METEORITE FALLS AND FINDS: SOME STATISTICS

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The statistics of meteorite falls and finds are presented. Histograms give the distribution of falls as a function of year, month and time of day. The distributions of the retrieved masses of fallen and found meteorites are given, as is also their distribution over the Earth's surface. The data for this analysis have been taken from the British Museum's Catalogue of Meteorites *(1966) and* Appendix *(1977).*

INTRODUCTION

Meteorites are continually falling through the Earth's atmosphere and most meteoritical scientists realise to their dismay that large numbers fall to ground completely unrecorded. The chance of one of these unrecorded falls being found subsequently is extremely small. This paper reviews the statistics of both meteorite falls and meteorite finds, with respect to time, mass and position, and brings up to date the excellent work done, for example, by Mason (1962), Leonard and Slanin (1941) and Brown (1960). Data for the 2310 meteorites listed by Hey (1966) and Hutchison, Bevan and Hall (1977) in the British Museum's *Catalogue of Meteorites* and *Appendix*, respectively, were fed into the University of Sheffield's computer and then sorted according to certain characteristics. Table 1 gives a crude breakdown of the numbers of meteorites in each class.

Table 1
The classification of the meteorites used in this analysis. The original data has been taken from Hey (1966) and Hutchison *et al.* (1977)
d stands for doubtful and v for very doubtful

Class	Falls			Finds			Totals
Irons	49	15d	5v	635	17d	1v	719
Stony irons	11	1d		66	4	1	83
Stones	794	39d	5v	567	13d	1v	1419
"unclassified"	4	63d	2v	2	13d	5v	89
							2310

TIME OF FALL

The number of recorded meteorite falls per five-year period between AD 1730 and AD 1975 are shown in Figure 1. The word 'fall' denotes the meteorite fragments which survive the passage through the atmosphere and, after landing, are large enough to be found and picked up. A steady increase occurred between 1800 and 1935, an increase which obviously reflected the increase in world population, the spreading of this population over the continents and the increase in the educational level and scientific inquisitiveness of this population. The decrease in the number of observed falls in the last few decades shown in Figure 1 is due in part to the time lag between a fall and its appearance in the record books. Intuitively one would expect the fall rate to continue increasing over the next century or so. Figure 1 however supports the tentative conclusion that this fall rate has become constant over the last few decades. This assumption leads to an expected fall rate of 60 ± 16 per decade.

The monthly variation in the occurrence of meteorite falls is shown in Figure 2. This histogram maximises between April and mid-October, and minimises between November and March. It will be shown later on that 88 percent of the falls have been recorded by northern hemisphere observers. So the variation shown in Figure 2 is caused in the main by the fact that the summer months in the northern hemisphere are more suitable for the sighting and recovery of fallen meteorites than the winter ones. Two other possibilities exist. Firstly, the orbits of the meteorite parent bodies might not be distributed uniformly with respect to the Earth's orbit and so the Earth encounters more meteorites over some ranges of solar longitude than others. This is thought to be unlikely. A very crude test of this supposition is to look at the distribution of the ascending nodes of asteroid orbits. Assuming that the origin of meteorites is closely linked to asteroids, a random distribution of asteroid nodes could be taken as circumstntial evidence that meteorite orbits are also randomly distributed in node and thus that the Earth actually intercepts equal number per unit time as it moves around its orbit. Figure 3 shows the asteroid node distribution. It is random.

The second possibility is caused by the apex effect. If meteorite 'out of atmosphere precursors' mainly have low inclination orbits (asteroids and short period comets do but observational selection is not absent from the data) more meteorites will be encountered by a specific hemisphere when the apex of the Earth's way is high above the horizon. For the northern hemisphere the apex is in the sky much longer during the summer than it is in the winter. The effect is the opposite for the southern hemisphere, but to date only 12 percent of the falls have occurred there.

The distribution of meteorites according to the local time of their fall is shown in Figure 4. There are 644 meteorites whose time of fall is well known. The distribution has a pronounced maximum between 1400 and 1800 hours and an equally pronounced minimum between 0000 and 0500 hours. Social bias is obviously a factor but the explanation is more complicated than 'more people are up and about during the day time than at night and therefore more meteorite falls are observed then'. Wetherill (1968) underlines the fact that the majority of meteorite falls have been observed by farmers working in the fields and their attentiveness should be independent of whether it is morning or afternoon. The hours between 0700 and 1800 have been shaded in in Figure 4, and it is plainly obvious that nearly twice as many meteorites fall per hour in the afternoon (1200-1800) than in the morning (0700-1200).

Wetherill (1968, 1969) interpreted this observation in terms of the orbits of the meteorite precursors and concludes that these orbits must be of low inclination with aphelia near the orbit of Jupiter and perihelia just within the orbit of the Earth. It is very instructive to compare the diurnal variation in the meteorite fall rate with the diurnal variation in the number of observed visual and radar detected meteors (see Hughes, 1974). The latter have preatmospheric meteoroids with much smaller masses but

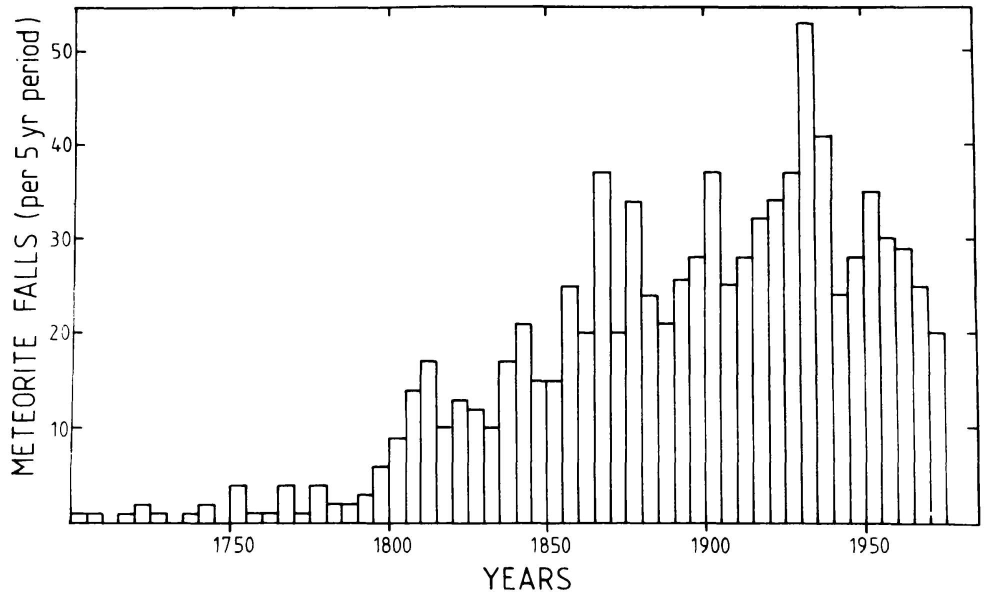

Fig. 1 **The number of recorded meteorite falls per five year period between AD 1700 and AD 1975.**

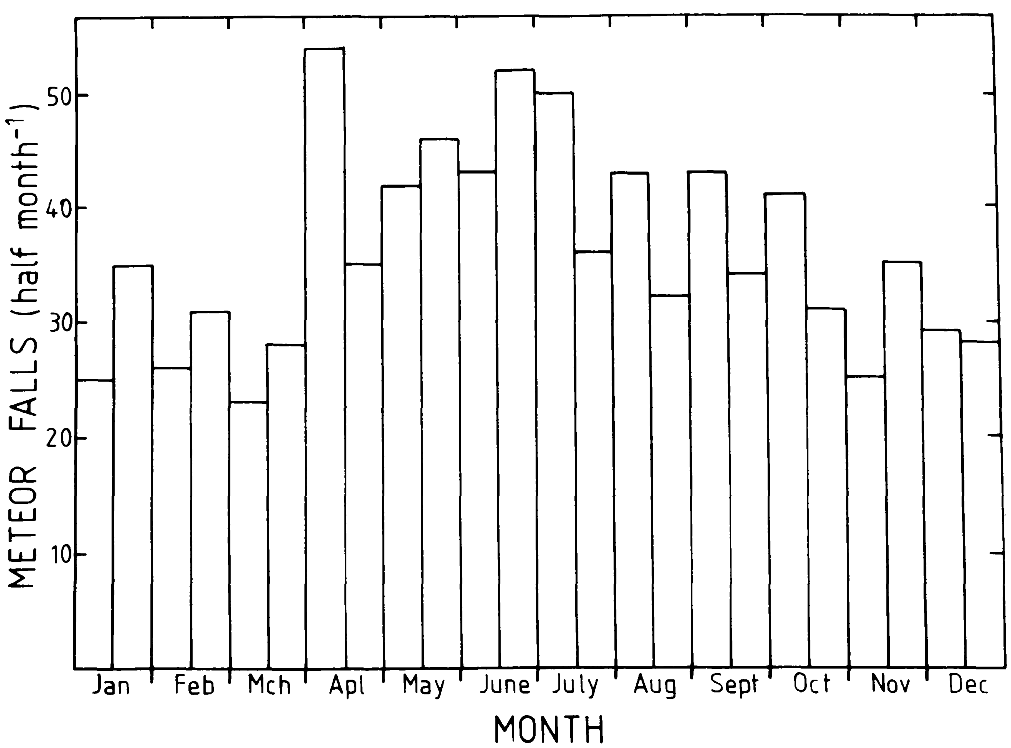

Fig. 2 **867 recorded meteorite falls sorted according to the time of year of the fall.**

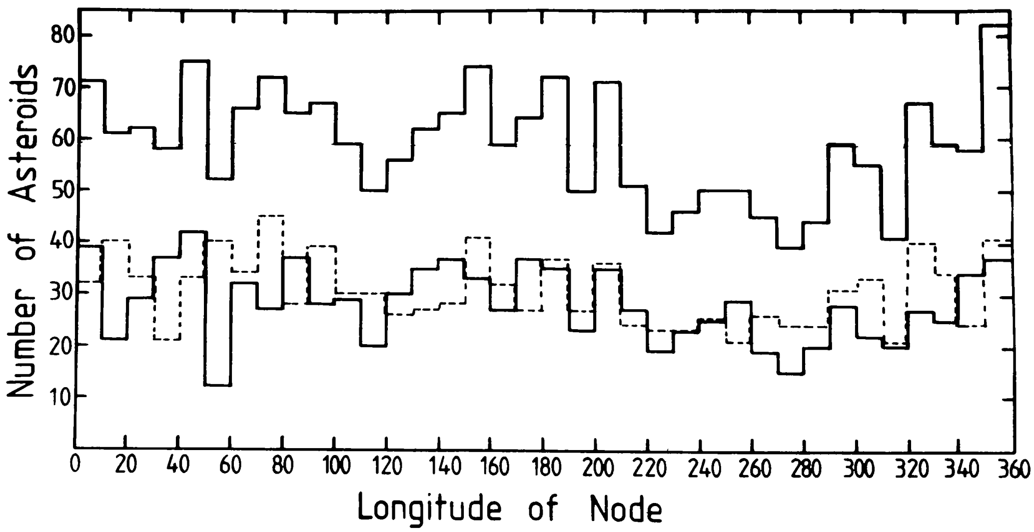

Fig. 3 The distribution of the ascending nodes of 2118 asteroids, the data coming from the list of oscillating orbital elements given by Bender (1979). The dashed line is for the first 1100, the lower full line for the remaining 1018, the upper full line is for all the asteroids. The thin line represents the mean.

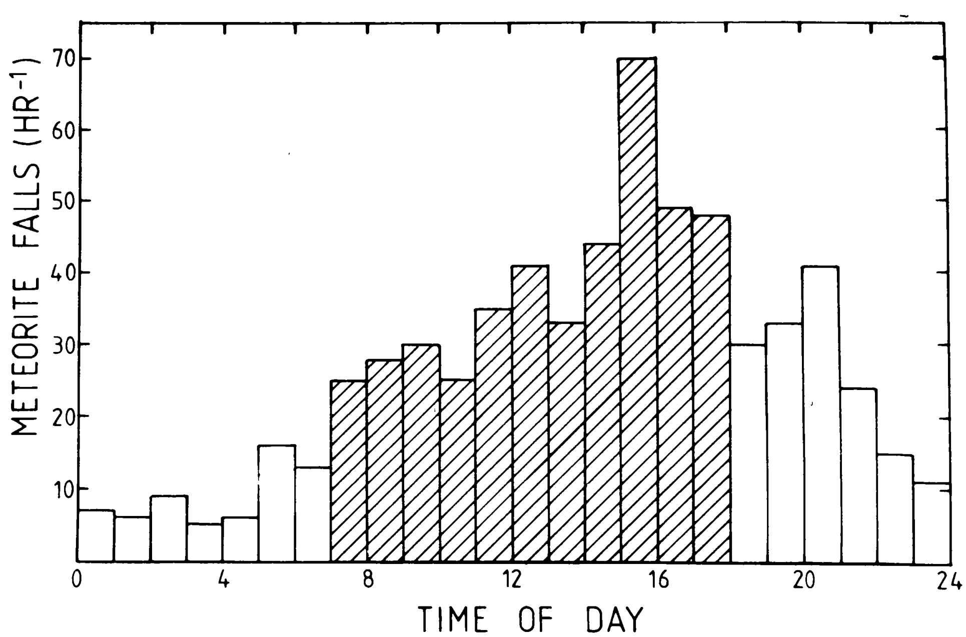

Fig. 4 644 meteorite falls for which the time of day of the fall is well known have been sorted according to that time. The hatched area covers the time of day when most people are awake and can reasonably be expected to observe a meteorite fall.

probably the same general orbital characteristics. The Earth with its heliocentric velocity of 30 km s^{-1} is continually 'ploughing' into the cosmic dust cloud which orbits the Sun. An observer on the forward side of the Earth, around 06.00 local time, will encounter more cosmic dust particles and thus observe more meteors than will an observer on the other side of the globe at 18.00 where the meteoroids have to catch up with the Earth and have a lower resultant geocentric velocity. The meteor curve is completely out of phase with the meteorite curve. It maximises around 04.00 local time and minimises at about 16.30 when the meteor rate has dropped to about 35 percent of the maximum rate. It is possible that the diurnal variation in the influx of meteorite precursors follows the meteor curve. However, for this to be the case the general intersection geometry between the Earth and comets (the main source of meteoroids) and the Earth and the meteorite precursors would have to be similar. These meteorite sources cannot just have Apollo-like orbits. Wetherill (1968) has calculated the distribution of the local times of fall for fragments of nine Apollo asteroids and shows that these orbits do not yield the observed afternoon excess. Simonenko has, however, been reported as finding that about a third of the meteorites falling on the Earth had precursors in Apollo-type orbits, while about two-thirds were in Amor-type orbits. About 10 percent of meteorites had very small orbits with semi-major axes less than 1 AU and were overtaken by the Earth near the aphelia of their orbits (see Levin 1977).

Another factor will introduce a difference between the visual meteor influx rate and the meteorite fall rate. Heide (1957) reminds us that the chance of survival and the actual mass percentage of the parent body that does survive to fall on the Earth's surface depends strongly on the entry velocity. Theory and observational data have been carefully knitted together by ReVelle (1979). The mass loss from a large meteorite during its hypersonic drag interaction with the Earth's atmosphere is approximately given by

$$m_f = m_o \, e^{-\frac{\bar{\sigma}}{2}(V_o^2 - V_f^2)} \tag{1}$$

where m_f and m_o are the final and initial meteorite mass, $\bar{\sigma}$ is the mean ablation parameter, V_o (km s^{-1}) is the meteorites' out-of-atmosphere geocentric velocity and V_f (km s^{-1}) is the velocity at which ablation ceases.

ReVelle compares entry predictions with the data from the Pribram, Lost City and Innisfree meteorite falls and fireball events. These meteorites were olivine-bronzite chondrite, olivine-bronzite chondrite and hypersthene chondrite, respectively. The conclusion is that the mean ablation parameter, $\bar{\sigma}$, is ~ 0.02 to $0.03\ s^2\,km^{-2}$ near the peak ablation altitude and that V_f is usually in the range 3 to 7 km s^{-1}.

Using equation 1 with $\bar{\sigma} = 0.025\ s^2\,km^{-2}$, $V_f = 5$ km s^{-1} and $m_o = 100$ kg the table below lists final mass values as a function of the out of atmosphere geocentric velocity.

V_o (km s^{-1})	12	15	20	25	35	45
m_f (kg) (m_o = 100 kg)	23	8	0.9	0.06	3×10^{-5}	1×10^{-9}

The atmosphere is obviously acting as an effective velocity filter, the meteorites reaching the Earth's surface having out-of-atmosphere precursors with low geocentric velocities or, in rare cases, radiant zenith angles very close to 90°.

FALL MASS

The masses of each meteorite fall and find have been carefully noted from the *Catalogue of Meteorites* and its *Appendix*. These have been used to produce a set of frequency plots. It must be remembered that the mass of the meteorite that is actually retrieved is, in many cases, a lower limit of the mass that actually hits the ground. It is very difficult to estimate the amounts of meteoritic material that are overlooked in the search.

Figures 5 and 6 show, on logarithmic scales, the numbers of iron and stony iron meteorite falls and finds that have retrieved masses in specific mass ranges. Typical mass ranges are 1.00-1.99 kg, 2.00-3.99 kg, 4.00-7.99 kg, etc. Figure 7 gives the data for stony meteorites, in this case subdivided into falls and finds.

All the distributions show a maximum in the frequency plot. Irons clearly maximise between 8 and 32 kg and the same can be said for stony irons. The stones seem to maximise at slightly smaller masses and Figure 7 shows the stone falls maximising between 2 and 4 kg whereas the maximum for the stone finds is slightly higher, between 4 and 8 kg. It is obviously slightly more difficult to discover a stone 'find' than it is to find a 'fall'.

The interpretation of Figures 5, 6 and 7 is best tackled from the high mass end. Over the range 16 to 16,000 kg it can clearly be seen that as the mass decreases so the numbers recorded increase. In this large mass range it is tempting to conclude that few meteorites

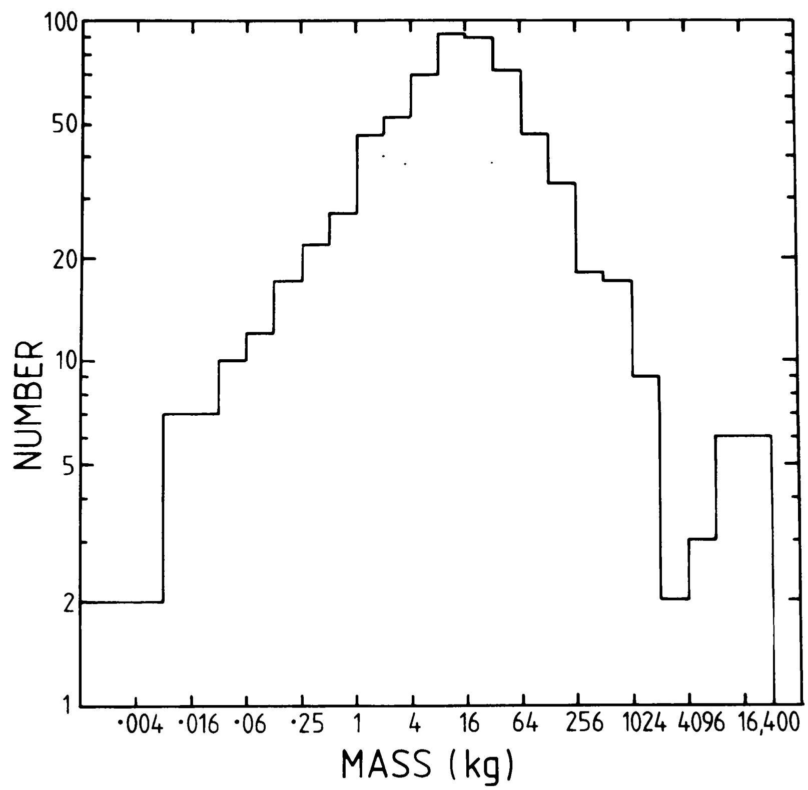

Fig. 5 **The distribution of iron meteorites, both falls and finds as a function of the retrieved mass. This figure contains the masses of 667 meteorites.**

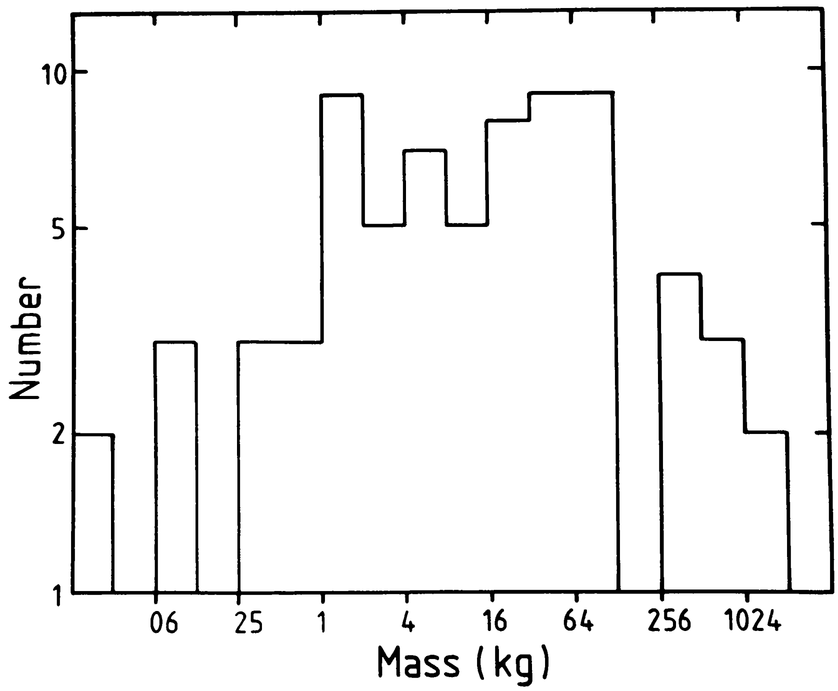

Fig. 6 **The mass distribution of the 77 catalogued stony iron meteorites.**

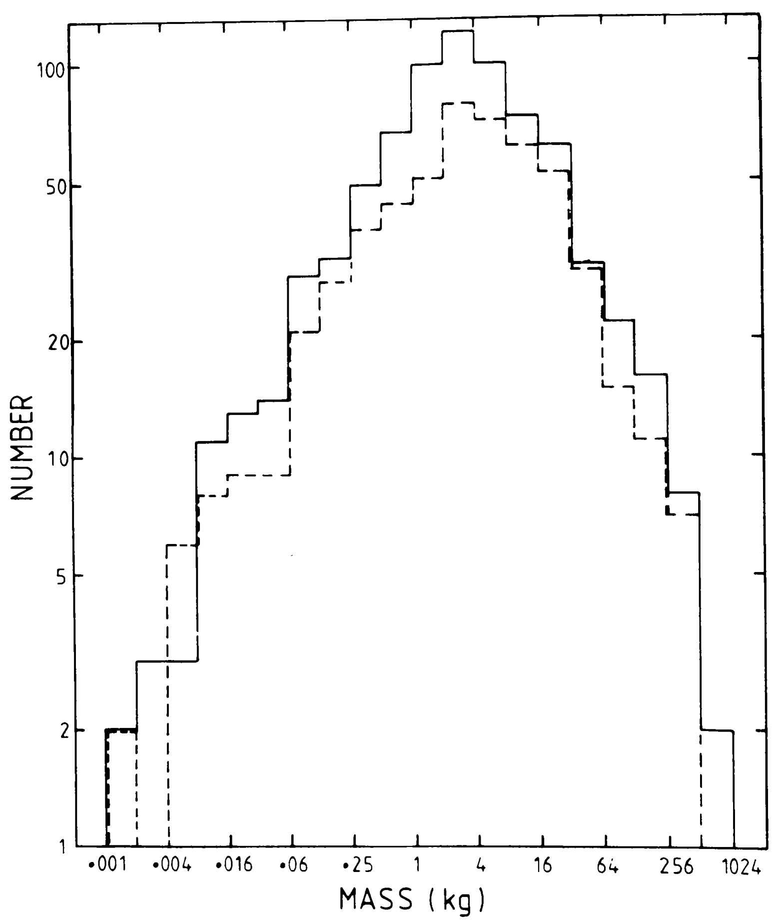

Fig. 7 **The mass distrubiton of stone meteorites. The full line represents the data from 755 recorded falls. The dashed line represents the data from 548 recorded finds.**

are missed and that the three histograms closely mirror the actual distribution. Two factors affect the lower mass data. Firstly, the probability of recovering and finding small meteorites on the ground becomes less and less as the size and mass decrease. Secondly, the mass loss of the parent body as it travels through the atmosphere depends in a complicated fashion on such factors as entry velocity, inclination of track to the vertical, meteorite composition and initial mass. It would be completely incorrect to assume that meteorite precursors lose a fixed percentage of their mass on entry (as was done by Hawkins, 1960. This means that many entries result in complete attrition and thus in no detectable meteorites, this being especially true as the mass decreases. The quasi-linear trend of the data in the high mass region of Figures 5, 6 and 7 cannot be wantonly extrapolated to low masses to give, by subtraction of the observed low mass recoveries, an indication of the numbers of small meteorites that are overlooked. It must also be stressed that the mass distribution of the recovered meteorites can bear scant similarity to the mass distribution of the precursors (see Hughes, 1980) and that comparisons between the mass distribution indices of meteorite and for example asteroids (see Brown, 1960) tell us very little about the source of meteorites. One of the better ways of representing the frequency distribution of meteorites as a function of retrieved mass is to use the mass distribution index, s. If N is the number of particles with mass greater than m then the mass distribution index, s, at any mass, is defined by the formula

$$N = A\ m^{1-s}$$

where A is a constant.

The high mass data given in Figures 5, 6 and 7 has been converted into cumulative numbers and Figure 8 shows a series of plots of log N as a function of log m. These plots have gradients of (1 - s). The lengths of the lines indicate the mass ranges used to obtain the s values. The resulting mass distribution indices are as follows, irons 1.62 ± 0.04, stony irons 1.59 ± 0.04, stone falls 1.80 ± 0.04 and stone finds 1.88 ± 0.03.

Due to the effect of atmospheric ablation and specifically to the fact that this ablation is a function of such things as mass, velocity, composition and entry angle, the mass distribution of the meteorites on the ground bears very little relation to the mass distribution of the out-of-atmosphere precursors. Asteroids and comets have been historically linked with meteorites. Large asteroids have been found (Hughes, 1981) to have a mass distribution index of 1.58 (for the few objects with diameters, D, greater than 260 km) and 2.24 for those with $150\text{ km} < D < 260\text{ km}$. It is only at such diameters that there is reasonable confidence that *all* the asteroids have been detected. Obviously the large majority of meteorites originate from precursors that are much smaller than 150 km but the statistics are far from complete in this size region. The nuclei of comets have been found to have mass distribution indices of about 1.64 ± 0.2 (Hughes and Daniels, 1980). Dohnanyi (1978) found that the products of a fragmentation event theoretically should have a mass distribution index of around 1.8.

DISTRIBUTION OF FALL AND FIND SITES

The distribution of these sites on the land masses of the Earth bear very limited relationship to the actual number of meteorites that fall to unit area of the Earth per unit time or to the numbers of meteorites that have fallen to the Earth during history and are

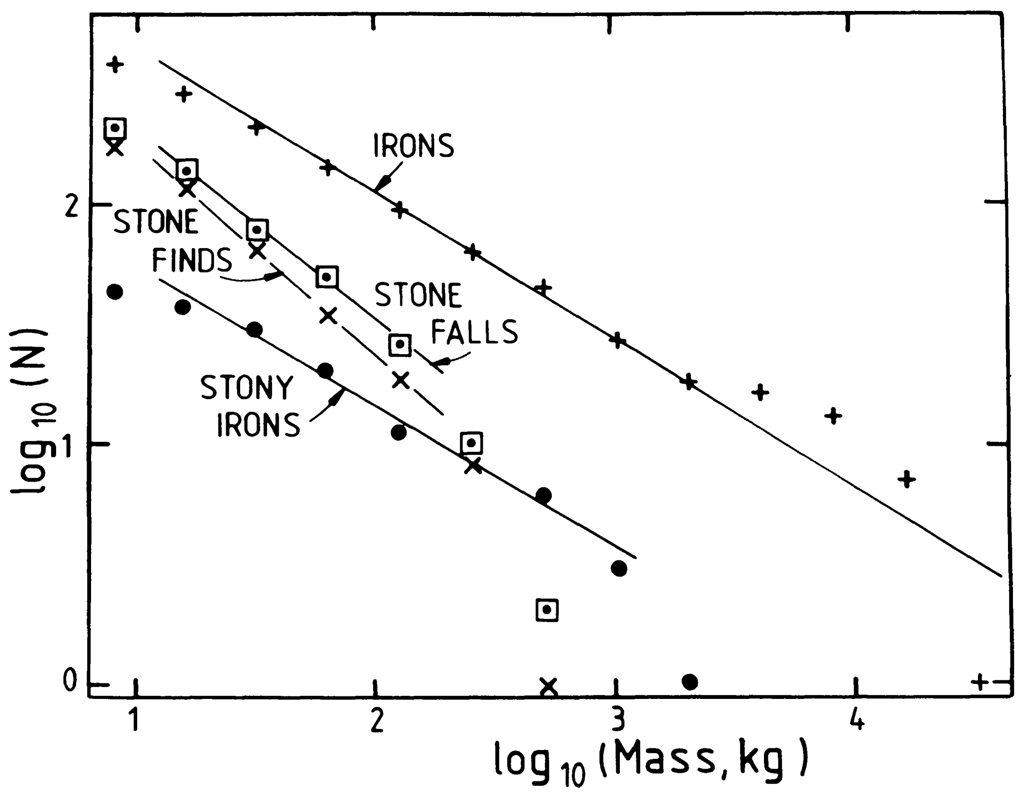

Fig. 8 **A logarithmic plot of the cumulative number of retrieved meteorites, N, as a function of mass, m. The gradient of the curves is (1-s) where s is the mass distribution index.**

there on the surface undiscovered. Figure 9 shows the fall sites. The fall distribution has a striking similarity to the distribution of regions of high population, intensive agriculture and scientific sophistication. The regions of maximum observed fall rates are Europe (excluding Norway, Sweden and the U.S.S.R.), with 0.30 ± 0.02 falls yr^{-1} $(10^6\ km^2)^{-1}$, Northern India (Uttar Pradesh, Bihar, West Bengal, Punjab and East Pakistan) with 0.49 ± 0.06 and Japan (excluding Hokkaido) with 0.66 ± 0.14. These figures have been taken from Millard, 1963.

The actual rate of fall of meteorites to the Earth's surface will be considerably higher than the values given above. Advancing from the work of Millard (1963), Hughes (1980) calculated that the actual rate of fall would be about 90 falls yr^{-1} $(10^6\ km^2)^{-1}$. The mass distribution of these meteorites would still have the form of Figures 5, 6 and 7.

The fall rate is large. If applied to the British Isles it predicts that about 5000 meteorites have fallen in the last 200 years. Only 20 were recovered. The subject of the meteorite influx rate is going to be considered in a subsequent paper.

It is extremely difficult to ascertain whether there is a variation of fall rate with Earth latitude. The distribution is shown in Figure 10. The population statistics obviously swamp the effect being sought.

Meteorite finds are shown in Figure 11. The effect of the searches carried out by Nininger in America and the Kalgoorlie School of Mines and the Western Australian Museum in Australia are clearly shown. Obviously the best terrain for searches are flat

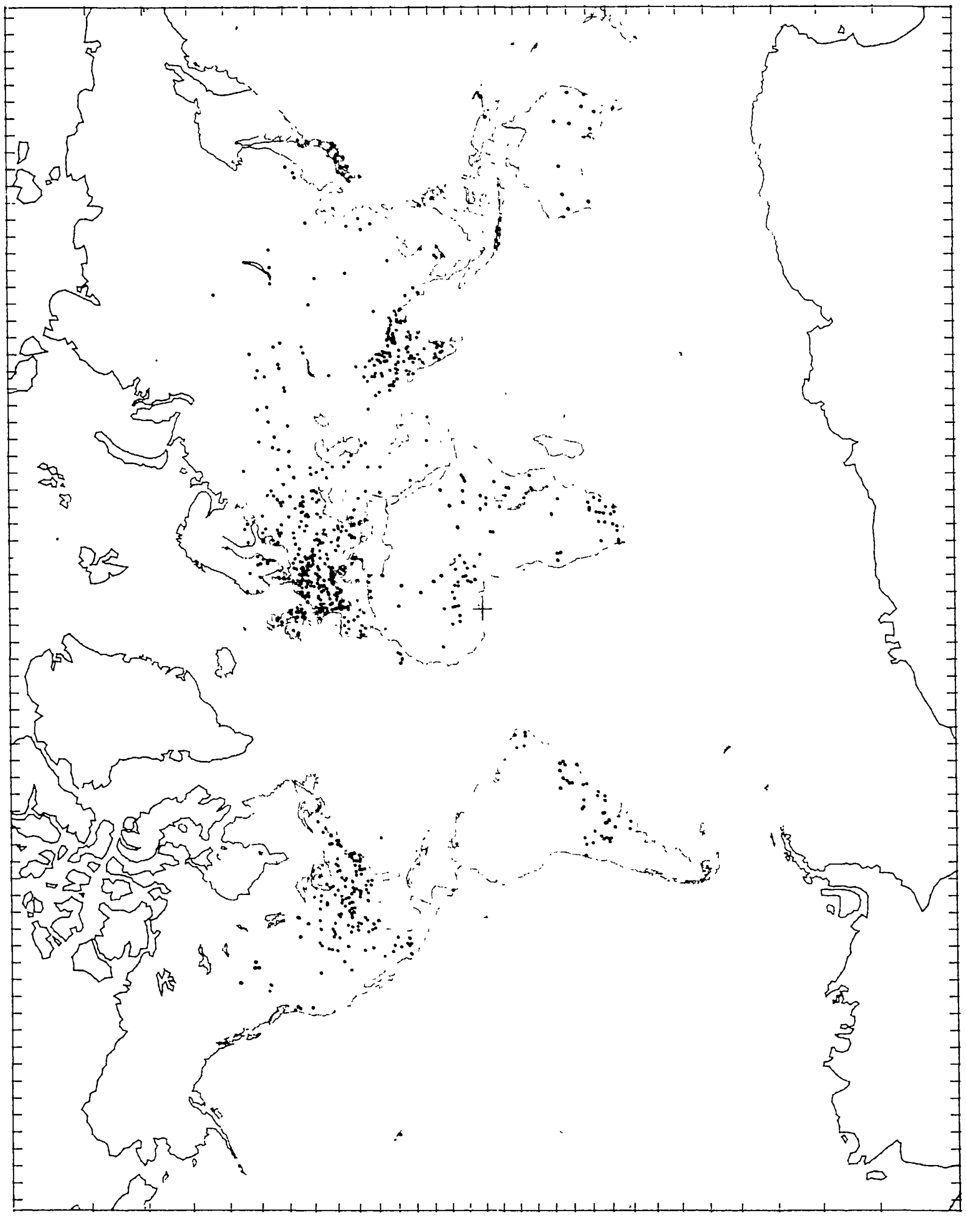

Fig. 9 A cylindrical Mercator projection of the world map. The dots represent the fall sites of meteorites.

regions of low rainfall in which the country rock differs considerably in superficial appearance from the typical meteorites. Many regions have very low find rates. The British Isles, France and Spain are typical examples. The meteorites must be there; we just have to be cleverer when we look.

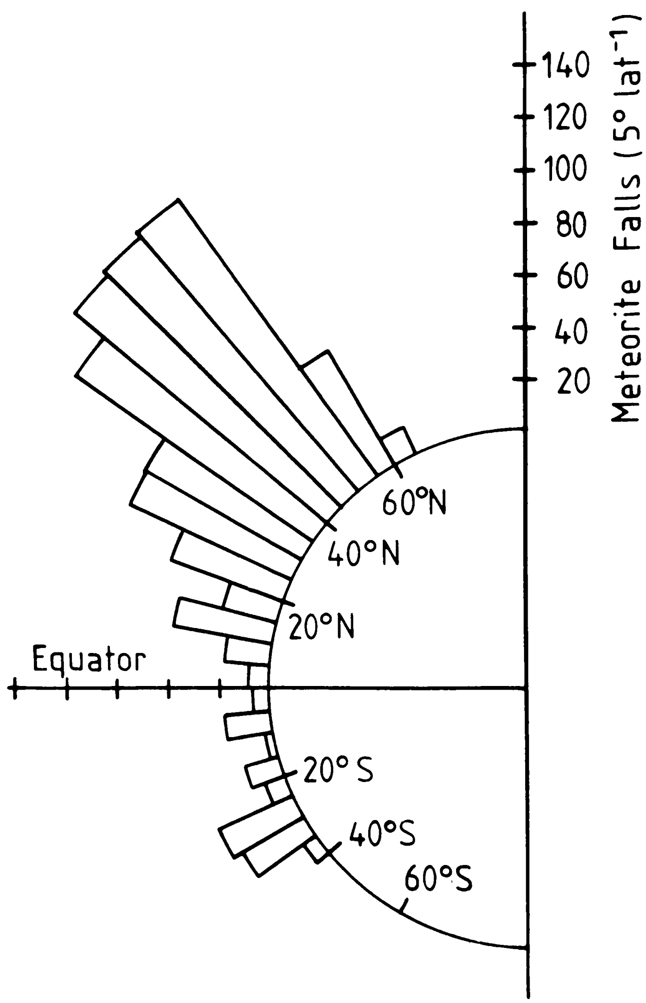

Fig. 10 **The sites of meteorite falls sorted into 5° latitude ranges.**

Fig. 11 **A cylindrical Mercator projection of the world map. The dots represent the places at which meteorites have been found.**

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