COMETARY SUPPLY OF TERRESTRIAL ORGANICS: LESSONS FROM THE K/T AND THE PRESENT EPOCH

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Abstract. The time-scales of import with respect to the physical survival of planet-crossing bodies (asteroids, comets, meteoroids, dust) in the inner solar system are considered, and characteristic times for different masses reviewed. These physical lifetimes range from 10^3–10^5 yr for dust (masses 10^{-12}–10^{-6} g), and 10^5–10^6 yr for small meteoroids (masses 10^{-6}–1 g), to 10^7–10^8 yr for larger bodies; bodies with aphelion distance $\gtrsim 4$ AU may have dynamical lifetimes lower than these figures due to ejection from the solar system by Jupiter. Values of terrestrial impact velocities and probabilities are given for characteristic orbits of long- and short-period comets, Earth-crossing asteroids, and near-Earth dust. Zodiacal dust particles, which are predominantly in near-circular, low-inclination orbits, have sufficiently low arrival velocities (< 20 km sec^{-1}) at the Earth to make organic survival plausible. Alternatively larger objects with short periods, perihelia near 1 AU, and $i \lesssim 20°$, will also impact at < 20 km sec^{-1}, but their impact probabilities are smaller. This argues for organic delivery predominantly from dust rather than directly through meteoroids, asteroids or comets. Such dust may have delivered the amino acids deposited over at most $\sim 10^5$ yr at the K/T boundary: this is also the appropriate time-scale for the hierarchical disintegration of a giant comet and its daughter products, and the accumulation by the Earth of the dust produced, but is too short for deposition by discrete large bodies produced in the disintegration of a large comet. This supports the conjecture that some organics arrived in the first $\sim 10^9$ yr of the planet's history as constituents of cometary dust gently decelerated in the atmosphere, allowing survival to the surface.

1. Introduction

With respect to the origin and evolution of life the influx of cometary material to the Earth may be of central importance. Oró (1961) suggested that organics on the Earth may have been supplied at least in part by comets, this conjecture having been strengthened in recent years by the discovery of plentiful quantities of organic matter in P/Halley (Kissel and Krueger, 1987). Recent work has also shown that some, if not all, of the terrestrial inventory of water could have been supplied 4.5 to 3.5 × 10^9 yr ago from comets (Chyba, 1987, 1990). Other volatile species, such as organics, may have arrived through this same route, although Anders (1989) points out the problem of the survival of organic matter in the high temperatures generated by large impacts, and argues for the source being cometary dust smaller than the micrometeor limit (the size at which the surface-area-to-mass ratio is high enough to enable efficient radiative cooling so that ablation does not occur: Bronshten, 1983). Anders (1989) was concerned with prebiotic matter; more recently Zahnle and Grinspoon (1990) have discussed the possibility that the amino acids detected at the K/T boundary by Zhao and Bada (1989) originated in cometary dust swept up by the Earth over at most $\sim 10^5$ yr. Therefore the record of the K/T boundary may indicate how organics accumulated in the first 10^9 yr of the

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Earth's history, if the interpretation of the distribution of amino acids as an extended depositional episode is correct: another interpretation is that the spreading occurred after a brief phase of organic injection to the Earth, with diffusion, biological action or other agents being responsible for the dispersion. Either way this time-scale sets an upper limit for the supply of amino acids to the Earth in that episode, so that the vehicles responsible for the deposition must have a characteristic decay time in space of at most 10^5 yr. The possibility of a single stochastic impact at that time, which could fit the amino acid data (one injection with later dispersion), has been counteracted by some recent work by Shoemaker and Izett (1992); a coherent set of impacts occurred, likely due to the break-up of a giant comet, as modelled by Clube and Napier (1984).

A pertinent question, then, is whether the organic material arrived on the Earth discretely as components of cometary or asteroidal bodies, or as a gradual influx of fragments, meteoroids and dust produced by the decay of such bodies in space. For a comet above a few hundred metres in size the major fraction survives atmospheric entry to reach the ground intact, and is then atomized in the impact (Emiliani *et al.*, 1981; Melosh, 1989). The absence of extraterrestrial Xenon in the K/T boundary layer indicates that the impactor(s) in that case did not survive the impact intact (Anders, 1989), and the modelling of Chyba *et al.* (1990) indicates that organics could not avoid incineration in impacts by bodies larger than ~ 100 m. For fragments (sizes ~ 10–100 m) it would be expected that an atmospheric detonation similar to the Tunguska explosion would occur (Turco *et al.*, 1982), but nevertheless the Earth could accumulate some of the original molecules intact (Chyba and Sagan, 1990). Chyba *et al.* (1990) suggest that such objects could have supplied organic matter to the surface with an early ~ 10 bar CO_2 atmosphere causing deceleration.

Stepping down in size, for objects of meteor-forming dimensions (sizes > 100 μm) ablation in the atmosphere occurs (e.g. Hughes, 1978; Bronshten, 1983) with most of the constituent molecules being dissociated, although some meteoroids produce refractory particles larger than 100 μm which survive intact without excessive heating, temperatures of ~ 900 K being reached for ~ 10 sec (Flynn, 1989, 1990; Sandford and Bradley, 1989); the arrival of organics shielded within these is therefore a possibility. For example, the Revelstoke carbonaceous chondrite which exploded in the atmosphere in 1965 rendered fragments around a millimetre in size which had unheated interiors within which organics survived (Folinsbee *et al.*, 1967; Cronin *et al.*, 1988). The smaller dust particles (sizes < 100 μm), which constitute the zodiacal dust cloud, are below the micrometeor limit and may deliver intact their complement of materials. It is these in 10^{-12}–10^{-6} g particles that Anders (1989) suggests the majority of the prebiotic organic matter was delivered. [Note that Anders used the term 'meteors' to describe all bodies of mass 10^{-14}–10^{2} g, and strictly-speaking this is a misnomer: the term correctly refers to the phenomena occurring in the atmosphere due to the entry of a meteoroid from space (luminous emission, formation of a trail of ionization). This would be a trivial imprecision if it not for the fact that Anders was making a case for particles in the mass range 10^{-12}–10^{-6} g – *i.e.* below those producing meteoric phenomena, and thus remaining intact – being the vehicles by which organics are injected into the terrestrial environment. Herein these 10^{-12}–10^{-6} g particles are referred to as 'dust'].

To summarize, the following plausible sources for extraterrestrial organic matter accumulated by the Earth in the first ~ 10^9 yr of its history have been suggested: (1) Comet-produced dust smaller than 10^{-6} g (Anders, 1989); (2) Meteorites of mass 10^1–10^8 g if a sizeable fraction of the mass of 10^8–10^{12} g (~ 10–200 m) small comets separated from the main body and gently decelerated in the atmosphere (Thomas *et al.*, 1989; Chyba *et al.*, 1990) although Anders (1989) finds that the input mass fraction of organics would be small; (3) Direct input from small comets of mass 10^8–10^{12} g (Chyba *et al.*, 1990).

How can one differentiate between these quite different mass regimes in terms of their likelihood of having been the actual source of organics? Obviously compositional studies allow one line of attack (Schramm *et al.*, 1989). The present paper is intended to provide some background on the astronomical and astrophysical evidence available from observations in the present epoch which bear upon this topic: For the decay of a meteoroidal/dust complex formed by the disintegration of a comet, what are the appropriate time-scales? What are the lifetimes of the meteoroids and dust? How do these compare with their collisional lifetime with the Earth? Are there any complexes seen in the present epoch which can give indicators of what happens as a comet breaks-up? What are the appropriate impact velocities for different characteristic orbits?

2. The question of time-scale

A. ENCOUNTERS WITH PLANETS

Since the frequency and effects (upon the particle) of encounters with planets are independent of the size of the particle in question (except that passage through the Roche lobe of a planet may disrupt a larger object such as a cometary nucleus) these are discussed first. It is assumed here that the particles of interest are in heliocentric orbits with periods $P \lesssim 20$ yr. Within such a group there are still two distinct divisions, in terms of time-scales: those which avoid close approaches to Jupiter, having aphelia $Q \lesssim 4$ AU, and those which can encounter that massive planet.

Aphelia $Q \lesssim 4$ AU

These particles can approach the terrestrial planets only. The precession of their angular elements (argument of perihelion ω and longitude of the ascending node Ω) still depends largely upon the Jovian perturbations, and these cause the inclination to vary in a cyclic manner, but the perturbations due to the terrestrial planets are also significant. For an example, see the results of Steel *et al.* (1991). Close approaches to the terrestrial planets, due to the high velocities and the low masses involved, do not cause very large changes to their orbital energies and these particles are not directly ejected from the solar system in such encounters although some may have their aphelion distance increased so as to allow approaches to Jupiter. Losses from the interplanetary system occur largely through planetary impacts, with a typical time-scale derived from the inverse of the collision probability for a typical orbit like a near-Earth asteroid (NEA), short-period comet (SPC) or meteoroid stream (MS) member being ~ 10^{8-9} yr (Öpik, 1951, 1976; Olsson-Steel, 1986; see also section 4 of this paper). However, this time-scale is that derived from the osculating orbits of observed celestial objects; in fact as the orbit evolves the collision probability increases by about an order of magnitude when an object has perihelion near the Earth's (or other planet's) orbit, as shown in section 4, reducing the typical collisional lifetime. Because of this the majority of observed meteorite falls result from meteoroids of perihelion distance $q > 0.9$ AU (Benoit *et al.*, 1991). In addition a theoretical time-scale of this order (10^{7-8} yr) is corroborated by the exposure ages of meteorites (Anders, 1962; Melcher, 1981; Perlmutter and Muller, 1988). The fact that interplanetary particles are more likely to hit the Earth when they have perihelion near 1 AU is also demonstrated by the q-distributions of radar-detected meteoroids (10^{-6}–10^{-2} g), which show peaks near this value despite the arrival velocity then being minimized, so that the radar detection probability is lowered (Olsson-Steel, 1988; Baggaley *et al.*, 1992).

For low-inclination, low-eccentricity orbits, such as occupied by zodiacal dust particles, this collision lifetime may be ~ 10^6 yr or even less: as an example one could choose an orbit with semi-major axis $a = 1$ AU, eccentricity $e = 0.05$ and inclination $i = 5°$; this orbit has a lifetime against collision with the Earth of about 5×10^6 yr (and would meet the atmosphere just above the escape velocity of 11.2 km sec^{-1}). Other examples are given in section 4.

Jupiter-Approaching Orbits

The fate of particles with $Q > 4$ AU is dominated by Jupiter unless it is small enough such that the Poynting-Robertson effect (Burns *et al.*, 1979) can cause orbital shrinkage fast enough to take it beyond the giant planet's grasp on a time-scale shorter than its lifetime against loss due to an approach to that planet: see Section 2 D below. Typical lifetimes are ~ 10^7 yr against collisions with Jupiter and ~ 10^6 yr against direct ejection from the solar system in a single close encounter (Olsson-Steel, 1986), but only ~ 10^{4-5} yr for ejection as a result of multiple encounters leading to a gradual increase in orbital energy. The latter is the time-scale found by Clube and Napier (1984) for the disintegration and dispersal of large comets entering the inner solar system after Oort Cloud disturbances, with pulses of such cometary arrivals lasting a few × 10^6 yr; this time-scale is supported by clustering in the cosmic ray ages of meteorites (Perlmutter and Muller, 1988).

The figures quoted here are based upon probabilistic calculations using osculating orbits. Numerical integrations of actual orbits have been carried out by several authors for SPC's, and the dynamical variations on relatively short time-scales investigated (e.g. Carusi *et al.*, 1985; Belyaev *et al.*, 1986). In addition the physical decay of comets has been investigated by many (e.g. Kresák, 1981a, 1991; Fernández, 1985) and it has been shown that dust-mantling probably occurs between successive attainments of smaller perihelion distances, with active lifetimes of order half of the dynamical lifetimes (Rickman *et al.*, 1991). An unresolved question is whether inactive comets, appearing as asteroidal objects, retain a substantial fraction of volatiles (Hartmann *et al.*, 1987; Weissman *et al.*, 1989; Kresák, 1991).

B. BREAK-UP OF LARGER BODIES/COMETS

It is well-known that comets often break asunder so as to produce two or more large fragments (Bailey *et al.*, 1990; Yeomans, 1991a). Such physical disintegration may occur due to passage through the Roche lobe of a planet, or in interplanetary space due to thermal stresses or possibly meteoroid impacts (Fernández, 1990; Babadzhanov *et al.*, 1991). Whilst many cometary splits result in only minor fragments being lost from a major residual, this is not always the case as evidenced by the Kreutz group of sungrazing comets (Marsden, 1989a) and several other well documented splits (Kresák, 1981b; Sekanina, 1982). The most recent example at the time of writing is the break-up of comet Chernykh (1991o; *see IAU Circulars* 5347 and 5391). There is also evidence that the Australasian strewn tektite field formed $\sim 7 \times 10^5$ yr ago was due to multiple impacts by a body which had fragmented immediately prior to impact (Wasson, 1991).

'Normal-type' decay of comets, with meteoroids being ejected so as to form a stream following in the cometary orbit, is of course well-known (Williams, 1990). The time-scale for the formation of such streams depends upon the size of the orbit and in particular upon the perihelion distance (since the spreading of the particles depends upon their ejection velocities and the solar flux, affecting the radiation pressure, Poynting-Robertson and Yarkovsky-Radzievskii effects: Olsson-Steel, 1987a). Typical time-scales are of order $\sim 10^2$–10^3 yr, with meteoroid ejections continuing for at least several thousand years in, for example, the case of P/Halley.

The largest body which may be lost from the nucleus of a comet under this normal-type decay (as opposed to catastrophic splitting) is limited by the gas outflow from the nucleus (Hughes, 1986). For very large comets (above tens of km), which hold most of the cometary mass in the solar system, it is difficult to explain the release of bodies of mass above $\sim 10^6$ g unless some other form of ejection is occurring (a possibility might be the rocket-effect as light volatiles evaporate from the newly-exposed large fragment), and smaller comets are more likely to produce such fragments in normal-type decay, but with a limited mass-supply. It therefore appears that the cataclysmic disruption of large cometary nuclei is the major source of 10^6–10^{12} g bodies.

C. PHYSICAL LIFETIMES OF COMETS

This is a subject which has been the subject of much debate, with a wide range of values being derived; the result is in any case dependent upon various factors such as the orbital parameters of the comets. Median values for typical SPCs appear to be in the range 10^3–10^5 yr (Kresák, 1991; Meech, 1991; Rickman, 1992) although SPCs may undergo periods during which they form an insulating crust and appear similar to NEAs; in fact a large fraction of NEAs may well be SPCs in such a dormant (e.g. Hartmann *et al.*, 1987; Weissman *et al.*, 1989) or semi-dormant (Russell *et al.*, 1984; Yeomans, 1991b) stage, with an NEA resulting also from total devolatilization (Wetherill, 1988).

D. LIFETIMES OF FRAGMENTS, METEOROIDS AND DUST

There are a number of competing processes which limit the physical lifetimes of such objects. Discussion of these processes and plots of their size-dependence have been given by Dohnanyi (1978) and Olsson-Steel (1986). A simple summary only will be given here.

In general 1 mm ($\sim 10^{-3}$ g) meteoroids have lifetimes limited by collisions with zodiacal dust particles (Whipple, 1967; Grün *et al.*, 1985), although those with small perihelion distances ($q \lesssim 0.1$ AU) may be limited by rapid orbital collapse caused by the Poynting-Robertson effect. For 100 μm ($\sim 10^{-6}$ g) and smaller meteoroids the P-R lifetime (τ_{pr}) is short and inspiralling towards the Sun occurs quickly, so that particles of small q are rapidly removed from Earth-crossing orbits. For 1 cm (~ 1 g) meteoroids the collisional lifetimes with zodiacal dust (τ_z) are shorter than the P-R lifetimes (τ_{pr}), although for some orbits the planetary collision probability is high enough to pose a comparable risk. Larger meteoroids still (masses $> 10^3$ g) have lifetimes limited by planetary collisions (time-scaled denoted τ_c), assuming that they do not approach Jupiter (i.e. they have aphelion distances $Q \lesssim 4$ AU).

Consideration of the Poynting-Robertson effect (Burns *et al.*, 1979; Olsson-Steel, 1987a; Gustafson *et al.*, 1987; Rusk *et al.*, 1988) shows that the orbits of particles smaller than ~ 100 μm undergo rapid orbital shrinkage, with the perihelion distance remaining sensibly constant, so that near-circular orbits are appropriate for such dust particles. Such shrinkage is counteracted immediately after release from a parent body by radiation pressure, but that has a one-off effect: the dust is released with a heliocentric velocity given by

$$v^2 = GM_\odot[(2/r) - (1/a)]$$

where r is the solar distance and a the semi-major axis of the particle orbit. The effect of the solar radiation pressure, which varies as $1/r^2$ as does the gravitational attraction, is effectively to reduce this attractive force by a small amount such that G must be replaced by a constant term $G(1 - \beta)$ where β is of order 10^{-4} and depends upon the particle size (Burns *et al.*, 1979). Since v is conserved at release, in the above equation a must increase so as to compensate, which may result in a hyperbolic heliocentric orbit if the parent were on a near-parabolic orbit and the dust particle were small enough (e.g. see the analysis of Fulle, 1988, 1989, 1990). This means that the initial dust orbit is larger than that of the parent, but soon shrinks under the P-R effect, which reduces v over an extended period. This is borne out by observations of the zodiacal dust (mostly of the zodiacal light is due to 10–100 μm particles) which indicate that the orbits are of low eccentricity, prograde, and are mostly close to the ecliptic (Giese *et al.*, 1986).

It is also possible that meteoroids above $\sim 10^3$ g with cometary, non-meteoritical, structures may be physically destroyed on shorter time-scales; in such disintegrations smaller meteoroids and dust are produced. For example the stability of small comets near 1 AU, if they are composed largely of water and other volatiles, as are large comets, would be limited by the vapor pressure of their constituents unless a strong insulating crust exists (McKay, 1986; Dessler, 1991). Further, Oberst and Nakamura (1991) find that the majority (85%) of meteoroids of mass $> 10^3$ g have orbits unlike those of meteorites, and suggest that they are more fragile than meteorite parents, making them unable to survive atmospheric entry; they conjecture that such meteoroids may be derived from SPCs and the more fragile NEAs.

The limiting lifetimes of meteoroids are therefore of the following order, these being upper limits for the largest masses if physical decay is more significant than planetary collisions:

Mass (g)	Lifetime (yr)
10^{-12}	$\tau_{pr} \sim 10^3$
10^{-9}	$\tau_{pr} \sim 10^4$
10^{-6}	$\tau_{pr} \sim 10^5$
10^{-3}	$\tau_z \sim 10^5$
1	$\tau_z \sim 10^6$
$> 10^3$	$\tau_c \sim 10^7$–10^8

These comparatively-brief theoretical physical lifetimes for the smaller particles (i.e. interplanetary dust) are supported by the space exposure ages determined from cosmic ray track densities (Bradley *et al.*, 1984; Brownlee, 1987).

3. Coherent Swarms of Meteoroids/Cometesimals

The existence of the zodiacal dust cloud in the present epoch, and therefore assumedly in the early history of the solar system, as a possible source of organics as described by Anders (1989) is obvious from many years of zodiacal light, comet tail, terrestrial collection and satellite impact experiments (Levasseur-Regourd and Hasegawa, 1991). However, the evidence for the existence of substantial numbers of 10–100 m objects on Earth-crossing orbits is not so well established, and will be summarized here. It is also possible that the present population of interplanetary dust is unusually high, being related to the recent ($\sim 2 \times 10^4$ yr ago) arrival of an exceptional comet in the inner solar system (LaViolette, 1983; Clube, 1987; Steel *et al.*, 1991); Whipple (1967) first suggested that P/Encke is the major source of the dust now extant, although some of the problems associated with the supply of the dust (Grün *et* *al.*, 1985) have since been resolved by the work of Fulle (1988, 1989, 1990).

The size region from the larger fireballs (~ 1 m) to the smaller Earth-crossing asteroids (~ 100 m) has been almost entirely unsampled until the Spacewatch telescope at Kitt Peak began routine operations in the past few years (Gehrels, 1991). A downward extrapolation from the fireball data in the size-frequency plot was well-known not to meet the asteroid data, leading to great uncertainty in the flux of 10–100 m objects near the Earth. The limited amount of data now available from Spacewatch indicates that in fact the population of such objects is one to two orders of magnitude higher than previously believed (Rabinowitz, 1991, 1992; Ceplecha, 1992). This indicates that cometary break-up to produce such objects may be a more common event than currently accepted (Clube and Napier, 1984), and it is pertinent to examine the evidence for complexes of objects produced in this way and observable in the present epoch: these may give important clues to the events which occurred in the early history of the planet.

One such complex, the existence of which is still controversial, is known as the Taurid Complex (TC). This is believed, at least by this author, to consist of comet P/Encke, possibly long-period comet 1967 II Rudnicki, at least seven Apollo asteroids, four well-known meteor showers (corresponding to the four intersections of the complex with the Earth's orbit: ascending and descending at both incoming and outgoing legs of the TC orbit), the Tunguska object, and several other phenomena (see Steel *et al.*, 1991, and the various papers cited therein, and Steel, 1992). Dynamical studies of the TC have shown that the time required to explain the current dispersion of the complex, in particular the spread in the orbits of observed TC meteors, is of the order of 2×10^4 yr (Steel *et al.*, 1991), with the spread in elements between plausible asteroidal members of the TC being similar (Asher, 1991). This time-scale is of the same order as the space-exposure lifetime of the Farmington meteorite, which provides an independent assessment of the time over which the TC has been spreading after the progenitor began to break up. We (Steel *et al.*, 1991) have accepted Farmington as being a likely member of the TC on the basis of its time of fall and radiant, this having been originally suggested by Oberst (1989); its exposure time and isotopic abundances appear to be anomalous which sets it apart for special consideration. Protestation that its mineralogical type (it is a L5 Chondrite) precludes its having been part of a comet pre-judges, we feel, any real understanding of the nature of cometary nuclei, and it would be negligent of us not to point out the possible association of Farmington with the TC. The origin of this meteorite has been a long-term problem (Anders, 1962), and it is interesting to note that Wood (1982) argues on the basis of fall statistics that ordinary chondrites may originate in comets; if this is the case then it may argue against comets in general being plentiful sources of organics and volatiles.

There is also evidence for the TC containing many large (~ 10^6 g) objects; for example lunar impacts seismologically-detected in 1975 (Oberst and Nakamura, 1987). Such evidence has been discussed by Clube and Asher (1990), who also point out that the IRAS-detected coherent trails associated with several SPCs (including P/Encke), and thought to be comprised largely of millimetre-sized particles (Sykes, 1988), may contain many boulder-sized bodies. Passage through such a trail, as must occur from time to time, would result in many coherent impacts upon the Earth.

The TC is therefore of interest from the point of view of the provision of macroscopic objects which would undergo airbursts, and therefore perhaps supply organic matter intact to the Earth; it is also of interest with respect to the supply of the zodiacal dust cloud (Whipple, 1967), and thus organic matter delivered to the Earth through that avenue.

Is the TC unique, or are there other similar complexes in the inner solar system? From time to time other groupings have been suggested (e.g. Drummond, 1991) although these are difficult to prove beyond reasonable doubt: the statistics are still very poor, with only ~ 1% of NEAs larger than 0.5 km yet having been discovered. One other possibility is indicated by 1566 Icarus and its recently-discovered 'twin', 1991 RC, which have virtually-identical values of (a, e, i); however, integrations of the two in fact show a divergence of the elements over the past 10^5 yr, so that a common origin is not proven at this stage (Steel *et al.*, 1992). Another example is P/Thatcher, the apparent parent of the April Lyrid meteor shower. Recent radar observations have shown a sudden increase in the activity of the shower, such as might be expected if the parent were returning to perihelion, but P/Thatcher is still far away in its orbit. This may indicate that there is another very large object, likely asteroidal in appearance and therefore undetected optically, in this orbit, with the two (and possibly other siblings) having been produced from a larger progenitor (Štohl, 1991).

Turning attention to meteorite-producing bodies, there is growing evidence contradicting the idea that these all arrive from random orbits (as would be expected for individual objects being ejected from the asteroid belt by chaotic dynamics: Wisdom, 1985), with evidence for meteorite streams accumulating (Oberst and Nakamura, 1987; Dodd, 1989; Halliday *et al.*, 1990). Such streams are not though to be dynamically stable for time-scales longer than a few times 10^5 yr (Wetherill, 1986), although streams such as the TC are certainly still recognizable, with considerable dispersion, a few times 10^4 yr after their formation (Steel *et al.*, 1991).

4. Impact Probabilities and Velocities Upon the Earth

In investigating the avenues by which organics might be delivered to the Earth's surface it is necessary to know both the likelihood of terrestrial impacts for characteristic orbits, and also the velocity at the top of the atmosphere in each case. For example, Chyba *et al.* (1990) find that organics are unlikely to survive cometary impacts upon the surface at velocities much above 10 km sec^{-1}, whereas the minimum velocity at the top of the atmosphere is 11.2 km sec^{-1}. What sort of orbits render low velocities and high impact probabilities?

Chyba (1990, 1991) has presented data pertaining to the impact probabilities and velocities for the currently-observed population of SPCs and NEAs. Whilst this is a reasonable starting point for any consideration of likely probability distributions of impact velocities, there are several drawbacks. Firstly, the orbital elements used are just those in the present epoch, whereas the collision probability (P_c) of a particular body with a planet will vary substantially as it orbit evolves. P_c will increase as the inclination falls, varying as ($1/\sin i$), and also gets much larger if the body has perihelion or aphelion close to the planet's orbit (see Olsson-Steel, 1987b, and the results below). Thus over the full orbital evolution of a comet its likelihood of impacting a particular planet may be dominated by the short epochs in which it has a low inclination and/or perihelion/aphelion near that planet. Secondly, in such epochs the impact velocity is lower (for a prograde orbit): when the inclination is low the angle between the orbital planes of the object and the Earth is reduced so that the relative velocity is decreased, and when an object has a perihelion distance near 1 AU it tends to be catching the Earth up from behind (rather than crossing the terrestrial orbit at a large angle) so that again the relative velocity is reduced. The effects of such considerations are clearly seen in the Figures presented below. It is anticipated that an analysis of SPC orbits and collision probabilities/velocities over an extended integration period would render a collision frequency/velocity distribution which peaks below 20 km $\sec^{-1}$, and thus bolster the argument of Chyba (1990) for the oceans being supplied from cometary impacts, contrary to the idea that the impact velocities are generally too high, with vapour plumes causing impact erosion of the hydrosphere (McKinnon, 1989).

Some mention of the technique used herein to determine the collision probabilities is necessary. This is based upon the technique of Kessler (1981), having a number of advantages over the Öpik (1951, 1976) scheme. The Öpik method, used for example by Zimbelman (1984) and Shoemaker *et al.* (1990) requires that the planet be on a circular orbit, but this is not a great problem with regard to calculations for the Earth since the terrestrial orbit is of low eccentricity; this would not be the case were a consideration of impact rates for Mercury or Mars required. However, a disadvantage of the Öpik method which negates its application here is that assumption is made that the orbit of the small body is a 'deep-crosser' of the planetary orbit, and this is not the case for the orbits with perihelia near 1 AU which are argued here to be of central importance with regard to the terrestrial delivery of volatiles.

Impact probabilities and velocities upon the terrestrial planets have previously been given for NEAs by Olsson-Steel (1990) and for both SPCs and Long-Period Comets (LPCs) by Olsson-Steel (1987b); similar tabulations have also been given by Weissman (1982), and Chyba (1990, 1991) has used these three papers as his data source. The expected crater-production rate from impacts and the rate obtained from the geologic record have been compared by Shoemaker *et al.* (1990). Here P_c has been calculated assuming, for simplicity, that the terrestrial orbit is circular since then, with the Earth's inclination being zero, only one impact velocity is

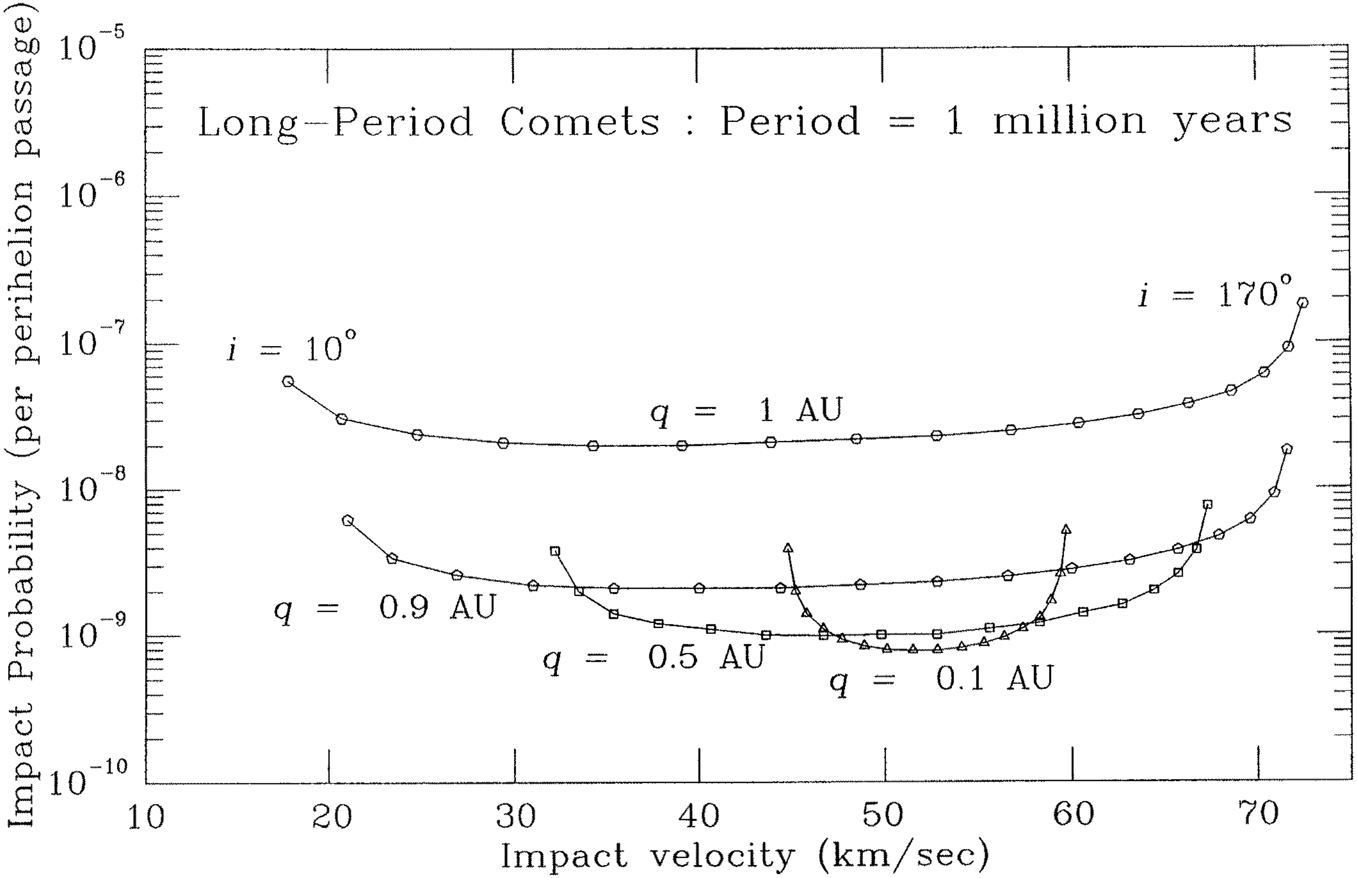

Fig. 1. Terrestrial impact probability versus impact velocity for long-period comets (all with period 1 million yr) having various perihelion distances (q) and orbital inclinations (i). The impact probability per year is the plotted value divided by the orbital period. The four curves show (from bottom) the results for $q = 0.1$, 0.5, 0.9 and 1.0 AU, for inclinations from 10° to 170° in 10° jumps. Note that the $q = 1.0$ AU orbits have collision probabilities about an order of magnitude higher than those with smaller values of q, with impact velocities $V_i < 20$ km sec^{-1} occurring only for those orbits with ($q = 1.0$ AU, $i < 20°$).

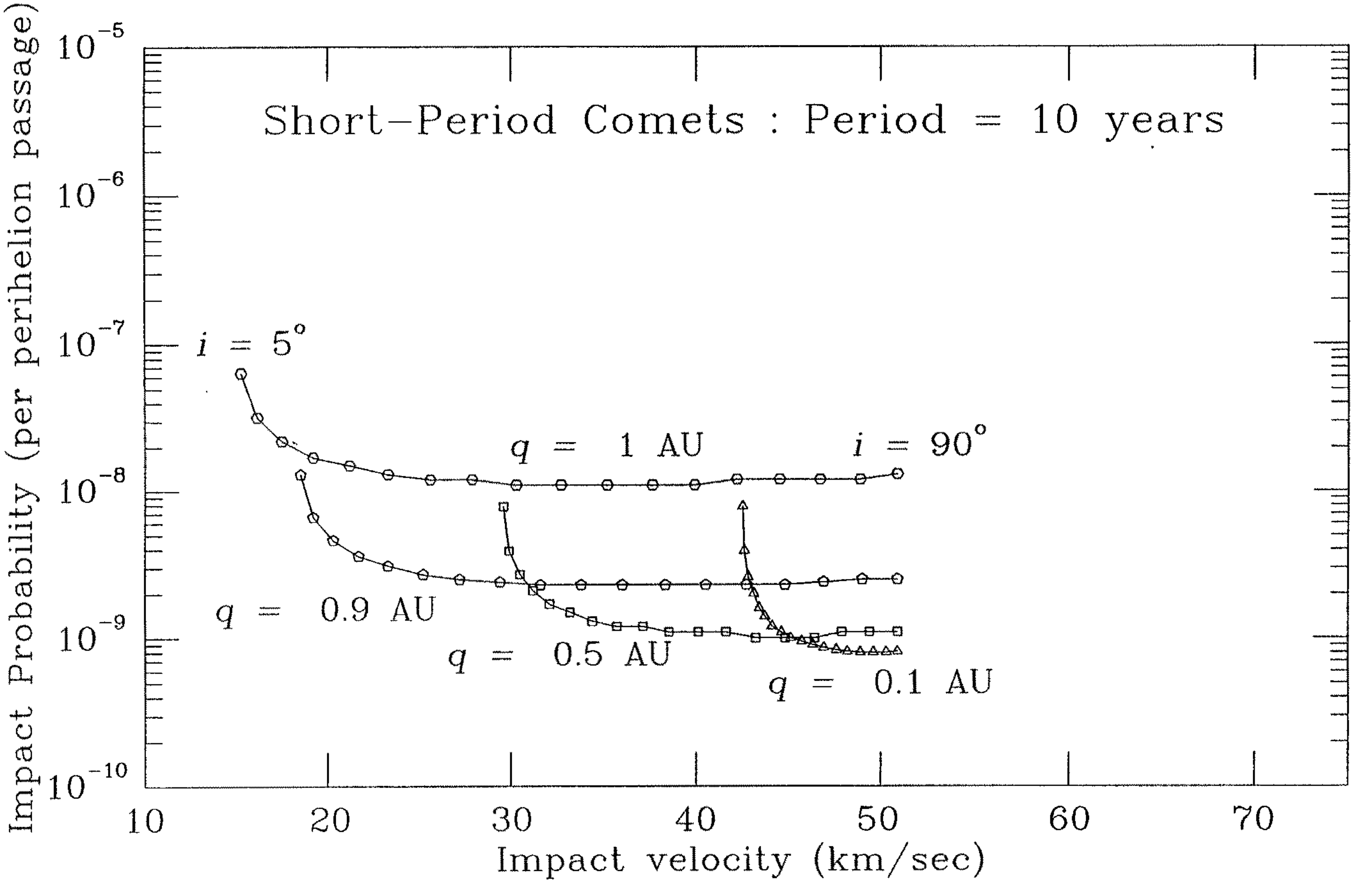

Fig. 2. As Figure 1 except for short-period comets (period 10 yr). Inclinations in 5° jumps from 5° to 90° are plotted. Again the impact probabilities are appreciably higher as q approaches 1 AU, with $V_i < 20$ km sec^{-1} occurring for $i \lesssim 15°$ at $q = 0.9$ AU, and $i \lesssim 22°$ at $q = 1.0$ AU.

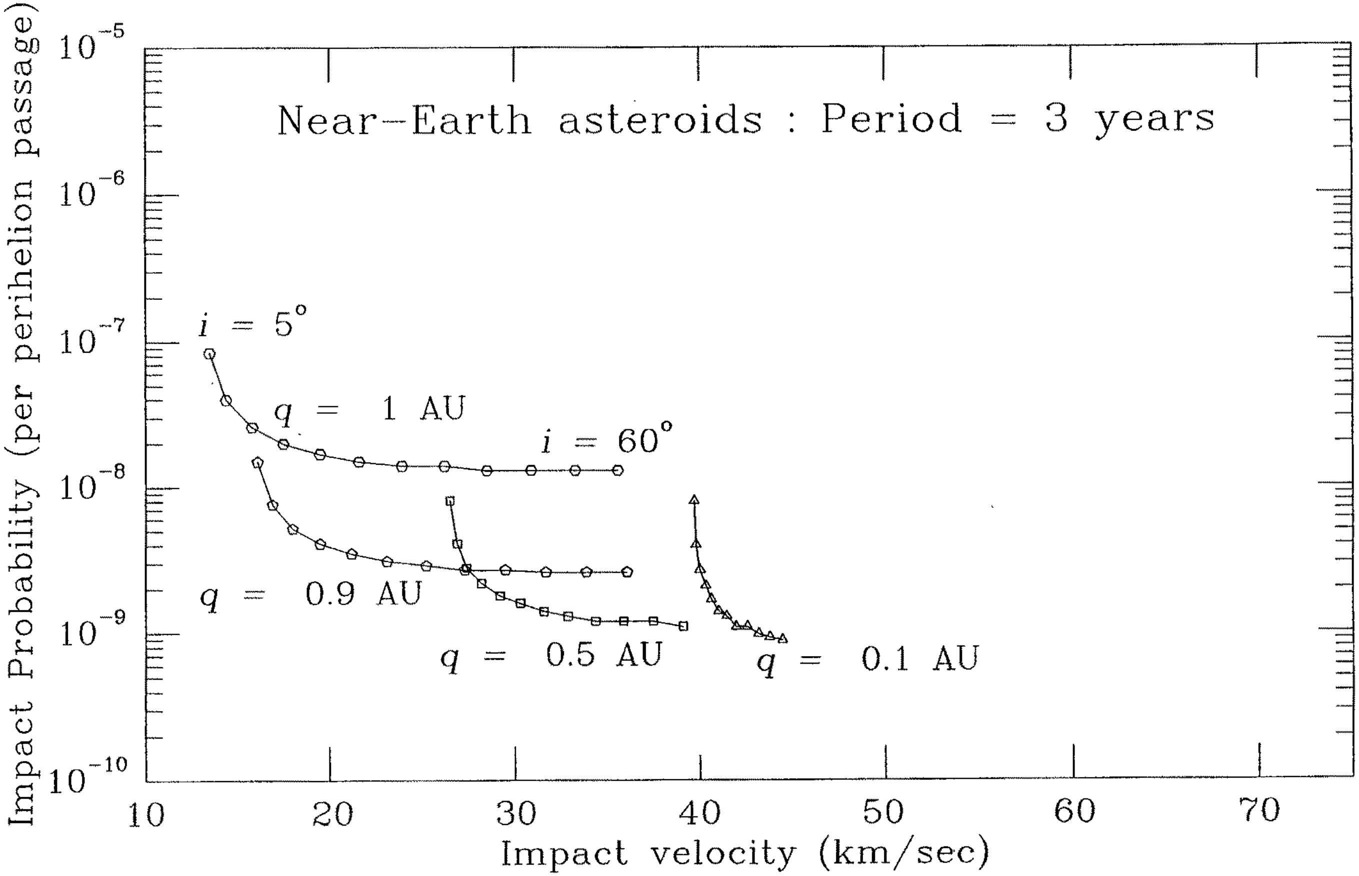

Fig. 3. As Figure 1 except for near-Earth (in this case, Apollo-type) asteroids of period 3 yr. Inclinations in 5° jumps from 5° to 60° are plotted. Again $q \gtrsim 0.9$ AU is needed for $V_i < 20$ km sec $^{-1}$, and $i \lesssim 21°$.

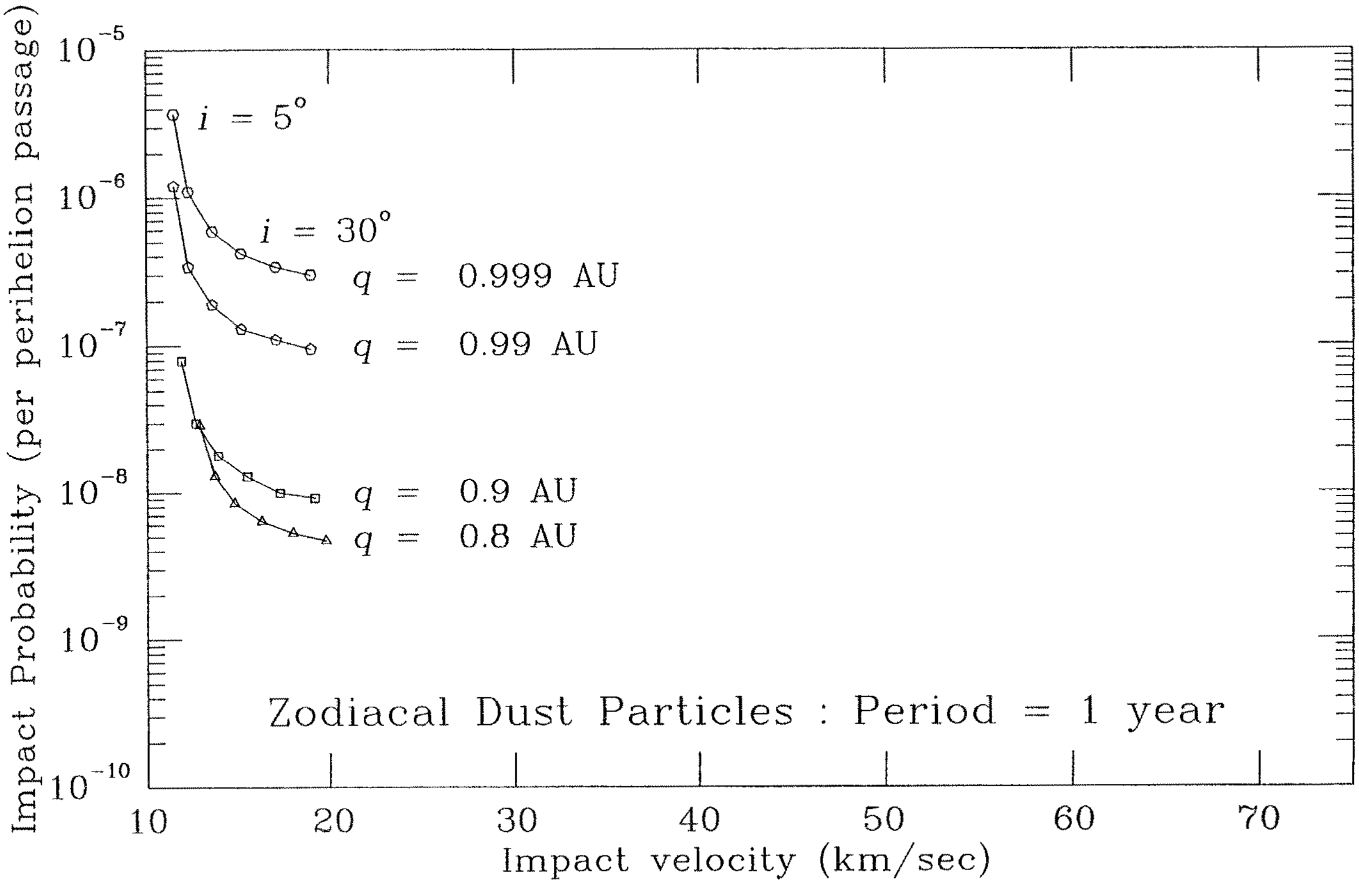

Fig. 4. Terrestrial impact probability versus impact velocity for zodiacal dust particles of period 1 yr. Here the four curves are for $q = 0.8$, 0.9, 0.99 and 0.999 AU, inclinations from 5° to 30° in 5° steps being considered: zodiacal dust is known to be predominantly in low-inclination, near-circular orbits. All impacts velocities are below 20 km sec^{-1}; note that the impact probabilities (per perihelion passage) are much higher than in Figures 1–3.

possible (else two slightly-different maximum and minimum impact velocities would be derived in each case). In Figures 1–4 are presented plots of P_c versus the impact velocity (V_i – the velocity at the top of the atmosphere being derived from the encounter velocity by adding it in quadrature with the escape velocity of the Earth) for a variety of test orbits.

In Figure 1 a set of LPC orbits is considered. These have perihelion distances of 0.1, 0.5, 0.9 and 1.0 AU, and inclinations of 10°–170°, with the eccentricities (all near 1.0) being chosen so that the orbital periods are all 10^6 yr (semi-major axes 10^4 AU). With regard to the survival of organics, low velocities are required and it is clear that the only LPCs which will give $V_i < 20$ km sec^{-1} are those with perihelia very near the Earth ($q \gtrsim 0.95$ AU) and low inclinations ($i \lesssim 20°$). The plots for lower-period but still high-eccentricity orbits would not be markedly different.

In Figure 2 a variety of SPC orbits were used, selected in a similar way to the LPCs but with periods of 10 yr being stipulated. Inclinations of only 5°–90° were used, and most SPCs in fact have inclinations towards the lower end of this range (Marsden, 1989b. The few intermediate-period comets like P/Halley would all have $V_i >> 20$ km sec^{-1}. Again perihelion near the Earth ($q \gtrsim 0.9$ AU) and a low inclination is required to obtain $V_i < 20$ km sec^{-1}.

Since NEAs are mostly of low inclination only $i = 5°–60°$ was used in constructing Figure 3, with a period of 3 yr. Lower values of V_i than for the comets considered above are found, due to the smaller eccentricities of the NEA orbits, and $V_i <$ 20 km sec $^{-1}$ is attainable for low-inclination NEAs of $q \gtrsim 0.9$ AU. It should be noted that there are some comets with orbits similar to these fictitious NEA orbits; for example, P/Encke.

Finally in Figure 4 typical zodiacal dust orbits are considered; as discussed in section 2 these are of low eccentricity and inclination; $i = 5°–30°$ were used, and $e < 0.2$ with period 1 yr. All values of V_i are below 20 km sec^{-1}, and some are only just above the terrestrial escape velocity. Such orbits have a high probability of intersecting the Earth, and the encounter velocity is so low that the collision cross-section is significantly enhanced by the terrestrial gravitational field: note that the impact probability is much higher for these orbits than those in Figures 1–3.

It is clear from these four Figures that the zodiacal dust particles are much more likely to arrive in the atmosphere with sufficiently low velocities to enable organic survival, favouring the hypothesis that dust particles rather than impacts by macroscopic objects supplied organics to the early Earth's surface. A possible scenario which would lead to a large mass influx to the planet would be the occasional comet with the appropriate orbit (low inclination, $q \simeq 1$ AU) spawning a dust and meteoroid trail with perihelion at or just beyond 1 AU. The dust would then obtain circular orbits under the P-R effect, and the meteoroids would be comminuted by collisions so as to add to the dust population, on a time-scale of $\sim 10^5$ yr. [However, for a massive injection of cometary dust the rate of meteoroid destruction may be enhanced so as to vary as f^2 rather than f, where f is the stream flux

(Steel and Elford, 1986); this would reduce the time-scale considerably.] Such a torus of dust is dynamically quite stable: Jackson and Zook (1989) find that 30–100 μm particles with $i < 10°$ and $e < 0.3$ are most easily trapped into such a dust ring, with orbit-orbit resonances with the Earth persisting for 10^5 yr and more. The formation of such structures must have occurred many times in the early history of the Earth, with a large fraction of the dust being swept up by the planet at low relative velocities.

5. Conclusions

Previous work has shown that impacts by large objects are unlikely to supply intact organic molecules to the surface of the Earth. An additional constraint upon the delivery of organics appears to come from the discovery of amino acids at the K/T boundary which were delivered over a period of at most 10^5 yr: if this is interpreted as being a gradual deposition over such a length of time (Zahnle and Grinspoon, 1990) then this also constrains the lifetimes in space of the vehicles supplying these organics to be of this order. It is noted that the physical lifetimes of meteoroids and dust of mass $< 10^{-3}$ g are 10^5 yr or less, whereas larger bodies persist in the inner solar system for longer periods unless they have aphelia beyond ~ 4 AU, in which case Jupiter may eject them, limiting their lifetimes to 10^{4-5} yr. The time-scale for the disintegration and dispersal of a large comet is also $\sim 10^5$ yr. The existence of an assembly such as the Taurid Complex would argue for such events being common (Clube and Napier, 1984): some large comets may well be ejected soon after arrival in the inner solar system, but many will break-up to leave substantial amounts of dust and meteoroids on inner solar system orbits ($Q \lesssim 4$ AU). At the K/T boundary there are now several candidate craters of the appropriate antiquity, with at least one growing season having occurred between impacts (Shoemaker and Izett, 1992) so that multiple impacts must have occurred, and the disintegration of a large comet is evidenced. Upon meeting the atmosphere small meteoroids ($10^{-6} \lesssim$ mass $\lesssim 10^3$ g) ablate so that their organic complements are destroyed, although meteorite-producing bodies can supply small amounts of organics to the surface; however, the dust (masses $< 10^{-6}$ g) does not ablate and survives largely intact. It has been shown herein that the arrival velocity of the dust in the atmosphere is generally lower, and the probability of collision with the Earth higher, than for the meteoroids, asteroids and comets. These considerations may be interpreted as evidence for organic material having been supplied to the Earth in the first $\sim 10^9$ yr of its history in the form of cometary dust, as suggested by Anders (1989).

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