THE COMETARY ORIGIN OF METEORITES

by

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ABSTRACT

The origin of any significant fraction of meteorites from recent (less than 4×10^9 years ago) asteroidal collisions is shown to be unacceptable for the following reasons: (1) the expected number of such objects falls short by four orders of magnitude; (2) the ejection velocities of sizable fragments surviving the shock of a collision is less than 100 m/sec, insufficient to produce any significant orbital change; (3) higher velocities of some favourably placed fragments, accelerated by the explosion gases and characteristic of lunar ray craters, cannot occur because gaseous products cannot be significantly formed at the low-velocity asteroidal collisions; (4) the orbital characteristics (especially the large eccentricities) of meteorites are unlike those expected from asteroidal fragments diverted to earth's space by Mars perturbations.

Some low-velocity (5 km/sec extraterrestrial) meteorites (probably tektites) may be of lunar origin, but these cannot account for more than 0.2 — 1.0% of all meteorites which have a much higher average velocity (18 km/sec).

A planet collapsing from instabilities of solid state phase transitions cannot cause meteorites to be ejected into space.

Only an origin from decaying comet nuclei can account for all the facts. It is suggested that the meteorites have been produced in planetary collisions at a time when the giant planets (Jupiter) were formed. They were then imbedded in the ices of comet nuclei, which were subsequently ejected to Oort's sphere of comets. As the result of an interplay of stellar and planetary (Jupiter) perturbations, some nuclei are now returning to the inner solar system. After evaporation of the ices the enclosed meteorites are released. The total mass of debris from the periodic comets alone is amply sufficient not only to account for the meteorites, but also to contribute a considerable fraction of the much larger total mass of interplanetary dust.

The absence of meteoritic objects from some meteor showers (Perseids) and their occurrence in others (Southern Taurids, from Encke's Comet) can be well explained by the circumstances of jet ejection of the particles competing with the gravitation of the nucleus.

There cannot be shock heating of ejected sizable meteoric bodies during collisions — those fragments which are heated and ejected are inevitably pulverized, while those ejected with sizable dimensions cannot have been significantly heated. Ultra-high shock can produce compaction heating and crystal transformation by all-sided compression, but the mass of sizable fragments so affected is very small and the surviving fragments are prevented from leaving the seat of impact with considerable velocities. The crowding of the helium retention ages of hypersthenes around an apparent value of 5×10^8 years cannot be explained by shock heating during a collisional event which happened at that time. They are rather an indication of the breakup of giant "sun-grazing" comets whose meteoritic material was shocked at the dawn of the solar system and is able to retain firmly only 12% of the helium, the rest being lost during the cosmic-ray exposure phase. The meteoritic debris could have continued on the original orbit for some 10^6 years, being heated in repeated perihelion passages until dispersed by planetary perturbations.

1. Asteroidal Origin

The origin of those centimetre to metre size stony and nickel-iron fragments of interplanetary stray bodies which, after surviving the passage through the terrestrial atmosphere, are now preserved in the museums, is at present most commonly ascribed to the asteroidal belt. Undoubtedly asteroids do collide and fragments of all sizes are produced there; these by way of orbital change, could then be diverted to the earth's space. As the main diverting agent, perturbations of the orbital elements of the fragments in repeated close encounters with Mars has been rightly postulated; these augment the relatively small peculiar velocities created in a collision and change the direction of the encounter velocity vector U (Jacobian velocity in a frame rotating with the circular orbital motion at heliocentric distance r but outside the sphere of action of a planet) so that earth crossing becomes possible. Within intervals of 50,000 – 100,000 years the secular motion (usually advance) of the argument of perihelion (angular distance of perihelion from node) then makes collisions with the earth possible, although originally the deflected orbit may not intersect the path of the earth but only interlock ("cross"). The mechanism leading to orbital change and collisions of stray bodies in close encounters (within the sphere of action) with the planets is one of straightforward celestial mechanics and probability calculus and has been treated consecutively in more and more detail by this writer (<u>Refs</u>. 1 – 4); the theory of formation and ejection of fragments in hypervelocity collisions offers a supporting branch, also developed by the writer (<u>Refs</u>. 5 — 8), though on less precise lines but, within a margin of 10-20% in the numerical results fully verified by experiment.

The collision and deflection encounter cross sections strongly depend on U (for small values nearly as U^{-2} and U^{-4}, respectively) which is an invariant in encounters with a planet in circular orbit (Jacobi integral) but is accelerated in repeated encounters with a planet in an elliptical and/or precessing orbit. The acceleration, an equipartition effect similar to the Fermi mechanism for cosmis rays, was overlooked by Öpik but empirically discovered by Arnold (<u>Ref</u>. 9) in Monte Carlo calculations or "experiments"; <u>post factum</u>, Öpik derived for it a simple statistical-mechanical expression (<u>Ref</u>. 4). Within the sampling error of the

Monte Carlo calculations, the theory of encounter probabilities as amended to account for the variable orbital elements, and the theory of acceleration of the encounter velocity are empirically confirmed and can be firmly used without recourse to, and with greater confidence and less labour than, the Monte Carlo method (Ref. 10). In any case, there is no difference of principle in the two methods of approach; the theoretical one, with a clear insight into the causes and consequences, and not affected by the sampling errors of a finite number of Monte Carlo numerical experiments, is to be preferred.

Although some meteorites undoubtedly may arrive from the asteroidal belt, their relative number must be negligible, and this for several reasons, each of which carrying considerable weight while in their complexity they seem definitely to exclude this source as a noticeable contributor.

2. Predicted Numbers

From a synthesis of observational data pertaining to the stray bodies moving in the earth's vicinity and either seen from a distance, or entering the earth's atmosphere and even striking the ground in cratering events, this writer has derived a probable distribution of their sizes (Ref. 6, p. 35). Selection factors have been carefully considered, and the author feels that the data are preferable to many other compilations of this sort which may have lacked a similar exhaustiveness of approach. As a check, the predicted fluxes agree with the observed numbers of craters on the lunar surface within the diameter range from 20 m to 5 km better than to a factor of 2 (Ref. 8). Over the size range we are interested in the meteorite flux can be represented as a superposition of three component populations distinguished by their orbital characteristics and having different population exponents, p, as defined by

$$dN = Cx^{-p}dx \qquad (1)$$

where dN is the number (either per unit of volume, or a flux per unit of time and area) within limits of x to x + dx of the equivalent radius (or diameter) of the particles. These components are: the "Apollo" group of apparent asteroids (to be identified with extinct comet nuclei) crossing the earth's orbit whose numbers for the smaller sizes merge into the bona fide meteorites (50 cm to 8 m diameter), with p = 3.7; the nuclei of "live" comets, i.e., those which have not exhausted their store of ices and whose evaporation products produce the characteristic gaseous envelopes and tails of comets (their dimensions are evaluated to about 30-50% reliability from photometric and physical data, cf. Refs. 3, 11, 12) with p = 3.2; and the asteroidal population around Mars, deflected by Mars perturbations in close approaches to earth crossings, with p = 2.6. The numbers for the latter group were calculated from the theory of gravitational encounters, on the basis of the observed asteroidal population in Mars crossings. The numbers in the first two groups are derived directly from observational data, duly allowing for selection effects. The relative numbers to different diameter limits of the three components are given in Table 1.

Table 1. Relative Cumulative Fluxes upon Earth of Stray Bodies (Apollo + meteorite group taken as unity)(mostly extrapolated)

Diameter lower limit, metres	2100	520	130	40	10	2.5
Comet nuclei	3.3	1.5	0.64	0.36	0.18	0.09
Mars asteroids	0.30	0.07	0.014	0.004	0.001	2×10^{-4}

Although the Mars asteroids deflected to earth are conspicuous among bodies of kilometre size and larger, their predicted numbers in the meteorite range become vanishingly small as compared to the actual observed number which is covered by the Apollo-meteorite group, taken as unity in the table. Mars asteroids are not expected to contribute significantly to the meteorite population unless their population exponent for smaller members considerably exceeds the value of p = 2.6 for the largest observable members of this group.

3. Ejection Velocity of Fragments

It has been suggested that the velocities imparted to the fragments of an asteroidal collision may produce orbital changes which make it easier for them to penetrate inwards toward terrestrial space which otherwise is forbidden to bona fide asteroids, on account of their small orbital eccentricities. To bring the perihelion of a fragment from a typical asteroid of the main population ($a = 2.8$ astron. units) into crossing with the orbit of the earth, a backward directed ejection velocity of 4-5 km/sec is required. Instead of one step, the fragment may be brought into contact with the outer fringe of the Martian orbit (1.67 a.u.) through a retro ejection velocity of 2.5 km/sec; Martian perturbations would than take over as a second step, to modify the orbit in such a manner that earth crossing can be achieved. This would increase the predicted number of small fragments in Martian space, above the numbers in the last line of Table 1 which were extrapolated from the observable members of the Martian family which are much larger than the meteoritic fragments — the hypotetical unobservable component of the Martian asteroidal population.

Against 34 listed Martian asteroids there are nearly 2000, or 60 times more asteroids of the main belt in the catalogues. There is an observational selection factor in favour of the Martian asteroids due to their nearness which, roughly, can be set equal to

$$\left[(a_2 - 1)/(a_1 - 1)\right]^{p - 1}$$

where $a - 1$ is the geocentric distance at opposition and p is the population exponent, the same as in Eq. (1), an integration of which yields $p - 1$ as the "population index" for cumulative numbers. With $a_2 = 2.8$, $a_1 = 1.5$ a.u., $p = 2.6$, the factor becomes 8 and the upper limit of enhancement of the supply of small fragments is then $60 \times 8 = 480$. The last figure in Table 1 becomes then $2 \times 10^{-4} \times 480 = 0.1$, or still insufficient by a factor of 10, to account for the actual flux of meteorites at $x = 2.5$ metres. The efficiency factor is undoubtedly grossly exaggerated, and the insufficiency of the Martian perturbations in providing the meteorite flux at the earth appears to be difficult to refute, even when the entire asteroid population is somehow made an efficient source replenishing Martian space.

Actually, however, the mechanism of cratering at collision does not leave such a loophole of extra supply from the main asteroidal belt.

In cratering events, two types of fragmentation and ejection are operative (Refs. 6, 7, and especially 8). The main mass of ejecta comes from the rock target shattered by an inelastic inertial shock wave, expanding radially from the region of impact ("central funnel"), inside a volume over which the rock is unable to accommodate vibrationally the energy of the shock. If y is the fractional mass inside the excavated volume (y = 0 at the centre and 1 at the periphery of the crater; the contour is that of the shock wave front), the size of the fragments (rocks at the periphery, dust or "rock flour" in the interior) is

$$x = 0.017Dy^{8} \qquad (2)$$

where D is the crater diameter (Ref. 8), and their average ejection velocity at y is

$$v = 0.7\lambda(s/\rho)^{\frac{1}{2}}/y \qquad (3)$$

where ρ = density, s = crushing strength of the rocky target and λ is a cofficient of elastic efficiency. For ordinary rocks, $s = 9 \times 10^{8}$ dyne/cm^{2}, $\rho = 2.6$, $\lambda = 0.5$ (experimentally; for granular targets $\lambda = 0.3$) and

$$v = 6.5 \times 10^{3} y^{-1} \text{ (cm/sec)} . \qquad (4)$$

These equations, derived from first principles, lead to a frequency distribution of the fragments with p = 3.875 [Eq. (1)]. Counts of particles on Luna 9 pictures gave p = 3.9 ± 0.2 (Ref. 13) and on Surveyor I p = 3.77 (Ref. 14) — for the volume distribution of particle sizes, a perfect confirmation (surface distribution of the fragments was actually counted; this is ruled by the exponent p - 1).

As an example, for a crater of 1 km diameter, fragments of $x > 50$ cm require $y > 0.64$ and $v < 100$ m/sec. This is absolutely insignificant and in no way can help to expand noticeably the store of fragments in Martian space at the expense of the asteroidal belt.

Another type of ejection depends on the formation and explosion of gaseous products near the point of impact. Some blocks of considerable dimensions, broken off the surface layers of the crater, can be carried along and accelerated by the vapour jet without excessive pressure, by way of gradual acceleration along a "runway" of the order of the depth of the crater. The larger the crater, the larger the fragments that can be accelerated to a certain velocity without being demolished (Ref. 7). Vaporization requires a high kinetic energy at impact, and only high-velocity collisions can yield such an effect. The ray craters on the moon are apparently examples of such events; from an application of cratering theory to certain craterlets on telescopic and Ranger VII photographs, interpreted as being produced by secondary ray ejecta, the following estimates (Table 2) of size and strength of the ejected "boulders" (not surviving the impact) are made (Ref. 8); the velocities can be calculated almost unambiguously from the distance of flight, an angle of 45° for ejection being assumed.

Table 2. Ray Crater Ejecta on the Moon

Parent Crater	Bullialdus	Tycho	Tycho	Copernicus	Copernicus
Flight Distance, km	236	1046	1050	150	590
Velocity, km/sec	0.60	1.16	1.16	0.48	0.94
Secondary Craters, Aver. Diam. km	1.94	1.02	1.36	6.0	3.0
Ejected Projectile Diam., km	0.80	0.25	0.32	2.5	1.03
Strength of Ejecta, s, 10^8 dyne/cm^2	6	5	7.5	8	13

These estimated velocities hardly exceed 1 km/sec, but it is possible that up to 2.5 km/sec can be attained by small fragments, if tektites are of lunar origin; it is indeed likely that some lunar ejecta actually are falling on earth, as the frequency distribution of meteor velocities seems to imply. At meteorite dimensions the fraction of such high velocity objects may be about 0.2% (Ref. 10), or less than 0.1% of the material currently crushed in lunar cratering events. A similar proportion may be expected in asteroidal collisions if vaporization occurs. This is too small a fraction to be reckoned with as a significant source of material entering the Martian space from outside, to compare with the indigenous population of Martian asteroids included in Table 1.

Moreover, the high-velocity ray crater ejecta require production of hot expanding gas. At an encounter velocity of 5 km/sec of two asteroids, the primary seat of impact, the "central funnel", becomes thoroughly mixed (Ref. 6); its mass is about 25 times that of the projectile, and the average heat developed in the funnel is

$$\tfrac{1}{2}(5 \times 10^5)^2/25 = 5 \times 10^9 \text{ erg/gram} .$$

This equals about 6% of the amount required for vaporization, and one-quarter of the heat needed for fusion. Significant amounts of vapours cannot be formed, and the mechanism for the high-velocity "ray crater" ejecta does not work in the low-velocity asteroidal collisions.

Only solid fragments with a velocity of the order of 100 m/sec are ejected; the collisional ejection mechanism is utterly unable to feed the debris from the asteroidal belt into Martian space. The vanishingly small figures of Table 1 for the share of Martian asteroids in the meteoritic population thus remain valid.

As to production of small fragments by collisions of, or with, the Martian asteroids themselves, their population is too small and collisions too rare to affect the distribution of fragment sizes to any significant degree. For these debris, Mars is the main collisional risk, yet no fragments of a collision could escape from the gravitational field of the planet. Those which survive the collisional fate, are — slowly but surely — led by perturbation to earth or Jupiter crossings and eliminated there much sooner than mutual collisions between themselves come into effect.

4. Orbital Characteristics

The statistics of true meteorite orbits is very incomplete because of the impossibility of having pre-arranged observations. The existing evidence shows that, with high eccentricities (e), and with inclinations (i) that are too small from the standpoint of equipartition of the components of encounter velocity (Ref. 10), they fall on the other side of the bright meteors and Apollo group objects with more or less equipartitioned components, as compared to the Martian and Belt Asteroids which have too small an average eccentricity for their inclinations. These two basic groups are definitely non-equipartitioned. However, if the meteorites are thrown into terrestrial space by Martian perturbations, in this process equipartition of e and i will be approached automatically, so that in this respect the criterion of equipartition is not very stringent. More important is the absence of equipartition among the Martian asteroids which indicates the insignificance of the perturbations over the age of the solar system. Cutoff of large eccentricities by earth and Jupiter crossings is undoubtedly also a factor here.

The most important orbital criterion is the Jacobian encounter velocity, U, given by

$$U^2 = 3 - 1/A - 2\left[A(1 - e^2)\right]^{\frac{1}{2}}\cos i, \tag{5}$$

in units of the circular velocity at heliocentric distance r, with $A = a/r$, a being the semi-major axis of the particle's orbit. When r is the mean heliocentric distance of a planet in circular orbit, U is an invariant in consecutive encounters with that planet. For crossings with different planets, U somewhat varies but not very much; thus, for the 10 members of the Apollo group all contained inside Jupiter's orbit (Comet Wilson-Harrington being excluded, as its preliminary orbit used in Ref. 3 turned out to be incorrect and the object is crossing Jupiter's orbit, comprised between aphelion of 5.60 and perihelion of 1.59 a.u., Ref. 15) the average with respect to earth is $U_e = 0.705$, and with respect to Mars $U_m = 0.706$ (cf. also Table 6). Generally, the difference of this parameter between earth and Mars crossings can be found from Equation (5) and is given by

$$U_e^2 - U_m^2 = 0.524/a - 0.380\left[a(1 - e^2)\right]^{\frac{1}{2}}\cos i. \qquad (6)$$

For small inclinations, as is actually the case for almost all these objects, $U_e < U_m$. Thus, at i = 0, a = 2, e = 0.5, or for a grazing approach to earth, $U_m = 0.505$, $U_e = 0.224$. At a = 1.262, e = 0.208, i = 25°.4, $U_m = 0.426$ (the average for Martian asteroids), $U_e = 0.468$, thus a slight increase in this very extreme case. The non-circularity and precession of the Martian orbit (around the invariable plane of the solar system) will introduce an acceleration of

$$\Delta\left(U_m^2\right) = +0.0109$$

per "full accumulated deflection" (of 90°)(Ref. 4). From the encounter tables (Table 2, Ref. 3), at U = 0.4 – 0.5 it takes an average of $1/\theta$earth = 2.8 full encounters per one deflection to earth crossing, or an acceleration $\Delta\left(U_m^2\right)$= +0.0306 at entering earth's space (unless the asteroid is eliminated by collision with Mars). In earth space, a further acceleration by earth,

$$\Delta U_e^2 = +0.0025$$

per full deflection is added. However, the elimination rate in earth space is high and allows only one full deflection to be achieved. Hence, from the acceleration mechanism, Mars asteroids diverted to earth space will show a total increase

$$U_e^2 - U_m^2 = +0.0331.$$

For U_m = 0.4 and 0.5, respectively (as the actual values are running), U_e = 0.440 and 0.533, respectively, could result. The average for the Martian asteroids is 0.426, and an increase from acceleration to about 0.47 should be counterbalanced by the decrease according to Equation (6). The U-parameters of deflected Martian asteroids should be more or less equal in Martian and terrestrial space and stay around an average of about 0.45, well below the averages for the Apollo group (n = 10, 0.70), the Superschmidt bright meteors moving inside

Jupiter's orbit (n = 891, U = 0.59), and the small sample of somewhat uncertain meteorite orbits (n = 13, U = 0.525)(Ref. 10, also Table 6 below). Most probably, the meteorites must be placed between the Superschmidt and Apollo groups, both with well determined orbital parameters, and their true average U value may be higher than indicated by their poor orbital data.

Selection effects must strongly enhance this conclusion. The encounter cross section for angular deflection and orbital change is essentially proportional to U^{-4} (Refs. 3 and 4), and the influx of Martian asteroids into terrestrial space (terrestrial crossings), to a fluctuating factor of the order of unity, must be proportional to this cross section. A further factor, J_E (Ref. 3, Table 7), or the probability that the object which escapes physical collision with Mars, will enter into terrestrial crossing, must be added; this slowly increases with increasing U. A strong bias toward small U- values for the objects deflected from Mars to earth crossings results, and the average U- value for the flux of Martian objects intercepted by the earth (not surviving in space) must be much lower than the Martian average of 0.426. Indeed, from Monte Carlo calculations Arnold arrives at an average of U = 0.252 for this class of objects. The actual elements for the 34 listed Martian asteroids (Ref. 3, Table 7) provide even a better direct estimate of this average. Those deflected to earth space and surviving the chances of physical collisions must have undergone a sufficient number of equipartitioning encounters with Mars, so that for them the statistical average of the deflection probability per revolution for randomly varying orbital elements can be used (Refs. 10 and 4)(except when U is very small):

$$p_m = 3\sigma^2/U \ , \tag{7}$$

where σ is the effective target radius for angular deflection of 90° ($\pi\sigma^2$ is the cross section). The influx into terrestrial crossings is proportional to $p_m J_E$. On the other hand, in space the lifetimes in terrestrial (τ_e) and Martian (τ_m) crossings will be in a more or less constant ratio; the injection rate will be proportional to $J_E \tau_m^{-1}$, the loss from terrestrial space proportional to τ_e^{-1} and, in the balance when injection equals loss, the distribution of the U- values of the objects injected into terrestrial space and surviving there will closely copy the distribution of the J_E values of the parent Martian population. With σ and

J_E taken from Ref. 3, Table 2, the original distribution of the U- values for the Martian asteroids is transformed into probable distributions when injected into terrestrial space as shown in Table 3.

Table 3. Probable Distribution of Peculiar Velocities (U) of Martian Asteroids (unit of σ is the mean heliocentric distance of the planet)

U (Mars or Earth)	<0.190	0.190–0.249	0.250–0.298	0.299–0.391	0.392–0.449
Present number of Mars crossings, n	0	7	4	0	7
J_E	-	0.247	0.296	-	0.362
σ^2, 10^{-10} units	-	7.94	3.42	-	0.630
p_m, 10^{-10} units	-	107.	37.3	-	4.50
$n_1 = nJ_Ep_m$ (terrestrial flux)	-	185.0	44.0	0	11.4
$n_2 = nJ_E$ (terrestrial space)	0	1.73	1.18	0	2.54

U (Mars or Earth)	0.450–0.499	0.500–0.599	0.600-0.699	0.700-1.006	Total	Average U
Present number of Mars crossings	7	4	4	1	34	0.426
J_E	0.375	0.388	0.398	0.408	-	-
σ^2, 10^{-10} units	0.385	0.214	0.112	0.038	-	-
p_m, 10^{-10} units	2.43	1.17	0.52	0.13	-	-
$n_1 = 10^{10}nJ_Ep_m$ (terrestrial flux)	6.4	1.8	0.8	0.1	249.5	0.249
$n_2 = 10^{10}nJ_E$ (terrestrial space)	2.62	1.55	1.59	0.41	11.62	0.452

The expected average for terrestrial flux of Martian asteroids or meteorites intercepted by the earth is U = 0.249, in good agreement with Arnold's Monte Carlo experiments, but hopelessly differing from the averages for meteorites, U = 0.525, (n = 13) and for photographic sporadic meteors inside Jupiter's orbin, U = 0.589 (Smithsonian, n = 891) or 0.603 (Babadjanov, n = 23)(Ref. 10). In terrestrial space, the expected average is U = 0.452, as compared to 0.704 for the ten objects of the Apollo group — two values which it is virtually impossible to bridge over by mechanical reasoning. Thus, from the expected rates of transfer (Table 1), as well as from the average encounter velocities neither the meteorites, the photographic meteors inside Jupiter's orbit, nor the Apollo objects can be derived from the Martian asteroids in any appreciable proportion. Their parent population must be sought among the short-period comets, captured by Jupiter and whose orbits have shrunk through a non-gravitational process (deceleration by evaporation jet) so that they no longer cross the orbit of Jupiter and no longer are endangered by the presence of the giant planet. It is clear from the preceding that neither the observed fluxes of meteorites nor their average orbital characteristics can be reconciled with an origin from the Martian or the main-belt asteroids.

The virtual impossibility of accelerating the members of the Martian asteroidal population by Martian gravitational encounters to the observed meteoritic velocities has led to a search of loopholes in the argumentation. In a lecture delivered at NASA, Greenbelt, on March 15, 1968, Professor Anders pointed out that in all the theoretical and empirical models of orbital change, the accelerating effect of Jupiter has not been considered, and that this could lead to higher velocities. Although this is true in a limited way, the loophole does not exist and has been given proper consideration by Öpik. When the Martian asteroids, induced to earth crossings, are also swinging over to Jupiter's orbit, they are so rapidly eliminated by Jupiter (chiefly ejected from the solar system) that at any time no significant proportion of them can stay in terrestrial space. At U = 0.4, the lifetime of objects in Jupiter crossings, according to Equation (7) and Table 2 of Ref. 3, is 1.3×10^5 orbital revolutions or 10^6 years, while for those in purely earth crossings it is 4×10^7 revolutions or 10^8 years; hence there is an adverse factor of 10^{-2} for survival of those in Jupiter crossings, and their number encountering the earth will not be more than one per cent of the number if they were not crossing Jupiter's orbit. In calculations of population exchange as governed by orbital perturbations, this writer therefore made the simplifying assumption that Jupiter crossing removes the object immediately, so that there are no objects of this kind to be considered; thus, 0% is assumed instead of 1% for the fraction of Martian asteroids which are in Jupiter crossings — and this out of a total of 0.02% of these objects expected in the meteorite range (Table 1).

Moreover, objects in Jupiter crossings will not have much of a chance to be accelerated beyond the limit of ejection from the solar system, $U = 2^{\frac{1}{2}} - 1 = 0.4142$. Calculations of acceleration versus survival from physical collisions (Ref. 4, Table 7) can be extended to include the probability of ejection from the solar system; the results for Jupiter crossings are given in Table 4.

Table 4. Acceleration of Encounter Velocity (U, r.m.s.) by Jupiter versus Elimination by Collisions ($U < 0.4142$) and by Ejection ($U > 0.4142$)(f = surviving fraction of the original population)

U	0.10	0.20	0.40	0.50	0.60
f	1.000	0.980	0.849	0.059	1.4×10^{-5}

Obviously, even the insignificant fraction of the Martian asteroids which at any time can stay in Jupiter crossings will not possess the high encounter velocities — the very quality for which they have been hypothesized. Omission of such objects from the statistics of small bodies in terrestrial space is thus amply justified.

5. Lunar Origin

As pointed out in the preceding section, high-velocity interplanetary projectiles (chiefly comet nuclei and the Apollo-meteorite group) which are responsible for the ray craters on the moon could cause the ejection of fragments from cratering events with velocities in excess of 2.3 km/sec, the moon's escape velocity. Only a small fraction of the cratering mass can be ejected in such a manner. A previous estimate by the writer (Ref. 7), based on the survival conditions of hard fragments (cohesive strength of granite) accelerated above the escape velocity over a "runway" equal to the depth of the crater, arrived at an upper limit of one meteorite of lunar origin for each 100 meteorites of 100 cm diameter or larger, i.e. 1% of the total; a further revision, showing that only high-velocity comet nuclei having sufficient velocity could participate, put the figure down to 0.2% as a theoretical prediction.

This figure has also been subject to observational test (Ref. 4). Escaping lunar ejecta will enter terrestrial interplanetary space with a low starting velocity $U \sim 0.10$(3 km/sec) or less. In successive encounters with the earth, acceleration competes with collisional elimination, so that at U = 0.20 about 30% survive, at U = 0.25 — 4.3%, at U = 0.30 — only 0.1%, etc. An average of U = 0.17 or 5.1 km/sec is obtained for meteorites of lunar origin entering the earth's atmosphere; an identical figure has been found from Monte Carlo experiments (Ref. 9). This is very much lower than the average for meteors and meteorites (this is the Jacobian velocity as taken outside the gravitational field of the earth; at entering the sphere of action of the earth, or even before, the velocity is of course increased by the terrestrial gravitational field). The frequency of the 891 Smithsonian Super-Schmidt velocities (objects with aphelia < 4.1 a.u.) (Ref. 16) could be represented as the superposition of two Maxwellian distributions, of 40 "lunar" objects with an average U- value of 0.170(5.1 km/sec), and 847 objects of an average velocity U = 17.5 km/sec. The presumably lunar objects appear to represent thus 4.5% of the meteors of the inner solar system (aphelion ≤ 4.1 a.u.) or 1.6% of all observed Super-Schmidt meteors (n = 2529); allowing for lesser luminous efficiency at lower velocity, it is found that among meteors of the order of 1 gram or 1 cm diameter the fraction of lunar ejecta returning to earth from interplanetary space is about 3.2%. For meteorites $p \sim 3.7$ [Equation (1)], for lunar ejecta $p \sim 3.9$ (Ref. 8), so that in the 100 cm range the ratio of lunar meteorites to all would decrease $100^{0.2} = 2.5$ times, leading to about 1% of lunar ejecta among the meteorites proper. This figure is 5 times higher but not very much in contradiction with the *a priori* estimate. Both estimates point to a small, almost negligible fraction of lunar ejecta among meteorites.

6. Meteorites from Collapse of a Planet

This mode of origin, proposed by W. H. Ramsey (Ref. 17), visualizes a planet collapsing inwards through phase transitions of silicates which become unstable under high pressure. In such a case the earth's core is thought to consist of molten silicates compressed into a metallic state, and not of molten nickel iron. This proposition has been critically analysed by Öpik (Ref. 18). Even if there were no iron core in the earth, the collapse of silicates in phase transitions would release too little energy, to eject fragments from the earth's surface (by a seismic shock) into space. A smaller planet, with smaller gravitation, could let the fragments out — but a small planet would never collapse, its internal pressure being insufficient in this respect. And it is now practically certain that the earth's core is molten metallic iron, not pressure-modified silicates. As a source of meteorites, the idea must be rejected altogether.

7. Cometary Origin

While the asteroidal and lunar sources are inadequate to account for the number and orbital characteristics of meteorites (as well as the bright meteors of the photographic range), their orbits are similar to those of the periodic comets, and to the objects of the Apollo group [which in all appearance are extinct comet nuclei confined to the inner solar system inside Jupiter's orbit

(Refs. 3, 4, 10)] as shown in Table 5 (U = Jacobian velocity, i = inclination, e = eccentricity).

Table 5. Orbital Characteristics of the Small Bodies in Direct Motion and with Aphelia less than 4.201 Astron. Units

Group	Number	U av.	$(\sin i)_{\text{av.}}$	e av.	$(\sin i/e)_{\text{av.}}$	$(\sin i/e)_{\text{equipartition}}$
Bright photographic meteors	891	0.589	0.217	0.540	0.402	0.377
Meteorites and fireballs	13	0.525	0.166	0.592	0.281	0.391
Apollo group	10	0.704	0.213	0.627	0.340	0.357
Mars asteroids	34	0.426	0.279	0.376	0.742	0.408
Asteroids of belt	1622	0.208	0.149	0.144	1.035	0.437

The last column of the table contains the theoretical "equipartition ratio" of inclination to eccentricity, corresponding to random or isotropic distribution of the direction of the U - vector, such as would establish itself after a "full gravitational encounter" or an average angular deflection of 90°. For the asteroids the observed ratio greatly exceeds the equipartition value, indicating too small an eccentricity for given inclination; these objects could not have been significantly influenced by gravitational encounters with Mars. For the meteoritic groups equipartition is more nearly fulfilled; if of cometary origin, this must be due to encounters with Jupiter which originally captured the parent comets into the inner space of the solar system.

The main source of the meteorites must be sought in periodic comets, not only because of the mutual similarity of their orbital elements, but also because in repeated short-period revolutions their contribution to the debris of the inner solar system may considerably exceed that from the non-periodic, nearly parabolic members of the cometary cloud surrounding the solar system. The so-called asteroids of the Apollo group can be identified as nuclei of extinct periodic comets, trapped in the inner solar system for some 100 million years, their dynamical elimination lifetime from collisions with, and close approach perturbations by earth, Venus, Mars, and Mercury; the lifetime of their existence as "live" comets, emitting gases to form the envelopes and tails, is determined by solar radiation, the rate of evaporation, and the dimensions of the nuclei and is in most cases less than 10^4 years. In the absence of erosion, the dynamical lifetime is more than 10^4 times longer, so that the space inside Jupiter's orbit must be filled with the remnants of 10^4 — 10^5 extinct comets, for each live one. Most of the extinct comets must have dinintegrated completely, shedding off dust simultaneously with the vapours, and sending out their meteoritic inclusions when relieved from their icy conglomerate enclosure (Whipple's mixture). Some among the hundreds of thousands of past comets may have been exceptionally large, leaving behind large extinct nuclei in the kilometre size range, which now are identified as the Apollo group "asteroids" — just a name without prejudice to their structure or origin. Table 6 lists all the known objects of this group, defined primarily by the condition that their aphelia are inside Jupiter's orbit while crossing the orbit of the earth. Average or typical elements for the two other related groups of observed objects — the meteorites, and the Super-Schmidt sporadic meteors with aphelia less than 4.10 a.u. (Ref. 16) — are included. Regarding meteorites it must be noted that, because of their ablation and destruction in the atmosphere, objects of low velocity are strongly favoured by selection; to fireballs this selection effect does not apply, however, and the low relative velocities of this group cannot be explained in such a manner alone. The group undoubtedly depicts a real, physically distinct population, akin to the other groups.

Table 6. Members of the Apollo Group

Object	Diameter km	Aphelion astron. un.	Perihelion astron. un.	Inclination deg.	U earth	Lifetime 10^6 years
Comet Encke (and S. Taurid meteors)	1.7	4.10	0.338	12	1.000	265
Geminid meteors	...	2.62	0.140	24	1.160	245
Apollo	1.0	2.34	0.65	6	0.574	64
Adonis	1.3	3.51	0.44	1.5	0.856	68
Hermes	0.4	1.90	0.68	5	0.485	39
Icarus	1.4	1.98	0.19	23	1.004	165
1950 DA	1.3	2.46	0.84	12	0.449	272
Geographos	2.8	1.65	0.83	13	0.382	152
1948 OA	4.8	1.98	0.77	10	0.443	185
1948 EA	6.3	3.63	0.89	18	0.696	1010
Average	...	2.62	0.58	12.5	0.705	115*
			Averages for Related Groups			
Meteorites and fireballs (n=13)	...	3.07	0.79	9.5	0.525	49:
Sporadic meteors (n = 891)	...	2.12	0.63	12.5	0.589	25:

*Harmonic mean of the lifetime.

Only one live comet — Comet Encke — occurs in the list of Table 6. Having been captured by Jupiter from the "parabolic" background population perhaps a few thousand years ago and diverted into a short-period orbit, its aphelion distance must have decreased through a non-gravitational process to its present value of 4.1 a.u. The process can be identified as preferential emission of the evaporation products in a forward direction, possibly conditioned by the direction of rotation of the comet nucleus being opposite to that of orbital revolution. The delayed effect of solar heating (hottest at "2 p.m." instead of noon) then displaces the jet of vapours asymmetrically in a forward direction. Loss of orbital momentum, shortening of the orbital dimensions (chiefly of the aphelion as for artificial satellites) and of the orbital period are a consequence; observations of this comet seem indeed to point to such a secular acceleration. The process of evaporation and loss of the volatiles of the nucleus, running into thousands of years, is short as compared to the dynamical lifetime in Jupiter crossings (10^6 years), so that a comet which has the required direction of rotation and a sufficient store of volatiles to keep the "retro rocket" going will easily escape from Jupiter's immediate sphere of influence and its orbit shrink into the safety of the inner solar system (Refs. 19, 3).

Another "object", the Geminid meteor shower, is undoubtedly a recent product of decay of a former "live" comet (Ref. 19) though no parent comet or a nucleus is known to exist on the orbit of the shower. The meteors have preserved their identity as a "stream", their accumulated angular deflections in close encounters with the planets not exceeding $\pm\ 0^\circ.2$ (Ref. 20); from the tables (Ref. 3), a full angular deflection of $\pm\ 90^\circ$ requires an accumulation period of 9.9×10^9 years, and thus one of 0.2° requires $(90/0.2)^2 = 2 \times 10^5$ times less or 5×10^4 years*.

*The deviation of $\pm 0^\circ.2$ is that of the radiant points on the same night; much of this could be caused by asymmetric drag in the atmosphere. Hence this is an upper limit measure of accumulated planetary perturbations in close encounters. The stream is stretching over 6 days which would imply angular deflections of $\pm\ 3^\circ$; these, however, cannot be identified with planetary perturbations which would have produced similar deviations for one night; the conditions of separation from the nucleus — jet acceleration and even radiation pressure — must in this case be the cause.

An age of less than fifty thousant years can thus be assigned to this stream as the time elapsed since the disintegration of its parent comet. This is 5,000 times shorter than its expected lease of life in planetary encounters (2.45×10^8 years) and implies that the dispersed remains of thousands of similar, more ancient showers may circle the sun before they are swept away by the planets or moved inwards by the Poynting-Robertson effect (important, of course, only for the finest dust particles).

A more powerful agent of removal of small meteors is seen in their sputtering or erosion by the micrometeorite contents of interplanetary space. This amounts to a secular decrease in the diameters or individual masses of the particles. It must be noted that a former estimate of the rate of erosion of stony meteorites (Ref. 10) and based on cratering theory arrived at a somewhat exaggerated value, by assuming the cohesive strength $s = 5 \times 10^7$ dyne/cm^2 equal to that of large stones breaking up from aerodynamic pressure in the atmosphere. These large stones are relatively weak structures, apparently shattered in a primeval explosion or collision. Micrometeorites, however, when impinging on a stone, are producing microscopic craterlets in the crystalline grains of the mineral which have a much greater cohesive strength than the macroscopic structure of the stone. The strength varies as the inverse $\frac{1}{4}$th power of the linear dimension (Ref. 8), and for the minicraters of the order of 0.02 cm produced by micrometeorites it should be 6 times the value of 9×10^8 valid for test blocks of 20 cm; $s = 5 \times 10^9$ or 100 times the formerly assumed value should be used in this case. Erosion varies as the inverse square root of s (Refs. 6,7) and a factor of one-tenth is thus introduced on this account. The former estimate, referring to a velocity of 20 km/sec (Ref. 10, p. 330), should be decreased 10 times but, for the Geminids (w = 35 km/sec) increased by the square of velocity (momentum flux) and a "radial momentum" factor K, 4.4/3.3; this leads to an erosion rate about 2.5 times less than in Ref. 10, or to $3.2 \times 10^{-8} \times 1720/2.5 = 2.2 \times 10^{-5}$ gr/year per cm^2 of the exposed surface. Thus, when the greater strength at microscopic dimensions is taken into account (theoretically derived, experimentally confirmed), at the velocity of the Geminids an interplanetary erosion rate results 80 times greater than the value of 2.7×10^{-7} gram per year as estimated for lunar exposed rocks (Ref. 8). With this, observational data on the Geminids lead to another estimate of their length of unprotected sojourn in interplanetary space. The Geminids, though believed to be denser than the average shower meteors, are still stony "dustballs" in the opinion of this writer, as can be judged from their heights of appearance and disappearance and their spectra (cf. Ref. 20), with a bulk density of the meteoroid about 0.7. At the 5th absolute magnitude and a velocity of 35 km/sec, the mass of a Geminid is about 0.007 gr (Ref. 21), which corresponds to a bulk volume of 0.01 cm^3 and a diameter of the dustball of about 0.27 cm. Their numbers increase more or less monotonously by a factor slightly greater than 2.5 per magnitude (Ref. 20) which would correspond to $p = 3.4$ in Equation (1), but at the 5th magnitude the rate falls off; this can be attributed to erosion having carried off about 13% of the present diameter at the 5th magnitude, a layer of 0.018 cm or 0.013 gr/cm^2 all round. With the above mentioned interplanetary rate of erosion, the age of exposure of these meteors becomes

$$0.013/2.2 \times 10^{-5} = 600 \text{ years only!}$$

This completely overrides the estimate based on perturbations. The Geminids must have been exposed quite recently, possibly they are currently released from a faint undiscovered comet nucleus. The conclusion seems thus to be warranted that the Geminids are the remnants of a recent periodic comet which became extinct not more than a few thousand years ago. They "represent the last survivors of a stream originated by a now evaporated comet, a stream whose older, lighter meteors have been swept away" (Refs. 23, 19).

The Geminids yield hourly rates of about 50, referring in visual observations to an area of about 3000 km^2 in the atmosphere. With 0.02 gr per meteor, this gives a flux of $10 \times 10^{-17} gr/cm^2 . sec$. The diameter of the stream, 1.5×10^7 km, gives a cross section of $2 \times 10^{24} cm^2$ or a flux rate 2×10^7 gram/sec. The period, 1.6 years or 5×10^7 seconds, then leads to a minimum mass of the debris circulating now on the Geminid orbit, $2 \times 10^7 \times 5 \times 10^7 = 10^{15}$ gram, with a lifetime of only about 5000 years (total erosion lifetime). The existence of a nucleus of at least 1 – 2 km in diameter can be suspected.

8. Total Amount of Debris

For each live comet in terrestrial space, of an evaporation lifetime t_e and removal lifetime t_o of the debris, there must have been released debris of

$$N_o = t_o/t_e \tag{9}$$

past extinct comets. For large bodies t_o is the dynamical lifetime, $\sim 10^8$ years, and the ratio is then of the order of $10^4 - 10^5$. Some large residual nuclei of extinct giant comets may still be orbiting as the "asteroidal" members of the Apollo group (Table 6). Surviving from a total of some 10^5 extinct comets, these must be the remnants of truly exceptional objects; many smaller undiscovered similar pseudo-asteroids, down to meteorite size, must be orbiting in our surrounding space.

In general, t_o is the shorter of the three measures of lifetime: the dynamical, the erosion or sputtering, and the Poynting-Robertson or drag lifetime.

For typical meteorites in the 100 cm range, the erosion lifetime is the shortest. At an average heliocentric velocity of 20 km/sec, the erosion rate of meteoritic stone by micrometeorites of the zodiacal cloud is $3.2 \times 10^{-8} \times 1720/10 = 5.5 \times 10^{-6}$ gr/cm^2 year or 1.6×10^{-6} cm/year; a radius of 50 cm will be eroded in $t_o = 3 \times 10^7$ years; this is 3 – 8 times shorter than the dynamical lifetime.

The evaporation lifetime of a comet can be estimated from the evaporation loss (Ref. 11) which can be expressed as a decrease in diameter per orbital revolution,

$$\Delta x = 380 q^{-0.5} \text{ (cm)} \tag{10}$$

where q is the perihelion distance in astronomical units. The lifetime is then

$$t_e = (X_o/\Delta X)\ a^{1.5}\ \text{(years)} \tag{11}$$

where X_o is the original diameter in cm and a the semi-major axis in astronomical units (or $a^{1.5}$ the period of orbital revolution in years).

Comet Encke, at present with $X = 1.7$ km, after original capture by Jupiter, could have been placed into its present orbit inside Jupiter's orbit and at an aphelion of 4.1 a.u. through the retro jet of its vapours by losing 7/8 of its original mass (Ref. 3); hence $X_o = 3.4$ km, $q = 0.338$, and $t_e = 1720$ years (520 apparitions). Although this comet is the only one of its kind, the Geminid shower implies that before its arrival there may have been another similar one, also that there may be fainter objects not yet discovered, so that the injection rate of this type of object into the inner solar system may amount to one for each $t_e = 2000$ years; hence $N_o = 15{,}000$ would represent the probable number of parent comets whose non-eroded meteoritic inclusions ($\sim$ 100 cm diameter) are still present in our surroundings.

In addition, there are 52 listed short period comets of Jupiter's family (32 repeatedly observed and 20 observed only once)(Ref. 24), with aphelia less than 6.0 a.u. (crossing the orbit of Jupiter) whose dynamical lifetime, $t_o \sim 10^6$ years, is the shortest of the two other lifetimes. With $\bar{q} \sim 1.4$ a.u., $X_o \sim 2.0$ km, and an orbital period of about 6 years, $t_e = 6000$ years, $N_o = 10^6/6000 = 170$ per comet or $170 \times 52 = 8800$ comets contributing to the meteorite population. With Encke's and the Geminids, this points to $\sum N_o = 40{,}000$ parent comets whose meteoritic blocks are at present travelling inside or near Jupiter's orbit.

The space density of this meteoritic material, about 10^{-24} in the earth's neighbourhood, or 3×10^{-25} gr/cm^3 as an average inside Jupiter's orbit (with a density distribution of the r^{-1} type), corresponds to a total mass of

$$3 \times 10^{-25} \times (4\pi/3)(8 \times 10^{13})^3 = 6 \times 10^{17}\ \text{gram},$$

1.5×10^{13} gram per parent comet which amounts to 1.5% of the residual mass of the Geminids or to 0.3% of the present mass of Encke's comet. Quantitatively, there does not seem to be any difficulty in supplying the presently observed meteoritic material from decaying comets.

On the contrary, there is a large surplus, most of which goes into evaporation losses and dust, the latter accounting perhaps for 50% of the loss. The injection rate is thus: one type Encke comet, furnishing 2×10^{16} gr dust per 1000 years, and 52 Jupiter family comets, yielding each about 2×10^{15} gr dust per 6000 years. The yield from the two classes is of the same order of magnitude and amounts to a total of 5.7×10^{13} gram per year, thus drifting into the sun by way of the Poynting-Robertson effect at a rate of about 2 tons per second. This may be short by one order of magnitude of the usually estimated rate (Ref. 19) but, then, there are the long-period and parabolic comets and other possible sources of the dust which have not been taken into account. The masses of the comets of Jupiter's family may be underestimated, and increasing their average diameter to 4 km would yield the required amount of material. In any case it is clear that the decay of periodic comets can yield a major fraction, if not all the supply of zodiacal dust, and that as a potential source of meteorites they may represent an adequate source.

One of the stumbling blocks in considering a cometary origin of meteorites was their absence from known showers. Showers such as the Perseids, rich in "ordinary" visual meteors some of which are quite bright, exhibit a notorious absence of fireballs and meteorites. There is, however, a natural explanation of this fact. According to Whipple's realistic model of the comet nucleus (Ref. 25), the solid contents released through evaporation of the ices are blown away by the vapour jet. Gravitation competes with the jet pressure, and there is an upper limit of particle size above which gravitation of the nucleus prevails and the particle cannot be separated. At a density of 3.4 for the particle and 2.0 gr/cm^3 for the nucleus (Ref. 11), the limiting diameter 2a for separation is given by (Ref. 10)

$$2a < 17.3/(r^2 X) \quad (cm) \qquad (12)$$

where r is the heliocentric distance in astronomical units and X the diameter of the nucleus in km. Thus, for the Perseids, $r > 0.96$ a.u., $X = 13$ km, $2a <$ 1.5 cm which just borders on fireball size (absolute magnitude -5, Ref. 21) but is far below meteoritic dimensions (stony meteorites would not survive anyway at the high velocity of the Perseids, almost 60 km/sec). On the other hand, for Encke's comet, $r > 0.34$ a.u., $X = 1.7$km, $2a < 89$cm which corresponds to sizable meteorites; and, indeed, this very comet has apparently contributed to some meteorite falls, according to Astapovitch, Suess, and Whipple (cf. Ref. 10). A shrinking comet nucleus may gradually release its meteoritic chunks, as soon as its acceleration of gravity becomes small enough.

9. Gas Retention Ages

An apparent objection to the cometary origin of meteorites and support for their asteroidal origin could be sought in the clustering of the He - U ages of hypersthene chondrites, a numerously represented class of meteoritic stones, around a value of 500 million years (Refs. 26, 27, 28). Their lead isotopic ages are normal (4.5×10^9 years), while their argon-potassium ages are partly normal, partly short. The favorite interpretation is that some 500 million years ago an asteroidal collision has caused shock heating of the meteoritic debris which led to outgassing of helium, and occasional outgassing of argon. Diffusion theory requires for this perhaps a temperature in excess of 1000° C, and even a time span of 10^6 years would require $+800^\circ$ C (Anders, verbal communication).

There is a physical-logical flaw in this theory of shock heating. It is quite true that hypervelocity shock may cause intense heating and that the shock will also cause fragmentation into an entire spectrum of particle sizes. However, considerable shock heating by asymmetrically applied pressure is inevitably accompanied by complete destruction-pulverization, even melting and vaporization, of the material, while ejected sizable surviving fragments can be heated only negligibly, by the very nature of the elastic properties of a solid. A stone under crushing (one-sided) stress such as required for ejection cannot be compressed by more than 10% of its linear dimension without breaking;

when s is the crushing strength, ρ the density, the work of non-destructive one-sided compression is less than $\frac{1}{2} s$. 0, $1/\rho$ erg/gram or, with a high value of $s = 9 \times 10^8$ dyne/cm^2, $\rho = 3.4$, it amounts to less than 1.3×10^7 erg/gram, equivalent to heating by 1.6 deg C only; even this is chiefly stored as elastic energy and not as heat.

From cratering theory, and in notations of Equations (2) and (3), in the crushed volume of the crater the shock heating leads to a release of friction heat, [for notations, cf. Equation (3)],

$$q = \tfrac{1}{2}\,(s/\rho)(1 - \tfrac{1}{2}\,\lambda^2) \tag{13}$$

erg per gram (Refs. 6, 7). For hard rock (type of quartz), the crushing strength as function of fragment diameter 2a (cm) can be represented as

$$s = 2.5 \times 10^9 (2a)^{-0.25} \tag{14}$$

dyne/cm^2, an interpolation formula supposedly valid down to molecular dimensions (Ref. 8). Setting $\lambda = 0.5$, $\rho = 2.6$, the shock heating for specific heat 8×10^6 erg/gr.deg C, becomes

$$\Delta T = 52\ (2a)^{-0.25} \quad (\text{deg C}), \tag{15}$$

independent of projectile structure and its velocity and determined solely by the size of the resulting fragments as shown in Table 7.

Table 7

Diameter of stony fragments, cm	100	1	0.01	10^{-4}	10^{-5}
Average crushing shock heating, deg C	16	52	165	520	940

Clearly, shock heating to 1000°C of a meter size meteoritic chunk, ejected from a crushed matrix (without all-sided compression), cannot be considered as feasible, and this especially because meteoritic stones are of much lower strength than assumed here (Ref. 29), probably because of some primeval shock which led to their fragmentation. It may be added that the figures of Table 7 represent chiefly friction heating on the surface of the surviving fragments, while internally the heating from inelastic compression is much smaller, of the order of 1 - 2°C as estimated earlier. Hence meteoritic stones, broken up by pressure shock in the atmosphere, are known to have been sometimes covered by a layer of ice when landing in a ditch — they preserved their low temperature of interplanetary space.

These views may seem to be in conflict with the findings of Anders (Ref. 26) and Heymann (Ref. 28) that the short helium retention ages are correlated with clearly marked shock effects. However, there hardly is any unresolvable contradiction. The shock apparently must have predated the heating and escape of helium; a primeval collision, dating back to some 4.5 billion years, may have shattered the rocky matrix, making it not only softer, as observed in meteorites easily breaking up during descent in the atmosphere (Ref. 29), but rendering it more permeable to helium (and partly also to argon), which escaped at the more recent reheating.

Another objection to the general validity of the figures of Table 7 can be seen in the fact that in terrestrial meteor craters traces of heating and phase transitions can be found that require pressures far in excess of the crushing strength of the materials; and yet sizable blocks with these traces have survived. Here we are dealing with the effects of all-sided compression, of a material which could not escape except by plastic flow; it must belong mostly to the bottom and depths of the crater. Much of this material is still found *in situ*, not being ejected; elastic after-effects, following the release of pressure, may have caused cracking and mild "jumping" of some blocks which, however, did not travel very far. On the contrary, the fragments ejected with sizable velocities must have been subjected to one-sided crushing stresses, with free escape in one direction. Most of the debris of cratering comes from this destructive crushing process, and only this seems to be able to send out independent meteorites into space. The figures of Table 7 refer to the bulk of crater ejecta. Hyperpressures (up to 8×10^{11} dyne/cm^2, Ref. 28) leading to heating, could have affected not more than 3% of the cratering mass (in proportion to the inverse square root of pressure), and sizable fragments preserved from destruction by all-sided compression must account for less than one-half of this — a tiny fraction lost among the mass of "ordinary" fragments.

The hypothesis of a planetary collision which happened 500 million years ago, involving asteroids or asteroidal fragments diverted to earth crossings by Mars perturbations, has such formidable quantitative and probability odds against it that it cannot be readily accepted unless all other possibilities fail. Yet this is by no means the case.

Hyperpressure shock may transform olivine (and other minerals) into a finely polycrystalline structure (Refs. 28, 30). Different minerals and different size crystals are formed whose gas retention abilities may be very different. If the hypersthenes are survivors of such an all-sided shock which happened 4.5×10^9 years ago, their short and nearly constant helium retention ages could be explained by assuming that about 12% of the shocked material kept helium firmly while from the rest this gas was leaking out. The variable ages for argon can then be explained by assuming that, in addition to the 12%, a variable proportion of the remaining matrix was able to retain argon while being permeable to helium. The rapid loss of the gases from the permeable fraction of the matrix could have taken place at a later stage, during the 30 ± million years of cosmic-ray exposure with occasional solar heating, after the fragments were released from the cold icy environment of the comet nucleus. The helium retention age of 520 ± 60 million years (Ref. 28) is then no timing landmark at all, but only reflects the distribution of components of different permeability, with respect to gas diffusion, in the shocked matrix. An age of 500 million years for the meteorites themselves, with the estimated rate of space erosion, would imply that the presently observed metre size objects are the residue of a population of 10-20 metre-size bodies. This would require an impossibly high wastage of meteoritic mass and, what is a more crucial criterion, instead of Equation (1), a different population formula,

$$dN = C(x + a)^{-p}dx \simeq C_1 x^{-q}dx, \tag{16}$$

where a is the ablation, or x + a the original radius. When a $\gg$ x as for an age of 500 million years and p $\sim$ 3.7 as for an original population of meteorites, the apparent population exponent, q becomes small, approaching zero,

$$q \to p/(1 + \frac{a}{x}) .$$

Thus, for x = 50 cm, a = 450 cm as for erosion over several hundred million years, q = 0.1 p = 0.27, or the frequency of radii should run very flat and terminate at a lower limit of complete erosion (x = 0). This is so much contrary to what we know of the frequency of meteorite sizes that the suggestion must be rejected as extremely improbable (for distribution of the weight of recovered hypersthene fragments, cf. Heymann, Table I in Ref. 28; these show indeed an effect in the expected direction — a flat distribution of sizes; but this is the result of atmospheric ablation and, when the latter is allowed for, the effect disappears).

Although, on our model, about 88% of the helium produced radioactively inside the minerals of these hypersthenes is likely to diffuse away, some heating is necessarily required for the process. For this, the fragments, in their orbital revolution, must have come sufficiently near the sun, during their cosmis-ray and erosion-limited exposure lifetimes of 0.03-60 million years (Ref. 28), being heated and reheated in repeated perihelion passages.

The sungrazing family of comets (Ref. 31) shows that such cometary objects with small perihelion distances may be quite common. Seven members of this family have been observed between 1843 and 1965, their nuclei ranging in size from 8 to 58 km. The dispersion in their orbital elements points to a tidal breakup in perihelion about 130,000 years ago of a nucleus 110-120 km in diameter, of a mass of the order of 5×10^4 Encke's comets. At a perhelion distance of

0.006 a.u. and a period of revolution around 1000 years, the evaporation ages amount to 1–2 $\times$ 10^5 years, indicating a considerable decrease in size of the nuclei since the original breakup. Also, during perihelion passage, the black body equilibrium temperature of a solid could reach several thousand degrees. If a similar or larger nucleus ($\sim$ 500 km)(or nuclei) was (were) directed by stellar perturbations and by Jupiter many million years ago into a near sungrazing orbit, the meteorites shed by it during some 10^5–10^6 years of its existence as a live comet could have been thoroughly heated in repeated perihelion passages and thus lost the less firmly held 88% of the helium, retaining the 12% fraction. The hypersthenes most probably are remnants of such a comet or comets. Subsequently the orbits of the meteorites must have been completely changed by planetary perturbations and dispersed all over the solar system.

10. The Dual Origin of Meteorites

In the preceding, a strong case has been made for an immediate cometary origin of the meteorites. Erosion precludes the survival of meter size stony meteorites for longer than about 3 $\times$ 10^7 years, and, while the cosmic ray exposure ages are of the same order or shorter, their upper limit is accounted for by erosion. Hence the meteorites must have been released from a protective envelope quite recently. This envelope we propose now to identify as a comet nucleus, disintegrating along with the evaporation of its ices. Some very short exposure ages determined by Anders (Ref. 32) of the order of 10^5 years, and even 30,000 years (black hypersthene chondrite Farmington, Ref. 28), are easily understandable from this standpoint, while the asteroidal collision theory, in addition to all the orbital and other difficulties enumerated above, would also require a miraculously high collision rate to account for such objects. This is especially clearly brought out by the distribution of the radiation (cosmis-ray exposure) ages of the hypersthenes as shown in Table 8 (from Fig. 13 in Ref. 28).

Table 8. Radiation Ages of Hypersthene Chondrites

Age, 10^6 years	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	All
					Number						
Normal Chondrites	17	13	20	10	18	8	8	6	1	1	102
Black Chondrites	3	5	2	1	4	1	1	1	1	1	20
All Hypersthenes	20	18	22	11	22	9	9	7	2	2	122

The black hypersthenes are those appearing to be severly shocked (Anders, Ref. 26), but the distribution of their radiation ages does not seem to be different from the rest, implying a "washed-out" but apparently uniform distribution of the "collision events" during the past 25 million years. While collisions at such a rate appear to be unacceptable, a release from just as many disintegrating comet nuclei is the most natural explanation.

On the other hand, all the structural properties of meteorites point to their origin inside asteroidal or sub-lunar size bodies whence they must have been released through catastrophic collisions (cf. Ref. 18, et alias). However, these events must be relegated to the dawn of the solar system when the giant planets were formed. At this time little planets were coming into existence out of the pre-planetary nebula, to be broken up again in mutual collisions. Some of the fragments were again imbedded in the ices of comet nuclei (which were probably the most common kind of the "planetesimals"). These were mostly absorbed by the planets, but some were ejected to Oort's sphere of the comets. This sphere, by way of stellar perturbations, continually supplies the inner solar system with newcomers — fresh comets. The mechanism of planetary accretion during the early stages of the solar system, accompanied by an acceleration and ejection of some of the residual debris to the extreme boundaries of the solar system, has been analysed elsewhere (Ref. 4); it works so smoothly, chiefly on account of a gradual acceleration in distant encounters with the planet, that few objects are overshot into interstellar space, while most settle in Oort's sphere, at 10^4–10^5 astronomical units, being "stabilized" there by perturbations from passing stars. Also, the ejection begins only when the planet (Jupiter) has been almost completely formed, otherwise the material in the "nebular" ring (partly solid debris, partly gas) is so dense as to damp the acceleration and to force all the objects into near-circular orbits.

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