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The Space Density of Atmospheric Dust in the Altitude Range 50,000 to 90,000 Feet [1]

By Paul W. Hodge[2] and Frances W. Wright[3]

The importance of collecting and analyzing meteoritic dust particles has been enhanced by the recent suggestion of a remarkably localized dust cloud about the earth (Whipple, 1961a), and by the likelihood that this dust has a lunar origin (Whipple, 1961b). Artificial satellites efficiently provide the evidence for the probable existence of the earth's dust belt; however, they are not yet capable of capturing samples of this material and returning them to earth for analysis. For such highly desirable samples we must at present rely on the earth's atmosphere to act as a cushion, braking the high-velocity particles and concentrating them in sufficient numbers for collection on high-flying aircraft and balloons.

The Smithsonian Astrophysical Observatory has been employing jet aircraft and balloons to collect particles from various levels of the stratosphere. In previous publications we have described a series of particle collections made at altitudes of 30,000 to 50,000 feet (Hodge and Rinehart, 1958; Hodge, 1961; Wright, Hodge, and Fireman, 1961). Fireman and Kistner (1961) and Riggs, Wright, and Hodge (1962) have made chemical analyses of some of these particles. The present paper presents results of the first of a series of collections at altitudes between 50,000 and 90,000 feet, made in cooperation with the Flight Research Center of the National Aeronautics and Space Administration.

Collecting procedure

The collector.—The device used in the present collecting program is a refinement of our first collector, which was flown on a U–2 (see photograph in the paper by Rados, 1960, that describes our U–2 program). It is nearly identical with the device flown on the B–52 (Hodge, 1961), although mounted on the aircraft differently. Air is admitted to an expansion chamber and filtered by a Millipore filter, which retains all particles down to the submicron range. The shutter mechanism and filter housing are so designed that exposure of the filter to air at times other than the period during which the shutter is open in flight is minimized.

Location on aircraft.—The collector was flown on an F–104A aircraft by the Flight Research Center of the National Aeronautics and Space Administration, out of Edwards, Calif. Plate 1 shows the device in place on the tip of the right wing of the aircraft; an identical collector was also mounted on the left wing, but it was not in operation. The wing tip was chosen as a prime location because contamination of the sample by the body of the craft was minimized.

Flight characteristics.—A pressure switch installed on the wing activated the shutter at an altitude of about 55,000 feet, so that dust was collected continuously at all heights above this limit. The flights of the F–104A on which

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collections were made were typically short-duration, high-altitude climbs to above 80,000 feet. Collections were made on nine such flights. Heights, velocities, temperatures and wind characteristics for each flight are shown in table 5.

Examination of samples

Microscope procedure.—We made a general survey of each filter (40 mm in diameter) from edge to edge, with a microscope of 200× magnification, and measured, described, and recorded the position of all types of particles larger than 6μ (mean diameter).

Then, within the central exposed portion of the filter (a circle of 14-mm diameter), we made a survey under 400× magnification, and measured, described, and recorded the positions of all opaque particles with mean diameters larger than 3μ. The numerical results of these two scannings are shown in table 1.

Classification of particles.—We found that all particles examined were included in the following classification scheme:

1. Black, shiny metallic particles; they may be rough or smooth. Designation, *M*.
2. Black, non-shiny particles. Designation, *B*.
3. Dark brown and dark gray particles. Designation, *D*.
4. Gray, stone-colored chunks. Designation, *Gy*.
5. Colored particles, usually with smooth outlines; most of these seem to be semitransparent. Designation, *C*.
6. Transparent, clear particles. Designation, *T*.
7. Aluminum chips, from the walls of the collector. Designation, *Al*.
8. Green-black ovals. Designation, *Gn-B*.
9. Metallic particles similar in appearance to iron filings. Designation, *M(C)*.

The second scan, within the 14-mm circle, excluded the very numerous colored and transparent particles.

The complete scanning data are given in table 4.

Results

Description of flights and collections.—The characteristics of the nine flights were all very nearly the same. Exposure times averaged 95 seconds, with a dispersion of about 20 percent; maximum altitudes averaged 83,000 feet with a dispersion of only 9 percent. The small differences in the exposure times or altitudes of different flights are not expected to affect greatly the number or nature of particles. For this reason the observed numbers of particles are expected to reflect primarily differences in space density rather than in flight characteristics.

Table 1 summarizes the individual flight characteristics and scanning results, details of which are given more completely in table 5. Table 1 shows the total numbers of particles (with mean dimensions greater than 3μ) on the exposed portions of each filter; this value was computed from counts on smaller areas, and over a different size range, by applying the appropriate multiplication factors (e.g., the known size distribution). The numbers of opaque particles given in table 1 are those directly observed and measured.

TABLE 1.—*Flight characteristics and number of non-aluminum particles*

Filter no.	Exposure (secs)	Alt. range (1000 ft)	Total no. particles (mean diameter >3μ)	No. opaque particles (mean diameter >3μ)
G8	103	51 to 85	80	43
G16	77	52 to 82	560	69
N1	92	51 to 83	2080	359
N2	94	53 to 85	160	81
N3	87	56 to 78	40	15
N4	96	52 to 83	80	40
N5	100	52 to 78	80	18
N7	102	52 to 85	5200	510
N9	103	52 to 87	120	63

From the data of table 1 three facts are evident. (1) The total number of particles and the number of opaque particles vary widely, over a range of two orders of magnitude. (2) The two values agree in their differences; when the number of all types of particles is high, the number of opaque particles is high. (3) The ratio of total to opaque varies between 2 and 10, and is larger when the actual values are larger.

Computed space densities.—Because the collector's altitude and velocity varied widely during the collections, we cannot obtain straightforward space densities as a function of height. Instead, we obtain a mean value, weighted according to altitude by the volume encountered as a function of altitude. This space density is computed by

$$\bar{\rho}=N_0/kV,$$

Wing tip of F-104A showing meteoritic dust collector in place. Photograph courtesy of NASA, Flight Research Center.

where $\bar{\rho}$ is the weighted mean density, k is the efficiency of the collector, N_0 is the number of collected particles (total minus contamination), and V is the volume encountered by the collector (kV is the volume swept out).

In our case, N_0 is taken as equal to the value given in table 1 if we assume no contamination (thus giving an upper limit to $\bar{\rho}$). The volume encountered is taken to be

$$V=A\int_{t_1}^{t_2} v(t)dt,$$

where A is the area of the opening of the collector ($3\times10^{-5}m^2$); $v(t)$ is the aircraft's velocity as a function of time; and t_1 is the time of the beginning, and t_2 the time of the end of the exposure.

We do not have direct values for $v(t)$, but we do know $M(t)$, the Mach number as a function of time. This value is related to the velocity of the plane with respect to the air by

$$v(t)=20.1M(t)\sqrt{T(t)},$$

where $M(t)$ is the Mach number and $T(t)$ is the temperature in absolute units.

Thus we can compute the average space density of particles by the equation

$$k\bar{\rho}=\frac{N_0}{6\times10^{-4}\int_{t_1}^{t_2} M(t)\sqrt{T(t)}\,dt}\ \text{particles/m}^3.$$

This has been done numerically for the flights, and results are given in table 2. The volume of air sampled in each case is nearly one cubic meter, and the value for $k\bar{\rho}$ is normally of the order of 150 particles per cubic meter for all particles with diameters greater than 3μ. The average value is 156, excluding N1 and N7 (see below).

The efficiency k of the collector has been determined from wind-tunnel tests carried out by P. Stroom of General Mills. He made an experimental calibration by injecting particles into the air stream, and then comparing the number collected by our device and that collected by a collector of known efficiency. The calibration showed that at Mach 0.6 and altitude 50,000 feet our collector is 15 percent efficient. This low efficiency results from the very small pore-size of the filters and from some loss on the walls and other portions of the collector. The central part of the collector retained 7 percent of the particles; the remainder were concentrated near the edges. Calculations based on pressure differentials measured in the wind tunnel indicate that the efficiency of filtering increases with velocity and decreases with height. For a typical F–104A flight this efficiency varies between 0.7 and 4.1 times that of the flights at 50,000 feet and Mach 0.6. Experimental tests with particles were not carried out for Mach numbers greater than 0.6, so that we estimate the efficiency from the pressure data. We believe that a realistic time average for the F–104A flights is an efficiency of approximately 15 percent ±3. We adopt a value of 0.15 for k; the derived space density $\bar{\rho}$ is nearly 7 times the values of $k\bar{\rho}$ tabulated in table 2. Thus the space density is normally of the order of 1000 particles larger than 3μ per cubic meter.

TABLE 2.—Particles per cubic meter (mean diameter $\geq 3\mu$).

Filter no.	$k\bar{\rho}$
G8	80
G16	480
N1	2290
N2	192
N3	38
N4	82
N5	85
N7	5720
N9	132

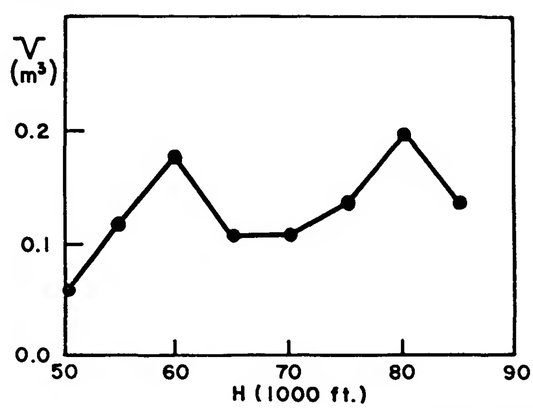

FIGURE 1.—The volume of air, V, encountered by the collector between heights H and H+5,000 feet, expressed as a function of altitude.

In figure 1, the volume of air encountered is shown as a function of altitude for the typical flight on which filter G8 was flown. The diagram indicates that the volume of air is not a rapidly varying function of altitude, and that, within the accuracy to which we can discuss the present data, the computed $\bar{\rho}$ is very nearly equivalent to a mean space density for altitudes between 55,000 and 85,000 feet.

On two filters, N1 and N7, the calculated values of $k\bar{\rho}$ are much greater than the average. This seems to be the result not of contamination, but of the encounter of the aircraft with a dust-enriched portion of air. We have found that accidentally contaminated samples, such as N6 and N8 (see table 4), contain large amounts of aluminum particles, while the amount of aluminum dust on filters N1 and N7 was equal to the normal background count. In each case, and especially for filter N1, there is a large cluster of particles, nearly centered on the filter, where most of the dust is located (fig. 2). The remainder of the filter has the density of particles typical of the other filters. Thus the unusually high count is due exclusively to the compact cluster, which appears to consist of fragments of a larger, conglomerate particle that may have disintegrated on contact with the filter or while entering the collector. Such a particle must have been relatively fragile and of low density, with a diameter of the order of 100μ and mass of the order of 10^{-7} gm. It is tempting to enquire whether such a particle can be extraterrestrial in origin. Meteor studies suggest that meteoroids are primarily low-density, fragile bodies derived from comets. Fragments of such bodies might well have the appearance of the object we collected. It is of great importance to check such a possibility by means of more collections.

TABLE 3.—The size distribution of particles with mean diameters larger than 3μ; the limiting mean diameter of opaque particles collected on these filters was 21μ.

Mean diameter (microns)	Percent of total sample
3.0 to 5.9	67.3
6.0 to 8.9	26.2
9.0 to 11.9	4.8
12.0 to 14.9	1.2
15.0 to 17.9	0.4
18.0 to 20.9	0.1

TABLE 4.—*Complete scanning data*

Filter No.	No. particles of all types in 14 mm² with mean diam. >6μ	No. particles in 140 mm² with mean diameter >3μ				
		Total: all but *C* and *T*	*B* and *M*	*Gy*	*M*(*C*)	*Al*
G8	1	43	34	3	0	27
G16	7	69	40	12	4	143
N1	26	359	309	87	1	99
N2	2	81	38	5	0	75
N3	0. 5	15	12	1	0	16
N4	1	40	24	1	0	16
N5	1	18	6	1	0	16
N6*	131. 2	441	86	36	133	1592
N7	65	510	227	39	6	122
N8*	5	260	32	35	151	947
N9	1. 5	63	28	3	2	2

* Unexposed and heavily contaminated; flown on left wing, new collector.

From our limited data, assuming $k=1$ for this encounter, we calculate tentative space densities of 0.1 such particle per cubic meter. This corresponds to a rate of fall on the earth of about 10^4 tons/day, using the method of estimating the mass rate of fall described by Fireman and Kistner (1961).

Conclusions

From microscopic studies of particles collected in the upper atmosphere, we find that at altitudes of 50,000 to 90,000 feet there are per cubic meter approximately 1000 particles larger than 3μ in diameter. This is approximately one-fourth of the value derived by identical methods at altitudes of 40,000 to 50,000 feet. The space density may fluctuate widely. A maximum of roughly 30 percent of these are opaque particles, so that the upper limit for the space density of *meteoritic* dust in the atmosphere must be approximately 300 particles larger than 3μ per cubic meter. Using the assumptions of Fireman and Kistner (1961), we calculate an upper limit to the influx rate of *meteoritic* material of roughly 10^4 tons/day. The tentatively identified *meteoric* particles give a lower limit of 10^4 tons/day for their influx rate.

We plan to make further collections with a more refined collecting device. These will attempt to determine (1) the nature and number of the large fragile particles, such as those

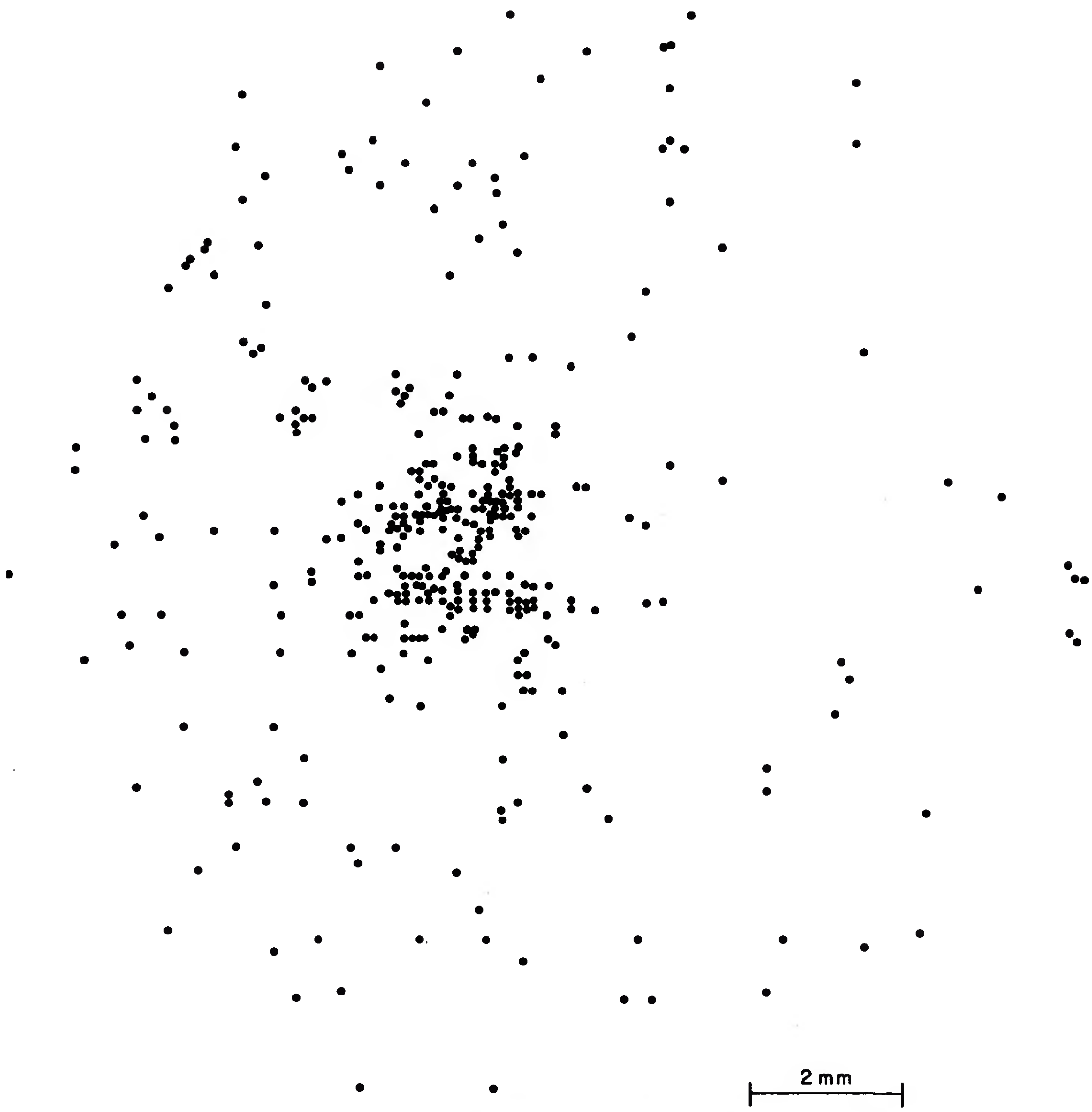

FIGURE 2.—The distribution of 359 opaque particles on filter N1, showing the clump of particles believed to have resulted from the disintegration of a larger fragile particle on impact or while entering the collector.

on filter N1; (2) the distribution with height of the opaque particles to test the present indication of a lack of decrease with height; and (3) the chemical composition of those particles that from their distribution with height appear to be extraterrestrial.

TABLE 5.—*Flight data for filters*

[Explanation of column heads: (2), time after take-off; (3), Mach number for plane's velocity; (4), the dynamic pressure of the air on the aircraft, measured in pounds per square foot. The figures in columns (5), (6), and (7) were obtained by a meteorological balloon on the day of the plane flight.]

FILTER G8

Date of flight, June 21, 1960. Altitude range at which filter was exposed, 51,600 to 85,400 feet. Mach number range during the exposure of the filter, 0.65 to 1.70. Airplane heading, from magnetic north, 0.65°. Take-off time, 0815 P.S.T. Length of time filter was exposed, 102.7 seconds. General atmospheric conditions, clear, ground haze. Time of temperature and wind data, 0810 P.S.T.

(1) Altitude (ft.)	(2) Time (sec.)	(3) Mach no.	(4) q (p.s.f.)	(5) Temp. (C)	(6) Wind speed (knots)	(7) Wind direction
50,000	75.5	1.75	515	−68.3°	35	260°
55,000	79.8	1.66	370	−65.9	14	265
60,000	84.0	1.54	250	−63.1	03	040
65,000	88.7	1.40	145	−66.7	12	099
70,000	93.3	1.25	100	−54.0	18	104
75,000	98.8	1.08	60	−52.6	21	100
80,000	107.8	0.89	30	−49.3	30	080
85,000	122.5	0.66	15	−45.8	31	090
85,000	130.0	0.66	12			
80,000	146.0	0.90	35			
75,000	154.0	1.10	60			
70,000	159.5	1.20	95			
65,000	164.5	1.30	140			
60,000	169.7	1.40	205			
55,000	174.5	1.46	285			
50,000	179.5	1.44	355			

FILTER G16

Date of flight, July 15, 1960. Altitude range, 51,600 to 82,000 feet. Mach no. range, 0.75 to 1.58. Airplane heading, from magnetic north, 065°. Take-off time, 0940 P.S.T. Length of time filter was exposed, 76.7 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0820 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	26.0	1.71	—	−67.7°	16	245°
55,000	30.0	1.61	—	−66.4	15	188
60,000	34.7	1.46	—	−64.7	13	156
65,000	39.5	1.30	146	−58.8	17	108
70,000	45.3	1.14	85	−56.3	22	72
75,000	51.2	1.00	53	−53.7	29	84
80,000	61.0	0.81	28	−50.1	33	90
85,000	—	—	—	−46.1	26	90
80,000	82.0	0.87	26			
75,000	93.5	1.10	50			
70,000	101.0	1.26	87			
65,000	106.8	1.36	132			
60,000	112.2	1.45	—			
55,000	117.0	1.48	—			
50,000	121.8	1.47	—			

FILTER N1

Date of flight, August 2, 1960. Altitude range, 51,000 to 83,200 feet. Mach no. range, 0.44 to 1.65. Airplane heading, from magnetic north, 245°. Take-off time, 0949 P.S.T. Length of time filter was exposed, 91.7 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0820 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	21.5	1.80	550	−65.8°	18	203°
55,000	25.6	1.66	365	−65.4	16	150
60,000	29.7	1.51	240	−60.8	12	130
65,000	33.8	1.37	155	−58.4	16	105
70,000	38.1	1.21	92	−53.2	19	106
75,000	43.6	1.07	61	−51.9	29	098
80,000	52.6	0.90	32	−48.3	24	124
85,000	—	—	—	−47.8	27	092
80,000	86.5	0.67	18			
75,000	97.2	1.00	50			
70,000	102.7	1.17	90			
65,000	107.1	1.30	—			
60,000	111.	1.40	205			
55,000	114.8	1.49	295			
50,000	118.2	1.57	410			

FILTER N2

Date of flight, August 9, 1960. Altitude range, 52,700 to 85,400 feet. Mach no. range, 0.57 to 1.69. Airplane heading, from magnetic north, 265°. Take-off time, 0958 P.S.T. Length of time filter was exposed, 94 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0925 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	30.4	1.83	550	−68.4°	16	300°
55,000	35.0	1.69	370	−68.6	9	114
60,000	39.2	1.51	235	−63.5	7	062
65,000	43.6	1.36	160	−67.3	15	096
70,000	48.7	1.16	95	−54.5	25	090
75,000	55.7	0.95	46	−51.8	25	097
80,000	61.8	0.83	28	−47.7	23	090
85,000	76.0	0.59	11	−45.6	24	094
85,000	86.5	0.59	11			
80,000	100.5	0.82	28			
75,000	107.2	0.99	50			
70,000	113.0	1.13	84			
65,000	120.4	1.35	190			
60,000	123.0	1.42	220			
55,000	127.1	1.51	300			
50,000	131.0	1.56	400			

FILTER N3

Date of flight, August 12, 1960. Altitude range, 55,500 to 78,000 feet. Mach no. range, 1.19 to 1.73. Airplane heading, from magnetic north, 245°. Take-off time, 1200 P.S.T. Length of time filter was exposed, 87 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0730 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	235.4	1.80	555	−69.9°	03	231°
55,000	241.2	1.74	420	−70.8	12	106
60,000	247.0	1.65	285	−63.5	15	088
65,000	253.7	1.53	190	−58.8	12	080
70,000	262.3	1.38	115	−56.7	20	070
75,000	273.0	1.25	75	−49.6	23	083
80,000	—	—	—	−50.7	24	100
85,000	—	—	—	−46.5	21	094
80,000	—	—	—			
75,000	301.4	1.25	80			
70,000	310.3	1.35	120			
65,000	318.2	1.46	175			
60,000	325.5	1.57	265			
55,000	331.3	1.65	385			
50,000	336.3	1.69	480			

TABLE 5.—*Flight data for filters*—Continued

FILTER N4

Date of flight, August 25, 1960. Altitude range, 51,600 to 82,700 feet. Mach no. range, 0.66 to 1.74. Airplane heading, from magnetic north, 245°. Take-off time, 1150 P.S.T. Length of time filter was exposed, 96 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0935 P.S.T. Airplane missed runway on landing; possible contamination by dust from crash trucks.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	36.4	1.78	530	−67.3°	30	250°
55,000	41.4	1.64	350	−67.0	18	257
60,000	46.6	1.43	215	−60.6	06	190
65,000	52.0	1.25	125	−57.9	07	143
70,000	58.7	1.07	75	−53.2	12	120
75,000	66.0	0.91	40	−51.2	21	100
80,000	72.0	0.80	30	−48.9	25	100
85,000	—	—	—	−45.0	24	090
80,000	99.3	0.77	30			
75,000	104.6	0.86	40			
70,000	112.7	1.05	70			
65,000	119.3	1.23	125			
60,000	124.7	1.35	190			
55,000	130.2	1.49	295			
50,000	135.0	1.57	430			

FILTER N5

Date of flight, August 31, 1960. Altitude range, 51,600 to 78,200 feet. Mach no. range, 0.66 to 1.75. Airplane heading, from magnetic north, 245°. Take-off time, 1015 P.S.T. Length of time filter was exposed, 99.5 seconds. General atmospheric conditions, clear. Time of temperature and wind data, 0835 P.S.T. Dusty landing.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	34.5	1.80	550	−61.8°	28	197°
55,000	40.0	1.63	380	−64.9	14	185
60,000	45.6	1.45	205	−61.2	12	171
65,000	51.5	1.28	140	−54.9	12	118
70,000	58.6	1.07	75	−54.9	15	090
75,000	68.5	0.82	35	−53.0	18	100
80,000	—	—	—	−50.2	19	086
85,000	—	—	—	−47.3	24	090
80,000	—	—	—			
75,000	104.5	0.88	40			
70,000	113.5	1.07	80			
65,000	120.4	1.22	125			
60,000	126.3	1.32	185			
55,000	131.7	—	—			
50,000	136.8	—	—			

FILTER N7

Date of flight, October 4, 1960. Altitude range, 52,000 to 85,200 feet. Mach no. range, 0.65 to 1.73. Airplane heading, from magnetic north, 245°. Take-off time, 0935 P.S.T. Length of time filter was exposed, 101.5 seconds. General atmospheric conditions, very clear, calm. Time of temperature and wind data, 1000 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	35.0	1.85	575	−60.3°	24	250°
55,000	39.7	1.71	390	−62.2	14	230
60,000	40.5	1.69	370	−60.2	07	224
65,000	49.6	1.39	360	−57.7	04	229
70,000	54.8	1.23	100	Data not acquired for higher altitudes.		
75,000	59.9	1.11	60			
80,000	68.3	0.87	30			
85,000	84.0	0.66	12			
85,000	91.0	0.65	12			
80,000	108.0	0.88	28			
75,000	115.5	1.06	60			
70,000	122.0	1.22	95			
65,000	127.0	1.31	135			
60,000	132.5	1.41	210			
55,000	137.5	1.46	280			
50,000	143.0	1.46	360			

FILTER N9

Date of flight, October 4, 1960. Altitude range, 52,500 to 86,600 feet. Mach no. range, 0.76 to 1.80. Airplane heading from magnetic north, 245°. Take-off time, 1345 P.S.T. Length of time filter was exposed, 102.5 seconds. General atmospheric conditions, clear, wind at 10 knots. Time of temperature and wind data, 1000 P.S.T.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
50,000	33.5	1.90	625	−60.3°	24	250°
55,000	38.7	1.76	420	−62.2	14	230
60,000	43.3	1.65	285	−60.2	07	224
65,000	48.3	1.47	175	−57.7	04	229
70,000	53.2	1.32	115	Data not acquired for higher altitudes		
75,000	59.8	1.14	60			
80,000	66.8	0.99	40			
85,000	77.8	0.81	20			
85,000	97.8	0.81	20			
80,000	108.4	0.99	40			
75,000	116.3	1.14	70			
70,000	122.0	1.27	105			
65,000	127.4	1.37	155			
60,000	132.3	1.45	215			
55,000	137.2	1.52	305			
50,000	142.5	1.57	410			

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Abstract

Collections of particulate matter have been made in the altitude range from 50,000 to 90,000 feet by means of high-altitude, short-duration flights of an F-104A jet aircraft of the NASA Flight Research Center. The average space density of particles larger than 3μ in diameter is estimated to be 1000 particles per cubic meter at these altitudes. The derived space density varies considerably, as previously found for altitudes in the range from 40,000 to 50,000 feet. Only a small percentage of these particles are possibly meteoritic.

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