[IN]TERACTION OF METEORIC BODIES WITH THE TERRESTRIAL ATMOSPHERE

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1. Phenomenology - Meteorites, from the dust particles of the zodiacal cloud measuring 0.001 cm in diameter, up to large chunks measuring meters and much more (whose fragments can be seen in museums, the Smithsonian in particular), are mostly members of the solar system. They travel around the sun with planetary velocities, tens of kilometers per second. However, their orbits lack the regularity of planetary orbits which do not intersect, thus preventing collisions between the planets, or too close approaches and strong mutual perturbations. Meteoric orbits may be of any shape and may intersect planetary orbits, so that collisions with the planets may take place.

When a meteorite collides with the earth, it first enters the terrestrial atmosphere which acts as a brake, stops and heats the body to the point of vaporization. Small meteorites are completely stopped by the atmosphere, with a certain proportion of their mass evaporated (depending on velocity and size). Large bodies may survive as meteoritic chunks, losing some of their skin layers but preserving the interior cold and intact as it was in interplanetary space.

When the load of the meteorite (assumed spherical) per cm^2 cross section,

$$m = M/\pi r^2 = \frac{4}{3} r\delta \text{ (gram/cm}^2\text{)} \quad (1)$$

(M = mass, r = radius, δ = density of the meteorite)

exceeds the mass of the atmospheric column along its path,

$$m_a = 10^3 \sec z \text{ (gram/cm}^2\text{)} \quad (2)$$

(z = zenith angle of incidence, or the angle of the meteor path with the vertical), the momentum of the meteorite cannot be transmitted to the atmosphere. The meteorite then strikes the ground with cosmic velocity, 10-30 km/sec or more, and produces a crater 10-20 times its diameter, the result of an explosion at the expense of its kinetic energy which per gram may exceed the energy of TNT 10-100 times. The Canyon Diablo Crater in Arizona, 1200 meters across, may have been produced in such a manner some 50,000 years ago, by an iron meteorite 90 meters in diameter, weighing about 2 million tons, travelling with a speed of 15 kilometers per second (these figures are consistently derived by several independent methods). Setting $z = 45^\circ$, $\sec z = 1.41$, $m > m_a$, $\delta = 7.8 g/cm^3$ as for iron, the limit of crater-producing meteorites becomes

$$R > 135 \text{ cm},$$

or a minimum diameter of 2.7 meters.

2. Velocities - When encountering the earth, at 1 astronomical unit or 150 million kilometers from the sun, meteorite velocities, 25-40 km/sec, are of the same order as the orbital velocity of the earth, 30 km/sec. The vector difference of the velocities of the meteor and the earth is the encounter velocity, U. According to the direction of encounter and the shape of the meteor orbit, this may range from a few km/sec up to 72 km/sec. Neglecting the eccentricity of the earth's orbit, the encounter velocity is given by

$$U = v_g \left[3 - \frac{1}{a} - 2\sqrt{a(1-e^2)} \cos i\right]^{\frac{1}{2}} , \tag{2}$$

where v_g = 29.76 km/sec = mean orbital velocity of the earth, a = semi-major axis (in a. u.), e = eccentricity, i = inclination of the meteor orbit to the ecliptical plane. Thus, for a typical meteorite orbit, swinging between an aphelion at 3.5 a.u. in the asteroidal belt, and a perihelion at 0.5 a. u. halfway between earth and sun, a = 2.0 a. u., e = 0.75, and

$$U = v_g (2.5 - 1.8708 \cos i)^{\frac{1}{2}} . \tag{3}$$

The gravitational field of the earth accelerates the meteorite, so that at entry into the earth's atmosphere its velocity becomes

$$v = (U^2 + s^2)^{\frac{1}{2}} , \tag{4}$$

where s = 11.1 km/sec ($s^2 = 123 \text{ km}^2/\text{sec}^2$) is the escape velocity of the earth from a mean altitude of about 100 km. v can also be directly calculated from eq. (2), substituting 3.1391 for 3, the numerical term in the brackets.

For a typical meteorite, Table 1 gives the encounter and entry velocities at different inclinations, according to eqs. (3) and (4).

The actually observed mean velocities of "asteroidal" meteoritic bodies, or those confined to the inner portions of the solar system, inside Jupiter's orbit [as is

TABLE 1

Encounter velocity (U) and entry velocity (v)(km/sec) for $\underline{a}$ = 2.0 a.u., e = 0.75

Inclination, i	0°	30°	90°	180°
Description	Overtaking the earth under an angle in the orbital plane; common case	Overtaking in a moderately inclined direct orbit; common case	Crossing at right angles to the ecliptic; rare case	Meeting the earth in retrograde motion in the orbital plane; uncommon case
U	23.64	27.93	47.05	62.22
v	26.08	30.04	48.34	63.20

the sample case of eq. (3) and Table 1], and which chiefly concern us here, are even smaller, as shown in Table 2. The most interesting are the particles of zodiacal dust, micrometeorites of 10^{-4} - 10^{-1} cm radius, for which the mean orbital elements are inferred from indirect (photometric) evidence; they spiral into the sun (with lifetimes of 10^{4} to 10^{7} years) from Poynting-Robertson (radiation) and corpuscular drag, which decreases their orbital eccentricities and heliocentric distances in much the same way as the earth's atmosphere acts on artificial satellites. Although the drag affects directly only the mean distances and eccentricities, tending to make the orbits nearly circular, through perturbations in close encounters with the planets inclinations and eccentricities can be exchanged in a kind of equipartition, and the mean inclinations must be decreasing, too. For small eccentricities and inclinations, and nearly circular orbits with $\underline{a}$ = 1 when encountering the earth, equations (2) and (4) can be approximated by

$$U = v_g(e^2 + \sin^2 i)^{1/2} \quad , \tag{5}$$

$$v = v_g(0.1391 + e^2 + \sin^2 i)^{1/2} \quad . \tag{6}$$

The similarity of the orbital elements and velocities in the first three groups of Table 2 is noticeable. These elements point to a common origin from decaying short-period comets (like Comet Encke), and cannot be reconciled with an origin from the asteroidal belt proper,

TABLE 2

Average encounter (U) and entry (v) velocities of meteoritic particles staying inside Jupiter's orbit

Class of Objects	Photographic meteors (Smithsonian Super Schmidt), magnitude 2 and brighter	Meteorites and fire-balls, magnitude -5 to -10	Apollo type "asteroids" (potential cratering meteorites, 0.5 - 6 km diameter)	Zodiacal dust particles (micrometeorites 10^{-4} to 10^{-1} cm) (a = 1)
U, km/sec	17.5	15.6	19.6	4.7
v, km/sec	20.7	19.1	22.5	12.0
sin i (av.)	0.22	0.17	0.20	(0.15)
e (av.)	0.54	0.59	0.61	(0.05)

between Mars and Jupiter. The fourth group, that of zodiacal dust, differs radically from the other three.

The minimum entry velocity of interplanetary objects is v = s = 11.1 km/sec when U = 0. Particles of lunar origin, as well as artificial satellites at grazing entry may have v = 7.8 km/sec.

The mass of zodiacal dust captured by the earth more than 100 times exceeds the total contribution from all other meteoritic sources and, thus, is the most important component of meteoritic accretion. According to Table 2, its mean entry velocity must be close to 12 km/sec.

3. Interaction at entry. At meteor velocities, which greatly exceed the thermal molecular velocities of atmospheric gases (high Mach number), drag resistance is determined by the momemtum swept by unit area of the body. Complications arising at low velocity, such as viscosity friction, do not exist even for bodies which are large as compared to the gas kinetic length of path (which is a necessary condition for the application of Stokes' law).

The shape of meteoroids is unavoidably a natural source of uncertainty, though less than could be expected a priori; the spherical model works quite well. The equivalent radius, r, can be defined through the volume, V, of the body,

$$V = (4/3)\ \pi r^3 \quad , \tag{7}$$

and its surface, S, is related to volume through the shape parameter, B:

$$B = rS/V \quad . \tag{8}$$

For a sphere, B = 3. For solid fragments of a not too unusual shape, B = 4 to 5.

Independently of the shape factor, the mean ratio of cross section (σ) to surface area (S) in random orientation (favored by tumbling and rotation) is the same as for a sphere, or one-quarter:

$$\sigma = 0.25\ S\ \text{(average)} \quad . \tag{9}$$

Choosing the cross section at right angles to the direction of motion, the atmospheric mass swept per unit time by the cross section equals $\sigma\rho v$, its momentum $\sigma\rho v^2$, whence the transfer of momentum from body to atmosphere, or the drag force acting against the motion of the body, becomes

$$-M\ dv/dt = F = K\sigma\rho v^2, \tag{10}$$

where K, of the order of unity, is the coefficient of drag.

Similarly, the kinetic energy swept in unit time is $\frac{1}{2}v^2 \cdot \sigma\rho v$. If γ is the heat transfer coefficient, or the fraction of the swept kinetic energy that goes into heating the meteoroid and h the heat of ablation, or the energy required to remove one gram from the meteoroid, either by vaporization, or by fusion and spraying, the equation of ablation becomes

$$- h\ dM/dt = \tfrac{1}{2}\gamma\sigma\rho v^3 \qquad (11)$$

Dividing (11) by (10), the basic equation of simultaneous ablation and motion becomes

$$h dM/M = (\gamma/2K)\ v dv \qquad (12)$$

For ordinary meteors and meteorites, $h = h_o$ is the conventional heat of vaporization or fusion, plus a certain amount to account for pre-heating of the material.

For small dust particles, micrometeorites of the zodiacal cloud, radiation losses compete with evaporation losses. The momentum of the meteorite is absorbed at high altitude and low atmospheric density, when the absolute heat transfer $\tfrac{1}{2}\gamma\rho v^3$ is small, the temperature low and evaporation not prominent. The conventional heat of evaporation is augmented by radiation losses, represented by a factor Θ (ratio of radiation to evaporation heat loss), so that the effective heat of ablation becomes

$$h = h_o\ (1 + \Theta) \qquad (13)$$

Θ is variable along the meteor path, and equation (12) can be solved only by numerical integrations. However, by assuming an effective constant value of the parameter, $\Theta = \Theta_a$, and also considering the other parameters as constants (which is much better justified), equation (12) can be symbolically integrated from v = v to v = o (conventionally, full stop) and yields the residual to original mass ratio

$$(r_f/r_o)^3 = M_f/M_o = \exp(-\gamma v^2/4hK) \qquad (14)$$

This depends crucially on the parameters, especially on h. For small micrometeorites dissipating their energy essentially through radiation, $\Theta\rightarrow\infty$, $h\rightarrow\infty$ and $M_f/M_o\rightarrow 1$; the micrometeorite survives, either after fusion when it descends as a "cosmic spherule", or without fusion when it preserves its original, probably angular shape.

4. The air cap and the interaction parameters. The parameters of eq. (14) depend on the presence and depth of an air cushion or cap, formed by air molecules and

meteor vapors on the front side of the meteoroid. The role of vapors is subordinate to that of the air molecules which, by their impact, and by aerodynamic pressure which exceeds the vapor pressure, preserve a "bald front", to 78° from the apex of motion at v = 16km/sec, to 61° at 60 km/sec (for a spherical model).

The coefficients of drag and heat transfer depend on the thickness of the air cap, which regulates the flow of heat to the meteoroid and decreases γ within a wide range, and, to a much lesser degree also affects K; the latter may include the recoil, or "rocket effect" of the outflowing vapors.

The kinetic thickness of the air cap, d, is the number of collisional "mean free paths", λ, or half-energy ranges across the cushion; λ varies with the meteor velocity and is considerably larger than the usual gaskinetic value. For a spherical meteoroid

$$d = 0.75\ (r\rho)/(\lambda\rho) \quad . \qquad (15)$$

Because $\lambda\rho$ is a constant for given velocity, and $\rho \sim r$ at the critical level of momentum transfer (deceleration) or ablation, roughly

$$d \sim r^2 \quad . \qquad (16)$$

Table 3 describes the variation of $\lambda\rho$ with velocity for nitrogen gas and, practically, for atmospheric air.

TABLE 3

Half-energy air mass, $\lambda\rho$

v, km/sec	0.6	1.2	2.3	4.7	9.4	13.2	18.7	26	53	75
$\lambda\rho, 10^{-8} g/cm^2$	1.3	1.9	3.1	4.8	7.0	8.4	8.9	14.2	13.8	13.6

Table 4 gives K as depending on d and velocity, including the recoil effect. Micrometeorites are isothermal, evaporation proceeds isotropically and the recoil effect is zero; with d = 0, there is no air cap; air molecules are colliding with the surface individually, without mutual interference. Other, somewhat larger meteoroids are not isothermal, evaporation is more intense on the front side and the recoil of vapors increases the apparent drag. Without recoil, at d = 0, K = 1, both for completely elastic and completely inelastic collisions with a spherical meteoroid (or of any other shape in random orientation) and closely same for intermediate cases. For a developing air cap, hydrodynamic flow around the meteoroid cushions off the drag, $K \rightarrow 0.5$, without much of a recoil effect because evaporation is suppressed by shielding.

TABLE 4

Drag coefficient, K, including recoil

d	0	1	2	4	6	10	∞
Micrometeorites $r < 0.07$ cm; all velocities							
K =	1.00	0.75	0.63	0.56	0.54	0.52	0.50
Stony meteors, $r > 0.1$ cm							
V = 12 km/sec, K =	1.00	0.75	0.69	0.56	0.54	0.52	0.50
V = 20 km/sec, K =	1.28	1.28	1.28	0.64	0.54	0.52	0.50
V = 30 km/sec, K =	1.92	1.92	1.92	0.96	0.64	0.52	0.50
V = 60 km/sec, K =	3.84	3.84	3.84	1.92	1.28	0.77	0.50

TABLE 5

Coefficient of heat transfer, γ, as depending on the kinetic thickness of the air cap, d

(a) conductivity only: ordinary meteors and fireballs

d	0	1	2	4	8	18	40	>40
γ	γ_o=0.6to0.8	$\frac{1}{2}\gamma_o$+0.29	0.58	0.39	0.25	0.15	0.10	$0.6d^{-\frac{1}{2}}$

(b) conductivity, turbulent convection and radiation from cap: large meteorites

d	$10^2 - 10^3$	10^3	10^5	$10^3 - 10^5$, $>10^5$
γ	$0.6/\sqrt{d}$ laminar flow	$1.2/\sqrt{d}$ turbulent flow	$3/\sqrt{d}$	$(0.9 \log_{10} d - 1.5)/\sqrt{d}$ Interpolation formula

Table 5 contains heat transfer coefficients as conditioned by the air cap. In part (a) of the table, for d = 0, or an unshielded meteoroid surface exposed to full impacts of the air molecules, $\gamma_o = 0.6$ for iron and $\gamma_o = 0.8$ for a stony surface. Part (b) of the table summarizes the results of theoretical study of air caps in large meteoritic events ($r \sim 100$ cm) (to be published), in which all possible processes were taken into account: ionization, radiation, vaporization, spraying of the melt, turbulent convective transfer, etc.

5. Kinetic thickness of air cap. The type of meteoroid interaction with the atmosphere depends primarily on the thickness of the air cap and on the process of dissipation of the kinetic energy. This again depends on the size and velocity of the meteor.

For very rough estimates, serving as guidelines to the general setting, and for weak ablation when a considerable fraction of mass remains, one may assume that at the characteristic layer where the meteor energy dissipation takes place, the penetrated air mass,

$$m_a = \rho H \sec z \qquad (17)$$

(H = scale height or equivalent height of the atmosphere), approximately equals the load of the meteoroid as given by eq. (1). With $H = 6.5 \times 10^5$ cm as a broad average for the meteor region of the atmosphere, and $\sec z = 1.41$ as for average incidence, the characteristic value of atmospheric density becomes

(continued on next page)

$$\rho_m = 1.5 \times 10^{-6}\ r\,\delta\ \ (g/cm^3) \quad , \tag{18}$$

where $r < r_o$ is an effective value of the (moderately) ablating radius. For the non-ablating case, $r = r_o$. For complete dissolution of the meteoroid, the radius at half mass is $r = 0.8\ r_o$. Assuming the latter value, at the same time without much deviating from the non-ablating case,

$$\rho_m = 1.2 \times 10^{-6}\ r_o\,\delta \tag{18'}$$

and, with $\rho = \rho_m$, $r = 0.8\ r_o$, eq. (15) yields the characteristic kinetic depth of the air cap as

$$d_m = 7.2 \times 10^{-7}\ r_o^{\,2}\,\delta/(\lambda\rho) \quad . \tag{19}$$

At the characteristic point, the velocity of non-ablating meteoroids is reduced to about 0.4 of the original value, whereas in typical ablating cases the velocity decreases but slightly, the main conversion of kinetic energy taking place in the vapors. Taking this into consideration, also that ablation is very much more efficient at high velocities, the character of the $\lambda\rho$ values in Table 3 is such that an overall average value of $\lambda\rho = 9 \times 10^{-8}$ g/cm^2 can be assumed for the entire range of meteor velocities (12 - 70 km/sec). Eq. (19) then yields

$$d_m = 8\ r_o^{\,2}\,\delta \quad . \tag{20}$$

This, with eq. (14) and Tables 4 and 5 may serve for a rough classification of meteoric phenomena. However, numerical integrations are required to obtain more precise solutions for the outcome of the meteor flight through the atmosphere, the surviving mass, the thermal and pressure history.

6. Types of meteoric phenomena.

(a) Micrometeorites, presumably dense mineral and metallic particles from the zodiacal cloud which are not observed individually at entry into the atmosphere (because of their faintness). Their existence is inferred from a photometric analysis of the zodiacal light. Their mass captured by the earth exceeds some 100 times the total influx from all other meteoritic sources. Within radii ranging from $3\text{-}5 \times 10^{-5}$ to 0.03 cm (the lower limit is set by radiation pressure), their frequency varies with an inverse power of about $p = 2.8$ of the radius,

$$n(r)\, dr = C\, r^{-p}\, dr \quad . \tag{21}$$

Attempts to link them with larger "ordinary" meteors, by assuming a higher power, $p \sim 4.5$ (to make the small particles more numerous), are unacceptable as they disregard photometric data and diffraction phenomena. Metallic spherules collected from the bottom of the Pacific Ocean can be interpreted as molten micrometeorites from the zodiacal cloud. The metallic mass is less than 1% of the total mass of the cloud which, thus, must consist predominantly of mineral, stonelike particles. The distribution of spherule diameters, ranging from 8 to 80 microns, when interpreted through the physical theory of their flight through the atmosphere (which gives the percentage of molten spherules *versus* unmolten angular objects, and the distortion of the frequency law of eq. (21) due to ablation), points to a rather narrow range of their entry velocities, $v = 11.1$ to 12.2 km/sec, or to very low encounter velocities, $U = 0$ to 5.1 km/sec. This is in agreement with concepts of the orbital characteristics of the zodiacal particles (see Table 2). The low velocity, so confirmed, also puts them into a different category from the "ordinary" meteors which have much higher velocities (Table 2).

For an upper limit of $r_o < 0.05$ cm, $\delta = 3$ to 8, eq. (20) yields $d_m < 0.06$ to 0.16, thus small or insignificant. For them (Tables 4 and 5), K = 1.00, $\Upsilon = 0.8$ (stone) or 0.6 (iron). From eq. (18'), the characteristic atmospheric density is

$$\rho_m = 4 \times 10^{-6}\, r_o \text{ (stone) or } 10^{-5}\, r_o \text{ (iron)} \quad . \qquad (22)$$

For a stony particle at $v_o = 12$ km/sec and $r_o = 10^{-3}$ cm (which are typical of the zodiacal light), $\rho_m = 4 \times 10^{-9}$ g/cm^3; this corresponds to an altitude of 89 km. With $\Upsilon = 0.8$, v = 10 km/sec (decelerated), the average heat released per cm^2 of the meteoroid surface (one-quarter the heat per cm^2 cross section) is, according to the right-hand side of eq. (11)

$$0.1\, \rho\, v^3 = 4 \times 10^8 \text{ erg/cm}^2 \text{ sec}$$

which equals black body radiation at about 1700°K. Because of evaporation, the temperature will be lower, about 1580°K, with $\theta = 6$ as the ratio of radiation to evaporation losses and $1 + \theta_a \sim 8$. For $h_c = 8 \times 10^{10}$ erg/g as the total heat of evaporation, $\Upsilon = 0.8$, K = 1, $v = 1.2 \times 10^6$ cm/sec, eqs. (13) and (14) yield a survival mass ratio of

$$M_f/M_o = e^{-0.45} = 0.638 \quad ,$$

$$r_f/r_o = 0.861 \quad .$$

Without radiation, $1 + \theta = 1$, the mass ratio would have been 2.5×10^{-4}, thus negligible. Through radiative cooling, over one-half the mass is conserved.

(b) "Visual" meteors. The ordinary meteors, visible to the naked eye, as well as those recorded photographically, are in the mass range from 0.03 to 1 gram and over (as derived from the emitted light). This would correspond to radii of compact stones of the order of 0.15 to 0.5 cm, characteristic atmospheric densities around 10^{-6} g/cm^3 [eq. (18')] and altitudes around 50 km. Actually they are displayed at altitudes of 85-100 km, according to velocity, where the atmospheric density is several hundred times less, and where also the display of bona fide micrometeorites must occur.

The explanation of the discrepancy is that these objects are dustballs, loosely bound conglomerates of dust-grains which break up at entry when the drag pressure ρv^2 attains about 10^4 dyne/cm^2 (0.01 of atmospheric pressure). Their luminous output corresponds to the total mass, whereas the process of ablation and deceleration is that for the individual grains. The grain radii may be as small as genuine micrometeorites, from 5 to 10 x 10^{-3} cm (Draconids), or of the order of 0.03-0.05 cm as for the average sporadic meteors.

Many of these meteors are organized into streams, or showers, directly related to comets. Others are sporadic, of random incidence; probably these too are members of ancient showers, disorganized by planetary perturbations. They apparently become detached from comet nuclei when the ices (Whipple's icy conglomerate) evaporate and dustball skeletons remain, to float into interplanetary space when blown away by the cometary gases.

For the individual dustgrains, the conditions of deceleration and ablation are similar to those of the micrometeorites. However, surviving grains are much fewer than from zodiacal dust, because of their much smaller total mass, as well as their higher entry velocities (see Table 2). Thus, for their slowest group--those moving in direct orbits of small eccentricity--v_o = 21 km/sec (Arizona Expedition for the Study of Meteors), characteristic altitude 89 km (same as for micrometeorites of $r_o = 10^{-3}$ cm), $\rho_m = 4 \times 10^{-9}$ g/cm^3, but r_o = 0.03 cm as derived from ablation (without much deceleration; eq. (22) is not applicable in this case, as it refers to feebly ablating meteoroids), $(\lambda\rho) = 10^{-7}$ g/cm^2 (Table 3), $r \sim 0.7\, r_o$ = 0.02 cm, eq. (15) yields

$$d = 6 \times 10^{-4} ,$$

thus negligible. Hence, from Tables 4 and 5, K = 1.3, $\gamma = \gamma_o = 0.8$. Further, the heat intake is now $0.1\, \rho\, v^3 = 2.5 \times 10^9$ erg/cm^2 sec, corresponding to an equilibrium radiation temperature of 2510° which, on account of evaporation, is lowered to about 1950° with $\theta = 0.4$. Setting $1 + \theta_a = 1.6$ as an average in eq. (13), and $h_o = 8 \times 10^{10}$, eq. (14) yields

$$M_f / M_o = e^{-5.3} = 3.35 \times 10^{-4} ,$$

$$r_f/r_o = 0.07 .$$

The dustballs, even of the slowest kind, can leave behind but negligible residual nuclei.

The Draconids of 1946, velocity 22 km/sec, were thoroughly studied photographically (Jacchia, Kopal, and Millman). Interpretation of these observations (Öpik) reveals their extreme dustball character, of small grain size, with 0.005 to 0.010 cm grain radius as an upper limit, much smaller than for the average visual meteors. For total dustball masses ranging from 0.5 to 70 gram the mean altitude of their trails was surprisingly constant, around 93.1 km, indicating that the size of the ablating grains, and the break-up pressure of the dustballs was independent of their total mass.

(c) Compact meteorites. The occurrence of stone and iron meteorite falls points to the existence of compact meteoroids among the larger groups, although there is little evidence for them in ordinary meteor observations which overwhelmingly refer to dustballs. Micrometeorites are preserved through radiative dissipation of energy, despite the large value of Υ, the coefficient of heat transfer. On the contrary, large meteoroids which penetrate deep into the atmosphere cannot rely on radiation. Boiling (for stone) or fusion (for iron) is so intense that practically $\theta = 0$, $1 + \theta = 1$. However, with deep penetration, large ρ and increasing r_o, the air cap grows according to eq. (20) and Υ decreases (Table 5). According to eq. (14), this now favors the survival of a considerable fraction of the mass of the meteoroid.

In the meteorite class with large air cap thickness d, $K \rightarrow 0.5$, $\theta = 0$, $h = h_o = 8 \times 10^{10}$ erg/g for stone in vaporization and 5×10^{10} for iron meteorites in mixed fusion spraying and vaporization. With these assumed parameters, the survival radii for meteorites are estimated according to eqs. (20), (14) and Table 5, and are given in Table 6.

Table 6. Survival radii (r_f, cm) for meteorites.

Stone (δ = 3.4 g/cm^3)

r_o, cm	5	10	20	50	100	200
d	680	2700	10900	68000	2.7×10^5	1.1×10^6
Υ	0.023	0.036	0.024	0.0128	0.0074	0.0044
v = 12 km/sec, r_f =	4.3	7.8	17.0	46	95	194
v = 15 km/sec, r_f =	3.9	6.8	15.4	44	92	191
v = 20 km/sec, r_f =	3.2	5.0	12.6	39	87	184
v = 25 km/sec, r_f =	2.5	3.4	9.8	34	80	175
v = 30 km/sec, r_f =	1.9	2.1	7.1	29	73	165
v = 40 km/sec, r_f =	<0.84	<0.6	<3.2	19	57	143
v = 60 km/sec, r_f =	<0.094	<0.04	<0.3	<5	28	94

Iron (δ = 8 g/cm^3)

r_o, cm	5	10	20	50	100
d	1600	6400	25600	1.6×10^5	6.4×10^5
Υ	0.042	0.029	0.0182	0.0092	0.0054
v = 12 km/sec, r_f =	3.1	7.3	16.4	45	94
v = 15 km/sec, r_f =	2.4	6.0	14.6	43	91
v = 20 km/sec, r_f =	1.4	4.1	11.3	38	85
v = 25 km/sec, r_f =	<0.7	2.5	8.4	32	77
v = 30 km/sec, r_f =	<0.3	<1.4	5.7	26	69
v = 40 km/sec, r_f =	<0.03	<0.3	<2.1	16	52
v = 60 km/sec, r_f =	$<10^{-4}$	$<10^{-3}$	<0.2	<5	26

In the deep atmosphere, there is another factor operative in the destruction of meteorites which have retained their cosmic velocities: it is the crushing by aerodynamic pressure. This is of importance chiefly for stony meteorites which break up into numberless fragments at altitudes from 4 to 23 km, according to velocity. At this "Hemmungspunkt" the breakup leads to a sudden increase in area, evaporation, and brightness, similar to an explosion. The mean crushing strength for the stony meteorites equal to $\frac{1}{2} \rho v^2$ at the point of breakup, is 1.7×10^8 dyne/cm^2, 170 atmospheres, about one-half the lowest figures for sandstone or limestone and one-tenth of those for basalt or granite. Nickel-iron meteorites, with a compressive strength of about 2×10^{10}, would not break up even in the lowest atmosphere unless their velocity exceeds 55 km/sec.

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