4 METEORS AND THEIR RELATION TO INTERPLANETARY DUST

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METEORS AND INTERPLANETARY DUST

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ABSTRACT

The contribution of meteor observations to our knowledge of meteoroids and interplanetary dust is reviewed under four headings - flux, mass distribution, physical structure and chemical composition. For lower limits of particle mass ranging from 1 g to 10^{-5} g the mean cumulative flux into the earth's atmosphere varies from 2×10^{-15} to 6×10^{-9} particles m^{-2} s^{-1} $(2\pi ster)^{-1}$, and the mean size distribution of these particles is given by $\log N = C - 1.3 \log M$, where N is the cumulative number of particles counted down to a lower mass limit M, and C is a constant. The physical structure of meteoroids in the above range is essentially fragile, with generally low mean bulk densities that tend to increase with decrease in mass. A minor fraction, about 10 or 15 per cent, with orbits lying inside that of Jupiter, have densities several times the average densities, approaching those of the carbonaceous chondrites. The mean chemical composition of meteoroids seems to be similar to the bronzite chondrites for the elements heavier than number 10, but with the probable addition of extra quantities of the light volatiles H, C and O.

INTRODUCTION

In this brief review I propose to summarize our current knowledge of interplanetary dust, acquired from the observational data of meteors. Direct ground-based observations of meteors have been made primarily by four techniques - classical visual recording; conventional photography utilizing the photographic plate or film; use of radar equipment, introduced since 1945; and, more recently, the electronic image-intensification systems where data is recorded on standard video-tape. In all of these techniques the actual observational data consists of a recording of a portion of the kinetic energy of the meteoroid, the solid particle which impacts on the upper atmosphere at high velocity. The kinetic energy appears as light, heat or ionization, and one of the major problems in meteor physics has been to relate this observed energy to the pre-impact mass of the meteoroid.

The observational parameters of meteors relevant to the present review may be grouped under four headings, as related to the complex of interplanetary particles at the earth's mean distance from the sun:-

(a) flux
(b) mass distribution
(c) physical structure
(d) chemical composition.

A statistical study of meteor orbits can give some information about variations in the above parameters as we move closer to the sun or proceed outward through the asteroid belt, but the problems of observational selection make this extrapolation difficult.

It is important to take note of the particle mass ranges over which meteor observations have given us reasonably reliable data. These are indicated in a general way only in Figure 1, since it is impossible to set exact limits of mass for the various types of data. At the lower end of the mass range lack of sensitivity in the recording equipment produces a cut-off, while at the upper end the observational events are too infrequent to give good statistics.

FLUX

It has become conventional to describe the flux of interplanetary particles by giving the total number that pass through a square metre of space in one direction (that is from one hemisphere = 2π steradians) per second, counted down to a given lower mass limit. Meteor observations have shown very clearly that for particle masses greater than about 10^{-5} g there are marked variations in the observed flux from day to day, after diurnal and seasonal effects resulting from the earth's motions have been removed. These variations are due chiefly to the superposition, on a relatively steady background flux, of particular groups of particles moving along orbits that correspond closely to periodic comet orbits. These groups of particles produce the well-known annual meteor showers, and in the mass range near 1 g the background flux may be increased by factors of 10 to 100, or even to 1000 in extreme cases, near the centre of a major meteor stream.

Most of the early meteor counting was performed visually and unfortunately it is difficult to reduce such records to standard flux figures since the visual recording is very incomplete for the faint meteors yet these, being more numerous than the bright meteors, are more influential in determining rates. Counting down to specified mass limits can be carried out more reliably when instrumental data are used. Good examples

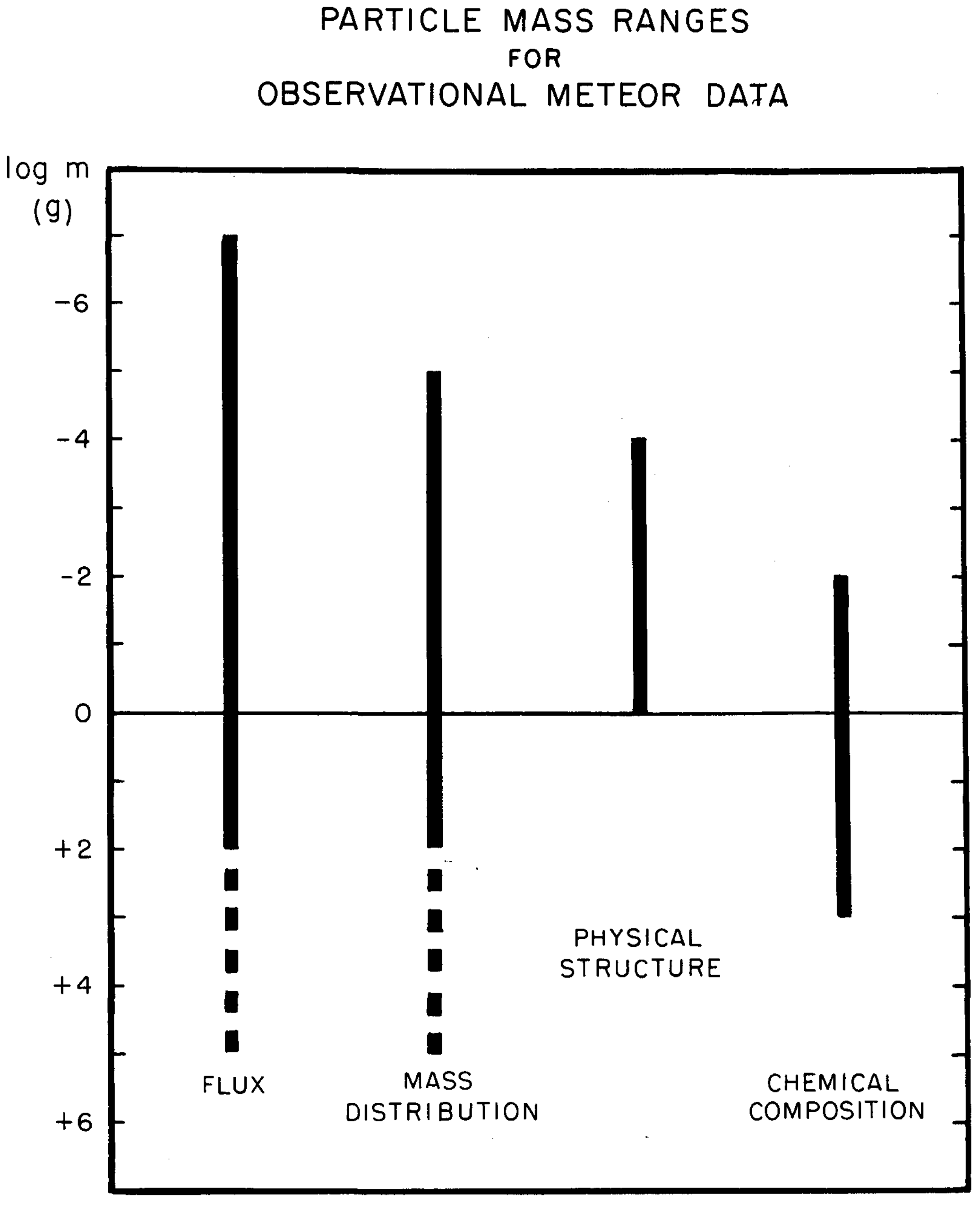

FIGURE 1

https://doi.org/10.1017/S0252921100052003 Published online by Cambridge University Press

of programs employing the three basic instrumental techniques referred to earlier are found in papers by Hawkins and Upton (1958), Hawkins (1963), Nilsson and Southworth (1968), Naumann and Clifton (1973) and Clifton (1973). It is reassuring that these completely independent methods of instrumental meteor observing give background fluxes in reasonable agreement. When care is taken to select visual counting that is statistically complete (Millman, 1970a), this also gives a flux close to the instrumental values. Making use of various compilations of meteor data we find that, in round figures, the mean background flux is 2×10^{-15} m^{-2} s^{-1} $(2\pi$ ster$)^{-1}$ counted down to a mass of 1 g, and 6×10^{-9} m^{-2} $s^{-1}(2\pi$ ster$)^{-1}$ counted down to a mass of 10^{-5} g.

Counting down to a lower mass limit of 1 g, the 12 major meteor showers have a total annual flux that is equal to 20 per cent of the total annual background flux. Examples of shower fluxes at the centres of some of the major meteor streams are listed in Table 1. These fluxes are based on material from Millman and McIntosh (1964), Millman (1967) and McIntosh and Millman (1970). As noted in earlier review papers (Whipple, 1967; Millman, 1975) most of the mass of the meteoritic complex is in the form of particles with masses near 10^{-5} g, and here the major showers merge into the background (Millman, 1970b). Southworth and Sekanina (1973) estimate the space density near the earth of all particles smaller than meteorites as 4×10^{-22} g cm^{-3}.

MASS DISTRIBUTION

The mass distribution of interplanetary particles may be defined by any one of a number of indices (Millman, 1973). Here I will use the integrated mass index "S", which is simply the negative slope of the mean line drawn through the plot of the $\log_{10}$ of the standard cumulative fluxes against the $\log_{10}$ of the lower mass limit to which the flux refers. As previously pointed out (Millman, 1973) year-round meteor programs by all four observational techniques show good agreement in mass distribution for background particles in the mass range from 10^{-5} to 1 g. The integrated mass index "S" increases from a value of 1.15 at 10^{-5} g to 1.35 at 1 g (McIntosh and Simek, 1969; Elford, 1967; Kaiser, 1961; Clifton, 1973; Hawkins and Upton, 1958; McCrosky and Posen, 1961; Kresáková, 1966; Millman, 1970a). For heavier particles there is some evidence from the photographic fireball networks that the mass index drops again (McCrosky, 1968) but so far the number statistics are low and there are uncertainties in the meteor theory that is available for meteoroids near a mass of 10^5 g (McCrosky and Ceplecha, 1970).

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TABLE 1

Peak fluxes of meteor showers, counted down to particles of mass one gram

shower	date	flux in units of background $= 2x10^{-15}\ m^{-2}s^{-1}(2\pi ster)^{-1}$
Quadrantids	January 3	15
Lyrids	April 22	1
Perseids	August 12	1.5
Orionids	October 21	0.5
Leonids (1833)	November 13	? 500 - 1000
Leonids (1966)	November 17	200
Geminids	December 14	25

TABLE 2

Physical structure of meteor showers

shower (associated comet)	shower centre	no. meteors	class	no. meteors	ρ g cm^{-3}	χ *	B
Sι Aquarids	Aug. 5	13	A	5	0.30	0.17	0.8
Geminids	Dec.14	77	B	20	1.06	0.20	0.5
δ Aquarids	Jul.30	22	B	9	0.27	0.54	1.6
Quadrantids	Jan. 3	17	B	10	0.20	0.41	0.8
Taurids (P/Encke)	Nov. 8	105	C_1	23	0.28	0.06	0.01
α Capricornids (1954 III Honda-Mrkos-Pajdusakova)	Jul.30	21	C_1	13	0.14	0.38	1.0
Orionids (P/Halley)	Oct.21	49	C_2	6	0.25	0.40	0.4
Perseids (1862 III Swift-Tuttle)	Aug.12	45	C_2	10	0.29	0.22	0.03
Giacobinids (P/Giacobini-Zinner)	Oct. 9	2	above C_1	2	<0.01	1.9	4.0

* Values of χ are reduced to standard initial mass $m_\infty = 0.8$ g.

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Mass indices for the meteor showers are more difficult to determine since on many programs it is not easy to make a clear separation between the shower meteors and the background meteors. Also, there is no guarantee that any one meteor shower will exhibit the same mass indices at all positions in the stream complex. In general, meteor showers have lower mass indices than the background meteors (Millman, 1972a), and Dohnanyi (1970) has shown that this is to be expected if collisional erosion is the dominant factor in the fragmentation of interplanetary particles, and if the background meteors are primarily former shower meteors that have dispersed into the general meteoritic complex.

PHYSICAL STRUCTURE

Since at most only one or two per cent of the meteoroids which produce visible meteors seem to be associated with the type of interplanetary material that reaches the earth as meteorites and is available for study in the laboratory, the physical structure of a normal meteor-associated meteoroid (a cometary meteoroid) becomes of considerable interest. Included under the term physical structure I am thinking of parameters such as the bulk density, the grain density, strength of the meteoroid in regard to the breaking off of major portions and to the fragmentation into dust particles, the speed of sublimation or melting and the shape of an average particle, both large and small.

Quantitative analysis of meteor photographs has made it possible to estimate the original mass of a meteoroid on entry into our atmosphere. This can be done by using the integrated luminosity (photometric mass) or by a study of the deceleration of the meteoroid (dynamic mass). The differences between these two give us a function of the bulk density of the meteoroid, since its surface area enters directly into the calculation of dynamic mass but does not for photometric mass. Verniani (1967, 1969) took 220 precisely reduced background meteors, photographed with Super-Schmidt cameras on a Smithsonian Observatory program (Jacchia et al., 1967) and found a mean bulk density of 0.28 g cm^{-3}. However, there was good evidence of a bimodal density distribution among these data and removing 31 high-density examples, mean density 1.38 g cm^{-3}, the remaining 189 had a mean density of only 0.21 g cm^{-3}. It is noteworthy that effectively all the high-density group were meteoroids with orbits whose aphelia lay within 5.4 a.u. distance from the sun, or inside the orbit of Jupiter, while some 60 per cent of the low-density meteoroids had aphelion distances greater than 5.4 a.u. It may be that, owing to uncertainties that still exist in meteor theory, Verniani's bulk densities are all somewhat too low, but the important result is the differential between the two groups of background meteoroids.

A much more direct body of evidence is found in a study of the beginning heights of Super-Schmidt meteors. Ceplecha (1967, 1968) has used the observational data for 2529 Super-Schmidt meteors (Jacchia and Whipple, 1961; McCrosky and Posen, 1961). The primary influence on the beginning height of the visible path of a meteor is the velocity with which the meteoroid enters the atmosphere "V_∞". Ceplecha made a statistical study of beginning heights versus velocity for 1848 background meteors and found good evidence for a bimodal height distribution, after the effect of velocity had been allowed for. At any given velocity the separation in height between the two peaks was roughly 10 km. Meteors with low initial heights were classified as A, those with high initial heights as C_1 (low velocity) and C_2 (high velocity), and those with a height distribution in between the primary peaks as B. On examining various possibilities for these beginning-height differences Ceplecha concluded that they resulted primarily from differences in what I have termed physical structure. Ceplecha also looked briefly at the classification of the shower meteors in these data, and recently Cook (1973a) has made a more detailed statistical study of the beginning heights of shower meteors. He finds that when sufficient observational data are available, individual showers can be classified as one of A, B, C_1, C_2, A+C_1, and above C_1, and suggests that as we progress from A to above C_1 we sample material progressively more porous and fragile, with lower bulk densities and from layers that had been progressively nearer to the surface of the parent comet nucleus. To illustrate the differences among some of the major showers I have given Cook's classification for nine showers in the first part of Table 2. Except for the ι Aquarids these are the same as those given by Ceplecha (1967). It is probably not a coincidence that the first four showers listed lack an associated comet. It has been suggested that Class B showers come from comets so small that they have lost all their outer icy layers and the nucleus that remains, if it still exists, is like a very small asteroid, difficult to detect. It should be added that showers of Class C_2 definitely favour orbits with greater aphelion distances than those of classes A, B or A+C_1. In the last-named type of shower we are evidently sampling material from two different levels in the parent comet, perhaps a result of some major fragmentation in the past history of the complex.

In the second part of Table 2 I have listed mean shower data from the precisely reduced Super-Schmidt meteors. The bulk densities "ρ" are those given by Verniani (1967). The progressive-fragmentation index "χ" is a logarithmic quantity that depends on the amount by which the increase in deceleration along a meteoroid's path exceeds the theoretical, single-body, increase in deceleration. This difference from single-body theory is generally attributed to progressive fragmentation of the meteoroid. Optical evidence of this effect is seen in photographs taken with an occulting shutter as blending "B" where, towards the end of the meteor path, the segments produced by the shutter are extended in length or blend completely due to the light of the trailing dust particles. The progressive-fragmentation index "χ" and the qualitative figure for blending "B" show reasonably good correlation and are listed in Table 2 as given by Jacchia et al. (1967). Of particular note are: the high density of the Geminid meteoroids, though these seem to crumble as readily as the Perseids and the S ι Aquarids; the resistance to crumbling of the lower-density Taurid meteoroids; and the exceptional character on all counts of the Giacobinid meteoroids. It should be remarked here that, although the actual figures given for the Giacobinids in Table 2 depend on only 2 Super-Schmidt meteors, there is good support for the exceptional character of these meteoroids from other photographic evidence (Jacchia et al., 1950).

Verniani (1973) has summarized the information on densities from 5759 meteors recorded on the Harvard Radio Meteor Project. These data give mean bulk densities of 0.8 g cm^{-3} for meteoroids of mass 10^{-4} to 10^{-2} g, with a higher density portion among the meteoroids that have small aphelion distances from the sun. The mass range as published by Verniani has been adjusted in the light of new information on ionizing efficiency (Cook et al., 1973a; Friichtenicht and Becker, 1973). These results, when compared with those for the brighter photographic meteors, indicate a trend towards higher densities for smaller masses, and this trend is confirmed by a study of microcratering on lunar rocks and high-altitude particle collecting (Millman, 1975). A model of fragile, porous structures in gram sizes breaking up into smaller, more solid particles at 10^{-5} gram sizes, fits in with the observed density trend.

The meteoroids associated with fireballs, such as those recorded by the Prairie Network in the mass range 10^2 to 10^7, do not seem to fit any simple pattern of physical structure (McCrosky et al., 1971). Theoretical bulk densities for these objects range from 0.1 to 1.5 g cm^{-3} with a mean value near 0.5 g cm^{-3} (McCrosky and Ceplecha, 1970), and on

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this basis the only recovered meteorite from the Prairie Network, Lost City, would have been considered of low density. Actually, Lost City had a bulk density of 3.7 g cm^{-3}. If initially these fireball meteoroids entered the atmosphere with appreciably flattened shapes, and moved flat side forward, the theoretical densities, which assume a nearly rounded shape, could be too small by factors of 5 to 8. Some fireball data, but not all, can be explained by this assumption. Do flattened shapes extend to smaller masses? We have little information on this at present until we reach the mass range of 10^{-3} to 10^{-15} g. Here, microcratering on lunar rocks indicates that the particles are not either platelets or needles (Hörz et al., 1975).

CHEMICAL COMPOSITION

Chemical abundances are normally given either by relative numbers of atoms of the various elements or by the relative weights of the elements. In discussing solids it is usual to employ the latter method, and only abundances by weight will be used here. Since the interplanetary dust is part of the solar system it is logical to discuss the composition of this dust in relation to that of the entire system. One of the most recent compilations of the mean chemical composition of the solar system is given in a review paper by Cameron (1973). The relative abundances of the 25 commonest elements from this paper have been plotted in Figure 2 on a logarithmic scale, normalized to 6.0 for Si. H and He account for over 98 per cent of the total mass in the solar system while the next eight elements, down to S, make up the greater part of the remainder.

Meteorites are the only samples of interplanetary material for which we have detailed chemical information. Of the total of recorded meteorite falls 84 per cent are of the type known as chondrites. The mean composition of the commonest type of chondrites, the olivine-hypersthene chondrites, is plotted in Figure 2 as given by Mason (1962, 1965). Mason has pointed out that if you add 30 per cent more Fe, Ni and Co (also plotted in Figure 2) to the abundances of the hypersthene chondrites you have almost exactly the average composition of the other large group of chondrites, the olivine-bronzite chondrites. The relative elemental abundances, estimated for both the solar system and for meteorites, are not independent since the latter have been used, along with other data, to determine the former. For the common elements the chief difference between solar-system and meteorite abundances is the depletion in meteorites of the light volatiles H, O, C N and S, and of the inert

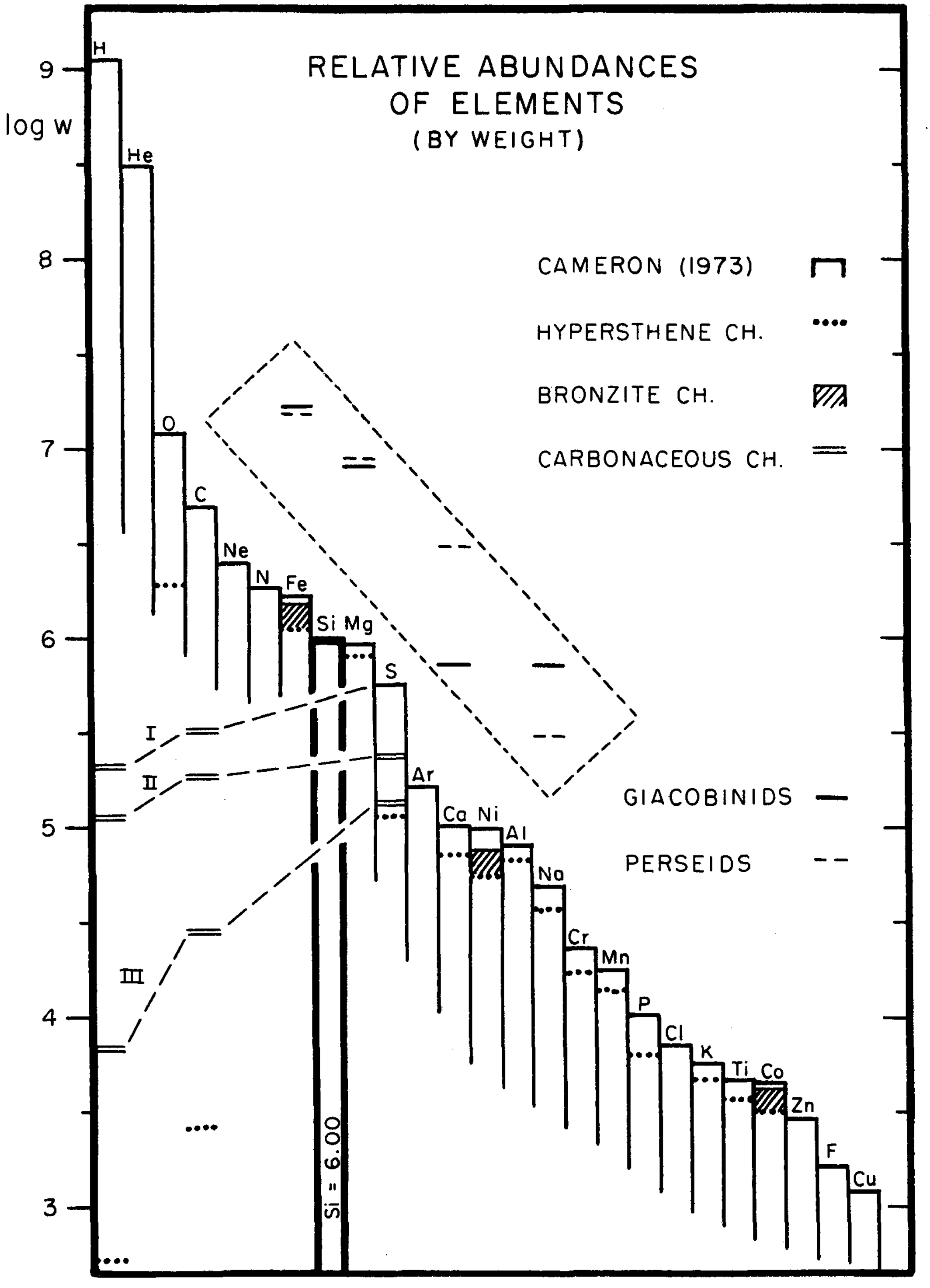

FIGURE 2

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gases He, Ne and Ar. In this connection one small group of meteorites, the carbonaceous chondrites, that account for only 4 per cent of the falls, is of interest. These meteorites have similar relative abundances to the olivine-bronzite chondrites, except for higher abundances of H_2O, C and S. Mean abundances for H, C and S relative to Si in the three classes of carbonaceous chondrites, I, II and III, as given by Mason (1971), are shown in Figure 2.

As noted earlier, most of the meteoroids we observe as meteors are probably cometary fragments and are so fragile that they do not reach the earth in pieces of any size. We have no a-priori reason to assume that their elemental composition will match that of the meteorites. Early meteor spectroscopy (Millman, 1963) gave qualitative information on the chemical composition of the cometary meteoroids and now a total of some 18 or 19 elements have been identified in meteor spectra, including 16 of the first 22 plotted in Figure 2. Absent are He, Ne, Ar and S, P, Cl. Unfortunately it is difficult to derive quantitative abundance data from a photometric study of meteor spectra since the atomic-line and molecular-band radiation are produced by collisional excitation, and the required collisional cross sections are largely unknown for the physical conditions under which the light of meteors is produced. Thanks to work by Savage and Boitnott (1973) it has been possible to find relative abundances for the elements Fe, Mg, Ca and Na in a few Giacobinid and Perseid meteors (Millman, 1972a, 1972b). Since these cannot be normalized to Si they are plotted in Figure 2 on a log scale with an arbitrary zero above the other abundance plots. Their significance is in the trend of abundance for these four elements, which corresponds closely with that for the olivine-bronzite chondrites and the carbonaceous chondrites.

No quantitative measures of the light volatiles are available as yet for meteor spectra, but H and O appear strongly. Data published by Ceplecha (1971) and Millman and Clifton (1975) show evidence for CN and possibly CH in both a bright fireball and in Geminid meteors, and the presence of C provides a good explanation for the peculiar spectrum of a meteor observed with the image-orthicon equipment (Cook et al., 1973b). Thus, there is certainly a strong suggestion that carbon is present in many of the meteoroids that produce visible meteors.

It is significant that, after the β Taurid meteor shower, associated with Comet Encke, Goldberg and Aikin (1973) found an enhancement of the ions of Na, Mg, Si, K, Ca, Cr, Fe and Ni at a height of 114 km, in abundances that agreed closely with chondritic meteorites. The residue in a microcrater found in a plate exposed on Skylab IV also showed abundances of Fe, Si, Mg, Ca, Ni, Cr and Mn similar to carbonaceous chondrites (Brownlee et al., 1974).

We can summarize the current knowledge of the average chemical composition of meteoroids in a broad mass range near one gram as apparently quite similar to the carbonaceous and bronzite chondrites for elements heavier than number 10, and with the light volatiles H, C, O probably present in appreciable quantities.

A few particles (less than one per cent) that behave like iron meteoroids or asteroidal fragments have been detected (Halliday, 1960; Griffin, 1975; Cook et al., 1963). Iron and sodium are two of the commonest elements in meteor spectra, but in a systematic program of meteor photography Harvey (1973) has found a few examples of iron free and sodium deficient meteoroids. However, these are exceptions to a rule of basic uniformity in most meteor spectra, the general character of which is governed primarily by velocity in the atmosphere and original mass.

DISCUSSION

The fluxes listed in this paper lead to a total of roughly 30 metric tons of interplanetary dust swept up by the earth each day integrated from the smallest particles up to masses of 10^3 g (Millman, 1975), and this order of magnitude is confirmed by the meteoritic residue found in lunar soils (Anders et al., 1973). For larger masses there are still too many uncertainties in both observation and theory to make a good quantitative estimate possible. Most of the material observed in meteor streams moves in orbits similar to, or identical with, periodic comets but a minor fraction may be associated with unusual earth-crossing asteroid orbits (Cook, 1973b; Southworth and Sekanina, 1973). There is no marked difference in physical parameters between the stream meteoroids and the background meteoroids and the observed mass distributions are consistent with a gradual dispersion from the streams into the background. The entire complex seems to consist primarily of rather fragile, low-density particles but with a significant high-density component among those particles in the mass range 10^{-4} to 10 g with orbits lying inside that of Jupiter. Since various erosional and fragmentation processes are active in the meteoritic complex it can only be maintained if there is a continuous source for this material. The disintegration of comets

https://doi.org/10.1017/S0252921100052003 Published online by Cambridge University Press

perturbed into short-period orbits by the major planets seems adequate to satisfy this requirement (Whipple, 1967). What information we have concerning the chemical composition of the meteoroids is consistent with this hypothesis.

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