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The cometary hypothesis of the K/T mass extinctions

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ABSTRACT

The correlation of the extended period of biological mass extinctions around the K/T boundary with extraterrestrial amino acids in the sediment record constitutes strong evidence of a cometary cause. While the fact that the dinosaurs' extinction coincided with the Chixculub cratering event and iridium-rich sediments suggests a chance asteroidal or cometary impact, the enhanced input of extraterrestrial matter over 10^5 yr supports the hypothesis of a Jupiter-associated giant comet, fragmented into a multitude of pieces, as demonstrated by comet Shoemaker–Levy 9, and perturbed into Earth-crossing orbits. Copious amounts of dust were released also, enhancing the dust abundance in the Solar system by several orders of magnitude. By studying the radiative properties of the submicron dust fraction of organic composition, we find that it is retained in the inner Solar system and is available for planetary accretion, unlike the IR-containing metallic and mineral dust. The shroud of dust accreted in the Earth's upper atmosphere can be sufficient to impose climatic stresses and cause extinctions of species over a protracted period of 10^5 yr. Dynamical arguments imply that the impacting comet most probably came directly from Jupiter's family. Details of the iridium record are compatible with re-accretion of some of the material ejected into space from the Chixculub impact.

Key words: gravitation – comets: general – Earth – interplanetary medium – planets and satellites: individual: Jupiter – Solar system: general.

1 INTRODUCTION

The speculation that mass extinctions of biological species, such as occurred at the K/T boundary 65 million years ago, had an astronomical cause was published as early as 1978. In a paper entitled 'Comets, Ice Ages and Ecological Catastrophes', Hoyle & Wickramasinghe (1978) wrote:

'A total mass of 10^{14} g added to the Earth's upper atmosphere in the form of small particles of high albedo for visual wavelengths would produce an inverse greenhouse effect, shielding ground level from sunlight but permitting infrared radiation from the ground to escape into space. Such a mass of small particles might be acquired by the Earth in a close approach to a cometary nucleus. Ice ages and ecodisasters, such as that which occurred 6.5×10^7 years ago, could arise from the effects of such an addition of small particles.'

Napier & Clube (1979) used the same idea in a wider study of terrestrial catastrophism. Subsequently, Alvarez, Alvarez & Azaro (1980) made the remarkable discovery that clays in the K/T boundary layer are greatly enriched in the element iridium, a rare element in the Earth's crust but one that is present in meteorites and presumably in comets. This discovery led to their claim that a large asteroidal impactor caused the extinction of the dinosaurs as well as other plant, animal and microbial species some 65 Myr ago. From this datum alone, no distinction could be made between the alternatives of an asteroidal or cometary impactor. However, some mineralogical evidence points to the involvement of iron, possibly in the form of an iron-rich meteorite (Palme 1982), or more likely in the form of iron grains.

Giant comets are thought to arrive in the Jupiter region from further out in the Solar system, on the average every 10^5 yr (Bailey et al. 1994). For instance, Chiron, of about 330-km diameter, is expected to join the Jupiter family of comets in 10^5 yr time. It may pass further in to the terrestrial planet region, be kicked back to the Solar system by a Jupiter orbit perturbation, or it may undergo fragmentation in a close encounter with Jupiter. The cross-sections for impacting a planet radius R, mean density ρ, and for passing within its Roche limit L are

$$\pi R^2(1+V_{\rm esc}^2/u^2), \qquad \pi R^2(L^2+LV_{\rm esc}^2/u^2), \qquad (1)$$

respectively, with $L=(C\rho/\rho_{\rm com})^{1/3}$. The gravitational attraction of the planet is expressed via the escape velocity $V_{\rm esc}$ relative to the comet approach speed u. The constant C in L

is about 2 for dividing a sphere or cube into equal halves, but C is larger for elongated bodies aligned along the radius from the planet (e.g. $8\pi/3$ for attached equal cubes, 14.5 for the self-gravitating fluid body). For Jupiter, with $V_{esc}=59.4$ km s^{-1} and $\rho=1.31$ g cm^{-3}, a representative low-inclination prograde comet with approach speed $u=3$ km s^{-1} (the differential for a $Q=15$ au, $q=5$ au comet), $C=3$ and density $\rho_{com}=0.5$ g cm^{-3}, the cross-sections in (1) are $390\pi R_J^2$ and $780\pi R_J^2$, respectively. Therefore fragmentation has a similar probability to that of impacting Jupiter, in a single-shot encounter. Comet Brooks 2 broke into two major pieces on a Jupiter passage at $2.0R_J$ in 1886; the identification of this as a marginal Roche break-up agrees with the above numbers for density and the shape-sensitive factor C. Comet Shoemaker–Levy 9's 1992 passage at $1.35R_J$ evidently had tidal forces sufficient to overcome weak structural forces, so ruptured substantially into more than 20 subcomets (Weaver et al. 1994).

Comets like Shoemaker–Levy 9 can be in temporary orbit of Jupiter, so fragmentation and impact probabilities are not simply related to cross-sections. Nevertheless, fragmentation via close encounter with planets does appear to be a not uncommon process in cometary evolution. Bailey et al. (1994) suggest that it happens to 10 per cent of Jupiter-family comets. We conceive that copious amounts of dust are emitted with the fragmentation and via subsequent evaporation of volatiles binding dust grains together; also that successive fragmentation of some of the subcomets from a giant comet will occur and fill the inner Solar system with enhanced levels of cometary debris over an extended period. Micron- and submicron-sized grains have been generally ignored on two accounts: first because observational techniques miss them, and secondly because radiation pressure effects imply that they are readily blown out of the Solar system. However, the space probes of Halley's comet discovered an abundance of such grains, so we are led to re-examine how radiation pressure affects low-density, porous submicron grains.

Although many mass-extinction events are found in the geological record, that at the K/T (Cretaceous/Tertiary) boundary represents the most dramatic episode in the last 100 million years. It is also remarkable in being the most sharply concentrated in temporal terms. The observed extinctions of species are spread across a finite but narrow time interval 65 ± 0.05 Myr ago in stepwise fashion (Hut et al. 1987). Although the width of this interval is not precisely defined, the evidence suggests that it exceeds 0.1 Myr. A similar temporal width is consistent with the recently observed distribution of extraterrestrial amino acids out to a metre above and below the K/T boundary layer (Zhao & Bada 1989). Fig. 1, adapted from Zahnle & Grinspoon (1990), adopts a sediment deposition rate of 1.9 cm kyr^{-1} and shows the distribution of alpha-isobutyric acid (AIB), as well as the sharp peak of iridium that coincides with the impact event (shown by soot, tsunami deposits, etc.). A second extraterrestrial amino acid, isovaline, is also detected with the AIB. The survival of organics like AIB requires that they reach the Earth not in large cometary lumps, but as small particles of cometary dust that soft-land through deceleration high in the atmosphere.

The K/T boundary peak is closely associated in time with the sea-bed Yucatan (Chixculub) crater (Bailey et al. 1994) and with tsunami deposits on the shore. If the most sharply defined extinction event, the extinction of the dinosaurs, was connected with a direct cometary strike, one can hypothesize that the more protracted attenuation and extinction of other genera and species, spanning some 100 000 yr or more, were connected with climatic perturbations resulting from the accretion of cometary dust (Hoyle & Wickramasinghe 1978) plus the toxic effects of organic materials from space (Ramadurai et al. 1994).

2 ACCRETED COMETARY DUST

Cometary dust includes a large fraction that is of a complex organic character. Recent studies of dust from Halley's comet have suggested the presence of exceedingly complex aromatic and aliphatic structures similar to those found in interplanetary dust particles (IDPs) and carbonaceous chondrites. Because the relevant mass spectroscopy was carried out in situ on the break-up products of hypervelocity grains, detailed chemical analysis of the original dust was not possible. The results of mass spectroscopy and IR spectroscopy are, however, fully consistent with organic particles that could be chemically as complex as biological material (Wallis et al. 1989; Kissel & Krueger 1987; Wickramasinghe 1994). The identification of extraterrestrial amino acids near the K/T boundary thus fits generally with the idea of cometary encounters. Further work (Bada & Zhao 1994) established that the AIB signature continues through the Ir peak, the low point in Fig. 1 being associated with the narrow layer of non-carbonate clay. The material brought in directly with the impactor would possess an enhanced iridium signal, but any organic material initially present would have been destroyed in the highly energetic impact.

For AIB alone, the surface density deposited over a depth of about 2 m is estimated at 5×10^{-5} g cm^{-2} (Zhao & Bada 1989). AIB constitutes about 12 parts per million of the Murchison meteorite and may plausibly be ~10 times higher in unfractionated cometary dust comprising a larger component of volatiles. Accordingly, assuming a fraction of about 10^{-4} in the accumulated sediments, the total input of cometary dust inferred from AIB measurements is $\sim5\times10^{-5}/10^{-4}=0.5$ g cm^{-2}. Averaged over a time of 50 000 yr, this gives a rate of accumulation of cometary dust of $\sim10^{-5}$ g cm^{-2} yr^{-1}. Over the 5×10^{18} cm^2 of the Earth's surface, the total mass input is then $\sim5\times10^{13}$ g yr^{-1}. With a typical residence time in the mesosphere of 2 yr, we obtain an average mass loading of 10^{14} g, close to that discussed by Hoyle & Wickramasinghe (1978) (2 yr is the settling time for a 3-μm porous particle, but residence times depend on ice growth and evaporation so probably do not much exceed the observed clearance time of volcanic dust). Bailey et al. (1994) calculate similar dust loadings, some 10^4 times present values. This compares with the present-day fluxes of $10^{9.5}$ g yr^{-1} of grains under 1 μg that are currently estimated (e.g. Hughes 1978), although in situ data on comet Halley imply that this micro-dust was seriously underestimated (see Section 4).

Micron-sized cometary grains are in general added to the Earth in a non-destructive manner. In the figures of Sandford & Bradley (1989), half the 10-μm grains of density 0.5 g cm^{-3} impacting at 14.5 km s^{-1} reach peak temperatures below 450 K. Small fractions of larger grains of radii in the

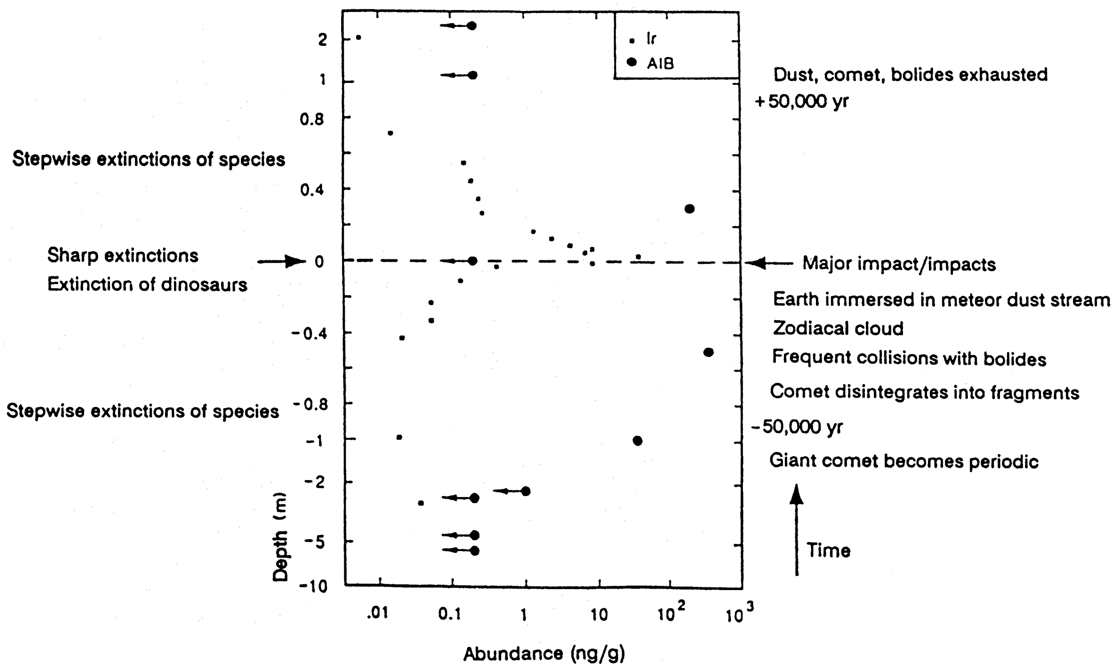

Figure 1. Possible interpretation of the events near the K/T boundary (adapted from Zahnle & Grinspoon 1990). The sediment deposition rate is taken as 1.9 cm per 10^3 yr.

range 10–100 μm with higher area-to-mass ratios also survive frictional heating, through entry on inclined trajectories. Submicron-sized grains almost all survive and are most important optically because of their high area-to-mass ratio and also because their residence time against gravitational settling is longer. Incoming dust particles are slowed down at a typical altitude of 100–120 km, and the main effect of the resulting dust veil at this height is to diminish the solar radiation reaching the lower atmosphere and thus reduce the average surface temperature. To calculate the behaviour of such a cloud, single-particle scattering amplitude functions computed from Mie theory have to be averaged over all orientations of incidence on the Earth's surface as well as over the solar spectrum (Hoyle & Wickramasinghe 1991). We compute the average backscatter mass efficiencies for spherical particles with the general characteristics of IDPs. Such particles may be taken to have siliceous/organic compositions with bulk refractive index $m=1.5$ and density 2 g cm^{-3}. We consider the behaviour of non-porous dielectric grains endowed with these properties (D_{100}) as well as of porous grains that are volume-filled to the extent of 60 and 40 per cent (D_{60} and D_{40}). The calculations of the average refractive indices for the latter cases were made adopting the Maxwell–Garnet approximation (Bohren & Wickramasinghe 1977). From Fig. 2 we see that, for porous grains with a volume filling factor of 40–60 per cent, the average value of κ is 2000 $cm^2\,g^{-1}$.

The effective scattering optical depth of an atmospheric loading of 2×10^{-5} g cm^{-2} is 0.04, which changes the net incoming visible radiation (240 W m^{-2}) by $\Delta F=-9.6$ W m^{-2}. This translates to a temperature drop $\Delta T=-4$ to -11°C on the IPCC scaling (Houghton, Jenkins & Ephraums 1990). Such a temperature drop develops over the apparent rise time of AIB of 10^4 yr (Fig. 1). It would lead

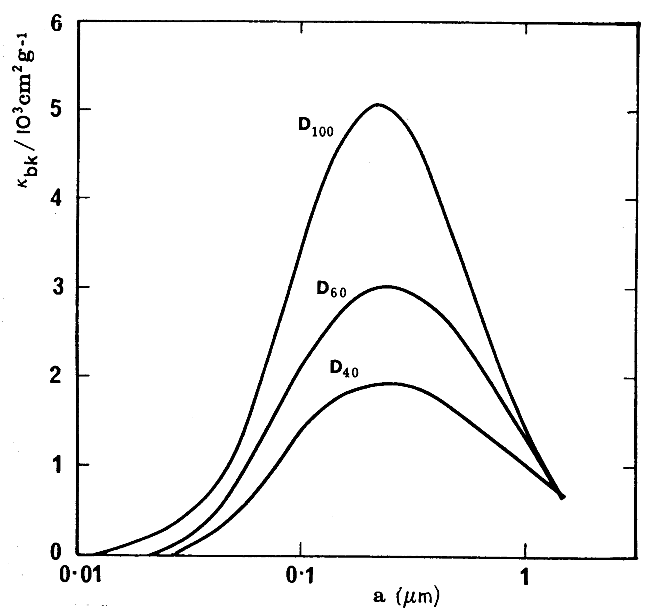

Figure 2. Average back-scatter function κ ($cm^2\,g^{-1}$) for organic/siliceous particles with $m=1.5$ and $s=2$. D_{100}, D_{60}, D_{40} refer to a sequence of non-porous grains, 60 per cent volume-filled porous grains and 40 per cent volume-filled porous grains.

to significant climatic change, cooling of the oceans, lowering of evaporation rates, and development of temperate-zone ice sheets. Some animals (e.g. dinosaurs) may have time to migrate and survive, but many species of flora and their dependent fauna would die out as a consequence. The stress of cumulative toxic organics such as AIB and isovaline could contribute further to faunal extinctions (Ramadurai et al. 1994).

The dust veil enveloping the Earth would fluctuate in its optical thickness over the 10^5-yr period. A comet like Halley actively evaporates and ejects dust for 100 orbits or more, and may crust over and rejuvenate erratically. Each of the subcomets has a chance of a second close, fragmenting, encounter with Jupiter – estimated using (1) at 10^{-4} per low-inclination ($<10°$) orbit – which would produce copious amounts of dust. Submicron particle orbits change over 10^4 yr, so inputs to the Earth would be smoothed over this time interval. There would be short-term peaks on passage of the Earth through the comet trail, but these would average out over the 2-yr settling time. The radiative forcing due to dust loading would thus vary primarily on the 10^4-yr time-scale, this variation imposing continuing stress on biology throughout the period. Grains ≥ 10 μm would contribute less to atmospheric opacity, partly because they settle faster through the atmosphere and because the surface area distribution peaks below this size, as observed for Halley (McDonnell et al. 1987).

3 GIANT COMET SCENARIO

The scenario envisaged here is of a giant comet of mass 10^{22} g (300-km diameter) fragmented via close encounter with Jupiter and perturbed into Earth-crossing orbits (e.g. Clube & Napier 1990; Bailey, Clube & Napier 1990) some 60 000 yr prior to the Chixculub impact. Like comet Shoemaker–Levy 9, it became a temporary satellite of Jupiter (Tancredi, Lindgren & Rickman 1990) and fragmented, but into Earth-crossing comets of the Jupiter family, rather than impacting Jupiter. Earth-crossing comets have orbital eccentricity $e \simeq 0.7$. Steel (1992) calculates the probability of an Earth impact by a typical comet with low inclination i and with $q=1$ au as about 2×10^{-7} per perihelion passage, i.e. 10^{-8} yr^{-1}. The cross-section (1) for an encounter within the Roche limit with $\rho_{\rm E}=5.52$ g cm^{-3}, $V_{\rm esc}=11.2$ km s^{-1}, $u=15$ km s^{-1} (low-inclination, 10-yr period) is $12\pi R_{\rm E}^2$, compared with $1.6\pi R_{\rm E}^2$ for Earth impact. Lunar encounters are unimportant at about 5 per cent of these values. Thus, on the 10-yr timescale, 250 subcomets would give about two such fragmenting encounters and a 25 per cent chance of an impact, while the remainder suffer multiple perturbations which eject them from the Solar system or into the Sun (Steel 1992; Bailey et al. 1994). A fraction of the subcomets are significantly perturbed by the Earth, bringing aphelia inside the orbit of Jupiter at a rate of about 10^{-5} per perihelion passage. Another fraction, 20–40 per cent (Öpik 1966), undergo tidal encounters with Jupiter before ejection into interstellar space. Steel's calculations for 3-au aphelia orbits ($q=1$ au, period $=3$ yr) and near-circular orbits ($q=0.9$ au, period $=1$ yr) indicate a higher collision rate of 1–4×10^{-7} yr^{-1}, but still too low a rate for strong Earth perturbation followed by impact to be significant compared with direct impact from the Jupiter family orbits.

To compare fragmentation probabilities at the Earth and Jupiter (Section 1), we scale the differences between the Roche and planet impact cross-sections (1) by the spatial element ($r_{\rm J}$ denoting the radius of Jupiter's orbit in au) to derive the ratio

$$(12-1.6)\pi R_{\rm E}^2 : (780-390)\pi R_{\rm J}^2/r_{\rm J}^2 = 6\times10^{-3}, \qquad (2)$$

indicating that fragmenting encounters with Jupiter are over 100 times more frequent than those with the Earth. (Since Jupiter's Roche radius is sensitive to the velocity of encounter, an average over a distribution in encounter velocities is needed to firm up this figure.) Fragmenting planetary encounters thus occur most frequently with Jupiter, occasionally with the other giant planets, but rarely with the terrestrial planets. Let us note that the Roche limit for significantly elongated bodies, and particularly for the self-gravitating ellipsoid often quoted, with factor $C=14.5$ in L of equation (1), gives quantitative differences from the numbers above. We do not, however, conceive of the comet as fluid; an elongated comet would lose only outlying parts on passage at larger distance. Still, the fluid model does imply that weak internal structures would be shaken up in passages outside our solid-body ($C=3$) Roche limit. On general grounds, the fragmentation of a giant comet via weak tidal forces is very plausible. A low-density body accreted from small grains and cometesimals with speeds of m s^{-1} has an escape speed of this order and thus little density enhancement from self-gravity. In the early days of the Solar system, radioactive heating probably sufficed to induce a liquid–vapour mix in the comet interior (Wallis 1980; Yabushita 1993), with subsequent re-freezing leading to a hollow structure. The bulk of a comet is therefore a loosely bound fragile structure accreted under low gravity, with the surface altered by high-speed dust collisions over a few billion years.

The fragmentation of comet Shoemaker–Levy 9 (1993e), in its 1992 passage by Jupiter at $1.35R_{\rm J}$, has provided a graphic demonstration of the break-up mechanism in action. Some 20 distinct nuclei were identifiable, 11 of 2.5–4 km diameter, and most with individual extended comas of ice/dust grains (Weaver et al. 1994). It may be that these subcomets are indicative of some coherent building blocks of comets generally – so that our giant 300-km comet would fragment into 10^5 or 10^6 of the few-km blocks. We favour the argument that inter-fragment collisions dominate through the close approach to Jupiter (Sekanina, Chodas & Yeomans 1994), however, so that a hierarchy of loosely bound subcomets results from such a Roche break-up. We infer that their number would scale as $R_{\rm com}^{\alpha}$ with $1<\alpha<2$, so the 300-km comet might split into 600–2000 subcomets of size ≈ 20 km. Pending modelling of the Roche disintegration process (started by Asphaug & Benz 1994), we guess that a size distribution down to smallest grains would emerge, with less than half the mass in sizes over 10 km. In our hypothesis, unlike in the case of SL9, the 600–2000 subcomets followed a subsequent orbit further from Jupiter, though still under that planet's influence. On later orbits, some were perturbed into orbits further from Jupiter, but a fraction came back to suffer fragmenting or impact encounters. If fragmenting passages are less probable, at e.g. 10 per cent of ejecting passages, a hierarchy of fragmenting encounters would create an abundance of all fragment sizes, from subcomets of the SL9 size (10 km) down to the smallest grains.

4 DUST DEBRIS

The Jupiter-induced disintegration and the ordinary evaporation of the subcomets when within 2 au would both contribute to an extremely high density of grains in the inner Solar system, persisting for some 10^5 yr. There would, however, be dramatic fluctuations in grain density as well as in the types and sizes of grains that were retained. The production of grains in comets is known to be a highly variable phenomenon, with the general rule that the older comets are less prolific dust producers. An individual comet tends to become crusted over and inactive after at most a thousand perihelion passages (Fernandez 1984). For a Jupiter-crossing comet, one might thus expect about 100 orbits of dust-producing activity, i.e. for 1000 yr. An old comet would, however, be restored to an active state following a fragmentation event, once more exposing pristine surfaces to evaporation and dust release. The fraction of dust in submicron sizes is relevant to the considerations below. Halley's comet showed submicron dust to be surprisingly abundant. Moreover, the *Giotto* PIA instrument underestimated it. Relative to the cometary gas production, grains under 1 μm constituted a fraction 3×10^{-5} according to McDonnell et al. (1987), but might be equal to the fraction 2×10^{-3} given for <10-μm dust – an upper limit that allows for an apparently missing part of the dust mass spectrum. We assume that this fraction eventually arises from the comet's disintegration, whether directly in comas when the subcomets outgas within 2 au, or when volatiles evaporate from grains released at larger distances. Bailey et al. (1994) suggest that there were even more small grains, because intergrain fragmenting collisions became far more important at the enhanced Solar system densities, smashing up >10-μm grains on the time-scale of 10^4 yr.

Radiation-pressure forces, acting with differing efficiencies on different particles, have an important role in separating the various grain types that emerge from comets. Some grains are retained in bound orbits, whilst others are quickly expelled. The critical ratio of radiation-pressure force P to gravity G for particle retention depends on the eccentricity of the parent cometary orbit, as well as on the precise point in the orbit at which the particles are released. For a comet in a circular (or near-circular) orbit, the condition for retention is $P/G<0.5$; for a comet in an elliptical orbit with eccentricity 0.7 (Jupiter comet), the condition is $P/G<0.85$ for aphelion emission, but $P/G<0.15$ for perihelion emission (Ishimoto & Mukai 1991). These criteria are indicated by the dotted and dashed lines in Fig. 3. The several curves plotted there show the ratio of radiation-pressure force to gravity (computed using the Mie formula) for the particle types considered earlier, including the case of porous dielectric grains. The dielectric grains (siliceous, organic) are assumed as before to have bulk refractive index $m=1.5$ and bulk density 2 g cm^{-3}. The mean refraction index for porous particles (60 and 40 per cent volume-filled) is calculated from the Maxwell–Garnet approximation (Hoyle & Wickramasinghe 1991), and the mean density is calculated taking account of porosity.

Iron and graphite particles incorporated within comets are thought to be mainly of pre-solar origin. We suppose that they were present in the original solar nebula and so came to be included within cometary objects. Particles comprised of iron (I) and graphite (G) with radii in the range 0.01–0.03 μm are likely to have been injected into interstellar space through condensation in giant star atmospheres and supernova ejecta (Hoyle & Wickramasinghe 1970, 1991). These grains, particularly iron grains, are likely to include other metallic elements as impurities. Both iron and iridium are products of explosive nucleosynthesis, and they plausibly co-exist in the same cometary dust population. The

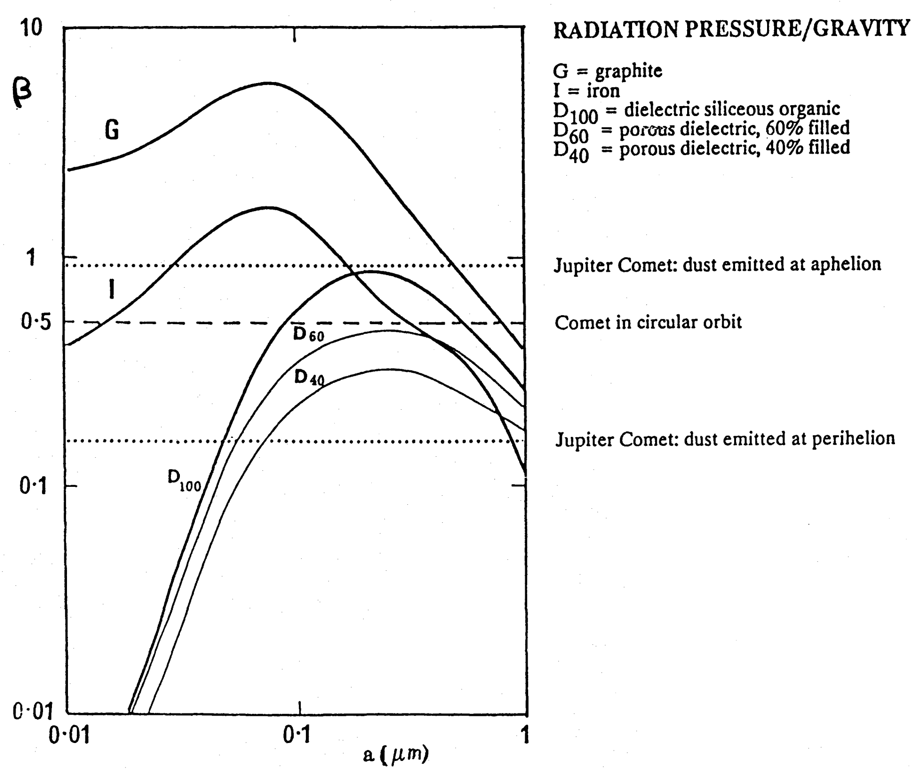

Figure 3. Ratio of radiation pressure to gravity for spherical particles near the Sun. The curve G refers to graphite; I refers to iron; D_{100}, D_{60}, D_{40} refer to a sequence of non-porous grains, 60 per cent volume-filled porous grains and 40 per cent volume-filled porous grains. The dotted and dashed lines show critical P/G values for retention in bound orbits.

sharp peak in iridium at the K/T boundary, with a decreasing fraction outside it, may be relevant in this context, and can be readily interpreted as arising from the selective exclusion of iridium-bearing grains from a cometary meteor stream. Fig. 3 clearly shows a possible reason for this, if indeed iridium is contained as an impurity element in pre-solar metallic grains: iron and graphite particles of the relevant sizes do not satisfy the conditions for retention in bound orbits under any of the three criteria considered. Furthermore, the calculations of Ishimoto & Mukai (1991) have shown that porosity in metallic particles increases the probability of grain expulsion.

For the solid and porous dielectric compositions considered, retention in Solar System orbits is assured for particles that are emitted from a Jupiter comet near aphelion. For particles emitted near perihelion, however, only porous grains that are smaller than 0.07 μm or larger than 1.5 μm will be retained. Whilst it is true that comets normally emit dust mostly near perihelion, the late eruptions found in the case of Halley's comet at 5 au and beyond show unequivocally that dust ejection does indeed take place at large perihelion distances. Particularly profuse bursts of dust emission are to be expected at times when the comet fragments on passing close to Jupiter.

Another effect to be considered is the Poynting–Robertson drag, which leads to a spiralling into the Sun of small dust grains. This effect is also dependent upon size and refractive index. In Fig. 4 we compute the Poynting–Robertson lifetime for particles in circular orbits of radii 1 au and of various sizes and compositions. It is seen that iron particles of radii 0.01 μm and organic/mineral grains of radii 0.3 μm have Poynting–Robertson lifetimes of 3000-yr on average, whereas graphite particles have shorter lifetimes. The longest Poynting–Robertson time-scale is for porous dielectric grains, where the calculated lifetime of submicron grains could be as long as 10^4 yr at 1 au (note that Poynting–Robertson lifetimes scale as the square of the radial distance). A meteor stream resulting from a single cometary evaporation episode will thus intersect the Earth's orbit for an average $\sim 3\times 10^4$ yr before spiralling into the Sun. This time-scale is of the order of the time-scale involved in repeated Jupiter encounters, but is considerably longer than the crusting-up time for a new comet.

While we refer for simplicity to 'Poynting–Robertson' time-scales, it should be borne in mind that there are stronger orbit-changing forces that act on non-spherical grains (Voshchinnikov & Ilin 1983). Poynting–Robertson

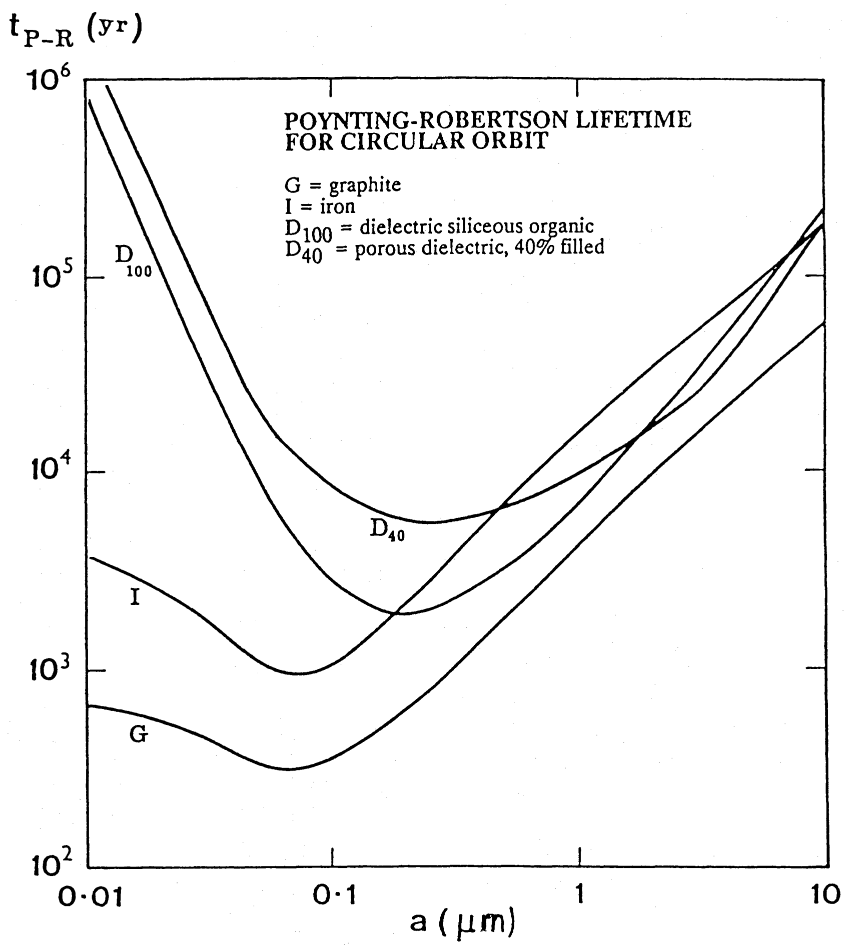

Figure 4. The characteristic Poynting–Robertson lifetimes for particles in heliocentric orbit at 1 au. The symbols marking the curves refer to the same cases as in Fig. 3. The lifetime parameter is $\sim q^2$ for high-eccentricity orbits, but orbits become circularized ($e\rightarrow 0$) rather faster (Wyatt & Whipple 1950).

time-scales are an upper limit, applying to spherical and near-spherical grains. Also, grains with dimensions <0.1 μm are electrically charged and subject to electromagnetic forces, giving diffusion in orbital parameters which dominates over the Poynting–Robertson drag (Wallis 1986).

While the K/T impactor coincides in time with the non-carbonate clay layer and the Ir peak, the levels of Ir remain enhanced for several kyr (Fig. 1). The asymmetry in the profile indicates that this reflects the real deposition rate rather than an artefact of diffusion in the sediments. If the post-impact tail is associated with the impactor, one possibility involves dust release from a marginal Roche encounter with Earth, which perturbed the comet and debris into a low-eccentricity orbit, the comet subsequently impacting the Earth. The debris, including iron grains >0.3 μm, are on bound orbits (according to Fig. 3) and will in part be gradually accreted by the Earth. Two Earth encounters are, however, rather improbable. The second possibility involves material ejected into space from the Chixculub impact (Melosh 1988). Ejection speeds reach as much as 85 per cent of the impactor speed, so can readily exceed escape velocity, but the material would still be retained as Earth-crossing debris for gradual re-accretion. All the impactor material would be vaporized. In the first case, moreover, original iron grains of radii 0.3–1.0 μm, whose Poynting–Robertson lifetimes are $\lesssim 10^4$ yr (spherical grains, Fig. 4), might be traced in the sediments.

To conclude, we recap the timetable of the main events envisioned in our model as follows.

65.05 Myr BP

Giant comet's close encounter with Jupiter, fragmenting into ≈ 1000 subcomets (Jupiter and Earth orbit crossing, $e \simeq 0.7$).

Further close encounters and fragmentation. Dust production kept high.

Comets emit dust: siliceous/organic dust component of sizes <0.1 μm retained in meteor streams; iridium-bearing dust of <1 μm lost from hyperbolic orbits.

Earth picks up organic dust to form shroud; optical depth varies on a 10^4-yr time-scale.

Ice-age conditions; intensity fluctuating with shrouding.

65 Myr BP

Comet of mass 3×10^{18} g collides with Earth – forms Chixculub crater.

Exploding debris escapes into Earth-crossing orbits, boosting the dust population, including iridium-bearing, metal grains in bound orbits around 1 au. Part of the dust is accreted by the Earth as it decays over a few 1000 yr.

Subcomets gradually lost via Jupiter perturbations over a few $\times 10^5$ yr.

Remaining comets in Jupiter family crust over and become inert; they are rejuvenated only in rare fragmentation events.

64.95 Myr

Dust environment clears due to action of scattering and drag forces.

Climate warms as shroud diminishes.

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