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I. STONY MICROMETEORITES

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TECHNICAL REPORT NO. 577

JUNE, 1966

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[1]This research was supported by grant NsG-58-60 from the National Aeronautics and Space Administration.

[2]This is Part I of a series which is in the course of preparation for publication. Part II, "Iron Micrometeorites"; Part III, "Large Iron Meteorites" (passage through the deep atmosphere, heat transfer, ablation and survival); Part IV, "Slow Meteorites at Grazing Entry" (tektite problem) are to follow.

Abstract. The process of energy dissipation through radiation and evaporation, deceleration by drag, and ablation through evaporation of spherical stony micrometeorites has been studied numerically. Interpolation procedures are developed, yielding survival radii and maximum temperatures for entry velocities ranging from 7.8 to 46 km/sec, and for initial radii less than 0.07 cm. The radii are tabulated for vertical incidence; for oblique incidence, they must be multiplied by the secant of the angle of incidence. The lower limit of initial radii of interplanetary particles which can be expected to enter the terrestrial atmosphere is about 2×10^{-5} cm as conditioned by solar radiation pressure. Micrometeorites of lunar origin can be very much smaller, down to near-molecular dimensions as conditioned by the luminosity-to-mass ratio of the earth, 1650 times smaller than the solar value. Micrometeorites of 0.4-2 micron radius can escape excessive heating during atmospheric entry at oblique incidence ($z = 75^{\circ}$ to near grazing) and could act as carriers of living germs from other planets.

1. Introduction. Micrometeorites of the zodiacal cloud presently constitute the major source of terrestrial accretion of cosmic material by some two orders of magnitude exceeding the mass arising from all other sources combined (Öpik, 1956). The large area to mass ratio of these small cosmic bodies favors the dissipation of their kinetic energy through radiation when they enter the atmosphere. As a consequence, they may survive the entry with little loss of mass, thus providing samples of cosmic dust which can be collected from the air, the sea bottom and even from geological deposits of sediments. This cosmic dust,

possibly the result of fragmentation of cometary "dustballs", may be the most ancient sample of condensable matter, dating back to the origins of the solar system and preceding the large meteorites which apparently are the product of a later stage of pressure compaction and differentiation of the dust material during temporary sojourn inside bodies of lunar or sub-lunar dimensions.

The main ingredient of the large meteorites is meteoritic stone. Its chemical composition (if not its mineralogical structure) may characterize the prevalent ingredients of any aggregate of non-volatile cosmic matter, including the zodiacal cloud. Despite radiation damage and the possible absence of a pressurized pre-history, it appears likely that most grains of zodiacal dust are simmilar to fragments of meteoritic stone. The behavior of such grains during passage through the terrestrial atmosphere is the subject of the following numerical study.

2. <u>First approximation</u>. The heat L released per unit of time and area of a meteoroid is $L \sim \rho v^3$, where ρ = atmospheric density, v = velocity. The logarithmic deceleration, $g_i = dv/(vdt)$, is proportional to $\rho/(r\delta)$, where r = radius, δ = density of the meteoroid, and $(4/3)r\delta$ is the mass load or the mass-over-cross-section ratio. Hence the main loss of momentum, at g_i = const., and the main transformation of kinetic energy into heat takes place at $\rho \sim r\delta \sim L$. The atmospheric density and energy dissipation at a characteristic point of the trajectory are proportional to r, the radius of the body. In other words, the larger the meteoroid, the deeper it penetrates into the atmosphere and the more intensely is heat released. The maximum heat release is thus proportional to $r\delta$, or to r. The surface temperature depends on L or $T \sim f(r\delta)$ as defined by radiation and evaporation losses, and for each radius and velocity there is a maximum surface temperature increasing with increasing radius. If this maximum

temperature is below that of efficient evaporation, the meteoroid survives without much of mass loss but may be molten and will come down as a spherule. If the maximum is below melting, the meteoroid will retain its--presumably irregular--shape.

Very small meteoroids will thus dissipate their energy at higher altitudes chiefly through radiation. Disregarding evaporation and the heat capacity of the meteoroid (which is of the order of 10^{-2} to 10^{-3} of the kinetic energy), as well as terrestrial or solar radiation, a first approximation theory (<u>Öpik</u>, 1936) for non-ablating particles which are reaching a maximum temperature T_m (^{o}K) during atmospheric flight yields a mass load of

$$r\delta = 0.00277\, H_p \sec z\, T_m^{4}/v^{3} \qquad (1)$$

(g/cm^2) where H_p(cm) is the scale height for pressure variation, z the zenith angle of incidence (for a "flat" earth), and v is the pre-atmospheric velocity (cm/sec). As a rough approximation, the formula can be used down to $z < 85^{o}$ beyond which the curvature of the earth becomes important.

On similar lines, <u>Whipple</u> (1950, 1951) considered the behavior of small non-ablating meteoroids. His values of the non-ablating radii at $T_m = 1600^{o}$K are very close to those of equation 1 if similar atmospheric models (V-2 by <u>Whipple</u>, Rocket Panel by <u>Öpik</u>) are used, as can be seen from Table 1.

Table 1. Radii, r, in microns, of non-ablating micrometeorites, $\delta = 3$ g/cm^3, which attain a maximum temperature $T_m = 1600^\circ K$ at atmospheric density ρ.

v, km/sec	11.3	15.0	20.0	25.0	40.0	50.0	70.0
ρ, 10^{-10} g/cm^3	56	24	10	5.2	1.3	0.65	0.24
r (Whipple, V-2)	24.3	11.8	5.6	3.2	0.96	0.54	0.23
H, km (Rocket Panel)	6.5	6.7	7.1	7.6	9.0	9.8	11.5
r (equation 1)	26.1	11.5	5.1	2.8	0.81	0.45	0.19

The agreement between the two sets of radii is better than could occur in nature, because of the various simplifications of the theory which is stretched beyond its limit of validity: at $1600^\circ K$ considerable ablation by evaporation is expected to take place.

In the following, a more precise theory of decelerating ablating meteoroids is applied in numerical integrations by taking into account heat and material losses through evaporation, as well as the small but not negligible heat intake of the meteoroid itself.

3. Theory of ablating decelerating micrometeorite. The maximum radius of stony particles for which calculations are here made is 640 microns. According to the general environmental theory (Öpik, 1958; cf. pp. 76 and 110), for slowly rotating (10 cm/sec or more), and practically also for non-rotating meteoroids environmental "case 2" applies, that is the case of an "isothermal stony meteoroid in normal environment, melting into one drop and then evaporating". Until r = 520 μ the drop remains spherical, between 520-720 μ the aerodynamic pressure flattens it out into a spheroid, and only at r > 720 μ the drop breaks up and spraying begins. These

limitations apply to practically the entire range of meteor entry velocities from 12 to 75 km/sec.

The heat intake of the small meteoroid is thus simply allowed for by assuming a temperature throughout equal to the instantaneous equilibrium temperature of its surface, without complications from imperfect conductivity.

The average melting point of meteoritic stone is around $1800^{o}K$ with 1400-$2000^{o}K$ for the different minerals. Before melting, the shape of the meteoroid, or more precisely, the ratio of mass to surface influences the process. After melting, the meteoroid assumes a spherical shape. The integrations have been made for spherical shape throughout, of a mass load $4\ r\delta/3$ per unit cross section. Some uncertainty in the unknown shape factor before melting remains, but its significance is less than of many other physical factors which had to be postulated without a knowledge of the true nature of real micrometeorites such as are the particles of zodiacal dust.

The details of the physical process and the physical constants are taken according to Öpik (1958). For vertical incidence with A = altitude and $x = A_o - A$ as the depth of penetration (inverted altitude) and considering that the acceleration $dv/dt = (dv/dx)\,(dx/dt) = v\,dv/dx$, the drag deceleration per unit path becomes

$$dv/dx = -\,B\,\rho\,v/(4\,r\delta) \qquad (2)$$

where r is the spherical equivalent radius defining volume, $V = \frac{4}{3}\pi r^3$, in former notations, with $B = \frac{rS}{V}$ the shape parameter which characterizes the ratio of surface S to volume V. With $\delta = 3.4\ g/cm^3$ as for typical stone, and B = 3 as for a sphere,

$$dv/dx = - 0.2203\ \rho\ v/r \tag{3}$$

in cgs units.

The ablation rate per unit length of path is

$$dr/dx = - B\,\xi/(\beta\ v\,\delta) \tag{4}$$

where ξ is the rate of surface mass loss by evaporation in g/cm^2 sec. With $B = 3$, $\delta = 3.4$, this becomes

$$dr/dx = - 0.2938\ \xi\ /v\quad . \tag{5}$$

The rate at which the temperature varies is determined by the difference between the heat intake from the impinging air molecules ($\frac{1}{2}\,\gamma\rho\ v^3$ per cm^2 cross section and second where γ = accommodation coefficient), and the radiation and evaporation loss:

$$(cr\delta\ /B)\ dT/dx = \gamma\rho\ v^2/8 - \varepsilon sT^4/v - h\,\xi/v\quad , \tag{6}$$

where c = specific heat, s = Stefan's constant of black-body radiation, ε = the grey emissivity, h = heat of vaporization. In random orientation, the average ratio of cross section to surface is $\frac{1}{4}$ as for a sphere, and the equation remains valid as an average condition for randomly oriented bodies of arbitrary shape.

With $\gamma = 0.8$, $B = 3$, $\varepsilon = 0.8$, $s = 5.67 \times 10^{-5}$ erg/cm^2 sec deg ^{4} , $h = 6.05 \times 10^{10}$ erg/g, and a "smoothed=out" average specific heat of $c = 1.07 \times 10^7$ erg/g deg which includes the relatively insignificant heat of fusion, the temperature increment per unit path becomes

$$dT/dx = 8.241 \times 10^{-9}\ \rho\ v^2/r - 4.989 \times 10^{3}\ (q + \xi)/(vr)\ , \tag{7}$$

where

$$q = \mathcal{E} sT^4/h = 7.551 \times 10^{-16} T^4 . \tag{8}$$

Here radiation is assumed proportional to T^4, disregarding background radiation of the earth. Whipple (1950, 1951) used $T^4 - T_o^4$ where $T_o = 300^oK$ for the background radiation. Actually, however, the radiation emerging from the earth corresponds to effective temperature about 260^oK; the meteoroid intercepts this one-sided radiation but radiates it in all directions. Hence its equilibrium radiative temperature is $(T_e/260)^4 = \frac{1}{2}$ or $T_e = 218^oK$. The corresponding compensation of radiation is much smaller than the uncertainty in the emissivity, $\mathcal{E}$, and it has been decided to neglect it altogether. In daytime the contribution from direct solar radiation is more important, but still negligible as compared to the actual rates of radiation of the meteoroid.

The three differential equations, 3, 5, and 7, with certain initial conditions depending on the atmospheric model, completely describe the problem. The three variables v, r, and T can be expressed as depending on x, the vertical path length, by way of numerical integrations. The strong dependence of radiation and evaporation on temperature necessitates the use of small intervals (steps) Δx, and iterations are even then unavoidable.

The vapor pressure of typical stone was conventionally assumed as

$$\log p_v = 10.600 - 13500/T \tag{9}$$

(dyne/cm^2), which corresponds to

$$\log \xi = 7.089 - \frac{1}{2} \log T - 13500/T \tag{10}$$

(Öpik, 1958).

For atmospheric density the ARDC model (1956) was assumed. From satellite observations, the model is considerably in error above 200 km, but for meteor theory (Minzner and Ripley) this is irrelevant because even micrometeorite phenomena are essentially displayed below 200 km. In work of this kind, stretching over a considerable interval of time, recent improvements of atmospheric models cannot be introduced without destroying the homogeneity and comparability of the results. One has to use one reasonable atmospheric model, even when it admittedly leads to some trivial systematic differences with modern improved models. The properties of the upper atmosphere are anyway variable, and the calculations can only refer to an assumed average state.

The calculations were made for vertical incidence with the length of path defined as

$$x = A_o - A \quad , \tag{11}$$

where A is the altitude and A_o a sufficiently high starting level for which the initial constants of integration, $r = r_o$, $v = v_o$, $T = T_o$ were close to or identical with their pre-atmospheric values and could be estimated with high accuracy from the differential equations themselves.

The calculations were made for vertical incidence, $z = 0^o$, sec z = 1. For an oblique path x sec z, the values of r when multiplied by sec z leave equations 2-7 unchanged. Thus, exact homology

$$r \sim \sec z \tag{12}$$

holds. For oblique incidence, the values of r as calculated for vertical incidence are to be multiplied by sec z, leaving the other variables x, $\rho = \rho(x)$, v, and T unchanged.

The same homology is fulfilled in equation 1. However, its other homologies,

$$r \sim T^4 \; v^{-3} \quad ,$$

which follow from the neglect of ablation, are not valid in the ablating case, and in an atmosphere of variable scale height. The purpose of the present calculations is, indeed, to find the deviations from the simple homologies of equation 1.

Tables 2 and 3 briefly describe the auxiliary variables ρ, q, and ξ used in the integrations. Besides the ARDC, an older (Rocket Panel, 1952) and a more recent (NASA et al, 1962) atmospheric models are cited for comparison. Conventionally smoothed function tables to four or five decimals in the logarithm were actually used. It may be noted that above 1800°K, $q < \xi$, or the main dissipation of kinetic energy is by way of evaporation, through loss of mass. Below 1800°K the dissipation is chiefly through radiation, with a tendency toward preservation of mass.

Table 2. Atmospheric models (ρ, density g/cm^3; H_p, scale height for pressure, km; A, altitude, km)

A	150	140	130	120	110	100	90	80	70	60	50
					Rocket Panel **("V2") (1952)**						
$-\log\rho$	11.468	11.119	10.720	10.249	9.684	9.065	8.389	7.676	7.012	6.457	5.936
H_p	15.4	13.7	11.9	10.0	8.2	7.3	6.5	6.2	6.5	7.6	8.1
					ARDC (Minzner and Ripley, 1956)						
$-\log\rho$	11.750	11.367	10.886	10.369	9.799	9.147	8.398	7.664	6.998	6.457	5.965
H_p	16.2	13.2	10.3	8.9	7.9	7.0	6.1	5.9	6.5	7.6	8.1
					U.S. Standard (NASA et al., 1962)						
$-\log\rho$	11.737	11.469	11.120	10.613	10.007	9.303	8.499	7.699	7.058	6.514	5.988
H_p	29.5	23.3	17.1	11.0	7.9	6.4	5.4	5.4	6.6	7.6	8.0

Table 3. Adopted auxiliary functions for stone, ξ (evaporation rate), $q + \xi$ (g/cm^2 sec), and $1 + \theta = 1 + q/\xi$

T, deg K	400	500	600	700	800	900	1000
log ξ	-	-	-	-	-	-	-7.911
log $(q + \xi)$	-4.714	-4.326	-4.010	-3.742	-3.510	-3.305	-3.122
log $(1 + \theta)$	-	-	-	-	-	-	4.789

T, deg K	1100	1200	1300	1400	1500	1600	1700
log ξ	-6.704	-5.701	-4.852	-4.127	-3.499	-2.951	-2.467
log $(q + \xi)$	-2.956	-2.805	-2.663	-2.526	-2.383	-2.217	-2.012
log $(1 + \theta)$	3.748	2.896	2.189	1.600	1.116	0.734	0.455

T, deg K	1800	1900	2000	2100	2200	2300	2400
log ξ	-2.039	-1.656	-1.312	-1.001	-0.719	-0.462	-0.226
log $(q + \xi)$	-1.768	-1.496	-1.215	-0.941	-0.680	-0.436	-0.208
log $(1 + \theta)$	0.2711	0.1599	0.0961	0.0595	0.0386	0.0257	0.0180

T, deg K	2500	2600	2700	2800	2900	3000
log ξ	-0.010	+0.189	0.373	0.544	0.703	0.850
log $(q + \xi)$	+0.003	0.199	0.381	0.550	0.707	0.854
log $(1 + \theta)$	0.0130	0.0097	0.0073	0.0057	0.0046	0.0037

4. Models of deceleration and ablation. Table 4 contains characteristic points of the calculated models of motion and ablation, obtained from numerical integration of the system of equations 3, 5, and 7. The figures are given with more decimals than could be physically significant; they correspond to the internal accuracy of the mathematical model. This may be needed in differential comparison. It is also not possible to perform satisfactorily the numerical integration without high digital accuracy, on account of the instability and sensitivity of equation 7 involving cumbersome iterations. The calculations themselves were made in much more detail (many more altitude steps) than conveyed by the selected data of Table 4.

The maximum temperature, T_m, and its altitude, A_m, are calculated from the parabolic interpolation formulae

$$\begin{aligned} A_m &= A - \Delta A \quad , \\ \Delta A &= \frac{1}{2} a \, (T_3 - T_1) / \left[(T_2 - T_1) + (T_2 - T_3) \right] , \\ T_m &= T_2 + \frac{1}{4} (T_3 - T_1) \, \Delta A / a \quad , \end{aligned} \tag{13}$$

when T_1, T_2, T_3 are the temperatures at three equidistant altitudes $A + a$, A, $A - a$, and $T_2 \geqslant T_1$, $T_2 \geqslant T_3$, or when T_2 is near the maximum.

Table 4. Motion and ablation of stony micrometeorites in vertical incidence. ARDC 1956 atmospheric model.

A = altitude, km; r = radius, r_o = initial radius, r_f = final radius, microns (10^{-4} cm); v = velocity, v_o initial velocity, km/sec; T = temperature, deg K; T_m = maximum of T, A_m = altitude of the maximum; dv/dx = velocity gradient sec^{-1} or (km/sec)/km; dr/dx, ablation rate of radius, microns per km of path.

Model 1. $v_o = 11.5$; $r_o = 640$; $r_f/r_o = 0.3478$; $T_m = 2097.81$; $A_m = 70.61$

A	98	90	85	80	75	72	71	70
r	640.000	640.000	640.000	632.318	557.999	481.745	450.467	418.449
v	11.5000	11.4324	11.3097	11.0290	10.3570	9.5692	9.2064	8.7786
T	400.00	687.92	1190.01	1938.37	2060.15	2093.22	2097.45	2096.93
-dv/dx	0.0039	0.0157	0.0362	0.0832	0.2028	0.3338	0.3945	0.4640
-dr/dx	0	0	0.0004	8.057	21.48	29.27	31.32	32.73
A	68	66	64	62	60	59.6	59.2	58.8
r	352.533	292.183	248.475	227.150	222.702	222.633	222.608	222.602
v	7.6921	6.2609	4.5602	2.8806	1.5612	1.3553	1.1689	1.0011
T	2077.16	2021.83	1916.57	1744.17	1451.83	1373.08	1290.14	1206.10
-dv/dx	0.6292	0.7991	0.8776	0.7720	0.5392	0.4904	0.4427	0.3968
-dr/dx	32.58	26.95	16.33	5.453	0.3048	0.1057	0.0295	0.0066

Table 4. Continued

Model No. 2. $v_o = 11.5$; $r_o = 160$; $r_f/r_o = 0.4769$; $T_m = 1905.04$; $A_m = 78.01$

A	108	100	95	90	85	80	79	78
r	160.000	160.000	160.000	159.936	153.349	130.861	124.029	116.536
v	11.5000	11.4486	11.3616	11.1557	10.6765	9.5323	9.1516	8.6954
T	400.00	611.40	945.86	1537.86	1808.04	1893.94	1901.99	1905.04
-dv/dx	0.0033	0.0112	0.0258	0.0614	0.1426	0.3474	0.3982	0.4994
-dr/dx	0	0	0	0.1373	2.713	6.474	7.211	7.785
A	77	75	73	71	69.0	68.5	68.0	67.5
r	108.602	92.978	81.467	76.766	76.307	76.306	76.306	76.306
v	8.1502	6.7585	5.0394	3.2810	1.8376	1.5467	1.2859	1.0582
T	1901.82	1866.57	1772.88	1587.63	1234.98	1135.92	1036.49	936.66
-dv/dx	0.5950	0.7939	0.9028	0.8249	0.6089	0.5598	0.4860	0.4267
-dr/dx	8.085	7.230	4.125	0.8659	0.0065	0.0009	0	0

Table 4. Continued

Model No. 3. $v_o = 11.5$; $r_o = 80$; $r_f/r_o = 0.5986$; $T_m = 1801.90$; $A_m = 81.62$

A	113	100	95	90	85	83	82	81
r	80.0000	80.0000	79.9983	79.1797	72.8883	67.9739	65.0185	61.8344
v	11.5000	11.3736	11.2013	10.7979	9.8619	9.2030	8.7805	8.2836
T	400.00	871.37	1297.69	1653.54	1772.44	1796.05	1801.45	1800.75
-dv/dx	0.0033	0.0223	0.0508	0.1200	0.2770	0.3886	0.4593	0.5376
-dr/dx	0	0	0.0045	0.5624	2.100	2.815	3.104	3.268

A	79	77	75	74	73	72.4	71.8	71.0
r	55.3744	50.2730	48.0870	47.9058	47.8876	47.8872	47.8872	47.8872
v	7.0319	5.4438	3.7066	2.9008	2.1839	1.8044	1.4661	1.0723
T	1777.25	1703.43	1530.85	1380.17	1195.11	1080.30	968.60	826.64
-dv/dx	0.7176	0.8586	0.8418	0.7636	0.6671	0.5984	0.5289	0.4322
-dr/dx	3.083	1.906	0.3776	0.0554	0.0025	0	0	0

Table 4. Continued

Model No. 4. $v_o = 11.5$; $r_o = 20$; $r_f/r_o = 0.9361$; $T_m = 1534.92$; $A_m = 88.52$

A	130	110	100	95	90	89	88	87
r	20.0000	20.0000	19.9999	19.9815	19.6280	19.4671	19.2893	19.1112
v	11.5000	11.3588	10.9143	10.2680	8.8602	8.4366	7.9572	7.4200
T	400.00	732.80	1152.26	1377.59	1526.85	1534.04	1533.92	1524.41
-dv/dx	0.0016	0.0199	0.0856	0.1864	0.3973	0.4516	0.5088	0.5657
-dr/dx	0	0	0.0002	0.0150	0.1500	0.1728	0.1830	0.1735

A	86	85	83	82	81	80	79	78
r	18.9535	18.8345	18.7325	18.7241	18.7228	18.7228	18.7228	18.7228
v	6.8257	6.1788	4.7685	4.0366	3.3149	2.6255	1.9914	1.4360
T	1503.72	1468.87	1342.98	1248.01	1138.13	1010.27	871.80	736.15
-dv/dx	0.6229	0.6717	0.7306	0.7314	0.7105	0.6696	0.6011	0.5134
-dr/dx	0.1434	0.0988	0.0183	0.0039	0.0004	0	0	0

Table 4. Continued

Model No. 5. $v_o = 11.5$; $r_o = 5$; $r_f/r_o = 0.99998$; $T_m = 1093.60$; $A_m = 96.24$

A	147	110	100	97	96	95	90	85
r	5.0000	5.0000	5.0000	5.0000	4.9999	4.9999	4.9999	4.9999
v	11.5000	10.8976	9.2908	8.2281	7.7794	7.2785	4.0534	1.0188
T	400.00	801.48	1052.34	1091.34	1093.38	1087.62	888.15	429.09
-dv/dx	0.0012	0.0762	0.2916	0.4237	0.4751	0.5282	0.7136	0.4172
-dr/dx	0	0	0	0.00006	0.00006	0	0	0

Model No. 6. $v_o = 23.0$; $r_o = 320$; $r_f/r_o = 0.009450$; $T_m = 2250.53$; $A_m = 79.96$

A	114	100	95	90	85	81	80	79
r	320.000	320.000	319.933	301.225	236.838	129.455	92.838	53.939
v	23.0000	22.9350	22.8477	22.6348	22.0591	20.6483	19.8406	18.4374
T	400.00	947.43	1619.30	2028.18	2157.24	2240.00	2250.52	2242.17
-dv/dx	0.0015	0.0113	0.0259	0.0661	0.1906	0.6401	1.020	1.932
-dr/dx	0	0	0.1805	7.807	19.43	34.88	38.44	39.37
A	78.5	78.0	77.5	77.3	77.1	76.9	76.7	76.6
r	34.812	17.599	5.751	3.681	3.062	3.024	3.024	3.024
v	17.2252	15.1377	10.6200	7.6536	4.8090	2.8558	1.6629	1.2604
T	2221.40	2169.80	2012.8	1866.92	1630.93	1239.42	873.42	736.40
-dv/dx	3.043	5.757	13.45	15.67	12.25	7.616	4.583	3.534
-dr/dx	37.18	30.70	14.86	6.403	0.9804	0.0046	0	0

Table 4. Continued

Model No. 7. $v_o = 23.0$; $r_o = 80$; $r_f/r_o = 0.02389$; $T_m = 2037.93$; $A_m = 87.22$

A	127	110	105	100	95	90	87.4	87.2
r	80.0000	80.0000	79.9972	78.8582	71.3101	48.4126	26.6184	24.6778
v	23.0000	22.9320	22.8487	22.6936	22.3284	21.2528	19.6316	19.4201
T	400.00	927.63	1369.51	1745.08	1887.43	2005.21	2037.61	2037.93
-dv/dx	0.0012	0.0100	0.0206	0.0452	0.1136	0.3866	1.007	1.111
-dr/dx	0	0	0.0059	0.6993	2.616	7.009	9.641	9.768

A	87.0	86.0	85.5	85.0	84.5	84.0	83.5	83.0
r	22.7156	12.8685	8.3068	4.5639	2.3733	1.9148	1.9111	1.9111
v	19.1859	17.4876	16.0266	13.6540	9.7536	5.5082	2.8432	1.3866
T	2037.47	2020.61	1993.17	1932.16	1786.06	1428.97	922.64	580.97
-dv/dx	1.234	2.351	3.631	6.125	9.158	6.961	3.925	2.082
-dr/dx	9.854	9.576	8.515	6.203	2.422	0.0619	0	0

Table 4. Continued

Model No. 8. v_o = 23.0; r_o = 40; r_f/r_o = 0.04620; T_m = 1946.08; A_m = 90.55

A	134	120	110	105	100	95	91.0	90.5
r	40.0000	40.0000	39.9997	39.8733	38.0614	30.7554	16.5161	14.1019
v	23.0000	22.9575	22.8532	22.7075	22.3946	21.6150	19.7000	19.2058
T	400.00	714.05	1246.83	1572.63	1749.92	1874.83	1944.60	1946.06
-dv/dx	0.0010	0.0054	0.0200	0.0411	0.0923	0.2550	0.8868	1.103
-dr/dx	0	0	0.0007	0.1043	0.7427	2.428	4.740	4.918
A	90.0	89.0	88.2	87.4	86.6	85.8	85.4	85.0
r	11.6231	6.7474	3.5227	1.9844	1.8479	1.8479	1.8479	1.8479
v	18.5833	16.6781	13.8769	9.2491	4.9708	2.4258	1.6262	1.0603
T	1943.78	1920.10	1855.37	1667.27	1194.19	745.55	578.93	445.46
-dv/dx	1.407	2.575	4.659	6.362	4.107	2.745	1.685	1.175
-dr/dx	4.992	4.596	3.194	0.7636	0.0010	0	0	0

Table 4. Continued

Model No. 9. $v_o = 23.0$; $r_o = 20$; $r_f/r_o = 0.09640$; $T_m = 1853.76$; $A_m = 93.37$

A	143	120	110	105	100	95	93.8	93.4
r	20.0000	20.0000	19.9947	19.7823	18.0234	11.7738	9.2622	8.3446
v	23.0000	22.9146	22.6954	22.4061	21.7754	20.0464	19.1422	18.7414
T	400.00	876.34	1358.20	1587.26	1738.53	1840.19	1852.33	1853.73
-dv/dx	0.0008	0.0108	0.0397	0.0817	0.1896	0.6177	0.9273	1.082
-dr/dx	0	0	0.0050	0.1263	0.6820	1.934	2.254	2.331
A	93.0	92.0	91.0	90.0	89.0	88.0	87.2	86.4
r	7.4022	5.0414	3.0395	2.0330	1.9281	1.9279	1.9279	1.9279
v	18.2707	16.6478	13.9654	9.9524	6.0845	3.3809	1.9522	1.0448
T	1853.05	1837.77	1781.18	1619.71	1252.98	855.10	603.28	412.89
-dv/dx	1.277	2.051	3.416	4.307	3.292	2.169	1.432	0.8760
-dr/dx	2.377	2.279	1.612	0.4165	0.0028	0	0	0

Table 4. Continued

Model No. 10. v_o = 23.0; r_o = 10; r_f/r_o = 0.2167; T_m = 1756.21; A_m = 95.5

A	154	120	110	105	100	96.5	96.0	95.5
r	10.0000	10.0000	9.9917	9.7870	8.3499	5.7162	5.2258	4.7222
v	23.0000	22.8186	22.3843	21.8148	20.5561	18.4743	17.9864	17.4183
T	400.00	973.61	1374.34	1574.90	1708.32	1756.78	1757.85	1756.19
-dv/dx	0.0007	0.0215	0.0785	0.1607	0.3863	0.9061	1.051	1.227
-dr/dx	0	0	0.0065	0.1116	0.5314	0.9627	0.9993	1.015

A	94.0	93.0	92.0	91.0	90.0	89.0	88.0	87.0
r	3.2710	2.5598	2.2248	2.1681	2.1666	2.1666	2.1666	2.1666
v	15.0490	12.7536	10.0191	7.3380	5.0502	3.2448	1.9220	1.0332
T	1725.10	1664.03	1538.72	1316.41	1047.23	794.32	574.64	398.01
-dv/dx	1.992	2.579	2.796	2.517	2.051	1.561	1.094	0.6963
-dr/dx	0.8620	0.5346	0.1538	0.0075	0	0	0	0

Table 4. Continued

Model No. 11. $v_o = 23.0$; $r_o = 5$; $r_f/r_o = 0.4835$; $T_m = 1646.23$; $A_m = 98.60$

A	167	120	110	105	100	99	98	96
r	5.0000	5.0000	4.9942	4.8530	4.0095	3.7105	3.3854	2.7716
v	23.0000	22.6262	21.7727	20.6752	18.3025	17.5125	16.5497	13.9613
T	400.00	997.31	1360.12	1536.70	1638.79	1645.62	1644.86	1607.28
-dv/dx	0.0006	0.0427	0.1526	0.3074	0.7163	0.8712	1.064	1.538
-dr/dx	0	0	0.0053	0.0730	0.2815	0.3175	0.3332	0.2569

A	94.0	93.0	92.0	91.0	90.0	89.0	88.0	87.2
r	2.4544	2.4220	2.4178	2.4176	2.4176	2.4176	2.4176	2.4176
v	10.5102	8.6518	6.8434	5.1649	3.6950	2.4856	1.5545	1.0044
T	1477.28	1354.17	1196.44	1019.07	834.21	657.05	496.66	396.59
-dv/dx	1.854	1.849	1.770	1.589	1.345	1.072	0.7932	0.5865
-dr/dx	0.0649	0.0122	0.0008	0	0	0	0	0

See p. 22a

Table 4. Continued

Model No. 12. $v_o = 23.0$; $r_o = 0.625$; $r_f/r_o = 1.0000$; $T_m = 1034.14$; $A_m = 111.43$

A	227	130	120	112	111	110	97.0	96.0
r	0.62500	=	=	=	=	=	=	0.62500
v	23.0000	21.9484	20.1014	16.2976	15.5725	14.7798	1.5609	0.9971
T	400.00	735.69	931.76	1033.75	1034.10	1029.70	329.54	...
-dv/dx	0.0003	0.1005	0.3030	0.6926	0.7591	0.8278	0.6431	0.4872
-dr/dx	0	0	0	0	0	0	0	0

Model No. 13. $v_o = 46.0$; $r_o = 2.5$; $r_f = 0.0250$; $r_f/r_o = 0.0100$; $T_m = 1748.82$

$A_m = 112.31$

A	200	150	140	130	120	115	112.6	112.2
r	2.5000	2.5000	2.5000	2.4996	2.3068	1.5016	0.6882	0.5268
v	45.9870	45.8825	45.7684	45.4591	44.4466	42.9475	40.9299	40.2525
T	400.0	756.46	954.60	1262.67	1603.05	1715.42	1747.75	1748.65
-dv/dx	0.0004	0.0072	0.0173	0.0520	0.1816	0.5088	1.456	1.975
-dr/dx	0	0	0	0.0005	0.0768	0.2736	0.3977	0.4079
A	111.8	111.6	111.4	111.3	111.2	111.1	111.0	110.9
r	0.3640	0.2840	0.2072	0.1706	0.1360	0.1039	0.0754	0.0525
v	39.2900	38.6194	37.7242	37.1460	36.4379	35.5315	34.3389	32.6914
T	1745.39	1741.06	1733.36	1727.48	1719.06	1708.50	1690.44	1659.99
-dv/dx	2.947	3.815	5.250	6.365	7.943	10.28	13.87	19.22
-dr/dx	0.4048	0.3946	0.3738	0.3577	0.3350	0.3079	0.2638	0.1996

Besides the main variables r, v, and T, the rates of variation dv/dx and dr/dx per unit path length are also given in Table 4. The acceleration (deceleration) is obtained from

$$g = dv/dt = v\ dv/dx \tag{14}$$

The loss of mass per unit path is

$$dm/dx = 4\pi r^2 \delta, \quad dr/dx \tag{15}$$

and the evaporation rate per unit time is

$$dm/dt = v\ dm/dx \tag{16}$$

When multiplied by the luminous efficiency of the radiating vapors, equations 15 and 16 yield the "line brightness" and the instantaneous brightness of the meteor at any point of its path respectively (Öpik, 1958). The first defines the photographic, the second the visual light curve of the meteor. However, for the micrometeorites, these notions are of little practical significance, because of their faintness which prevents their observation by optical means.

5. Interpolation formulae. The simultaneous process of ablation and deceleration of micrometeorites, which is the object of the present numerical study, is too complicated to be accurately expressed by explicit mathematical formulae. However, in view of the uncertainty or variability of the basic data, such as structure, composition, and physical properties of the meteorites themselves as well as of the terrestrial atmosphere, precision is of little significance here. What is required is a reasonable degree of approximation, a numerical framework which describes the phenomenon with an error that is less than the possible natural

("cosmic") error due to the uncertainty in, or intrinsic variability of, the basic constants.

By a combination of theoretical reasoning with empirical adjustments to the calculated models (graphically applied), it turned out to be possible to develop a procedure by which the survival radius (r_f) and maximum temperature (T_m) can be predicted with an accuracy better than 5 percent, for initial velocities ranging from v_o = 11.5 to 46 km/sec, initial radii (r_o) less than 720 microns, and with some extrapolation outside this range being permissible. Among other things, the procedure also allows empirically for the variation of the scale height within a limited range of altitude for the adopted atmospheric model.

As stated, the radii refer to vertical incidence. For oblique incidence, the radii are to be multiplied by the secant of the angle of incidence, leaving all other data unchanged.

As a convenient yardstick for interpolation, the schematical non-ablating case as expressed by equation 1 can be used. For a fixed value of the scale height $H_p = 6.1 \times 10^5$ cm, as corresponds to the average altitude of the micrometeorites, and for sec z = 1, the equation yields a maximum temperature $T_m{}^1$ such that

$$\log T_m' = -0.6736 + 0.25 \log r_o + 0.75 \log v_o \qquad (17)$$

Because of the radius decreases through ablation, and heat is lost into vaporization, the true maximum temperature must be less than this

$$T_m < T_m' \qquad (18)$$

Take for an independent variable, to be used as argument for our empirical functions, the reciprocal

$$U = 10^4/T_m' \tag{19}$$

$$\log U = 4.6736 - 0.25 \log r_o - 0.75 \log v_o \tag{20}$$

Then the maximum temperature can be approximated by the expression

$$T_m = \tau - 4.5\,(v_o - 23) \tag{21}$$

in deg K, where v_o is in km/sec. Table 5 describes the "semi-empirical" function τ as it depends on U.

Table 5. Maximum Temperature Parameter, τ

U	1.8	2.0	2.2	2.4	2.6	2.8	3.0
τ	2280	2212	2153	2101	2055	2013	1975
U	3.2	3.4	3.6	3.8	4.0	4.2	4.4
τ	1941	1909	1879	1850	1822	1794	1766
U	4.6	4.8	5.0	5.2	5.4	5.6	5.8
τ	1739	1713	1688	1663	1638	1610	1578
U	6.0	6.5	7.0	7.5	8.0	8.5	≥ 9.0
τ	1547	1445	1340	1248	1171	1097	$T_m'-79$

For a schematical description of simultaneous heating, deceleration, and ablation, the process can be decomposed into two stages. The first would consist in pure heating without radiation or evaporation losses until efficient evaporation begins, with the intake of an amount of heat E_o per unit mass. The second stage would consist in ablation at a constant effective evaporation-radiation temperature

T_a which is adjusted in such a manner as to lead to the proper ablation ratio r_f/r_o. The value of $\theta = q/\xi$ (see Table 3) corresponding to T_a will be called θ_a. During the first stage the velocity decelerates from v_o to v_1, during the second from v_1 conventionally to zero.

According to meteor theory (Öpik, 1958, p. 68 ff.) and in notations of Section 3, for the first stage the equations of heating and deceleration of a spherical meteoroid are

$$mdE/dt = \frac{1}{2} \Upsilon \sigma \rho v^3 \quad (22)$$

$$mdv/dt = - K \sigma \rho v^2 \quad (23)$$

where m = mass, σ = cross section of the meteoroid, K = drag coefficient. The ratio of the two equations yields

$$vdv = - (2 K/\Upsilon) dE \quad (24)$$

or, after integration,

$$v_1^2 = v_o^2 - (4 K/\Upsilon) E_o \quad (25)$$

With K = 1 as in the present case, $\Upsilon = 0.8$, $E_o = 2.03 \times 10^{10}$ erg/g as the average pre-heating energy,

$$v_1^2 = v_o^2 - 1.015 \times 10^{11} \quad (26)$$

$(cm/sec)^2$.

During the second stage, the heat spent per cm^2 sec of the surface consists of the heat of evaporation, $h\xi$, plus the radiation loss $Q = \varepsilon s T^4$. Per gram of ablated (evaporated) mass this yields an apparent heat of evaporation of $h + Q/\xi = h\ (1 + \theta)$ (see equations 6, 7, 8 and Table 3). The energy spent per second on ablation is then (see equation 22)

$$h\,(1 + \theta)\ dm/dt = - \frac{1}{2}\ \gamma \sigma\ \rho\ v^3 \qquad (27)$$

while equation 23 remains valid as before. Dividing equation 27 by equation 23, the general equation of simultaneous ablation and deceleration for the second schematical stage becomes

$$dm/m = \left(\gamma / \left[2\ Kh\ (1 + \theta)\right]\right)\ vdv \qquad (28)$$

or, with $\gamma = 0.8$, $K = 1$,

$$dm/m = 0.2\ d(v^2) / \left[h(1 + \theta)\right] \qquad (28')$$

By definition of the effective evaporation parameters T_a and θ_a, the final mass, m_f, is obtained by integration of equation (28') setting $\theta = \theta_a$ = const. within the limits $v = v_1$ to $v = 0$. Thus

$$\ln(m_f/m_o) = - v_1^2 / \left[5\ h(1 + \theta_a)\right] \qquad (29)$$

or

$$\ln(r_f/r_o) = - v_1^2 / \left[15\ h(1 + \theta_a)\right] \qquad (30)$$

With $h = 6.05 \times 10^{10}$ erg/g and equation 26 this yields

$$(1 + \theta_a)\ \log_{10}\ (r_f/r_o) = - 4.785 \times 10^{-13}\ (v_o^2 - 1.015 \times 10^{11}) \qquad (31)$$

From the calculated ratios r_f/r_o for each model (see Table 4) the values of $1 + \theta_a$ were calculated and the corresponding effective evaporation temperatures T_a derived from an extended version of Table 3. The results are summarized in Table 6, as set against the argument U (equation 19).

Table 6. Characteristic ablation parameters of the models.

Model No.	1	2	3	4	5	13
v_o, km/sec	11.5	11.5	11.5	11.5	11.5	46
r_o, 10^{-4} cm	640	160	80	20	5	2.5
U	2.670	3.776	4.490	6.350	8.977	3.776
T_m'	3745	2648	2227	1574	1114	2648
$-\log(r_f/r_o)$	0.4587	0.3216	0.2236	0.0287	0.0000	2.0000
T_m, deg K	2098	1905	1802	1535	1094	1749
$\log(1 + \theta_a)$	0.1048	0.2595	0.4177	1.3057	...	0.7020
T_a, deg K	1983	1809	1717	1458	...	1616

Model No.	6	7	8	9	10	11	12
v_o, km/sec	23	23	23	23	23	23	23
r_o, 10^{-4} cm	320	80	40	20	10	5	0.625
U	1.888	2.670	3.175	3.776	4.490	5.339	8.977
T_m'	5295	3745	3149	2648	2227	1873	1114
$-\log(r_f/r_o)$	2.0246	1.6218	1.3354	1.0159	0.6642	0.3156	0.0000
T_m, deg K	2251	2038	1946	1854	1756	1646	1034
$\log(1 + \theta_a)$	0.0896	0.1857	0.2696	0.3884	0.5727	0.8958	...
T_a, deg K	2005	1872	1801	1731	1653	1554	...

For a fixed value of the argument U, there is a systematic shift in T_a depending on velocity which can be allowed for by a linear shift in the argument similar to that used for T_m (equation 21 and Table 5). Setting

$$\chi = U + a\,(v_o - 23) \qquad (32)$$

v_o being given in cm/sec, T_a and $\underline{a}$ can be represented as functions of χ or, which is the same, χ and $\underline{a}$, as well as U by way of equation 32, can be represented as unique functions of T_a. Table 7 describes these functions as they follow from a graphical representation of the parameters of the models (Table 6). Thus, with the aid of the table, for given T_a, χ and $\underline{a}$ can be found, and for given v_o, U and, thus r_o, are then determined through equations 32 and 20.

In such a manner interpolated ablation parameters as given in Table 8 have been calculated by using Tables 7 and 5, and equations 20, 21, 31 and 32. The range of the table is that from maximum ablation to practically complete survival, covering characteristic mass survival ratios of around 0.01, 0.1, 0.5 and 0.9. For v_o = 23 km/sec, more detailed data are given.

Table 7. Interpolation parameters for stony meteorite ablation (v_o from 11.5 to 46 km/sec)

T_a	2000*	1950*	1900*	1850	1800	1750
$1 + \theta_a$	1.248	1.329	1.445	1.615	1.867	2.251
χ	1.910	2.185	2.485	2.815	3.180	3.600
$\underline{a}$	0.0582	0.0582	0.0582	0.0582	0.0582	0.0548
T_a	1700	1650	1600	1550	1500	1450
$1 + \theta_a$	2.850	3.814	5.416	8.164	13.06	22.16
χ	4.040	4.500	4.945	5.375	5.790	6.190
$\underline{a}$	0.0508	0.0461	0.0393	0.0312	0.0242	0.0174
T_a	1400	1350	1300	1250	1200	< 1200
$1 + \theta_a$	39.86	76.07	154.6	336.0	787.0	> 800
χ	6.430	6.610	6.870	7.145	7.432	$9550/(T_a+75)$
$\underline{a}$	0.0104	0.0043	0.0017	0	0	0

*Only for $v_o < 30$ km/sec

Table 8. Interpolated ablation parameters for stony micrometeorites.

v_o = 7.8 km/sec

T_a	(∞)	2000	1750	1500
U	(0)	2.795	4.433	6.158
r_o, 10^{-4} cm	(∞)	1710	270	72.5
r_f/r_o	0.573	0.640	0.782	0.958
m_f/m_o	0.188	0.262	0.478	0.880
T_m	(∞)	2082	1830	1583
r_f, 10^{-4} cm	...	1090	211	69.4

v_o = 11.5 km/sec

T_a	(∞)	2000	1800	1600	1400
U	(0)	2.580	3.850	5.397	6.550
r_o, 10^{-4} cm	(∞)	734	148	38.3	17.7
r_f/r_o	0.260	0.340	0.486	0.780	0.967
m_f/m_o	0.0176	0.0394	0.115	0.474	0.903
T_m	(∞)	2102	1881	1690	1487
r_f, 10^{-4} cm	...	250	72.0	29.9	17.1

v_o = 14 km/sec

T_a	(∞)	1900	1700	1550	1350
U	(0)	3.010	4.458	5.655	6.649
r_o, 10^{-4} cm	(∞)	220	45.7	17.6	9.28
r_f/r_o	0.129	0.243	0.488	0.778	0.973
m_f/m_o	0.00215	0.0143	0.116	0.471	0.922
T_m	(∞)	2013	1782	1641	1454
r_f, 10^{-4} cm	...	53.5	22.3	13.7	8.61

v_o = 18 km/sec

T_a	(∞)	1750	1600	1500	1300
U	(0)	3.874	5.142	5.911	6.879
r_o, 10^{-4} cm	(∞)	37.6	12.1	6.95	3.79
r_f/r_o	0.0315	0.215	0.528	0.767	0.978
m_f/m_o	3.1×10^{-5}	0.0100	0.148	0.452	0.935
T_m	(∞)	1862	1692	1583	1387
r_f, 10^{-4} cm	...	8.09	6.39	5.33	3.57

Table 8. Continued

v_o = 23 km/sec; U = $\mathcal{S}$ (Table 7)

T_a	(∞)	2000	1950	1900	1850	1800	1750	1700	1650
$r_o, 10^{-4}$ cm	(∞)	305	178	107	64.8	39.8	24.2	15.3	9.92
r_f/r_o	0.00327	0.0104	0.0136	0.0194	0.0293	0.0472	0.0815	0.137	0.224
m_f/m_o	3.5×10^{-8}	1.1×10^{-6}	2.5×10^{-6}	7.2×10^{-6}	2.5×10^{-5}	1.0×10^{-4}	5.4×10^{-4}	0.0026	0.0113
T_m	(∞)	2243	2157	2081	2010	1945	1879	1816	1752
$r_f, 10^{-4}$ cm	...	3.17	2.42	2.08	1.90	1.88	1.97	2.10	2.22

v_o = 23 km/sec; U = $\mathcal{S}$ (Table 7)

T_a	1600	1550	1500	1450	1400	1350	1300	1250	1200
$r_o, 10^{-4}$ cm	6.81	4.87	3.62	2.77	2.38	2.13	1.83	1.56	1.33
r_f/r_o	0.349	0.492	0.647	0.773	0.867	0.928	0.964	0.983	0.993
m_f/m_o	0.0426	0.119	0.271	0.461	0.651	0.799	0.895	0.950	0.979
T_m	1695	1641	1580	1509	1459	1423	1367	1312	1260
$r_f, 10^{-4}$ cm	2.38	2.40	2.34	2.14	2.06	1.98	1.76	1.53	1.32

Table 8. Continued

	v_o = 30 km/sec					v_o = 38 km/sec				
T_a	(∞)	1600	1500	1400	1250	(∞)	1550	1450	1350	1250
U	(0)	4.669	5.620	6.357	7.145	(0)	4.908	5.929	6.545	7.145
$r_o, 10^{-4}$ cm	(∞)	3.86	1.84	1.12	0.703	(∞)	1.55	0.729	0.491	0.346
r_f/r_o	5.5×10^{-5}	0.163	0.472	0.782	0.971	1.4×10^{-7}	0.145	0.491	0.813	0.954
m_f/m_o	1.7×10^{-13}	0.00436	0.105	0.478	0.916	2.7×10^{-21}	0.00302	0.118	0.537	0.869
T_m	(∞)	1698	1575	1442	1281	(∞)	1632	1490	(1368)	(1245)
$r_f, 10^{-4}$ cm	...	0.629	0.868	0.876	0.683	...	0.225	0.358	0.399	0.330

Radii of 5–700 μ completely atomized

	v_o = 46 km/sec				
T_a	(∞)	1500	1400	1300	1200
U	(0)	5.232	6.190	6.830	7.432
$r_o, 10^{-4}$ cm	(∞)	0.677	0.346	0.234	0.166
r_f/r_o	6.5×10^{-11}	0.169	0.558	0.860	0.971
m_f/m_o	5.4×10^{-31}	0.00483	0.174	0.637	0.916
T_m	(∞)	1555	(1404)	(1272)	(1157)
$r_f, 10^{-4}$ cm	...	0.114	0.193	0.201	0.161

Radii of 2-700 μ completely atomized

The ultimate or survival radius, r_f, as given in the last line of the table, follows the trend of r_o in the lower velocity groups ($v_o \leq 18$ km/sec) but with a compressed range of sizes; this would lead to an enhanced frequency function over the ablating range of the radii r_f of surviving fragments, as compared to the frequency function of the initial radii r_o in space.

For higher velocities ($v_o \geq 23$ km/sec) the trend of r_f may be inverted, the size of the surviving fragment increasing with the decreasing size of the parent. The survival radii at vertical incidence show flat maxima, $r_f = 2.41\ \mu$ at $v_o = 23$ km/sec, $r_f = 0.89\ \mu$ at 30 km/sec, $r_f = 0.405\ \mu$ at 38 km/sec, $r_f = 0.215\ \mu$ at 46 km/sec. At these radii, frequency bulges in the size distribution of the fragments must be formed, with a complete absence of larger sizes. However, $v_o = 23$ km/sec is a transitional case, r_f increasing again for very large r_o though the effect of this increase on the frequency distribution can be but slight, on account of the small number of the large parent meteoroids. A velocity dispersion will, of course, tend to level out the bulges, however without removing the general enhancement of the frequency of survival radii above the ablation limit. Similarly, oblique incidence will introduce additional spread by a factor of sec z.

For $v_o = 46$ km/sec, the ablation limit drops below $r_o = 0.166$ sec z (μ) or 1.66×10^{-5} sec z (cm). Except at very oblique incidence , this is close to the radiation pressure limit, 1.5×10^{-5} cm, for stony grains in the solar field (Öpik, 1956). Grains of this size cannot stay in the solar system, and those of somewhat greater size will not be subject to full solar gravitation and will possess low heliocentric velocities; if in direct orbits, their velocities of encounter with the earth will hardly exceed 30 km/sec, and in retrograde orbits the upper limit of v_o for such objects will be 45-50 km/sec. Thus, in so far as the most interesting, non-ablating component of interplanetary dust is concerned, Table 8 essentially covers the entire velocity range including the upper limit.

For velocities in excess of 50 km/sec sputtering by molecular impact begins. At 60 km/sec, sputtering for stone leads to $r_f/r_o = 0.918$, at 72 km/sec to $r_f/r_o = 0.775$ (Öpik, 1958, p. 72). This is insignificant as compared to ablation by evaporation except for very small meteoroids which, however, must be eliminated from the solar system by radiation pressure. Sputtering as a factor of meteoroid ablation in the terrestrial atmosphere is thus of little practical significance.

Interplanetary dust has been advocated as a means of transport of living germs in the universe. Thus, Fedorova (1964) shows that dust may offer sufficient protection against ultraviolet radiation for microorganisms in space. However, the dust is subject to an extreme heat sterilization test at entry into a planetary atmosphere. Still, very small and slow dust particles may pass the test at oblique incidence. At the lowest entry velocity $v_o = 11.5$ km/sec for interplanetary particles, and $T_m < 400^oK$ as an upper limit for germ survival, Table 5 and equation 20 lead to

$$r_o < 1.09 \times 10^{-5} \sec z \text{ (cm)} \qquad (33)$$

as the upper limit of dust grain radius for the transport of living germs. To obtain a low entry velocity, the heliocentric velocity in a circular orbit must not differ much from the orbital velocity of the earth; for this, radiation pressure must not exceed 0.40 of solar gravity, which corresponds to $r_o > 4 \times 10^{-5}$ cm or $\sec z > 4$. At an angle of incidence of 75^o or greater, relative to the vertical, these dust grains could then indeed survive the sterilization test. On the other hand, grains of so small a size may not offer sufficient protection against ultraviolet and other penetrating radiations. Yet, under very specific conditions, the possibility of transport of germs cannot be outright denied.

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