

The flux of meteorites on the Earth's surface

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(Received 27 February 1989; accepted in revised form 28 July 1989)

Abstract—We derive values for the number and size distributions of meteorites landing on Earth from a study of photographic observations of bright fireballs with the Canadian camera network. The observations cover 11 years from 1974 to 1985. This analysis is an extension of a previous study and represents a 30% increase in the data base.

The cumulative plot of numbers vs estimated mass of the largest fragment for each event shows a change in slope near 0.6 kg due to a deficiency of small meteorites surviving from the group of slow fireballs. The change can be explained by a mass dependence of the fraction of the incoming object that survives as the largest fragment. For larger falls, the main mass appears to represent a decreasing fraction of the total mass of the surviving meteorites and estimates of these effects are used to derive the final distribution of both main masses and total masses of meteoritic events. For total masses greater than 1 kg the population index is 1.82, close to previous estimates. About 9 events per year drop at least 1 kg of meteorites in an area of a million square km and the same area receives an annual influx of 54 kg from meteorite events with total masses between 0.01 and 100 kg.

There is sufficient confidence in these results that they may be used for comparison of the present flux of meteorites with values inferred for other times, in particular the long accumulation times of the Antarctic meteorite collections.

INTRODUCTION

SEVERAL ATTEMPTS HAVE BEEN MADE during the past three decades to determine the frequency of meteorite falls on the Earth as a function of the size of the meteorites. Our preliminary study of data from the MORP (Meteorite Observation and Recovery Project) camera network in western Canada (Halliday *et al.*, 1984) included references to the earlier work. Our results were based on 43 events observed in a carefully monitored interval of clear-sky conditions during nine years, up to 31 March 1983. Each event is believed to have dropped a meteorite with a main mass of at least 50 grams. The present paper extends the period of observation by two years, to the end of observations when the network was closed on 31 March 1985.

OBSERVATIONAL DATA

As described in our earlier paper, a fireball was eligible for inclusion in the flux survey if it was observed by at least two camera stations at an elevation of 8° or higher in sky conditions that were rated as essentially clear. The effective area of observation for the network was $1.26 \times 10^6 \text{ km}^2$ and the total coverage in the 11 years was $1.51 \times 10^{10} \text{ km}^2\text{-hours}$, an increase of 30% over the previous study. A total of 56 events qualify as meteorite candidates observed in suitable sky conditions, also an increase of 30% from the previous total of 43 fireballs.

Table 1 lists the MORP numbers and the values of m_t , the terminal mass (in grams) of the largest surviving fragment and the initial velocity, v_∞ , in km s^{-1} . The photographic trails usually show clear positions for the ends of individual segments of the leading, most massive object whereas, when they are visible at all, trailing fragments are frequently confused by overlap with the main trail. Dynamical masses for the main piece of each event are estimated late in the trail from the observed deceleration and known atmospheric densities. These are shown for the 56 fireballs in Table 1, arranged in order of decreasing mass. Detailed descriptions have been published for 32 of these 56 events (Halliday *et al.*, 1989a) including all 18 with values of m_t greater than 0.5 kg. It is intended to publish the orbits and parameters of the atmospheric paths for 366 MORP meteors and Table 1 would permit the objects used in the flux analysis to be identified for correlation with the orbits.

ANALYSIS OF THE DATA

Cumulative distributions are a convenient way to describe the distribution of the data, in this case the number of meteorite events larger than any chosen mass limit that occur per year in a standard area, taken as 10^6 km^2 . At the effective latitude of the Canadian camera network (52° N) we expect the rate of meteorite falls per unit area at night to be 0.99 of the mean daily rate for the entire Earth, averaged throughout the year in both cases (Halliday and Griffin, 1982). An area of 10^6 km^2 has an annual exposure of $8.77 \times 10^9 \text{ km}^2\text{-hours}$, so our total coverage is equivalent to 1.72 years over an area of 10^6 km^2 . If N' is the number of events in Table 1 with mass greater than some value and N is the number of similar events per year in 10^6 km^2 , then the conversion from N' to N (including the small correction for the latitude effect) is given by:

$$\log N = \log N' - 0.23 \quad (1)$$

The cumulative plots we wish to study are logarithmic plots of numbers of events vs mass of the meteorites. Two such distributions are shown in Figs. 1 and 2. Fig. 1 is a plot of $\log N$ vs $\log m_t$ (in grams) for the 43 events in the earlier study. It is the same data plotted in fig. 1 of Halliday *et al.* (1984) except that the mass scale has been shifted by 0.30 since, at present, we are plotting values for the largest fragments, m_t , rather than assumed total masses, $m_T = 2m_t$. The straight line has a slope of -0.69 , as before. Fig. 2 is a cumulative plot of $\log N$ vs $\log m_t$ for the new group of 56 events. The suggestion of a change of slope near $\log m_t = 2.8$ is present in Fig. 1, but is more pronounced in Fig. 2. The data in Fig. 2 have been represented by two straight solid lines, for small and large masses, while the dashed line is the solid line of Fig. 1 for comparison.

There is no consistent shift between Figs. 1 and 2 in the values of N for a given mass, as is seen from the dashed line, which is still a good fit in Fig. 2 if a single line is used. The change in slope at $\log m_t = 2.8$ appears real, however, so we represent the MORP data by two equations, as follows.

If we apply equation (1) to convert to N , the cumulative number of events per 10^6 km^2 per year with a terminal mass of the main fragment larger than m_t (grams) then:

for values of m_t less than 600 grams:

TABLE 1. MORP flux meteorites in order of decreasing terminal mass, m_t (grams).

No.	m_t	v_∞	No.	m_t	v_∞	No.	m_t	v_∞
288	6200	12.4	498	360	13.7	591	98	20.4
544	5900	14.5	884	360	12.4	856	90	27.2
897	4400	25.1	751	280	18.9	368	86	20.1
545	1800	14.7	844	270	14.9	425	85	17.2
687	1600	16.7	503	240	14.8	305	81	16.4
364	1400	11.3	683	230	17.6	355	75	13.9
331	1300	13.3	345	210	17.4	138	73	17.4
174	1240	19.1	231	185	27.9	933	70	15.3
886	1100	13.8	888	170	25.5	676	69	22.3
565	920	13.3	171	165	18.1	903	65	19.5
792	880	17.3	771	160	17.1	227	63	16.1
626	770	13.5	977	160	23.3	540	63	12.4
172	620	12.5	511	150	18.1	163	60	18.6
672	600	13.7	654	120	13.8	193	57	22.7
189	590	14.5	669	120	20.6	241	57	16.7
207	560	17.9	346	115	15.7	892	57	29.3
261	520	12.4	303	110	14.1	169	50	12.6
930	520	13.4	840	100	23.6	604	50	29.0
937	380	17.9	287	98	23.4			

$$\log N = -0.53 \log m_t + 2.42 \quad (2)$$

and for values of m_t greater than 600 grams:

$$\log N = -1.00 \log m_t + 3.72 \quad (3)$$

We wish to devise a model to explain the change in slope at a mass of 600 grams. The mass distribution of asteroidal fragments arriving at the Earth is believed to obey a power law of the form given by Dohnanyi (1969) in his equation (67):

$$f(m) dm = A m^{-\alpha} dm \quad (4)$$

where $f(m)$ is the particle number density function, m is the mass and α is the population index, frequently denoted s by other authors. The population index is $1 -$ (slope of the line in a cumulative plot) and is close to $11/6$ or 1.83 for asteroidal debris, according to Dohnanyi.

As explained earlier, our observational data is a distribution of terminal mass estimates, m_t , for the largest surviving meteorite fragment from the observed events. If the distribution of meteorite-producing objects entering the atmosphere follows a simple power law but the distribution of m_t is best represented by differing power laws for large and small masses (Fig. 2) the change must be due to some mass dependence relating to ablation and fragmentation in the atmosphere.

ReVelle (1979) has shown that ablation changes significantly as a function of mass, due to a change in the relative importance of convective heat transfer (small bodies) and radiative heat transfer (larger bodies). In principle this could change the slope in our Fig. 2. ReVelle's fig. 10 shows that while the percent mass loss is strongly velocity dependent, there is a considerable range of sizes at each velocity where the change is slight with mass and this is just the mass range of our MORP data. Adopting equation (4) for the initial mass distribution we used the form of equation (5) below and divided the MORP data into five velocity groups. ReVelle's mass loss factor was applied to each group to obtain the distribution of surviving meteorite sizes, which was still quite linear in a cumulative plot.

If ablation does not explain the phenomenon then some fragmentation effect may be responsible. In our analysis of the statistics of 44 probable falls from the MORP network (Halliday *et al.*, 1989b) the fraction of the entry mass surviving as the largest recoverable fragment appeared to reach a maximum for

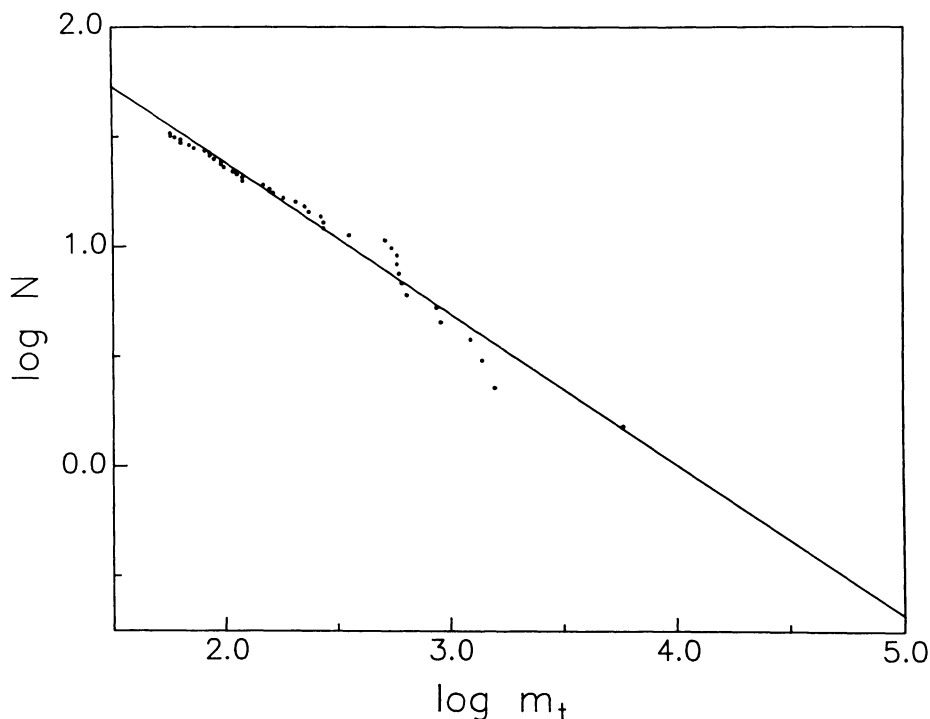


FIG. 1. Cumulative plot for the 43 events studied in 1984, showing $\log N$ vs $\log m_t$, where N is the number of events per year in 10^6 km^2 for which the main terminal mass had an estimate larger than m_t (grams). The straight line has a slope of -0.69 corresponding to a population index of 1.69 .

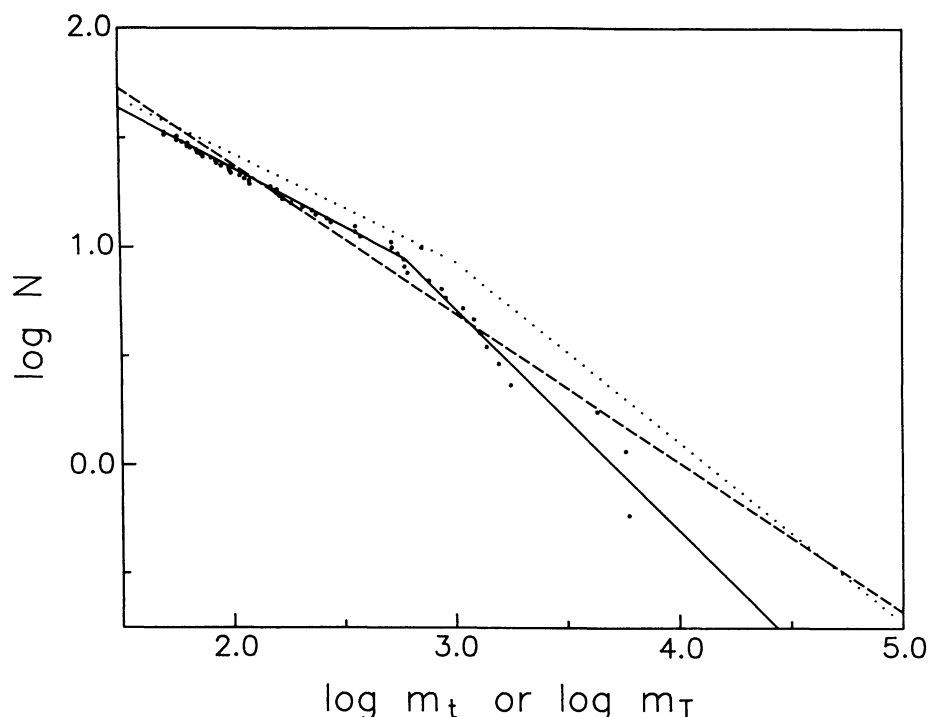


FIG. 2. Cumulative plot of $\log N$ vs $\log m_t$ (grams) for the 56 events of this paper, represented by the solid lines. The dashed line is the corresponding line from Fig. 1. The dotted line is the final plot of total masses, m_T (grams), as given by equations (6) and (7).

values of m_∞ , the initial entry mass, of a few kg (see fig. 5 of that paper). Large bodies maintain a higher velocity than small ones at any atmospheric height and will, therefore, experience somewhat more severe ablation. A more important effect, however, is greater fragmentation, aided by the greater dynamic load late in the flight, but the dominant factor is probably a network of pre-existing cracks in the meteoroid, as indicated by the fact that fragmentation begins not infrequently above 50 km height. The theoretical explanation for the poor survival of objects between 1 and 0.1 kg is not clear since the corresponding entry masses are too large for ReVelle's model to account for the greater loss.

Let us consider whether a maximum in the fraction of the mass surviving as the largest fragment can account for the change of slope in Fig. 2. In general, a linear relation between $\log m_t$ and $\log m_\infty$ would change the population index to a different, but still constant, value. A non-linear relation, such as the one implied by a maximum in the value of m_t/m_∞ , will introduce a curvature to the cumulative plot that may approximate the solid lines in Fig. 2.

We adopt Dohnanyi's population index of 1.83 for the incoming masses and express the cumulative distribution of these objects by:

$$\log n = -0.83 \log m_\infty + 5.0 \quad (5)$$

where n is the number of objects with initial mass greater than m_∞ (grams) and the constant is chosen to give a reasonably large population for purposes of the calculation. We divide the range in m_∞ into convenient bins and use equation (5) to determine the population in each bin. Since there is considerable dispersion in the values of m_t for a given value of m_∞ , we divide each bin into three groups containing the upper quartile, the middle half

and the lower quartile of the m_t values. A typical value of m_t was selected for each of these three groups for the various values of v_∞ , based on fig. 5 of Halliday *et al.* (1989b). Differing relations were tried since the data are scarce, especially for the larger entry masses. Table 2 shows an acceptable relation for the three ranges of m_t , as a function of m_∞ (both in kg). A cumulative distribution of m_t was formed using Table 2 and is shown in Figure 3, with the solid lines of Fig. 2 for comparison. An arbitrary constant has been added to all the ordinates to position the new distribution properly since the constant in equation (5) was also arbitrary.

The MORP data in Fig. 2 are represented by the two solid straight lines corresponding to population indices of 1.53 for small masses and 2.00 for larger ones. The calculated data points in Fig. 3 are not a perfect match to the MORP data but the agreement is reasonable. It is clear that the distribution of largest surviving fragments from the MORP observations may be the result of an incoming distribution such as the one predicted by Dohnanyi, modified by a survival relationship similar to the one shown in Table 2.

If the distribution of terminal masses in Table 1 is examined as a function of initial velocity, a surprising result emerges. The deficiency of small meteorites (m_t less than about 0.4 kg) is confined entirely to the slow fireballs with $v_\infty < 16 \text{ km s}^{-1}$. The cumulative distribution for faster objects shows no bend at all, whereas the observed number of slow objects with m_t between 100 and 400 grams is less than one-fifth the number that would be required to remove the bend in Fig. 2.

One might suspect that these slow and relatively small objects are too faint to be detected at great range from the cameras and the deficiency could be an observational selection effect. Examination of the ranges from the camera stations for the small,

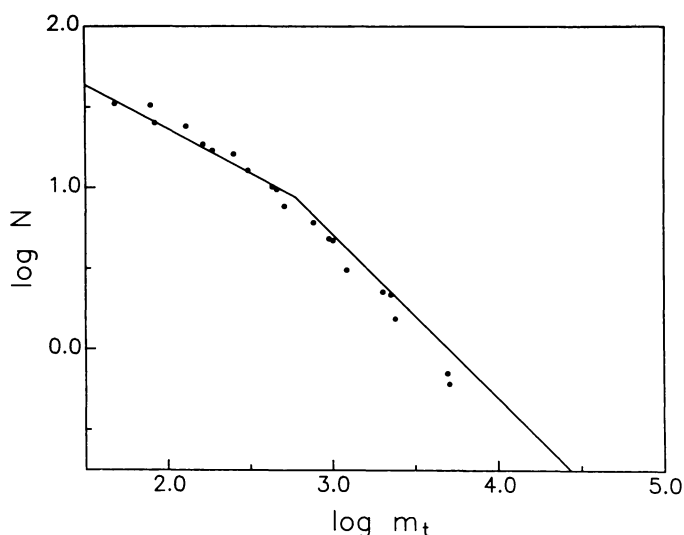


FIG. 3. The solid lines represent the cumulative plot of $\log m_t$, as in Fig. 2. The dots show the shape of the distribution derived by application of the survival factors from Table 2 to the population index predicted by Dohnanyi.

slow objects that were observed showed median values slightly greater than the median for the 44 best events (Halliday *et al.*, 1989b) hence the sensitivity of the camera system should be entirely adequate.

Is there a deficiency of meteoroids with entry masses in the appropriate range to produce small values of m_t ? We can plot the cumulative distribution of entry masses for the 44 objects in tables I and II of Halliday *et al.* (1989a) and we note that there are 12 other events in table III. These are the 56 events believed to have dropped main masses greater than 0.1 kg, even if they were observed under poor conditions and were thus ineligible for the flux study. Dohnanyi's population index fits the data very well for entry masses between 3 and 30 kg. There is a slight surplus of very large masses and an apparent deficiency of small ones, but this deficiency may be the result of the lower limit on m_t . An entry mass of 1 kg with $m_t/m_\infty < 0.1$ would not be included, *i.e.*, the large area in the lower left corner of fig. 5 (Halliday *et al.*, 1989b) appears capable of explaining the turnover in the m_∞ plot.

We are left with the possibility that the deficiency of small values of m_t for slow objects may be caused in some way by fragmentation. If initial masses of at least a few kg tend to fracture into a distribution of sizes with a modest clustering of largest fragments near 1 or 2 kg, then ablation and further frag-

TABLE 2. The adopted distribution of terminal masses, m_t , for various entry masses, m_∞ .

m_∞ (kg)	m_t (kg)		
	upper quartile	middle half	lower quartile
1000	280.	110.	22.
300	83.	35.	6.6
100	38.	16.	3.0
30	16.	6.4	1.1
10	6.2	2.3	0.33
3	1.5	0.43	0.035
1	0.24	0.029	—

TABLE 3. Assumed values of T , the ratio of total mass to largest fragment, m_t .

m_t (kg)	T
0.05	1.25
0.1	1.3
0.3	1.5
1.0	1.8
3.0	2.3
6.0	2.75
10.0	3.2
20.0	4.0

mentation may be more effective at smearing out the final distribution for faster objects. The largest fragments from slow fireballs may survive in the 0.4 to 2 kg range, with fewer cases for which the largest piece has been reduced to the order of 0.1 kg. While this argument is scarcely compelling, fragmentation is expected to play a major role in the actual mechanism that explains the shortage of small main masses from slow fireballs.

TOTAL MASSES ON THE GROUND

Essentially all meteorites fracture during their atmospheric flight and the magnitude of a meteorite event is probably best represented by the total mass of the surviving pieces on the ground. Our values of m_t are estimates of the mass of the largest piece and some assumption is required to convert these values to total masses.

In our earlier study we adopted a value of 2.0 as the ratio of the total mass of meteorites to the largest single mass. It was recognized that this value is probably too small for major meteorite events but it was close to the well-determined value of 2.2 for the Innisfree fall, which had a total recovery of 4.58 kg (Halliday *et al.*, 1981). From experience with the MORP pictures it appears that small falls, with a main mass less than perhaps 0.5 kg, are likely to have one piece that represents a very high proportion of the surviving material. This may be understood if fragmentation occurs while the velocity is still high enough that ablation is very active. A lesser fragment, representing the same fraction of the total mass in flight in two cases, may be completely consumed by ablation in a small event whereas it could survive as one of several small meteorites in a large event. On this basis we adopt the values of T shown in Table 3, where T is the ratio of the total surviving mass to that of the largest fragment, m_t . Although T is certainly not well determined, we believe Table 3 is an improvement over the previous use of the constant value of 2.0.

If m_T is the total mass of meteorites to reach the ground in any event, then we derive the distribution of m_T from the solid lines in Fig. 2 combined with the factors in Table 3. For any value of m_t , each event that exceeded m_t in mass will have a total mass m_T that is equal to or larger than $m_t \times T$, where T is found from the curve defined by Table 3. In other words, the cumulative plot of m_t is found by adding $\log T$ to the corresponding abscissa, m_t , in Fig. 2. The dotted lines in Fig. 2 represent this plot of m_T . This cumulative distribution of the total mass of meteorites to reach the ground, analogous to equations (2) and (3) for main masses only, is given by:

for values of m_T less than 1030 grams,

$$\log N = -0.49 \log m_T + 2.41 \quad (6)$$

and for values of m_T greater than 1030 grams,

$$\log N = -0.82 \log m_T + 3.40 \quad (7)$$

Equations (6) and (7) replace equation (3) of our earlier analysis (Halliday *et al.*, 1984).

Table 4 shows the same result in tabular form, listing the number of events per year that deposit a total mass of meteorites equal to or greater than each mass value, in an area of a million square km. The final column, ΣM , is an estimate of the total mass of meteorites to reach the ground for falls with individual masses between 10 grams and any listed value of m_T . For example, 26 kg per year fall in 10^6 km² in events where each fall has a total mass between 10 grams and 10 kg. Note that, for a population index less than 2.0, the largest contributions to the total mass come from the rare events with very large masses, so the integrated values in Table 4 are the values between a threshold of 10 grams and the various tabulated values of m_T .

DISCUSSION

Based on accurate observational data, we have derived expressions for the numbers of meteorites and their mass distribution presently arriving on the Earth. This may be useful in comparisons of statistics from collections in Antarctica or wind-eroded exposures such as found in arid regions of the American southwest. It may also be useful in estimating the efficiency of meteorite recovery in various locations and times from the data in meteorite catalogs. It is *not* the distribution of very small astronomical bodies encountered by the Earth in its orbital motion, bodies that represent some mixture of cometary and asteroidal debris. An estimate of this flux may be available from further studies of our data, but for the present we have shown that the population of meteorites on the ground is compatible with the expected mass distribution of small solar system objects.

The values for the flux of meteorites derived in this paper from 11 years of data are very similar to the earlier result that was based on a smaller sample. The data in Table 1 may include a few small masses that are doubtful meteorite events, but at this end of our mass range there are also likely to be a few genuine meteorites with compensating underestimates of their end masses. It is perhaps surprising that the data points in Fig. 2 are still linear at a mass of 50 grams and show no turnover due to incompleteness of the sample.

Our best estimates for the size distributions of main masses and total masses (Fig. 2) show bends in the cumulative distributions near masses of 1 kg. We have shown how this may be the result of the fact that the main mass of a fall represents a varying fraction of both the incoming mass and the total mass of meteorites, as we consider events in different mass ranges. The bend in the distribution is caused by a deficiency of small meteorites from slow fireballs and we suggest this is due to some poorly understood aspect of fragmentation.

The revised distribution, given by equations (6) and (7), predicts slightly more events for limiting masses between 0.63 and 2.02 kg than the previous power law (population index 1.69) but somewhat lower values outside this range. For larger masses, our population index of 1.82 is close to the value of 1.90 found

TABLE 4. Number of events per year in 10^6 km² with total mass of meteorites greater than m_T and the integrated masses in the range between 0.01 kg and m_T .

m_T (kg)	N	ΣM (kg)
0.1	58.	1.6
0.3	23.	3.3
1.0	8.7	6.8
3.0	3.5	14.
10.0	1.3	26.
30.0	0.54	37.
100.0	0.20	54.

by Hughes (1980) for stone meteorites (and happens to agree exactly with his value for irons).

Our previous discussion (Halliday *et al.*, 1984) of the possible magnitude of errors in our mass estimates is still valid, namely that individual values might be in error by factors as large as 3 or 4 but a *systematic* error larger than a factor of 2 is unlikely. Errors in the observed numbers of fireballs, *i.e.*, events that should have appeared in Table 1 but were missed in searching the films or selecting appropriate events for study, must be very small in comparison to the mass uncertainties.

The flux of meteorites reaching the Earth during the 11 years of our data has been determined from direct observations of the fireballs and estimates of the surviving masses, within the errors just mentioned. It is possible, but seems very unlikely to us, that this flux could change significantly over the interval of two or three centuries for which we have some statistical data on witnessed falls. Such data appear incapable of providing flux data that could claim to rival the precision of the direct observation of fireballs. The possibility of changes in the flux increases as we consider periods of a few millennia, such as might be sampled in dry areas with windblown soil erosion. It increases markedly again if we consider the much longer periods that appear to be involved in the collections of meteorites from the Antarctic (Lipschutz and Cassidy, 1986).

One recent report (Anonymous, 1988) discusses a flux estimate based on collections in areas of Texas and New Mexico that have been severely eroded by wind. The flux is reported to be very high, although the lower mass limit is not specified so a direct comparison with our data is not available. It is difficult to determine the effective lifetime against weathering in such collections and the value must also be calibrated as a function of mass. The most serious problem arises from the fact that each blowout area is small compared to a typical strewn field so each area samples many more falls than are representative of the area itself. One square meter of forest floor may contain leaves from ten different trees but it would be wrong to infer the density is 10 trees m⁻².

We stress that the direct observation of meteoritic fireballs in a known interval of observation has great advantages over any technique that relies on the study of meteoritic fragments. The flux derived in this paper for meteorites arriving between 1974 and 1985 cannot be in error by a large amount and certainly the number of meteorite falls cannot be revised upward to a point where it begins to rival the total number of meteors observed. Any estimate of the flux of meteorites over a long interval that differs greatly from the current values should, of course, be accompanied by at least some speculation on the reason for the change.

Acknowledgements—We gratefully acknowledge valuable suggestions and helpful comments on the manuscript by R. E. McCrosky, Bruce A. McIntosh and an anonymous referee.

Editorial handling: G. W. Wetherill.

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