Interplanetary Dust

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The interplanetary dust cloud, total mass 10^{19}–10^{20} g in round figures, originates as fragments of comets and produces a mean flux at the earth-moon system in the range 10^{-13}–10^{-12} g m^{-2} s^{-1}. Over $^2/_3$ of the mass consists of particles with individual weights 10^{-3} to 10^{-6} g. They are fragile, are continually broken up into smaller pieces by collisions, and have a chemical composition similar to that assumed as the average for the entire solar system. The cloud extends to roughly 3 a.u. from the sun in the ecliptic plane, with a particle space density falling off as r^{-v}, where r is distance from the sun and v is in the range 1 to 1.5.

The term "interplanetary dust" refers to the complex of small solid particles, observed chiefly in the central portion of the solar system occupied by the terrestrial planets and the asteroids. The individual particles range in size from diameters only a small fraction of a micron up to 10 cm or more, and from masses less than 10^{-15} g up to several kg. In terms of the overall mass of the solar system (2.0×10^{33} g) interplanetary dust is very insignificant. This can be seen from the following table of mass distribution, taken from a previous review paper [1]:

	mass % of solar system
sun	99.866
planets	0.134
comets	0.000,3
satellites	0.000,04
asteroids	0.000,000,1
interplanetary dust	0.000,000,000,001

Observationally, however, the dust is quite evident – as a faint white luminosity which is reflected sunlight, centred on the sun and known as the zodiacal light; as meteors, which are particles encountered by the earth and vaporized in our upper atmosphere; or as the origin of tiny impact craters on the surfaces of lunar rocks, scars which bear silent testimony to the constant bombardment by this dust of all surfaces in space that are not protected by an atmosphere. Techniques have been developed for collecting and identifying remnants of space dust from the upper atmosphere, from glacial snows and ice, from deep-ocean sediments, and even from lunar-soil samples.

The purpose of this paper is to survey briefly our current knowledge of these interplanetary particles. Numerous reviews in this field have been written in the last few years and it is not my intention to repeat in detail the information already summarized, but to present a broad picture of the interrelations present among various sets of data found by different observational methods, and to inform you of the most recent results. The subject is an active one and new information is becoming available at an accelerated pace. I should also point out that the major portion of this interplanetary dust, as we observe it, probably does not originate in the types of material found in the meteorites, space samples fallen to earth as relatively large objects that can be studied in great detail in the laboratory. I will make little reference to this area, one phase of which was covered recently in this Journal by Laurel Wilkening [2].

Orbits and Origins

The dust particles are too small for individuals to be observed at any appreciable distance, but on entry into the earth's atmosphere at velocities in the range 12–72 km s^{-1} some of the kinetic energy is converted into visible light or detectable ionization and the trajectories of individual particles can be recorded as meteors by optical and radar techniques. The observational programs of the Smithsonian Astrophysical Observatory provide the best data [3–6]. The pho-

Naturwissenschaften 66, 134–139 (1979) © by Springer-Verlag 1979

tographic orbital data (2587 meteors) cover in general the particle mass range from 10 to 10^{-2} g, and the radar orbital data ($\sim$39 000 meteors) from 10^{-2} to 10^{-5} g. In this material there is no real evidence for an interstellar component. Most of the orbits are small with the mean distances from the sun less than 3 a.u. and the entire orbits lying inside the orbit of Jupiter. Motion is generally direct, with inclinations to the ecliptic less than 40°. However, there is a small but significant component with higher inclinations, and some over 90°, especially among the photographic orbits which represent the larger particles. These also have higher eccentricities on the average and may have orbits taking the particles out beyond all the known planets. We must not forget that these statistics are severely limited by several types of observational selection, the most important of which requires that all observed meteor orbits intersect the orbit of the earth. Fortunately we now have available in-situ records, from spacecraft, of the particle flux and of the zodiacal light out to more than 3 a.u. from the sun. These indicate a particle space density that decreases steadily with increasing distance from the sun until it becomes relatively insignificant beyond the orbit of Jupiter. Hence, the meteoroid orbits missed by the constraints of earth-borne observations apparently do not greatly affect the estimated limits of the interplanetary cloud.

In looking for the origins of the interplanetary dust the most important parameter of the complex of meteor orbits is the tendency for them to cluster into particle streams exhibiting various degrees of concentration [7]. Sekanina, in a statistical analysis of radio orbits [8, 9] lists well over 300 meteor streams. When the earth, in its motion around the sun, intersects one of the more concentrated streams, the event becomes evident as a meteor shower. As early as 1861 Kirkwood [10] had published reasons for believing that meteors were "the debris of disintegrated comets" and in 1866 Schiaparelli [11] proved this to be correct for one meteor shower by demonstrating the identity of the orbit of Comet 1866 III (Swift-Tuttle) with the orbit of the Perseid meteors that appear in the northern hemisphere every August. We can now list between 15 and 20 cases of close connections between known comets and meteor showers. Add to this fact the commonly observed phenomenon of dust dispersing into interplanetary space through the tail of a comet, and the number of cases where comets have actually broken up into two or more smaller comets while under observation, and it seems clear that comets must be considered as the origin for at least a part of the interplanetary dust cloud.

Quantitative estimates by Delsemme [12] and Röser [13] indicate that the total contributions of the short-period comets are not enough to maintain the observed dust. Whipple [14] finds that an input of some 10^7 g s^{-1} is necessary to replace the mass continually lost by various processes, including collisional fragmentation and the action of solar radiation pressure. The occasional arrival of bright, long-period comets several times a century, plus a very exceptional comet two or three times a millennium, would be adequate to preserve the status quo. From the observational standpoint it should be pointed out that meteors of a given shower have the unique property of sharing a common origin, whether or not the associated comet has ever been observed.

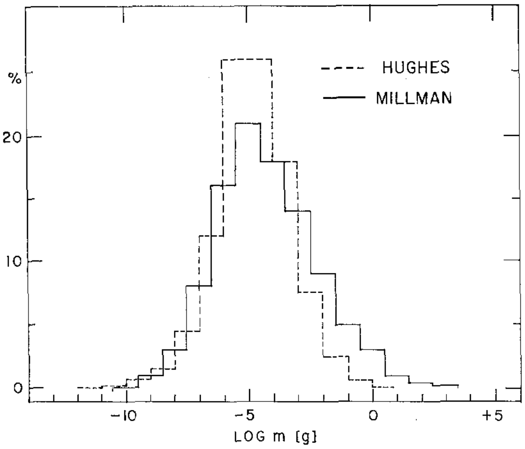

Fig. 1. Two independent calculations of the frequency distribution of integrated mass for various meteoroid mass values "m". The distribution by Hughes [15] was presented at the 1974 COSPAR meeting in Brazil, that by Millman [16] at the Whipple Symposium in Cambridge, Mass., October 1973

Dust-Particle Masses

Direct measurements of particle masses are not possible in the case of the observations of the zodiacal light, meteors, microcraters, or impacts on spacecraft. Even when particles are collected there is always the problem of estimating the mass lost since the particle was orbiting in space. For most observational data cumulative particle counts down to various limits of some physical parameter, such as size or energy, can be tabulated. Calibration to mass usually requires theoretical assumptions combined with empirical information from laboratory experiments. Figure 1 illustrates two independent estimates of the percentage distribution of integrated mass in uniform increments of log particle mass. These frequency plots are based primarily on meteor observations for the larger masses and microcratering plus impact counts for the smaller masses. They refer to the general average background flux of the interplanetary dust as encountered by the earth-moon system at a distance of 1 a.u. from the sun. A concentrated meteor shower will usually show a higher percentage of larger masses [15, 17].

Particle Flux

One of the basic observational parameters of interplanetary dust is the flux of particles on a unit surface in space. This is usually represented as a plot of log N against log m, where N is the cumulative number of particles impacting on a unit surface of 1 m^2 each second from one hemisphere, counted down to a limiting mass m, given in grams. Numerous calculations of flux have resulted from a wide diversity of observational programs and most of these show a broad general agreement. As examples, two envelopes for flux values, taken from recent review papers, are plotted in the upper portion of Fig. 2. These are essentially the same as other compilations such as that by Hörz et al. [19]. Results for kilogram masses derived from seismographs operated on the lunar surface [20], are added on the right of Fig. 2. The slope of the log N vs. log m curve indicates the particle-mass distribution and is discussed in more detail elsewhere [21]. This slope is fairly uniform down to masses near 10^{-6} or 10^{-7} g and then levels off somewhat, but rises again at about 10^{-10} g. This characteristic is particularly apparent in some of the best microcrater statistics for lunar rocks [16, 19, 22, 23], and may indicate a bimodal mass distribution with a division near a particle mass of 10^{-10} g. Supporting such a possibility was the identification of fast sub-micron particles (β-meteoroids) from the analysis of records made by detectors on Pioneers 8 and 9 over a period of some 8 years [24, 25]. In general β-meteoroids were moving in a direction away from the sun and were assumed to originate in the fragmentation of larger dust particles. As a result of their small size solar radiation pressure could accelerate them into hyperbolic, or near-hyperbolic orbits. More recently it has been realized that the interpretation of the crater counts on lunar rocks is complicated by the accretion on the rock surfaces of very small splashes and droplets from the surrounding lunar surface. This action may seriously modify the number of craters counted in the micron size range. In the final analysis we may have to allow for both a bimodal mass distribution of dust particles and lunar regolith accreta for a complete explanation of the details of microcrater counts.

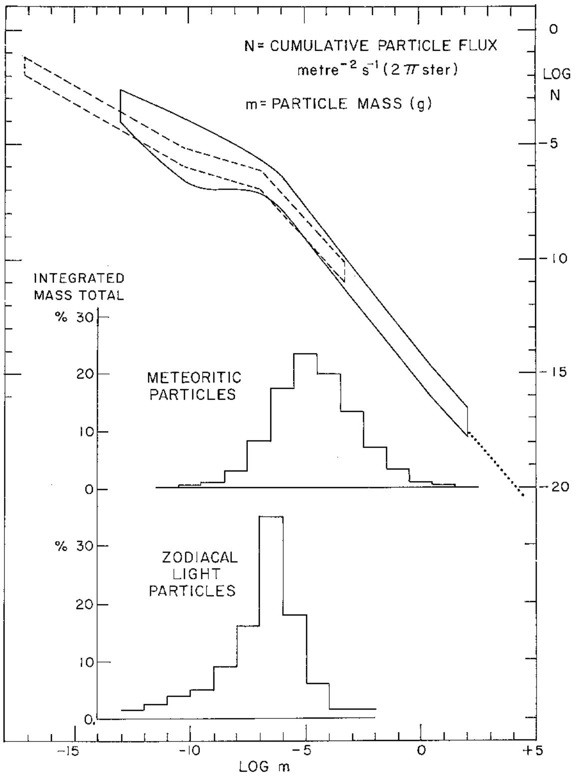

Fig. 2. *Upper plot:* ----- Cumulative particle flux determined from microcrater counts on lunar rocks, as summarized by Fechtig [18]: —— general area of cumulative flux values found by numerous observational techniques, based on a review by Millman [16] and revised to include recent corrections; ..... a portion of the flux curve, estimated from results secured with the seismographs located on the lunar surface, as reported in [20]. *Lower plots:* Frequency distributions for integrated mass totals of various particle masses. The distribution for meteoritic particles is a mean of the values in Fig. 1; that for zodiacal-light particles is taken from [33], and represents the mass distribution of the particles which contribute to the luminosity of the zodiacal light in the wavelength range from the ultraviolet near 2000 Å to the near infrared at about 20 µm

The log N vs log m curves indicated in Fig. 2 are for average conditions in the interplanetary dust cloud as encountered by the earth at 1 a.u. distance from the sun. Using the best mean values from these curves to calculate the total mass flux Hughes [15] found 9.9×10^{-13} g m^{-2} s^{-1} (2π ster) and Millman [16] 6.8×10^{-13}. Morgan et al. [26] give an average mass flux for micrometeoroids on the lunar surface as 7.6×10^{-13} g m^{-2} s^{-1}. This was estimated by measuring the abundances of trace elements (Ir, Re, Au, Sb, Ge, Br, Bi) in the lunar soil from four landing sites. The close agreement of these three mass-flux values must be somewhat fortuitous in view of the uncertainties still present, but at least it gives us confidence that we are in the right order of magnitude.

Estimates of dust flux for solar distances other than 1 a.u. are not very reliable if made from earth-based observations, since major corrections must be made for observational selection. It is best to use records of the interplanetary cloud made at solar distances ranging from 0.3 to 3.3 a.u. [27–31] by instruments on board Pioneers 10, 11, and Helios 1, 2. Although there are still some small inconsistencies to be resolved the general conclusion reached is that, within the range of solar distances given above, and in the ecliptic plane, the space density of micrometeoroids falls off as r^{-v}, where r is distance from the sun and v is in the range 1.0 to 1.5, with the preferred mean value 1.3. For some size ranges there may be a two-component model with a slight increase in numbers of particles at the asteroid belt for $r=2.0$–3.5 a.u. The subject is discussed in greater detail in [32].

On the basis of the distribution of particle fluxes summarized above, and using a scattering function which combines diffraction with isotropic reflection, Giese et al. [33] have calculated the relative contributions of dust particles of various masses to the luminosity of the zodiacal light. This mass distribution is plotted in the lower part of Figure 2 and compared with the mean of the two mass distributions for the entire interplanetary cloud, taken from Figure 1. This recent work raises the masses of zodiacal-light particles by several orders of magnitude above earlier estimates.

Meteoroid Densities and Physical Characteristics

The density of a meteoroid, instrumentally recorded in the atmosphere as a meteor, can be derived by combining a mass, based on the luminosity, with a surface area, based on the observed deceleration. Verniani has published the statistics of densities determined in this way for 324 photographic meteors [34] and for >2500 radio meteors [35], recorded at the Harvard-Smithsonian Observatories. For the first group of meteoroids, in the mass range near 0.1 to 10 g, a mean density of 0.3 g cm^{-3} was found; while for the meteoroids observed by radar, with mean masses near 10^{-4} to 10^{-3} g, mean density was 0.8 g cm^{-3}. Owing to various difficulties in choosing the correct constants and theory to be used, the absolute values of bulk density quoted above may not be correct. However, there is a definite suggestion of overall low densities and a trend to higher densities for the meteoroids of smaller masses. Meteoroid fragmentation is commonly observed in photographic meteors and results both from aerodynamic-pressure and heat-transfer effects [36, 34].

In regard to average dynamical and physical characteristics of the dust particles that have been observed as meteors, there is nothing to separate those meteoroids that belong to well-recognized cometary streams from the members of the general meteoroid background. Differences in mass distributions have been shown by Dohnanyi [37] to be consistent with the gradual dispersal of streams into the background complex, and it has been generally accepted that the large majority of these particles are of cometary origin. On theoretical grounds, and using his "collisional model" for the dust complex, Dohnanyi [38] finds that the contribution of asteroidal particles is small compared to that of the cometary particles. A concept of rather fragile, low bulk-density conglomerates for many of the meteoroids in the mass range 10^{-15} to 10^{2} g certainly seems to fit the observational data, a suggestion strengthened by the fact that no meteorite has yet been firmly identified with any meteor stream.

It should be noted here that differences in dynamical and physical parameters are evident among the various meteor streams [36, 39, 40] and some outstanding examples are summarized in a recent review paper [41]. Local irregularities in the interplanetary dust cloud, independent of the meteoroid streams, may also be produced. For example, there is evidence [42] that the flux of random particles may be enhanced by a factor of 3 near the earth, owing to its gravitational field, and local areas within a radius of 60 000 km of the earth may have small-particle flux enhanced by 2 or 3 orders of magnitude as a result of the electrostatic disruption of larger meteoroids passing through the earth's magnetosphere. Pioneer 10 has detected an increase by 2 orders of magnitude in particle impacts near Jupiter [43] due to the Jovian gravitational field.

Laboratory studies of microparticles impacting on various types of surface at high velocity have led to the conclusion that the diameter/depth ratio of microcraters depends primarily on the density of the impacting particle, while the degree of circularity of the crater indicates the shape and angle of impact of the particle [44–46]. Measures of the diameter/depth ratio and of the circularity of microcraters on lunar rocks show that the impacting dust particles are in general of equi-dimensional shape, that is the ratios of the extreme diameters are <2, and that the particles have three preferred density ranges, near 8, 3, and 1 g cm^{-3}. Chemical analysis of particle residues in craters confirm that iron-nickel and iron-silicate particles produced the first two groups of craters. It is assumed that the so-called "fluffy" particles produced the third. Giese et al. [33] conclude, mainly on the basis of both empirical and observed polarization curves, "that absorbing particles having a rough or fluffy surface structure" seem to be typical in producing the observed zodiacal light. Collections of extraterrestrial dust particles [47] contain aggregates of this type, with typical grain sizes of 0.2 down to <0.01 μm. Most of the aggregates are compact and the percentage of loosely bound, porous aggre-

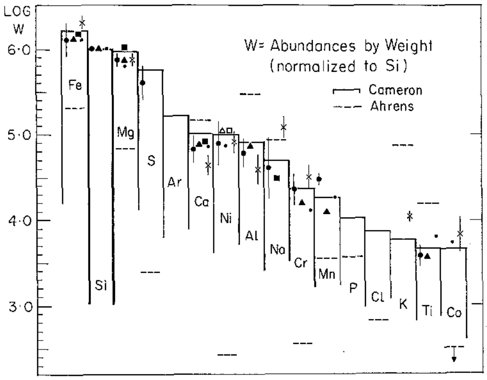

Fig. 3. Observational evidence for the relative abundances of the chemical elements in interplanetary dust. Cameron's 1973 values [49] for the solar system are used as a basis for comparison. To illustrate strongly differentiated material, approximate average abundances for the earth's crust are also plotted. These are essentially those given by Ahrens in 1965 [50], modified slightly in several cases to agree with more recent estimates. *Large dots:* 13 particles collected in the upper atmosphere, diameters 3–25 μm [51], the vertical lines representing root-mean-square deviations for a single observation; *triangles:* 19 deep-sea spherules from the mid-Pacific at depth 5000 m, diameters 300–400 μm, analyzed with the electron microprobe [53]; *squares*: 16 meteor spectra [54–56]; *small dots*: meteoritic residue in one impact crater from Skylab-IV, diameter 110 μm [57]; *crosses*: abundances of upper-air positive ions, as measured at heights from 95 to 120 km above sea level, vertical lines indicating mean deviations of the measures among four groups of experimenters [59–62]. Since neither meteor spectra nor upper-air ions provide reliable mean silicon values, normalization in these cases was to the average of iron and magnesium. The mean nickel values for meteor spectra and deep-sea spherules are less reliable than for the other elements, and this has been indicated by open symbols

gates is lower than one would expect on the basis of meteoroid densities found from meteor observations. This is not surprising as the collected particles are in the mass range 10^{-8} to 10^{-11} g, three or four orders of magnitude below the meteor data. For details, see the excellent photographs in reviews by Brownlee [47] and Hemenway [48].

Chemical Composition of Dust Particles

Quantitative information on the chemical composition of interplanetary dust particles is now available from at least five independent observational techniques. Data for the average composition of the most common type of dust particle is summarized in Fig. 3. A convenient basis for comparison is Cameron's 1973 tabulation of elemental abundances in the solar system [49]. Since in this context we are dealing with solid objects the relative abundances have been converted to weight and the relevant sequence of elements plotted on a log scale, normalized to Si at 6. Ahrens' values [50] for the earth's crust have also been plotted to illustrate a strongly differentiated material in the solar system. The 13 particles collected by Brownlee [51] were all of his "chondritic aggregate" type which accounts for more than half of the complete collection of > 300 extraterrestrial particles. Other types include nickel-bearing iron sulphide and single-mineral grains of enstatite, olivine, or magnetite. Deep-sea silicate spherules from the mid-Pacific are of extraterrestrial origin on the basis of the abundances of certain trace elements [52]. Iron spherules of interplanetary origin were also collected from the same red-clay core samples as the silicate spherules. The average abundances from the 16 meteor spectra are for members of 5 well-known cometary streams. Residues from impacting particles can be detected inside microcraters, and the abundances plotted in Fig. 3 are for a relatively large crater produced by a meteoroid about 30 μm in diameter. Smaller craters, down to sub-micron sizes, have been analyzed for particle residues [57, 58] and in general show fewer elements than the larger craters, as would be expected for the impact of much smaller dust grains. A strong enhancement of metallic upper-air positive ions is sometimes detected after the earth has passed through a meteor stream and these ions can be recorded by rocket-borne mass spectrometers. This gives us a fifth method of measuring average abundances of the elements in interplanetary dust.

It is evident from Fig. 3 that the overall average chemical composition of the interplanetary dust is very similar to that for the solar system, at least for the range of elements shown. It is completely unlike differentiated material such as the earth's crust. This must also be true to a reasonable extent for the various trace elements of higher mass than Co, as interplanetary material can be recognized in the lunar soils by a measure of these same trace elements. For the volatile elements more abundant by weight than iron we have no good average figure. Both the aggregates collected by Brownlee and certain meteor spectra show evidence of C, H, and O, though the last element is probably also present as a contaminant from the atmosphere. The presence of atmospheric Na likely causes the high value of this element in the upper-air ions. In summary we see that, among the abundant elements, interplanetary dust is most easily recognized by its high content of Fe, Mg, S, Ni, and Cr as compared with Si, Ca, Al, and Na.

Conclusion

Most of the interplanetary dust cloud originates in comets. The cometary particle streams gradually disperse into a general background of fragile cometary meteoroids, originally made up of ices mixed with iron and silicate grains. These meteoroids soon lose most of their light volatile gases and are continually broken into smaller and smaller pieces by collisional erosion, until they reach a small enough size for radiation pressure to blow them out of the inner solar system at high velocity. The majority of the larger particle aggregates show a chemical composition remarkably similar to that assumed for the entire solar system, but as particle sizes approach the micron and sub-micron range they may break down into a single grain of a simple compound or element. This meteoritic complex must be fed by the disintegration of comets: a small or medium-sized comet every century or so with a much brighter comet at considerably longer intervals.

It is a pleasure to acknowledge profitable discussions with the following colleagues while preparing this paper: F. Arnold, O.E. Berg, D.E. Brownlee, A.F. Cook, H. Fechtig, R.H. Giese, E. Grün, I. Halliday, M. Hanner, Z. Sekanina. Part of this work was carried out while in Heidelberg as a consultant at the Max-Planck-Institut für Kernphysik.

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Received November 16, 1978