The Distribution of Small Interplanetary Dust Particles in the Vicinity of Earth

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One of the components of the solar system is a cloud of dust particles surrounding the sun. The importance of the cloud arises not only from cosmogonal aspects such as the sources and composition of the dust particles, but also from cosmological aspects such as the rapidity with which changes occur in their dynamical characteristics. Properties of the dust particles and the general shape and extent of the dust cloud have been inferred from observations of meteors and from photometric studies of the zodiacal light and the solar corona. Uncertainties in conclusions reached on the basis of such inferences arise because of the differences that possibly exist between the classes of dust particles responsible for the two vastly different phenomena. New and independent methods of determining selected parameters of the dust particles are needed in order to remove the uncertainties that presently exist in the knowledge of their physical characteristics and distributions.

A new technique that holds great promise for supplying some of the most-needed parameters has been developing very rapidly during the past few years. This technique is that of measuring (in space) various parameters of statistical samples of dust particles. The direct measurements that are presently available have been obtained as dust particles impacted onto special sensors mounted on rockets, earth satellites, and other spacecraft.

The sensors that have been flown have necessarily been of very simple design and have provided only limited information about the dust particles. The experiments have been designed primarily to give preliminary information about the influx rate or spatial density of dust particles over a limited but astronomically important range of particle mass. More sophisticated experiments capable of defining selected parameters of individual dust particles are possible and technically feasible in the very near future.

Radar, visual, and photographic techniques are used in observing meteoric phenomena produced by meteoroidal dust particles. The dust particles studied by direct measurement techniques are too small to produce meteoric phenomena and cannot be observed by the ground-based techniques common to studies of meteors. The magnetic spherules found in deep-sea deposits and in high-altitude collections of atmospheric aerosols may include extraterrestrial material, but positive identification of this component is extremely difficult. Volatile cometary debris does not appear in either of the collections, and there has been little or no success in the identification of siliceous particles as being of extraterrestrial origin.

One is left with the conclusion that there are basically two effective techniques of experimentally acquiring reliable information about the distributions and physical characteristics of small interplanetary dust particles. The first technique is photometry of the zodiacal light and the solar corona (from outside the atmosphere of Earth as well as from the surface of Earth). The second technique is that of making statistical samples within the dust cloud by the direct-measurements technique. The direct-measurements technique can include the returning to Earth of collections of dust particles from outside the atmosphere of Earth as well as the direct measurements of selected parameters

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of dust particles in space. The two techniques must remain complementary. Each should supply information unique to the method as well as provide information to be used in advancing the other technique.

Spacecraft carrying instruments for obtaining direct measurements can be used for probing comets and meteor streams simultaneously with studies of the dust cloud. Probes sent through comets and meteor streams would provide valuable information about the physical conditions and processes within such collections of dust particles. The direct-measurements technique represents an interesting, useful, and almost unique means of studying small particulate aggregates of matter in selected regions of the solar system as well as in the vicinity of Earth.

Interpretations of direct measurements

The available direct measurements must be periodically reviewed in order to determine how consistently they fit into one or another pattern that has physical meaning. The direct measurements have, until just recently, been of such a nature that they could be given either of two interpretations. The choice of interpretation depended critically upon the assumptions that one was willing to accept during an analysis of the data.

The two interpretations of direct measurements that could be given prior to obtaining the new direct measurements from Explorer VIII (Satellite 1960 Xi) were: (1) The mass distribution and spatial density of small interplanetary dust particles indicated by the direct measurements differ significantly from those predicted on the basis of linear extrapolations (over about six orders of magnitude) of results from observations of meteors; or (2) the direct measurements indicate the existence of an appreciable geocentric concentration of interplanetary dust particles. The conjectural geocentric concentration mentioned here is of the type proposed by Beard (1959), and should not be confused with concentrations arising from the temporary suspension of dust particles above the temperature inversion layers in the atmosphere of Earth.

The direct measurements obtained with Explorer VIII strongly indicate that the first of the two interpretations of the presently available direct measurements is the correct one. The second interpretation is not compatible with an analysis in which the direct measurements from Explorer VIII are used as a basis for analyzing other direct measurements. The first interpretation should, therefore, be regarded as correct until direct measurements of the vectorial velocities of impacting dust particles have been obtained. The direct measurements from Explorer VIII serve as the first firm basis for analyzing existing direct measurements of interplanetary dust particles. A review of the available direct measurements (including those from Explorer VIII) obtained with microphone systems is sufficient to demonstrate the validity of the foregoing statements about the interpretation of the direct measurements.

Direct measurements from Explorer VIII

A definitive set of direct measurements recently was obtained with the satellite Explorer VIII. Two independent systems for studying interplanetary dust particles were mounted on the satellite. The systems provided data from launch on 3 November 1960 until the power supplies were exhausted on 13 December 1960. One of the systems included a photomultiplier tube as the sensor for measuring the luminous energy generated in hypervelocity impacts of dust particles. A microphone was used as the sensor in the other system for the purposes of counting impacts and determining the magnitudes of the impulses delivered by impacting dust particles.

Two sounding boards of the microphone system were mounted on the lower cone of the spin-stabilized satellite. The spin vector of the satellite lay within approximately 40° of the apex of Earth's motion during the active lifetime of the satellite. The "sounding boards" were arranged to detect dust particles for which the radiants generally lay on the hemisphere centered on the antapex of Earth's motion. An average particle velocity of 25 km/sec has been assigned for Explorer VIII until the velocity distribution of interplanetary dust particles can be determined.

The best calibrations that are at present possible for the microphone system show that it is sensitive to a quantity which is closely related to the momentum of an impacting dust particle. Calibrations have been accomplished with low-velocity particles impacting elastically onto sounding boards to which the microphones were attached. Hypervelocity particle accelerators are now being used in order to obtain more realistic calibrations. The mass sensitivity of a microphone system can be computed from the momentum sensitivity if an average particle velocity is assumed.

The microphone system of Explorer VIII was designed to count impacting dust particles, and to determine in which of three ranges the momentum of each particle lay. A preliminary readout of the data has established approximately the number of dust particles encountered for each of the three ranges of sensitivity. In addition to determining the average influx rate within each range, the data have defined the shape of a section of an average mass-distribution curve. This section extends over a limited but significant range of particle mass, and provides a basis for analyzing all the other available direct measurements of interplanetary dust particles.

A tabulation of the preliminary data from Explorer VIII has not been included in this paper, to avoid the unnecessary propagation of preliminary numerical results that may change slightly. The three datum points obtained with the microphone system on Explorer VIII are corrected for the effect of shielding by Earth, and are plotted as a cumulative mass-distribution curve in figure 1. The three datum points represent the impacts of more than 3,100 dust particles registered during an interval of 40 days. The large number of impacts provides statistical weight for the datum points from the two ranges of highest sensitivity. The spacing of the threshold sensitivities allows one to establish definitively the shape of a segment of an average distribution curve that extends over approximately three orders of magnitude in particle mass.

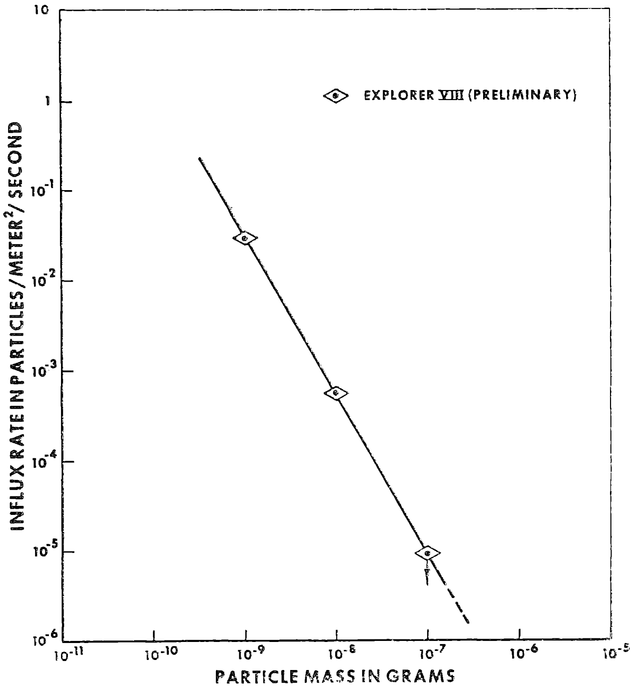

FIGURE 1.—The average distribution curve established by preliminary results from Explorer VIII.

Direct measurements from other satellites and spacecraft

Direct measurements have been obtained with rockets, earth satellites, and space probes flown by both the United States and the Soviet Union. Dust-particle sensors carried by these payloads have included microphones, photomultiplier tubes, thin films, erosion grids, wire grids, and pressurized chambers. The microphone system is probably the best calibrated of all the sensors, and certainly has been flown more times and on more payloads than any other sensor.

It is sufficient, for the analysis summarized in this paper, to consider only those direct measurements obtained with microphone systems. The data obtained with microphone systems are entirely adequate to establish an average distribution curve for interplanetary dust particles in the vicinity of Earth. It may be qualitatively stated that the direct measurements obtained with other systems do not indicate that a distribution curve different from the one established by the direct measurements obtained with microphone systems should be considered.

The U.S. satellites and spacecraft for which direct measurements with microphone systems have been obtained are listed, together with the relevant data, in table 1. The data for Explorer I (Satellite 1958 Alpha) and Pioneer I are those given by Dubin (1960). The total number of impacts (145) for Explorer I was used in computing an average influx rate even though approximately one-half the impacts probably represented a "shower" component (Dubin, 1961). The high influx rate during the "shower" is approximately counteracted by an interval with a low influx rate. An influx rate computed from the total number of impacts serves very well as the average influx rate from Explorer I to be used in establishing an average distribution curve. A factor of 2 was used in correcting the influx rate from Explorer I for the shielding effect of Earth.

The microphone system on Pioneer I registered 25 impacts, of which 17 probably represented dust particles. The average influx rate was computed on the basis of 17 impacts. No correction was made for the shielding effect of Earth because Pioneer I spent most of its time at large geocentric distances (2 to 19 Earth's radii).

Preliminary results for the microphone system on Vanguard III (Satellite 1959 Eta) were reported by LaGow and Alexander (1960). Reading of the telemetered data is still in progress, so the preliminary results shown in table 1 may change slightly. Approximately 6,000 impacts were recorded during 80 days of operation. Approximately 2,800 of the impacts occurred during a 70-hour interval on 16–18 November (Alexander, McCracken, and LaGow, 1961). An average influx rate was computed for Vanguard III on the basis of ~3,500 impacts. This number allows for the sporadic background during the 70-hour interval. A factor of 1.5 was used to correct for the shielding effect of Earth. An average particle velocity of 30 km/sec was used in computing the threshold mass sensitivities for the microphone systems on all the spacecraft listed in table 1.

Direct measurements reported by Nazarova (1960) from the microphone systems mounted on Soviet satellites and spacecraft are included in table 2. Portions of the information shown have been computed from information given by Nazarova in order that data from United States and Soviet spacecraft may be included in the same analysis.

The sensitivities for the microphone systems on the Soviet spacecraft were expressed by Nazarova in terms of particle mass. Nazarova computed the mass sensitivities by assuming that the microphone systems were energy-sensitive and that the average particle velocity was 40 km/sec. McCracken (1959) used 40 km/sec in an early analysis of direct measurements, but this value is almost certainly too high.

Whipple (1957) assigned different values of average velocity to different sizes of dust particles. The velocities varied from 28 km/sec for meteoroids to 15 km/sec for small dust particles of the direct-measurements range of particle size. In order to avoid prematurely constraining the model distribution of interplanetary dust particles, we have assigned a value of 30 km/sec as the average particle velocity when the spacecraft is not oriented or when the dust particle sensors are open to an omnidirectional flux. Average particle velocities for oriented sensors are chosen according to the orientation of the solid viewing angle of the sensor.

The mass sensitivities for the systems on the Soviet spacecraft are reduced by the square of the ratio of 40 to 30 in order to compensate for the difference in the assigned average particle velocities. The spacecraft—Lunik I (Mechta, 2 January 1959), Lunik II (Lunar Probe, 12 September 1959), and Lunik III (Satellite 1959 Theta)—operated at large geocentric distances, so corrections for the shielding effect of Earth are not necessary.

The influx rates measured by Sputnik III (Satellite 1958 $\delta 2$) underwent tremendous changes during the first 3 days of operation of the equipment. The influx rates, as reported by Nazarova (1960), were 4 to 11 particles m^{-2} sec^{-1} on 15 May (launch day), 5×10^{-4} particles m^{-2} sec^{-1} on 16–17 May, and less than 10^{-4} particles m^{-2} sec^{-1} during the interval 18–26 May. Nazarova attributes the high influx rates during the first few days to a meteor shower, but the manner in which the influx rate changed could also be suggestive of payload interference. Only the influx rate for the last 9 days of operation of Sputnik III is of any value in establishing an average distribution curve. It is not clear whether Nazarova corrected the influx rate from Sputnik III for the shielding effect of Earth, so the influx rate is left as it was given.

The method of encoding information into the telemetered signal for Lunik I was such that only very crude upper limits for the

TABLE 1.—*Direct measurements obtained with microphone systems on the U.S. satellites and space probes*

Spacecraft	Momentum sensitivity (dyne seconds)	Mass sensitivity (grams)	Effective area (meter ^{2})	Exposure time (seconds)	Exposure (m^2 sec)	Number of particles	Cumulative influx rate (particles/m^2/sec)	
							Observed	Corrected for earth shielding
Explorer I	$>2.5\times10^{-3}$	8.3×10^{-10}	2.3×10^{-1}	7.9×10^{4}	1.8×10^{4}	145	8.4×10^{-3}	1.7×10^{-2}
Pioneer I	$>1.5\times10^{-4}$	5.0×10^{-11}	3.9×10^{-2}	1.1×10^{5}	4.2×10^{3}	25 (17)	4.0×10^{-3}	4.0×10^{-3}
Vanguard III	$>1.0\times10^{-2}$	3.3×10^{-9}	4.0×10^{-1}	6.9×10^{6}	2.8×10^{6}	~3500	1.3×10^{-3}	2.0×10^{-3}

TABLE 2.—*Direct measurements obtained with microphone systems on the Soviet satellites and space probes*

Spacecraft	Mass sensitivity (grams)		Effective area (meter^2)	Exposure time (seconds)	Exposure (m^2 sec)	Number of particles	Influx rate (particles/m^2/sec)	
	$\bar{v}_G=40$ km/sec	$\bar{v}_G=30$ km/sec					(Nazarova)	Cumulative
Sputnik III	8.0×10^{-9}—2.7×10^{-8}	1.4×10^{-8}—4.8×10^{-8}	0.34	$\sim8\times10^{5}$	$\sim3\times10^{5}$	?	(see text)	$<1\times10^{-4}$
	2.7×10^{-8}—1.5×10^{-7}	4.8×10^{-8}—2.7×10^{-7}						
	1.5×10^{-7}—5.6×10^{-6}	2.7×10^{-7}—1.0×10^{-5}						
	$>5.6\times10^{-6}$	$>1.0\times10^{-5}$						
Lunik I	2.5×10^{-9}—1.5×10^{-8}	4.4×10^{-9}—2.7×10^{-8}	0.2	3.6×10^{4}	7.2×10^{3}	<16	$<2\times10^{-3}$	$<2.9\times10^{-3}$
	1.5×10^{-8}—2.0×10^{-7}	2.7×10^{-8}—3.6×10^{-7}				<4	$<5\times10^{-4}$	$<7.0\times10^{-4}$
	$>2.0\times10^{-7}$	$>3.6\times10^{-7}$				<1	$<1\times10^{-4}$	$<1.4\times10^{-4}$
Lunik II	2.0×10^{-9}—6.0×10^{-9}	3.6×10^{-9}—1.1×10^{-8}	0.2	1.1×10^{5}	2.2×10^{4}	0	$<5\times10^{-5}$	
	6.0×10^{-9}—1.5×10^{-8}	1.1×10^{-8}—2.7×10^{-8}				0	$<5\times10^{-5}$	
	$>1.5\times10^{-8}$	$>2.7\times10^{-8}$				2	9×10^{-5}	9.1×10^{-5}
Lunik III	1.0×10^{-9}—3.0×10^{-9}	1.8×10^{-9}—5.3×10^{-9}	0.1	2.3×10^{4}	2.3×10^{3}	1	4×10^{-4}	3.0×10^{-3}
	3.0×10^{-9}—8.0×10^{-9}	5.3×10^{-9}—1.4×10^{-8}				5	2×10^{-3}	2.6×10^{-3}
	$>8.0\times10^{-9}$	$>1.4\times10^{-8}$				1	4×10^{-4}	4.3×10^{-4}

TABLE 3.—*List of rockets with microphone-type dust-particle sensors*

Rocket	Launch time and date	Zenith altitude (kilometers)	Type of data
V–2 Blossom IV–D	8 Dec. 1949	~135	First direct measurement
V–2 Blossom IV–G	31 Aug. 1950	~135	Qualitatively fair data
Aerobee No. 58	14 Sept. 1955	100	Qualitatively fair data
Aerobee No. 77	0819 MST 9 Apr. 1957	27	No data, vehicle failure
Aerobee No. 80	0630 MST 16 July 1957	122	Quantitatively good data
Aerobee No. 81	0730 MST 18 July 1957	----	No data, vehicle failure
Aerobee No. 87	0808 MST 14 Oct. 1957	146	No data, telemetry difficulty
Aerobee No. 88	2212 MST 16 Oct. 1957	114	Quantitatively good data
Nike-Cajun AF–1	0944 MST 24 Apr. 1958	167	No data, thermal interference
Nike-Cajun AF–2	0533 MST 1 May 1958	137	Quantitatively fair data
Nike-Cajun AA6.203	2200 CST 15 Oct. 1958	151	Quantitatively good data
Nike-Cajun AA6.204	0600 CST 14 Oct. 1958	137	Quantitatively good data
Nike-Cajun AA6.205	2125 CST 17 Oct. 1958	143	No data, mechanical failure
Nike-Cajun AA6.206	2145 CST 21 Oct. 1958	157	Quantitatively fair data
Spaerobee 10.01	1047 CST 22 Oct. 1958	177	Quantitatively fair data
Spaerobee 10.02	1327 CST 25 Oct. 1958	420	No data, telemetry failure

influx rates could be set. Only that influx rate measured by the scale of highest sensitivity is of any value in the present analysis.

Direct measurements from rockets

Signals that could be ascribed to no other source than the impacts of dust particles onto the skins of rockets were first found on the telemetry records for two V–2 rockets. The rockets were V–2 Blossom IV–D flown on 8 December 1949, and V–2 Blossom IV–G flown on 31 August 1950. Microphones and the associated electronics had been designed and installed by personnel of Temple University under the direction of Prof. J. L. Bohn. The equipment was flown for the purpose of measuring acoustical intensities in the warheads and on the skins of the rockets. Descriptions of the instrumentation and the data have been given in detail by Bohn and Nadig (1950).

Bohn and Nadig tentatively suggested that the unexplained pulses observed on the telemetry records were caused by the impacts of meteoric particles on the skins of the rockets. This explanation may now be regarded as the correct one. The data from these flights were the first direct measurements of interplanetary dust particles ever obtained. Both sets of data should be regarded as being qualitatively fair but of no use in quantitative discussions of interplanetary dust particles.

The spare equipment from the V–2 flights was mounted on Aerobee No. 58 and flown on 14 September 1955, as has been reported by Dubin (1956). The rocket did not reach a sufficiently high altitude for observation of dust particles that had not been appreciably decelerated by atmospheric drag forces. Signals that probably were caused by the impacts of dust particles were recorded, but the data must be classified as qualitatively fair.

Bohn and Nadig (1950) also proposed that rockets carrying special acoustical systems for counting the impacts of dust particles be flown. Preferably, the rockets were to have nose tips that could be ejected in order to expose a circular diaphragm. Shielding the diaphragm during the passage of the rocket through the lower atmosphere served to eliminate the possibility that spurious counts were being introduced by the aerodynamic heating of the sensor. The type of rocket program that was suggested was carried further under the direction of Mr. M. Dubin, then of the Air Force Cambridge Research Center.

A list of the rockets that have carried microphone systems is given in table 3. Aerobee No. 77 was the fourth rocket to carry a micro-

TABLE 4.—*Basic corrected data for the successful OSU rockets*

Rocket	Range of momentum sensitivity (dyne seconds)	Effective area (meter ^{2})	Time $h \geq 110$ km. (seconds)	Exposure $h \geq 110$ km. (m^2 sec)	Number of impacts
Aerobee No. 80	$6.0 \times 10^{-4} - 3.0 \times 10^{-3}$	0. 05	100	5. 0	39
	$3.0 \times 10^{-3} - 8.0 \times 10^{-3}$	0. 05		5. 0	10
	$1.0 \times 10^{-3} - 3.0 \times 10^{-3}$	0. 5		50	2
	$3.0 \times 10^{-3} - 1.8 \times 10^{-2}$	0. 5		50	1
Aerobee No. 88	$1.3 \times 10^{-4} - 2.0 \times 10^{-3}$	0. 05	60	3. 0	5
	$2.0 \times 10^{-3} - 2.6 \times 10^{-2}$	0. 05		3. 0	1
	$4.7 \times 10^{-4} - 1.0 \times 10^{-3}$	0. 5		30	10
	$1.0 \times 10^{-3} - 2.8 \times 10^{-3}$	0. 5		30	7
Nike-Cajun AF-2	$6.0 \times 10^{-4} - 1.2 \times 10^{-3}$	0. 2	154	31	30
	$1.2 \times 10^{-3} - 4.0 \times 10^{-3}$				12
	$4.0 \times 10^{-3} - 3.0 \times 10^{-2}$				3
Nike-Cajun AA6.203	$3.0 \times 10^{-4} - 3.0 \times 10^{-3}$	0. 2	186	37	52
	$3.0 \times 10^{-3} - 1.8 \times 10^{-2}$				3
Nike-Cajun AA6.204	$7.0 \times 10^{-4} - 3.0 \times 10^{-3}$	0. 2	167	33	31
	$3.0 \times 10^{-3} - 3.0 \times 10^{-2}$				1
Nike-Cajun AA6.206	$1.5 \times 10^{-4} - 1.0 \times 10^{-3}$	0. 2	118	24	11
	$1.0 \times 10^{-3} - 6.0 \times 10^{-3}$				1
	$7.0 \times 10^{-4} - 5.0 \times 10^{-3}$				6
Spaerobee 10.01	$5.0 \times 10^{-4} - 7.5 \times 10^{-3}$	0. 04	202	8. 1	20

phone system and was the first of a series of 13 rockets instrumented with microphone systems and flown by Oklahoma State University under contract with the Air Force. The series of rockets was flown especially for the purpose of directly measuring influx rates and momenta of interplanetary dust particles. Aerobee No. 77, like the other Aerobees in the series, had two crystal microphones mounted on the skin of the instrument compartment, and two microphones mounted on a circular diaphragm that could be exposed by ejecting the nose tip of the rocket at an altitude of about 60 km. The diaphragm had been highly polished by Bohn in the hope of observing hypervelocity craters on the recovered diaphragm. The rocket reached zenith at an altitude of 27 km, which was too low for proper operation of the microphone system. The recovered diaphragm was examined photochemically by Yagoda (Dubin, 1957), who found several tiny craters resembling those formed by hypervelocity impacts of small dust particles.

Seven of the thirteen rockets provided data that are of use in quantitative discussions of interplanetary dust particles. A preliminary readout of the data from six of these rockets was included in an early analysis of direct measurements by McCracken (1959). A final readout of the uncorrected data from the seven rockets was made available as a final report on the contract, being dated 14 April 1960 (Buck, 1960).

The data for the seven rockets are given in table 4. Corrections have been applied for the counts that possibly could have causes other than the impacts of dust particles. The data from Nike-Cajun AF-2 are slightly rearranged in order to compensate for a change in sensitivity that occurred as a result of a low battery potential during the flight. A corrected tabulation of the data from the OSU rockets has not previously been made available in the open literature because of the series of corrections that were in progress and have only recently been completed.

Only those impacts that occurred when the rockets were at altitudes greater than 110 km are counted. The deceleration of dust particles by atmospheric-drag forces becomes quite appreciable at altitudes below approximately 100 km. The velocities of the dust particles become functions of altitude and zenith angle, making the determination of the velocities of the particles relative to a rocket an almost impossible task. Setting the lower limit on

TABLE 5.—*Direct measurements obtained with the OSU rockets*

Rocket	Momentum sensitivity (dyne seconds)	Particle velocity (km/sec)	Mass sensitivity (grams)	Number of impacts	Exposure $h \geq 110$ km. (m² sec)	Cumulative influx rate (particles/m²/sec)
Aerobee No. 80	6.0×10^{-4}	70	8.6×10^{-11}	49	5.0	9.8
	3.0×10^{-3}	70	4.3×10^{-10}	10	5.0	2.0
	1.0×10^{-3}	40	2.5×10^{-10}	3	50	6.0×10^{-2}
	3.0×10^{-3}	40	7.5×10^{-10}	1	50	2.0×10^{-2}
Aerobee No. 88	1.3×10^{-4}	20	6.5×10^{-11}	6	3.0	2.0
	2.0×10^{-3}	20	1.0×10^{-9}	1	3.0	3.3×10^{-1}
	4.7×10^{-4}	35	1.3×10^{-10}	17	30	5.7×10^{-1}
	1.0×10^{-3}	35	2.9×10^{-10}	7	30	2.3×10^{-1}
Nike-Cajun AF-2	6.0×10^{-4}	40	1.5×10^{-10}	45	31	1.5
	1.2×10^{-3}		3.0×10^{-10}	15		4.8×10^{-1}
	4.0×10^{-3}		1.0×10^{-9}	3		9.7×10^{-2}
Nike-Cajun AA6.203	3.0×10^{-4}	35	8.6×10^{-11}	55	37	1.5
	3.0×10^{-3}		8.6×10^{-10}	3		8.1×10^{-2}
Nike-Cajun AA6.204	7.0×10^{-4}	40	1.8×10^{-10}	32	33	9.7×10^{-1}
	3.0×10^{-3}		7.5×10^{-10}	1		3.0×10^{-2}
Nike-Cajun AA6.206	1.5×10^{-4}	35	4.3×10^{-11}	12	24	5.0×10^{-1}
	1.0×10^{-3}		2.9×10^{-10}	1		4.2×10^{-2}
	7.0×10^{-4}		2.0×10^{-10}	6		2.5×10^{-1}
Spaerobee 10.01	5.0×10^{-4}	60	8.3×10^{-11}	20	8.1	2.5

altitude at 110 km allows one to assume that the majority of the dust particles impacting onto the sensors had not been appreciably decelerated by atmospheric-drag forces. Geocentric velocities of dust particles above the atmosphere of Earth lie between 11 and 72 km/sec, so velocities of the dust particles (relative to the rocket) lie approximately between the same limits.

It seems reasonable to assign average particle velocities for each sensor of each rocket until the velocity distribution becomes known. The average particle velocities have been assigned on the basis of the region on the celestial sphere (relative to the apex of Earth's motion) to which each sensor was exposed. The limiting mass sensitivity of each sensor is computed from the momentum sensitivity and the assigned average particle velocity. Table 5 contains the limiting momentum sensitivities, the assigned average particle velocities, the limiting mass sensitivities, and the numbers of impacts from which datum points for a cumulative mass distribution curve were computed.

The direct measurements made with the rockets served as an early and preliminary determination of the influx rate and mass distribution of small interplanetary dust particles. The data were of considerable importance in the design of the dust-particle experiments for the early satellites and space probes. The degree of importance may be partially illustrated by the fact that the rocket data showed influx rates higher by a factor of 10^4 than was expected on the basis of an extrapolation of the tabulation by Watson (1941) of the results from observations of meteors, and higher by a factor of 10^2 than was expected on the basis of a similar extrapolation by Whipple (1957). The weight and power allotments on the early satellites did not permit one to build in enough dynamic range to allow for such uncertainties in the influx rate. It is interesting and perhaps of moderate quantitative value if the rocket data agree with and support the more definitive direct measurements now available from satellites. The rocket data probably should not, however, be used as the decisive element in a critical test of the validity of a particular model of the distribution of dust particles in the vicinity of Earth.

Analysis of the direct measurements

The available direct measurements that have been obtained with microphone systems on

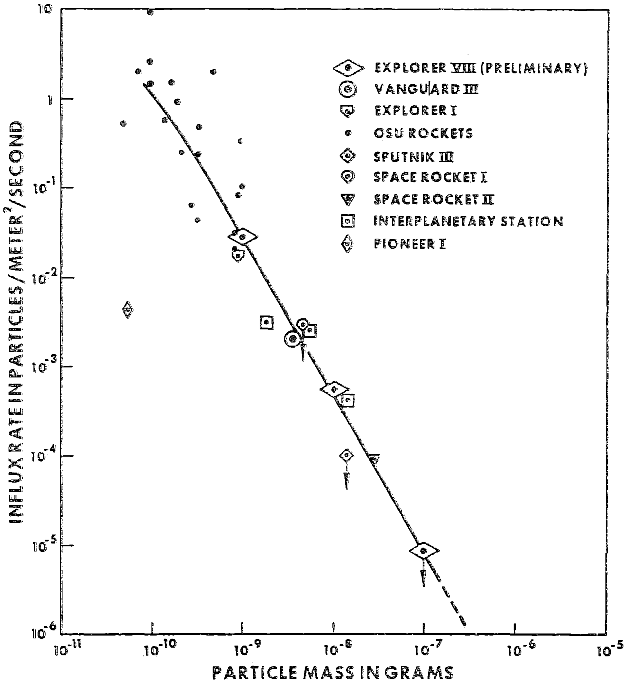

Figure 2.—The average distribution curve established by direct measurements from microphone systems for interplanetary dust particles in the vicinity of Earth. (Space Rocket I, Space Rocket II, and Interplanetary Station are referred to in the text as Luniks I, II, and III, respectively.)

the OSU rockets, U.S. spacecraft, and Soviet spacecraft are shown plotted as a cumulative mass-distribution curve in figure 2. The various direct measurements, with the exception of the one from Pioneer I, fit remarkably well onto the distribution curve, regardless of the geocentric distance or sensitivity at which the measurement was made. The departure of the direct measurement for Pioneer I from the average distribution curve can easily be explained on the basis of the actual fluctuations in the influx rates measured with Explorer I, Vanguard III, and Explorer VIII. Pioneer I was active for about 1½ days and easily could have flown during an interval of low dust-particle activity.

The direct measurements listed in tables 1, 2, and 5 encompass a variety of altitudes, sensitivities, lengths of sampling interval, and times of the year. The fact that all except the direct measurement from Pioneer I fit the distribution curve established by Explorer VIII lends substantial support to the validity of the curve shown in figure 2 as an average distribution curve that can be used until more sophisticated experiments have established the curve over a considerably larger range of particle mass.

It is quite advantageous to the present analysis to point out the uncertainties that are encountered in displaying the direct measurements as a mass distribution. Qualitative discussions of the uncertainties are followed by attempts to assign them numerical values.

The values of average particle velocity assigned in converting from momentum sensitivity to mass sensitivity for the systems may be slightly too high. The correct values depend on the velocity distribution that exists for dust particles in the direct-measurements range of particle size. Lower average velocities would apply if most of the dust particles were in geocentric orbits or direct circular heliocentric orbits. The use of lower particle velocities would tend to shift the direct measurements toward slightly higher values of particle mass without markedly changing the shape of the distribution curve. Even a radical reduction from about 30 km/sec to the value 15 km/sec used by Whipple would lower the threshold mass sensitivities by only a factor of 2.

The impulse delivered to a sensor as a dust particle impacts at hypervelocity is almost certainly greater than the impact-momentum of the dust particle, but the value remains unknown. A value greater than unity (which is used in tables 1, 2, 4, and 5) for the ratio of the impulse to the impact-momentum increases the momemtum sensitivities for microphone systems. The proper correction factors probably lie between 2 and 3, and are now being established by hypervelocity accelerators.

Allowing for the impacts of dust particles at angles of incidence appreciably different from 0° effectively decreases the momentum sensitivity, but the decrease is probably less than a factor of 2. This uncertainty can be largely removed through the use of more directional sensors.

The magnitude of the correction for the shielding effect of Earth depends on the velocity distribution of the dust particles. The corrections that have been applied involve the assumption that the dust particles are predominantly in heliocentric orbits and are not necessarily confined to direct circular orbits. If this assumption is not valid, then slightly smaller corrections would be applied. The factors applied to correct for Earth's shielding of the spacecraft were all less than or equal to 2. Smaller correction factors would shift the direct measurements toward slightly lower values of influx rate without changing the shape of the distribution curve.

Knowing which of the minor corrections to apply requires a better knowledge than exists at present of the mass distribution, velocity distribution, and spatial density of the interplanetary dust particles. All of the direct measurements have been handled in as consistent a manner as possible, so that introducing minor corrections will change only the position of the direct measurements on a plot of mass distribution without changing the shape of the distribution curve. It seems reasonable to assume that likely combinations of the minor uncertainties will leave the distribution curve as it is shown in figure 2. Direct measurements obtained at large distances from Earth and/or a determination of the velocity distribution are needed before much further progress can be made in defining a model distribution of the interplanetary dust particles.

The distribution curve shown in figure 2 can be approximated reasonably well by a straight-line segment. The equation of the straight line is

$$\log I = -17.0 - 1.70 \log m,$$

where I is the influx rate in particles m^{-2} sec^{-1}, and m is the particle mass in grams (McCracken, Alexander, and Dubin, 1961). The equation should not be used outside the range 10^{-10} gm $\leq m \leq 10^{-6}$ gm, and applies for an average particle velocity of 30 km/sec.

The distribution curve shown in figure 2 is intended to be an average for dust particles in the vicinity of Earth. Whether the distribution is the same in interplanetary space is a question that cannot yet be answered. If an appreciable concentration exists near Earth, then the influx rates measured at comparable sensitivities but at different geocentric distances should be functions of the geocentric distance. The influx rates measured at large geocentric distances (Lunik II, 3.6×10^5 km; Lunik III, 4.7×10^5 km) should fall appreciably below those from the earth satellite Explorer VIII. The low altitude (~150 km) rockets should have shown influx rates considerably higher than those obtained with Explorer VIII. With the exception of the direct measurement from Pioneer I, the departures of direct measurements from the distribution curve established by Explorer VIII are negligible.

The distribution curve of figure 2 is shown, together with the model distributions of meteors from Watson (1941) and Whipple (1957, 1960), in figure 3. None of the linear extrapolations of the results from observations of meteors fits the direct measurements. The curves labeled "Watson (1941)" and "Whipple (1957)" approximately represent limits for the uncertainty encountered in placing average influx rates for meteors on a mass-distribution curve. The uncertainty of approximately 200 arises because the mass-to-magnitude relationships are not well known for meteors, and exceeds by one to two orders of magnitude the uncertainties that exist for the direct measurements. The curve labeled "Whipple (1960)" represents a revision by Whipple of the curve

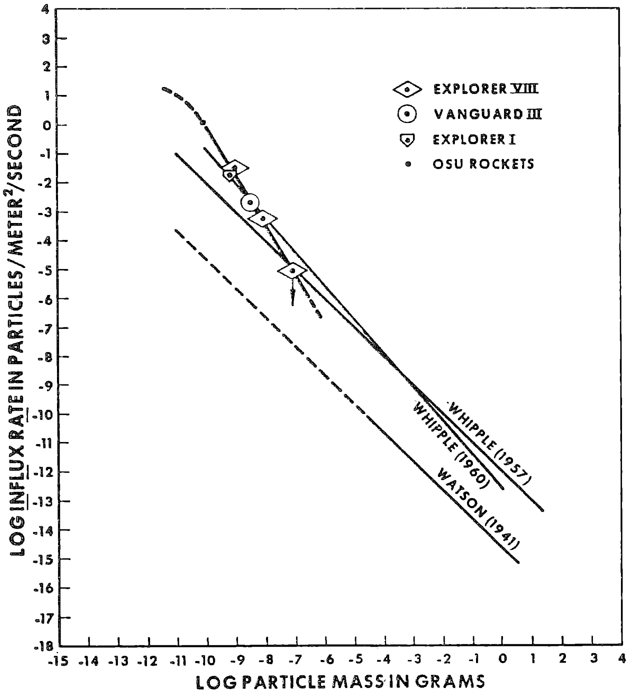

FIGURE 3.—Comparison of model distribution curves obtained from extrapolations of results from observations of meteors.

labeled "Whipple (1957)" made in an attempt to remove the discrepancy between the linearly extrapolated meteor curves and the direct measurements.

Whipple (1960, 1961a, 1961b) performed an analysis of the direct measurements and concluded that "Acoustical impacts of meteoritic dust on counting devices that are carried by satellites and space probes show clearly that a high concentration of interplanetary dust occurs near the earth" (Whipple, 1961b, p. 21). In his analysis, Whipple used the departures of direct measurements from the curve that is labeled "Whipple (1960)" in figure 3 in order to show that the geocentric concentration varied inversely as the 1.4 power of distance from the surface of Earth. Such an interpretation represents the second of the two interpretations that were possible before the direct measurements were obtained with Explorer VIII. Whipple's approach is incompatible with the new direct measurements from Explorer VIII and is not particularly supported by any of the other available direct measurements.

The following paragraphs present arguments against statements that the direct measurements confirm the existence of a geocentric concentration of dust particles.

The datum points representing the largest numbers of impacts (Explorer VIII, Vanguard III, Explorer I, OSU rockets) fit the same straight-line segment (see fig. 2), regardless of the altitude at which a particular direct measurement was obtained.

One must allow for the differences in sensitivity of the various microphone systems before comparing the influx rates to see if an altitude dependence exists. This requires normalizing all the direct measurements to a given value of particle mass. The distribution curve used as the normalization standard is extremely critical to the interpretation of the direct measurements. Using the conjectural curve labeled "Whipple (1960)" as the normalization standard leads one to the conclusion that the direct measurements indicate a geocentric concentration. Using the empirical distribution curve established by Explorer VIII leaves one with no discernible evidence from the direct measurements that a geocentric concentration of dust particles exists.

The slopes of straight-line segments of the distribution curve shown in figure 2, separately indicated by each of the three groups of direct measurements (U.S. spacecraft, Soviet spacecraft, OSU rockets), are between -1.5 and -2.0. These values differ significantly from the value of approximately -1.2 that was used by Whipple (1960) in order to normalize the direct measurements in such a manner that a geocentric concentration would be evident.

The most critical datum points in Whipple's analysis were the direct measurements from the OSU rockets and those from Explorer VI. It should be pointed out that in adjusting the sensitivities of the systems on the rockets, Whipple has introduced an error of about 15 in the influx rate. The data from Explorer VI have not been placed in the open literature by the experimenters, so it should not be used as a critical point.

Conclusions

Several interesting conclusions can be reached on the basis of the new distribution curve that has been established by the direct measurements of interplanetary dust particles. Some of the more important are discussed in the following paragraphs.

The average distribution curve established by the direct measurements can be approximately represented over the range of mass $10^{-10}\text{ gm} \leq m \leq 10^{-6}\text{ gm}$, by a straight-line segment. The equation of the line segment is

$$\log I = -17.0 - 1.70 \log m,$$

where I is the omnidirectional influx rate in particles $\text{m}^{-2}\text{ sec}^{-1}$.

Particulate aggregates of matter accreted by Earth consist primarily of dust particles smaller than the faintest radar meteors, with an accretion rate of approximately 10^4 tons per day on Earth. This rate is in good agreement with the earlier estimate (Dubin, 1959) based on the direct measurement from Explorer I.

The convenient constant-mass-per-magnitude relationship, common to discussions of results from observations of meteors, does not hold for dust particles in the direct measurements range of particle mass. The distribution curve established by the direct measurements departs markedly from the distribution curves obtained by extrapolating linearly the results from observations of meteors.

The available direct measurements extend almost into the range of particle mass where radiation-pressure control becomes important. A rather marked change in the shape of the distribution curve should occur as a result of radiation pressure at values of particle mass slightly lower than those presently covered by the direct measurements.

The distribution curve established by the direct measurements can be joined to a model constant-mass-per-magnitude curve for meteors within the range of particle size typical of the faint radar meteors. Such a junction probably has little physical meaning until the mass-to-magnitude relationship can be established for meteors, or until statistically significant direct measurements can be obtained in the range of particle mass 10^{-7} gm$\leq$m$\leq 10^{-5}$ gm.

The direct measurements now available show (within themselves) no discernible evidence for the existence of an appreciable geocentric concentration of interplanetary dust particles. If a geocentric concentration does exist, then its existence can be reliably inferred from the type of direct measurements that is presently available only if future direct measurements obtained at large geocentric distances deviate appreciably from the average distribution curve shown in figure 2.

This curve can be used only to describe average conditions. It is already known from the direct measurements that fluctuations in the influx rate of at least ± 10 occur within intervals of a few hours for particles with masses of approximately 10^{-10} gm (Dubin, Alexander, and Berg, in this symposium, p. 109). The magnitude of the fluctuations presumably becomes quite large for particles near the radiation pressure limit on particle size. The distribution curve is slightly biased toward the autumn of the year because of the distribution in time of year of the direct measurements. If the annual variation in influx rate of dust particles resembles that of meteors, then the curve shown in figure 2 represents influx rates that are slightly higher than the true average values.

Large inconsistencies have been attributed to the direct measurements several times in the literature (Whipple, 1959; Kaiser, 1961). The various direct measurements seem to be remarkably self-consistent when analyzed on the basis of the new measurements from Explorer VIII, in which the authors place much confidence.

Discussion

Unidentified speaker.—I wonder about the assumption of the average velocity of 25 to 40 km/sec for micrometeorites. It appears that the average velocity of meteorites is below 20 km/sec, and I would expect these particles to be in even more circular orbits and therefore at even lower velocities.

C. W. McCracken.—I assumed a value of 30 km/sec. That, at most, introduces an uncertainty of a factor of 2 in the placement of the curve on the mass distribution plot.

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Abstract

Existing direct measurements of small interplanetary dust particles in the vicinity of Earth are analyzed on the basis of a new set of data obtained with the satellite Explorer VIII. All but one of the direct measurements made with microphone systems fit remarkably well onto the distribution curve derived from the Explorer VIII data. This good fit allows one to establish an average distribution curve for small interplanetary dust particles in the vicinity of Earth.

The equation of a straight-line segment that approximately fits the new distribution curve for particle masses in the range $10^{-10}\text{ gm} \leq m \leq 10^{-6}\text{ gm}$ is

$$\log I = -17.0 - 1.70 \log m,$$

where I is the influx rate in particles $m^{-2}\ sec^{-1}$. One of the more important consequences of the new distribution curve is the fact that the particulate matter accreted by Earth is dominated by particles with characteristic dimensions of a few microns.