Reports

The Frequency of Meteorite Falls on the Earth

Abstract. *Photographic observations from a network of 60 cameras in western Canada are used to derive the influx rate of meteorites on the earth's surface, the first time instrumental data have been used for this purpose. Forty-three observed events are believed to have dropped between 0.1 and 12 kilograms of meteorites each. The flux values are corrected for a minor latitude effect and agree with earlier estimates near 10 kilograms but vary more slowly with mass. Eight events per year drop at least 1 kilogram of meteorites in an area of 10^6 square kilometers.*

Determining the frequency of meteorite falls on the surface of the earth is a difficult observational task. Hawkins (*1*) and Brown (*2, 3*) used data on the recovery of meteorites in densely populated regions to estimate the rate of arrivals. Brown's values were revised by Millard (*4*) on the basis of further assumptions about how population distribution and cultural levels would affect meteorite recognition, with the revision from Brown (*2*) to Millard (*4*) amounting to an increase of about 25 times in the estimated rate of falls.

Major networks of cameras for photographing bright fireballs have been operated for large parts of the past two decades in the United States, Central Europe, and Canada. Each of these projects has recorded one event in which detailed photographs of the fireball were used successfully to locate pieces of the fallen meteorites (*5–7*). McCrosky and Ceplecha compared (*8*) the mass influx at the top of the atmosphere (derived from camera network data, assuming a knowledge of the luminous efficiency for fireballs) with the estimates of Brown and Hawkins, modifying these values for an assumed deficiency of fireballs during hours of darkness. Although the derived flux entering the atmosphere was higher by two or more orders of magnitude than expected from meteorite recovery data, it was not clear at the time whether the low recovery rates from the networks were due to generally complete fragmentation of the fireballs in the atmosphere or to the difficulties associated with finding meteorites on the ground.

In principle, the camera networks should be able to provide a more reliable estimate of the frequency of falls than any statistical treatment of either witnessed falls or chance recoveries. Much progress has been made in recent years in understanding the luminosity and ablation of meteorites in flight, so that it is now possible to decide which fireballs observed by the networks are candidates for actual meteorites (*9*).

We report on observations made by the Canadian network, known as the Meteorite Observation and Recovery Project (MORP), for a period of exactly 9 years, from 1 April 1974 to 31 March 1983. A description of the network has been given by Halliday *et al.* (*7*), including an explanation of the method used to calculate the area of clear sky under observation at any time. Although very bright fireballs may be photographed through thin clouds and very close to the horizon, the flux calculations are based on only those meteors observed in an essentially clear sky at an altitude of at least 8° by two or more camera stations. The total product of area and hours of observation is 1.16×10^{10} km^2-hours in 9 years. With an effective area of 1.26×10^6 km^2 for the MORP network, the coverage is equivalent to 9200 hours of clear sky over the network, or 29 percent of the night hours.

Any fireball that penetrates the atmosphere sufficiently to be a candidate for a meteorite fall will show appreciable deceleration late in its flight. The drag equation may be written as follows:

$$\frac{M}{C_D S} = \frac{-\rho v^2}{2\dot{v}} \qquad (1)$$

where M, S, v, and $\dot{v}$ are the mass, cross-sectional area, velocity, and deceleration, respectively, of the meteorite at any time; ρ is the known atmospheric density; and C_D is the dimensionless drag coefficient. With a suitable choice for C_D, Eq. 1 may be used to estimate the mass/area ratio of the meteorite late in its luminous flight, after significant ablation has ceased, since v and $\dot{v}$ are observable quantities. If we adopt a typical value of 3.5 for the specific gravity of stony meteorites, this yields a measure of the "average thickness" of the meteorite, measured in the direction of flight. By assuming a typical shape and orientation, the mass can then be estimated.

Most meteorites in the kilogram size range have a chunky shape with several rather flat faces, and they may be expected to orient themselves in a maximum-drag mode during highly supersonic flight. We choose $C_D = 1.0$ for a chunky object and adopt a bricklike shape with sides in the ratio of 2:3:5. To assess the uncertainties in the mass estimates, let us consider three quite unlikely shapes for a meteorite: a sphere, a hemisphere, and a cube. A 1-kg stone "brick" with our chosen ratios, oriented with the largest face to the direction of flight, would have a mass/area ratio of 14.8 g cm^{-2}. This same ratio would apply to a sphere of mass 467 g, a hemisphere of 1870 g, or a cube of 265 g (oriented with one side forward). Although errors of a factor of 4 in the mass are thus not ruled out, for four observed fragments of the Innisfree fall (*10*) Eq. 1 with the present assumptions yields masses that are 0.95, 2.82, 0.51, and 1.27 times the actual recovered masses. It appears that this procedure should usually indicate a mass within a factor of 2 of the correct value.

Falls of stony meteorites involve numerous fragments, and the MORP photographs frequently reveal smaller pieces trailing the main mass. Usually there are insufficient data to permit estimates of the masses for these fragments, although for Innisfree five of six observed trails could be studied in some detail. We wish to estimate the total mass of a fall by applying a constant factor to the mass derived from Eq. 1 for the largest fragment. For large falls with a total mass exceeding 100 kg, the largest piece may represent 10 percent or less of the total (Bruderheim, Murchison, Allende falls). Our observations near the 1-kg size range, however, almost invariably show one major piece. We believe the recovery was unusually complete for Innisfree, where the 2-kg main mass represents 0.45 of the total mass of nine recovered fragments. We adopt a factor of 2.0 to convert the estimated mass of the main fragment to the total mass of a typical fall.

In a recent study of the orbits of meteorites observed by camera networks (*11*), Halliday *et al.* presented data on 50 MORP fireballs for which the estimated dynamic mass of the largest fragment was at least 50 g. Of these, 32 were observed in good sky conditions. By 1 April 1983 we had observed 67 events that met the 50-g mass limit, of which 43 were observed in clear-sky conditions, and these constitute our sample for estimating the frequency of falls. The total mass for each fall is taken to be twice the dynamic mass of the main piece, as discussed above.

The relative rates of meteorite falls were examined by Halliday and Griffin (*12*) as a function of time of day, time of year, and geographic latitude, based on a distribution of meteorite orbits chosen to agree with network data. They found that the average rate during darkness at the latitude of the MORP network should be 0.99 of the average rate for the whole earth over the year. A reduction of 1 percent in the MORP coverage of square kilometer-hours should then convert the rates to a worldwide average.

To derive the actual fall rates, we plot the number of events N' for which the total mass exceeds m grams, in the form $\log N'$ plotted against $\log m$. If the distribution can be represented by a simple power law such as

$$N' = A^{1-s} \tag{2}$$

then the plot will be linear with a slope of $1 - s$, where s is the mass distribution index (*13*). Figure 1 shows a plot for our 43 events, covering the mass range from 0.114 to 12.4 kg. A straight line with a slope of -0.69 represents the data quite well. The corresponding value of s is 1.69, and extreme slopes of lines through the data confine s to between 1.61 and 1.77. The ordinate scale has been converted to $\log N$ instead of $\log N'$, where N is the number of events depositing a total mass of meteorites on the ground exceeding m grams in 10^6 km^2 in 1 year. (An area of 10^6 km^2 is the area of Egypt or 0.11 of the area of the United States.) The conversion to $\log N$ includes the 1 percent correction for the latitude effect, and our result is then

$$\log N = -0.689 \log m + 2.967 \tag{3}$$

For comparison, Fig. 1 also shows the relation derived by Hawkins (*1*), the frequencies of falls from Brown (*3*) and Millard (*4*), and also the relation of Hughes (*14*) for stone meteorite falls, based on the use of a modification of Brown's data. Our result agrees with Hawkins's curve near 10 kg, but his steeper slope would predict an order of magnitude more events if the curves are extrapolated to a mass of 10 g. To extrapolate to such small masses is not unreasonable, in view of the size distribution found in recent Antarctic recoveries where the mode of the distribution is

Table 1. Predicted annual number of meteorite falls.

Area	Minimum total mass for each fall		
	0.1 kg	1 kg	10 kg
10^6 km^2	39	7.9	1.6
North America	920	190	38
Land area of the earth	5,800	1,200	240
Entire earth	19,000	4,100	830

about 15 g (*15*). The values of Brown and Millard refer to any meteorite "large enough to be found and picked up" (*3*), but the data suffer severely from incomplete recovery for masses below 8 kg although some very small events are included. Brown's value (*3*) appears to be low, whereas Millard's revision is high unless the data were essentially complete down to masses of 0.4 kg. Hughes's distribution is close to that of Hawkins but relies on an assumed diurnal variation in fall rates, which is not supported by the results of recent studies (*12*).

Our data refer to meteorite masses at the bottom of the atmosphere, but there is also considerable interest in the flux

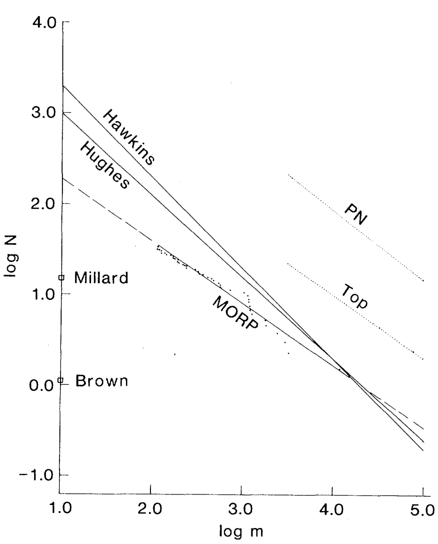

Fig. 1. Plot of $\log N$ versus $\log m$, where N is the number of events per year in 10^6 km^2 with mass exceeding m grams. The instrumental results presented here are labeled "MORP"; the distributions derived by Hawkins (*1*) and by Hughes (*14*) and the frequencies published by Brown (*3*) and by Millard (*4*) are shown for comparison. All of these refer to meteorite masses on the ground. Dashed portions of the MORP line are extrapolations beyond the observed mass range. The dotted line labeled "Top" indicates the flux entering the atmosphere for those fireballs that produce meteorites on the ground, while the line labeled "PN" is the estimate of the total flux entering the atmosphere from Prairie Network data (*8*).

entering the atmosphere, for such comparisons as impact rates on the moon (*16*) or the mass distribution index of large fireballs (*17*). Using ReVelle's curves for the percentage of mass loss as a function of size and velocity (*18*, figure 10), we have estimated the initial masses for our 43 events. The distribution is shown by the line labeled "Top" in Fig. 1, which fits the data points for initial masses larger than $\log m = 3.5$. The indicated slope is once again -0.69, and this flux may be represented by changing the last term of Eq. 3 from 2.967 to 3.76. On average, the logarithm of the residual mass is 1.04 less than the logarithm of the initial mass, corresponding to a "mean survival rate" of 9 percent of the mass for our 43 events, which had a mean entry velocity of 17.3 km sec^{-1}.

The flux curve of McCrosky and Ceplecha (*8*) from Prairie Network observations is shown as the line labeled "PN" in Fig. 1 and was derived from photometric masses of the meteoroids. At $\log m = 4.0$, the PN curve is higher than our "Top" curve by 0.94 in $\log N$. [McCrosky and Ceplecha plotted their observed nighttime rate, which has since been shown (*12*) to be very close to the 24-hour average, but they reduced the values of Hawkins and Brown by a factor of 2 in the belief that the flux during darkness was well below average.] Our "Top" line includes only those meteoroids that appear to have dropped meteorites and does not include stony material completely consumed in flight or the more fragile material normally associated with carbonaceous chondrites or cometary fireballs. Although the reductions are not complete, an examination of an unbiased selection of 90 MORP fireballs suggests that the meteorite events comprise about a third of those fireballs that endure at least 2 seconds and that raising N by a factor of 3 above "Top" would approximate the total flux entering the atmosphere. The remaining factor of 3 between the PN curve and our estimated flux is presumably accounted for by the low value of the luminous efficiency used in the PN reductions, which led to an overestimate of the masses (*19*).

Earlier attempts to define the frequency of meteorite falls suffer from the assumptions that had to be made concerning the inefficiency of the detection system (an uncertainty in the ordinate of Fig. 1) plus the unknown and serious effect of only partial recovery of the various fragments from each fall (an uncertainty in the abscissa). What are the residual uncertainties with the data from a camera network? The first problem is now quite minor, since the number of events observed is not in much doubt. Only intervals with good observing conditions are counted; for example, the Innisfree meteorite event is not included in this analysis since only one camera station had good conditions. The uncertainties lie in the calibration of the masses. Effects due to the shape of the largest fragment could lead to errors as large as a factor of 3 or 4. Somewhat larger factors would apply when the density of a stone meteorite is assumed for an object that is actually an iron meteorite, but iron and stony-iron meteorites combined account for only 4.4 percent of meteorites from well-classified witnessed falls (*20*). The systematic errors in placing our mass scale should be less than a factor of 2 due to this problem. There could be another error in our use of the factor 2 to convert the mass of the main fragment to the total mass of the fall. By definition the correct factor must exceed 1 and is unlikely to exceed 4, so the mass scale should not be incorrectly positioned by more than a factor of 2 or 3 by the sum of these two effects. As far as we know, our result is the first to be based on instrumental observations of fireballs. The slope of our plot in Fig. 1 should be considerably more secure than that of earlier plots, and uncertainties in log N should not exceed 0.4 over the observed mass range.

Table 1 converts our data to the annual number of meteorite falls expected in specific areas on the earth. For values of log m between 2.0 and 6.0, the total mass deposited on the ground is 142 kg year^{-1} in 10^6 km^2. With a normal recovery rate of one or two dozen meteorites per year for the world, excluding the Antarctic recoveries, it is obvious that a very small portion of the potential harvest is ever located.

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Fossils of Hydrothermal Vent Worms from Cretaceous Sulfide Ores of the Samail Ophiolite, Oman

Abstract. *Fossil worm tubes of Cretaceous age preserved in the Bayda massive sulfide deposit of the Samail ophiolite, Oman, are apparently the first documented examples of fossils embedded in massive sulfide deposits from the geologic record. The geologic setting of the Bayda deposit and the distinctive mineralogic and textural features of the fossiliferous samples suggest that the Bayda sulfide deposit and fossil fauna are remnants of a Cretaceous sea-floor hydrothermal vent similar to modern hot springs on the East Pacific Rise and the Juan de Fuca Ridge.*

Deep-sea hot springs surrounded by metal-rich mineral deposits and communities of unusual organisms have been found recently at several hydrothermal vent fields distributed along the crests of volcanic spreading ridges throughout the eastern Pacific Ocean (*1–6*). These hot springs evidently are common features of medium- to fast-rate spreading centers, where heat from rising magma beneath the spreading axis drives hydrothermal convection of seawater through newly solidified oceanic crust. The circulating seawater is modified by heat and reaction with the basaltic host rock into an oxygen-depleted acidic solution enriched in transition metals and hydrogen sulfide (*7, 8*). When solutions of this composition vent onto the sea floor, a suite of sulfide minerals rich in iron, zinc, and copper is deposited locally (*2, 3, 9–12*). The reduced sulfur in the outflowing hydrothermal solutions is a source of chemical energy for chemolithotrophic bacteria, which apparently constitute the base of a food chain for dense faunal communities clustered around the vents (*13–16*). Although the faunal composition of these communities varies among different vent areas, most com-

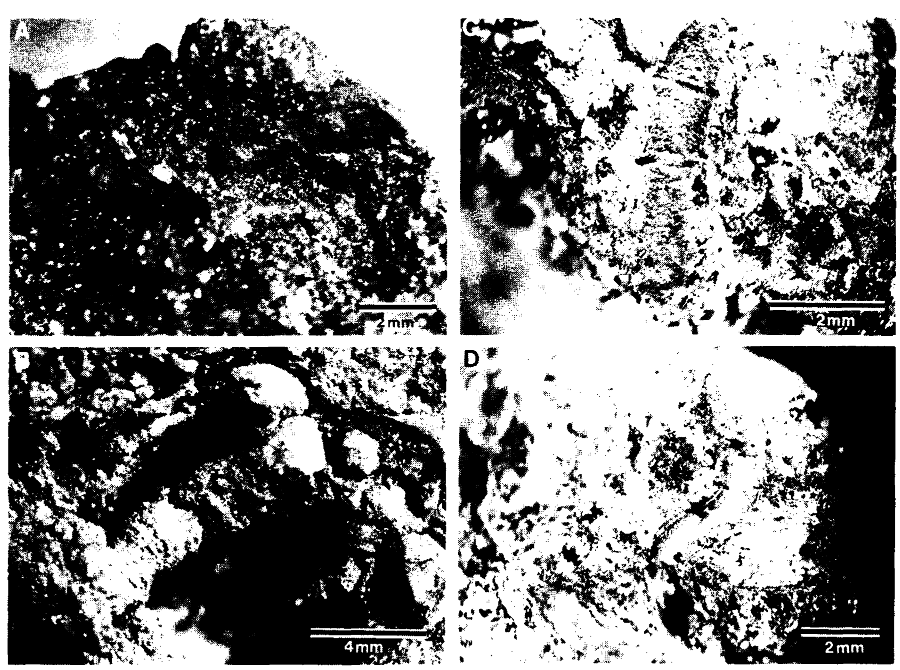

Fig. 1. Fossil worm tube molds and casts in massive zinc- and iron-sulfide from the Bayda mine. (A) Two pyritic tube casts exhibiting longitudinal ornamentation preserved in a sphalerite-quartz matrix. (B) Pyritic tube cast showing numerous closely spaced annulations preserved in a pyrite matrix. (C) Tube mold displaying two prominent annulations. (D) Sinuous tube mold showing two prominent annulations.