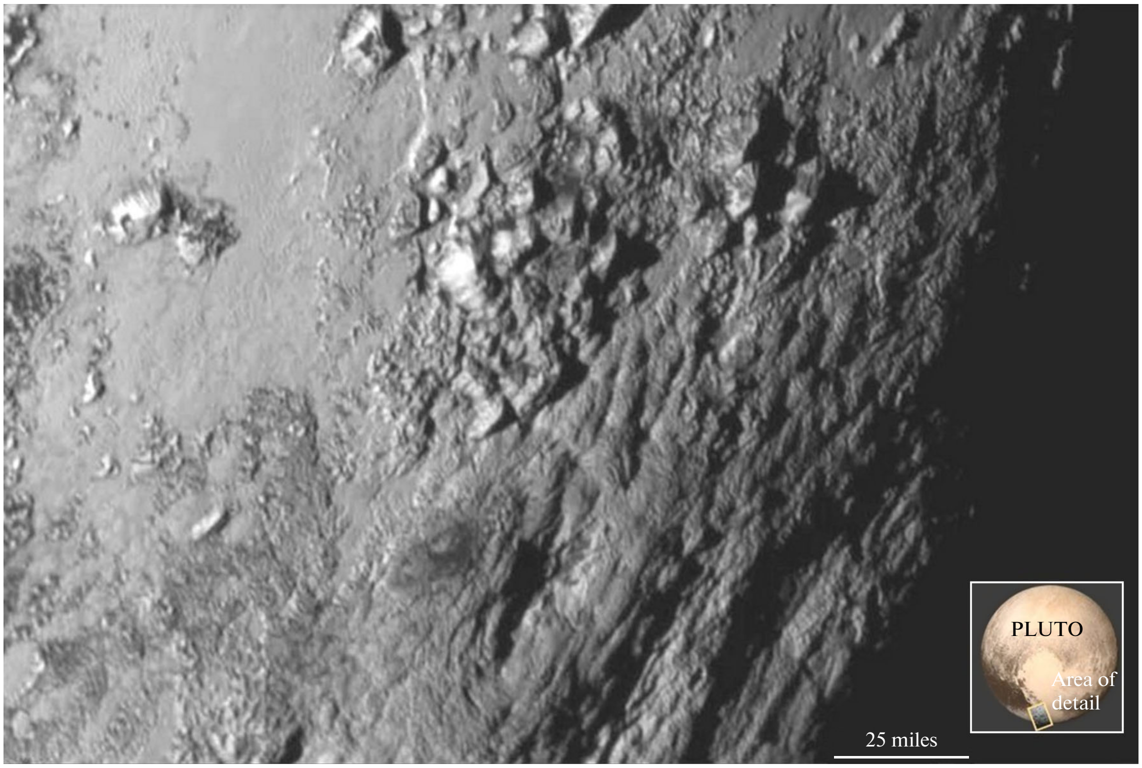

Fig. 8. The highlands of Norgay Montes at the southern border of Sputnik Planum.

2° leads to the condensation of a half of the atmospheric methane on Pluto. Because of this, the methane content in the atmosphere should vary greatly depending on Pluto's position in its orbit that induces the seasonal changes of temperature.

The problem of methane is that it is photolytically destroyed under the impact of solar ultraviolet radiation. According to some estimates, the available resources of methane should have disappeared over 5–10 Myr. However, methane has not disappeared. Consequently, something replenishes its resources. Note that the same problem faces the presence of methane on Mars and Titan.

From the ground-based measurements, the thickness of Pluto's atmosphere was estimated at 7.3×10^{22} molecule/cm^2 (around 1/3 of the carbon dioxide content in an atmospheric column on Mars). However, this estimate was made only for methane, while Pluto's atmosphere contains more nitrogen than methane. There are also carbon monoxide and, probably, argon. Note that Triton and Titan, the moons of Neptune and Saturn, respectively, also have nitrogen atmospheres. In 1988, the occultation of a star by Pluto was observed: the brightness of the star was gradually, for several seconds, decreasing, which points to a rather dense atmosphere. According to the measurements carried out before the *New Horizons* encounter, it was supposed that the atmosphere of Pluto can be denser that had been earlier expected. However, thorough investigations of the surface and atmosphere of Pluto performed with the *Ralph* spectrometer onboard the *New Horizons* spacecraft yielded a substantially lower estimate of the pressure near the surface than

Fig. 9. The increased color contrasts allow the regions of different nature to be distinguished.

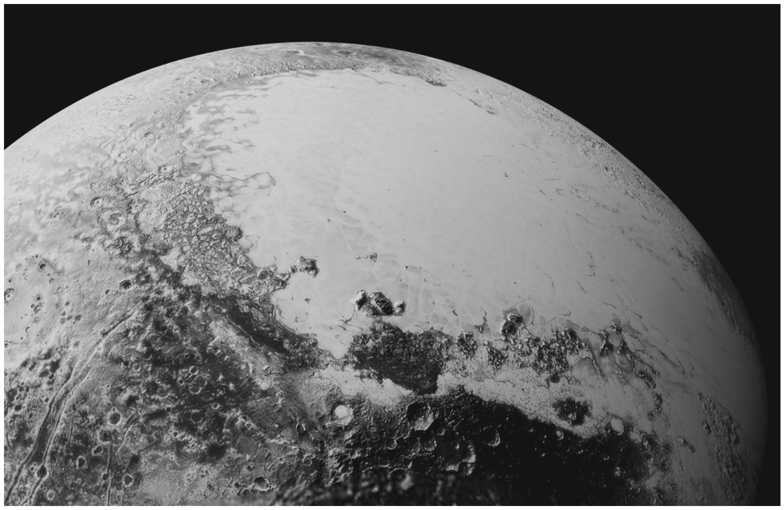

Fig. 10. The terrain of Tombaugh Regio with Sputnik Planum in the center.

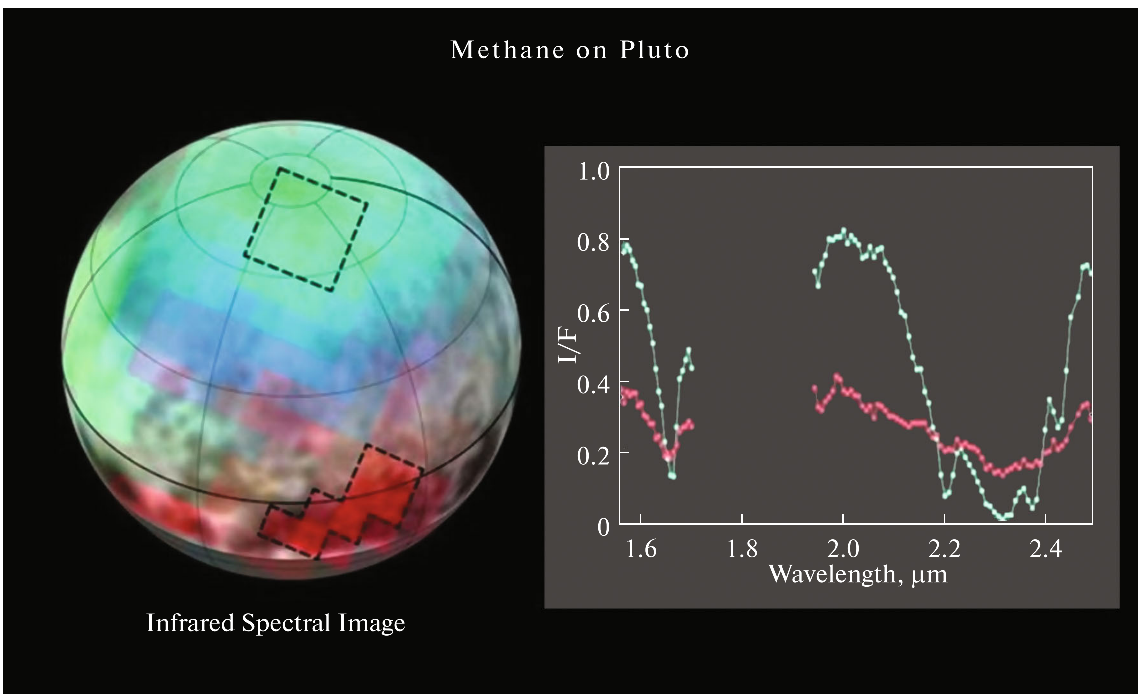

Fig. 11. The methane bands at 2 μm near the northern pole (upper curve) and in the equatorial region.

had been expected before. From the preliminary estimates, it is only 0.01 mbar (around 1 Pa).

Observations in the eclipse experiment turned out to be especially successful (Fig. 12). In the left image of Fig. 12, the "corona" resulting from the scattering of solar light by aerosol particles and gas in the atmosphere is seen. In the eclipse experiment (Fig. 12, right), a high brightness of the luminous halo and a large extension of the atmosphere were detected. The visible brightness of the Sun started to gradually decrease approximately 5 min before the total eclipse. First, the absorption of light by molecular nitrogen (N_2) was mainly detected. While the sunset proceeded further, the absorption bands of methane and complex hydrocarbons showed themselves more and more distinctly. When the Sun appeared from behind the planet, the atmospheric effects repeated almost in the same way, in reverse order.

In the same experiment, the aerosol layers containing the signs of organic compounds were found (Fig. 13). The image was taken from the shadow of the planet from a distance of 360000 km on July 14, 2015.

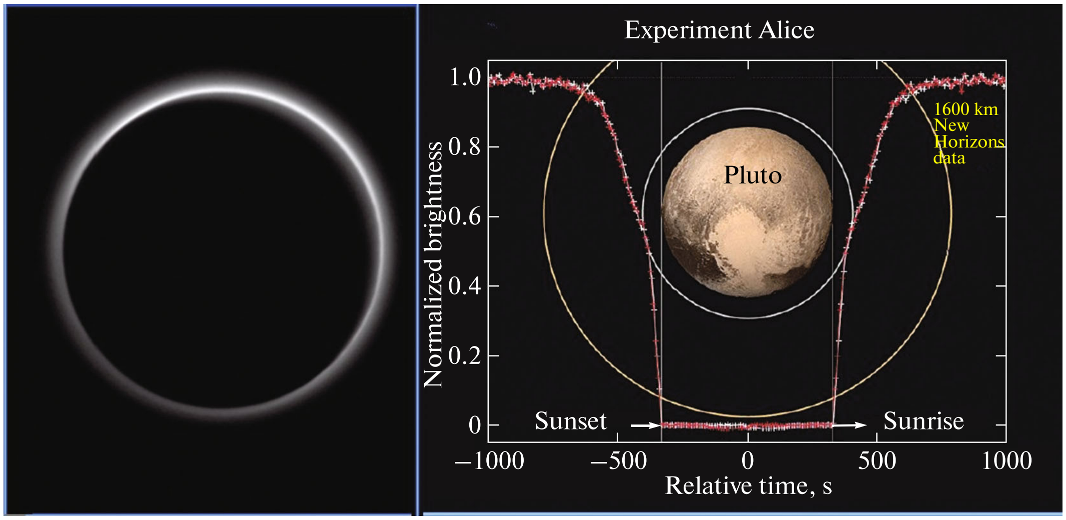

Fig. 12. The image of Pluto taken from the shadow of the planet from a distance of approximately 2 million kilometers (left) and the observations of the solar eclipse by Pluto with the *Alice* instrument (right).

The scattering becomes stronger due to a large amount of solid particles of nonvolatile complex hydrocarbons suspended in the atmosphere. Aerosols are traced to an altitude of 130 km above the surface. The image processing showed that the aerosol concentration (indicated by conventional colors) nonuniformly decreases with altitude and has two peaks at the 50- and 80-km marks. Later many other layers are found.

While the seasons on the Earth alternate mainly due to the inclination of the equator of the planet to its orbital plane, the situation on Pluto and Charon is different: the effect of a large inclination of the equator is supplemented by that of a large eccentricity of the orbit (0.25), which changes the solar radiation flux coming to the surface by ±56% over 248 years. This leads to global warming at perihelion of the orbit and to cooling at aphelion. Pluto passed perihelion in 1989. Probably, for this period, a substantial portion of methane and nitrogen moved from the surface to the atmosphere.

In our epoch, the spin axis of Pluto is oriented in such a way that its equator faces the Sun at aphelion and perihelion. This makes the seasonal effects to be rather complicated. In the polar regions of Pluto, the seasons generally alternate in the same way as on the Earth. Namely, there are one winter and one summer each year, though there is a difference between the hemispheres: in the southern hemisphere, the summer comes quickly and the winter comes slowly, while their behavior is contrary in the northern hemisphere. However, in the equatorial regions, four seasons alternate with each other: there are two seasons of a low Sun and two seasons of a high Sun. The high-Sun seasons may be called “summer”, though one summer is warmer than the other one. In the warmer summer period, the temperature reaches 50 K (–220°C), while it may decrease to 25–30 K in winter.

At the same time, the results of the *New Horizons* mission show that the physics of Pluto is much more complex than the theoretical models (Fig. 14). In the center of Sputnik Planum (a part of Tombaugh Regio), solid deposits of carbon monoxide (ices) were found. In the image, the contours illustrate the increase of the monoxide concentration to the center of the marked area. In general, Sputnik Planum is a strange and unique place on the planet, where unusual geologic processes are concentrated and where they most evidently manifest themselves.

An interesting, though not confirmed, result was obtained in the calculations of the structure of Pluto’s atmosphere. Due to the small distance between Pluto and Charon, they may have a common atmosphere (Cruikshank et al., 2008). This supposition required confirmation, especially due to the fact that the calculations were performed for a rather dense atmosphere, which has not apparently been confirmed. To search for the atmosphere of Charon, the *New Horizons* spacecraft took images from the shadow zone of Charon. The results are still awaited because the information obtained in observations is transmitted slowly, only at a rate of 768 bit/s; and the accumulated gigabytes of the scientific data are stored in the spacecraft’s memory. It has been confidently determined that the main component of Pluto’s atmosphere is nitrogen with an admixture of methane and carbon monoxide. The *New Horizons* eclipse experiments traced the rarified nitrogen atmosphere to an altitude of 1600 km above the planetary surface. Behind the planet, the spacecraft found the nitrogen “tail” that originates from the interaction of the solar wind plasma with the upper layers of the atmosphere and extends to 100000 km behind the orbit of the planet. Somewhat different, though rather close, estimates were found in new observations of Pluto and Charon at

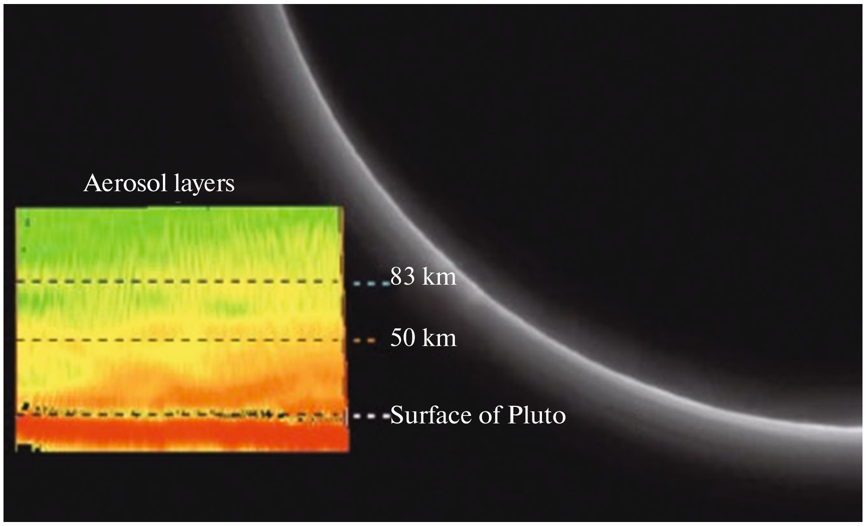

Fig. 13. Light scattering in the nitrogen–methane atmosphere of Pluto indicates the aerosol layers in the atmosphere.

Fig. 14. Solid deposits of carbon monoxide concentrated in the central part of Sputnik Planum.

the high-altitude Mauna Kea Observatory (Hawai'i). According to the obtained results, the spherical albedo should be around 0.2 (Cruikshank et al., 2007, 2008), i.e., substantially smaller than the actual value specified above.

CHARON, NIX, AND HYDRA

Charon turned out to be equally interesting, though it does not demonstrate such a wide diversity of tints and shapes, as Pluto does. The surface of Charon is much darker, and the hues are muted. According to the preliminary data, their surface albedos differ by three times. The high-resolution image of Charon is shown in Fig. 15. It was taken by the LORRI camera from a distance of 466000 km. The diameter of the moon is 1208 km. The extensive dark terrain, named Mordor, is near the northern pole. Its spectra were obtained, and they point to the presence of high-molecular-weight solid hydrocarbons. It is supposed that such organic compounds are rather abundant on Pluto and Charon; however, in most cases, they may be covered with a layer of nitrogen–methane ice or frost.

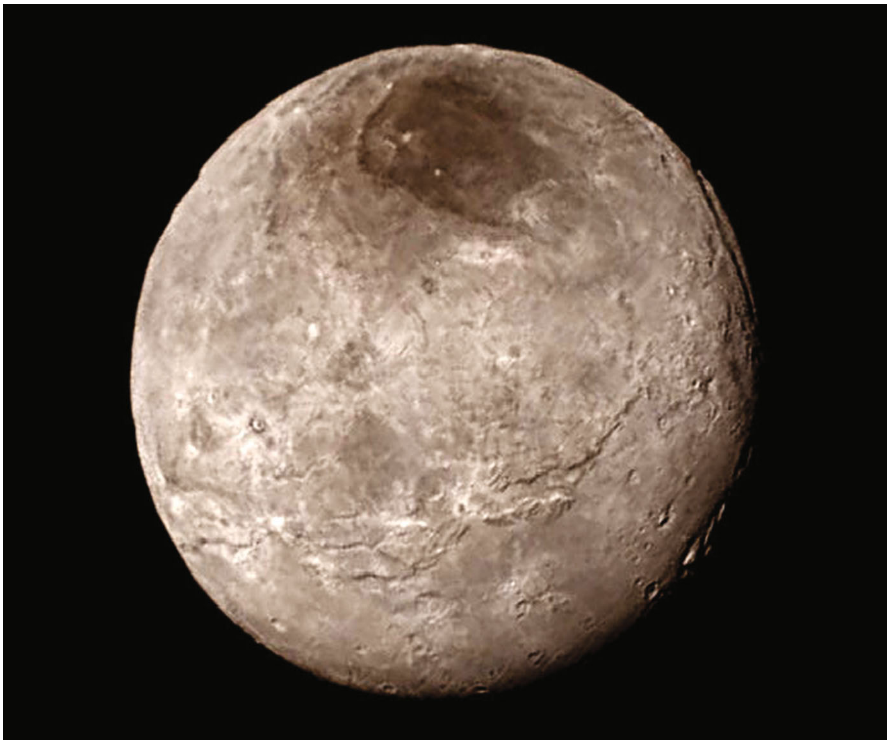

Fig. 15. The appearance of the moon Charon. The relief features with sizes down to 5 km are distinguished. The dark terrain Mordor surrounds the northern pole of the moon. The extended canyon crosses the equator. On the terminator, one more deep lengthy canyon is seen (upper right).

The satellite's equator is crossed by the extended canyon that contains twisting fissures and scarps. They could appear due to both the surface contraction and the other processes of the surface evolution on Charon. On the very terminator, in the upper half of the image, there is one more, extremely deep canyon; its depth is approximately 8 km. On the surface of the satellite, few impact craters are seen; in the left part of the image, there is a ray crater (in lunar terms) with an internal diameter of around 25 km. A crater twice as large is seen in the terrain on the right; here, from the approximately 5-km deep depression, the central peak of a comparable height protrudes. In the images of Charon, there are no clear signs of geologic activity like those seen on Pluto.

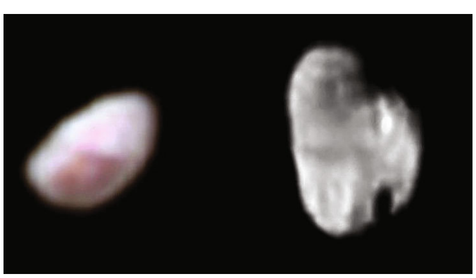

Fig. 16. Small moons of Pluto: Nix (left) and Hydra.

It is also worth mentioning that Pluto has four small moons besides Charon. Figure 16 shows two of them—Nix and Hydra. Their sizes are 42 × 36 and roughly 54 × 39 km, respectively. Both satellites are irregular in shape, and Nix is reddish in color. To compare them to Charon (Fig. 15), we enlarged the sizes of their images in Fig. 16 by 5 times.

CONCLUSIONS

The *New Horizons Pluto* mission made it possible to carry out the investigations of the dwarf planet 134340 Pluto that belongs to TNOs by origin. Before the *New Horizons* mission, it was supposed that the physical properties of Pluto should be, in a great measure, close to those of the moons of giant planets, especially Triton, Neptune's moon. Ground-based and near-Earth orbital observations, as well as theoretical calculations, allowed the ranges of the expected parameters to be narrowed, but nothing more. The HST observations gave evidence of the substantial heterogeneity of the surface of the planet, but to obtain the images of the 0.082″-angle object in more detail was impossible. With the *New Horizons* spacecraft, such images have been successfully acquired. The results obtained demonstrate that this remote object of the Solar System is of a completely unknown type, with obscure global effects of the previously unknown geologic and atmospheric phenomena. How regular are such properties for the planet at the edge of the Solar System? Should we expect that the properties of the other TNOs are analogous to those of Pluto? The *New Horizons Pluto* mission turned out to be destined to add new pages to planetary physics. Russian scientists are pleased to congratulate American colleagues for this outstanding achievement. Finally, we are reminded that the spacecraft was launched by the American Atlas V rocket with the Russian RD-180 engine.

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