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Estimates of the impact frequency of cosmic bodies on the Earth*

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Abstract. A new method of estimating the impact frequency of celestial bodies on the Earth, with corrections for the rate of crater erosion is proposed. This method is based on the content of the Expert Database on the Earth's impact structures (EDEIS) that has been developed and is being maintained in the Tsunami Laboratory of the ICMMG SB RAS. The EDEIS contains both fully proven and justified craters and structures whose impact origin is still needed to be confirmed. To take into account the crater erosion on the Earth's surface, the balance equation is used. The crater size–frequency distribution contains a single empirical constant and is applied to the range of crater diameters varying from 0.025 to 200 km. The results show a good agreement with the estimates of impact frequencies obtained by other authors. The dependence of impact frequency on the kinetic energy, the diameter of the crater and projectile diameter has been established.

1. Introduction

At present, on the Earth's surface there are many dangerous technogenic objects like hydroelectric dams, nuclear waste storage, chemical plants, nuclear-power plants and their number continuously grows. Destruction of any such object may result in serious consequences for human society. Since the planned operation time for many of these objects may be up to several hundreds years, the risk of damage resulted from a meteorite impact should be taken into account. To evaluate the risk of a damaging event for these facilities associated with cosmic impacts, we need to know the overall frequency of such an event in the recent geological history. Especially important is to know realistic estimates of the impact frequency for projectiles of 10–25 m in diameter, because the intervals between such events are comparable to the service life of technogenic objects [1].

There is a considerable number of the works already published that deal with the problem of estimating the asteroid-comet hazards [3, 9, 14, 20, 28, 29, 31, 35, 36]. It should be noted that these estimates are of an approximate probabilistic sense and may differ from each other. This is primarily due to differences in the approaches used: when using the "crater" methods, the erosion processes of impact structures and incomplete data on the number of craters on some territories are of critical importance. As for the astronomical

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methods, difficulties are associated with the completeness of observations of small-diameter asteroids (50–250 m). In spite of all the efforts applied during the last decade for the identification and tracing of potentially hazardous asteroids (NEO-asteroids), this task is still far from being completed. Also, it is important to estimate the rate of falling celestial bodies, depending on the physical properties of asteroids. However, comparing the estimates of impact frequencies obtained with the help of different approaches, it is possible to conclude that the crater formation rate is kept on almost a constant level during the last 3.5 billion years [7].

2. Review of methods used for estimating the impact frequency

The existing approaches to estimating the impact frequency from the projectile diameter d can be divided into the following types:

1. Astronomical approach currently giving a fairly accurate assess of the impact frequency of large asteroids ($d > 1000$ m) [8, 23, 30, 37].
2. Planetological approach, allowing the estimation of the impact frequency of large asteroids ($d > 300$–400 m), whose final collision speed is practically unaffected by the Earth's atmosphere. The data on the age and size of meteorite craters on the terrestrial planets and the Moon are used, and the difference in acceleration due to gravity on the surface of planets as compared to the Earth is taken into account [20, 23, 31].
3. Space observations of the Earth's atmosphere, currently allowing obtaining the most precise estimations of the impact frequency of small asteroids and meteoroids ($d < 10$ m). This method is based on processing the observations of the Earth's atmosphere from special satellites (Fireball Network) [16, 17, 27].
4. Historical approach, based on geological-geophysical data on the Earth's impact structures (diameter, age and spatial distribution), which are collected in special catalogs of impact structures ($d > 20$–40 m) [11, 14, 31, 36]. To estimate the impact frequency of small bodies ($d < 10$–20 m), the data from meteoritic catalogs are used [5].

An advantage of the latter approach over the others is that the impact craters and meteorites identified on the Earth surface are the direct evidence of collisions of our planet with celestial bodies occurred in the past. The complexity of this approach is associated with intensive processes of craters erosion on the Earth's surface which, on the one hand, complicate the craters detection and on the other hand, are forming structures similar to some of the diagnostic features with impact craters.

To estimate the impact frequency of cosmic bodies that represent the greatest threat to the life on the Earth, the number of impact craters within the intervals on their main characteristics, i.e., diameter and age of formation, is calculated. The volume of data on meteorite craters is associated with the geological knowledge about the Earth's surface, therefore until the 1970s, the above approach, based on the number of confirmed craters in estimating the impact frequency was not used. As a degree of refinement in the geological study of the Earth's surface increases as well, the number of known impact structures increases, first of all, in the most studied and geologically stable parts of the Earth's surface. Thus, the first works were based on meteorite craters located in the most developed regions of the world: Canada, the USA, Australia, and Europe. Among them one should mention the paper published in 1977 by E.M. Shoemaker [34], devoted to the problem estimating the fluxes of sufficiently large cosmic bodies capable of producing sizable impact craters on the Earth. Two alternative approaches to this problem are considered: the astronomical search for potential crater-forming projectiles, and the study of geological records of impact craters. Based on astronomical observations, the estimates of the crater formation rate for craters of more than 10 km in diameter have been obtained: $(0.7 \pm 0.35) \cdot 10^{-14}$ km^{-2}yr^{-1} ([34, Table 2]). From the analysis of the data for the four proven structures younger than 500 million years, located within the Mississippi River basin (area of on $7 \cdot 10^5$ km^2): $(2.2 \pm 1.1) \cdot 10^{-14}$ km^{-2}yr^{-1}, or one crater of 10 km in diameter on the whole Earth's surface during 90 thousand years. Finally, as the most realistic the estimate of $(1.2 \pm 0.6) \cdot 10^{-14}$ km^{-2}yr^{-1} was adopted.

In 1979, the estimate of the crater-forming rate on the basis of a larger number of structures was obtained by R.A. Grieve and M.R. Dence [13]. They have considered 15 craters about 20 km in diameter and aged up to 600 million years on crystal shields — Canadian, Ukrainian, and Scandinavian: $(3.5 \pm 1.3) \cdot 10^{-15}$ km^{-2}yr^{-1}.

The second important work belongs to E.M. Shoemaker in 1983 [35]. In it, physical characteristics of NEA bodies, that were derived from astronomical observations, are discussed in comparison with theoretical models of the impact craters formation, geological-geophysical characteristics of known impact structures on the Earth and observations of the lunar craters for calculating the impact frequency estimates depending on the kinetic energy of a projectile and geological time. By the methods of similarity, it has been determined, that for the formation of a 10-km continental crater an asteroid of 0.63 km in diameter is needed. Based on different approaches, the dependence of "*estimated cumulative frequency distribution of kinetic energy of bodies colliding with the Earth*" was obtained, which formed the basis for further research.

The new approaches to the problem of studying of the impact crater formation laws were developed in 1994 by R.A.F. Grieve and E.M. Shoemaker [14]. Based on the data for 140 impact craters, a logarithmic dependence of the impact frequency N_c on the diameter $D > 1$ km for known terrestrial craters was constructed. For the structures of less than 20 km in diameter, the estimate is defined as $N_c \propto D^{-1.8}$. The estimate of the crater-forming rate for craters about 20 km in diameter and of the age < 120 Ma is $(5.6 \pm 2.8) \cdot 10^{-15}$ km^{-2}yr^{-1}.

In the papers published in 1999 and 2000, D.W. Hughes [18, 19] obtained estimates of the crater formation rate in the last 125 ± 20 million years in a greater range of diameters: $2.4 < D < 35$ km.

One of the most important papers was published in 2002 by B.A. Ivanov, G. Neukum, W.F. Bottke, and W.K. Hartmann [20]. In this paper, well-investigated size-frequency distributions (SFD) for the lunar craters, based on the construction of a production function (Neukum Production Function — NPF), are employed using the similarity laws for the SFD for the terrestrial planets. The results obtained reveal that over the past ~ 4 billion years the form of the production function for the Moon within the accuracy of observations for craters of < 300 km in diameter has not changed.

A new approach to the problem was proposed by P.A. Bland and N.A. Artemieva in 2006, in which the results of other authors were compared [3]. In this paper, the effect of the atmosphere on the rate of collisions of cosmic bodies with the Earth's surface is theoretically investigated. The model takes into account deceleration, ablation and fragmentation by the motion of celestial bodies in the densest layers of the atmosphere. The behavior of iron and stone bodies in the range of masses 1–10^{12} kg (the size d from 6 cm up to 1 km) is considered. A significant effect of the atmosphere on the speed of cosmic bodies and the crater size for the cosmic bodies of diameter $d < 50$ m is detected. To test the adequacy of the model for a small-size projectile ($d < 10$ m), the Fireball Network data were used. The obtained dependence of the mass-frequency distributions or the crater size-frequency distributions is well consistent with the cosmic observations and with the published results of other researchers using planetological, astronomical and historical approaches.

The published works, based on the historical approach, are focused on finding the diameter–age dependence and estimates of a possible number of impact structures on the Earth's surface. Simple empirical dependencies of the distribution of craters by diameter based on the analysis of 116 craters were obtained in 1979 by A.I. Dabija, I.T. Zotkin, V.V. Fedynsky [11]. In this work, it was shown that the most probable distribution of craters by the diameter and age satisfies the condition

$$0.1 \le \frac{\sqrt{T}}{D} \le 10,$$

where T is the relaxation time (years), D is the diameter of crater (m). This means that namely in this range it is most probable to find a crater of a given diameter and age.

In the paper by A. Walter and E.P. Gurov published in 1979, a rapid growth in the number of newly discovered impact craters since 1960 is marked [39]. For craters of diameters $D > 1$ km, the assessment of the number of still undiscovered structures of the Phanerozoic age ($\sim$ 542 Ma), using the data in geologically stable regions of the Earth, is given. The assessment of the density of craters per 1 km^2 for the structures of the Baltic Shield ($7 \cdot 10^{-6}$), the North American platform ($6.7 \cdot 10^{-6}$) and the place Canadian Shield ($5 \cdot 10^{-6}$) gives the estimate of the number of such structures on the whole Earth as, approximately, 2,500–3,500.

In some papers an attempt to count the number of preserved impact structures of the Earth with allowance for differences in the intensity of erosion on its different parts is made. For example, in [25], where the rate of destruction of craters is determined by the intensity of erosion (m/year), a possible number of structures of diameters exceeding 1 km could amount around 2,000.

The estimate of the number of undiscovered craters younger than of 500 million years, obtained with the use of statistical criteria and data on probable structures from Catalog by D. Rajmon [33], is given by S.A. Stewart in 2011 [36]. The number of undetected craters with diameters exceeding 1 km on the whole Earth's surface can be from 322 to 1,490, the most probable number being 714). At present, we know of more than 700 probable structures, whose data are contained in special catalogs [26, 33, 24], including those in Russia, for example, in Moscow [6] and Nizhny Novgorod [22].

The above-said allows us to use data about probable structures, whose impact origin has not been fully proved yet, when calculating the assessment of the impact frequency. Thus, the volume of data used in the analysis can be considerably increased [36]. Since the information about the structures was obtained from various sources, these data should be verified. It should be noted that such a verification is needed not only for probable but for some proven impact structures as well. For example, in [21], some conclusive facts are given, which make doubtful the previously published estimates of the age of the proven impact crater Zhamanshin — 10–12 thousand years instead of 1 million years, as was widely recognized before.

3. The database on the Earth's impact structures

In further analysis of the available geological and geophysical information on the reliability and characteristics of impact structures and for obtaining estimates of the impact frequency on the Earth, we use the Expert Database on the Earth Impact Structures (EDEIS) that was compiled on the basis of the MS Access and is being maintained by the Tsunami Laboratory of the ICMMG SB RAS in Novosibirsk [2, 32]. In addition to the completely confirmed impact structures, the EDEIS also contains the data on probable structures, whose impact genesis still needs verification.

This database is provided with a specialized graphic shell PDM / IMP (Parametric Data Manager), which is running in the Windows Operating System and provides a convenient user interface for data retrieval, sorting, visualization and processing [15]. The full version of the database, along with a supporting graphic shell has the volume of 500 Mb.

The web-version of the database is available at http://tsun.sscc.ru/nh/impact.php. It includes 14 data fields: country or region, the name of a structure, latitude, longitude, diameter, age, index of validity, the type of a structure, the depth of the true crater floor, the number of structures in the crater field, the degree of erosion, the view on the Earth's surface, the view from space, the target rocks. The resource allows selecting data from the first 7 fields and sorting the data on any field.

The current version of the EDEIS includes parametric data on 1,117 structures. For each structure, the validity of impact origin is reflected in the index V, which varies from 4 (confirmed) to 0 (rejected) with intermediate values: 3 (probable), 2 (possible) and 1 (proposed for further

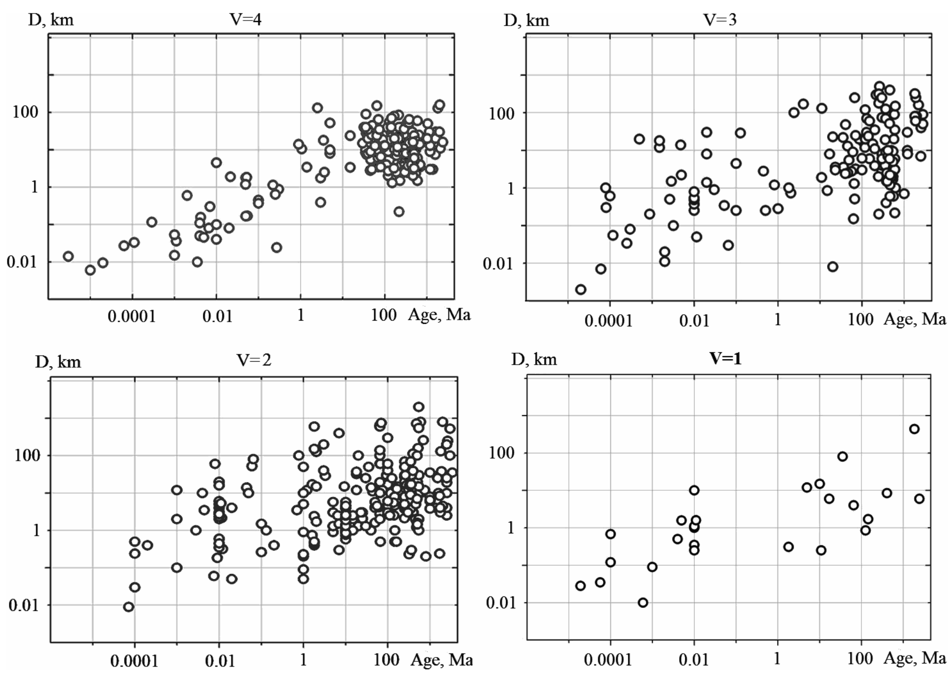

Figure 1. Distribution of the terrestrial impact structures according to the age and diameter with the validity indices at $V = 1$–4. The EDEIS data [24]

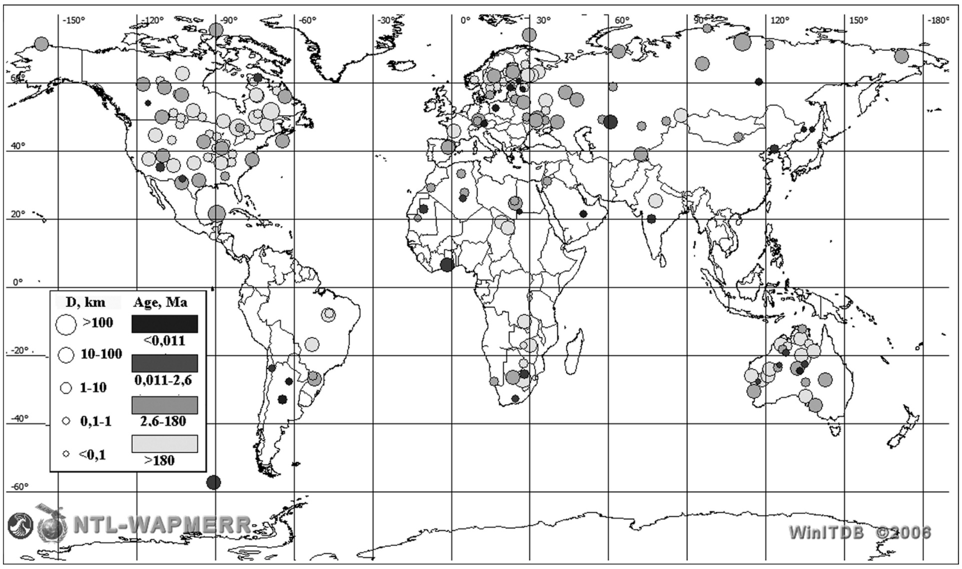

Figure 2. Geographical distribution of 200 confirmed impact structures on the Earth's surface ($V = 4$) having the age and diameter estimates. The size of circles is proportional to the crater diameters. The EDEIS data [24]

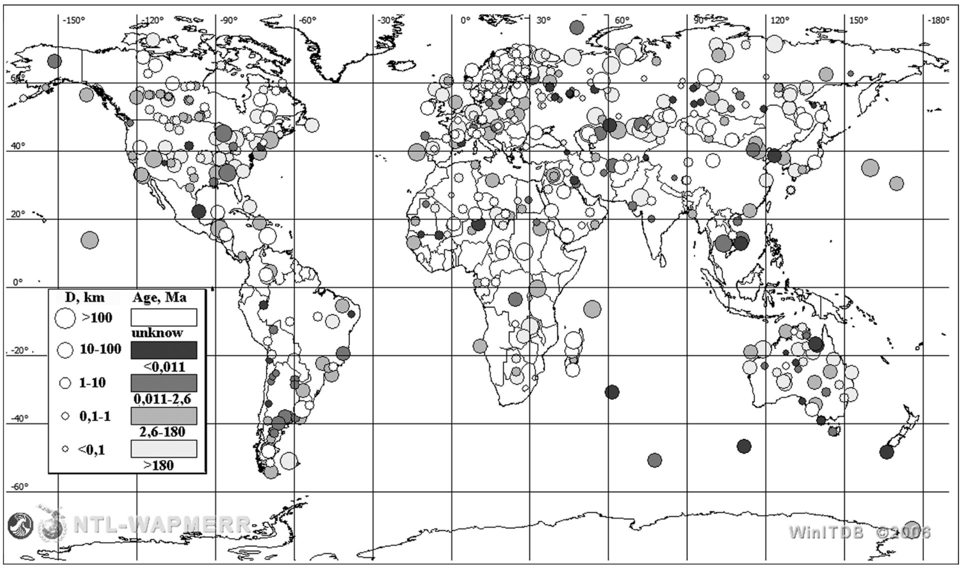

Figure 3. Geographical distribution of 685 probable impact structures on the Earth's surface ($V = 2$, 3) with known coordinates, of which 396 have estimates of the age and diameter. The size of circles is proportional to the crater diameters. The EDEIS data [24]

study). The classification of structures is based on expert assessments and reflects the presence of impact criteria at four different levels — morphological, structural-geological, petrographic, microstructural. In addition to the parametric information, the database contains over 3,600 photographs, maps and diagrams, 956 text descriptions and 1,512 references.

The number of structures in the database with the index V is as follows: 212 ($V = 4$), 187 ($V = 3$), 501 ($V = 2$) and 98 ($V = 1$), that is, 998 altogether. Their distribution according to the age and diameter is shown in Figure 1, which shows that the most "filled" is the area with the age > 10 million years old and $D > 1$ km. The number of craters of a smaller diameter is much less, in particular, due to erosion. Due to insufficient knowledge about the structures with $V = 1$, only structures with the index $V = 4, 3, 2$ will be used for further calculations.

Figures 2, 3 show the location of impact craters according to the EDEIS data on the geographical maps, which show that the observed structures are mainly located on the area of Eurasia, North and South America, Africa and Australia, constituting about 25 % of the total surface area of the Earth.

4. Methods of calculating the impact frequency

The impact structures detected on the Earth's surface are the most reliable evidence of comet and asteroid collisions with the Earth. However, their number is essentially less than the total number of impact strikes. This is due to an insufficient study of some territories and effects of crater erosion as well as tectonic and geological processes occurring on the surface of the Earth. In order to define more precisely the impact frequency of bolides associated with the intensity of craters erosion, consider the balance equation for the observed rate of formation of craters with a diameter D [7]:

$$\frac{dN(D)}{dt} = N_1(D) - \frac{N(D)}{t_1(D)}, \tag{1}$$

where $N(D)$ is the number of observed craters, $N_1(D)$ is the impact frequency (yr^{-1}), $\frac{N(D)}{t_1(D)}$ is the intensity of craters erosion on the Earth's surface (yr^{-1}), $t_1(D)$ is the mean relaxation time of a crater (yr). Let us consider equation (1) in the intervals $D_L \le D \le D_R$, for the case when $D = \text{const}$. Then its solution can be written down as

$$N(t) = N_1 t_1 (1 - \exp(-t/t_1)).$$

To illustrate the resulting dependence of the number of the discovered craters on time, let us present the data from the EDEIS Catalog in terms of the cumulative number of structures ($N > t$) for the range of $D = 0.8$–1.6 km ($E = 5$–50 Mt TNT). In Figure 4, points represent the cumulative number

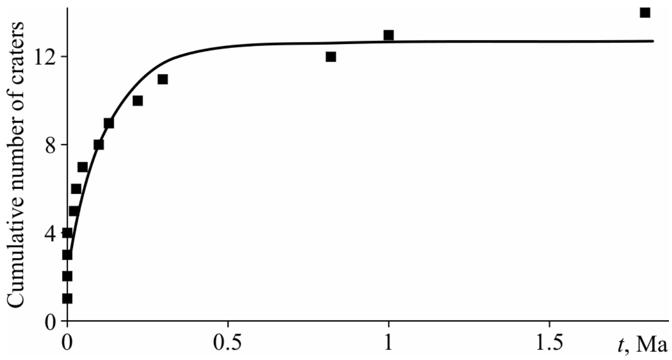

Figure 4. The dependency of cumulative number of impact structures of diameter $D = 0.8$–1.6 km on the age. The EDEIS data [24]

of the identified structures depending on the age and their approximating function $N(t) = -9.859\exp(-t/0.127) + 12.68$.

The characteristic relaxation time of the crater t_1 (yr) is evaluated by its diameter D (m): $t_1 \approx D^2$ [11]. To take into account the incompleteness of the information available on the impact structures of the Earth, we introduce a coefficient K_N, which is defined as the ratio of the whole area of the Earth's surface to the surface area, on which craters are detected (without allowance for the surface area of the oceans and seas, offshore areas, mountains, the Arctic and the Antarctic [39], see Figure 2). As a result we obtain $N_1 = K_N N/(D^2(1-\exp(-t/t_1)))$, where $t = t_{\max}$ is a maximum age of the craters in the database within the range of diameters selected. Analysis of the data shows that $t_{\max} > t_1$ for the crater of $D \le 20$ km in diameter and $1 - \exp(-t/t_1) \approx 1$. Therefore, to estimate the impact frequency, we will consider the ratio in the form $N_1 = K_N N D^{-2}$, where N_1 (yr^{-1}), D (m) is the diameter of the crater in the selected range, and extend it to diameters $D > 20$ km.

The number of craters of the Phanerozoic age of $D > 1$ in diameter in the database when $V = 2$–4 is 412. We will use the empirical value $K_N = 6.35$. In this case, the number of impact structures on the whole Earth is $K_N \times 412 = 2616$, which is consistent with the results from [39], based on the density of craters on the platform areas. Thus, in the calculations for all ranges of diameters we will use the ratio

$$N_1 = 6.35 N D^{-2}. \tag{2}$$

Consider the dependence of the impact frequency on the diameter of a crater for different values of V: $V = 4$, $V = 3$–4, $V = 2$–4. The results are demonstrated in Figure 5, which shows that, with increasing the number of structures, the curve becomes smoother and the impact frequency N_1

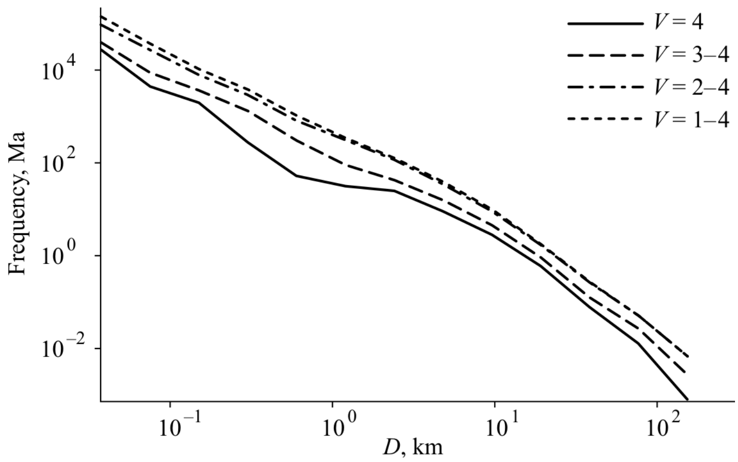

Figure 5. Crater size-impact frequency distribution with an increase of the number of structures depending on the validity index V

increases. Thus, when $D = 1.2$ km, N_1 increases by an order: $N_1 = 30$ at $V = 4$ and $N_1 = 300$ at $V = 2$–4.

Destructiveness of catastrophic cosmic impacts is characterized by the released energy value. Depending on this, the scales of disasters are divided into local, regional and global (Table 1).

Table 1. The spatial scale of natural disasters, depending on the kinetic energy of a cosmic body [29]

Event type	Energy (Mt TNT)
High atmosphere break-up	< 10
Tunguska-like events	10^2–10^3
Sub-global lands impacts	2×10^3–5×10^5
Sub-global ocean impacts	2×10^3–5×10^5
Threshold global catastrophe	10^5–10^6
Mass extinction events	$> 10^7$

For the calculation of the kinetic energy of projectiles, colliding with the Earth's surface, we use the empirical formula, which was proposed by E.M. Shoemaker [35]:

$$E = K\rho_E D^{3.4}, \tag{3}$$

where E is the kinetic energy of a projectile before the collision in kt TNT (1 kt TNT $= 4.184 \cdot 10^{12}$ J), D is the diameter of the observed crater in kilometers, ρ_E is the density of a target substance (rocks of the Earth) in kg/m^3. The proportionality coefficient K is calculated from the ratio: $K = \left(\frac{c_f}{D_0}\right)^{3.4}\frac{1}{\rho_0}$, where ρ_0 is the density of rocks on the site of nuclear tests in Nevada ($\rho_0 = 1800$ kg/m^3), $c_f = 1$ for craters below 4 km in diameter and $c_f = 0.77$ for the craters exceeding 4 km in diameter (the coefficient that determines the ratio of the diameter of the initial (transition) crater to the observed crater), $D_0 = 0.074$ km/(kt TNT)$^{1/3.4}$ is an empirical constant. The result is a value of the coefficient K of the dimension (m^3/kg) (kt TNT) km$^{-3.4}$: $K = 3.8845$ for $D < 4$ and $K = 1.5974$ for $D \geq 4$. Let $\rho_E = 2600$ kg/m^3 in (3).

To determine the dependence of the estimated impact frequencies of cosmic bodies on the diameter of a crater, the database EDEIS [24] was used. We carry out the selection of impact structures with the validity index $V = 2$–4 (proven and probable, 900 altogether). The resulting data are divided in such a way that the range of variations of the kinetic energy (in Mt TNT) of events E_i of each sample varied within the same order of magnitude: $E_L < E_i < E_R$, where $E_L = 10E_R$. Since $E \sim D^{3.4}$, according to (3) we obtain appropriate intervals for the crater of $D_R = 1.97D_L \approx 2D_L$ in diameter. We will consider the values of D in the range from 0.025 to 200 km.

In addition, the projectile diameter d (m) can be determined from the equation $E = \pi d^3 \rho v^2/(12 \cdot 4.184 \cdot 10^{12})$ given values of the density ρ (kg/m^3), the speed of falling v (m/s^2) and the kinetic energy E with allowance for the trotyl equivalent value (kt TNT). Let the density of the projectile $\rho = 3500$ kg/m^3 (a stone meteorite) and the speed of falling be varying depending

Table 2. Projectile sizes and kinetic energy-impact frequency (a stone meteorite). Data are divided according to the scales of catastrophic events (see Table 1)

Crater diameter D (km)	Approx. projectile diameter d (m)	Energy E (Mt TNT)	Impact frequency (# per yr × 10^6, whole Earth)	Mean impact interval (yr, whole Earth)	Expected velocity of impact (km/s)	Number of craters (EDEIS)
0.025–0.05	5	1.4E−4	95,000	10	2	21
0.05–0.1	8	1.5E−3	27,000	37	4	24
0.1–0.2	13	1.6E−2	7,900	130	6	28
0.2–0.4	23	1.7E−1	3,000	340	8	42
0.4–0.8	43	1.8E+0	810	1.2E+3	10	46
0.8–1.6	84	1.9E+1	300	3.3E+3	12	69
1.6–3.2	170	2.0E+2	120	8.5E+3	14	107
3.2–6.4	250	8.6E+2	35	2.8E+4	16	128
6.4–12.8	500	9.1E+3	9.4	1.1E+5	18	136
12.8–25.6	1,100	9.6E+4	1.7	5.8E+5	18	101
25.6–51.2	2,400	1.0E+6	0.26	3.8E+6	18	61
51.2–102.4	5,300	1.1E+7	0.05	2.0E+7	18	47
102.4–204.8	12,000	1.1E+8	0.007	1.4E+8	18	26

on the impact energy E (kt TNT) from $v_{\min} = 2$ km/s^2 at $E \sim 10^{-4}$ to $v_{\max} = 18$ km/s^2 at $E > 10^3$ with a step $v = 2$ km/s^2 with increasing E by an order of magnitude, since for small values of the energy of a projectile the effect of braking in the atmosphere is significant [3].

The calculation results are presented in Table 2. The following values and formulas have been used: mean value of D in the interval, frequency distributions from (2), crater-forming energy (3), spherical projectiles with $V = \pi d^3/6$, crater-forming energy = projectile kinetic energy = $mv^2/2$. Atmospheric effects on small projectiles have been neglected (in real impacts, projectiles of $d < 50$ m are probably destroyed in the atmosphere).

5. Analysis of results

According to Table 2, we can estimate a potential scale of impact events, depending on the projectile diameter d, and its kinetic energy E.

1. Fall of bolides ($d < 50$ m, $E < 5$ Mt TNT). The atmosphere provides partial protection. An intensive explosion in the upper atmosphere, no damage.
2. The Tunguska-type explosion ($d \sim 50$–250 m, $E \sim 50$–10^3 Mt TNT). Damage can result in destroying a city. The average frequency for the whole Earth: from 2 to 30 thousand years. Small relative risks of other natural disasters (earthquakes, etc.).
3. A regional-scale disaster ($d \sim 250$–500 m, $E \sim 10^4$ Mt TNT). Can destroy an area equivalent to a small country. Fall without braking in the atmosphere. Possible global effects (fires, earthquakes, tsunamis). The average frequency for the whole Earth is 110 thousand years.
4. A global catastrophe ($d \sim 500$–2500 m, $E \sim 10^5$–10^6 Mt TNT). Global environmental damage that threatens civilization. The average interval for the whole Earth is 0.5–4 Ma.
5. Mass extinction events ($d > 5000$ m, $E > 10^7$ Mt TNT). Interval > 20 Ma.

We will compare the results with those obtained by other authors as related to the estimated impact frequencies. The Web site [38] of the Lunar and Planetary Institute, Houston, Texas presents the table "*Terrestrial meteorite impact craters: Crater sizes, projectile sizes, frequencies, and comparable terrestrial events*" [14, 31] with data for the craters of 35 m up to 200 km in diameter and, also, the values of impact energy and the interval between events. The paper by P.A. Bland, N.A. Artemieva [3] contains the table "*Estimates for the impact rate at the Earth's surface, taking our best-fit to the upper atmosphere data set and scaling it based on the results of SF and pancake modeling*" including the projectile mass m (kg), the diameter

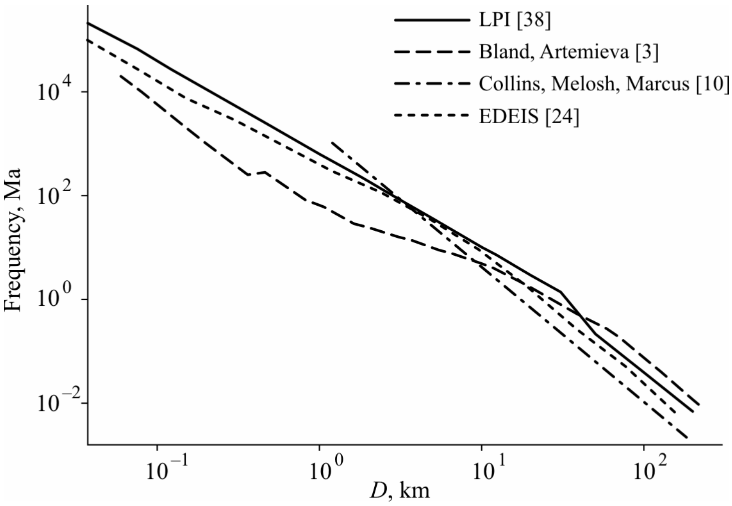

Figure 6. Estimates of crater size-frequency distribution of asteroid strikes

of the crater D (km), the frequency of impacts $N > m$ (yr) and the interval $1/N$ [3]. Let us also mention the table "*Comparison of environmental effects 200 km away from various impacts*" with data for 3 types of craters with a diameter of 1.2 km (simple), 23.7 km (complex), and 186 km (complex) given in the paper by G.S. Collins, H.J. Melosh, and R.A. Marcus [10].

Figure 6 compares the calculated data from Table 2 with the results obtained in [3, 10, 38]. For craters of $D > 10$ km in diameter, a close correspondence with all the data is observed and, in the whole range of diameters obtained, the best fit to LPI data is obtained [38]. Table 3 represents a comparison of impact frequencies per year on the example of the crater with diameter $D = 1.2$ km using the data from [3, 10, 38].

Table 3. Comparison of impact frequencies (one per year) for the crater of $D = 1.2$ km

Data source	Impact interval (yr)
EDEIS [24]	3300
LPI [38]	2300
Bland, Artemieva [3]	4200
Collins, Melosh, Marcus [10]	1000

Conclusion

The methods of estimating the impact frequencies proposed in this paper using the crater-chronology of the Earth, take into consideration the process of erosion of craters in terms of time and incomplete information about the impact structures. The inclusion into the analysis not only of the proven but also of the probable structures, whose impact origin is just suspected and still needs the confirmation, considerable increases the amount of data available for analysis. The estimates of the frequency of the impact events obtained in this paper are in good agreement with the earlier published works within the whole range of the craters of 0.025–200 km in diameters.

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