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Terrestrial and Lunar Flux of Large Meteorites in the Last Two Billion Years

WILLIAM K. HARTMANN

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

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The Canadian shield can be divided into three main provinces with exposure ages ranging from 8×10^8 to 2×10^9 years. Craters of diameter greater than 10 km should be observable there even after such long periods. Counts of probable meteorite craters give determinations of the cratering rate in each province. The three independent determinations lie well within the range 1×10^{-4} to 15×10^{-4} craters larger than 1 km per km^2 per 10^9 years, and the true rate is expected to lie within these limits. These figures are within the uncertainty of other published determinations for more recent periods of time. A 1-km crater diameter corresponds to an impacting mass of about 6×10^{10} gm on the Earth and about 1.6×10^{11} gm on the Moon. The cratering rate can thus be transformed into a mass flux. After a survey of other published determinations it is estimated that the terrestrial cratering rate over the last 2×10^9 years has averaged about 12×10^{-4} craters larger than 1 km/km^2/10^9 years and in the same units the lunar rate has averaged 5×10^{-4} since the formation of the lunar maria.

I. THE CANADIAN SHIELD AS A METEORITE COUNTER

The flux of meteoritic material onto planetary surfaces during the history of the solar system must be known in order to establish any theory of planetary evolution, and, as discussed by Shoemaker, Hackman, and Eggleton (1962), it may provide a dating method of importance comparable to radioactive dating.

Determination of the present rate of infall of large objects by direct observation is nearly impossible because of the great scarcity of large falls. No visible crater has been definitely seen to form on the Moon, and on the Earth records of large crater formation are nonexistent. Neither of the two largest recorded falls in recent history resulted in a major observable crater. The Tunguska fall of 1908 was probably cometary, and although its mass was exceptionally large, the interaction between the atmosphere and this loosely bound object greatly reduced the potential for crater formation (Krinov, 1963). The Sikhote-Alin fall of 1947 was much less energetic than the Tunguska fall, and involved a nickel-iron meteorite of some 7×10^7 gm mass with an initial fall velocity of 14.5 km/sec (Krinov, 1963). This could suffice to form a crater of 100-meter diameter, neglecting energy losses to the atmosphere (see below). However, in fact the object began to break up in flight and the largest of many craters was 26.5 meters in diameter (Krinov, 1963). Thus, observations of presently falling objects are of no help because (1) not enough big objects fall, and (2) even the biggest objects observed to fall on the Earth lose a great deal of energy in passage through the atmosphere, so that resulting crater diameters are not representative. Thus we must use old exposed surfaces of known age as counters. This technique has the advantage that we integrate over time back to the origin of our counting surface, and thus can get average values applicable to most of solar system history.

The shield areas of the Earth, being exceptionally ancient stable areas where mountain formation has ceased, are ideal counting surfaces. The Canadian shield is the best studied of these. Three major provinces are distinguished by the fact that isotopic age determinations cluster around different values in three regions (Stockwell, 1962). Each clustering indicates a period of orogeny accompanied by folding and metamorphism of existing rocks, and intrusion of new rock material. In the Kenoran province this occurred 2.5×10^9 years ago; in the Hudsonian, 1.7×10^9 years; in the Grenville, 0.95×10^9 years. Since the uncertainty in dating is estimated by Stockwell at 0.15×10^9 years, it is immediately apparent that our determinations of flux can scarcely have better than one significant figure.

Since the time of the last orogeny in each province, listed above, each province has been stable in spite of subsequent orogenies in neighboring provinces. Peneplanation must be nearly completed in each province before that province becomes a good counting surface, and therefore the exposure age will be less than the time since orogeny. As typical peneplanation times can run well over 10^8 years, this correction is worth investigating. Table I shows the estimated exposure age in each province. The corrections applied in the oldest provinces are the largest to compensate for longer erosion times after peneplanation.

TABLE I
EXPOSURE AGES IN THE CANADIAN SHIELD

	Time since orogeny (10^9 years)	Age of oldest unfolded overlying rocks (10^9 years)	Estimated mean exposure age (10^9 years)
Kenoran Province	2.5 ± .15	2.5 to 1.7	2.0
Hudsonian Province	1.7 ± .15	1.7 to 0.9	1.4
Grenville Province	0.95 ± .15	less than 0.9	0.75

II. CRATER SURVIVAL

Craters of diameter less than a certain limit are useless in this work because they could not have survived erosion throughout the exposure age of the counting surface. This diameter limit is estimated in the following way.

A catalogue of all suspected impact craters was compiled, and the best available age estimate was listed for each. Log diameter was plotted against log age in an attempt to look for an age limit marking the longest survival at any given size. It is important to note that it is not crucial to include only genuine meteorite craters, since we are interested in measuring the survival time of any structure resembling an impact-explosion crater. Also, because the age scale ranges over nine orders of magnitude, the estimated age can be off by several orders and still be of use. The suspected impact craters in the Canadian shield were detected by aerial survey, and therefore the survival time to be measured is defined as the time after which circular structure is still recognizable given optimum survival conditions such as those in a stable shield area.

A log diameter–log age plot for craters known to be meteoritic and for structures of uncertain origin is shown in Fig. 1. As expected, the small craters are generally young, because they can resist erasure for only short periods. The line defines the upper limit of survival time under optimum conditions.

Figure 1 shows, at least by extrapolation, that a crater larger than 10 km should be able to survive throughout the history of the Canadian shield. Even if such a crater formed in the Kenoran province immedi-

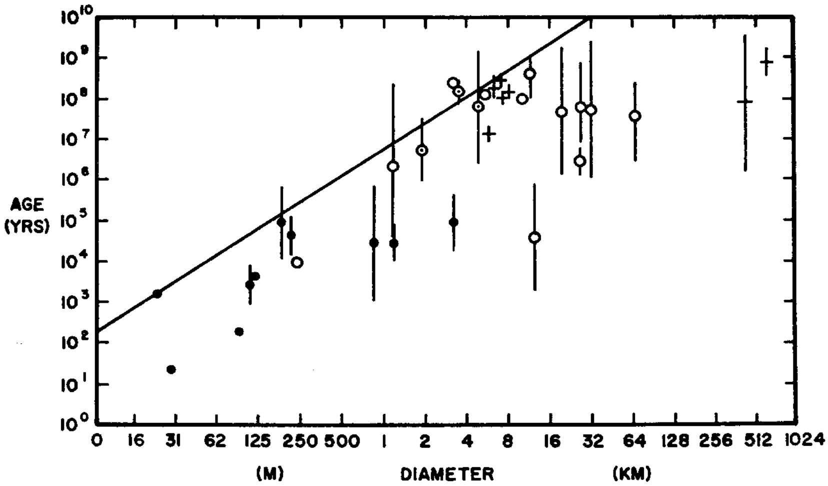

FIG. 1. Crater age vs. crater diameter for terrestrial craters. This figure is used to estimate the maximum survival time of terrestrial meteorite craters under ideal conditions. The assumed maximum survival time is given by the straight line; ●, known meteorite crater; ⊙, very probable meteorite crater; ○, probable meteorite crater; +, possible meteorite crater.

ately after peneplanation, we should still see it. Therefore the counts made here will be restricted to craters larger than 10 km.

III. METEORITE BREAK-UP

It is known that many meteorites break up during their passage through the atmosphere (Nininger, 1963). A cluster of close, small craters thus results instead of a single, large crater. An example is the Sikhote-Alin fall discussed in Section I. Conceivably, if all craters were counted indiscriminately, the estimated flux would be too high, and biased toward small craters. There are several reasons to believe that the present estimate is not so biased: (1) Impact craters larger than 10 km must have been caused by bodies of mass nearly 10^{14} gm (see Section IV). For such large bodies, substantial break-up in the atmosphere may be infrequent. (2) The few cases of multiple craters used in this study were twin craters. In each case it was assumed that one parent body was responsible, and it was clear that the parent must have been larger than necessary to form a 10-km crater.

IV. RELATION OF CRATER DIAMETER TO IMPACTING MASS

The relation of crater diameter to impacting mass is discussed by Shoemaker, Hackman, and Eggleton (1962), and Baldwin (1963). From experience with large explosions on Earth, we have the following relation between crater diameter D and energy E:

$$D = CE^k, \tag{1}$$

where C and k are constants. The full kinetic energy of impact is assumed to be available for cratering. On the Earth the initial kinetic energy of the meteorite gives only an upper bound on D because of loss of energy on passage through the atmosphere, an effect of decreasing importance toward large masses. With V as the final impact velocity and M as the mass, we have

$$D = \frac{C}{2^k} M^k V^{2k}. \tag{2}$$

Shoemaker, Hackman, and Eggleton state that k lies between 1/3 and 1/3.4. On the additional strength of Baldwin's arguments, we may choose a value of $k = 1/3.06$ for large impacting masses. From Shoemaker's equations, allowing for uncertainty in k and other factors, C in cgs units then lies between 2.15×10^{-3} and 3.97×10^{-3}. Impact velocity is now the only parameter left in converting from crater diameter to impacting mass. Since the impact velocity varies from one planet to another because of differences in solar orbital velocity, gravity field, and energy loss to atmospheres, it is convenient to list several equations with different values of velocity.

$$\begin{aligned}
D &= (6.5 \text{ to } 12.0)M^{1/3.06} && \text{for } V = 3 \text{ km/sec} \\
D &= (9.1 \text{ to } 16.7)M^{1/3.06} && 5 \text{ km/sec} \\
D &= (14.3 \text{ to } 26.2)M^{1/3.06} && 10 \text{ km/sec} \\
D &= (18.6 \text{ to } 34.2)M^{1/3.06} && 15 \text{ km/sec} \\
D &= (20.5 \text{ to } 37.8)M^{1/3.06} && 20 \text{ km/sec}
\end{aligned} \qquad (3)$$

These relations are plotted in Fig. 2.

The distribution of asteroid and meteorite masses is compatible with this; therefore

$$N_1/N_{10} = (10/1)^{2.4} = 250. \qquad (6)$$

This figure is entered in column 4 of Table II.

Column 5 of Table II gives the minimum number of meteoritic craters in each province, based on a count of only the most probable meteorite craters, and in effect on the assumption that as little as one-third of the observed craters are meteoritic. Column 6 gives the maximum number estimated from the existing counts by assuming that all observed craters are meteoritic and that on the basis of Fig. 1, not more than twice this number could have been eroded away and that Eq. (2) should be followed by large enough samples. The area of each province, given in column 7, is a rough estimate of the well-surveyed area, based on a total shield area of 4.5×10^6 km^2. The exposure ages are those calculated in Section I.

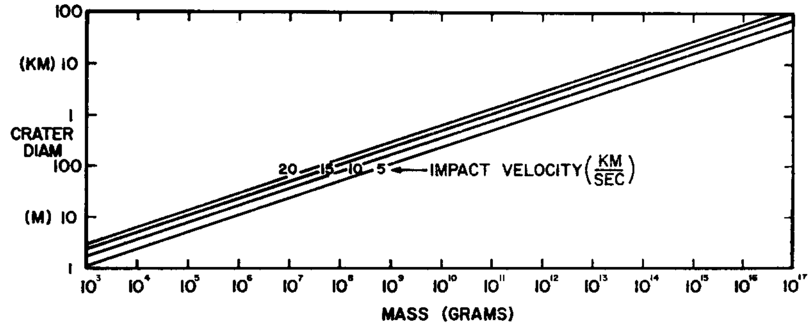

FIG. 2. Crater diameter vs. impacting mass. Four curves are plotted, corresponding to four impact velocities. There is a small range of uncertainty for each curve, as shown in Eq. (3).

V. CRATER COUNTS AND CALCULATION OF FLUX

Table II shows the calculation of the flux in each province. The craters listed in column 2 are those described by Beals, Innes, and Rottenberg (1963). While the counts deal only with the number of craters larger than 10 km, it is convenient to use craters larger than 1 km to define the flux, i.e.,

$$F \equiv \text{flux} \equiv \frac{\text{no. craters larger than 1 km}}{\text{km}^2\ 10^9 \text{ years}}. \qquad (4)$$

To convert from the number of craters larger than 10 km to the number larger than 1 km, we appeal to the observation that lunar craters in the diameter range from 1 km to 1000 km are distributed according to the relation (Hartmann, 1964; and unpublished)

$$N_D = \text{number of craters of diameter larger than } D = (\text{const})\, D^{-2.4}. \qquad (5)$$

The fundamental assumption underlying this determination of flux is that at least some of the structures listed here are meteoritic craters. The structures are those listed by Beals, Innes, and Rottenberg (1963), found during a search of the Canadian Air Photo Library photographs for possible fossil craters. If more than one-third of the listed craters are meteoritic, then the fluxes in Table II must approximately bracket the true flux, because there very probably were never more than 20 meteoritic craters (corresponding to our maximum flux) larger

TABLE II

CALCULATION OF CRATERING RATE IN CANADIAN SHIELD

Province	Craters >10 km	Diam. (km)	Correction to craters >1 km	Min. no. meteorite craters >1 km	Max. no. meteorite craters >1 km	Approx. area studied (km^2)	Time since orogeny (K–Ar age)	Estimated exposure age	Cratering rate $\left(\frac{\text{no.} >1\text{ km}}{\text{km}^2\,10^9\text{ yr}}\right)$
Kenoran	Clearwater[a]	16 32	$2.5(10^2)$	$2(10^2)$	$20(10^2)$	$1.3(10^6)$	$2.5(10^9)$	$2.0(10^9)$	$0.8(10^{-4})$ to $8(10^{-4})$
	Lac Couture	16							
	Menihek	8 9							
	Hudson Bay	440							
Hudsonian	Deep Bay[a]	14	$2.5(10^2)$	$2(10^2)$	$15(10^2)$	$1.2(10^6)$	$1.7(10^9)$	$1.4(10^9)$	$1(10^{-4})$ to $9(10^{-4})$
	Carswell	29							
	Sudbury	40							
Grenville	Mecatina	12	$2.5(10^2)$	$1(10^2)$	$15(10^2)$	$1.2(10^6)$	$0.95(10^9)$	$0.75(10^9)$	$1(10^{-4})$ to $17(10^{-4})$
	Manicouagan	65							

[a] Most likely of meteoritic origin.

than 10 km on the present Canadian shield (by Fig. 1 we would see them), and because for our minimum flux we have in effect assumed that about one-third of the observed craters are meteoritic.

This discussion also suggests that the suspected very large craters (Nastapoka Island arc, 440 km; Gulf of St. Lawrence, 290 km; Ungava Bay, 240 km) listed by Beals, Innes, and Rottenberg are either (1) nonmeteoritic, or (2) pre-Kenoran, i.e. pre-Canadian shield, in age. This follows from the distribution of crater diameters mentioned above. If there are three meteorite craters larger than 100 km, there should be on the order of 750 meteorite craters larger than 10 km, and by the discussion in Section II, all of these should have survived, but they are not to be found. The three large circular features, which approach the dimensions of lunar mare basins, may therefore have formed by impact more than 2×10^9 years ago. There is evidence that the flux was higher at that time (Hartmann, in press). Small craters would have been erased during the subsequent orogenies.

Table II indicates that the cratering rate is between 1×10^{-4} and 15×10^{-4} craters larger than 1 km formed per km^2 per 10^9 years, and this value is probably within a factor of 3 of the true average terrestrial rate over the last two billion years. This value may also be expressed as a flux of 1×10^{-4} to 15×10^{-4} bodies of mass greater than about 6×10^{10} gm/km^2/10^9 years, by Eq. (3), assuming that the modal ground impact velocity of large meteorites is about 18 km/sec. According to the calculations of Heide (1964), meteorites of such mass probably lose somewhat less than 10% of their initial velocity in passage through the atmosphere, so an assumed impact velocity of 18 km/sec indicates an atmosphere entry velocity of closer to 19 km/sec.

VI. COMPARISON WITH OTHER DETERMINATIONS

Shoemaker, Hackman, and Eggleton (1962) employed virtually the same method used here to determine the flux in the central United States over the last 0.24×10^9 years. Their reduction gave a mean flux of 0.6×10^{-4} craters larger than about 3 km/km^2/10^9 years. Through Eq. (5), this reduces to our units and we find the approximate flux is 7×10^{-4} craters larger than 1 km/km^2/10^9 years. It is possible to use the raw data of Shoemaker, Hackman, and Eggleton to rederive the flux taking into account the considerations in this paper. In an area of about 7.06×10^5 km^2 with a mean exposure age of about 2.35×10^8 years, they find 10 cryptovolcanic structures, all of which they assume for this calculation to be astroblemes. Eight of these are thought to correspond to craters larger than 3-km diameter (from Fig. 1, we would expect the smallest cryptovolcanic structure of age 2.35×10^8 years to be close to 5 km across). The oldest of the structures has an age of about 4×10^8 years, which is even greater than the mean exposure age. In calculating the flux it is crucial to know the original crater size, because the frequency varies sharply with size. The uncertainty in original size of these astroblemes, if such they be, introduces an uncertainty of, say, a factor of 5 in the calculated flux. Perhaps as large an uncertainty comes from the questionable origin of these structures. But just as in Section V, we may argue that if one or two of the structures are meteoritic, the true flux is bracketed by our calculation, because if there were more than about eight formed, we should still see the larger craters with no question, and because we have assumed that at least one crater is meteoritic. If we assume that between one and eight craters larger than 3 1/2 km formed in this area in the last 2.35×10^8 years, the flux F is 1.2×10^{-4} to 10×10^{-4} craters larger than 1 km/km^2/10^9 years.

The terrestrial flux can also be estimated from present day observations of asteroids and from extrapolations of present day observations of small meteorite falls. Three published determinations are considered here. Öpik (1958) tabulated the flux due to both cometary and asteroidal objects of large mass. In units of the total number of falls of mass greater than 6×10^{10} gm/km^2/10^9 years Öpik's value is about 32×10^{-4}. About one-third of the material is cometary, according to his tabulation based on astronomical observations and extrapolations from recorded falls. The cometary material suffers significant energy loss to the atmosphere, and therefore in our units of the number of craters larger than 1 km/km^2/10^9 years a better estimate from Öpik's figures is $F = 21 \times 10^{-4}$.

Brown (1960) made a similar study in which the distribution of masses among recorded falls was fitted to the observed asteroidal mass distribution to give a table showing impact frequency from 1 to 10^{11} gm. In our units, Brown's value of F is from 5×10^{-4} to 23×10^{-4}.

Hawkins (1960, 1963) studied the statistics of observed falls and finds and concluded that there was evidence that while stoney meteorites outnumber irons at small masses, the situation reverses for large masses. Hawkins' result is that the published determinations of fall rates for large masses are too low. In our units, Hawkins' value of F is about 160×10^{-4}.

The discrepancy between Hawkins' value and those of Öpik and Brown can be discussed in terms of the slope of the log cumulative frequency–log mass distribution curve. For most classes of objects in the solar system this relation is nearly linear. Hawkins found that at large masses the slope for stoney meteorites approaches a value which is significantly different from that for iron meteorites. Brown, however, found that the slopes were effectively the same and that furthermore they were identical with that derived for asteroids from observations of their magnitudes. Hawkins' value of the slope for irons is effectively the same as the values of Brown, but the curve lies at a flux level an order of magnitude above that of Brown. The lower fluxes derived by Öpik and Brown are favored by the facts that (1) they agree remarkably well with the entirely independent determinations based on crater counts, and (2) the high flux of Hawkins divided into the mare crater density gives a mare age of only 0.3×10^9 years. It appears highly unlikely that the Moon could be 4.7×10^9 years old and the maria all roughly 0.3×10^9 years old without there being any other large mare areas of intermediate age.

It should be noted that the cratering rate depends on the conversion from impacting mass to crater diameter. If the mass to form a 1-km crater is actually twice that given here, the last three determinations will be cut by a factor of 1.7 according to Eq. (7) (next section).

VII. Lunar Flux

In determining the exposure age of a given planetary surface, one counts *craters*. Therefore the flux in this paper is defined in terms of the rate of formation of craters larger than a certain size. This is preferable to working in terms of the rate of infall of objects larger than a certain mass, because a given mass causes a variable-sized crater, depending on the impact velocity, as shown in Eq. (3) or Fig. 2, and because impact velocity varies from one planet to another.

In the case of the Earth, we assumed in Section V a modal impact velocity of 18 km/sec, corresponding to an entry velocity of 19 km/sec. Further discussion of the problem is given by Shoemaker, Hackman, and Eggleton (1962). At this impact velocity a mass of about 6×10^{10} gm creates a crater 1 km across by Eq. (3). On the Moon the modal impact velocity, undiminished by any atmospheric effects, probably lies closer to 12 km/sec (Shoemaker *et al.*, 1962). In this case a mass of 1.6×10^{11} gm creates a crater 1 km across, by Eq. (3). This increase by a factor of 2 1/2 in limiting mass corresponds to a decrease by a factor of 2 in flux, assuming that asteroidal and meteoritic material in this mass range is distributed according to

$$\log N = -0.75 \log M + \text{const}, \qquad (7)$$

where N is the number of objects of mass larger than M. This equation is compatible with the results of Hawkins (1964) and Brown (1960). Therefore as a first correction in calculating the lunar flux as defined here in terms of cratering rates, the terrestrial flux must be divided by 2.

Other corrections could be made to convert terrestrial flux to lunar flux. However, it is assumed here that (1) the net effect on the earthward side of the decrease in flux due to the Moon's lower gravitational field and the increase due to the focusing effect of the Earth is a decrease in flux by 0.8,

TABLE III
DETERMINATIONS OF POST-MARE TERRESTRIAL AND LUNAR CRATERING RATE

Reference used for basic data	Method	Number of craters of diameter >1 km (km^2 10^9 years)	
		Earth	Moon
Öpik (1958)	Meteorite and asteroid observations	21×10^{-4}	12×10^{-4}
Brown (1960)	Meteorite and asteroid observations	5 to 23×10^{-4}	2 to 9×10^{-4}
Hawkins (1964)	Meteorite and asteroid observations	110×10^{-4}	45×10^{-4}
Shoemaker, Hackman, and Eggleton (1962)	Astrobleme counts in central U.S.A.	1 to 10×10^{-4}	0.5 to 4×10^{-4}
This paper	Crater counts in Canadian shield	1 to 15×10^{-4}	0.4 to 6×10^{-4}
Best estimate	Estimated from above results	12×10^{-4}	5×10^{-4}

consistent with Öpik (1960); (2) the effect of the Moon's lower gravity on crater size can be neglected; (3) through most of post-mare lunar history the Moon was at nearly its present distance from the Earth so that the focusing effect of the Earth can be assumed constant; (4) cometary masses are more effective cratering agents on the Moon than on the Earth.

VIII. SUMMARY

Table III gives the final summary of determinations of the terrestrial and lunar flux through post-mare lunar history. There is evidence (Hartmann, in press) that the flux decreased rapidly in pre-mare time and much less rapidly in post-mare time, based on crater counts in continental and mare regions of the Moon. However, the determinations of flux in this paper are not accurate enough to measure the actual decrease, and the values arrived at here can be considered either as mean values of the flux in post-mare time, or as present day values.

The best estimate of cratering rate is about 12×10^{-4} craters larger than 1 km/$\text{km}^2/10^9$ years on the Earth and 5×10^{-4} craters larger than 1 km/$\text{km}^2/10^9$ years on the Moon. These values are probably correct within a factor of 4. Comparison with crater counts on the Moon gives an age of about 3.6×10^9 years for the lunar maria. This is very consistent with current isotopic ages of meteorites of about 4.5 to 4.7×10^9 years. Assuming the maria to be lava flows, it is consistent with estimates of a period of less than 2×10^9 years for maximum melting to have occurred near the lunar surface as a result of radioactive heating (MacDonald, 1961; Kopal, 1962).

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