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The approximate ratios between the diameters of terrestrial impact craters and the causative incident asteroids

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ABSTRACT

When a large asteroid of diameter d hits the surface of the Earth, it produces a crater of diameter D. This paper uses the near-Earth asteroid (NEA) size and miss-distance statistics to calculate the rate at which asteroids hit the Earth. Comparison of this with the known rate at which craters have been produced on the Earth's surface indicates that $E = 9.1 \times 10^{24} D^{2.59}$ erg, where E is the kinetic energy of the incident NEA, and D is the diameter of the resulting crater, in km. So the ratio D/d varies from about 8 for the small 0.88-km 'Wolfe Creek type' craters, up to about 16 for craters like Chicxulub, which has a diameter of about 200 km.

Key words: Earth – minor planets, asteroids.

1 INTRODUCTION

The planetary surface cratering process is governed by only three equations. These are often assumed to be power laws over the rather restricted parameter ranges being considered.

(i) The impactors that produce large craters on a planetary surface have a power-law size distribution. The majority of these impactors are thought to be asteroids, as opposed to comets (see for example Bailey 1991; Kresák 1978a,b; Hughes 1999). The size distribution of the impactors can be written logarithmically as

$$\log N(d) = C_1 - C_2 \log d, \qquad (1)$$

where $N(d)$ is the number of impactors with diameters greater than d in a specific sample, or, for example, the number of potential impactors that approach to within a certain distance of Earth, within a specific period of time. Detailed observations of large asteroids in the main belt and the large members of well-studied asteroid families (see for example Hughes & Harris 1994; Hughes 1994) indicate that C_2 is very close to 3.0.

(ii) The relationship between the kinetic energy, E, of the impactor and the diameter, D, of the crater that it produces in the surface of a planet is again thought to be a power-law, i.e.

$$E \propto D^{C_4}.$$

If it assumed that most impacting asteroids have reasonably similar densities and reasonably similar impact velocities (assumptions that will be returned to later on), this relationship can be written as

$$3 \log d = C_3 + C_4 \log D, \qquad (2)$$

where C_3 and C_4 are constants. Unfortunately, the value of C_4 has, until now, been uncertain, experimentation in the relevant crater size range ($1.5 < D < 250$ km) and impactor size range ($0.2 < d < 15$ km) clearly being impossible. Hughes (1998) noted that C_4 values of 3.0, 3.18, 3.25, 3.4, 3.57 and 3.89 had all been given in the literature.

(iii) The rate, $\Phi(D)$, at which craters are produced on a planetary surface, and thus the number of craters $N(D)$ on an area of known extent that has been exposed for a known time, is related to the crater diameter D by a power law. This can be written logarithmically as

$$\log N(D) = C_5 - C_6 \log D, \qquad (3)$$

where $N(D)$ is the number of craters with diameters greater than D, and C_5 and C_6 are constants. Many papers from the 1980s, see for example Grieve (1989), concluded that C_6 was close to 2.0. Morrison, Chapman & Slovic (1994) concluded that C_6 was 1.862. Hughes (2002) found that C_6 was 2.59.

By combining equations (1), (2) and (3) it can be seen that the powers in the specific relationships are related by

$$C_6 = C_2 C_4 / 3.$$

It is therefore clear that if two of the powers are known, and the assumptions made above are valid, the third power is automatically determined. We contend in this paper that the power C_2 is known to be close to 3.0, and that the power C_6 is known to be close to 2.59. So the least well-known power, C_4, is also around 2.59 and not in the 3.0 to 3.89 range given above.

Two data sets are going to be used. The last two decades have seen an ever-increasing realization of the hazard to civilization posed by asteroidal impact. In this context, special efforts have been made to find asteroids that have the potential to hit the Earth. The Spaceguard Survey has searched diligently for near-Earth asteroids. (NEAs, which are defined usually as being objects with orbital perihelion distances less than 1.3 au). The goal of the Survey, set in 1998, was the discovery and orbital cataloguing of as many NEAs as possible, and specifically at least 90 per cent of all the NEAs larger than 1 km

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in diameter, before the year 2008. The individual projects have been extremely successful, and this has led to the publication of meaningful lists of the NEAs that are predicted to get close to the Earth during a specific 1-year period. We are going to use the list for the year 2002. The 10-year deadline is in keeping with the orbital period distribution of NEAs. These have a median period of about 2.2 yr, 64 per cent of the NEAs having periods lying between 1.1 and 3.4 yr, and 95 per cent between about 0.7 and 4.3 yr. [These values have been obtained by analysing the Aten and Apollo asteroid data given by Morrison (1992).]

The second data set contains the age, size and position of known impact craters on the surface of the Earth. We now have a very reasonable estimate of both the rate at which large craters (typically diameter $D > 20$ km) are being produced, and the size distribution of these large craters.

These two data sets will lead us to a relationship between the size of the impactor and the size of the crater that it produces.

2 THE SIZE DISTRIBUTION OF NEAs

The list of NEAs that were predicted, at the time of writing the paper, to pass close to the Earth during the year 2002 were taken from the Close Approaches Table on the web site http://www.nearearthobjects.co.uk (see also the original site http://cfa-www.harvard.edu/iau/lists/CloseAppLong.html produced by the Minor Planet Center). Notice that this list does not contain those NEAs discovered *during* 2002 that happened to pass close by.

'Close' is defined here as being within 0.20 au (i.e. 2.99×10^{10} m or 77.8 LD, where LD is the average Earth–Moon distance, this being $3.844\,01 \times 10^{8}$ m). This list contains 62 asteroids in total, and the names, sizes and miss-distances of these asteroids are given in Table 1. Notice that comets are excluded from the calculations made in this paper. They are thought to pose a much smaller threat than asteroids. Hughes (1998) concluded that the craters in the size range being discussed in this paper ($1.5 < D < 250$ km) are 250 times more likely to be produced by an asteroidal as opposed to a cometary impact. Kresák (1978a,b) estimated that there were about 46 more impacting asteroids than impacting comets in this size range, and Shoemaker et al. (1979) stated that the cometary impact rate was less than 10 per cent the asteroidal impact rate. The fact that cometary impacts are much rarer than asteroidal impacts can be seen from http://cfa-www.harvard.edu/iau/lists/ClosestComets.html and also Sekanina & Yeomans (1984).

The size distribution of the 62 asteroids listed in Table 1 is shown in Fig. 1. This is a logarithmic plot of the cumulative number, N, as a function of diameter, d. Here N is the number of known asteroids larger than d. It has been suggested in the past (see, for example, Zappalà et al. 1984; Chapman et al. 1989; Hughes 1994; Hughes & Harris 1994) that complete collections of asteroids obey relationships close to

$$\log N = a - 3.0 \log d, \tag{4}$$

where a is a constant, this relationship being produced by continual collisional fragmentation over the lifetime of the solar system. Forcing a relationship with a gradient of −3.0 through the large-diameter data given in Table 1 (i.e. the linear right-hand portion of Fig. 1) gives

$$\log N = (11.15 \pm 0.5) - 3.0 \log d. \tag{5}$$

The data given in Fig. 1 and Table 1 have *not* been used to calculate the actual size distribution of NEAs [this being constant C_2 in equation (1)]. The distribution of the data around the line of gradient 3.0 indicates, however, that 3.0 is a reasonable value for the NEA size distribution. We conclude that there is little indication, in the presently available data, that NEAs have a significantly different size distribution from main belt asteroids.

The actual data in Table 1 break away from a linear logarithmic relationship (equation 5) for diameters less than about 2200 ± 200 m. There is no a priori reason to expect that this diameter of 2200 m is in any way special in the NEA context. Its only significance concerns the present state of the Spaceguard Survey. One possible interpretation of Fig. 1 is that we know all the $d > 2200$ m NEAs that pass within 0.2 au of Earth in 2002 but that our list is incomplete for $d < 2200$ m. Morrison et al. (2003) stressed (writing on 2002 August 6) that the Spaceguard Survey 'has already discovered more than half of the NEAs larger than 1 km diameter'. Increasing the low-diameter limit from 1 km to, say, 1.5 and 2.0 km will quickly change the 'more than half' to 'very nearly all'.

One could conclude, from an extrapolation of equation (5), that the number N of NEAs that pass within 0.2 au of Earth in a typical year is actually given by $N = 1.1$, 9.0, 140, 1100 and 9000 for $d =$ 5000, 2500, 1000, 500 and 250 m, respectively.

It is clear that, with the improvement of NEA search programmes, more and more asteroids will be added to lists such as that given in Table 1. The vast majority of these asteroids will be small. This

Table 1. The 62 asteroids that were both known at the time of writing this paper and then predicted to pass within 0.20 au, 77.8 mean lunar distances (LD), of the Earth during the year 2002.

Name	Diameter (m)	Miss-distance (LD)	Name	Diameter (m)	Miss-distance (LD)
2001 GP2	20	67	2000 BF19	790	54
2000 AG6	50	71	1998 SU27	830	55
2001 FR85	70	46	2000 RV37	940	63
2001 ED18	80	31	2001 EB18	960	13
2000 PH5	190	5	asteroid 2101	990	63
1998 XN17	190	73	1999 TF5	990	62
2001 CQ36	190	57	2001 FZ57	1040	69
2001 XX4	230	29	asteroid 4660	1040	11
1999 JZ10	250	29	1999 LU7	1110	57
1998 OX4	310	57	2001 CC21	1250	71
2001 WK15	360	33	asteroid 3362	1300	58
1998 HT31	390	60	1997 VM4	1310	74
2000 GE2	430	51	2000 BM19	1440	54
2001 VC2	470	61	2000 SL	1440	66
2000 AZ93	470	62	1998 RO1	1570	72
1998 UP1	490	47	1999 OR3	1580	36
2000 EE104	500	49	1989 VA	1600	69
2001 YB5	510	2	2001 SK162	1650	71
1993 HA	510	71	2000 GD2	1730	28
2001 FC58	520	29	1993 OM7	1820	35
2001 HY7	540	41	1998 WT	1920	42
2000 OK8	540	66	1991 VK	2390	28
2001 TE2	590	70	1992 FE	2510	30
asteroid 3361	600	66	2000 ED104	2530	64
2000 WN10	640	74	2001 VG5	2850	48
2001 UU92	650	50	1997 XF11	2870	25
2001 VB76	650	29	1999 KW4	2950	35
1999 LT7	650	54	1999 KV4	3220	71
2001 WT1	680	64	1999 JT6	3310	74
2001 SH276	710	38	2001 TN41	3410	66
1999 GU3	720	32	1999 HF1	7280	69

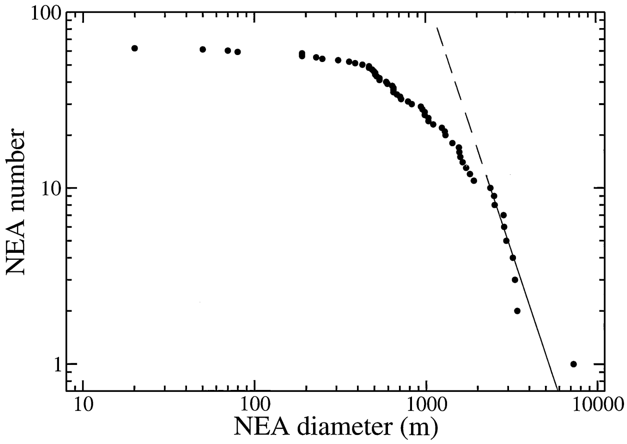

Figure 1. The size distribution of the 62 NEAs that pass within 0.20 au of the Earth during the year 2002. The logarithm of the number of NEAs with diameter greater than d m is plotted as a function of the logarithm of the diameter. The 'complete' data are taken to be represented by the straight line, this line having a gradient of -3.0.

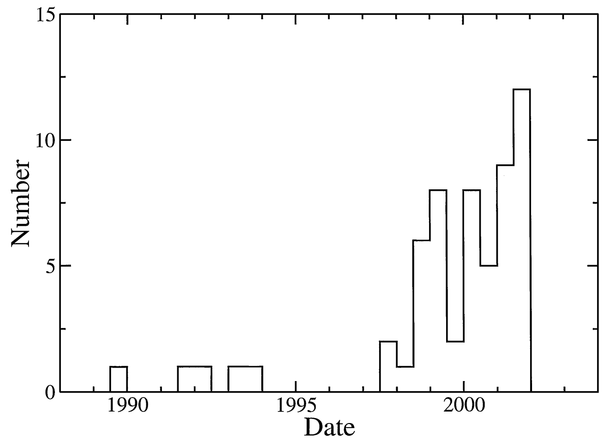

Figure 2. The 62 NEAs that pass within 0.20 au of the Earth during the year 2002 have been sorted according to the year of their discovery, and the number discovered per year is plotted as a function of date.

should lead to a gradual diminution of the 'break away' diameter in Fig. 1, but should not significantly affect the conclusions drawn in this paper from the large-diameter data. [The word 'significantly' is used advisedly. A few large NEAs must still await discovery, the fact that 2002 NT_7 (diameter about 2.4 km) was found in 2002 July underlining the point.]

The asteroids in Table 1 have been sorted according to their date of discovery, and the results are shown in Fig. 2. It can be seen that over half of these asteroids have been discovered in the last 2 years. When it comes to the largest 10, i.e. those used to obtain equation (5), two were discovered in 2001, one in 2000, four in 1999, and one each in 1997, 1992 and 1991. This indicates that the impact analysis being used in the present paper has only been possible in the last year or so.

The ability to detect new NEAs depends on their apparent magnitudes. In converting apparent magnitudes into equivalent diameters (i.e. the diameters of a spherical body with the same surface area) we follow Morrison et al. (2003). They assumed that the NEAs were a 50–50 mix of light and dark asteroids with albedos of 0.20 and 0.05 respectively. Note that, according to Zellner & Bowell (1977), a typical relationship between the asteroidal diameter d(m), its surface geometric albedo p and its absolute magnitude H is

$$\log(0.25d^2p) = 11.642 - 0.4H. \quad (6)$$

Using the 50–50 albedo mixture,

$$\log d(\mathrm{m}) = 6.60 - 0.2H. \quad (7)$$

The knee diameter of 2200 ± 200 m corresponds to an absolute magnitude of 16.3 ± 0.2. We conclude that NEAs fainter than this are being missed all the time.

3 THE MISS-DISTANCE DISTRIBUTION OF NEAs

Let us now investigate the way in which the number of NEAs passing Earth in the year 2002 varies as a function of miss-distance, r. Considering a sphere of radius r, centred on Earth, the expectation is that the number of asteroids, n, that get to within a distance of r is simply proportional to r^2. This expectation is supported by Fig. 3. Here n is plotted as a function of r^2 for the 31 NEAs in Table 1 with $d > 750$ m, and the 31 NEAs with $d < 750$ m. Both graphs show reasonably linear relationships that pass very close to the origin.

Introducing the $n \propto r^2$ relationship to equation (5) gives

$$\log N(\mathrm{yr}^{-1}) = (7.41 \pm 0.5) - 3.00 \log d(\mathrm{m}) + 2.00 \log r(\mathrm{LD}), \quad (8)$$

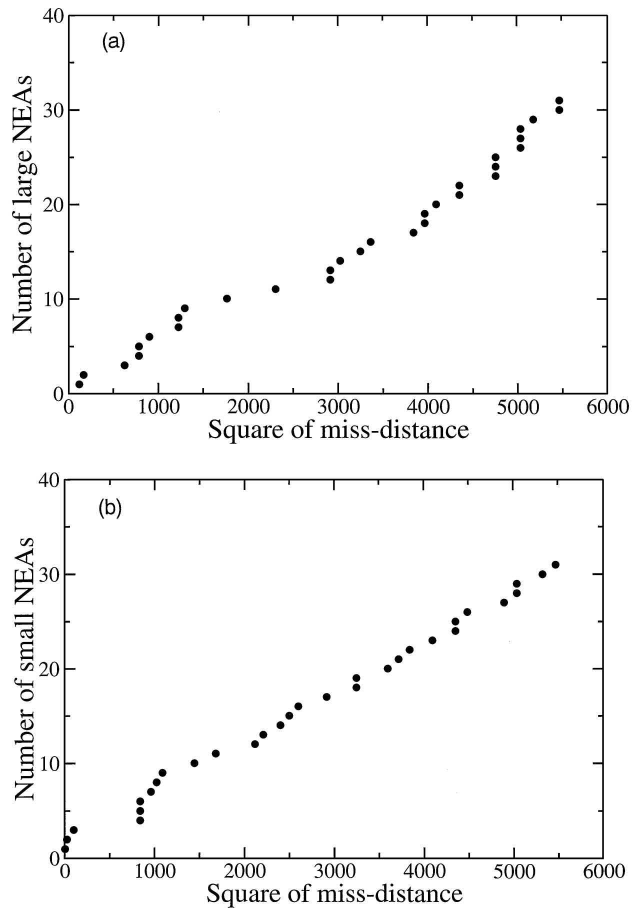

Figure 3. The 62 NEAs have been divided into (a) a large group with diameters $d > 750$ m, and (b) a small group with $d < 750$ m. The graphs show how the numbers n of NEAs that pass the Earth at a miss-distance r vary as a function of the square of the miss-distance. The proportionality between n and r^2 is clear. (The units of the abscissa are square lunar distances.)

an equation that enables us to calculate how many NEAs of diameter greater than d(m) get closer to Earth than r(LD) every year. Now the collision radius of the Earth R_C is given by

$$R_C = R_E\sqrt{\left(1+\frac{v_e^2}{u^2}\right)},$$

where R_E is the actual radius of the Earth (6378×10^3 m), u is the mean intersection velocity between an asteroid and the Earth (20 800 m s^{-1} according to Harris & Hughes 1994) and v_e is the Earth's escape velocity (11 180 m s^{-1}). So

$$R_C = 7240 \times 10^3\ \mathrm{m} = 0.018\,84\ \mathrm{LD}. \qquad (9)$$

Substituting this collision radius into equation (8) gives

$$\log N_E(\mathrm{yr}^{-1}) = (3.96 \pm 0.5) - 3.0 \log d(\mathrm{m}),\ \text{or}$$

$$\log N_E(\mathrm{yr}^{-1}) = -(5.04 \pm 0.5) - 3.0 \log d(\mathrm{km}), \qquad (10)$$

where $N_E(\mathrm{yr}^{-1})$ is the number of NEAs larger than d(km) that actually hit the surface of planet Earth each year. So $N_E = 7.3 \times 10^{-8}$, 5.8×10^{-7}, 9.1×10^{-6}, 7.3×10^{-5} and 5.8×10^{-4} yr^{-1} for $d = 5$, 2.5, 1.0, 0.5 and 0.25 km, respectively.

The use of a mean intersection velocity in equation (9) indicates that gravitational focusing has enhanced the impact frequency by a factor of $(7240/6378)^2$, i.e 1.29. A more rigorous approach to the problem would not use a single velocity but would consider the probability distribution of potential impact velocities for the whole NEA population (see Steel 1998). As the probability distribution is skewed toward the lower velocities, this increases the enhancement factor. Using this technique, Morrison et al. (2003) found that the enhancement factor was 1.66. Assuming that this is the case, the $N_E(\mathrm{yr}^{-1})$ numbers given above should be increased by a factor of 1.29. (The fact that there are two 1.29s is a coincidence.)

4 DISCUSSION

Now let us change perspective completely. In the previous sections we have been looking up, gazing at the heavens hunting for NEAs, and trying to assess how many NEAs will hit the Earth in the near future as a function of NEA diameter and time. Let us now look down and scan the stable ancient continents of our planet for the craters that NEAs have produced in the geologically recent past (i.e. the last 125 ± 20 Myr). Many researchers have tried this. Here we are going to concentrate on recent large craters, and also the size distribution of these craters. Most researchers have concluded that, above a certain size (usually found to be around 20 km), there is a simple power law between the number of craters larger than a specific diameter and the value of the diameter. Hughes (2002) analysed the large craters on Venus, the Moon and the Earth, and concluded that the crater production relationship in the recent past was of the form

$$\log \Phi = C_7 - (2.59 \pm 0.05) \log D(\mathrm{km}), \qquad (11)$$

where Φ is the rate (per year) at which craters larger than diameter D are produced on the whole surface of the Earth. (We ignore here the fact that much of the Earth is covered by water.) Much time has been spent in trying to estimate the value of C_7. Many previous researchers have used the rate of production of $D \geqslant 20$ km craters as a benchmark. Hughes (1981) gave $(2.6 \pm 0.9) \times 10^{-15}$ km^{-2} yr^{-1}, Grieve & Dence (1979) gave $(3.5 \pm 1.3) \times 10^{-15}$ km^{-2} yr^{-1}, Grieve (1984) gave $(5.4 \pm 2.7) \times 10^{-15}$ km^{-2} yr^{-1}, and Grieve & Shoemaker (1994) gave $(5.6 \pm 2.8) \times 10^{-15}$ km^{-2} yr^{-1}. The data in Morrison et al. (1994) yield 14.4×10^{-15} km^{-2} yr^{-1}. In a recent paper Hughes (2000) concluded that the rate was $(3.46 \pm 0.30) \times 10^{-15}$ km^{-2} yr^{-1}. This value (noting that the Earth has a surface area of 5.11×10^8 km^2) can be substituted into equation (11) to give

$$\log \Phi = -(2.38 \pm 0.04) - (2.59 \pm 0.05) \log D(\mathrm{km}). \qquad (12)$$

As the number of craters produced on the Earth's surface each year has to equal the number of causative NEA impacts per year, the right-hand sides of equations (10) and (12) have to be equal. Thus

$$-(5.04 \pm 0.5) - 3.0 \log d(\mathrm{km}) = -(2.38 \pm 0.04)$$
$$-(2.59 \pm 0.05) \log D(\mathrm{km}),$$

and

$$\log D(\mathrm{km}) = (1.026 \pm 0.5) + (1.16 \pm 0.04) \log d(\mathrm{km}). \qquad (13)$$

Table 2. A list of D/d values (obtained using equation 13) for typical Earth impact craters, where D(km) is the diameter of the crater on the Earth's surface and d(km) is the diameter of the causative NEA.

D(km)	D(km)	D/d
20	343	17.2
10	153	15.3
7	101	14.5
5	68.5	13.7
3	37.9	12.6
2	23.7	11.85
1	10.6	10.6
0.7	7.02	10.0
0.5	4.76	9.5
0.3	2.63	8.8
0.2	1.65	8.3
0.1	0.74	7.4

This equation is extremely important and is illustrated in Table 2. This table lists the diameters of the craters that are produced by NEAs of specific diameters. Notice that D/d varies from about 8 for very small Earth craters like the 0.88 km diameter Wolfe Creek (latitude 19°18′S, longitude 127°47′E) up to about 16 for the very large craters like the one supposedly responsible for the death of the dinosaurs, Chicxulub (diameter ≈200 km, latitude 21°17′N, longitude 89°31′W). Considering the immediate post-formation enlargement and slumping of large craters (see Melosh 1989), this D/d range is only to be expected.

Let us now try to estimate the energy required to form a specific crater. This procedure has to be simplified because clearly both the densities of the impacting asteroids and the velocities of impact vary across the NEA population. The Ni–Fe meteorite that produced the Barringer Crater in Arizona had a density of around 8000 kg m^{-3}. Spacecraft investigation of asteroid 253 Mathilde found that its density was around 1300 kg m^{-3}. As rocky asteroids dominate the asteroid belt, however, let us tentatively assume that the impacting NEAs have a density similar to that of rocky meteorites (i.e. around 3650 kg m^{-3}). (Notice that we are overlooking the fact that recent spacecraft investigation indicates that some of the NEAs are clearly not monoliths. These are rubble piles and as such have a lower density.) Following the analysis of the typical impact geometry carried out by Harris & Hughes (1994), it is also assumed that the mean impact velocity is 20 800 m s^{-1}. These values are then used to obtain the kinetic energy E of the incident NEA. Equation (13) can then be used to give

$$E = 9.1 \times 10^{24} D^{2.59}\ \mathrm{erg}, \qquad (14)$$

where the crater diameter D is in km.

The only sizable Earth craters that have been produced where both the resultant diameter and the causative energy release are well known are nuclear test craters. Let us take four well-known examples, these being Danny Boy (diameter 0.066 km), Teapot ESS (0.09 km), Schooner (0.26 km) and Sedan (0.368 km). These were produced (see Nordyke 1977) by just-below-surface and surface nuclear explosions with energies of 0.42, 1.2, 35 and 100 kilotons of TNT equivalent respectively (1 kt = 4.185×10^{19} erg). A least-squares fit to these nuclear test crater data gives

$$\log E(\mathrm{erg}) = (23.02 \pm 0.03) + (3.18 \pm 0.03) \log D(\mathrm{km})$$
$$[0.066 < D(\mathrm{km}) < 0.368], \tag{15}$$

i.e.

$$E = 1.05 \times 1023 D^{3.18}\,\mathrm{erg} \quad [0.066 < D(\mathrm{km}) < 0.368]. \tag{16}$$

The fact that equation (14) indicates that 87 times more energy is required to produce a 1 km diameter crater than does equation (16) underlines the problem. Maybe it is completely incorrect to assume that a hyperbolic impact cratering event has any physical similarity (or end result) to a nuclear explosion. When it comes to typical Earth impact craters it is clear that experiments cannot, and have not, been carried out in the relevant size range. When it comes to assessing the energy required to produce 10-, 20- and 100-km craters on the surface of the Earth, the method described in this paper is the only sound approach. Everything else relies either on the careful theoretical assessment of the energy required to produce the geological damage and mass removal indicated by the features of the crater and its surroundings, or on unfortunately huge extrapolations from impact experiments where both the projectile masses and their velocities are much lower than those experienced by the Earth's surface.

Examples of the former geological approach were put forward by, for example, Krinov (1963), Dence, Grieve & Robertson (1977) and Wood (1979), and are given as equations (17), (18) and (19) below:

$$E = 4 \times 10^{22} D^3\,\mathrm{erg}, \tag{17}$$

$$E = 1.45 \times 10^{23} D^3\,\mathrm{erg} \qquad (D < 2.4\,\mathrm{km}), \tag{18a}$$

$$E = 1.01 \times 10^{23} D^{3.4}\,\mathrm{erg} \qquad (D > 2.4\,\mathrm{km}), \tag{18b}$$

$$E = 8.41 \times 10^{23} D^{3.57}\,\mathrm{erg} \qquad (D < 1\,\mathrm{km}), \tag{19}$$

D, the crater diameter, being in kilometres.

Subscale physical experiments, numerical simulations and scaling laws are discussed by, for example, Holsapple (1987) and Schmidt & Housen (1987). An example of a typical end-product is the Melosh (1989) equation

$$D = 1.8 \rho_{\mathrm{i}}^{0.11} \rho_{\mathrm{t}}^{-0.33} g^{-0.22} d^{0.13} E^{0.22}\,(\mathrm{MKS\ units}). \tag{20}$$

Here ρ_{i} is the impactor density, ρ_{t} is the surface density of the target body being impacted, and g is the gravitation acceleration at that surface. If one assumes that the impactor is an asteroid with a mean density of 3 650 kg m^{-3}, equal to the average density of the stony meteorites that fall to Earth (see Sears 1978), and that the impacted surface of the Earth has a mean density of 3000 kg m^{-3}, $g = 9.81$ m s^{-2}, and the mean collision velocity is 20.8 km s^{-1} (see Harris & Hughes 1994), then equation (20), for the Earth, becomes

$$E = 8.45 \times 10^{22} D^{3.89}\,\mathrm{erg}. \tag{21}$$

The fact that the present paper suggests that E is proportional to $D^{2.59}$, whereas Melosh (1989) suggested that E is proportional to $D^{3.89}$, underlines the importance of this novel approach to the estimation of the crater/impactor diameter ratio.

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