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Asteroidal Fragments*

GERALD S. HAWKINS
Boston University, Boston, Massachusetts, and Harvard College Observatory, Cambridge, Massachusetts
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The meteorite catalogue of Prior and Hey was used to determine the rate of fall and mass distribution of meteorites. An analysis for the United States and Europe shows that 3.3 meteorites with a mass $\geqslant 10$ kg reach the earth per day. The cumulative number with mass greater than or equal to a chosen value m varies as $1/m$. This law holds for stone finds and falls and iron falls. The iron finds include an excess of larger objects, attributed to selection effects on the ground. If this influx has been constant, the earth has collected the equivalent of an asteroid 14 km in diameter during the last 5×10^9 years. It is estimated that the asteroids consist of 16.7% by weight of nickel-iron, indicating a primary object that before breakup was intermediate in size between the moon and Mars. The space density of meteorites is shown to vary as $(\text{radius})^{-4}$ and the total mass of meteorites with radius between 1 cm and 1 km is at least 5.6×10^{-24} g cm^{-3}. The size distribution of particles produced by the crushing of rock is similar to that found for meteorites and suggests that meteorites undergo a considerable number of collisions in space.

INTRODUCTION

If we accept the thesis that meteorites are remnants of a collision between two or more asteroids, then a study of meteorites will yield data on the original asteroids and will lead to an understanding of the collisional process in which they were destroyed. Meteorites are, of course, rare objects; and it is also rare for a person to see a meteorite enter the atmosphere and to witness its fall. Nevertheless, during the past 150 years enough information on meteorites has accumulated to justify some preliminary statistical research. This paper attempts to derive data on asteroids and asteroidal collisions from a study of meteorites.

The catalogue of Prior and Hey (1953) gives details on meteorites from all the continents of the world except Antarctica. The author considers this catalogue to be the most comprehensive and reliable one now available, and has used it as the primary source of data for the analyses that follow.

MASS DISTRIBUTION

The catalogue gives an account of 1447 meteorites from which a reliable estimate could be made of the mass of the material recovered at the surface of the earth. To determine the mass distribution it was convenient to choose a logarithmic sampling interval. That is to say, the meteorites were divided into categories according to mass as follows: 1.0 to 4.9 g, 5.0 to 24.9 g, 25.0 to 124.9 g, . . . , where the mass in each succeeding category increases by a factor of 5. The mass distribution was obtained separately for each of four classes of meteorites. The first division, into two groups, separated the meteorites composed almost entirely of iron from those composed of stony material; pallasites were grouped with the stones amd mesoiderites with the irons. Each of the two groups was then subdivided into "falls" (meteorites that were actually seen to fall), and "finds" (meteorites found on the earth's surface or in the subsoil).

The distribution of mass in the four classes is shown in Figs. 1 and 2, where we plot the number, N, of meteorites with mass greater than or equal to a chosen value, m kg. As the mass m increases, the distribution curve approaches a gradient of -1.0 ± 0.3 for all classes except iron "finds." Thus we may write

$$\log N = N_0 - s \log m, \tag{1}$$

where logarithms are to the base 10, $s=1.0 \pm 0.3$ and N_0 is a constant. The curvature of the distribution for small values of m is due to several causes. A small meteorite, weighing a few grams, is not easily recovered. Even if an observer witnesses its entry into the atmosphere, the specimen makes a relatively inconspicuous addition to the countryside. Smaller meteorites are probably dissipated by ablation in the atmosphere. Although a large object, weighing several tons, might lose less than 50% of its material by vaporization, a smaller object loses a considerably greater fraction. The mass distribution of the iron "finds" is anomalous in that the gradient is -0.5. This group therefore contains a higher proportion of large objects. Since the gradient for iron "falls" is -1.0, we may presume that the discrepancy results from observational bias—large

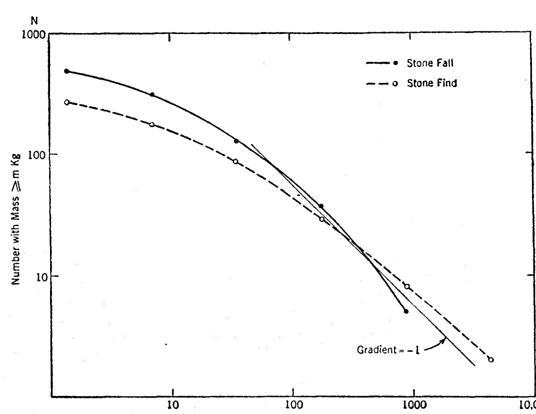

FIG. 1. The cumulative mass distribution of stone meteorites.

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iron objects are more easily discovered, and they weather less rapidly than do large stone specimens.

Equation (1) represents the mass distribution of meteorites after passage through the earth's atmosphere. To deduce from this the mass distribution of meteorites in interplanetary space requires a correction for the effects of ablation and fragmentation in the atmosphere, and a correction for any selective bias that is inherent in the original data. It is probably fair to assume as an approximation that these effects are independent of the mass of the object, at least for the linear portion of the observed distribution. Equation (1) may then be taken to represent the mass distribution of asteroidal fragments, and we may write

$$\log N = N_\infty - s \log m_\infty, \tag{2}$$

where N_∞ is a constant, s defines the mass distribution, and m_∞ is the mass of the meteoroid in space. Differentiation of Eq. (2) yields the incremental law,

$$dN = C d\rho / \rho^{3s+1}, \tag{3}$$

where C is a constant and ρ is the radius of the asteroid, assumed to be a spherical fragment. The quantity dN represents the number of meteorites with radii between ρ and $\rho + d\rho$. The mean value of the exponent in Eq. (2) is therefore -4.0 and the limits of uncertainty are -3.1 and -4.9. One may deduce from direct observation of the asteroids an inverse 4th-power dependence and the exponent varies from -2.8 to -4.6 within the asteroid zone. The meteorite (Hawkins 1959) and asteroid (Kuiper *et al.* 1958) observations are therefore in fair agreement and indicate that the exponent in the radius distribution law [Eq. (3)] is close to -4.0. Piotrowski (1953) deduced on theoretical grounds that Eq. (3) should show an inverse 3rd-power dependence on radius if the number of collisions between the asteroids has not been large.

It is of interest to estimate the relative abundance of stone and iron fragments among the asteroids. To avoid the problems associated with differential effects of weathering, I have considered only the witnessed "falls." Figure 1 represents 590 stones with a total mass of 1.349×10^4 kg. Figure 2 gives the data for 50 iron falls with a total mass of 2.699×10^3 kg. The figures indicate that stony asteroids out-number the irons in the ratio 11.80:1, and that the mass of the asteroids comprises 16.7% of nickel-iron.

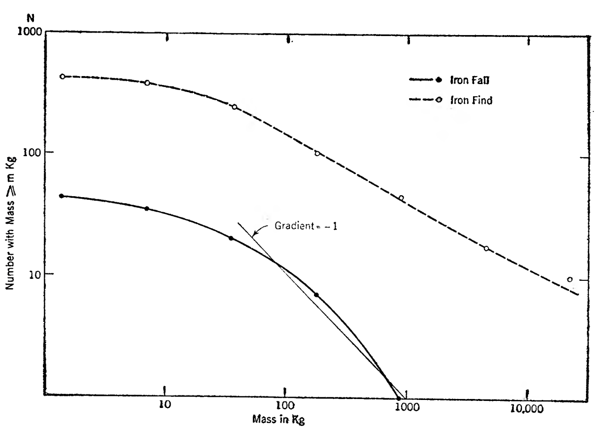

FIG. 2. The cumulative mass distribution of iron meteorites.

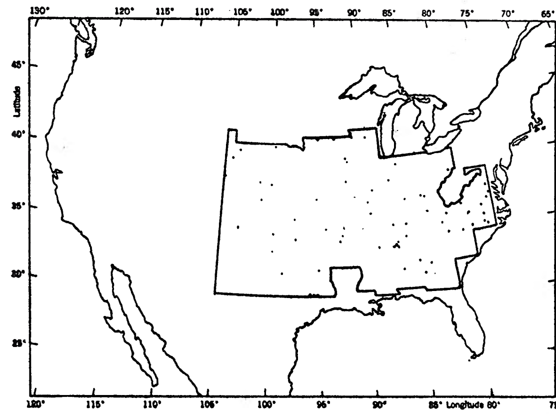

FIG. 3(a). Observed falls in United States.

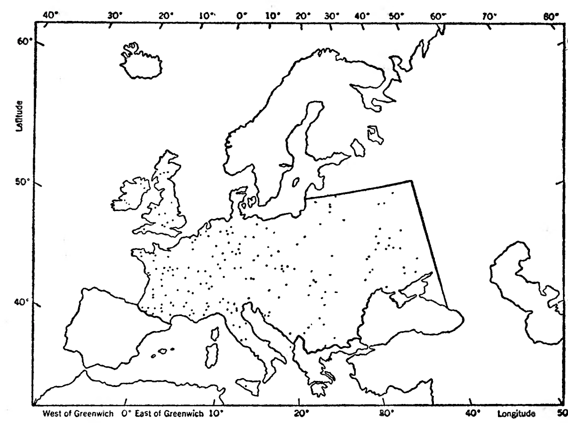

FIG. 3(b). Observed falls in Europe.

NUMBER OF METEORITES IN SPACE

Before estimating the number of meteorites per unit volume in the space surrounding the earth we must determine the influx rate at the surface of the earth. The catalogue of Prior and Hey (1953) gives the latitude, longitude, and date of observed falls. For this analysis I have chosen two areas where the terrain is mostly unforested and cultivated intensively. The first area is in the United States east of the Rocky Mountains; the boundaries are shown in Fig. 3(a); the second area covers most of Europe and is shown in Fig. 3(b). On these maps each dot represents the location of a meteorite fall. The number of falls observed per decade is shown in the histograms of Figs. 4(a) and 4(b). The number of falls observed per decade is clearly not constant in either area. This variation results in part from

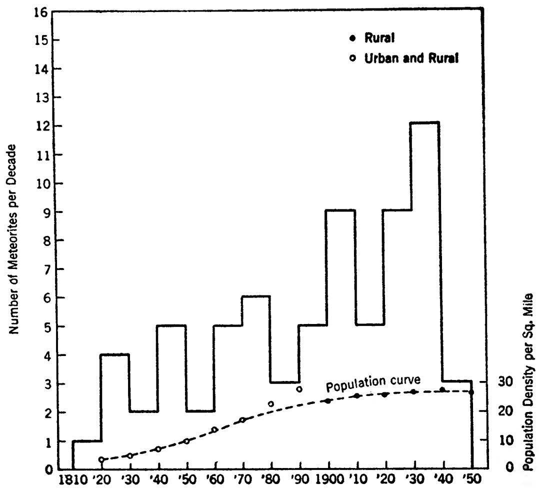

FIG. 4(a). Meteorite falls per decade in United States, and number of people per sq. mile.

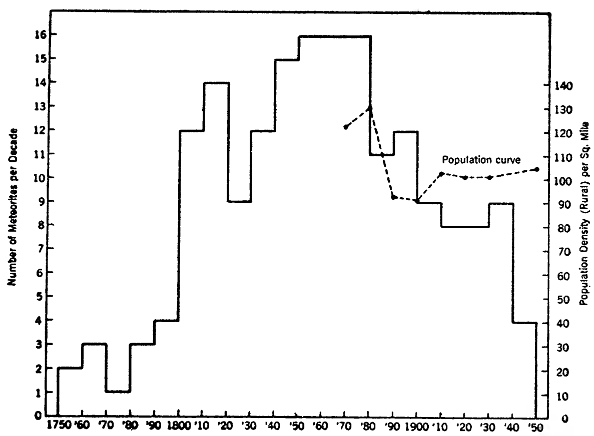

FIG. 4(b). Meteorite falls per decade in Europe, and number of people per sq. mile in England and Wales.

the irregular occurrence of meteorites but mostly from the changing numbers of people living in the selected area. The number of nonurban people living within the selected area is indicated in Fig. 4(a) and 4(b), which show that the number of falls observed per decade in the United States is apparently correlated with the size of the population, although the increase in observed meteorites is not so pronounced as the increase in population. The only figures on population growth readily available for Europe are those for the British Isles, but we may assume that these numbers are representative of Europe. The correlation between meteorite rate and density of population is present in Europe, but is not so good as in the United States; therefore, additional factors must be present. We can probably account for the sudden increase in the number of falls in 1800–1810 by the fact that the fall of stones at L'Aigle was authenticated by a scientific investigation. The phenomenon was given considerably publicity and the French Academy officially recognized

TABLE I. Rate of meteorite falls.

	Europe	United States
Mean number per decade	4.18	5.14
Peak number per decade	16	12
Area (sq km)	4.05×10^{6}	2.95×10^{6}
Mean influx (kg km^{-2} yr^{-1})	1.99×10^{-6}	8.06×10^{-6}
Peak influx (kg km^{-2} yr^{-1})	7.62×10^{-6}	1.88×10^{-5}
Mean influx (number km^{-2} hr^{-1})	1.18×10^{-11}	1.99×10^{-11}
Peak influx (number km^{-2} hr^{-1})	4.51×10^{-11}	4.65×10^{-11}

the source of the meteorites. It is unlikely that the influx of meteorites actually decreased in Europe between 1860 and 1950, and one must conclude that the apparent decrease in rate is due to a drift of the rural population to the cities during the industrial revolution and, perhaps, a waning of interest in meteoritical phenomena. In view of these uncertainties, as a first approximation I have taken the influx rate to be the highest rate observed in any ten-year period. Thus the rate for the United States is 12, and for Europe is 16 meteorites per decade. The observational data for each area are summarized in Table I.

It can be seen that the peak influx rate for the United States and Europe is approximately 4.5×10^{-11} meteorites km^{-2} hr^{-1}. The close agreement is almost certainly fortuitous since one would expect an error of $+30\%$ from statistical variations, and the many observational uncertainties must also influence the result. One can infer, however, that the peak rate would not increase appreciably if the density of the population were increased, because the observed rate for Europe is the same as that for the United States; yet the population density is greater in Europe by a factor of 5.

It is difficult to determine whether the peak rate does indeed represent the actual influx. Many meteorites must fall in forest, woodland, lakes and in regions that are uninhabitable. From an earlier calculation, Nininger (1933) determined a rate of 1.4×10^{-11} meteorites km^{-2} hr^{-1}, and estimated that under the most favorable circumstances the observed rate might be greater by a factor of 10. Nininger did not consider in detail the increase of population, as has been done in the present paper, but his factor presumably makes allowance for the population growth curve. From the data in Table I it is probably reasonable to assume that with ideal terrain and an active populace the observed rate would be 2×10^{-10} meteorites km^{-2} hr^{-1}.

Even under such ideal conditions, the recovery of small meteorites would still be difficult and the mass distribution would no doubt follow the curve for "falls" shown in Figs. 1 and 2. If we correct for the curvature in the observed mass distribution we find that a total of 640 observed falls corresponds to 740 meteorites landing on the earth with mass m equal to or greater than 10 kg. The true influx rate of meteorites with $m\geqslant10$ kg is therefore $2.0\times10^{-10}\times740/640=2.3\times10^{-10}$ km^{-2} hr^{-1}. We may write the cumulative number N of meteorites landing with mass $\geqslant m$ as

$$\log N\ (\text{km}^{-2}\ \text{hr}^{-1}) = -\log m - 8.64. \quad (4)$$

The mass m_∞ before ablation is difficult to determine but the meteor theory (Levin 1946) indicates that for meteors of the same velocity the ratio $m_\infty/m = \text{const} = f$. Thus the number expressed in terms of initial mass m_∞ become

$$\log N\ (\text{km}^{-2}\ \text{hr}^{-1}) = -\log m_\infty - 8.64 + \log f. \quad (5)$$

The value of f is difficult to determine; an estimate of $f \simeq 5$ has been made from a study of the Grant meteorite (Fireman 1959), and a value of $f = 700$ was obtained for the Luhy (Ceplecha 1960) meteorite. In view of these uncertainties we may tentatively adopt $f = 10$ as a lower limit.

Assuming that the mean geocentric velocity for meteorites is 17 km/sec (Whipple and Hughes 1955), we can deduce the number of meteorites per cm^3 in the space through which the earth passes. The number dN with radius between ρ and $\rho + d\rho$ cm is given by the expression,

$$dN = 7.63 f \times 10^{-27} (d\rho/\rho^4)\ \text{cm}^{-3}, \quad (6)$$

where a mean specific gravity of 3.5 g cm^{-3} is assumed. The cumulative number N with radius $\geqslant \rho_1$ is then

$$N = \frac{2.54 f \times 10^{-27}}{\rho_1^3} \text{cm}^{-3}. \quad (7)$$

To obtain the total mass per cm^3 we must integrate the quantity $m_\infty dN$. Again assuming the specific gravity of meteorites to be 3.5, we find the total mass per cm^3, $\sum m_\infty$, is given by the expression,

$$\sum m_\infty = 1.12 f \times 10^{-25} \log \frac{\rho_1}{\rho_2} \text{g cm}^{-3}, \quad (8)$$

where ρ_1 and ρ_2 are the upper and lower limits on radius ρ.

The total mass falling on 1 cm^2 of the earth per sec is given by the equation,

$$\sum_{\oplus} m_\infty = 6.33 f \times 10^{-20} \log \frac{m_{\infty 2}}{m_{\infty 1}} (\text{g cm}^{-2}\ \text{sec}^{-1}), \quad (9)$$

where $m_{\infty 2}$ and $m_{\infty 1}$ are the upper and lower limits of mass. The total mass reaching the earth in the form of solid meteorites is, of course, in g cm^{-2} sec^{-1},

$$\frac{1}{f} \sum_{\oplus} m_\infty.$$

DISCUSSION

The observations of asteroids in space and meteorites on the ground indicate a fourth power law for the distribution according to size. Since meteorites and asteroids are a product of collisions, it is of interest to compare this distribution with the results obtained in the crushing of terrestrial rock. The process of mineral dressing, whether it be by stamp mill, rod mill or standard tumbler, produces a continuous gradation of particle sizes. The results of mineral dressing are usually expressed by the comminution law (Gaudin 1944)

$$\log p = k \log x + \log A, \quad (10)$$

where p is the percentage of the total mass contained in particles with diameters between x_1 and x_2, after the crushing process. In Eq. (10), k and A are constants. The quantity x in the comminution law is a mean value of the sizing limits; the sizing interval is chosen to be logarithmic so that $\sqrt{2}x_1 = x_2$, $\sqrt{2}x_2 = x_3$, etc.

The number of meteorites as a function of mass may be written to correspond to the comminution law by the following transformations. Let us assume that dN particles in the meteorite sample have a radius between ρ and $\rho + d\rho$ and that the distribution is given by the expression,

$$dN = C d\rho / \rho^\alpha, \quad (11)$$

where C is a constant. We may convert ρ and $d\rho$ into the mass m and differential dm. Equation (11) then transforms into the expression

$$dN = B m^{-(\alpha+2)/3} dm, \quad (12)$$

where B is a constant. The total mass in the interval dN is

$$m dN = B m^{(1-\alpha)/3} dm. \quad (13)$$

The total mass p between the mass limits m_1 and m_2 is then found by integration:

$$p = \int_{m_1}^{m_2} B m^{(1-\alpha)/3} dm = B' [m_2^{(4-\alpha)/3} - m_1^{(4-\alpha)/3}]. \quad (14)$$

If a logarithmic mass interval is used in the sample, then $m_2 = \beta m_1$, where β is a constant. This leads to the expression,

$$p = B' m_1^{(4-\alpha)/3} [\beta^{(4-\alpha)/3} - 1]. \quad (15)$$

We may now express the distribution as a function of diameter x. Equation (15) becomes

$$p = A x^{4-\alpha}, \quad (16)$$

where A is a constant. Taking the logarithm of this equation produces the comminution law,

$$\log p = k \log x + \log A, \quad (17)$$

where $k = 4 - \alpha$.

The integration involves a singularity when $\alpha = 4$. By a separate integration for this singularity it can be shown that the relation $k = 4 - \alpha$ still holds when $\alpha = 4$.

The law giving the number of meteorites as a function of size may now be compared directly with the comminution law of mineral dressing. In particular it should be noted that the meteorite and asteroidal law with $\alpha = 4.0$ corresponds to a value of $k = 0$.

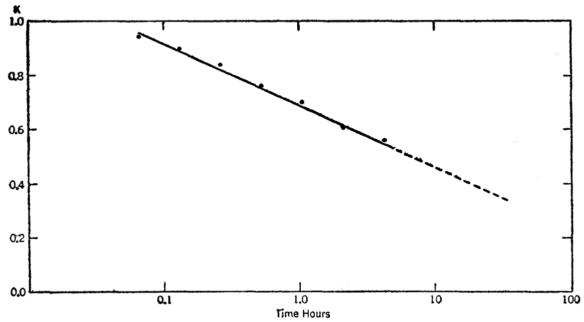

FIG. 5. The comminution parameter k as a function of time.

In rock crushing a deliberate attempt is made to avoid the production of small particles, and the primary objective is to produce particles of uniform size. In the early stages of a crushing process the value of k is close to unity, and an inverse cube law results for Eq. (11) with $\alpha=3$. Further grinding, however, reduces the value of k and produces an increasing number of small particles. This process is referred to as "over grinding." Figure 5 plots the value of k as a function of time for the grinding of quartz in a rod mill (Gaudin 1944). As the grinding continues, the value of k approaches zero and with a linear extrapolation we may deduce that $k=0$ after 600 hours of grinding. The tendency for k to decrease is noticeable in all crushing processes regardless of the mechanism involved. It is not possible to determine from the published data whether the relationship in Fig. 5 is linear or whether k approaches zero asymptotically. One may infer, however, that if $k=0$, and $\alpha=4$, then the debris has probably been subjected to a considerable amount of mechanical disturbance.

Low velocity collisions among asteroidal fragments are probably similar in action and effect to the grinding mechanisms used in dressing minerals. The observed mass distribution of meteorites and asteroids therefore indicates that these bodies have undergone a large number of collisions, and one may assume that this process of attrition is still in progress in the asteroid zone.

Since a large number of meteorites consist of metallic iron we must presume that one or more of the precollisional bodies were large enough to possess an iron core. The percentage of iron in the asteroid is given approximately by the ratio of iron to stone meteorites falling on the earth. The percentage of iron will be underestimated if one or more of the asteroids involved in the collision did not possess an iron core. The percentage will be overestimated if fragments of stone meteorites are lost due to weathering and other selection factors as indicated by the differences in Figs. 1 and 2. The analysis in this paper shows that the percentage of iron by mass is 16.7%. This corresponds (Urey 1951) to the composition expected from the core of a body intermediate in size between Mars and the moon. At least one of the original asteroids, then, must have been between 2000 and 4000 km in diameter.

The influx laws [Eqs. (4) and (5)] are probably uncertain by $\pm 50\%$, but there is agreement with the influx law determined by another method. Hawkins (1959) deduced from the observed rate of bright fireballs that $\log N = \log m_\infty - 7.98$. We may therefore adopt an influx law:

$$\log N = -\log m_\infty - 7.5 \text{ km}^{-2} \text{ hr}^{-1}. \tag{18}$$

This law shows that the earth encounters one asteroidal fragment with $m_\infty \geqslant 13\times 10^6$ kg every 100 years.

If the influx rate has remained constant for the last 5×10^9 years, Eq. (9) indicates that the earth has collected 4.60×10^{18} g of meteoritic material during this period. This mass is equivalent to an asteroid with a diameter of about 14 km and a mean density of 3.5. This is an insignificant fraction of the total mass in the asteroid zone.

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