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Terrestrial Late Heavy Bombardment (TLHB)– evidences and questions

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Abstract. *About 3.8 billion years ago was the greatest meteoritic bombardment in the history of the Inner Solar System bodies. The record of this event is still legible on the lunar surface, but we can find it also on the Mars, Venus or Mercury. The problem is to find traces of this catastrophe on the Earth. Tectonic plates, metamorphism and erosion obliterate signs of meteorite impacts on our planet. In this paper I try to present the most recent data about this event on the surface of the Earth.*

Keywords: *Terrestrial Late Heavy Bombardment, TLHB, meteorite collisions, beginning of the Earth*

Introduction

Meteorite collision record derived from the lunar surface indicates that about 3.8 billion years ago there was a very violent bombardment of meteorites and comets. It was concentrated not only on the Moon but also on the other bodies in the Inner Solar System. Excessive collisions occurred after the accretion phase and formation of all initial spheres of the primary planets. A record of the Late Heavy Bombardment (LHB) on the Moon has been repeatedly confirmed by the analysis of samples provided by the American and Soviet space missions, as well as by analyzing the density of craters on the lunar surface [18]. Actually lunar data is a model which allows to reconstruct the early evolution of Mercury, Venus, Earth and Mars, and the Main Belt asteroids.

Despite the obvious evidence of heavy collisions on the Moon, there is still no clear confirmation of LHB on the surface of the Earth. After many analysis of the oldest Earth's rocks there is still more questions than answers about Terrestrial Late Heavy Bombardment.

Earth as a massive body with greater cross section than the Moon had to be exposed to the meteorite impacts more than her satellite and more than other inner planets and these collisions should leave some traces on the surface of the planet.

Late Heavy Bombardment – reasons and theories

Creation of numerous meteorite craters about 3,8 billion years ago was caused by very strong meteorite and comet shower. Primarily it was assumed that LHB was a constant supply of meteorites, which began in the moment of the creation of the Moon (about 4.6–4.55 billion years ago) and ended about 3.8 billion years ago. Further analysis of meteorite craters and the lunar lavas indicate that the inflow rate has changed over a time [10]. In some papers it is assumed that the initial influx of matter rapidly increased about 3,9 and ended about 3,8 billion years ago [28]. Other dates it back at 4,1/4,0–3,8 billion years ago [5] or at the time of formation of the lunar basins created at Nectarian and Lower Imbrian periods [22].

There are several theories to explain the LHB origin. The most popular theory says that bombarding was initiated during the formation of Uranus and Neptune [9] or during migration of these planets through the Solar System [15]. It caused disturbances of minor bodies that moved towards the Sun and hitting planets and moons of the Inner Solar System.

The great bombardment could also be a consequence of the formation of the main belt asteroids. Asteroids collided, changed their orbits and some of them were ejected from main belt and hit inner planets [37].

Heavy bombardment could also be a consequence of gravitational knocking of matter by massive body (planet or star) that was in the Solar System about 3,8 billion years ago and disrupting the balance of small objects [35]. It also could be the main belt disorder caused by a fifth terrestrial planet. In this model the orbit the fifth planet was probably initially almost circular, and then changed to a highly elongated and intersecting the Main Belt. The planet was maintained at this trajectory about 600 million years and ejected asteroids. After that time planet hit the Sun and LHB was stopped [5].

Lunar Late Heavy Bombardment

The Moon is the standard body for analyzing collisions in the Inner Solar System because it is a small object which cooled down relatively quickly, and his surface solidified in a very short time. As the temperature inside the Moon was relatively low there was not tectonic changes which could destroyed craters. So there is still readable record of the oldest meteorite collision dated to the Prenectarian, Nectarian and Low Imbrian periods (these periods correspond to Priscoan and Archean on the Earth).

A collision record indicates that the intensification of bombardment was around 3.85±0.05 billion years ago [29]. The mast of the greatest lunar impact craters (lunar sees) are dated at this time. They were formed from 3.92 (Mare Nectaris) to 3.72 (Mare Orientale) billion years ago. The interval of maximum intensity of the bombardment could also be different. It depends on the data of the boundaries of the lunar periods. Lunar LHB could be in Nectarian (3.92–3.85 billion years ago, or Nectarian and Lower Imbrian (3.92–3,8 billion years ago) or only in Lower Imbrian (3.85–3.84 billion years old) [34].

The age of lunar craters is tested using several methods. The oldest of these methods is comparing the density of craters on the surface of the Moon. The greater density of craters means older age of the area. It allows for relative dating the lunar surfaces. This method was complemented by analysis of the lunar samples taken by the spacecrafts [27, 25], which allowed a precise dating of some craters.

It is estimated that during the LHB on the Moon was formed more than 9 thousand impact craters. Which means that per year was formed a $2{,}453 \cdot 10^{-4}$ craters per square kilometer with diameters exceeding 16 km. For comparison, today is form from $3{,}07 \cdot 10^{-13}$ to $6{,}13 \cdot 10^{-13}$ craters of this diameter per square kilometer per year [2], which gives about 10 to 20 craters per million years.

Analysis of the shape of the craters on the Moon and the chemical composition of the lunar surface does not give a conclusive answer to the question, what kind of space objects collided during the LHB. The iridium content on the lunar surface is comparable with iridium in the Earth's mantle and it is about 10 ppt (parts per trillion). For comparison, the Earth's crust contains about 20 ppt of iridium and meteorites contain up 465 000 ppt of this element. Small content of iridium on the lunar surface suggests comet impacts, but other traces of lunar collision (size and shape of craters, ejected material, etc.) do not give clear evidences of cometary impacts. On the other hand evidence from the Earth's surface suggest that during TLHB was o significant share of the comet collisions [20].

Differences between the geological record of the Moon and the Earth are explained by differences between the speed of the comet (comet's average speed is 20 km/s) and asteroids (12 km/s), and the escape velocity of the Earth (11,2 km/s) and the Moon (2,4 km/s). Bolides hitting on the surface of the Moon ejected matter with speed exceeded escape velocity. It concerned about 50% of asteroids and 100% of comets. Impact of comets on the Moon eject all comet material and a lot of fragments of regolith and bedrock. On the Earth, these share is 10% for asteroids and 50% for comets, the escape velocity of the Earth is five times greater than on the Moon. This and the presence of the atmosphere caused, that the fragments of the comet became geospheres components [20].

These calculations show that the analysis of the lunar surface are a good estimations for the surface of the Earth, but they do not give answers for all questions.

Estimations of the intensity of the Terrestrial Late Heavy Bombardment

Late Heavy Bombardment on the Earth took place about 50–100 million years after the gravitational collapse. This means that the Earth had already all initial geospheres with atmosphere and hydrosphere too [8, 36]. The period between the end of accretion, and the time of solidification of first preserved until today crust is named Hadean. It includes Priscoan (pre-Archaean) and 200 million years of Lower Archean [29]. Terrestrial Late Heavy Bombardment took placed in the Upper Hadean (boundary of the end of Priscoan and Archean).

Estimation of bombardment of the Earth’s surface during the LHB is very difficult because of deficiency of rocks from this period. The oldest rocks are approximately 3,85 billion years old, and the oldest preserved minerals (zircon grains) are about 4,1 – 4,2 billion years old. The lack of Earth’s crust older than 3,8 billion years could be one of the proofs of great bombardment. The energy of the LHB was changed in heat and melted rocks of the initial crust [29].

Estimations of the intensity of a collision during the LHB based on an analysis of the gravitation of the Earth, its cross-section and lunar data. This data allow to estimate that during the LHB on the Earth took place from 2 to 20 times more collisions than on the Moon [29]. This means that, that the surface of the planet was hit from 18 to 180 thousand bolides with diameters greater than 16 km, so more than 40 % of the Earth’s surface was covered by impact craters .

Other estimations of accretion of extraterrestrial matter gives $1\text{-}2 \cdot 10^{15}$ g/year or $2\text{-}4 \cdot 10^{-4}$ g/cm^2. In this estimation total mass of matter accumulated on the square meter surface during the 100 million years is 200 tons [30]. This huge mass of extraterrestrial matter (for all surface of the Earth it could be $2 \cdot 10^{20}$ kg) gives a very small percentage increase in total mass of the Earth.

There are different estimations of intensity of Terrestrial Late Heavy Bombardment. Barlow [2] calculate that during the LHB on the one square kilometer of the Earth's surface has fallen from $3{,}2 \cdot 10^{-4}$ to $3{,}7 \cdot 10^{-4}$ objects. Ryder et al. [29] evaluate the number of collisions with diameter over 100 km at 2,5–3 thousand, with diameter over 200 kilometers at more than thousand, and collisions that forming craters on the sizes of lunar sees at ten. The biggest collision in Hadean (but not always dated on LHB) is the collision of Earth with a planet of the Mars size which leads to the creation of the Moon [7, 13, 24, 29].

Other estimates gives the mass ratio of bolides hitting the Earth to bolides hitting the Moon. This proportion is 1,8 for asteroids (asteroids hitting the Earth/asteroids hitting the Moon) and 1,3 for comets. The average speed of asteroids and comets hitting the Earth is 20.9 km/s and bolides hitting the Moon have speed 19.2 km/s [18]. Hence the ratio of the energy of bolides hitting the Earth and the Moon is equal to 3.2 for asteroids and 1.7 for comets [20].

The energy yielded during TLHB was about 10^{28} J. That energy on the planet of the Earth's size initiates geological activity (tectonic and volcanic), which probably led to the remelting and metamorphism almost all rocks and to complete obliteration of the traces of bombardment [29]. At the time of LHB could have been a few huge collision, which complete transformed the environment of the Earth and changed the composition of the geospheres of the planet. It is estimated that on the Earth a collision with a size comparable to the Mare Imbrium could lead to the evaporation of ocean water of thickness of 40 meters, and impact of the asteroid with diameter of hundreds of kilometers could lead to the complete evaporation of one of the contemporary oceans [29].

Impact traces on the Earth

Most markers of cosmic collisions are known from study of sediments from the Cretaceous-Tertiary boundary. Chicxulub crater and related sediments are the pattern of impact traces [31].

For collision markers are considered tektites, spherules and mikrospherules [6, 33], but spherules migrate in the sediments and it can interfere geologic record [29], shock minerals (the most common is shock quartz, but there are also grains of shock zirconium, amphibole, pyroxene, olivine and feldspar [12, 19]. The collision traces are also platinum group elements in the Earth's crust [31, 4]. The most characteristic element of the platinum group is iridium, but in impact sediments can be also platinum, osmium or palladium. The characteristic elements are also chrome with unusual for the Earth isotopic composition and gold. In the impact sediments sometimes are amino acids of the extraterrestrial origin [32].

Crater identification is possible even if its slopes are destroyed. In the crater floor are shock metamorphic rocks e.g. impact breccia (suevite), impact structures of rocks e.g. shatter cones and minerals changed during the impact high-presure (e.g. graphite is converted to mikrodiamonds and quartz to stishovite and coesite) [12].

Collisions with comets are preserved in sediments as excess of ^{3}He isotope. In many cases Helium is trapped in fullerenes [3]. Helium is a good indicator of impact even in the oldest rocks because it do not decay and do not migrate in the sediments. The oldest sediments indicating the comet collision have 450 million years [11].

To distinguish two separable meteorite collisions in the geological record, interval between them must be over 2000 years [29].

Terrestrial Late Heavy Bombardment – where look for evidence?

Evidences of TLHB are limited to the oldest rocks on the Earth's surface, because only there could preserved traces of Archaic and Priscoian meteorite collisions. The oldest rocks are dated on 3,6-3,9 billion years and they are located in the province of Isua in Greenland, on islands surrounding Greenland (e. g. Akili Island) and on the Labrador Peninsula. Those rocks are fragments of the same greenstone belt dated at about 3,7 – 3,8 billion years ago [30]. The surface of these rocks is about 3000 km^2 and they has different genesis: metamorphic rocks (gneisses and ortogneisses), igneous rocks (granitoids) and sedimentary rocks formed at the bottom of deep oceans [29]. Primary rocks were metamorphosed, deformed and were cut by tonalit intrusions [20].

Those sedimentary-volcanic rocks originally belonged to three types: shallow-water pelagic rocks with alkaline volcanic intrusions, shallow-water clastic sediments, and detrital facies containing oxidized iron ore [20]. Some fragments of these rocks have been preserved in its original form, which allows to examine their original composition and structure. The share of these unchanged parts is about 10% [17].

Greenstone belts are remnants of oceanic crust similar to present-day oceanic crust or acid crust created in igneous and metamorphic processes [14]. However, characteristic metamorphism in these rocks can suggest extraterrestrial factors on the process of the formation of these belts. The lower part of geenstone belts contains ultra-alkaline magma, which was injected into the surface of the Earth's crust in temperature of 1600-1650°C. These magma was probably formed as a result of the sudden melting of 60–80% of crust rocks, which could be a consequence of heavy bombardment. Collisions have led to differentiation of the crust and mantle. According to this theory, greenstone belts are preserved traces of impact basins originally filled by alkaline and ultra-alkaline impact magma [16].

Evidences of TLHB in Earth's crust

The search for evidence of the great bombardment on the Earth is difficult because of the small surface and local distribution of Archaic rocks, and their later transformation. These rocks are highly metamorphosed and deformed what making them difficult for dating and interpretation of their original composition and structure. Rocks, which have been selected do tests are composed of metamorphic rocks with weakly transformed fragments of sedimentary rocks formed in the seas of eroding land rocks. In these case the record LHB should be readable.

Studies in the Isua gneiss complex give ambiguous results. Koeberl et al. [21] researches do not show clear siderophile's anomalies. Iridium anomaly (0.2 ppm) is too small to be evidence of extraterrestrial origin. The tests of Koeberl et al. [21] show that 15 samples indicates anomalies of some elements such as iridium – a small exceeds in four samples and platinum – a surplus in one sample. In most analyzed rocks appeared elevated content of platinum, palladium, gold, nickel, cobalt and chromium, but there were not constant differences and, in the case of rubidium, rhodium and iridium anomalies in some samples were negative. Similar results gives a study in a gneissic complex of the Akili Island (western Greenland). There are also no anomalies of markers of meteorite collisions [17].

On the other hand the analysis presented by Jorgensen et. al [20] show a significant excess of iridium, rhodium and rubidium in Isua province dated at 3,77-3,8 billion years. According to these studies iridium content is about 150 Isua ppt and never exceeds this level. The iridium content in the rocks of Isua belonging to three different genetic types, gives comparable content of this element, which is higher than today's about seven times (today's crust contains about 25 ppt of iridium). This level of iridium in Hadean rocks suggests that comets were dominant collided bolides [20].

Sediments dated at TLHB preserved in Isua province greenstones belt should also contain strictly defined proportions of isotopes of chemical elements such as hafnium and tungsten (^{182}Hf-^{182}W) with a half-life of 9 million years, manganese and chromium (^{53}Mn and ^{53}Cr), with the half-life of 3,7 million years, and the surplus of Cr/Ti and Ni/Nb which is characteristic for chondrites and iron meteorites [30].

Tungsten isotopic ratio ^{182}W and ^{183}W in the Earth's crust and mantle should give a uniform distribution for all globe. In meteorites these proportions are different. A surplus of lighter isotope of tungsten is a product of the decay of hafnium, so the excess of this isotope in the crust may be the evidence of cosmic collisions [30].

In the Isua province excess of impact tungsten is clear [30]. However, it significantly exceeds the estimated content of tungsten which should sediment during TLHB. If the rocks in which tungsten is located initially were magmatic, the intensity of collisions had to exceeded all previous estimations. For sedimentary rocks, the excess of tungsten could be result of intensified accumulation from land [20].

In Isua rocks has been confirmed exceed of Ni/Nb isotopes characteristic for impact sediments [30], but the study of nickel isotopes give ambiguous results. Furthemore Frei and Rosing [26] did not find any evidence of presence of other impact trace - extraterrestrial chromium.

For Archaic rocks is also characteristic carbon (graphite) excess, whose genesis is not clearly defined. According to some authors e.g. Mojzis et al. [23] it is organic carbon came from living organisms, while others e.g. Schoenberg et al. (30] recognize that it comes from carbonaceous chondrites and it is one of evidences of cosmic collisions.

Another important indicator of meteorite collisions is the presence of shock minerals such as shock quartz and shock zircon but there is no traces of shock minerals in archaic rocks. Absence of shock quartz may be the result of metamorphism, which completely transformed the grains of this mineral. Unfortunately the search of shock zirconium was also negative [23, 21]. Lack of shock minerals may result from multiple metamorphism of the Isua province. Some dating of these rocks give the date of only 3,65 billion years, not correlated with TLHB 3,85 billion years ago [20].

Another markers of meteorite bombardment are microspherules. The oldest impact spherules are dated at 3,5 billion years, so they could not be traces of TLHB [23].

Evidences of TLHB in Earth's atmosphere

Study of archaic rocks do not gives conclusive results, so scientist are looking for evidence of Terrestrial Late Heavy Bombardment in other geospheres like atmosphere and hydrosphere. These researches are justified because there was no major changes in these geopheres associated with the mass collisions, release of gases from the mantle or escape of gases from the atmosphere since 3,8 billion years [1].

Volume of noble gases in the primary atmosphere was dependent on the content of volatiles in the Earth's mantle. As a result of the later evolution, the atmosphere left more than 98% of noble gases. The current composition of the atmosphere is the result of the supply of gases from chondrites and objects from the Kuiper Belt [1].

This is confirmed by analysis of the chemical composition of the atmosphere, mantle and chondrites. Fraction of neon, argon, krypton and xenon in the atmosphere and hydrosphere is much higher than that which could be released from the Earth's mantle. Neon probably comes from the solar wind captured by the Earth's atmosphere. Argon and krypton probably come from the icy bodies came from external Solar System [1]. A similar volume of noble gases have been measured on Mars, which may indicate that these two bodies had a similar evolution of the atmosphere [1].

The isotopic composition of the contemporary atmosphere shows that the share of comets from the Kuiper belt in TLHB was small (about 0.5%). It is also possible that the share of the comet was much larger, but hitting objects contained much less noble gases than the objects studied by spacecrafts. It could be due to their original construction (composition of comets is very variable) or to the loss of part of the gas during the moving from the Kuiper Belt to the Inner Solar System. It is also possible that the great bombardment ejected part of the atmosphere to the outer space [1].

In addition to currently observed noble gases TLHB had to deliver on the Earth other elements and chemical compounds such as water (about 1.3%), atmospheric nitrogen (about 6%) and organic carbon ($1.15 \cdot 10^{16}$ kg). And provided energy to initiate redox reactions necessary for the organic synthesis [1].

Summary

Analysis of the surface of the Moon and inner planets, gives clear evidence of increased bombardment dated at 3,85±0,05 billion years. Earth as a more massive body with bigger cross section was exposed to more asteroid and comet impacts than the Moon (0,0123 Earth's mass) or Mars (0,107 Earth's mass).

Small fragments of archaic crust give ambiguous results of content of the collision markers. Note, however, that this crust was created in extremely different conditions, and the accumulation of minerals from bolides and from the mantle occurred in other conditions than present, which resulted in an atypically large or low content of particular elements.

There is no conclusive evidence TLHB in the geological record but it can be considered as the most important evidence of TLHB. Small amount of Archean rocks is a consequence of the strong volcanism and tectonics, but the large igneous processes are strictly related with energy of great bombardment of extraterrestrial matter.

This article shows that the Terrestrial Late Heavy Bombardment still gives more questions than answers. There are needed further studies both on Earth and on other bodies of the Inner Solar System. Lack of compelling evidence of Terrestrial Late Heavy Bombardment does not confirm of uniqueness of the Earth. We have to accept the fact that the Earth is only one of many object in Solar System and it is subject to the same processes as other planets, moons and asteroids in the Inner Solar System.

Bibliography

1. Meibom A. Noble gas signature of the Late Heavy Bombardment in the Earth's atmosphere / A. Meibom B. Marty // eEarth. – 2007. – No 2. – P. 43–49.
2. Barlow N. G. Estimating the terrestrial crater production rate during the Late Heavy Bombardment period / N. G.Barlow // International Workshop on Meteorite Impact on the Early Earth : Abstracts. – 1990. – P. 4–5.
3. Becker L. Fullerenes: An extraterrestrial carbon carrier phase for noble gases / L. Becker, R. J. Poreda, T. E. Bunch // Proceedings of the National Academy of Sciences. – 1999. – No 97(7). – P. 2979–2983.
4. Brooks R. R. Palladinum and gold as indicators of K/T boundary sections / R. R. Brooks, A. W. Cook, R. B. Stewart // In Catastrophic events and mass extinctions: impacts and beyond, Boulder, USA. – 2000. – P. 19–20.
5. Chambers J. E. A new dynamical model for the lunar late heavy bombardment / J. E. Chambers J. J. Lissauer // Lunar and Planetary Science. – 2002. – No 33. – P. 1093.
6. Cisowski S. M. Magnetic microspherules associated with the k/t and upper Eocene extinction events / S. M. Cisowski // Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. 1988. – P. 28–29.
7. Dahl T. W. Turbulent mixing of metal and silicate during planet accretion and interpretation of the Hf-W chronometer // T. W. Dahl, D. J. Stevenson // Earth and Planetary Science Letters. – 2010. – No 295. – P. 177–186.
8. Drake M. J. Accretion and primary differentiation of the Earth: A personal journey / M. J. Drake // Geochimica et Cosmochimica. – 2000. – No 64(I 4). – P. 2363–2370.
9. Duncan M. J., Could the lunar late heavy bombardment have been triggered by the formation of Uranus and Neptune? / M. J. Duncan, K. Zahnle // Icarus. – 2001. – No 151. – P. 286–306.
10. Elkins-Tanton L. T. Magmatic effects of the lunar late heavy bombardment / L. T. Elkins-Tanton, B. H. Hager, T. L. Grove // Earth and Planetary Science Letters. – 2004. – No 222. – P. 17–27.
11. Farley K. A. The extraterrestrial 3He record: How far back can we go? / K. A. Farley, S. Mukhopadhyay, A. Montanari. – In Impacts and the origin, evolution, and extinction of life, page 22. Department of Earth and Space Sciences and University of California, Los Angeles, 2002.
12. French M. Traces of Catastrophe / M. French // A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures. – LPI Contribution, Smitsonian Institute. – 1998. – Vol. 954.
13. Galimov E. M. Origin of the Earth-Moon system / E. M. Galimov, A. M. Krivtsov // Journal of Earth System Science. – 2005. – No 114(6). – P. 593–600.
14. Glikson Y. On the basement of Canadian greenstone belts / Y. Glikson // Geoscience Canada. – 1978. – No 5(1). – P. 3–12.
15. Origin of the cataclysmic late heavy bombardment period of the terrestrial planets // R. Gomes, H. F. Levison, K. Tsiganis, A. Morbidelli // Nature Letters. – 2005. – No 435. – P. 466–469.
16. Green H.. Archean greenstone belts may include terrestrial equivalents of lunar maria? / H. Green // Earth and Planetary Science Letters. – 1972. – No 15(3). – P. 263–270.
17. Harrison T. M. Vestigates of beginning: clues to the emergent biosphere recorded in the oldest known sedimentary rocks / T. M. Harrison S. J. Mojzsis // GSA Today. – 2000. – No 10(4). – P. 1–6.
18. Ivanov B. A. Earth/moon impact rate comparison: Searching constraints for lunar secondary/primary cratering proportion / B. A. Ivanov // Icarus. – 2006. – No 183. – P. 504–507.
19. Izett G. A. The western north American Cretaceous-Tertiary (K-T) boundary interval and its content of shock-metamorphosed minerals: implications concerning the K-T boundary impact extinction theory / G. A. Izett // Global

Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. – 1988. – P. 83–84.
20. The Earth-Moon system during late heavy bombardment period - geochemical support for impacts dominated by comets / U. G. Jorgensen, P. W. U. Appel, Y. Hatsukawa, M. Oshima, Y. Toh, A. Kimura // Icarus. – 2008. – No 204. – P. 368–380.
21. Koeberl C. Search for petrographic and geochemical evidence for the late heavy bombardment on the earth in early Archean rocks from Isua, Greenlad / C. Koeberl, W. U. Reimold, I. McDonald, and M. Rosing // Impacts and the Early Earth Lecture Notes in Earth Sciences. – 2000. – No 91. – P. 73–97.
22. The onset of the lunar cataclysm as recorded in its ancient crater populations / S. Marchi, W. F. Bottke, D. A. Kring, A. Morbidelli. – 2012.
23. Evidence for life on Earth by 3800 million years ago / S. J. Mojzsis, G. Arrhenius, K. D. McKeegan, T. M. Harrison, A. P. Nutman, C. R. L. Friend // Nature. – V. – No 384. – P. 55–59.
24. Solar System formation and early evolution: the first 100 million years / T. Montmerle, J. C. Argereau, M. Chaussidon, M. Gounelle, B. Marty, A. Morbidelli // Earth, Moon and Planets. – 2006. – No 98. – P. 39–95.
25. Neukum G. Cratering records in the inner Solar System in relation to the lunar reference system / G. Neukum, B. A. Ivanov, W. K. Hartman // Chronology and Evolution of the Mars. – 2001. – No 96. – P. 55–86.
26. Rosing M. T. Search for traces of the late heavy bombardment on Earth- results from high precision chromium isotopes / M. T. Rosing, R. Frei // Earth and Planetary Letters. – 2005. – No 236. – P. 28–40.
27. Ryder G. Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the Inner Solar System / G. Ryder D. Stoffer // Space Science Reviews. – 2001. – No 96. – P. 5–54.
28. Ryder G. Lunar samples, lunar accretion and the early bombardment of the Moon / G. Ryder // Eos. – 1990. – No 71(10). – P. 313–323.
29. Ryder G. Origin of the Earth and Moon, Heavy Bombardment of the Earth at 3,85 Ga: The Search for Petrographic and Geochemical Evidence / G. Ryder, C. Koeberl, S. J. Mojzsis // University of Arizona Press, Tuscon, 2000.
30. Tungsten isotope evidence from 3,8-gyr metamorphosed sediments for early meteorite bombardment of the Earth / R. Schoenberg, B. S. Kamber, K. D. Collerson, S. Moorbath // Nature. – 2002. – No 418. – P. 403–405.
31. The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary / P. Shulte, L. Alegret, I. Arenillas, J. A. Arz, et al. // Science. – 2010. – No 327. – P. 1214–1218.
32. Distribution of siderophile and other trace elements in melt rock at the Chicxulub impact structure / B. C. Schuraytz, D. J. Lindstrom, R. R. Martinez, V. L. Marin // The Twenty-Fifth Lunar and Planetary Science Conference, 1994. – No 25. – P. 1221–1222.
33. Simonson B. M. Spherule event horizons: The other (and better?) record of impact in early Earth history / B. M. Simonson S. W. Hassler. – In Impacts and the origin, evolution, and extinction of life, pages 53-56. Department of Earth and Space Sciences and University of California, Los Angeles, 2002.
34. Telecka M. Empiryczne dowody wielkiego bombardowania (LHB) na Księżycu na podstawie danych zaczerpniętych z „Geological Atlas of the Moon" Annales UMCS sectio B (print)
35. Wetherill G. W. Late heavy bombardment of the Moon and terrestrial planets / G. W. Wetherill // Proceeding of the 6-th Lunar and Planetary Science Conference, 1975. – P. 1539–1561.
36. Zahnle K. Before uniformitarianism: Impacts in the Hadean / K. Zahnle. In Impacts and the origin, evolution, and extinction of life, page 66. Department of Earth and Space Sciences and University of California, Los Angeles, 2002.
37. Asteroid showers on Earth after family breakup events / V. Zappala, A. Cellino, B. J. Gladman, S. Manley, F. Miglioroni // Icarus. – 1998. – No 134. – P. 176–179.

Аннотация. *М. Телеска* ***Земная Поздняя Тяжелая Бомбардировка (ЗПТБ) – доказательства и вопросы.*** *Около 3,8 миллиардов лет назад произошла величайшая метеоритная бомбардировка в истории тел солнечной системы. Отпечатки этого события до сих пор разборчиво видны на лунной поверхности, но мы можем найти его также на Марсе, Венере или Меркурии. Проблема заключается в том, чтобы найти следы этой катастрофы на Земле. Тектонические плиты, метаморфизм и эрозия стерли с лица Земли признаки метеоритов. В этой статье я попытаюсь представить самые последние данные об этом событии на поверхности Земли.*
Ключевые слова: *Земная Поздняя Тяжелая Бомбардировка, ЗПТБ, столкновение с метеоритом, начало Земли*

Анотація. *М. Телеска* ***Земне пізнє важке бомбардування (ЗПТБ) – докази і питання.*** *Близько 3,8 мільярдів років тому сталося найбільше метеоритне бомбардування в історії тіл сонячної системи . Відбитки цієї події досі розбірливо видно на місячній поверхні , але ми можемо знайти його також на Марсі , Венері або Меркурії. Проблема полягає в тому , щоб знайти сліди цієї катастрофи на Землі. Тектонічні плити , метаморфізм і ерозія стерли з лиця Землі ознаки метеоритів. У цій статті я спробую уявити самі останні дані про цю подію на поверхні Землі.*
Ключові слова: *Земне пізнє важке бомбардування, ЗПТБ, зіткнення з метеоритом, початок Землі*

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