67P/Churyumov-Gerasimenko Comet and Chelyabinsk Meteoroid: Collation of some Characteristics of their Substance

Yu. I. Lobanovsky

IRKUT Corporation

68, Leningradsky prospect, Moscow, 125315, Russia

E-mail: streamphlow@gmail.com

Phone: +7 916 533 0430

Abstract

According to earlier investigations, Chebarkul meteorite (another name is «Chelyabinsk» meteorite) is a fragment of surface crust of Chelyabinsk meteoroid. Some images of «bedrock» of 67P/Churyumov-Gerasimenko comet's nucleus and surface of breaking of Chebarkul meteorite are compared in this paper. The average bulk density of the nucleus of this comet and Chelyabinsk meteoroid and strength of the surface layers of these objects are compared also. From these data, it follows that the compared objects are very similar and their considered characteristics are close. Therefore, earlier made conclusion is confirmed that Chelyabinsk meteoroid is the fragment of nucleus of some comet. It is also shown that the study of Chebarkul meteorite may give some additional information about 67P/C-G comet.

Keywords: 67P/Churyumov-Gerasimenko comet, Chelyabinsk meteoroid, meteorite, crust

I. Introduction

As it's known, November 12, 2014 Philae lander from Rosetta European spacecraft made a soft landing at the surface of the nucleus of comet 67P/Churyumov-Gerasimenko (67P/C-G) after double jump about half a kilometer, and then at 3 meters in a height. The point of landing was about a kilometer from the first touch point and, apparently, in a narrow valley between the hills with steep slopes. Because of the shading of Philae by elements of terrain, illumination by the Sun was only 1.5 hours per one rotation of the comet (duration of which is over 12 hours), not 6 as originally planned. In connection with this, the program study on the nucleus surface of the comet was reduced to 57 hours [1, 2], and expectations that the received data will be enough for a full analysis of the characteristics of a comet, weren't justified. Therefore, to get the most out of this extraordinary space mission we should to apply methods of analysis less trivial than the usual.

Over 21 months before this event, the morning of February 15, 2013, near Chelyabinsk an object exploded in the sky, which was, as proved in papers [3 – 8], some fragment of a comet nucleus (as well as Tunguska meteoroid). Sole large (about of the order of 1 m) fragment of Chelyabinsk meteoroid was raised from Chebarkul Lake, and this splinter, as follows from a chain of pretty obvious reasonings, was a piece of the outer surface crust of meteoroid. This crust arises when solar radiation heats up to ablation the snow-ice composite contaminated by chondrites, from which mainly consist nuclei of comets and so their fragments [3, 4]. Obviously, only a small portion of the crust remained after the explosion, and the snow and ice, main part of the meteoroid material, evaporated completely. Apparently, no special explanation should be that the outer surface crust arises not only on the fragments of nuclei but also on nuclei of comets in whole.

Therefore, collation of the characteristics of the meteoroid in a whole with the nucleus of the comet as well as the surface crusts of both objects can be useful even when using available to us such the simple «organoleptic» method, solely on the basis of which in the XIX century was developed the foundation of modern geology – the relative geochronological scale of geological events.

II. Visual analysis of some of the available images

In archive of photos of the European Space Agency we may see the surface of nucleus of 67P/C-G comet, obtained during Philae lander first approaching to touch point named Agilkia. Photo, presented in Fig. 1, was made at Agilkia before first touch to the comet from a height of 40 m [9]. The biggest stone in the upper right corner of the frame is about 5 m.

Fig. 1– Agilkia point.

Worth mentioning the fact that this stone from Agilkia is quite similar outwardly to Chebarkul (or «Chelyabinsk») meteorite – fragment of Chelyabinsk meteoroid crust from Chebarkul Lake, almost in everything except size. First is in 3 – 4 times more than the second, see, for example, Fig. 2 [10].

Fig. 2 – Chebarkul meteorite after lifting from the lake.

In fact, after washing of lake sediments with Chebarkul meteorite (see also Fig. 5) and scattering by the dust on its lower left edge, it would be difficult to distinguish it from the Agilkia big stone. However, the dynamics of the rebound of Philae lander from the nucleus surface of comet indicates that the thickness of the dust layer in Agilkia point is apparently several centimeter and in fact Agilkia stone is flatter than Chebarkul meteorite.

But in general, the terrain at Agilkia looks very similar to the vast lunar deserts, covered by regolith, see Fig. 3 [11].

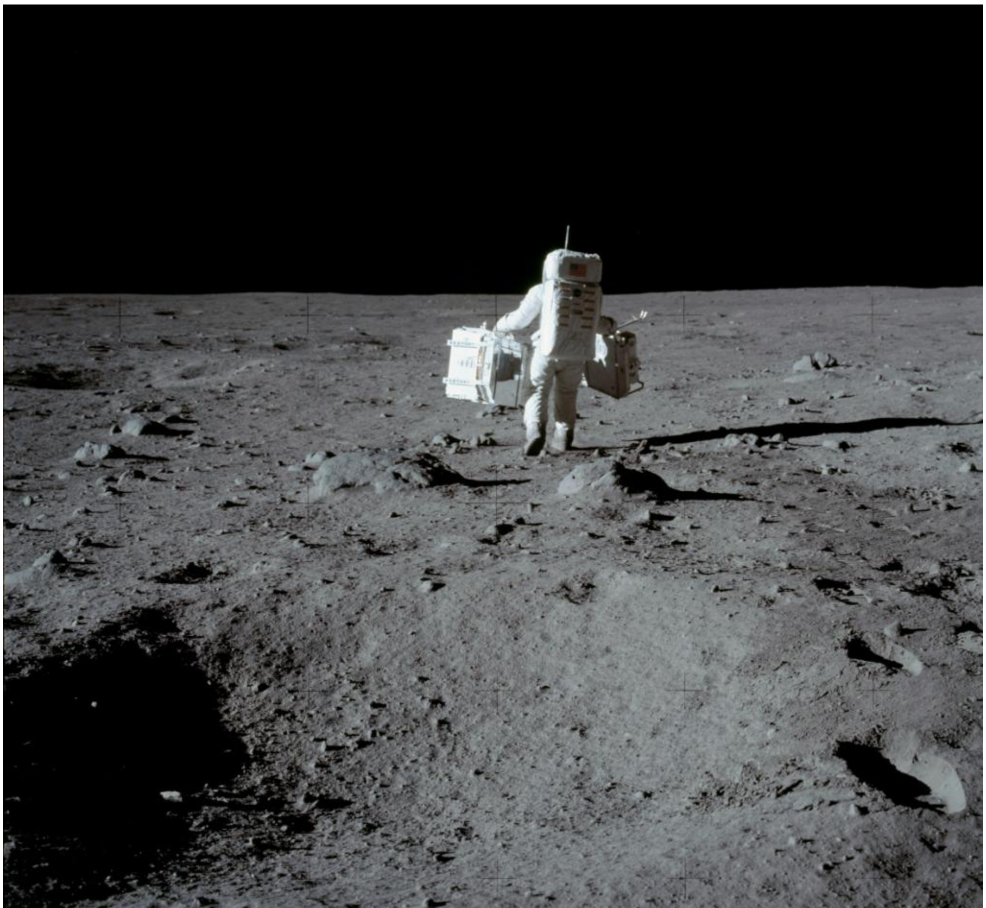

Fig. 3 – Surface of the Moon.

However, the layer of regolith on the Moon, apparently, is thicker, and stones at Agilkia, which are visible in Fig. 1, lying on a layer of dust, are fairly flat slivers from the surface crust. In this case, the transverse dimensions of the largest stone in Fig. 1 are close to the size of Chebarcul meteorite. In general, it is hardly surprising that in a more or less similar conditions (in vacuum) stone surfaces are subjected to cracking and erosion, which is caused primarily by thermal stresses in the material because of change of its illumination by the Sun.

Clearly more interesting is the final landing point of Philae. There is practically no dust, and we can see the «bedrock» of the comet's crust in Fig. 4 [12].

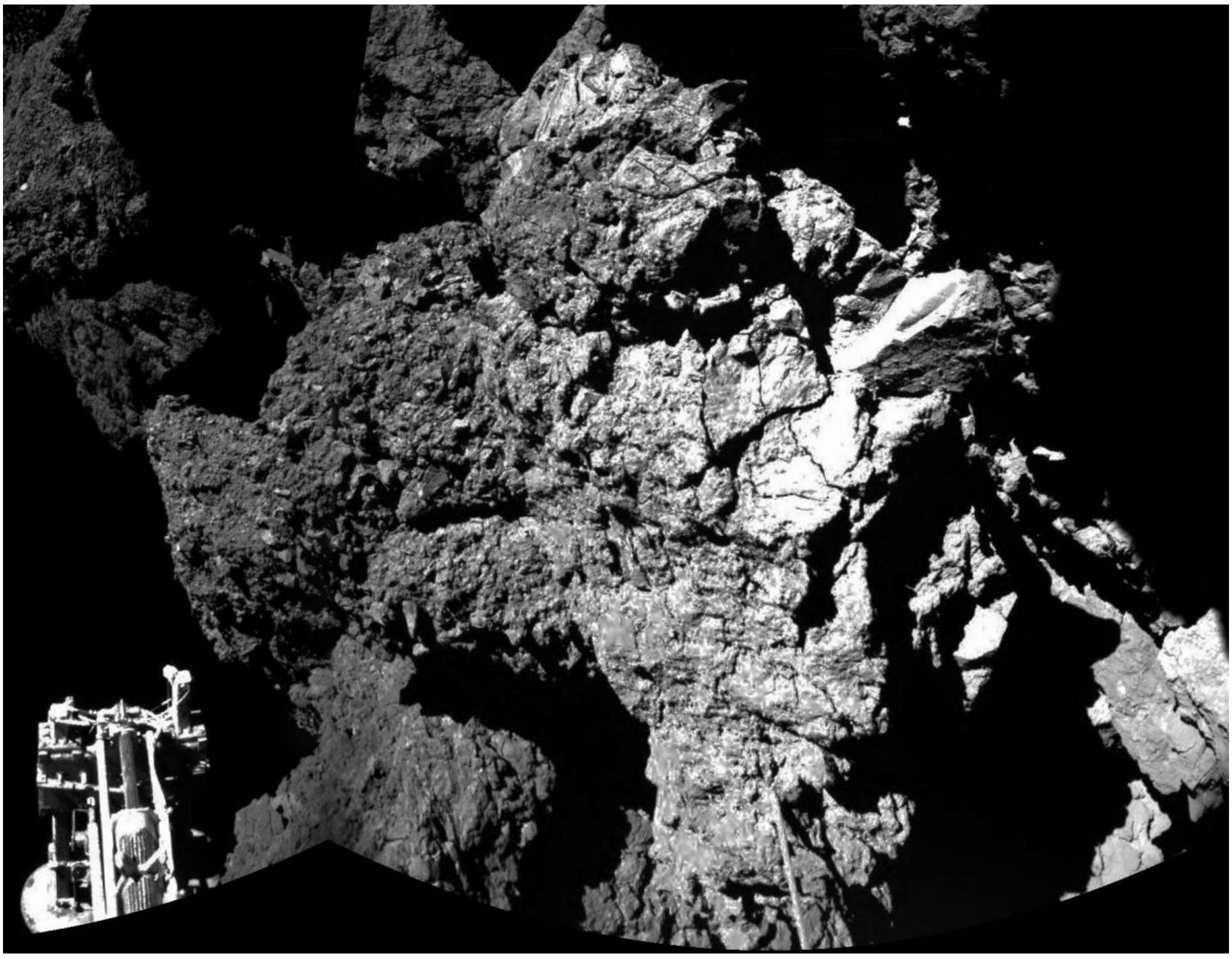

Fig. 4 – «Bedrock» of the comet's crust.

At first glance, the surface of Chebarkul meteorite (see. Fig. 5) differs from the rocky outcrops at the nucleus of the comet. However, we should remember that Chebarkul stone (meteorite), which is the piece of outer crust of the Chelyabinsk meteoroid, went via the process of the strongest aerothermodynamic erosion, as well as through the extremely powerful explosion.

It seems obvious that the top of the surface of the meteoroid fragment (see Fig. 5, [13]) was the outer surface of the crust before explosion and has experienced sintering and ablation. Closer to the initial state (before braking of meteoroid in the Earth's atmosphere) was material which is located on the lateral sides of the fragment – fractures of meteoroid's crust formed in the explosion. And there it is quite similar to what we observe in Fig. 4. It is hard to doubt that after this treatment, a piece of 67P/C-G comet, shown in Fig. 4, when photographing in the same spectral range was not easy to distinguish from the wreckage of Chelyabinsk meteoroid (see Fig. 5), which is an ordinary chondrite LL5 type [14].

Fig. 5 – Chebarkul meteorite.

Black-and-white image (in a greater scale) of another relatively small fragment of Chelyabinsk meteoroid is shown in Fig. 6 [15]. It seems that the only differences in the size and illumination of the surface lead to such differences, which the human eye is able to differentiate in Fig. 4 and Fig. 5, 6.

Fig. 6 – Fragment of Cheliabinsk meteoroid.

Thus, a collation of photos of surviving after the stratospheric explosion of surface crust's fragments of Chelyabinsk meteoroid and the nucleus of the comet at the point of descent of lander Philae, where is no dust covering a significant part of its surface, demonstrates their undoubted external conformity. Obviously, this similarity of comet's crust and a piece of crust of other comet’s fragment is unlikely to be much of a surprise.

III. Determination of the average bulk density of the objects to be compared

However, all the considerations examined above are qualitative only. Quantitative data are necessary for their confirmation. So, only two quantitative parameters from Rosetta and Philae's data are in the public domain which we can use now for the analysis of the characteristics of both 67P/C-G comet and Chelyabinsk meteoroid. The first of these parameters is the average bulk density of these objects.

Rosetta probe after reaching the orbit of 67P/C-G comet from the beginning of August 2014 was flying within 100 kilometers from its nucleus. There have been made many photos, which can be used to determine its shape and size (see, for example, Fig. 7 [16].

Fig. 7 – 67P/C-G comet's nucleus.

In general, the shape of the nucleus of the comet is quite close to combination of two interconnected ellipsoids with dimensions of 4.1 × 3.3 × 1.8 km (large lobe) and 2.6 × 2.3 × 1.8 km (small lobe), see [17]. Then the estimate of its volume will be about 18.5 km^3. Isthmus between these two parts of the comet and various protrusions are increasing its real volume compared with this assessment, and depressions are reducing. According to paper [17] the volume of nucleus of 67P/C-G comet is 21.4 ± 2.0 km^3. However, after survey the comet's areas, which were earlier in shadow, the assessment of the volume was decreased to 18.7 ± 1.2 km^3 [18]. There was found from the trajectory measurements at a distance of about 100 km from the center of the comet's nucleus that its mass is 10.0 Gt [17]. Dividing the mass of the comet by its volume we can obtain that its bulk density is 535 ± 35 kg/m^3.

It should be noted that prior to rendezvous of Rosetta with the comet, mass of the comet was determined in three and a half times less than now (but, nevertheless, up to three (!) of significant digits) – 3.14 ± 0.21 Gt, and the bulk density – 102 ± 9 kg/m^3 (!) [19]. In other sources the initial estimate of the average density of the comet substance by the method of modeling non-gravitational forces given its value in the range of 100 – 370 kg/m^3, but an upper limit on the nucleus density was of about 500 – 600 kg/m^3 [20]. Radar observations done with the radar system of the Arecibo Observatory led to the evaluation of the density of the top layer of comet nucleus of 600 – 1000 kg/m^3 [21]. All of this, by the way, characterizes the reliability of the data on the parameters of solar system's small bodies, received by astronomers, if they don't use direct measurements with spacecraft in close flight.

It is quite an adequate assessment of the average bulk density of the comet's nucleus is easily obtained from the parameters of the cometary fragment, that is from Chelyabinsk meteoroid data. In fact, from the calculations followed that its dimension was 182.5 m, and the average density – 570 kg/m^3 [4]. Then it was calculated that the mass was of about 1.82 Mt, which is approximately in 5500 times smaller than the mass of 67P/C-G comet. Matching of densities of comet and meteoroid is much better than matching of early and current data on the density of the comet's nucleus.

But there is another aspect that should be considered when comparing the mean densities of 67P/C-G comet's nucleus and relatively small fragment of another comet. The density of the crust of Chelyabinsk meteoroid consisting of ordinary chondrite is 3300 kg/m^3 [14]. Its thickness, if the «height» of largest surviving fragment – Chebarkul meteorite to take as a basis, was approximately 0.75 % of the radius of the meteoroid, that is, about of 0.65 m. No doubt, that this fragment was a piece of the «front shield», where surface crust had maximum thickness. The size of nucleus of 67P/C-G comet was about 20 times greater, so the influence of its crust can be neglected into the average density. Then, in order to the densities of Chelyabinsk meteoroid excluding the surface crust and the nucleus of 67P/C-G comet were the same, it is required that the volume of the surface crust was about 1.25% of the volume of the meteoroid. That is, the thickness of it was a few more than 0.4 % of its radius, or about 0.4 m. When compared it to the size of Chebarkul meteorite, this estimate seems quite adequate.

Accordingly, the value of average density of snow nucleus of 67P/C-G comet (with mineral and other impurities), as well as of Chelyabinsk meteoroid (without surface crust) will be approximately 535 kg/m^3. Of course, possible differences in the origin of 67P/C-G comet and the parent comet of the meteoroid could lead to some differences in the quantity and chemical composition of the mineral material of their nuclei. In addition, 20 times smaller size of meteoroid and about 1.3 times greater surface temperature in the perihelia [3, 4, 22] may lead to some differences in the internal structure of the objects. However, the almost complete coincidence of their average densities is another proof that Chelyabinsk meteoroid was a fragment of the comet's nucleus.

The latter conclusion is confirmed by the results presented in Section II of this paper.

IV. Durability of the surface layer of objects to be compared

Some information about the operation of Philae's penetrator has been received – its hammer was consistently in all operating modes up to the maximal and broke, without destroying the surface of the comet's nucleus. From these data, it was determined that the compressive strength of the nucleus surface was more than 2 MPa: «Surface must be > 2 MPa hard!» [23]. It is surprising that the penetrator has been designed for such a low strength of a «soil», as all have always assumed that the nuclei of comets are composed primarily of water ice with various contaminants. In fact, even the strength of sea ice on Earth (ice with contaminants also) is at least 2 – 3 MPa at temperatures $T \approx 245 – 260$ K [24] that is significantly higher than the comet's temperatures even in the sunlit portions of the surface not too far from the snow line of the solar system. Of course, the nucleus of the comet is a snowball rather than a piece of ice. But count on the fact that the penetrator will never turn out on a piece of solid ice – it seems to be a completely unjustified optimism. Moreover, the lower temperature, the stronger compressive strength of ice [25]. And at the temperature of about 120 – 160 K [26], which was registered on the surface of 67P/C-G comet in whole in the period of our interest and in landing point, the strength of the ice may exceed 10 MPa. Nevertheless, the «comet engineering models properties of its surface coated with a range of compressive strength of 60 kPa to 2 MPa». Options with the strength of the surface just a few kilopascals have been considered also (see [27]).

It is known that the compressive strength of a sample with size 10 × 10 × 20 mm, cut from splinter of Chelyabinsk meteoroid, that was found on the ground, is slightly exceeded 60 MPa, and the strength of microscopic samples was in several times even above [14] – allegedly like as for high strength of carbon steel. However, these data refer to samples of material that experienced a strong aerothermodynamic influence and the explosion with energy about 57 megatons of TNT [4, 5]. It is possible that their strength was markedly lower before these affects.

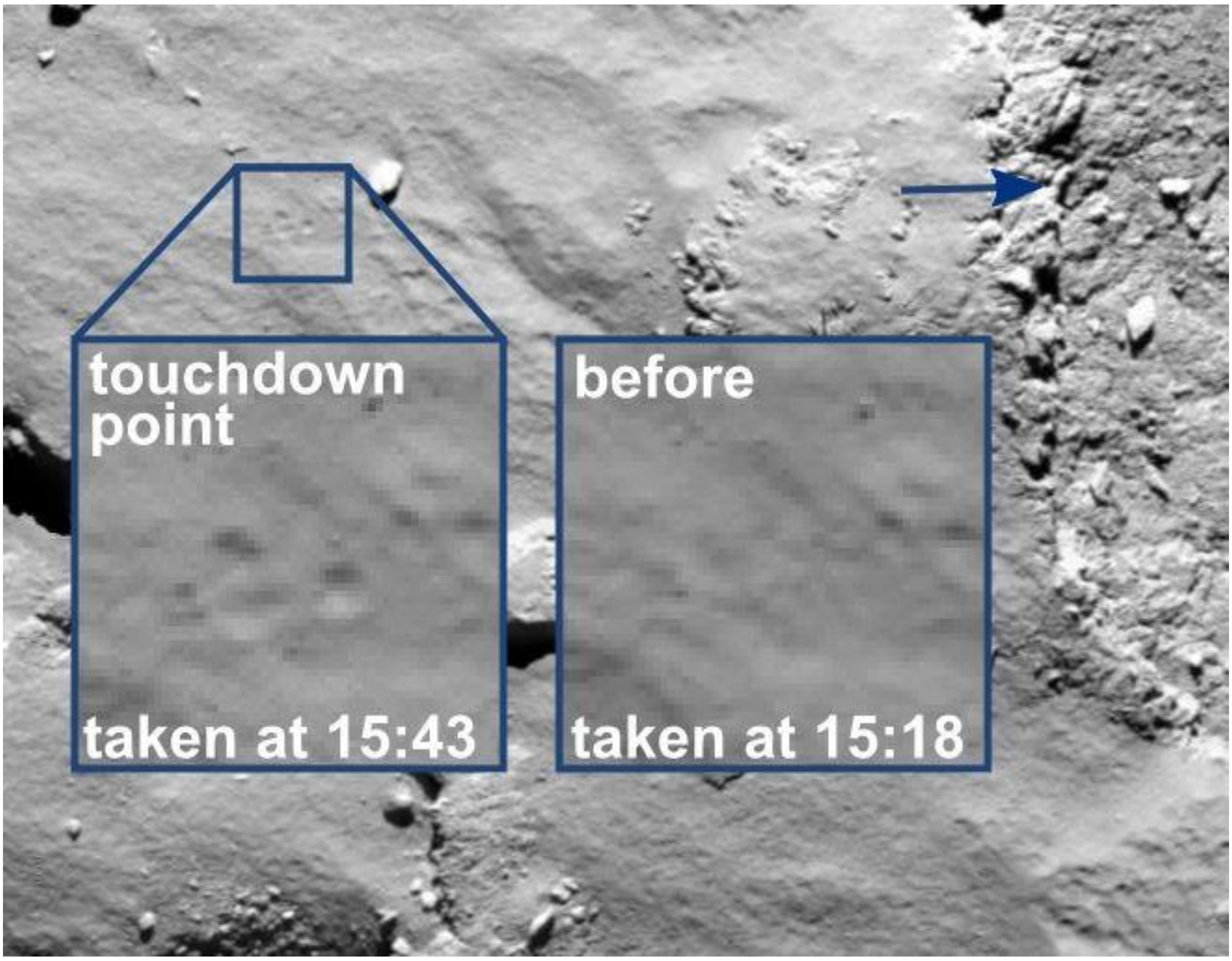

Fig. 8 – The point of Philae contact.

Anchoring harpoons, which were to hold the lander on the comet's surface and proved to be unable to do so, have been calculated on the strength of the material, not exceeding 8 – 10 MPa [27]. Although, judging by the prints of Philae's chassis in the first touch point of the surface of the comet [28] and data from the speed sensor, the approach to it was made quite normal, and large stones at the point of contact, which could somehow to prevent landing, wasn't seen (see Fig. 8). It was found that harpoons «did not deploy as planned» [26] and weren't shot. However, a comparison of the most probable compressive strength of the surface crust of the comet (at least on the order of several tens of MPa), and the design characteristics of harpoons (maximum strength of breaching of material – less than ten MPa), their operability couldn't affect the possibility of fixing the lander on the surface of the comet. Durability in several kilopascals for the above described sample cut from fragment of Chelyabinsk meteoroid was obtained in the tests also, but at tension of the sample [14].

Thus, the available extremely meager data of the durability of the surface crust of 67P/C-G comet is also quite consistent with those of a similar durability of fragments of Chelyabinsk meteoroid.

Conclusions

1. Jumps of Philae on the 67P/C-G comet's surface proved to be extremely successful for the visual analysis of material of its nucleus, as led eventually to the exit point of «bedrock», that was critical to this analysis.
2. Visual analysis of the images of «bedrock» outputs on the surface of 67P/C-G comet from beneath the dust layer and facets of Chebarkul meteorite (the largest fragment of the surface crust of Chelyabinsk meteoroid), which were not subjected to prolonged exposure to intense aerothermodynamic effects, shows their considerable similarity.
3. The values of the average (without surface crust) bulk density of Chelyabinsk meteoroid's core and the average density of the nucleus of 67P/C-G comet are virtually identical and are equal to 535 kg/m^3.
4. The compressive strength of the surface crust of the comet 67P/C-G far exceeded the expectations of researchers and was much higher than the strength of polluted water ice.
5. Data on the strength of surface crusts of Chelyabinsk meteoroid and 67P/C-G comet are quite consistent together.

6. All this fully confirms the earlier conclusion that Chelyabinsk (and, hence, Tunguska) meteoroids were belonged to family, members of which are the debris of the comet's nucleus.
7. If, due to the problems encountered with Philae, information on the chemical composition and physical characteristics of the surface layer of 67P/C-G comet will not enough, the participants of this program can complement these data in Chelyabinsk State Regional Museum, which houses Chebarkul meteorite.

References

1. Rosetta (spacecraft). *Wikipedia* // http://en.wikipedia.org/wiki/Rosetta_(spacecraft)
2. Rosetta. Rendezvous with a comet. *ESA* // http://rosetta.esa.int/
3. Yu. I. Lobanovsky – Parameters of Chelyabinsk and Tunguska Objects and their Explosion Modes. *Arxiv.org*, July 8, 2013 // http://arxiv.org/abs/1307.1967
4. Yu. I. Lobanovsky – Parameters of Chelyabinsk and Tunguska Meteoroids. *Synerjetics Group*, August 15, 2014 // http://www.synerjetics.ru/article/objects_3_eng.htm
5. Yu. I. Lobanovsky – Acoustic Methods for Evaluation of High Energy Explosions. *Arxiv.org*, March 6, 2014 // http://arxiv.org/abs/1311.6565
6. Yu. I. Lobanovsky – Chelyabinsk Meteoroid: Critique of Sources and Proving of Conclusions. *Synerjetics Group*, June 6, 2014 // http://www.synerjetics.ru/article/springs_critique_eng.htm
7. Yu. I. Lobanovsky – Comet and Meteor Threat: Historical Aspects. *Synerjetics Group*, June 18, 2014 // http://www.synerjetics.ru/article/history_eng.htm
8. Yu. I. Lobanovsky – What was the Chelyabinsk Meteoroid really? *Synerjetics Group*, August 15, 2014 // http://www.synerjetics.ru/article/two_arguments_eng.htm
9. Comet from 40 metres. *Space in images. ESA*, November 13, 2014 // http://www.esa.int/spaceinimages/Images/2014/11/Comet_from_40_metres
10. Museum staff made mistakes in handling the meteorite «Chelyabinsk». *RIA News, Science*, February 13, 2014 // http://ria.ru/studies/20140213/994662402.html (in Russian)
11. Remembering Apollo 11. *The Big Picture, boston.com*, July 15, 2009 // http://www.boston.com/bigpicture/2009/07/remembering_apollo_11.html
12. Welcome to a comet. *Space in images. ESA*, November 13, 2014 // http://www.esa.int/spaceinimages/Images/2014/11/Welcome_to_a_comet
13. The Chelyabinsk meteorite will be exhibited in the museum. *In dreams about space* // http://ru-universe.livejournal.com/668127.html (in Russian)
14. O. P. Popova et al. – Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization. *Science*, **342**, no. 6162, November 29, 2013 // https://www.sciencemag.org/content/342/6162/1069
15. O. Streltsova, Yu. Timoshin – Chelyabinsk meteorite «has flown» up to the capital. *TVC Center, Science*, January 21, 2015 // http://ria.ru/studies/20140213/994662402.html (in Russian)
16. Measuring comet 67P/C-G. *Rosetta blog*, ESA, 03.10.2014 // http://blogs.esa.int/rosetta/2014/10/03/measuring-comet-67pc-g/
17. H. Sierks et al. – On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko. *Science*, **347**, no. 6220, 23.01.2015 // http://www.sciencemag.org/content/347/6220/aaa1044.full
18. F. Preusker et al. – Shape model, reference system definition, and cartographic mapping standards for comet 67P/Churyumov-Gerasimenko – Stereo-photogrammetric analysis of Rosetta/OSIRIS image data. *Astronomy&Astrophysics*, **583**, November, 2015 // http://www.aanda.org/articles/aa/abs/2015/11/aa26349-15/aa26349-15.html
19. L. Maquet et al. – 67P/Churyumov-Gerasimenko mass determination based on a new method for modeling non-gravitational forces and accelerations. *Asteroids, Comets, Meteors*, 2012 // http://www.lpi.usra.edu/meetings/acm2012/pdf/6282.pdf
20. BJR Davidsson, PJ Gutierrez – Nucleus properties of Comet 67P/Churyumov-Gerasimenko estimated from non-gravitational force modeling. *Instituto de Asrofisika de Andalucia, IAA-CSIC*, 2012 // http://www.iaa.es/node/6962
21. P. Kamoun et al. – Constraints on the subsurface structure and density of the nucleus of Comet 67P/Churyumov-Gerasimenko from Arecibo radar observations. *SAO/NASA ADS Astronomy Abstract Service* // http://adsabs.harvard.edu/abs/2014A%26A...568A..21K
22. 67P/Churyumov–Gerasimenko. *Wikipedia* // http://en.wikipedia.org/wiki/67P/Churyumov%E2%80%93Gerasimenko
23. MUPUS on Philae. Results (15) *@Philae_MUPUS*, November 15, 2014 // https://twitter.com/Philae_MUPUS
24. V. I. Odinokov, A. M. Sergeeva – The evolution of discontinuity process in the destruction of the ice cover. *PMTPh*, 2008, vol. 49, no. 1 // http://www.sibran.ru/upload/iblock/ce0/ce09c0ac3889ae5a6b655c9a0d6e9cd7.pdf2

25. SNiP 2.06.04-82*. Loads and impacts on the hydraulic structures (wave, ice and from ships). *Ministry of Construction of the USSR, Moscow*, 1989 // http://www.gosthelp.ru/text/SNiP2060482Nagruzkiivozde.html (in Russian)
26. Philae settles in dust-covered ice. *Rosetta Blog*, *ESA*, 18.11.2014 // http://blogs.esa.int/rosetta/2014/11/18/philae-settles-in-dust-covered-ice/
27. S. Ulamec, J. Biele – From Rosetta lander Philae to an asteroid hopper: Lander concept for small bodies missions. *DLR*, 2006 // http://solarsystem.nasa.gov/docs/pr395.pdf
28. OSIRIS spots Philae drifting across the comet. *Space in images. ESA*, November 17, 2014 // http://www.esa.int/spaceinimages/Images/2014/11/OSIRIS_spots_Philae_drifting_across_the_comet

6 April 2015 – 2 March 2016 Yu. I. Lobanovsky