# GIANT COMETS, EVOLUTION AND CIVILIZATION

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**Abstract.** Giant comets thrown into short-period, Earth-crossing orbits are a major source of mass flux into the inner planetary system. Their disintegration products may give rise to climatic cycles, ice epochs, periodic mass extinctions and other global disturbances. Comets $\gtrsim$ 100 kilometres in diameter, in chaotic orbits beyond Jupiter, probably constitute a more substantial current hazard than stray asteroids.

## 1. Introduction

Evidence for a 30 million year periodicity in the incidence of large-scale or global terrestrial phenomena (mass extinctions, mountain-building episodes, sea-level variations, ice epochs etc.) has grown substantially since it was first proposed 70 years ago (Holmes, 1927). Evidence has also grown that the period (now considered to be $\sim$ 26 Myr) of this 'Holmes cycle' is identical to that between successive crossings of the Galactic plane (McCrea, 1981). This latter interval is inferred from the Sun's motion with respect to the local standard of rest and the density of dark matter within the Galactic disc. If a causal relationship between these cycles could be established, it would follow that the occurrence of global terrestrial phenomena could no longer be explained by internal, 'uniformitarian' mechanisms; rather a 'catastrophist' interpretation would almost certainly be required, in which processes as diverse as mountain-building and the evolution of life through 'punctuated equilibria' are activated by a predictable celestial mechanism.

If so, what then emerges is a new paradigm in which the punctuational episodes represented by outbursts of global phenomena are *prima facie* evidence of an accelerated process of biochemical processing whenever the ecological niches on Earth and the species which inhabit them experience some kind of cosmic interference. Such interference can in principle include extreme differential culling, excessive physical disturbance and/or substantial (bio)chemical accretions – such as are most probably associated with the rather frequent encounters between the Earth and trains of cometary/asteroidal debris (Hoyle and Wickramasinghe, 1978,

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1985; Napier and Clube, 1979; Clube, 1995). The effects such trains may have on the Earth were strikingly illustrated by the rapid sequence of encounters which the Comet Shoemaker-Levy 9 train of debris made with Jupiter in July 1994.

In fact, mechanisms yielding the empirical galacto-terrestrial connection appear to exist. Periodic variations in the Galactic tidal stress experienced by the Oort comet cloud, both impulsively (Clube and Napier, 1996) and continuously (Napier, 1987; Bailey *et al.*, 1990; Matese *et al.*, 1995) yield a proportionately variable flux of comets entering the inner planetary system. The dislodged comets, which have a top-heavy mass distribution, undergo hierarchic disintegration; the resulting trains of debris induce a range of interactions with the Earth which depends not only on the process whereby typical 'giant comets' (diameters $\gtrsim$ 100 km, say) split but also on the commensurability and nodal precession rate of the short-period orbits into which the comets are ultimately deflected (Asher and Clube, 1993; see also the reviews by Bailey *et al.*, 1994 and Napier and Clube, 1996). The predicted terrestrial effects span the range from geological upheavals on the one hand (Hoyle, 1984) to cultural ones on the other (Hoyle, 1993; Clube, 1995). For example the $\sim$ 26 Myr period of the late Phanerozoic pulsation (i.e. since about 260 million years BP) is indicative of the Galaxy's longer term influence on the Oort cloud while the current (Pleistocene/Holocene) ice epoch and its $\sim$ 0.1 Myr alternation between glaciation and greenhouse are broadly indicative of a current more localized Galactic influence close to the plane (Clube and Napier, 1984, 1996). However the current arrival rate of giant comets implies that they are also a prime hazard to civilization; thus it appears that the last (i.e. latest Pleistocene) glacial and its aftermath, the current (Holocene) inter-glacial, may be associated with the disintegration and decline of the single, most recent, giant comet in near-Earth space (Steel *et al.*, 1994). This has led to a very natural focus now on the lesser but still significant hazards due to the still disintegrating debris of this giant comet, producing dark- and mini-ice ages on millennial and centennial timescales respectively (Bailey *et al.*, 1994). The arrival frequency of giant comets into short-period, Earth-crossing orbits, $\sim 10^{-5}$ per annum, is much the same as that of $\sim$ 1-kilometer asteroid impacts, but the adverse environmental effects of giant comets, although comparable in severity, are much more prolonged.

Although the rôle of impacts in evolution is now widely accepted, that of cometary dusting has been relatively neglected. A point at issue is the greater complexity of the cometary as opposed to the asteroidal hazard, as well as its more pervasive effects. Thus a stray impact may yield only prompt geological effects. A disintegrating giant comet, on the other hand, may induce climatic trauma for a time in excess of critical time constants in the Earth system, and this may lead to load shifting between hydrosphere and cryosphere with the potential for irreversible geophysical change. In the present study we consider the giant comet issue from both astrophysical and climatic perspectives.

## 2. Periodic Extinctions and External Forcing

The coincidences in age between tektites and Tertiary extinction events were an early indication that extinctions and cometary impacts could well be related (Urey, 1973). An extinction mechanism then proposed was the attenuation of sunlight through stratospheric dust injection from the meteor stream of a large comet, not least for the Cretaceous-Tertiary event (Hoyle and Wickramasinghe, 1978, 1991; Wickramasinghe and Wallis, 1994). Furthermore, it did seem that both impact cratering and global tectonic events could be understood in terms of bombardment episodes every $\sim$ 26 million years (Seyfert and Sirkin, 1979). The specific Galactic connection only emerged however with the realization that global terrestrial disturbances associated with bombardment episodes could be both regular (periodic) and random on appropriate timescales provided large comets were correspondingly dislodged from the Oort cloud as the Solar System moved through the Galaxy. Conceived as a general theory of catastrophic evolution, this meant that major extinctions such as the KT event were probably caused by bombardment episodes involving $\sim$ 10-kilometre (cometary), asteroids (Napier and Clube, 1979; Clube and Napier, 1984). Thus the implied galacto-terrestrial relationship was based on prior astrophysical considerations and was not simply an *ad hoc* response to the discovery of iridium anomalies (Alvarez *et al.*, 1980) or other extraterrestrial markers at the KT boundary. The likely agent of periodicity is the Galactic tide which acts on the Oort cloud in a 25–33 Myr cycle (Napier, 1987; Matese *et al.*, 1995; Clube and Napier, 1996).

Appropriate geological databases have now improved to the point where the $\sim$ 30 Myr periodicity claims can be subjected to quantitative analysis and accurately assessed. Thus Fischer and Arthur (1977) and Raup and Sepkoski (1984) claimed that the fossil extinction record, including mass extinctions, seemed to fit a regular periodicity, the latter authors finding a 26 Myr periodicity in the extinction of global marine families. A 1992 compilation (Rampino and Caldeira, 1992) of databases of the past $\sim$ 260 Myr, 76 well-dated major geological events were catalogued comprising 11 mass extinction peaks, 13 ocean anoxic and black shale events, 12 continental flood basalt vulcanisms, 9 large discontinuities in sea-floor spreading rates, 17 dates of widespread stratigraphic sequence boundaries (usually indicating major periods of low sea level) and 14 mountain building events. Power spectrum analyses (Rampino and Caldeira, 1992; Clube and Napier, 1996) yield evidence of a phase-matched $\sim$ 26 Myr periodicity in both the biological and geological datasets, coupled with a recent out-of-phase surge. The latter surge commenced some 5 Myr BP and seems to merge with the onset of the Pleistocene glaciations about 2.5 million years ago.

Table I summarises the statistical analysis of these datasets (see also Figure 1; for details see Clube and Napier, 1996). The 'best fit' periodicity for all the data combined is compared with the individual mass extinction peaks from the compilation, and with the periodicity for all the other geological phenomena. In constructing the

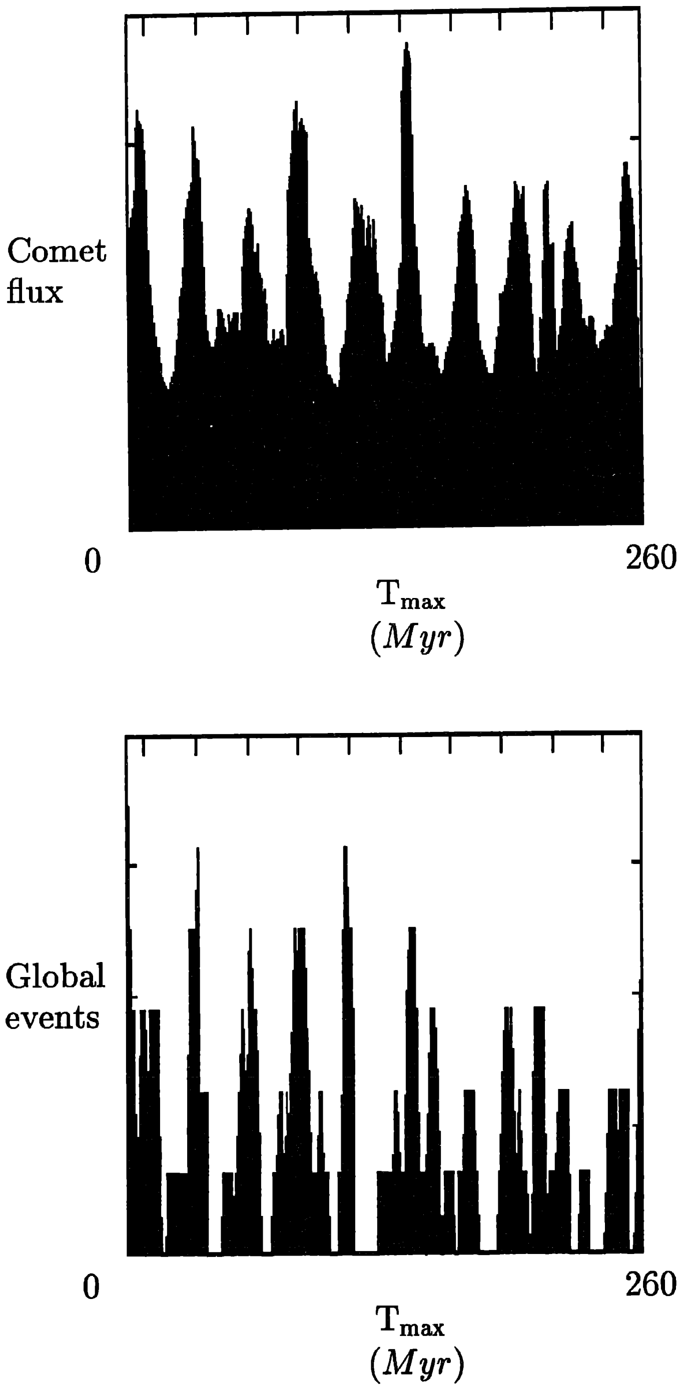

*Figure 1.* Top: Variation of the long-period comet flux due to vertical oscillations of the Sun through the Galactic disc, assuming a central disc density of 0.15 $M_\odot$ pc$^{-3}$ and scale height 50 pc, and a 70 pc amplitude of oscillation of the solar orbit. After Clube and Napier (1996). Bottom: Major geological events (Rampino and Caldeira, 1992), plotted with exponential smoothing within a 4 million year window. Best-fit periodicity, excluding recent activity, of $P = 10.3 + 26.3n$, $n = 0, 1, 2\ldots$ is marked by vertical dashes.

Table I

Periodicity in the terrestrial record. The left-hand column represents the best-fit periodicity of per genera marine extinctions and global geological events combined, excluding those $\leq$ 8 Myr BP; the central column lists individual peaks in the marine extinction record alone; and the right-hand column represents the best-fit periodicity from global geological events alone

| 'All data' peaks | Extinction peaks | Geological peaks |
|---|---|---|
| – | 1.6 | 2.0 |
| 11.9 | 11.2 | 10.3 |
| 37.8 | 36.6 | 36.6 |
| 63.7 | 66.0 | 62.9 |
| 88.8 | 91.0 | 89.3 |
| 115.5 | 113.0 | 115.6 |
| 141.4 | 144.0 | 141.9 |
| 167.3 | 176.0 | 168.2 |
| 193.2 | 193.0 | 194.5 |
| 219.0 | 216.0 | 220.9 |
| 245.0 | 245.0 | 247.2 |

peaks the recent significant surge of activity (in the Pleistocene) has been excluded. Clearly the mass extinctions, and the other major geological events, fit closely to the same ~ 26 Myr periodicity, separately and together. The periodicity is present at a high confidence level (*loc. cit.*) and its amplitude is large, the whole Earth switching on and off in a regular cycle.

Loper *et al.* (1988) have suggested that outbursts of global vulcanism might recur quasi-periodically due to a dynamical instability in the mantle of the Earth. However the terrestrial impact cratering record reveals evidence of the predicted bombardment episodes closely matching the Holmes cycle (Matsumoto and Kubotani, 1996; Clube and Napier, 1996). For example the end-Cretaceous extinctions (~ 63 Myr) and the Deccan Trap outpourings (~ 65 Myr BP) fit on to the 64 Myr BP peak of the 'Holmes cycle' but are also closely coincidental in age with the Chicxulub impact crater ($65 \pm 0.2$ Myr BP). Thus the periodicity cannot be explained by endogenous forcing. The cycle also constrains the possible external forcing mechanisms: the impact of stray bodies from the asteroid and Edgeworth-Kuiper belts seems not to be primarily involved since these belts are not, so far as is known, subject to disturbances with this periodicity. Further, the dynamical lifetimes of objects in near-Earth orbits is about 30 million years, adequate to smear out any periodicity in their arrival rate unless the perturbing Earth-crossers are physically short-lived. Rocky or iron asteroids are therefore excluded as prime movers, consistently also with the absence of bulk meteoritic material at the KT and other extinction boundaries.

The importance of cometary dusting in climatic change is empirically supported by the recent detection of $^3$He, of probable cometary origin, in a North Pacific pelagic clay core dating back over 70 Myr (Farley, 1995; Farley and Patterson, 1995). The implied flux of cometary dust is highly variable, showing strong peaks at $\sim$ 66 Myr, $\sim$ 37 Myr and $<$ 2 Myr BP (cf. Table I). There is thus direct evidence for an association between comet dusting and geologically noisy epochs. At higher resolution, the dust deposition correlates strongly with a 0.1 Myr cycle in the climatic record of the past million years (Farley and Patterson, 1995). The latter seems to imply a likely enhanced capture probability of comets as the ecliptic crosses mid-latitude Galactic bands (Delsemme and Patmiou, 1986) and where comets have perihelion and nodal precession rates $(g, f)$ which match the 'grand cycles' close to simple fractions or multiples $k_j$ $(j = 5, 6, 7, 8)$ of the major planetary secular resonances $(g_j, s)$ (Knezevic *et al.*, 1991). Thus giant comets from the standard Oort cloud having orbital planes close to the ecliptic plane and $|g|, |f| \sim 3.25$ arcsec/yr, which are capable of making repeated encounters with Jupiter to produce a cumulative perturbation, are likely to be preferentially transferred at $\sim$ 0.1 Myr intervals into low-inclination, sub-Jovian orbits along four distinct corridors corresponding to the ecliptic intersections of these Galactic bands, consistent with the current Holocene epoch.

## 3. Comet Splitting and Stratospheric Dust

The observed inverse semi-major axis (i.e. orbital energy) distributions of long- and short-period comets have long been understood in terms of strong planetary encounters in association with hierarchical splitting (cf. Comet P/Shoemaker-Levy 9), the fragments being increasingly faded and resilient, as would be expected, for example, were the largest representatives (diameters $>$ 100 kilometers, say) to have carbonaceous chondritic cores just as the larger parent bodies of meteorites (diameters $>$ 500 km, say) are expected to have more purely chondritic ones. Thus, to the extent that the long-period comets are also the source of short-period ones, classified as Jupiter-family or Halley-type (Levison and Duncan, 1990), it is natural that these derivatives should continue to split and are represented as a whole by populations in excess of the expected unsplit dynamical transfers which include large devolatilized members such as Chiron. Splitting is a commonly observed process: 21 comets have been recorded as having done so between 1846 and 1976 and three since 1989 (Chen and Jewitt, 1994). It occurs at a rate of one or more events per comet per century and is a likely major mode of disintegration and evolution. The precise mechanism is not known except for those comets which pass within the Roche limit of a planet or the Sun; and the emergence of differing constitutional types among remnants on the occasions of these rare events seems to indicate compositions which are heterogeneous on all scales, including some which cannot withstand typical tidal or explosive forces. It is likely that short-period comets make close passages to Jupiter every century or so and if one in a thousand of these is a giant comet (diameter $>$ 100 kilometers), splitting into thousands of fragments, then major upsurges in the Jupiter-family population will take place within its dynamical lifetime, thereby accounting for an observed excess in this population (Pittich and Rickman, 1994). A more extended disintegration pattern can be expected for the giant comets deflected into sub-Jovian space as they will tend to experience insolation and small-body impacts as well as close encounters with terrestrial planets. For example sub-Jovian space currently contains a single broad complex of (cometary) asteroidal and meteoroidal debris known as the Taurids, with a dynamical lifetime of $\sim 10^{-2}$ Myr (Steel *et al.*, 1994).

In general, visible comets grow tails, losing dust and volatiles, when their orbits acquire perihelia of $q < 2.5$ AU and many are associated with meteor streams observed when the Earth intersects their orbital tracks. The active comets are clearly evanescent bodies, with lifetimes one to ten millennia, and so represent the tip of an iceberg, with a large undiscovered population of inert bodies belonging to the Jupiter and Halley families. The mass distribution of comets is a power law with index $\sim -1.7$, possibly steepening to $\sim -2$ at the high mass end. The cumulative flux of large long-period comets is given by $F \sim 1 \times (d/5)^{-2}$ comets AU$^{-1}$ yr$^{-1}$, $d$ the diameter of the comet in kilometers (Bailey *et al.*, 1994). There is no securely known upper limit to $d$, but several historical comets, such as the Great Comet of 1577 and Comet Sarabat of 1729, appear to have had diameters in the range $100 - 300$ km and masses $\sim 10^{21} - 10^{23}$ g. Chiron, in a chaotic orbit which currently lies beyond Saturn, may be $180 \pm 30$ km in diameter. A giant long-period comet ($d > 100$ km) is therefore expected to cross the Earth's orbit about once every 400 yr, a Sarabat-sized body ($>$ 300 km) once within the timescale of civilization. The injection rate of giant comets from a chaotic, trans-Saturnian orbit into a stable Earth-crossing one is of order 10 Myr$^{-1}$.

A comet with $d = 200$ km and mass $M = 10^{23}$ g thrown into a Taurid-like orbit ($P \sim 3.3$ yr, eccentricity $\sim 0.85$) will lose $\dot{M} \sim 10^{18}$ g yr$^{-1}$ due to outgassing, more than half of it as meteoroidal dust with diameters in the range 0.01 $\mu$m to several mm (Fulle, 1990). A particle size distribution $n(a)da \propto a^{-3}da$, $a > 0.01$ mm, is indicated by the Halley data, implying a significant pile-up of mass in the submicron size range. Outgassing and dust production will not be uniform with time: the overall active lifetime of the comet $\sim$ 3000 yr may be interspersed with dormant periods when the surfaces become temporarily crusted. During its active lifetime such a comet could generate a zodiacal cloud of mass $\sim$ 300 times that of the present one.

Solar radiation pressure forces have an important role in separating the various grain sizes and compositions within the cloud. The critical ratio of radiation pressure force to gravity below which particles will be retained in bound orbits depends on the eccentricity of the parent cometary orbit as well as the precise point on the orbit at which the particles are released. For a comet in a circular (or near circular) orbit with radius 1 AU, the condition for retention is $P/G < 0.5$;

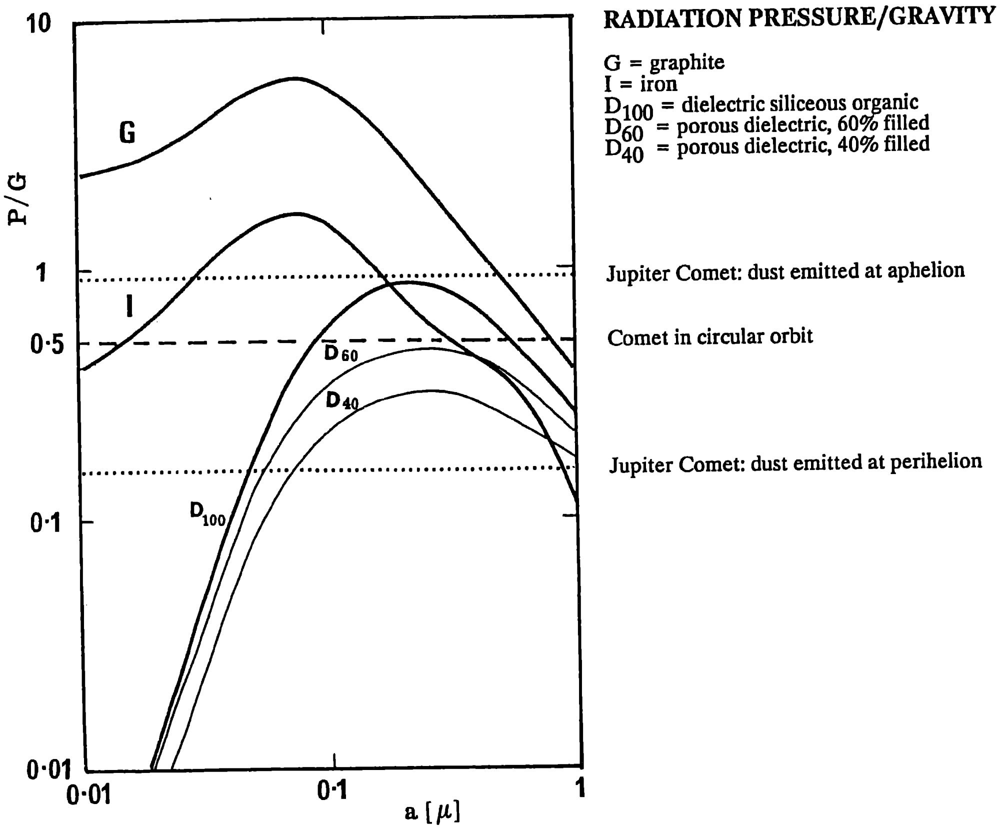

*Figure 2.* The ratio of radiation pressure to gravity for spherical particles near the Sun. The curve $G$ refers to graphite; $I$ refers to iron; $D_{100}$, $D_{60}$, $D_{40}$ refer to a sequence of non-porous grains, 60% volume-filled porous grains and 40% volume-filled porous grains respectively. The dotted and dashed lines show critical $P/G$ values for retention in bound orbits.

for a comet in an elliptical orbit with $e = 0.7$ (a Jupiter comet) the appropriate condition is $P/G < 0.85$ for aphelion emission, and $P/G < 0.15$ for perihelion emission (Ishimoto and Mukai, 1991). These conditions are marked by the dotted and dashed lines in Figure 2. The several curves show the ratio $P/G$ from Mie-type computations for spherical particles of graphite, iron and dielectric compositions (minerals or organics). We consider dielectric grains with varying degrees of porosity, $D_{100}$, $D_{60}$, $D_{40}$ referring to non-porous, 60% volume-filled and 40% volume-filled respectively. The dielectric material in these calculations is taken to have a bulk refractive index $m = 1.5$ and density 2 g cm$^{-3}$. Whilst submicron iron and graphite (metallic) grains are seen to be easily lost according to our computed $P/G$ criteria, organic or mineral grains of all sizes which are < 60% volume-filled would be wholly or mostly retained in bound orbits, depending upon the point in the orbit at which they are released.

For dust particles in bound orbits the main loss mechanism from the zodiacal cloud would be due to Poynting-Robertson drag forces. The Poynting-Robertson timescale at 1 AU is plotted in Figure 3 for each of the grain types considered. We

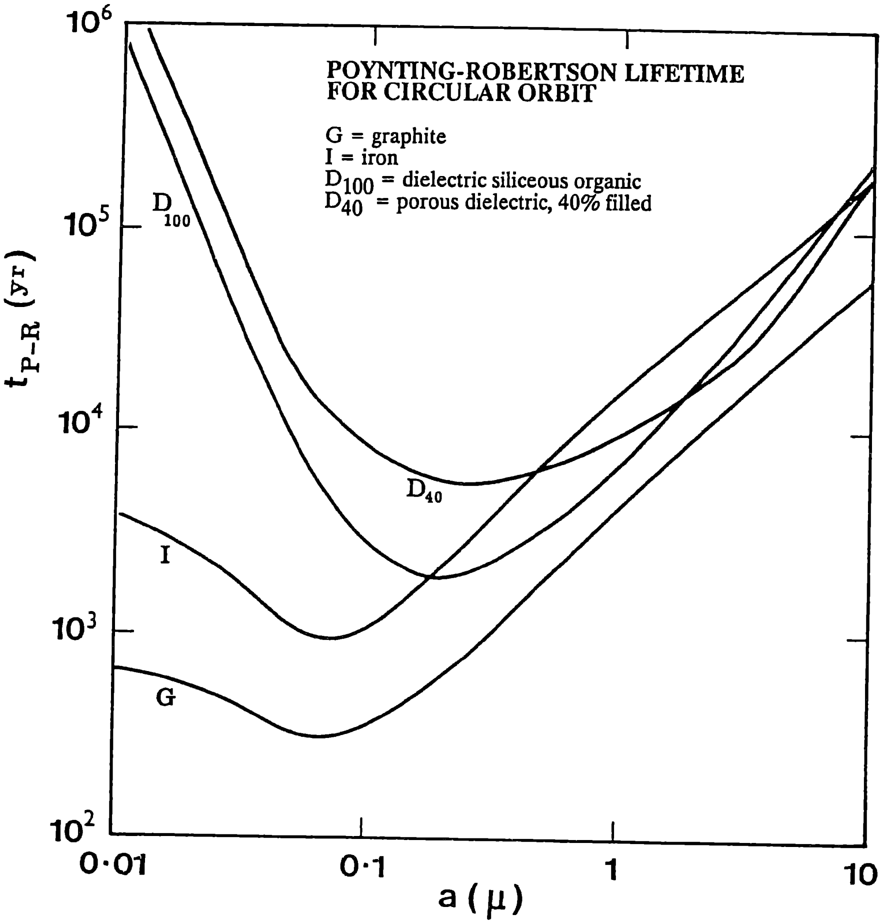

*Figure 3.* The characteristic Poynting-Robertson lifetimes for particles in heliocentric orbit at 1 AU. The symbols marking the curves refer to the same cases as in Figure 2.

note that iron grains of radii 0.1 $\mu$m and organic/mineral grains of radii 0.03 $\mu$m have Poynting-Robertson timescales of 3000 yr on the average, whereas graphite particles have considerably shorter lifetimes. The longest Poynting-Robertson timescale is calculated for porous dielectric grains, with $t \geq 10^4$ yr. A zodiacal cloud resulting from a cometary evaporation episode would thus have an average lifetime of $\sim 10^4$ yr. Modelling this temporary zodiacal cloud as a disc of mass $5 \times 10^{21}$ g, radius 1 AU and thickness 0.2 AU it is found that $\sim 10^9$ tons of dust are swept up by the Earth annually over a few millennia when the comet is active. A porous mineral/organic IDP particle of radius $0.1 - 0.3$ $\mu$m and density 1 g cm$^{-3}$ has a settling time through the atmosphere of about $3 - 10$ yr and such grains are efficient scatterers in the optical wavelength range. It is readily estimated that the Earth gathers up a stratospheric dust veil whose optical depth may fluctuate in the range $0.05 \lesssim \tau \lesssim 3$ during the cometary active lifetime of $10^3 - 10^4$ yr.

For a mixture of micron and submicron grains incident on the Earth's upper atmosphere, the submicron component would tend to be optically dominant. The mean scattering angle of a 0.1 $\mu$m particle is $\sim$ 90° (Hoyle and Wickramasinghe, 1991), almost independently of composition, and its settling time through the stratosphere is about a decade (Kasten, 1968). Because the settling time of $\sim$ 1 $\mu$m grains is about 1 year, it follows that if equal masses of $\sim$ $\mu$m and 0.1 $\sim$ $\mu$m grains are incident on the upper atmosphere, the smaller sizes will accumulate in the stratosphere relative to the larger ones. Further, very fragile sub-cometary meteoroids of $\sim$metre dimensions may disintegrate to $\sim$ 0.1 $-$ 1 $\mu$m particles during their pre-atmospheric descent (Fechtig, 1982), and may compete with the preformed zodiacal dust as a major source of optical depth. One thus expects that, in the presence of a disintegrating giant comet, the Earth will be enveloped in a highly reflective dust cloud.

## 4. Glaciation and Greenhouse

Without the greenhouse effect the Earth's mean temperature, averaged over latitude, day and night, and land and sea, is given by $[F_\odot(1 - A)/ac]^{1/4}$ where $F_\odot = 1.37 \times 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ represents the solar energy flux at the Earth's distance from the Sun. Here $A$ is an averaged value for the Earth's albedo, $c$ is the speed of light and $a = 7.565 \times 10^{-15}$ erg cm$^{-3}$ deg$^{-4}$ is the radiation density constant. Thus for an albedo of 0.4 the Earth would have a mean temperature $\sim$ 245 K or $-28$ C. Opacity sources are highly wavelength dependent, and we seek an approximation with the virtue of physical rectitude rather than attempt to set up a supposedly accurate computation in which approximations of uncertain physical validity are nevertheless made in the end! Thus if we divide the re-radiated energy at ground and sea level into two essentially equal halves about a central wavelength at $\lambda = 13.5$ $\mu$m (say), then we may suppose that half the emission, longward of 13.5 $\mu$m, is completely blocked by the heavy opacity of greenhouse gases while the remainder, shortward of 13.5 $\mu$m, is completely free to escape. It follows that the greenhouse effect raises the Earth's mean temperature by a factor of $2^{1/4}$, i.e. to about 292 K (19 C) rather than 245 K, a result agreeing closely with experience.

In practice, water vapour and $CO_2$ are the main greenhouse gases. The $CO_2$ produces essentially the whole of its effect through absorption in the infrared over 13.5 $\mu$m to 17.5 $\mu$m. Because the blocking by carbon dioxide over this interval is large, the band having steeply-falling wings, additions of $CO_2$ have only a second-order influence on the greenhouse effect and are inconsequential compared to the major factor, water vapour, controlling the Earth's climate. There is weak absorption by water vapour shortward of $\lambda = 13.5$ $\mu$m while its blocking effect rises all the way from 17.5 to $\sim$ 100 $\mu$m. In other words, there is a partial window at $17.5 \lesssim \lambda \lesssim 20$ $\mu$m which roughly compensates the blocking shortward of $\lambda = 13.5$ $\mu$m essentially justifying the adopted approximation. Evidently then, it is water vapour, that of a 'standard atmosphere' implying 1 cm cm$^{-2}$ of precipitable water, which raises the Earth's temperature by $\sim$ 40 C and without it, the Earth would now be locked in a permanent ice age (Hoyle, 1996).

Reducing the water content of the atmosphere to a few mm cm$^{-2}$ weakens the greenhouse, dropping the Earth's mean temperature (for the same $A$) to $\sim$ 280 K, which corresponds closely to what is required for typical ice age conditions. It follows that a reduction of the average water content by about two thirds, while maintaining the albedo, would produce an ice age. The same result would be achieved if $A$ increased from 0.4 to 0.5 or if the insolation of the upper atmosphere declined by about 16 percent. Such albedo and insolation are readily attained when the Earth intersects material in orbit associated with the disintegration of a giant, active comet. Very large comets, it appears, will trigger the onset of glaciations.

Ice-age conditions have generally been dry and cold. The great deposits of loess (wind-blown soil) in Eastern Europe and China imply a climate that was dusty in the lower atmosphere, implying a low precipitation rate. Low precipitation is not a handicap in the accumulation of large glaciers, which will grow even at annual precipitation rates as little as a few cm/yr, provided that the temperature is low enough to prevent summer melting.

During the ice ages the whole Earth was cooled, including the tropics. This is proved by glaciers extending down to about 10 000 feet on tropical mountains which do not at present hold glaciers, such as those on Hawaii. The need for the whole Earth to be appreciably cooled is difficult to reconcile with ice-age theories depending solely on small oscillations of the Earth's rotation axis relative to the ecliptic plane, and small oscillations in the Earth's orbital eccentricity. Neither of these effects produces any change in the amount of solar energy incident on the Earth and so could not lead to widespread cooling. Oscillations of tilt merely produce slight latitudinal variations in the incidence of solar energy, which are in any case much smaller than the transport in latitude of heat by atmospheric storms and ocean currents. The transport of oceanic heat towards the poles gives a far larger effect and would easily buffer slight latitude variations of insolation. Oscillations in eccentricity of the Earth's orbit produce small shifts of solar energy between one geographical hemisphere and the other, and so should tend to cool one hemisphere and warm the other. But ice-ages occur contemporaneously in both hemispheres, not alternately, a disproof that was already understood more than half a century ago. The presence of the Milankovitch cycles is currently controversial: the most accurate climatic chronology covering the last 500,000 yr, obtained from calcite deposits in the Devil's Hole fissure in Nevada, appears to indicate a chaotic behaviour for the climate over this period (Winograd, 1992; Ludwig *et al.*, 1992). However the marine pelagic record appears to support the 100 000-year cycle (Farley and Patterson, 1995); this may be due to a combination of planetary resonances resulting in periodic giant comet dusting.

If we were to imagine a cold, dry atmospheric state being brought about today, evaporation from the relatively warm surface layers of the ocean would quickly resupply water vapour to an amount of 1 cm of precipitable water per cm$^2$, and the cooling due to a reduced greenhouse effect would quickly be gone. Thus it is the heat of the ocean which saves us from the possibility of an immediate onset of ice-age conditions. Reckoning the heat of the ocean as being the energy content above freezing point, which can be thought of as available heat, almost all is contained in a surface layer with depth no greater than a few hundred metres, the amount being equivalent to a supply of sunlight over a time interval of a few years, say 3 to 5 years. It is because the ocean has this back storage of heat that we do not drop almost immediately into an ice age.

In distant geological periods the heat storage in the ocean was considerably greater than it is at present. Today the ocean waters are close to freezing, whereas only 50 million years ago the bottom temperature was $\sim$ 15 C and the available oceanic heat was then equivalent to a 50 year supply of sunlight. The difference has been attributed to drifting continents, especially by the positioning of Antarctica and Greenland at or close to the poles. Melt water from Arctic glaciers has gradually filled the lower ocean with water close to freezing, greatly reducing the margin of safety against ice-age conditions developing. The past two million years have essentially been a continuing ice-age therefore, broken occasionally by short-lived interglacials. But clearly, from this perspective, the prospect of a drift away from an ice age, through an enhanced greenhouse effect, may be of less concern than that of a drift back into an ice age. Thus we need sustain the insolation at a significantly lower value than at present for only several years to lock enough water vapour into ice to create the permanently cold, dry atmospheric conditions of an ice age.

## 5. Changes in the Earth's Albedo

A remarkable feature of the Earth's albedo is that it may very easily be raised to values close to unity. The mass extinction coefficient, through the scattering back into space of sunlight, produced by dielectric crystals with radii of a few tenths of a micrometer, is $\sim 3000\ \mathrm{cm}^2\ \mathrm{g}^{-1}$ (backscattering amounts to about 10% of the total scattering: Hoyle and Wickramasinghe, 1991). Such an albedo change would arise, for example, if even a very small fraction of even a very dry atmosphere were to condense into ice crystals. Thus a crystallization of only 0.1 percent of the water in a very dry atmosphere (say with only 1 mm of precipitable water) would yet contribute about 0.3 to $A$. Essentially no water must be condensed into ice crystals if $A$ is to be appreciably less than unity; otherwise the Earth would appear from the outside as an intensely bright white planet with an albedo even higher than that of Venus, while below the haze of ice crystals it would be exceedingly cold at ground level. The same result would arise from the injection of $\sim 10^{14}$ g of $\sim 0.1\ \mu$m dielectric particles to the upper atmosphere. This might easily happen if the zodiacal cloud were to be flooded with the debris of an exceptionally large, disintegrating comet in a short-period orbit, or if asteroidal debris from such a comet were to strike the Earth. We discuss here the ice and dust mechanisms in turn.

The saving grace in the case of ice crystals is that they do not form in supersaturated water vapour except at very low temperatures, say $-50$ C (Hoyle, 1981). For the Earth's emission into space of radiation at wavelengths longer than $\lambda = 20\ \mu$m we can think of a photosphere at which the optical depth out into space is of order unity. If only radiation were involved in determining the water vapour temperature at this photosphere the temperature would be of order $290\tau^{-1/4}$, where $\tau$ was the optical depth from ground level up to the photosphere, suitably averaged at wavelengths $> 20\ \mu$m. In a typical atmosphere $\tau$ would be about 10, leading to a photospheric temperature for water vapour (and hence for surrounding air) of as little as 163 K, i.e. $-110$ C, far below that needed for ice crystal formation. The circumstance that ice crystals do not form profusely except under special circumstances in Antarctica shows that calculating for radiation alone cannot be correct. A convective transport of energy from ground-level to the water-vapour photosphere is required. This cannot be carried by air movements but must come from the upward transport of the water vapour itself. To keep the photospheric water vapour temperature above $-50$ C, and so to prevent ice crystal formation, the transport of water vapour must be such as would lead to an annual precipitation rate of about 50 cm (Hoyle, 1981). For comparison, the present-day worldwide average of the precipitation rate is about 80 cm of rain, sufficient to prevent ice crystal formation, but not by a wide margin. Let the world climate decline, however, sufficiently for the surface layers of the ocean to cool to the point where an annual average rainfall of 50 cm cannot be maintained, and the consequent formation of an atmospheric haze of ice crystals would plunge the Earth immediately back into an ice-age. Such sensitivity of the Earth's albedo due to ice crystallization would appear to indicate an additional tendency on the part of the atmosphere-ocean circulation to produce rapid ice age conditions in the presence of externally injected dust.

## 6. The KT Event Revisited

Amongst the effects which were predicted (Clube and Napier, 1986) as a consequence of giant comet incursions into short-period, Earth-crossing orbits were multiple impacts, high concentrations of extraterrestrial material, prolonged climatic deterioration, ocean regressions and a complex depositional history. These effects are over and above the prompt effects associated with large impacts, and permit a discrimination between the stray impact and cometary hypotheses. Since the KT boundary has been intensively studied for the past decade, it provides a good test between them. Thus amino acids of probable extraterrestrial origin appear to have been laid down over a $\sim 0.1$ Myr period around the boundary. Any such molecules would have been destroyed in the $\sim 10^5$ K fireball (Zahnle and Grinspoon, 1990; Clube and Napier, 1990). The data, however, are consistent with a protracted input of extraterrestrial organics in the form of submicron-sized interplanetary dust particles. Another observation suggesting a prolonged period of dust input is that the probable extraterrestrial component of minerals at several impact sites appears to be one or two powers of ten too high to be consistent with the dilution factor $\sim 10^3$ expected for impacts (e.g. $\sim$ 100% for a basal layer of clay at Woodside Creek, New Zealand: Schmitz, 1988). Likewise the mass of iridium deposited worldwide is overabundant by a similar factor in relation to the probable size of the Chicxulub impactor (Yabushita, 1995).

As we have already seen, porous submicron grains ($a \sim 0.1$ $\mu$m) of either mineral or organic composition expelled from comets are mostly retained in bound orbits and have Poynting-Robertson lifetimes of $\sim$ 0.1 Myr at an orbital radius of $\sim$ 1 AU. Such particles injected into the zodiacal cloud will be accreted by the Earth over the timescale as witnessed in the distribution of extraterrestrial amino acids (AIB). On the other hand, iridium-bearing graphite/metallic grains of sizes 0.01 $\mu$m (appropriate for supernova condensates) will be expelled from the inner solar system on a much shorter timescale. On this basis it is possible to understand why the iridium peak at the K/T boundary clays is considerably sharper than the 0.1 Myr-wide profile of the extraterrestrial amino acids (Wickramasinghe and Wallis, 1994).

A shroud of reflective dust accumulated by the Earth and maintained for some 0.1 Myr would lead to oscillations of climate and environmental stresses causing an extended episode of extinctions of species. Such a picture is consistent with terrestrial mean annual temperatures estimated from studies of fossilised leaves. There is an indication of a fourfold rise in precipitation and 10% increase in temperature for a period of 0.5 – 1 Myr around the K/T boundary (Woolf, 1990). A wide range of geological and paleontological data seems to require the combination of a fairly sharp extinction spurt centred at 65 Myr as well as a more extended episode of stepwise extinctions. For dinosaurs, however, a consensus is emerging that there was no gradual decline in diversity of genera towards the end of the Cretaceous, but rather a sudden extinction consistent with a concentrated cluster of bolide impacts (Sheehan *et al.*, 1991). On the other hand, groups such as the rudists and inoceradists (bivalves) seem to have disappeared $\sim$ 1 Myr before the mass extinctions on land. Similarly, Cretaceous foraminifera and dynocysts in K/T boundary clays start disappearing well before the Ir enhancement begins (Bhandari *et al.*, 1994). Depositional and palynological evidence of a double impact layer in the western USA has been presented by a number of workers (Fastovsky *et al.*, 1989; Wolfe, 1991). The intervals given vary from a few months to $\sim$ 100 yr, which are several orders less than those expected for a comet shower, but readily expected from a dense swarm of cometary debris within the debris stream of a short-period, Earth-crossing orbit. Multiple bolide strikes are also indicated by the extensive distribution of soot and products of resinous combustion found in the K/T boundary clay layer (Wolbach *et al.*, 1990; Ivany and Salawitch, 1993). The evidence that a quarter of the entire biomass was combusted is inconsistent with a single impact, but favours the idea of multiple bolide impacts leading to extensive forest fires.

## 7. Effects on Civilization and Culture

During the last twenty years or so, there has grown up the idea that random impacts due to stray asteroids are the dominant external influence on evolution (Alvarez *et al.*, 1980). However if, rather, such dramatic events as mass extinctions of species and global climatic catastrophes are attributed to swathes of cometary debris à la Shoemaker-Levy 9, it would be naive to gloss over the possible implications of the same process in relation to human culture. The Tunguska event of 1908 seems most likely to have been caused by a bolide of ~ 100 m diameter exploding at a height of some 8 km. The resulting blast wave felled trees over a distance of 40 km, charring them for up to 15 km from the centre of impact. Estimates of a 300 – 100 year timescale for successive Tunguska-type collisions are based on lunar cratering data (Shoemaker, 1983); this calculated rate has already triggered interest in projects such as *Spaceguard*. However the lunar maria are ~ 3.9 Gyr old, and there is no obvious reason why the contemporary impact rate should bear much relation to that averaged over this long time interval. Recent satellite observations of the Earth between 1975 and 1992 have revealed that some 136 sub-Tunguska bolides impacted the Earth's upper atmosphere during this interval, yielding a rate of a few per annum for objects 10 – 30 m in diameter. For 100 m sized Tunguska-like bolides the current impact rate could well be one in 30 – 100 years (Clube and Napier, 1982, 1990).

One Tunguska-like strike per century, despite its attendant horrors, would have little sociological impact. But if in times past similar strikes occurred at the rate of several tens per annum the effect upon our social systems would unquestionably have been profound. Such collisions are possible if the Earth intercepts a debris stream from a disintegrated giant comet, as we have seen. A wealth of historical data exists (Clube and Napier, 1990; Hoyle, 1993) to support the hypothesis that fragmentation of a particular comet began some 30 000 years ago and the interception of its fragments on a periodic basis has led to events that moulded our religions, mythology, beliefs and history. The beginning of the present interglacial period is marked by a very sharp rise in temperature at ~ 13 000 BP followed by cooling, and a further sharp rise at ~ 10 500 BP which is subsequently maintained. If this cooling event was occasioned by an intense spurt of cometary bolide impacts due to fragments of a giant comet in Earth-crossing orbits, similar collision episodes with declining intensity may have continued repeatedly throughout history. One could regard otherwise enigmatic events in history such as the sudden collapse of the Indus Valley Civilization of Mohendojaro and of the Old Kingdom in Egypt (accompanied by the most puzzling phenomenon of Pyramid building), both occurring at ~ 2500 BC, as fitting well with precession of the primary orbital nodes, the countdown to nodal intersection ca. 500 ± 2500$n$ AD $n = 0, 1, 2\ldots$ (Asher and Clube, 1993) and the (Taurid) cometary collision picture in general. Such intersections accompanied by widespread global cooling are predictably complemented by extended periods of global warming ca. 1750 ± 2500$n$ AD apparently characterised now by the recorded ice-rafting of oceanic sedimentary debris at these epochs throughout the Holocene (Kerr, 1996). The oldest celestial myths, which involve battles for supremacy between gods in the sky, may date from the third millennium BC although they survived at least through to Homer and Hesiod ∼ 800 BC (Clube and Napier, 1990). The next episode of violent collisions at ∼ 1000 BC may well have generated Old Testament accounts such as the destruction of Jericho. On this basis the most recent episode of severe Tunguska-type collisions may have occurred at ∼ 500 AD a time which tallies with a range of bizarre phenomena that seem to have accompanied the end of the Roman Empire. Gibbon (1979) refers to a 'fever of the Earth that raged with uncommon violence during the reign of Justinian (AD 527–565) . . . Each year is marked by the repetition of Earthquakes, of such duration and severity that Constantinophe has been shaken for above forty days . . . '. As the Roman Empire collapsed, so did that of the Guptas in India, which it seems was torn asunder by the revolt of the Huns. Further, W.M. Smart refers to Islamic text at a similar time which states: 'In the year 599 on the last day of Moharrem, stars shot hither and thither and flew against each other like a swarm of locusts; people were thrown into consternation and made supplication to the Most High'.

Purely scientific evidence from dendrochronology has also been adduced to support the idea of an externally caused ecodisaster occurring at around 540 AD (Baillie, 1990). From studies of tree ring thicknesses corresponding to the early decades of the 6th century AD, it has been found that a major dip in the Earth's temperature occurred over the entire period AD 536 – 546. The competing idea that a volcanic eruption was responsible for a dust shroud that lowered the mean temperature and reduced tree growth for a decade or more does not accord with the lack of an acid signal in Greenland ice-drills encompassing the same age. Furthermore, volcanic dust is known to settle in a couple of years at the outset, so cannot easily explain the protracted episode of cooling that has been found. We note that contemporary literature also concurs with dendrochronological data. It has been stated that 'the sun was dark and its darkness lasted eighteen months . . . the sun appears to have lost its wonted light and appears of a bluish colour . . . fruits did not ripen . . . cold and drought finally succeeded in killing off the crops in Italy and Mesopotamia and led to terrible famine in the following years'. The scene was surely set for widespread mayhem and the collapse of empires that followed.

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